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Optics and photonics — Lasers and laser-related equipment — Measurement of phase retardation of optical components for polarized laser radiation

Optique et photonique — Lasers et équipements associés aux lasers — Mesurage du retard de phase des composants optiques pour le rayonnement laser polarisé

Reference number
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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 24013 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 9, *Electro-optical systems*.

Introduction

Normally it is desirable that the state of polarization be not influenced by the optical components used. For the generation or maintenance of specific states of polarization the influence of optical components on the beam polarization is crucial. For generating circularly polarized radiation from linearly polarized radiation $\pi/2$ phase retarders are used.

This International Standard describes methods to determine the relative phase retardation of optical components with respect to the x- and y-axes of the polarization and s- and p-polarization, respectively. This International Standard is necessary for optics manufacturers, suppliers and customers of such optics for the determination of the influence of phase retardation of optical components.

Optics and photonics — Lasers and laser-related equipment — Measurement of phase retardation of optical components for polarized laser radiation

1 Scope

This International Standard specifies test methods for the determination of the optical phase retardation of optical components by polarized laser beams.

2 Normative references

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

ISO 11145, *Optics and photonics — Lasers and laser-related equipment — Vocabulary and symbols*

ISO 12005, *Lasers and laser-related equipment — Test methods for laser beam parameters — Polarization*

ISO 14644-1:1999, *Cleanrooms and associated controlled environments — Part 1: Classification of air cleanliness*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11145 and ISO 12005 apply.

4 Symbols and abbreviated terms

Symbols used and units of measure

Symbol	Unit	Term
ρ	1	degree of linear polarization
ϕ	rad	angle of analyser
a_1	V/m	amplitude of electric field in x-direction
a_2	V/m	amplitude of electric field in y-direction
a, b	V/m	principal axes of the vibrational ellipse
δ	rad	phase difference
$\Delta\delta$	rad	phase retardation
E	V/m	electric field vector
α_x	1	absorptance in x-direction
α_y	1	absorptance in y-direction
ψ	rad	angle of the principle axis of the vibrational ellipse

5 Measurement principle

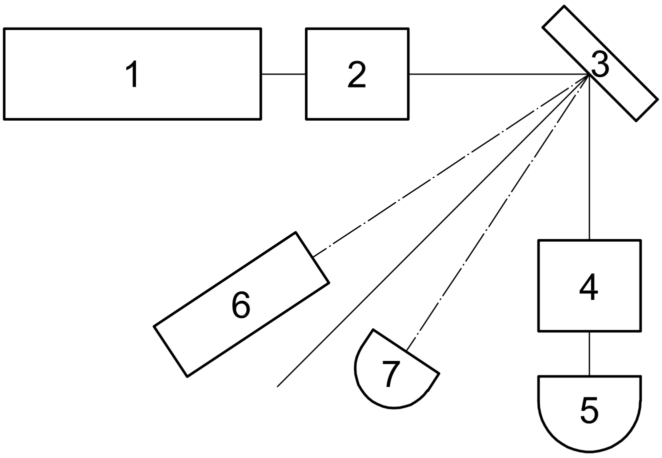
The optical component under test is irradiated by a laser beam with a defined state of polarization. After passing the component the state of polarization of the beam is determined by using an analyser. The phase retardation is then evaluated from the change of the state of polarization.

There are two cases to distinguish:

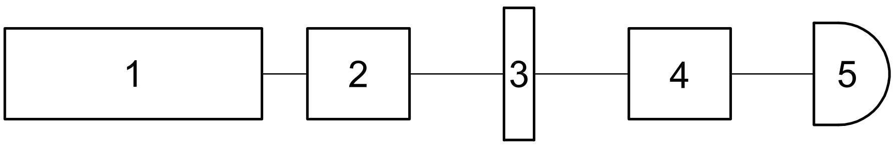
a) the expected phase retardation is near zero: in this case a circularly polarized beam shall be used for the test;

b) the expected phase retardation is near $\pi/2$: in this case a linearly polarized beam shall be used for the test.

Figure 1 shows the measuring set up.



a) Optical path for reflective samples



b) Optical path for transmissive samples

Key

1 laser

2 polarizer (linear or circular)

3 sample under test

4 analyser

5 detector

6 alignment laser

7 positional sensitive detector

Figure 1 — Schematic drawing of the measuring set up

A laser and a polarizer generating linearly or circularly polarized radiation shall be used in combination with an analyser and a power detector. For measuring reflective samples an alignment laser in combination with a positional sensitive detector ensures a reproducible angle alignment of the sample under test.

6 Preparation of test sample and measuring arrangement

6.1 General

Storage, cleaning and the preparation of the test samples are carried out in accordance with the manufacturer's instructions for normal use.

The environment of the testing place consists of dust-free filtered air with less than 60 % relative humidity. The residual dust is reduced in accordance with, for example, the clean-room ISO class 7 as defined in ISO 14644-1:1999.

A linearly polarized laser shall be used as the radiation source. To keep errors as low as possible, the beam power stability should be as high as possible.

Wavelength, angle of incidence and state of polarization of the laser radiation used for the measurement shall correspond to the values specified by the manufacturer for the use of the test sample. If ranges are accepted for these three quantities, any combination of wavelength, angle of incidence and state of polarization may be chosen from these ranges.

6.2 Laser beam preparation

The accuracy of the measurement is strongly influenced by a clear definition of the state of polarization of the laser beam. Therefore it is necessary to prepare the polarization state of the probe beam (linearly or circularly) carefully.

If the expected phase retardation is near $\pi/2$, a linearly polarized beam shall be used. The quantity $(1 - \rho)$, where ρ is the degree of linear polarization, shall be less than 10^{-3}. This shall be verified by using the analyser without the sample in the beam path.

NOTE 1 Such a state of polarization can be achieved by using a linearly polarized laser beam in combination with additional polarizing elements.

If the expected phase retardation is near zero, a circularly polarized beam shall be used. The degree of linear polarization ρ shall be less than 10^{-3}. This shall be verified by using the analyser without the sample in the beam path.

NOTE 2 Such a state of polarization can be achieved by using a linearly polarized laser beam in combination with additional linearly polarizing elements and a $\pi/2$ phase retarding element.

All optical elements shall not increase the quantity $(1 - \rho)$ in the case of a linearly polarized beam and ρ in the case of a circularly polarized beam, by more than 10^{-3}. For this reason the use of folding mirrors in the test setup is discouraged and all other optical elements shall be used under normal incidence.

6.3 Sample adjustment and system calibration

6.3.1 Reflective samples

The sample shall be mounted very accurately at the angle of incidence according to the manufacturer's specification. The deviation from the intended angle of use shall be less than 2 mrad. For this purpose the component shall be mounted on a precision rotary stage. Back reflecting the laser beam into the laser cavity defines the normal incidence.

Additionally, in the case of a linearly polarized probe beam, the angle between the plane of vibration of the incoming laser beam and the plane of incidence shall be ($\pi/4 \pm 2$) mrad.

6.3.2 Possible alignment procedure

First, the laser beam shall be adjusted so that the beam propagation is parallel to the surface of the optical table. Second, the beam reflected from the sample shall be adjusted so that the propagation of the reflected beam is also parallel to the surface of the optical table for all angles of incidence. Third, in case of a linearly polarized incoming beam, the angle between the plane of vibration and the plane of the optical table shall be adjusted to be $\pi/4$. This can be achieved by adjusting the linear polarizer initially so that the plane of vibration is parallel to the optical table. This can be checked by using a Brewster window, the turning axis of which is perpendicular to the optical table. If under these conditions the reflected minimum power is propagating parallel to the optical table, then turning of the linear polarizer by $\pi/4$ finally provides the desired angle of the linearly polarized beam.

When the alignment has been calibrated according to the procedure described above, the correct alignment of the additional samples can be simplified by using an additional laser with high pointing stability and a positional sensitive detector (see Figure 1). In this case the additional laser beam hits the component under near-normal incidence and the adjustment of the sample under test is performed so that the reflected laser beam hits the positional sensitive detector at the same position.

6.3.3 Transmissive samples

The sample shall be mounted under the angle of incidence according to the manufacturer's specification. The deviation from the intended angle of use shall be less than 2 mrad.

6.4 Detection system

6.4.1 General

The detection system consists of a polarization analyser and a power detector.

6.4.2 Polarization analyser

To determine the state of polarization of the laser beam after passing the test sample a polarization analyser mounted on a rotary stage is necessary.

The analyser shall be capable of characterizing the state of polarization of the laser beam after passing across the additional polarizer with the specified accuracy (see 6.2).

6.4.3 Power detector

To ensure that the entire beam hits the detector area, the detector width should be at least twice the beam diameter.

A high dynamic range of the signal to noise ratio is required for the low noise detector since this directly influences the resolution. Furthermore, the detector characteristics shall be linear over a wide signal range since this directly influences the accuracy of the measurements.

NOTE Silicon detectors for the visible and near infrared spectral range as well as pyroelectric detectors for the infrared spectral range may meet these specifications.

7 Test procedure

7.1 Test procedure for zero phase retardation

7.1.1 General

If the expected phase retardation is near zero, the polarization of the probe beam shall be circularly polarized. This shall be achieved by using a linearly polarized laser in combination with a quarter-wave plate or similar means. Before the test the state and the degree of this circular polarization shall be measured and recorded. The initial state of polarization is characterized by (see also Annex A).

$$\cos\delta = \frac{E^2(45°) - E^2(135°)}{2\sqrt{E^2(90°)\,E^2(0°)}} \tag{1}$$

where E^2 is the detector signal magnitude.

7.1.2 Simple test procedure for zero absorptance difference

In the case of no absorptance difference, it is sufficient to measure the detector signals at two analyser positions, 45° and 135°. The phase difference is then given by

$$\cos\delta = \frac{\frac{E^2(45°)}{E^2(135°)} - 1}{\frac{E^2(45°)}{E^2(135°)} + 1} \tag{2}$$

7.1.3 Test procedure for non zero absorptance difference

If there is a difference in the absorptance for the two polarization components it is sufficient to measure the detector signal at four analyser positions, 0°, 45°, 90° and 135°. The phase difference is given by Equation (1).

The relative difference in the absorptance is then given by

$$\frac{E^2(90°)}{E^2(0°)} = \left(\frac{a_2}{a_1}\right)^2 \qquad \frac{a_2}{a_1} = \sqrt{\frac{1-\alpha_y}{1-\alpha_x}} \tag{3}$$

7.2 Test procedure for π/2 phase retardation

7.2.1 General

If the expected phase retardation is near π/2, the polarization of the probe beam shall be linear. Before the test, the state and the degree of this linear polarization shall be measured and recorded. The initial state of polarization is characterized by a curve fit to the function given by Equation (A.4).

7.2.2 Simple test procedure for zero absorptance difference

In the case of no absorptance difference, it is sufficient to measure the detector signals at two analyser positions, 45° and 135°. The phase difference is then given by Equation (2).

7.2.3 Test procedure for non zero absorptance difference

If there is a difference in the absorptance for the two polarization components it is sufficient to measure the detector signal at four analyser positions, 0°, 45°, 90° and 135°. The phase difference is given by Equation (1).

The relative difference in the absorptance is then given by Equation (3).

8 Evaluation

8.1 General

The initial phase difference of the probe beam shall be evaluated according to 7.1 and 7.2, respectively, using Equation (1). The phase retardation shall be evaluated by subtracting the phase difference before the sample from the phase difference after the sample.

$$\Delta\delta = \delta_{\text{after sample}} - \delta_{\text{before sample}} \tag{4}$$

8.2 Evaluation for zero phase retardation

8.2.1 Evaluation for zero absorptance difference

The phase retardation caused by the test sample is given by the difference of the measured phase difference of the probe beam [without test sample, see 7.1.1, Equation (1)] and the measured phase difference after passing the test sample [see 7.1.2, Equation (2)].

8.2.2 Evaluation for non-zero absorptance difference

The phase retardation caused by the test sample is given by the difference of the measured phase difference of the probe beam [without test sample, see 7.1.1, Equation (1)] and the measured phase difference after passing the test sample (see 7.1.3). Additionally, the relative absorptance difference can be determined according to Equation (3).

8.3 Evaluation for $\pi/2$ phase retardation

8.3.1 Evaluation for zero absorptance difference

The phase retardation caused by the test sample is given by the difference of the measured phase difference of the probe beam [without test sample, see 7.1.1, Equation (1)] and the measured phase difference after passing across the test sample [see 7.1.2, Equation (2)].

8.3.2 Evaluation for non-zero absorptance difference

The phase retardation caused by the test sample is given by the difference of the measured phase difference of the probe beam [without test sample, see 7.1.1, Equation (1)] and the measured phase difference after passing the test sample (see 7.1.3). Additionally, the relative absorptance difference can be determined according to Equation (3).

9 Test report

The following information shall be included in the test report:

a) General information

1) test has been performed in accordance with ISO 24013:2006;

2) date of test;

3) name and address of test organization;

4) name of individual performing the test.

b) Information concerning the test sample

1) type of sample;

2) manufacturer;

3) manufacturer's model designation;

4) serial number.

c) Test conditions

1) laser wavelength(s);

2) laser parameter settings:

— output power or energy;

— current or energy input.

3) mode structure;

4) polarization;

5) environmental conditions:

— temperature;

— humidity;

— room illumination.

d) Information concerning testing and evaluation

1) test method used;

2) detector and sampling system:

— response time of the detector system;

— trigger delay of sampling (for pulsed lasers only);

— measuring time interval (for pulsed lasers only).

3) beam forming optics and attenuating method:

— type of attenuator;

— type of beam splitter;

— type of focusing element.

4) other optical components and devices used for the test (polarizer, monochromator, etc);

5) other relevant parameters or characteristics of the test which have to be chosen (aperture setting, reference plane, reference axis, laboratory system);

6) measured phase retardation $\Delta\delta$;

7) uncertainty of measurement.

Annex A
(informative)

Theoretical background

A.1 Description of a polarized wave

An arbitrarily polarized electro-magnetic wave with the field vector E propagating in the z-direction is described by

$$\begin{aligned} E_x &= a_1 \cos(\tau + \delta_1) \\ E_y &= a_2 \cos(\tau + \delta_2) \\ E_z &= 0 \end{aligned} \quad \text{(A.1)}$$

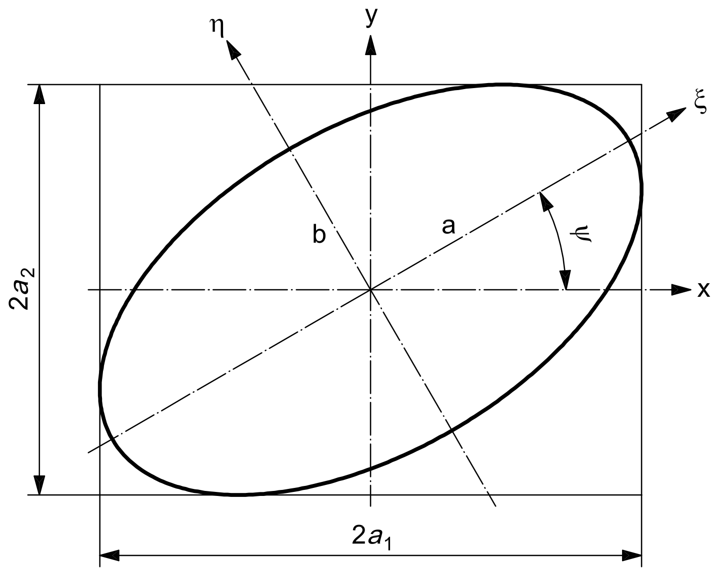
where

a_1 and a_2 are the amplitudes in the x- and y-directions;

τ is the variable part of the phase factor;

δ_1 and δ_2 are the constant part of the phase factor.

The state of polarization is generally represented by the vibrational ellipse for the electric vector as shown in Figure A.1.



Key

a principal axis of the vibrational ellipse

b principal axis of the vibrational ellipse

a_1 amplitude of electric field in x-direction

a_2 amplitude of electric field in y-direction

x, y coordinate axes of the absolute coordinate system

ξ, η coordinate axes of the principal coordinate system

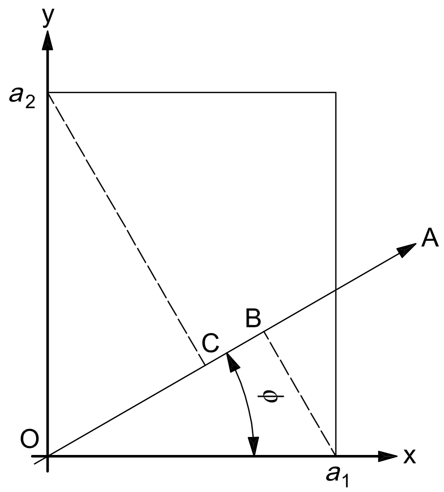
ψ angle between the principal axis of the vibrational ellipse and the x-axis

Figure A.1 — Vibrational ellipse of a polarized wave

In the general case the polarization is represented by an ellipse with the two principal axes a and b where the principal axis ξ is rotated about the reference axis x about the angle ψ. The state of polarization is either described by a, b and ψ or by a_1, a_2 and δ, where $\delta = \delta_1 - \delta_1$.

A.2 Analysing the state of polarization

For analysing the state of polarization an analyser is rotated through the beam to be characterized. The analyser transmits only the part of the electric field orientated in the same direction as the analyser as shown in Figure A.2.



Key

a_1	amplitude of electric field in x-direction	B	point of intersection of the perpendicular to A to a_1 with A
a_2	amplitude of electric field in y-direction	C	point of intersection of the perpendicular to A to a_2 with A
x, y	coordinate axes of the absolute coordinate system	O	origin of the coordinate system
A	direction of the analyser	ϕ	angle between the analyser and the x-axis

Figure A.2 — Transmitted light at an analyser

Of the electric field with the amplitudes a_1 and a_2 in the x- and y-direction respectively, only the components parallel to the analyser are transmitted. The angle between the analyser and the x-direction is given by ϕ. These components are OB and OC that are given by

$$\mathrm{OB} = a_1 \cos\phi \qquad \mathrm{OC} = a_2 \sin\phi \tag{A.2}$$

The measured signal on the detector after the analyser is directly proportional to E^2. It is obtained from the interference of these two monochromatic waves with the phase difference, δ, by

$$E^2 = E_1^2 + E_2^2 + 2\sqrt{E_1^2 E_2^2}\cos\delta \tag{A.3}$$

With the amplitudes given by Equation (A.2) this yields

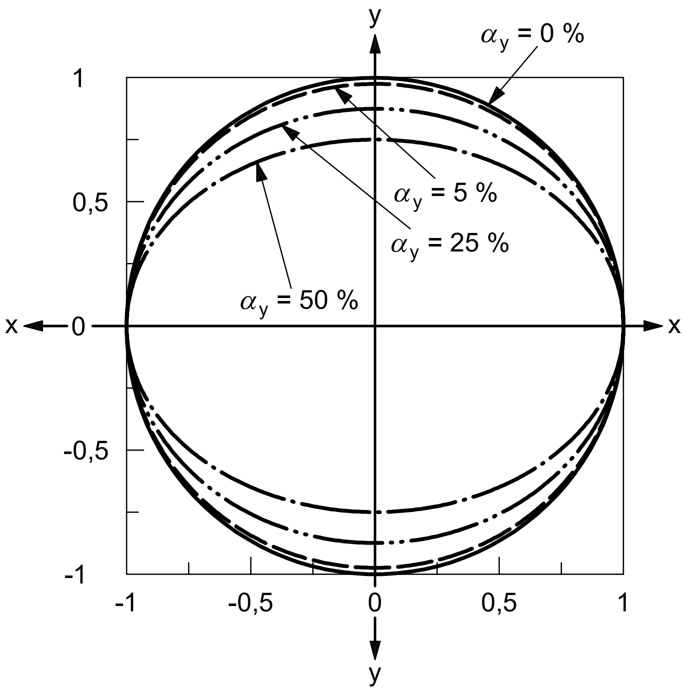
$$\frac{E^2(\phi)}{a_1^2} = \cos^2\phi + \left(\frac{a_2}{a_1}\right)^2 \sin^2\phi + \frac{a_2}{a_1}\sin(2\phi)\cos\delta \tag{A.4}$$

The signal on the detector for different angles ϕ of the analyser is described by Equation (A.4).

A.3 Influence of absorption

In the case of absorbing samples the beam before the analyser should ideally be circularly polarized for samples with phase retardations both near zero and near $\pi/2$. A difference in the absorption of the electric field between the x- and y-direction does not affect the phase difference δ of the components of the electric field but changes their amplitudes. Figure A.3 and Figure A.4 show the effect of the absorption, where the absorption in the y-direction is assumed to be greater than zero and the absorption in the x-direction is assumed to be zero.

The change in the modulation of the detector signal after the analyser does not result from a phase retardation (the phase difference remains at $\pi/2$) but from a change in the amplitudes of the two components of the electric field vector. The maxima of the detector signal are at 0° and 180° for a greater absorption in the y-direction are at 90° and 270° for a greater absorption in the x-direction.

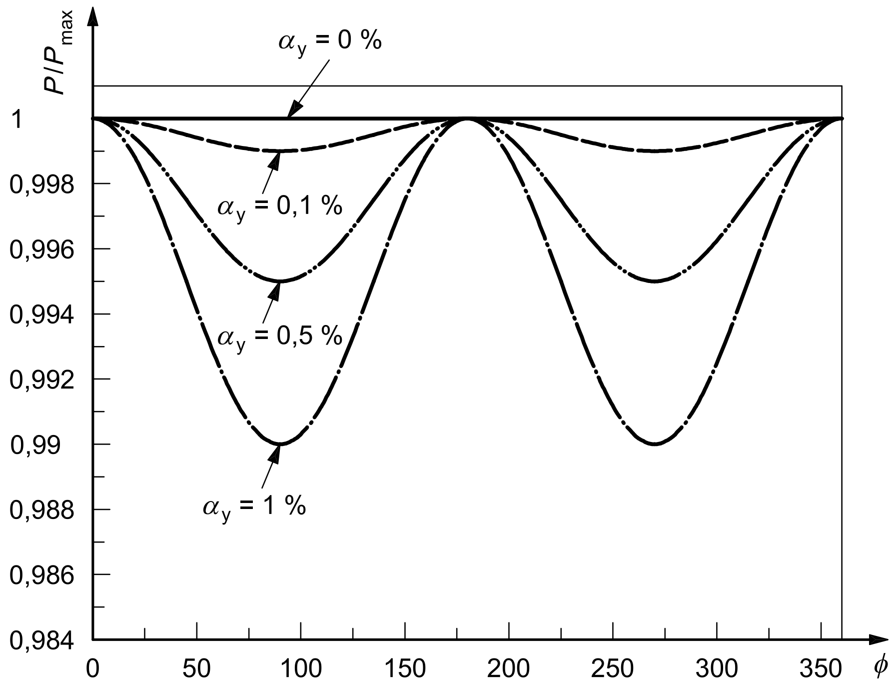


Key

x, y coordinate axes of the absolute coordinate system

α_y absorptance in y-direction

Figure A.3 — Influence of absorptance difference on vibrational ellipse



Key

P/P_{max} normalized detector signal

ϕ angle between the analyzer and the x-axis

α_y absorptance in y-direction

Figure A.4 — Influence of absorptance difference on detector signal

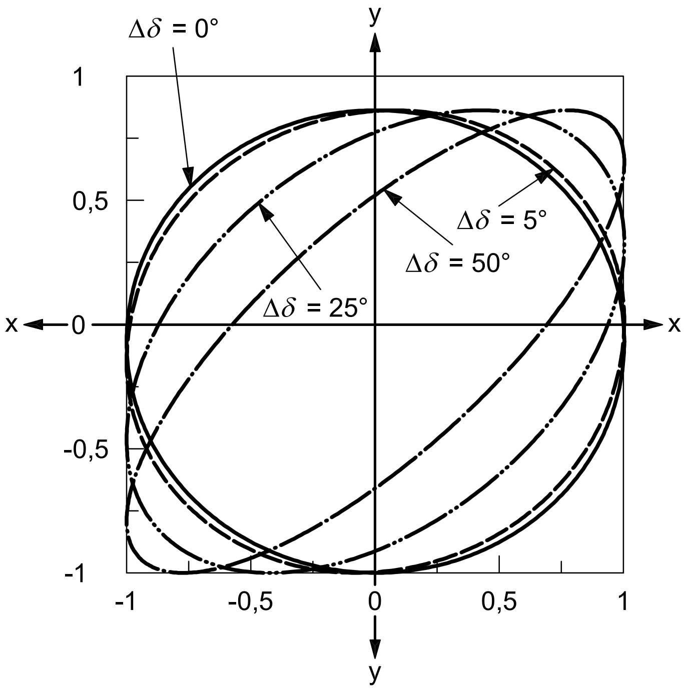
A.4 Influence of phase retardation

A pure phase retardation with the absence of a difference of the absorption does not affect the amplitudes of the incident wave. Since the ratio of the amplitudes in the x- and y-direction remains constant the angle, ψ, of the incident wave does not change. The phase retardation $\Delta\delta$ induces a deformation of the vibrational ellipse as seen in Figure A.5.

The phase retardation is given by the difference of the phase difference after and before the sample.

$$\Delta\delta = \delta_{\text{after sample}} - \delta_{\text{before sample}} \tag{A.5}$$

According to Figure A.6 the maxima of the detector signals are recognized at 45° and 225° for a phase retardation larger than zero, while the maxima are located at 135° and 315° for a phase retardation smaller than zero.

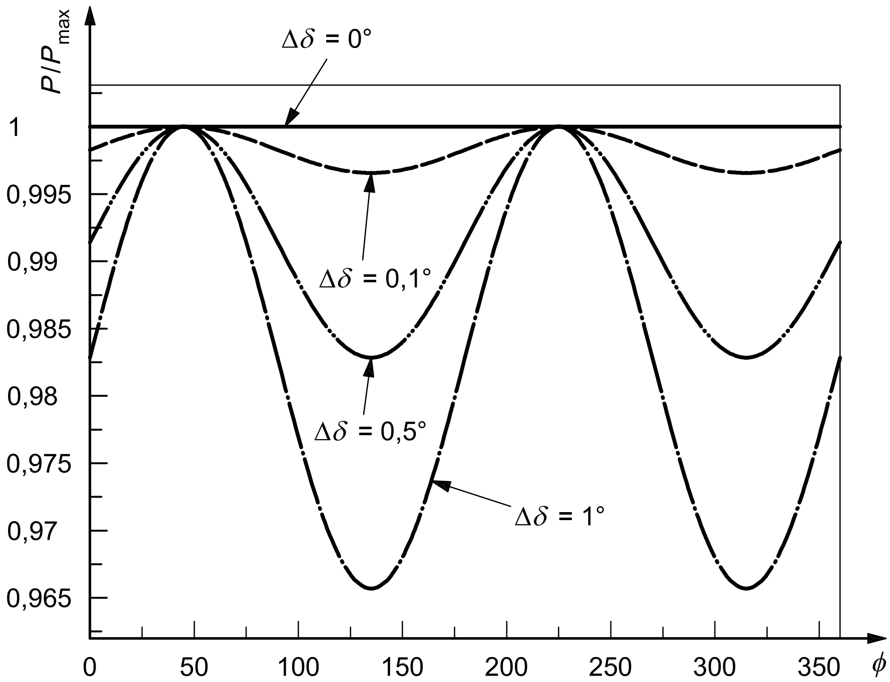


Key

x, y coordinate axes of the absolute coordinate system

$\Delta\delta$ phase retardation

Figure A.5 — Influence of phase retardation on vibrational ellipse



Key

P/P_{max} normalized detector signal

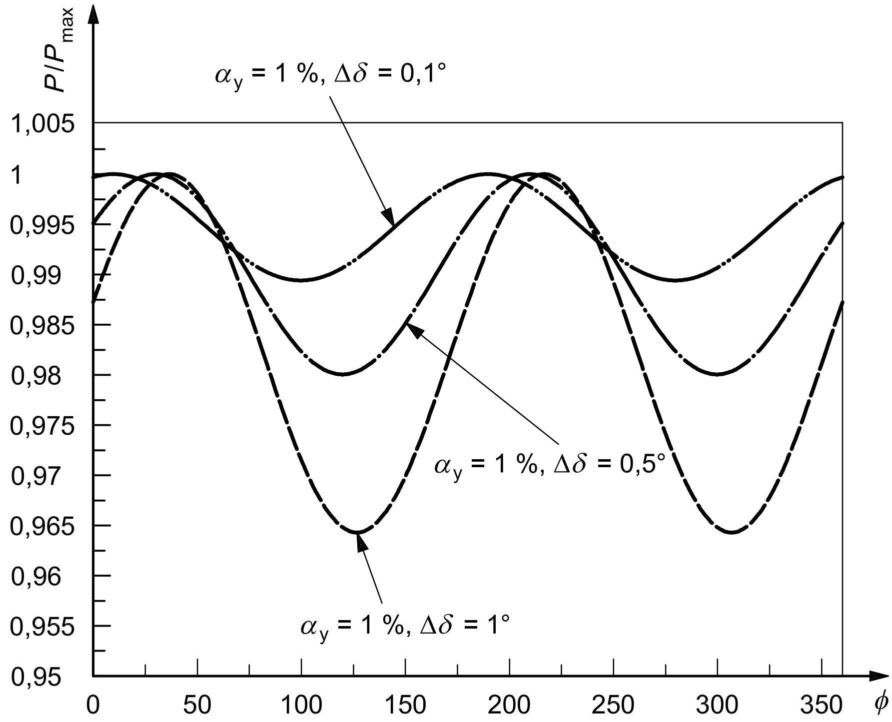
ϕ angle between the analyzer and the x-axis

$\Delta\delta$ phase retardation

Figure A.6 — Influence of phase retardation on detector signal

A.5 Influence of absorption and phase retardation

The simultaneous presence of absorption and phase retardation results in a modulation of the detector signal and a change of the angle ψ as shown in Figure A.7. Equation (A.4) includes the influence of the absorption and the phase retardation.



Key

P/P_{max}	normalized detector signal
ϕ	angle between the analyser and the x-axis
α_y	absorptance in y-direction
$\Delta\delta$	phase retardation

Figure A.7 — Influence of absorptance difference and phase retardation on detector signal

A.6 Measurement of the phase retardation — Summary of the formulae used

A function of two unknowns, described by Equation (A.4), is to be fitted on the measured signal of the detector. The fit parameters are the amplitude ratio a_2/a_1 and the phase difference δ. The amplitudes a_1 and a_2 describe the effect of the absorption. For an incident wave under ψ = 45° and for a circularly polarized beam the ratio of the amplitudes is given by

$$\frac{E^2(90°)}{E^2(0°)} = \left(\frac{a_2}{a_1}\right)^2 \qquad \frac{a_2}{a_1} = \sqrt{\frac{1-\alpha_y}{1-\alpha_x}} \tag{A.6}$$

where α_x and α_y are the absorptances in the x- and y-direction respectively.

The angle ψ is calculated from the fit parameters by

$$\tan(2\psi) = \tan\left[2\arctan\left(\frac{a_2}{a_1}\right)\right]\cos\delta \tag{A.7}$$

In the case of no absorptance difference it is sufficient to measure the detector signals at two positions, 45° and 135°, of the analyser. The phase difference is then given by

$$\cos\delta = \frac{\dfrac{E^2(45°)}{E^2(135°)} - 1}{\dfrac{E^2(45°)}{E^2(135°)} + 1} \tag{A.8}$$

In the case of a non-zero absorptance difference the phase difference is given by

$$\frac{E^2(45°)}{E^2(0°)} - \frac{E^2(135°)}{E^2(0°)} = 2\frac{a_2}{a_1}\cos\delta = 2\sqrt{\frac{E^2(90°)}{E^2(0°)}}\cos\delta$$

$$\cos\delta = \frac{E^2(45°) - E^2(135°)}{2\sqrt{E^2(90°)\,E^2(0°)}} \tag{A.9}$$

The relative difference in the absorptance is given by Equation (A.6).

Bibliography

[1] BORN, M. and WOLF, E., *Principles of Optics*, 6th Edition, Chapter 1.4.2 *The harmonic electromagnetic plane wave*, pp. 24-28; Chapter 14.4.3 *Interference with crystal plates*, pp. 694-696, Pergamon Press

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