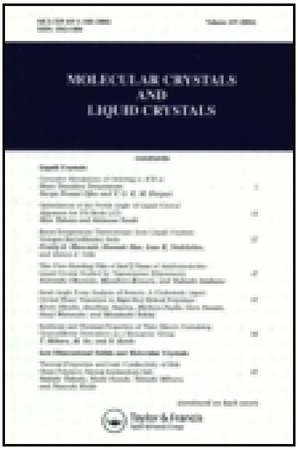

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Interferometric and Fourier Techniques for Measurements of Optical Properties of Fibers

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Overview of variable wavelength interferometric methods for measuring optical properties of cylindrical textile fibers precedes the latest approach based on the optical Fourier theory of birefringent fibers. Computer-Aided analysis of the optical Fourier transform pattern observed in a polarizing microscope is described as well as discussion of the results.

Keywords: birefringent fibers; automatic fringe analysis; optical Fourier transform; variable wavelength interferometry

INTRODUCTION

Interferometry is a family of non-destructive testing techniques applied in many fields of engineering and science. Interferometric methods play an important role also in medicine and industry. They provide phase information on tested objects, which relates to a variety of physical properties.

In most cases, interferometric systems suffers from the spectral dispersion of the refractive index or birefringence which causes the zero-order fringe to be usually colored in white light when difference of the mentioned dispersion between the object, its surrounding medium and the interference system are not balanced. Thus, the crucial problem of any measuring technique involving interferometry is determination of the interference order in the image of the object under study. The variable wavelength interferometry (VAWI methods), which has been developed by Pluta[1-5], is one of the most successful approaches. This technique is especially suitable when used jointly with Pluta's double-refracting interference microscope[6].

The new technique is based on the optical Fourier transform (OFT) of birefringent fibres and is applied to analyze birefringent properties and possible structural and geometrical defects of highly birefringent polymer fibres. First OFT images were observed by Pluta about 20 years ago[7,8]. He reported that a cylindrical birefringent textile fiber can produce specific interference pattern in the exit pupil of the standard polarizing microscope outfitted with a subcondenser slit diaphragm. These occur when the birefringent fiber is oriented diagonally between two crossed polarizers and is trans-illuminated by monochromatic light. These patterns behave as the optical Fourier transforms. Pluta used the optical Fourier transform pattern observed in a polarizing microscope to measure the spectral dispersion of the birefringence of polymer textile fibers[8]. That task was performed manually. He used monochromatic light of continuously variable wavelength to change intensity of the center of the interference pattern from maximally bright to dark, and so on. In addition, the method visualizes any irregularities in the fiber structure in terms of the distortion of the fringes. Also, this technique does not involve any immersion oils, as it is usually necessary in conventional polarizing microscopy or microinterferometry of highly birefringent textile fibers. The only disadvantage of this method is that it cannot be used for measurements of weak birefringent fiber because the number of the interference sequences is less than 2. The measurement process using the optical Fourier transforms technique is particularly useful for fully automatic operation due to the invariance of the optical Fourier transforms when the fiber under study translates within the field of view of the polarizing microscope which creates potential industrial applications.

In the presented work an automatic image processing technique for analyzing the optical Fourier transform patterns of the birefringent fibers is presented. A new procedure of the VAWI method is applied to determine the interference orders in the image of the object under study. The main idea of this procedure consists in the relation of the radius of the annular dark fringes and the light wavelength (λ) for each sequence of interference patterns. The number of these sequences depends on the object birefringence. The light wavelength is continuously varied using Lyot tunable birefringent filter. Starting from long-wavelength region and passing toward the short-wavelength region ($\lambda_s = \lambda_1 > \lambda_2 > \ldots \lambda_N$) a flow of the interference pattern and its annular dark fringes of consecutive orders can be observed. To determine the interference order in the OFT image of the object the radii of the annular dark fringes should be precisely measured. Having determined the radii of the annular dark fringes and applied the new procedure based on the VAWI method the interference orders in the OFT image of the object and then the spectral dispersion of the object birefringence can be calculated. This method makes possible to carry out the experiment over a small range of the visible spectrum for measuring the initial interference order and the birefringence if two or more fringes are visible in the exit pupil which occurs for highly birefringent fibers. Additionally, this method is suitable for quick and precise detection of irregularities of the geometrical shape of the object under study. The spectral dispersion of weak birefringent objects can be also calculated using this method.

THEORY

Focusing Properties of Birefringent Fibers

A birefringent fiber surrounded by air and oriented diagonally between crossed polars acts as a bifocal lens (Fig. 1). The focal lengths $f_\perp$ and $f_{\parallel}$ are defined by [8]:

$$f_\perp = \frac{t}{4}\cdot\frac{n_\perp}{(n_\perp - 1)} \qquad f_{//} = \frac{t}{4}\cdot\frac{n_{//}}{(n_{//} - 1)} \tag{1}$$

Where t, $n_\perp$, $n_{||}$ are the thickness, ordinary and extraordinary refractive indices of the fiber, respectively. The birefringence (B) and the optical path difference (δ), that are produced by the fiber under study, can be expressed by

$$\delta = t \cdot B \text{ and } B = n_{//} - n_\perp \quad (2)$$

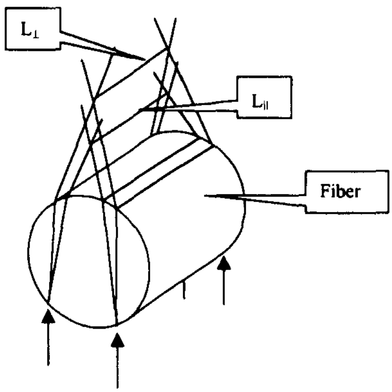

FIGURE 1. Birefringent fiber as a bifocal cylindrical lens producing two focal lines

Optical Fourier transform of polymeric textile fibers

About 20 years ago, Pluta [7,8] observed that a cylindrical birefringent textile fiber can produce specific interference pattern in the exit pupil of a standard polarizing microscope outfitted with a subcondenser slit diaphragm.

Assuming that a cylindrical birefringent fiber has a significant birefringence, a distance longer than the light wavelength separates its two focal lines. The lines can be considered as two light slits, one of which follows the other. They are mutually coherent across their widths but incoherent along their lengths[8]. Each pair of coherent points produces spherical wavefronts whose radii of curvature are slightly different. The two wavefronts can interfere with each other and produce an interference pattern with annular/circular fringes observed in the exit pupil of the microscope objective. Any other pair of coherent points gives rise to a separate interference pattern identical with that produced by light wavefronts appearing from the former two coherent points. These separate interference patterns are mutually incoherent and they occupy the same position in the Fourier plane of the microscope objective. They produce an intense resultant interference pattern of annular symmetry. The advantage of this interference pattern is that; it does not change its position in the exit pupil of the objective when the cylindrical birefringent fiber is transversely or vertically translated which is the well-known property of the Fourier transformation.

Intensity Distribution in the Fourier Plane

The resultant intensity distribution at the Fourier transform plane will be[10]:

$$I = \frac{I_o}{f_{Ob}^2}\left\{ f_{//}^2 + f_{\perp}^2 - 2 f_{//} f_{\perp} \cos\left[\frac{\pi\rho^2}{\lambda f_{Ob}^2}(f_{\perp} - f_{//}) - \frac{2\pi t}{\lambda}(n_{//} - n_{\perp})\right]\right\} \quad (3)$$

Where $\rho = (u^2 + v^2)^{1/2}$ is the radial coordinate, f_{Ob} focal length of the objective, t – thickness of the fiber. This equation gives the relationship between the light intensity and the light wavelength of the Fourier transform pattern. Because the most interesting is the term under cosine function it is convenient to neglect the intensity difference between interfering waves which leads to a simpler form i.e.:

$$I = I_o\left\{ \sin^2\left[\frac{\pi\rho^2}{2\lambda \cdot f_{Ob}^2}\Delta f - \frac{\pi t}{\lambda}(n_{//} - n_{\perp})\right]\right\} \quad (4)$$

where $\Delta f = f_{\perp} - f_{||}$

The minimum light intensity occurs when phase difference along the fiber diameter is given by:

$$\left[\frac{\pi\rho^2}{2\lambda f_{Ob}^2}\Delta f - \frac{\pi t}{\lambda}(n_{//} - n_{\perp})\right] = m\pi \quad (5)$$

which immediately leads to the equation:

$$\rho^2 = 2\frac{f_{Ob}^2}{\Delta f}\left[t\left(n_{//} - n_{\perp}\right) + m\lambda\right] \tag{6}$$

The light intensity distribution at the center of axially-symmetrical optical Fourier transform pattern (ρ=0) is given by

$$I_{\rho=0} = \frac{I_o}{f_{Ob}^2}\left\{f_{\perp}^2 + f_{//}^2 - 2 f_{\perp} f_{//} \cos\left[-\frac{2\pi t}{\lambda}\left(n_{//} - n_{\perp}\right)\right]\right\} \tag{7}$$

In particular, the interference patterns with a dark central patch occur when the phase difference along the fiber diameter is given by

$$\frac{2\pi t}{\lambda}\left(n_{//} - n_{\perp}\right) = 2m\pi \tag{8}$$

Then, the optical path difference (δ) can be derived as

$$\delta = t\cdot\left(n_{//} - n_{\perp}\right) = m\lambda \tag{9}$$

Fourier Transform Observation Setup

The polarizing microscope configured for observing OFT consists of the following elements[10,11]: a polarizer, subcondenser slit diaphragm, objective 40x (N.A. 0.65 and 0.95), analyzer, Bertrand lens, and ocular. The Bertrand lens is normally used, together with the ocular, for observation of conscopic images of birefringent objects. It transfers the exit pupil of the microscope objective into the primary image plane where the field diaphragm of the ocular is placed. In the presented work, this lens is used for either visual observation of the optical Fourier transforms of birefringent fiber or grabbing the image by a CCD camera. In the latter case the camera is equipped with the standard 12mm camera lens. The polarizer and analyzer are crossed and their directions of light vibration form an angle of 45° with the fiber axis. The slit is oriented parallelly to the fiber axis. The diffraction pattern of the output field of the microscope is captured by the CCD camera for further automatic processing and analysis by the computer-aided system.

General Principle of VAWI Method

The main problem of interferometry is to determine the interference orders in the image of the object under study. During the last 10 years, this aim has been simplified significantly by Pluta. He created the VAWI family now well known as VAWI-1, VAWI-2, and VAWI-3 techniques[6]. These methods depend on using monochromatic light with continuously variable wavelength. Their specific feature is the fact that the interfringe spacing (b) is the only parameter measured directly, while other quantities are observed, read out from the calibration plot b(λ), and derived from a simple formula. Assuming that a fringe interference field is produced by superposition of two plane wavefronts inclined to each other at a small angle ε the optical path difference (δ) between the wavefronts is given by:

$$\delta = m \cdot \lambda = (m_1 + q) \cdot \lambda \qquad (10)$$

Where $m = m_1 + q$ is the current interference order, m_1 is a suitable selected integer number, which will be called the initial interference order, q is the increment or decrement of the current interference order m with respect to m_1.

Let a birefringent object be placed in the object plane of the transmitted-light interferometer and the fringes appear in the field of view of the interferometer due to interference between two rays passing through the medium and the object under study. This technique consists in selection such particular wavelength $\lambda_s = \lambda_1 > \lambda_2 > \lambda_3 > \ldots \lambda_s$, for which interference fringes displaced by an object under study become consecutively coincident and anticoincident with the reference (undisplaced) fringes; thus, interference order increments $q_s = 0$, 0.5, 1, ... are observed. The optical path difference for λ_1 along the fiber diameter is given by

$$\delta_1 = (n_{//} - n_{\perp})_1 \cdot t = B_1 . t = m_1 . \lambda_1 \qquad (11)$$

If the light wavelength is continuously varied, the optical path difference is given in general form as

$$\delta_s = (n_{//} - n_{\perp})_s \cdot t = B_s . t = m_s . \lambda_s \qquad (12)$$

where, s = 2, 3, 4, ...

From Eqs. (11) and (12) it follows that

$$m_1 = q_s \frac{\lambda_s}{B_{s1} \cdot \lambda_1 - \lambda_s} \tag{13}$$

and

$$B_{s1} = \frac{(n_{//} - n_{\perp})_s}{(n_{//} - n_{\perp})_1} = \frac{B_s}{B_1} \tag{14}$$

If the fiber does not suffer from the spectral dispersion of birefringence, the coefficient $B_{s1} \cong 1$ and equation (13) becomes:

$$m_1 = q_s \frac{\lambda_s}{\lambda_1 - \lambda_s} \tag{15}$$

The above formula shows that the optical path difference δ is wavelength independent which is called the object-adapted variable-wavelength interferometry. On the other hand, if the coefficient (B_{is}) is not exactly equal to unit, the technique is called the quasi-object-adaptive variable wavelength interferometry. There is a stringent and constant relation between the interfringe spacing (b) and the value of the wavelength (λ). The simple relation expresses this variation

$$\varepsilon \cdot b = \lambda \tag{16}$$

where ε is the angle between two interfering wavefronts which is given by

$$\varepsilon = 2(n_e - n_o) \cdot \tan(\alpha) = 2D \tan(\alpha) \tag{17}$$

In equation (17) α denotes the apex angle of the main Wollaston prism, $D = n_e - n_o$ is the birefringence of a double-refracting crystal the Wollaston prism is made of, and n_e and n_o are the extraordinary and ordinary refractive indices of the crystal, respectively. If the wavelengths λ_l and λ_s are replaced by $\varepsilon_l.b_l$ and $\varepsilon_s.b_s$, respectively the spacing between the interference fringes is measured by rotating the micrometer screw (called phase screw), which is associated by the transversal displacement of the birefringent prism No.2 in the head of the microscope[6]. The formula (13) may be rewritten in the forms

$$m_1 = q_s \cdot \frac{b_s}{B_{s1} \cdot D_{1s} \cdot b_1 - b_s} \quad \text{or} \quad m_1 = q_s \cdot \frac{b_s}{B_{s1} \cdot \varepsilon_{1s} \cdot b_1 - b_s} \tag{18}$$

In Eq. (18), the coefficient $\varepsilon_{ls}=\varepsilon_l/\varepsilon_s$ expresses the spectral dispersion of the intersection angle (ε) and the coefficient $D_{1s}=D_1/D_s=(n_e-n_o)_1/(n_e-n_o)_s$ expresses the spectral dispersion of the birefringence of the Wollaston prism. If the terms $B_{sl}.\varepsilon_{ls} \cong 1$ or, $B_{sl}.D_{ls} \cong 1$ the object-adaptive variable wavelength interferometry functions in the domain of interfringe spacing The assumption mentioned above makes it possible to rewrite Eq. (18) as follows:

$$m_1 = q_s \cdot \frac{b_1}{b_1 - b_s} \tag{19}$$

In general, when air surrounds the fiber, the coefficients $D_{ls} \leq 1$ and $B_{sl} \geq 1$. It is therefore self-evident that conditions $B_{sl}.\varepsilon_{ls} \cong 1$ or , $B_{sl}.D_{ls} \cong 1$ are more practical than condition $B_{s1} \cong 1$. The main advantage offered by the variable wavelength interferometry technique is that it allows us to identify the interference order when the object under study deflects the interference fringes. The quick measurement of the optical path differences within the whole visible spectrum is another advantage of the variable wavelength interferometry technique.

VAWI Technique Adopted to OFT of Birefringent Fibers

Pluta[8] applied the optical Fourier transforms to measure the spectral dispersion of the birefringence of the textile fibers. These measurements were done manually and now computer-aided technique is proposed.

Let a cylindrical birefringent fiber is placed in the object plane of the microscope. Because of birefringence nature of this fiber two focal lines $L_{//}$ and $L_{\perp}$ are separated from each other by a significant distance greater than λ (Fig.1). An annular or circular dark fringe appears in the exit pupil of the microscope objective. This pattern is recorded with a *CCD* camera and processed by an automatic system. In the presented work, a new procedure is used to measure the initial interference order against the relation between the radius of the annular dark fringe of the OFT pattern and the wavelength. Starting from the long-wavelength region of the Lyot filter and passing continuously toward the short-wavelength region one can observe a sequence of the interference patterns consisting of annular fringes of consecutive orders. When the dark fringe appears as a circular patch at the center of the objective exit pupil, the radius of this fringe increases with decreasing wavelength, and finally the annular fringe reaches the edge of the objective exit pupil. Subsequent decreasing the wavelength repeats the above sequence of interference patterns. The number of these sequences depends on the birefringence of the fiber. When only one fringe is visible in the pupil (at the particular wavelength) it is necessary to select a wavelengths $\lambda_s=\lambda_1>\lambda_2>\ldots\lambda_N$, for which an annular dark fringe becomes consecutively maximum bright and dark in its center. The fiber birefringence can be calculated through the relations 11 and 12. Much more favorable situation occurs when at least two fringes are visible simultaneously and their radii can be measured at the same wavelength. The formulas for radii ρ_{s1} and ρ_{s2} (see Eq. 6) take the forms:

$$\rho_{s1}^2 = 2\frac{f_{Ob}^2}{\Delta f_s}\left[t \cdot B_s + m_1\lambda_s\right] \tag{20}$$

and

$$\rho_{s2}^2 = 2\frac{f_{Ob}^2}{\Delta f_s}\left[t \cdot B_s + (m_1 + q_s)\lambda_s\right] \tag{21}$$

where s= 1,2,3... and q_s is the increment or decrement of interference order ($q_s = \pm 1$). When the above formulas are divided each other, the birefringence of the fibre is given by

$$B_s = \frac{m_1 \cdot \lambda_s(1 - A) - A \cdot q_s \cdot \lambda_s}{t(1 - A)} \tag{22}$$

where A= $(\rho_{e1}/\rho_{e2})^2$ and the spectral dispersion of the fibre birefringence can be calculated using equations (22).

Description of Automatic Measurement Procedure

The digital image processing technique is used to analyze the interferogram shown in Fig.2. At the beginning of the measurement the OFT pattern is adjusted so that the displacement of the fringe center with respect to the frame center is smaller than the radius of the fringe (ρ). The initial radius (ρ_{01}) should be as large as possible on condition that it does not touch the edge of the exit pupil of the microscope objective. These manipulations, at the beginning of the measurements, speed up the process of the following automatic operation which extracts the parameters of the fringe shape[10,11].

Sometimes the annular dark fringe is deformed and takes elliptical shape due to either the condenser slit and the fiber axis are not parallel or the fiber suffers from local optical inhomogeneities or geometrical irregularities. In this case, the ellipse fitting is applied for the pattern and then the ellipse parameters are calculated. The above procedures except initial stage must be applied each time when the wavelength is changed using Lyot tunable birefringent filter or the fiber under study is translated along its axis.

EXAMPLES OF EXPERIMENTAL RESULTS

The spectral dispersion of birefringence of exemplary textile fibers has been determined for comparison purposes using the fringe field interference method (VAWI)[3] and optical Fourier transform method. Fig. 3 displays a comparison between the spectral dispersion of birefringence of the fiber using the optical Fourier transform technique and the fringe field method when the fiber is surrounded by liquid. It is seen that, the spectral dispersion of these fibers using the OFT technique and fringe field method (fiber is surrounded by liquid) approximately agree each other. Using immersion liquid it is possible to avoid any confusion with identification of interference orders (if the fringe displacement is smaller than the interfringe spacing).

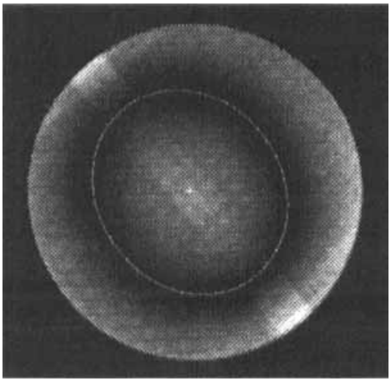

FIGURE 2. The result of the automatic image processing.

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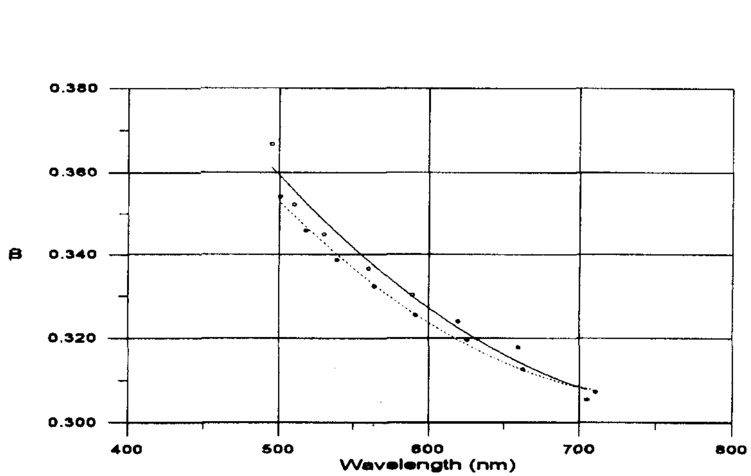

FIGURE 3. Spectral dispersion of birefringence of the highly oriented fiber using the OFT technique (unfilled circles) and the fringe field method when the fiber is surrounded by liquid (filled circles).

CONCLUSION

In the presented work, fringe field interference method and optical Fourier transform techniques have been tested. Using these techniques the spectral dispersion of birefringence of the polymeric fibers has been measured. The concept of the VAWI technique has been found particularly useful when the OFT pattern is processed with computer-controlled automatic analysis system.

The optical Fourier transform pattern observed in a polarizing interference microscope has been processed automatically to measure the radii of the dark fringes as a function of the wavelength. The advantage of the presented method is that the evaluation is simple, the processing time is short, and the results are satisfactory precise, compared with the classical methods. Using the OFT method, there is no any confusion with identification of the interference orders when the highly birefringent fiber under study is surrounded by air. Also, this method does not require immersing highly birefringent fibers in liquids, as it is usually necessary in conventional microinterferometry and allows detecting and assessing rapidly the optical and geometrical microdefects of the cylindrical birefringent fibers. The only disadvantage is that it is not possible to measure separately the refractive indices $n_{\parallel}$ and $n_{\perp}$.

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