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Optics and photonics — Holography —

Part 2:
Methods for measurement of hologram recording characteristics

Optique et photonique — Holographie —

Partie 2: Méthodes de mesurage des caractéristiques d'enregistrement holographique

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Foreword

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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 on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information.

The committee responsible for this document is ISO/TC 172, *Optics and Photonics*, Subcommittee SC 9, *Electro-optical systems*.

ISO 17901 consists of the following parts, under the general title *Optics and photonics — Holography*:

— *Part 1: Methods of measuring diffraction efficiency and associated optical characteristics of holograms*

— *Part 2: Methods for measurement of hologram recording characteristics*

Introduction

A hologram is an optical device utilizing interference and applied in numerous fields. In order to know the exposure characteristics of materials on which the hologram is to be recorded, it is enough to initially record the hologram under common conditions and subsequently establish the numeral values representing exposure characteristics by measuring the diffraction efficiency. Though the hologram-related terms and the measurement method of critical evaluation parameters (diffraction efficiency, angular selectivity, wavelength selectivity) pertinent to optical characteristics are specified in ISO 17901-1, there is no stipulation as to the conditions concerning hologram recording or the way to calculate the numeral values. Therefore, the purpose of this part of ISO 17901 is to provide the terms and measurement method concerning the hologram exposure characteristics. This part of ISO 17901 does not intend to restrict manufacturing process.

Optics and photonics — Holography —

Part 2:
Methods for measurement of hologram recording characteristics

1 Scope

This part of ISO 17901 specifies the terms and measurement method concerning exposure characteristics (exposure characteristic curve, exposure at half-maximum, R-value, amplitude of refractive index modulation) for the hologram recorded by double-beam interference. The materials of hologram to be measured are not restricted to any particular ones. This part of ISO 17901 does not intend to restrict manufacturing process.

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 15902, *Optics and photonics — Diffractive optics — Vocabulary*

ISO 17901-1:2015, *Optics and photonics — Holography — Part 1: Methods of measuring diffraction efficiency and associated optical characteristics of holograms*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 15902, ISO 17901-1, and the following apply.

3.1
exposure
product of the laser beam irradiance and exposure time on the recording material surface, when the hologram is to be recorded on the recording material

Note 1 to entry: Exposure is represented in Joules per square meter (J/m^2) in the SI unit system, but may also be expressed in micro-Joules per square centimetre (μJ/cm^2) or milli-Joules per square centimetre (mJ/cm^2).

Note 2 to entry: If the object wave or reference wave enters the detector obliquely in the course of the measurement of the irradiance, the value of irradiance might not be measured correctly because of reflection on the surface of the detector. In such an event, it is enough to allow the object wave or reference wave to enter the detector in an approximately vertical direction to measure the radiant flux and then to divide the obtained value by the flux sectional area on the recording material surface.

3.2
exposure characteristics curve
<of the hologram> curve of measured values plotted with the exposure taken on the axis of abscissa and the diffraction efficiency taken on the axis of ordinate, which indicate the characteristics of hologram recording materials

Note 1 to entry: This curve is also called η -E characteristics curve.

3.3
exposure at half-maximum
<of the hologram> smallest exposure that can achieve 50 % of the highest diffraction efficiency in the exposure characteristics curve

Note 1 to entry: This term is a measure to indicate the sensitivity of the hologram recording material. The smaller the exposure at half-maximum, the smaller the light quantity required for hologram recording.

3.4
R-value
diffraction efficiency of the hologram that has recorded the interference fringes of a certain spatial frequency

Note 1 to entry: For the spatial frequency of interference fringes, the value measured in air is used.

Note 2 to entry: This is an index to indicate the resolution of a recording material in terms of the fine detail of the interference fringes identified spatially in the hologram. For the finer interference fringes, the recording material that can achieve the high R-value (diffraction efficiency) can be the recording material that ensures the high resolution in the hologram. For example, R (1000) is equal to 30 when the diffraction efficiency of hologram recorded with the spatial frequency of interference fringes being 1 000 lines/mm is assumed to be 30 %.

3.5
spatial frequency
<of the hologram> number of interference fringes per unit length

Note 1 to entry: This indicates the density of a periodic pattern of interference fringes and is expressed by the number of interference fringes repeated per unit length (lines/mm). This is proportional to the reciprocal of the spacing of interference fringes.

3.6
amplitude of refractive index modulation
<of the hologram> amount of modulation of the refractive index and equivalent to the contrast of interference fringes and the mean refractive index in the recording material of a phase hologram in which the phase is modulated according to the difference in the refractive indices of the recording material.

Note 1 to entry: This is an index to indicate the phase modulation capacity of recording material and expressed also in Δn.

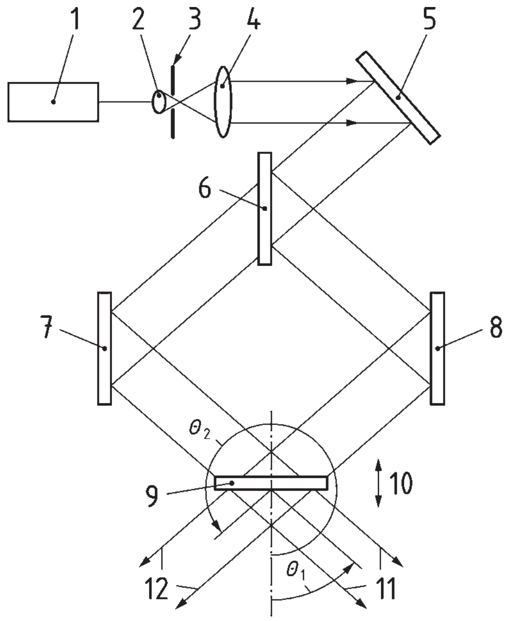
4 Symbols and abbreviated terms

NA	Numerical aperture of objective
λ	Laser wavelength in air (µm)
η	Diffraction efficiency (%)
T	Thickness of hologram (µm)
θ'_B	Bragg diffraction angle (angle inside the hologram) (radian)

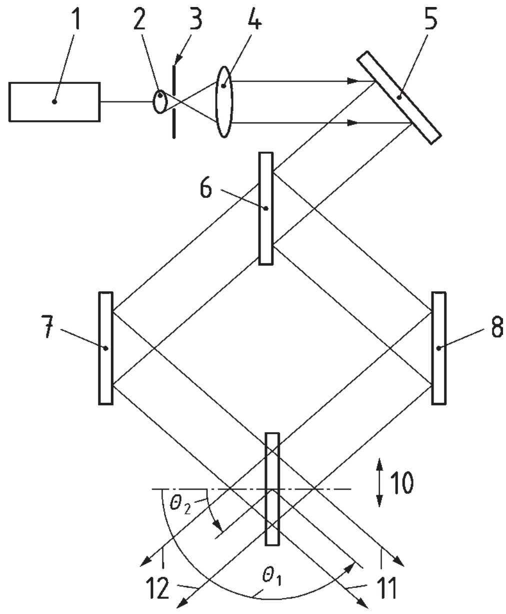
5 Principles

Holograms are recorded through mutual double-beam interference of plane waves. Examples of hologram recording optical systems are shown in Figure 1. The measurement is made of the diffraction efficiency of each hologram according to any one of measurement methods specified in ISO 17901-1:2015, 6.5. The exposure characteristics curve, exposure at half-maximum, R-value, or amplitude of refractive index modulation is derived from the relationship between the measured diffraction efficiency value and exposure conditions.

To derive the exposure characteristics curve or exposure at half-maximum, multiple holograms are recorded while changing the exposure and the diffraction efficiency is then measured for each hologram. To derive the R-value, one or multiple holograms are recorded while adjusting the incident angle of double beams in such a manner that the interference fringes with specific spatial frequency are obtained and subsequently, the diffraction efficiency of each hologram is measured. To derive the amplitude of refractive index modulation, the diffraction efficiency is measured according to any one of measurement methods specified in ISO 17901-1:2015, 6.5. Finally, the amplitude of refractive index modulation can be obtained from the Formula (2) or Formula (3) described in 6.8 to substitute values of the wavelength of light used for the measurement of diffraction efficiency, volume of the hologram, double-beam incident angle, mean refractive index of hologram, and the measured diffraction efficiency.



a) Transmission hologram



b) Volume reflection hologram

Key

1 laser
2 objective
3 pinhole
4 collimating lens
5 mirror
6 half mirror
7 mirror 2
8 mirror 3
9 hologram recording material
10 holder
11 reference wave
12 object wave

Figure 1 — Example of optical arrangements for hologram recording

6 Measurement methods

6.1 General

The exposure characteristics (exposure characteristics curve, exposure at half-maximum, R-value, and amplitude of refractive index modulation) as specified in this part of ISO 17901 are measured as follows on the basis of the diffraction efficiency as specified in ISO 17901-1. It should be noted that, according to this part of ISO 17901, the exposure characteristics during a hologram recording is derived by measuring the diffractive efficiency of holograms recorded through double-beam interference of plane waves.

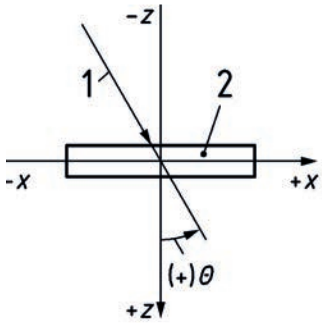
6.2 Definition of the Coordinate System

The axis of coordinate and the angle of wave are defined as follows.

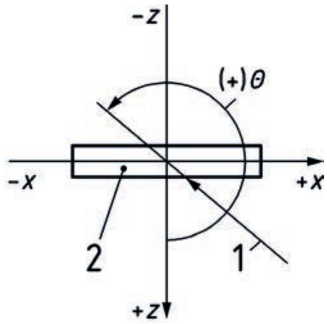
a) The recording material (or hologram) plane shall be the *xy*-plane while the axis vertical to the plane shall be the *z*-axis.

b) For the *z*-axis, the advance direction of the object (or reconstructed) wave shall be positive.

c) As shown in Figure 2, the angle of incidence, *θ*, is formed between the *z*-axis in positive direction and the extension of the incident wave; the positive symbol indicates a counter-clockwise direction).



a) Wave advancing in the +*z* direction



b) Wave advancing in the –*z* direction

Key

1 light wave

2 recording material or hologram

Figure 2 — How to establish the coordinate system and wave angle in measurement of exposure characteristics of hologram

6.3 Hologram recording environment

Hologram recording shall be made inside a dark room at stable room temperature and humidity and under conditions with thorough countermeasures against mechanical vibration and air turbulence.

For example, mechanical vibration can be prevented by mounting all of the equipment, including a laser, on a vibration-isolation optical table. In order to prevent air disturbance, the whole optical table may be enclosed in the plastic cover or blackout curtain to shut off the air flow from the air conditioner, etc. When the laser is of either air-cooling or a water-cooling type, due care should be taken on air turbulence or vibration generated from the laser itself.

6.4 Measurement device and apparatus

The optical system as shown in Figure 1 shows an example of an optical system that can be used for the measurement of the exposure characteristics of hologram recording materials. This system consists of the following components:

NOTE Refer to Annex A for the recommended assembly procedure and stability confirmation method for the hologram recording optical system, Annex B for the hologram recording procedure, and Annex C for the relationship between the spacing of hologram interference fringes of double-beam interference based hologram and the incident angle of object (and reference) waves.

a) Laser

The laser should ensure high temporal stability of the output (for example, ±5 % or less in output fluctuation over 30 min).

b) Objective

An adequate objective to be selected should be the one capable of expanding the beam diameter so that the irradiance of the laser beam irradiating the collimating lens becomes approximately even within the effective diameter of the collimating lens (for example, the magnification of ×10 to ×40).

c) Pinhole

The pinhole to be used should have the adequate hole diameter (for example, 5 approximately 25 μm) relative to the laser wavelength and the objective focal length.

NOTE The theoretical formula for the beam diameter, d, at the focal point of the objective is given by Formula (1). The value twice as large as the value given by Formula (1) can be used as a rough standard for the pinhole diameter.

$$d = \frac{4 f \lambda}{\pi \omega} \approx \frac{4\lambda}{\pi \, NA} \quad (1)$$

where

f is the focal length of objective (μm);

ω is the beam diameter of incident light (the width at which the beam intensity becomes $1/e^2$ of the maximum value (μm);

NA is the numerical aperture of objective.

d) Collimating lens

Lens as attached to the lens mount which has its spherical aberration corrected relative to the wavelength of the laser to be used.

e) Mirror

The mirror should have a sufficiently high surface flatness (for example, better than the wavelength level of about 1/10). The stage on which the mirror is to be mounted should be capable of fine motion of rotation and tilting and is best achieved using a micrometre controlled mount.

f) Half-mirror

The half mirror should be capable of achieving the reflected light/transmitted light ratio of 1:1.

NOTE Such half-mirrors include, for example, those with multi-layer derivative or chromium coating, those shaped like wedges with the wedge angle of 1 deg [=π/180 (rad) to avoid interference noise caused by backside reflection, and those provided with the anti-reflection coating.

g) Test-piece holder

The holder should be capable of moving within a range approximately equal to the test piece size while holding the hologram recording material. In this situation, the holder should have anti-vibration characteristics.

Removal or attachment of recording materials has to be done in a dark room and therefore, the holder should be configured to enable easy removal and attachment. For example, the holder may be an edged metal frame of a size approximately equivalent to the test piece (a frame with a width of about 10 mm, and matte-black coated), with the test piece clamped with leaves (clamps).

h) Detector

The detector should have a sufficient dynamic range and responsivity to the light intensity to be measured and should have been calibrated.

6.5 Exposure characteristics curve measurement method for recording of the hologram

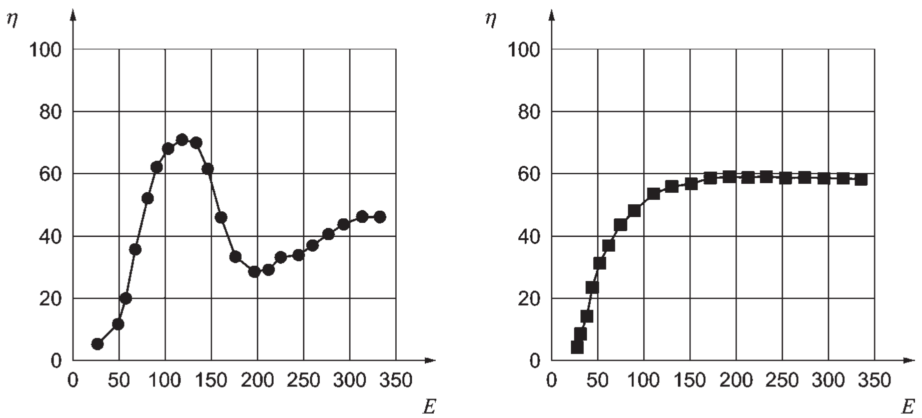
The exposure characteristics are defined by the exposure characteristics curve illustrated in Figure 3. The exposure characteristics curve (a η-E characteristics curve representing the relationship between the exposure and diffraction effects) is plotted as follows.

a) The wavelength of the light source and the incident angle of object and reference waves for a hologram recording shall be determined as required. Using the optical system shown in Figure 1, the processing specified for each recording material (development, bleach, etc.) shall be done for the recording material that has been exposed under different exposure conditions.

b) The diffraction efficiency shall be measured according to any of the measurement methods specified in ISO 17901-1:2015, 6.5.

   The diffraction efficiency can be divided into several types and generally, the corresponding values vary. Therefore, measurement of diffraction efficiency requires selection of the measurement method appropriate to the object to be measured. For the volume reflection hologram, it is recommended to use either the spectral transmission diffraction efficiency measurement or the spectral diffraction efficiency measurement by reflectance according to ISO 17901-1:2015, 6.5.4 and 6.5.5, respectively.

c) To obtain the exposure characteristics curve, the measurement results shall be plotted by taking the exposure (μJ/cm^2) along the abscissa and the diffraction efficiency (%) along the ordinate.



Key

η diffraction efficiency in (%)

E exposure in (mJ/cm^2)

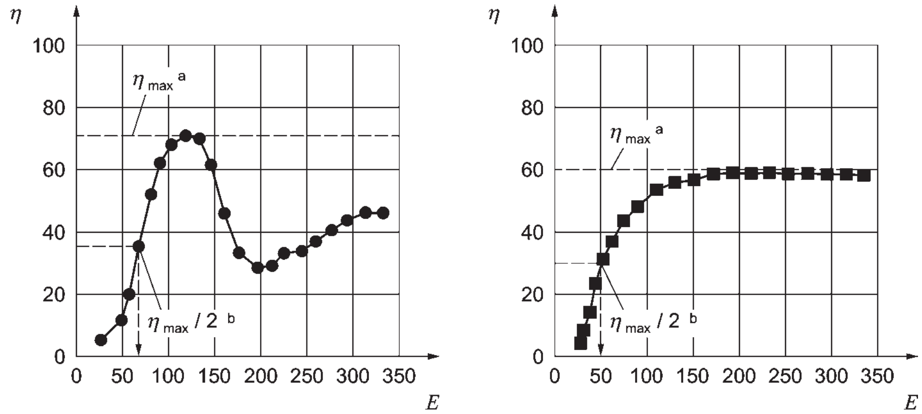
NOTE The curve showing a peak (left) and the curve asymptotic to the saturation value (right) are shown above as typical examples.

Figure 3 — Example of exposure characteristics curve (η - E characteristics curve)

6.6 Exposure at half-maximum measurement method for recording of the hologram

For the exposure at half-maximum, the lowest exposure among those (μJ/cm^2) equivalent to 1/2 of the highest diffraction efficiency in the exposure characteristics curve (Figure 3) obtained according to 6.5 (or 1/2 of the diffraction efficiency assumed to be saturated) shall be read from the graph of Figure 4.

The smaller number means the smaller exposure required for hologram recording. The exposure at half-maximum can be used as a measure to represent the sensitivity of the material for hologram recording. It should be noted here that this exposure at half-maximum is simply a rough standard to determine the exposure and is not necessarily the optimum exposure during hologram recording.



Key

η	diffraction efficiency in (%)	η_{max}	highest diffraction efficiency
E	exposure in (mJ/cm^2)	$\eta_{max}/2$	exposure at half maximum

Figure 4 — Typical exposure characteristics curve and the way of reading the exposure at half-maximum

6.7 Method to measure the R-value of the hologram

The R-value is an index to indicate the resolution of the hologram material and is defined as follows.

a) The holograms shall be recorded by changing the incident angle, θ, of the collimated double-beam. In the double beam transmission hologram case, it is assumed that the incident angle of the object wave is θ and that of the reference wave is $2\pi - \theta$. In the double beam reflection hologram case, it is assumed that the incident angle of the object wave is θ and that of reference wave is π.

   The incident angle θ shall be set so that the spatial frequency of interference fringes in air (n = 1,0) at the position of recording material becomes, for example, 500 lines/mm, 1 000 lines/mm, 2 000 lines/mm, 3 000 lines/mm, and 4 000 lines/mm (refer to Formula (C.4) for the transmission type and Formula (C.8) for reflection type).

b) The diffraction efficiency of each hologram shall be measured according to any of the measurement methods specified in ISO 17901-1:2015, 6.5.

c) The diffraction efficiency at each spatial frequency of, for example, 500 lines/mm, 1 000 lines/mm, 2 000 lines/mm, and 3 000 lines/mm, in air shall be assumed to be the R-value.

EXAMPLE Assuming that the diffraction efficiency when the transmission hologram of spatial frequency of 1 000 lines/mm in air is recorded to a certain recording material is 30 %, the R-value at the spatial frequency of 1 000 lines/mm is 30, which is represented as R (1 000) = 30.

6.8 Method to measure the amplitude of refractive index modulation of the hologram

6.8.1 General

The amplitude of refractive index modulation of volume phase holograms shall be derived from the measurement of the diffraction efficiency of the transmission or reflection hologram. Formula (2) and Formula (3) are applicable only to sinusoidal index modulation.

6.8.2 Measurement using the transmission hologram

The amplitude of refractive index modulation is measured using the transmission hologram as follows.

a) Using a collimated double-beam, the hologram shall be recorded while assuming the incident angle of object wave as θ and the incident angle of reference wave as $2\pi - \theta$.

b) The highest diffraction efficiency value (or the diffraction efficiency value recognized for saturation) shall be determined in the exposure characteristics curve (see Figure 3) derived in 6.5.

c) The amplitude of refractive index modulation (Δn) shall be calculated from Formula (2):

$$\Delta n = \frac{\lambda}{\pi T} \cos\theta'_B \arcsin\sqrt{\frac{\eta}{100}} \qquad (2)$$

The value of arcsin shall be calculated in radians.

NOTE The relationship between the Bragg diffraction angle, θ'_B, and double-beam incident angle, θ, can be expressed as follows according to the Snell's law:

$$\theta'_B = \arcsin\left(\frac{\sin\theta}{\bar{n}}\right)$$

where

$\bar{n}$ is the mean refractive index of hologram.

For the mean refractive index of hologram, it is recommended to use the value measured on the recorded hologram. Since the correct measurement is not easy generally, the value calculated on the basis of composition of materials of hologram may be used.

EXAMPLE The hologram is recorded using the 7 µm thick silver-halide photosensitive material with the wavelength of 0,532 µm and $\theta = \pi/8$ (radian) and the diffraction efficiency of 50 % were achieved. The amplitude of refractive index modulation in this case is estimated to be Δn = 0,018 when $\bar{n}$ is taken to be 1,63. Note that this value represents the amplitude of refractive index modulation when the diffraction efficiency reaches 40 % for the first time in an example of transmission hologram as shown in the left figure of Figure 3 concerning the diffraction efficiency, exposure characteristics.

6.8.3 Measurement using the reflection hologram

The amplitude of refractive index modulation is measured using the reflection hologram as follows.

a) Using the collimated double-beam, the hologram shall be recorded while assuming the incident angle of object and reference waves as 0 (radian) and π (radian) or θ (radian) and $\pi - \theta$ (radian), respectively.

b) The exposure characteristics curve (see Figure 3) shall be plotted on the basis of the diffraction efficiency measured according to ISO 17901-1:2015, 6.5.4. On this curve, the highest diffraction efficiency value (or the value of diffraction efficiency that can be recognized as saturated) shall be determined.

c) The amplitude of refractive index modulation (Δn) shall be calculated from Formula (3):

$$\Delta n = \frac{\lambda}{2\pi T} \cos\theta'_B \cdot \log\frac{1+\sqrt{\eta/100}}{1-\sqrt{\eta/100}} \qquad (3)$$

7 Description of measurement results

7.1 General

The result of measurement of the exposure characteristics of a hologram recording shall be described according to 7.3, 7.4, and 7.5. In addition, the recording procedure and conditions for the hologram concerned shall also be described as shown in 7.2.

7.2 Description of the information concerning the object to be measured

a) Name of recording material (for example, identifiable information such as the brand name, developing code no., etc.).

b) Thickness of hologram recording material before exposure (excluding the substrate or support members).

c) Type of substrate (or support members) (discrimination of glass, polymer film, etc.).

d) Features (wavelength and whether the laser is continuous wave laser or pulsed laser) of the laser beam used for the hologram recording.

e) Processing (development, bleach) applied during recording (if applicable only). The information should be enough to be reproduced by the other party.

7.3 Description of the measurement results on the exposure characteristics curve and exposure at half-maximum for hologram recording

a) The exposure characteristics are represented by both or either of the exposure characteristics curve ($\eta - E$ characteristics curve) and/or the value (μJ/cm^2) of maximum half-value exposure derived in 6.6.

b) For a description of the exposure characteristics curve, the following information shall also be described:

   1) incident angle [degree (°) or radian] of object and reference waves during hologram recording;

   2) which method(s) of 6.5 has been employed for measurement of the diffraction efficiency;

   3) incident angle of the illuminating wave [degree (°) or radian] during measurement of diffraction efficiency;

   4) wavelength of illuminating wave (the wavelength of laser when ISO 17901-1:2015, 6.5.2 or 6.5.3 is used, wavelength at the position where the transmittance becomes minimum when ISO 17901-1:2015, 6.5.4 is used, and wavelength at the position where the reflectance becomes minimum when ISO 17901-1:2015, 6.5.5 is used).

7.4 Description of the R-value measurement result of the hologram

a) The R-value shall be represented by the value obtained from measurement in 6.7.

b) In addition to the description of the R-value, the following information shall also be described:

   1) whether the object to be measured is a transmission hologram or reflection hologram;

   2) incident angle [degree (°) or radian] of object and reference waves during hologram recording;

   3) exposure (μJ/cm^2) during hologram recording;

   4) which method(s) of 6.5 has been employed for measurement;

   5) incident angle of the illuminating wave [degree (°) or radian] during measurement of diffraction efficiency;

6) wavelength of illuminating wave (the wavelength of laser when ISO 17901-1:2015, 6.5.2 or 6.5.3 is used, wavelength at the position where the transmittance becomes minimum when ISO 17901-1:2015, 6.5.4 is used, and wavelength at the position where the reflectance becomes minimum when ISO 17901-1:2015, 6.5.5 is used).

7.5 Description of the measurement result of refractive index modulation of the hologram

a) The refractive index modulation shall be represented by the value obtained in 6.8.

b) For a description of the refractive index modulation, the following information shall also be described:

1) incident angle [degree (°) or radian] of object and reference waves during a hologram recording;

2) incident angle [degree (°) or radian] of the illuminating wave during measurement of diffraction effect;

3) wavelength of the illuminating wave (μm) (wavelength at the position where the transmittance becomes the smallest in the spectral diffraction efficiency by transmittance measurement described in ISO 17901-1:2015, 6.5.4);

4) measurement or calculation (including estimation) method for the mean refractive index of hologram.

Table 1 — List of reporting items

Items	Information to be described	Necessity of entry
(1) Information concerning the object to be measured	a) Name of recording material (for example, identifiable information, such as the brand name, developing code no., etc.) b) Thickness of hologram recording material before exposure (excluding the substrate or support members) (μm) c) Type of substrate (or support members) (discrimination of glass, polymer film, etc.) d) Features [wavelength (μm) and whether the laser is continuous wave laser or pulsed laser] of the laser beam used for hologram recording e) Processing (development, bleach) applied during recording (if applicable only; the other party shall report at least the reproducible information) f) Where the diffraction efficiency has polarization dependence, show the state of the polarization of the laser beam	Mandatory
NOTE 1 If the information is common to listed items, the description may be omitted after identification of the reference relationship. NOTE 2 Among report items, at least either one of (2) or (3) shall be mandatory.		

Table 1 *(continued)*

Items	Information to be described	Necessity of entry
(2) Exposure characteristics curve for hologram recording	a) Graph of the exposure characteristics curve (an $\eta - E$ characteristics curve) b) Incident angle [degree (°) or radian] of object and reference waves during hologram recording c) Diffraction efficiency measurement method (any one or two or more of methods described in ISO 17901-1:2015, 6.5.2 to 6.5.5) d) Incident angle [degree (°) or radian] of illuminating wave during measurement of diffraction efficiency e) Wavelength of illuminating wave (μm) (wavelength of the laser when the diffraction efficiency measurement method is as described in ISO 17901-1:2015, 6.5.2 or 6.5.3, wavelength at the position where the transmittance becomes the smallest in the case of ISO 17901-1:2015, 6.5.4, and wavelength at the position where the reflectance becomes the largest in the case of ISO 17901-1:2015, 6.5.5)	Note a)
(3) Exposure at half-maximum for hologram recording	a) Maximum value of diffraction efficiency (%) b) Exposure at half-maximum value (mJ/cm^2 or uJ/cm^2) c) Diffraction efficiency measurement method	Note a)
(4) R-value of hologram	a) R-value b) Whether the transmission hologram or reflection hologram is to be measured c) Incident angle of object and reference waves during hologram recording [degree (°) or radian] d) Diffraction efficiency measurement method (any one or two or more of methods described in ISO 17901-1:2015, 6.5.2 to 6.5.5) e) Incident angle of illuminating wave during measurement of diffraction efficiency [degree (°) or radian] f) Wavelength of illuminating wave (μm) (wavelength of the laser when the diffraction efficiency measurement method is as described in ISO 17901-1:2015, 6.5.2 or 6.5.3, wavelength at the position where the transmittance becomes the smallest in the case of ISO 17901-1:2015, 6.5.4, and wavelength at the position where the reflectance becomes the largest in the case of ISO 17901-1:2015, 6.5.5)	Optional
NOTE 1 If the information is common to listed items, the description may be omitted after identification of the reference relationship. NOTE 2 Among report items, at least either one of (2) or (3) shall be mandatory.		

Table 1 *(continued)*

Items	Information to be described	Necessity of entry
(5) Amplitude of refractive index modulation of hologram	a) Amplitude of refractive index modulation b) Incident angle of object and reference waves during hologram recording [degree (°) or radian] c) Incident angle of illuminating wave during measurement of diffraction efficiency [degree (°) or radian] d) Wavelength of illuminating wave (μm) (wavelength at the position where the transmittance becomes the smallest in the spectral diffraction efficiency by transmittance measurement described in ISO 17901-1:2015, 6.5.4) e) Measurement or calculation (including estimation) method for the mean refractive index of hologram	Optional
NOTE 1 If the information is common to listed items, the description may be omitted after identification of the reference relationship. NOTE 2 Among report items, at least either one of (2) or (3) shall be mandatory.		

Annex A
(informative)

Assembly procedure and stability confirmation of hologram recording optical system based on double-beam interference

A.1 Hologram recording optical system assembly procedure

The recommended hologram recording optical system (see Figure 1) assembly procedure is described as follows.

a) Setting the reference height of the optical system

The level of the laser main body is adjusted in such a manner so that the laser beam becomes horizontal relative to the vibration-isolation optical table surface. It is recommended to assume the height of the beam above the table surface as a reference optical system height. The height of the beam can be easily aligned by using, for example, a reference height stand; namely, a glass plate having a cross mark of a thin line attached to this stand and the centre of the cross mark to be aligned to the reference height.

b) Setting the optical system

The laser beam passes through the optical system to include the mirror, half mirror, and test piece holder while bypassing the objective, pinhole, and collimating lens. The reference height stands are inserted sequentially between the components and adjustment is made by rotating or tilting each mirror until the beam height between optical paths is in line with the reference height. Finally, the two beams are adjusted to the same reference height in the test piece holder plane.

c) Setting the angle

It is recommended to set the angle of reflection of the mirror and half mirror, as well as the incident angle to the test piece holder plane simultaneously with b) above as follows.

1) When the laser beam enters the mirrors, the reference height stand is to be placed before the mirrors and the centre of the cross line is aligned to the beam centre. With the beam entering the mirror, the mirror is turned and adjusted so that the reflected beam comes back to the original position, that is, the centre of the reflected beam is aligned to the centre of the cross line. This will be the reference for angle setting.

2) The half mirror of Figure 1 has a function to transmit, as it is, the light flux from the mirror 1 toward the mirror 2 while reflecting such flux toward the mirror 3. To set the angle of the half mirror, the reference height stand is placed between the mirror 1 and the half mirror for adjustment to reset the above beam then the half mirror is turned by 45°. The same adjustment is made for other mirrors.

3) It is recommended to set and measure the beam incident angle to the surface of the test piece holder as follows.

A glass plate of a size the same as the test piece is set to the holder and the reference height stand is placed between the test piece holder and mirror 2 and between the test piece holder and mirror 3. The centre of the cross line is aligned to the centre of the beam.

Firstly, the holder is moved forward and backward to adjust its position so that two beams align in the plane of the glass plate set on the holder.

Then, the holder is turned to set the angle to zero by allowing the beam from mirror 2 to be reflected by the glass plate to return to the original position. Moreover, the holder is turned so that this reflected beam aligns with the cross line placed between the test piece holder and mirror 3. This angle of rotation corresponds to the θ_1 angle shown in Figure 1 a).

d) Setting the collimating lens

It is important when setting the collimating lens to allow the laser beam to pass through a centre (optical axis) of collimating lens and to ensure that the beam enters normal to the lens surface in the centre of this collimating lens.

1) Checking if the beam passes through the centre is made as follows.

The reference height stand is placed at a point with a distance equivalent to the focal distance from the collimating lens position toward mirror 1 and the centre of cross line is aligned with the beam centre.

2) The collimating lens is placed in the specified place and is adjusted in terms of its height and lateral shift until the beam spot converged by the collimating lens aligns with the centre of cross line.

3) Checking if the beam enters vertically to the lens surface is made as follows.

The reference height stand is placed at a focal distance point of collimating lens toward the laser side and the centre of cross line is aligned with the centre of cross line. Then, to allow the central portion of the beam reflected at the centre of collimating lens aligns with the centre of cross line, the orientation of collimating lens is adjusted by adjusting or tilting the collimating lens.

e) Setting the objective and pinhole

A unit (a spatial filter unit) incorporating both of the objective and pinhole is available and should be used. Place this unit in such a manner that the pinhole position is located at the primary forward focal point distance of the collimating lens. The pinhole is removed to align the beam with the optical axis of objective. While confirming that the good spherical wave is generated, adjustment is made to enable that the centre of the spherical wave comes to the centre of the collimating lens. Then the pinhole is inserted and moved slightly forward/backward and upward/downward until the light converged by the objective passes completely through the pinhole.

f) Confirmation of the irradiance ratio between reference and object waves

The irradiance is measured separately for reference and object waves by using the detector and the measured irradiances are confirmed to be equal to each other. If not, take steps a) through e) again.

This subclause has described an example of the procedure to make up the hologram recording optical system by mounting ordinary optical components on the vibration-isolating optical table. However, the optical system is not limited to the above one if it is a hologram recording optical system that is thoroughly adjusted and ensures recording through mutual double-beam interference of stable plane waves.

g) Confirmation of the stability of the optical system

The Mach-Zehnder interferometer is made up with the optical system and the stability of the optical system is confirmed. Specifically, a half mirror 2 is placed instead of test piece holder of Figure 1 b). The light from mirror 2 reflected by half mirror 2 and the light from mirror 3 transmitted by half mirror 2 are merged on a screen and the interference fringes on the screen are observed. The optical system is considered stable if the movement of interference fringes is sufficiently small during the assumed exposure period. If the optical system is not stable, the contrast of interference fringes recorded in the recording material lowers, resulting in deterioration of the diffraction efficiency of hologram. It is therefore recommended to confirm the stability of the optical system.

Annex B
(informative)

Hologram recording procedure

B.1 Hologram recording procedure

a) The recording material shall be fixed, for exposure, to the optical system of Figure 1 installed in a dark room.

b) During exposure, either lighting in the dark room shall be turned OFF completely or the light of wavelength for which the recording material is not sensitive shall be used.

c) The irradiance on the recording material surface, exposure time, etc. shall be recorded.

d) By recording multiple holograms while changing the exposure, the exposure characteristics of hologram recording materials can be measured in 6.5 and 6.6.

e) Since the processing might be necessary before, during, and after exposure depending on the recording material, such processing shall be implemented according to the recipe of such materials.

It should be noted that no vibration occurs during exposure in the hologram recording system. Due care should be taken because such vibration occurs because of shutter opening/closing operation, sound, air currents, thermal deformation, etc.

Annex C
(informative)

Relationship between the hologram and interference fringes due to double-beam interference

C.1 Transmission hologram

As shown in the Figure 1 a), the hologram recorded by entering double-beam at θ_1 and θ_2 relative to the perpendicular line to the recording material surface and by entering them from the same side into the recording material is generally a transmission hologram. The interference fringes spacing "*d*" on the recording material surface to which recording is made by this optical system can be expressed by Formula (C.1):

$$d = \frac{\lambda}{(\sin\theta_1 - \sin\theta_2)} \tag{C.1}$$

where

d is the interference fringes spacing (μm).

In the case of volume hologram, the interference fringes spacing "*a*" in the hologram should be determined by taking into account the refractive index of the hologram. In this case, "*a*" is expressed by Formula (C.2):

$$\mathrm{a} = \frac{\lambda_\mathrm{P}}{2\sin\left(\dfrac{\theta_1' - \theta_2'}{2}\right)} \tag{C.2}$$

$$\lambda_\mathrm{P} = \frac{\lambda}{\bar{n}}$$

where

λ_P is the wavelength in material (μm);

θ'_1 is the incident angle of object wave in the material (radian);

θ'_2 is the incident angle of reference wave in the material (radian);

$\bar{n}$ is the mean refractive index of material.

On the other hand, the following relationship is given by the Snell's law:

$$\sin\theta_1' = \sin\theta_1 / n$$

$$\sin\theta'_2 = \sin\theta_2 / n$$

Assuming that double-beam enters symmetrically relative to the perpendicular line, that is, when the double-beam is assumed to enter with $\theta_1 = \theta$ and $\theta_2 = 2\pi - \theta$, Formula (C.1) may be rewritten into Formula (C.3):

$$d = \lambda / (2 \cdot \sin\theta) \tag{C.3}$$

In this case, interference fringes become fine fringes in the vertical direction relative to the material surface.

When Formula (C.3) is expressed in terms of the spatial frequency (v), Formula (C.4) is derived:

$$v = 2 \cdot \sin\theta / \lambda \tag{C.4}$$

For measurement of the exposure characteristics of transmission hologram, it is recommended to perform recording by allowing the double-beam to enter symmetrically relative to the perpendicular line, that is, by allowing them to enter with $\theta_1 = \theta$ and $\theta_2 = 2\pi - \theta$. This is to eliminate the effects caused by expansion and shrinkage of recording materials. However, the incident angle need not be symmetrical when the light angle in the actual use environment is to be used or when evaluation is to be made on the recording material featuring expansion and shrinkage.

C.2 Volume reflection hologram

If the test piece holder of Figure 1 a) turned 90° counter clockwise, the optical arrangement of Figure 1 a) comes to Figure 1 b). The hologram recorded by allowing double-beam to enter from both the front and back sides of the recording material is called a volume reflection hologram. Interference fringes recorded in this way are stratified almost parallel (or completely parallel, depending on the condition) relative to the material surface.

The spacing of interference fringes recorded on the volume reflection hologram is determined according to the procedure described below.

Double-beam enters as shown in Figure C.1; namely, the reference wave comes in at θ_1 from the front side while the object wave comes in at θ_2 from the backside. These waves enter into the material at angles of θ'_1 and θ'_2, respectively.

Similar to the case of Formula (C.1), the spacing (d) of interference fringes is the shortest distance between neighbouring fringes and can be expressed as Formula (C.5):

$$d = \lambda / \left|\sin\theta_1 - \sin\theta_2\right| = \lambda_P / \left|\sin\theta'_1 - \sin\theta'_2\right| \tag{C.5}$$

$$\lambda_P = \frac{\lambda}{\bar{n}}$$

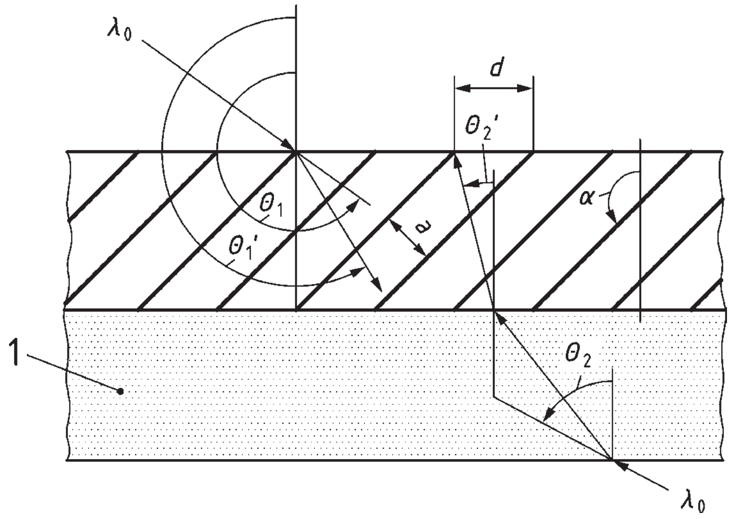
where

λ_P is the wavelength in material (μm);

θ'_1 is the incident angle of object wave in the material (radian);

θ'_2 is the incident angle of reference wave in the material (radian);

$\bar{n}$ is the mean refractive index of material.



Key

1 substrate

Figure C.1 — Forming of interference fringes during recording of volume reflection hologram

The inclination angle of interference fringes to be recorded is given by $\alpha = (\theta'_1 + \theta'_2)/2$, so that the spacing ($a$) of interference fringes can be expressed by Formula (C.6):

$$a = \frac{d}{|\cos\alpha|} = \frac{\lambda_P}{\left|2\sin\left(\frac{\theta'_1 - \theta'_2}{2}\right)\right|} \quad \text{(C.6)}$$

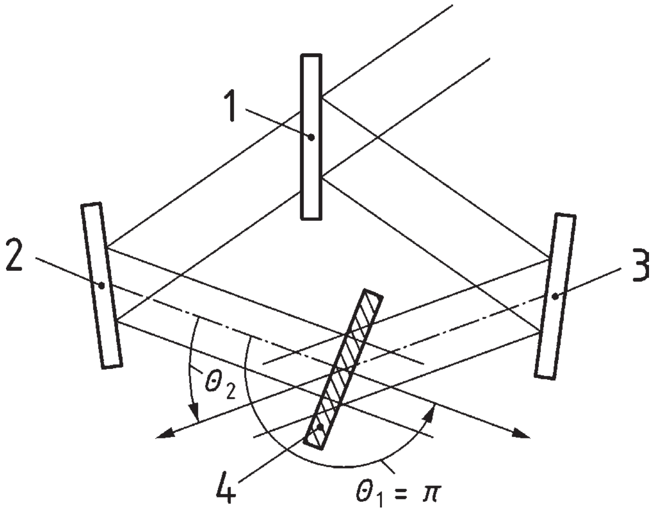
Similar to the case of Formula (C.4), this may be expressed in terms of the spatial frequency (ν) in the form of Formula (C.7):

$$\nu = \frac{\left|2\sin\left(\frac{\theta'_1 - \theta'_2}{2}\right)\right|}{\lambda_P} \quad \text{(C.7)}$$

Note that the spatial frequency (ν_{air}) in air (n = 1,0) at the recording material position can be expressed by Formula (C.8):

$$\nu_{air} = \frac{\left|2\sin\left(\frac{\theta'_1 - \theta'_2}{2}\right)\right|}{\lambda} \quad \text{(C.8)}$$

For measurement of the reflection hologram characteristics, it is recommended for recording to allow one of double beams to enter perpendicular to the recording material surface so as to separate the regular reflected light and diffracted light on the material surface. In this case, as shown in Figure C.2, the beam (reference wave) from mirror M_2 is entered vertically ($\theta_1 = \pi$) while allowing the beam (object wave) from M_3 to enter at an arbitrary angle θ_2.



Key

1 half mirror

2 mirror 2

3 mirror 3

4 hologram recording material

Figure C.2 — Optical arrangement for volume reflection hologram recording

C.3 Relationship between the spatial frequency and incident angle of interference fringes of hologram based on double-beam interference

For laser wavelength used commonly for hologram recording, the incident angle, θ, that gives the typical spatial frequency in air is shown in Table C.1 and Table C.2. ($\theta_1 = \theta$, $\theta_2 = 2\pi - \theta$ for the transmission type and $\theta_1 = \pi$, $\theta_2 = \theta$ for the reflection hologram).

Table C.1 — Relationship between the spatial frequency (ν) of interference fringes and incident angle (θ) (for transmission hologram)

	Wavelength (µm)	**Spatial frequency** (lines/mm)			
		500	**1 000**	**2 000**	**3 000**
Semiconductor laser	0,405	0,101 (rad) [5,81(deg)]	0,204 (11,68)	0,417 (23,89)	0,653 (37,41)
He-Cd laser	0,4416	0,111 (6,34)	0,223 (12,76)	0,457 (26,21)	0,724 (41,48)
DPSS laser	0,473	0,119 (6,79)	0,239 (13,68)	0,493 (28,23)	0,789 (45,19)
Ar ion laser	0,488	0,122 (7,01)	0,246 (14,12)	0,510 (29,21)	0,821 (47,05)
Ar ion laser	0,5145	0,129 (7,39)	0,260 (14,91)	0,540 (30,96)	0,882 (50,51)
DPSS laser	0,532	0,133 (7,64)	0,269 (15,43)	0,561 (32,14)	0,924 (52,94)
He-Ne laser	0,6328	0,159 (9,10)	0,322 (18,45)	0,685 (39,26)	1,25 (71,66)

Table C.1 *(continued)*

	Wavelength (µm)	**Spatial frequency** (lines/mm)			
		500	**1 000**	**2 000**	**3 000**
Kr ion laser	0,6471	0,162 (9,31)	0,329 (18,88)	0,704 (40,32)	1,33 (76,08)

Table C.2 — Relationship between the spatial frequency (*ν*) of interference fringes and incident angle (*θ*) (for reflection hologram)

	Wavelength (µm)	**Spatial frequency** (lines/mm)	
		3 000	**4 000**
Semiconductor laser	0,405	— —	1,25 (71,62)
He-Cd laser	0,4416	— —	0,976 (55,92)
DPSS laser	0,473	— —	0,660 (37,82)
Ar ion laser	0,488	1,50 (rad) [85,94(deg)]	0,439 (25,15)
Ar ion laser	0,5145	1,38 (79,07)	— (—)
DPSS laser	0,532	1,29 (73,91)	— (—)
He-Ne laser	0,6328	0,640 (36,67)	— (—)
Kr ion laser	0,6471	0,486 (27,85)	— (—)

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