IEC/TR 62469

Edition 1.0 2007-08

TECHNICAL REPORT

Guidance for residual stress measurement of optical fibre

IEC/TR 62469:2007(E)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE P

ICS 33.180.10

ISBN 2-8318-9301-1

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

GUIDANCE FOR RESIDUAL STRESS MEASUREMENT OF OPTICAL FIBRE

FOREWORD

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IEC/TR 62469, which is a technical report, has been prepared by subcommittee 86A: Fibres and cables, of IEC technical committee 86: Fibre optics.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86A/1143/DTR	86A/1148/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

GUIDANCE FOR RESIDUAL STRESS MEASUREMENT OF OPTICAL FIBRE

1 Scope

The measurement of residual stress distribution in an uncoated glass optical fibre is considered to be important as it affects critical fibre parameters such as refractive index, intrinsic polarization mode dispersion, mode field diameter and dispersion. The optical polarimetric method is a well-established technique to measure the residual stress of an optical material. This technical report describes a transverse polarimetric method to measure the residual stress profile of any type of optical fibre.

The principle and detailed procedure for measuring the optical transverse stress profile of a fibre, which is cylindrically symmetric, is described in detail. It is based on a polariscope, which is constructed with a fixed polarizer, a quarter-wave plate and an analyzer. An optical tomographic technique is also described for measuring the stress profile of a fibre with a cylindrically non-symmetric structure.

2 Justification of measurement

Residual stress in an optical fibre is induced by the combination of the fibre construction and the drawing process. The stress information is important because it affects many important parameters of an optical fibre due to the following reasons.

- Temperature dependent changes of fibre parameters are larger for a fibre with larger residual stress, and these are responsible for the statistical behaviour of polarization mode dispersion (PMD) changes in deployed fibre links. (See references [10-12].)[1)]
- The variation of important fibre parameters such as chromatic dispersion, mode field diameter, PMD depends on the intrinsic residual stress of an optical fibre. (See references [13-17].)
- The asymmetric residual stress profile of a fibre causes fibre curl, which affects cleaving quality for an optical fibre ribbon.
- The asymmetric residual stress of a fibre is a major cause of the intrinsic PMD of an optical fibre. (See references [18-20].)
- Excessive residual stress can lead to core cracking that might be seen in, for example, the preparation of the ends for connectors.
- The design of polarization retaining fibres normally involves inducing a non-symmetric stress field. This measurement can be used to confirm these designs.

Much progress has been made in measuring the residual stress profile of an optical fibre (see references [1-9]) such that spatial resolution can be as small as 0,6 μ and accuracy in measuring stress can be as low as 0,4 MPa.

Depending on the application, either one- or two-dimensional stress data may be needed. This document describes methods by measuring the polarization rotation of a transversely exposed laser light across a fibre cross-section using a polarimetric method.

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1) Figures in square brackets refer to the Bibliography.

3 Apparatus

3.1 General

An optical transverse phase retardation measurement method is used to determine the residual stresses in a fibre. Figure 1 shows a simple polariscopic phase retardation measurement setup consisting of a polarizer, fibre sample, Babinet variable phase compensator, and an analyzer. Stressed material shows stress-induced birefringence for light propagating through the medium. By measuring the polarization dependent phase retardation of light transmitted through a sample, the stress can be measured.

3.2 Light source

The light source shall be a laser with a specified optical wavelength and narrow optical spectrum bandwidth (maximum 2 nm at FWHM [full width at half maximum]). A collimated laser light source is recommended. When a laser is used, a rotating diffuser is recommended in order to remove coherent interference effects.

3.3 Polarizer and analyzer

The polarizer and the analyzer shall have a minimum polarization dependent transmission contrast of 1:200. The transmission angles of the polarizer and the analyzer are set perpendicular with each other within 0,1-degree accuracy.

3.4 Sample fibre preparation

The fibre sample shall be a few centimetres long. The jacket or plastic coating on the sample shall be removed. The prepared sample is placed between the polarizer and the analyzer. Immerse the sample in an index matching gel or fluid. The refractive index difference between the cladding material of the fibre and the index matching material shall be less than 0,005. The angle between the fibre axis and the polarizer or the analyzer shall be 45° within 0,1-degree accuracy.

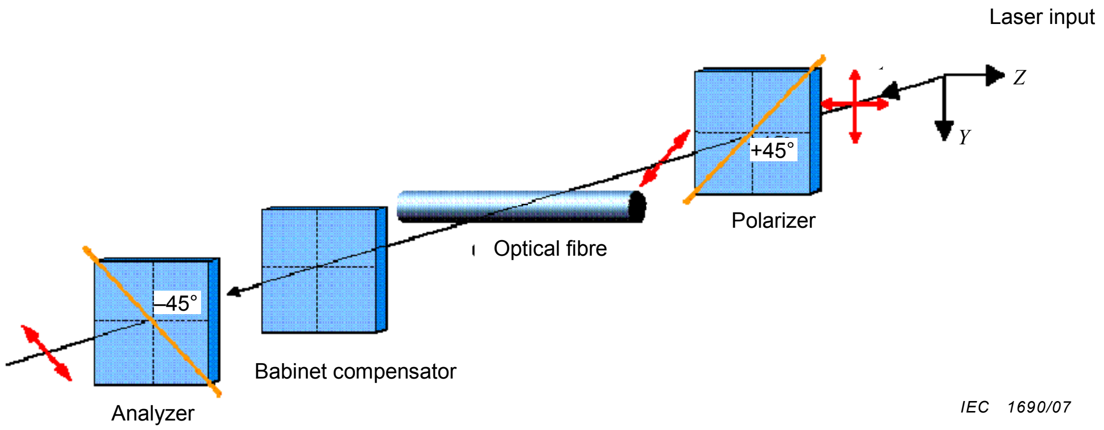

Figure 1 – Polariscopic phase retardation measurement setup for an optical fibre

For measuring a two-dimensional stress profile, a fixture that holds the fibre on a constant axis at the holding position and allows the fibre to be rotated through 180° is required. The fixture is required in order to be rotated with a motorized stage with an accuracy of 0,1°.

3.5 Variable phase compensator

A Babinet variable phase compensator is placed just after a fibre sample to add an external phase term, which is used for an accurate phase retardation measurement. If the fibre sample has non-zero axial stress components, it acts as a phase retarder due to stress-induced birefringence. Without a fibre sample and the Babinet phase compensator, no light can pass through the analyzer.

3.6 Optical intensity detection

An optical intensity detection system is needed to detect the transmitted light intensity after the optical analyzer shown in Figure 1. Such a device may consist of a single optical detector with a small aperture size in the order of a few microns combined with a motorized linear scanning system. A detector array may be used to provide a more precise location of the deflections than might be obtained by a single detector. Such a system might include a detector array or a CCD with a frame grabber.

3.7 Data acquisition

A computer is recommended to provide motion control, acquire data and perform computations.

4 Data analysis and formula

4.1 General

The transmitted optical intensity $I(y)$ as a function of the transverse distance of a fibre y, can be written as:

$$I(y,\theta) = I_o \sin^2\{(\delta(y)+\theta)/2\}, \qquad (1)$$

where I_o is background intensity, θ is the external phase retardation term from the Babinet compensator and $\delta(y)$ is the phase shift induced by linear birefringence due to the stress profile of the fibre sample located between the polarizer and the analyzer. Figure 2 shows typical sine square intensity profiles as a function of θ for each ray displaced y value from the centre of the fibre sample.

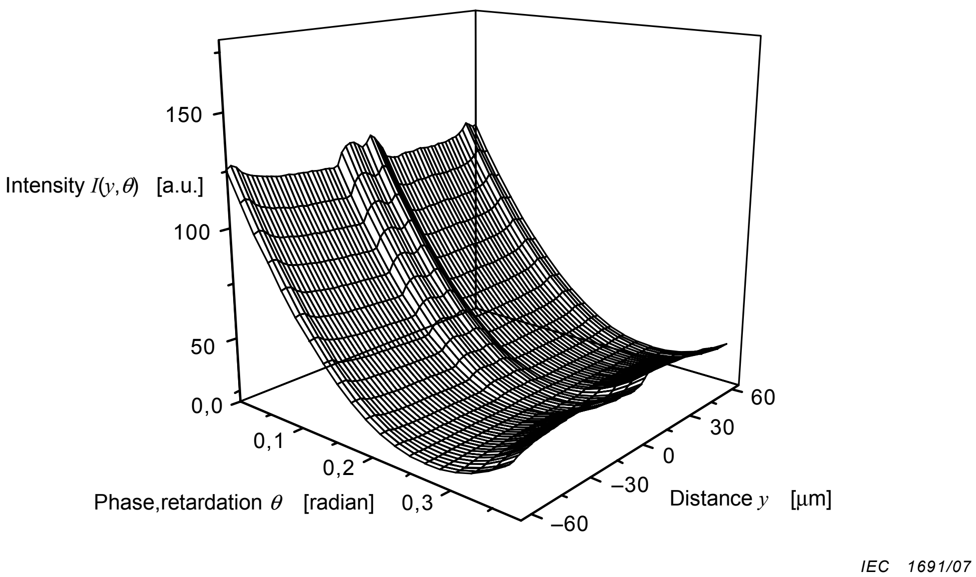

Figure 2 – Measured transmission intensity as a function of fibre radius and external phase

As illustrated in Figure 3, laser light passes through the fibre's cross-section along the x axis and c is the outer radius of a fibre. For each transversely propagating ray through the cross-section its phase $\delta(y)$ can be expressed as:

$$\begin{aligned}\delta(y) &= \frac{2\pi}{\lambda}\int_{-\sqrt{c^2-y^2}}^{\sqrt{c^2-y^2}}(n_z - n_y)dx \\ &= \frac{2\pi}{\lambda}\int_{-\sqrt{c^2-y^2}}^{\sqrt{c^2-y^2}} C\sigma_z dx\end{aligned} \tag{2}$$

where n_z is the refractive index along the fibre axis z, n_y is the refractive index along the transverse axis y, c is the outer radius of a fibre, λ is the wavelength of a light source and σ_z is the axial stress of a fibre. Here, C is the stress optic coefficient of silica given as $C = 35{,}5\times10^{-13}Pa^{-1}$ [1].

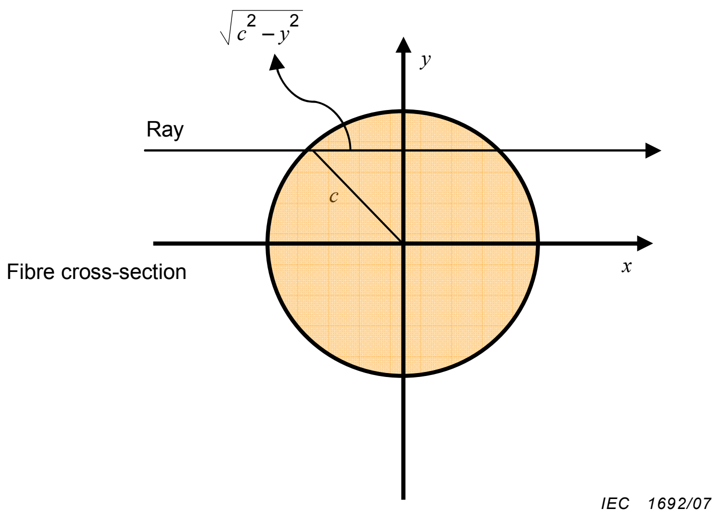

Figure 3 – Propagation of laser light across the fibre cross-section.

4.2 1-D stress profile for a fibre with a cylindrically symmetric structure

By using the Abel transformation [1-5], the stress profile $\sigma_z(r)$ of an axially symmetric fibre can be obtained as:

$$\sigma_z(r) = \frac{-\lambda}{2\pi^2 C}\int_r^c \frac{d\delta(y)/dy}{\sqrt{y^2-r^2}}dy \tag{3}$$

Figure 4 shows a typical calculated stress profile for a jacketed depressed inner cladding fibre. It shows large stress peaks for the boundary between the substrate and the jacketing tube as well as the boundary between the core and inner cladding.

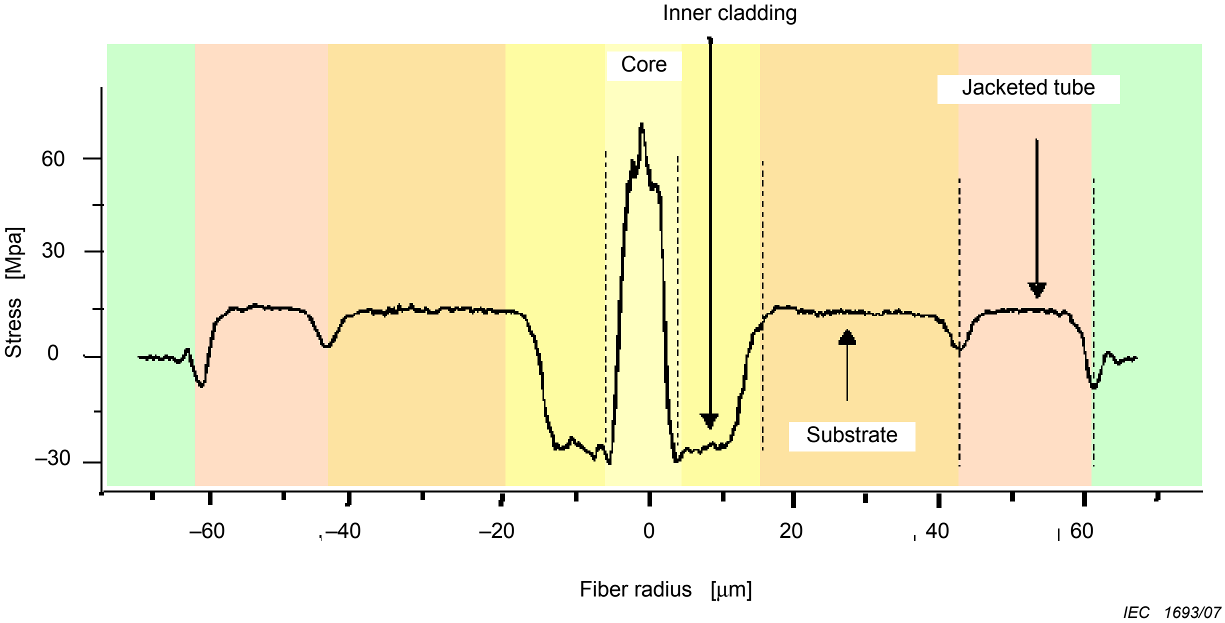

Figure 4 – Stress profile for a fibre with depressed inner cladding and jacketed tube

4.3 2-D stress profile for a fibre with a cylindrically non-symmetric structure

For a fibre with a non-axially symmetric stress distribution such as a polarization maintaining (PM) fibre, a two-dimensional (2-D) cross-sectional stress profile can be determined from one or more projected phase profiles with different projection angles α between 0° and 180° [6,7].

Figure 5 illustrates an example of the measurement procedure of projected phase retardation measurements for a PM fibre. The PM fibre is rotated along the fibre axis by 45° for each measurement. The phase retardation $\delta(y,\alpha)$ is measured as a function of the fibre radius y for each projection angle α.

For a certain projection angle α, the projected phase retardation profile can be written as a line integral:

$$\delta(\mathrm{y},\alpha) = 2\pi/\lambda \int [\mathrm{n}_z - \mathrm{n}_y]\mathrm{dx} \tag{4}$$

Figure 6 shows projected phases for fifty different projection angles between 0° and 180° for a PM fibre. Such phase retardation profiles with many different projection angles form a 2-D projected phase retardation profile and are used to calculate the 2-D axial stress distribution $\sigma_{zz}(x,y)$ of a fibre with non-axially symmetric structure by using the inverse Radon transformation [8, 9]:

$$\sigma_{zz}(x,y) = \lambda/2\pi C \cdot \boldsymbol{iradon}\{\delta(y,\alpha)\} \tag{5}$$

where ***iradon***{} represents the inverse radon transformation. The actual reconstruction of cross-sectional stress data is obtained by using the filtered back-projection algorithm that is explained in [8] and [9]. Figure 7 shows an example of a calculated 2-D stress profile $\sigma_{zz}(x, y)$ for a PM fibre.

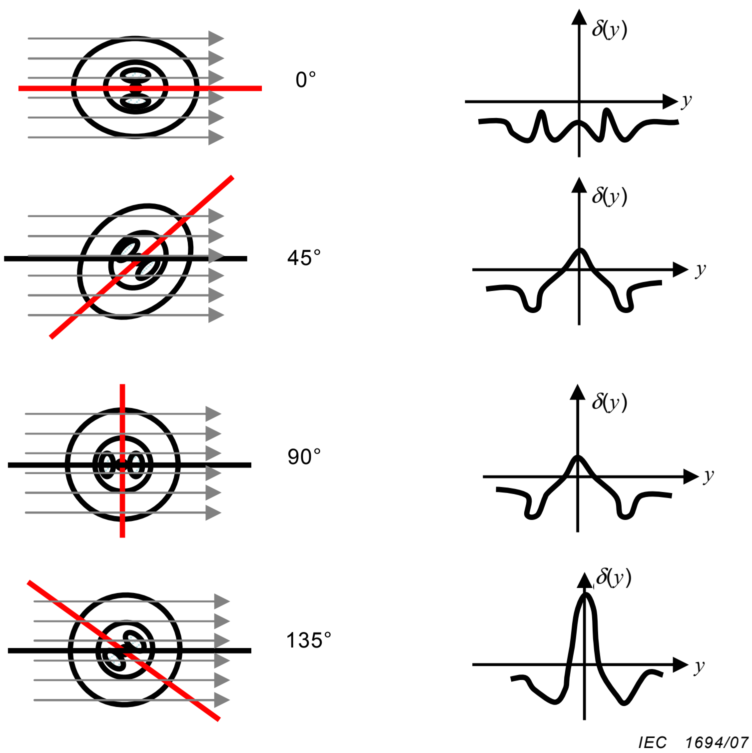

Figure 5 – Examples of projected phase retardation measurement $\delta(y)$ for a PM fibre as a function of fibre radius y when the projected angle α is 0°, 45°, 90°, and 135°

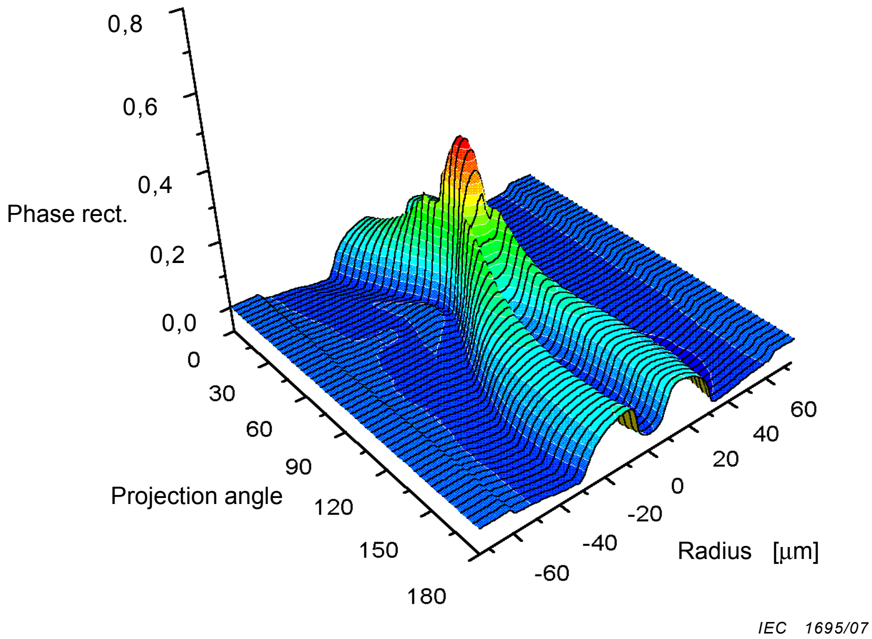

Figure 6 – Measured projected phases $\delta(y,\alpha)$ of a PM fibre for various projected angles as a function of fibre radius

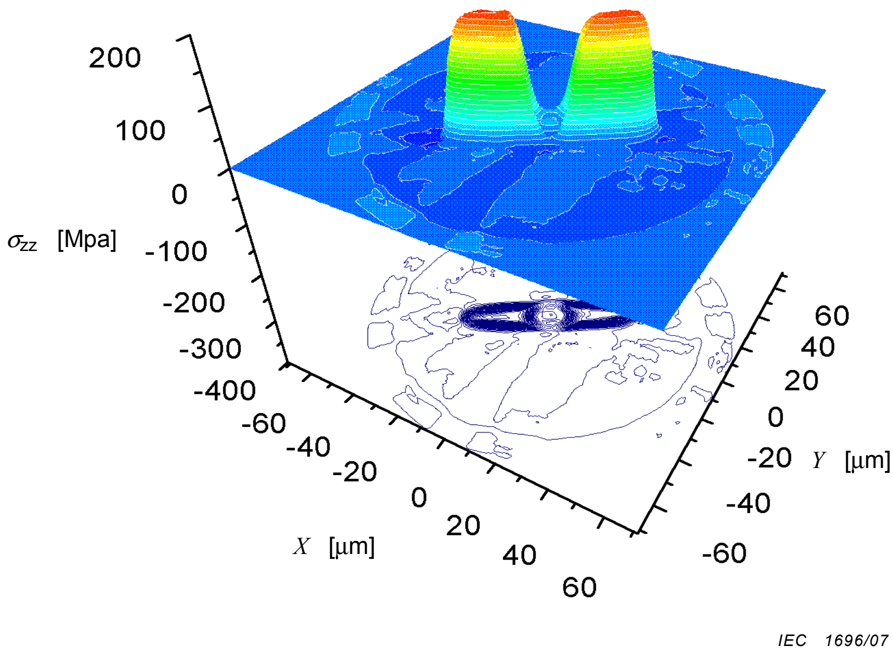

Figure 7 – Calculated 2-D stress profile of a PM fibre

5 Measurement procedure

5.1 Alignment of polarizer and analyzer

Without a fibre sample in the setup, rotate the axis of the analyzer in such a way that minimum light can pass through the analyzer. This makes the angle between the polarizer and the analyzer 90°. Place a Babinet compensator between the polarizer and the analyzer. Calibrate the compensating angle θ of the Babinet compensator by making the transmitted light a minimum when θ = 0.

5.2 Fibre mounting

Prepare a fibre sample with a minimum length of 10 mm. Strip the plastic coating with a solvent, note that mechanical stripping or thermal stripping is not recommended because of the stress changes they may cause. Mount the bare fibre in the holding fixture and straighten it without applying any force. Sandwich the fibre between two thin glass plates with an index matching fluid or gel between them, note that the plates must be parallel. Place the sample between the Babinet compensator and the polarizer.

5.3 Taking transmitted intensity data $I(y,\theta)$

For a given external phase retardation angle θ from the Babinet compensator, obtain a transmitted optical intensity $I(y,\theta)$ as a function of the transverse distance of a fibre y, which corresponds to $I(y,\theta) = I_o \sin^2\{(\delta(y)+\theta)/2\}$. Repeat this transmitted optical intensity measurement while scanning the external phase retardation angles θ such that sine square intensity function $I(y,\theta)$ can be obtained as a function of θ for a given radius position y. The external phase retardation angle θ needs to be scanned at least for 30° with a step size of 1° to reduce errors during the curve fitting process. The scanning range of the external phase retardation θ needs to be carefully chosen so that the transmitted intensity data $I(y,\theta)$ has at least one maximum or minimum point of a sine square function.

5.4 Calculation of 1-D stress profile for a fibre with a cylindrically symmetric structure

For each transverse position y, calculate the phase retardation $\delta(y)$ by fitting the $I(y,\theta) = I_o \sin^2\{(\delta(y)+\theta)/2\}$ curve with a sine square function by using a least square curve fitting method. The stress profile of a fibre $\sigma_z(r)$ can be calculated from $\delta(y)$ using equation (3).

5.5 Calculation of 2-D stress profile for a fibre with a cylindrically non-symmetric structure

For a fibre with a non-axially symmetric stress distribution, measure a series of phase retardations $\delta(y,\alpha)$ in equation (4) for many different projection angles α between 0° and 180°. At least 20 different projected phase retardation measurements $\delta(y,\alpha)$ with regularly spaced projection angle α need to be measured. A sample fibre should be rotated along the fibre axis with a computer controlled motorized rotating stage. Using equation (5), obtain the 2-D stress profile of the fibre $\sigma_{zz}(x,y)$.

6 Documentation

6.1 Information to be reported for each measurement

1) Identification of each test specimen
2) Date of the measurement

3) Wavelength of the light source

4) 1-D fibre stress profile $\sigma_z(r)$

5) Optional 2-D fibre stress profile $\sigma_{zz}(x, y)$

6.2 Information that should be available upon request

1) Description of the measurement method used

2) Description of the measurement equipment, including: light source, polarizer and analyzer, Babinet compensator, imaging lens, detection device

3) Spatial resolution and stress resolution of the measurement equipment

4) Date and results for the most recent instrument calibration

5) Data on measurement reproducibility

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