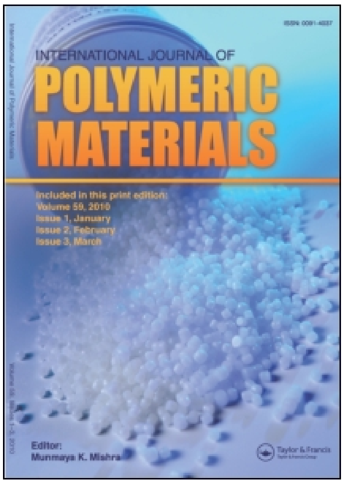

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Determination of the Spectral Dispersion Curves of Highly Oriented Fibers Using Multiple-Beam Microinterferometry

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A method is suggested with its mathematical analysis to determine the spectral dispersion curves of highly oriented fibers using multiple-beam Fizeau fringes in transmission. This method depends on the use of the well-known Caushy's dispersion formula for determining the initial interference order of the deviated fringes inside the fibers. The suggested method overcomes the difficulties of measuring large optical path length differences that are produced by highly oriented fibers. The spectral dispersion curves obtained using this method are in good agreement with those obtained using conventional variable wavelength interferometry (VAWI) technique. Microinterferograms are given for illustration.

Keywords: Fizeau fringes, VAWI, refractive indices, dispersion, PEN fiber

INTRODUCTION

The highly oriented fibers are in focus for many researches. Studying the dispersion properties of highly oriented fibers throws light on the internal structure of these fibers. A full understanding of the relationship between microstructure and dispersion properties of highly oriented fibers will lead to an increase in understanding of the behavior of polymeric fibers [1].

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Many authors [2,3] used the interferometric techniques to study the optical and spectral dispersion properties of highly oriented fibers. Multiple-beam technique is an accurate interferometric technique to measure the optical properties of fibers [4–7]. Using this interferometric technique, the highly oriented fibers give large optical path length differences. So, liquids of refractive indices must be used close to that of these fibers. Unfortunately, most of these liquids are rare, toxic, and opaque for the transmitted light. To overcome this difficulty, a method is suggested with its mathematical analysis to determine the spectral dispersion curves of highly oriented fibers. The method depends on the use of the well-known Cauchy's dispersion formula, at three different monochromatic wavelengths, to measure the initial interference order of the deviated fringes inside the fibers using multiple-beam technique. The spectral dispersion curves of highly oriented PEN [poly(ethylene 2,6-naphthalene-dicarboxylate) fiber, 1000 denier/248 filaments, PEN-Q50M4] are determined. The conventional VAWI [8,9] technique is used to determine the spectral dispersion curves for the same fiber to confirm the results obtained using the suggested method.

THEORETICAL CONSIDERATIONS

Multiple-beam Fizeau fringes [4,5] is an accurate interferometric technique to measure the optical properties of fibers. This technique is extensively used to determine the mean refractive index n of fibers using the following equation [10]:

$$n - n_L = \frac{Z\lambda}{2bt} \tag{1}$$

where n_L is the refractive index of the immersion liquid, t is the thickness of the fiber, Z is the fringe displacement produced by the fiber, b is the interfringe spacing, and λ is the wavelength of monochromatic light used.

In the case of highly oriented fibers, a large optical path length difference is given and the connection between the fringes crossing the fiber and the immersion liquid medium is not clear, so that it is difficult to measure fringe displacement Z. To overcome these difficulties, the following theoretical consideration is suggested.

In Eq. 1, when Z is equal to an integer number m, multiplied by the interfringe spacing b (i.e., $Z = m\ b$), this integer number is called interference order. Then, Eq. 1 can be rewritten as:

$$(n - n_L)2t = m\lambda \tag{2}$$

Eq. 2 represents the optical path length difference between the fiber material and the immersion liquid. Using this equation at three different arbitrary monochromatic wavelengths λ_1, λ_2, and λ_3, three different shapes of the fringe shifts are obtained, as shown in Figure 1.

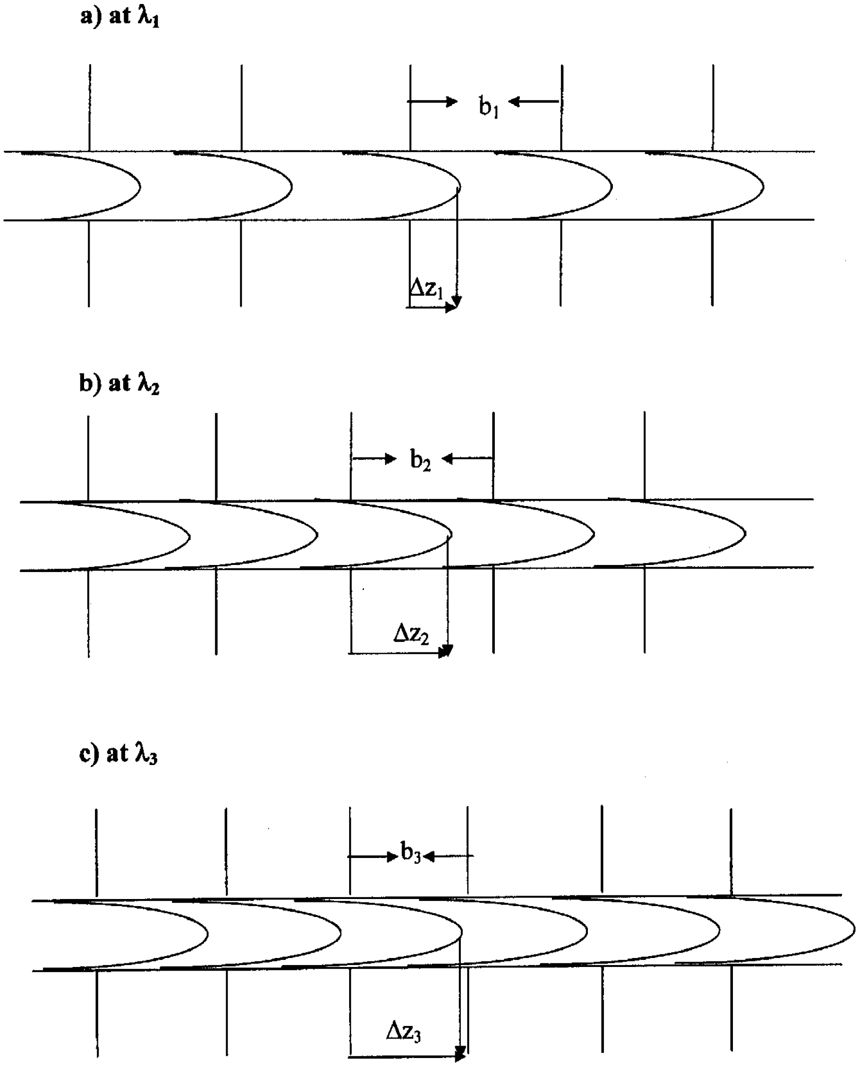


FIGURE 1 Schematic diagram showing the shapes of the fringe shifts at three arbitrary monochromatic wavelengths λ_1, λ_2, and λ_3 using multiple-beam Fizeau fringes in transmission.

The optical path length differences can be written as follows:

$$\delta_1 = (n_1 - n_{L1})2t = (m_1 + q_1)\lambda_1 \tag{3a}$$

$$\delta_2 = (n_2 - n_{L2})2t = (m_1 + q_2)\lambda_2 \tag{3b}$$

$$\delta_3 = (n_3 - n_{L3})2t = (m_1 + q_3)\lambda_3 \tag{3c}$$

where n_1, n_2, and n_3 are the refractive indices of the fiber at λ_1, λ_2, and λ_3, respectively n_{L1}, n_{L2}, and n_{L3} are the refractive indices of the immersion liquids at the same wavelengths. q_1, q_2, and q_3 are the increment of interference order with respect to the initial interference order m_1 at these wavelengths. The increment q_1, q_2, and q_3 can be calculated by using the following family of equations:

$$q_s = \frac{\Delta Z_s}{b_s} \tag{4}$$

where s equals 1, 2, 3,... and ΔZ_s is the distance between the displaced interference fringes and un-displaced fringes as shown in Figure 1(a–c). b_1, b_2, and b_3 are the corresponding interferfringe spacing.

The well-known Cauchy's dispersion formula is given by [11]:

$$n = A + \frac{B}{\lambda^2} \tag{5}$$

where A and B are constants characterizing the medium concerned. Substituting n_1, n_2, and n_3 from Eqs. 3(a, b, and c) in Eq. 5, the following equations can be obtained:

$$n_1 = A + \frac{B}{\lambda_1^2} = n_{L1} + \frac{(m_1 + q_1)\lambda_1}{2t} \tag{6a}$$

$$n_2 = A + \frac{B}{\lambda_2^2} = n_{L2} + \frac{(m_1 + q_2)\lambda_2}{2t} \tag{6b}$$

$$n_3 = A + \frac{B}{\lambda_3^2} = n_{L3} + \frac{(m_1 + q_3)\lambda_3}{2t} \tag{6c}$$

Solving Eqs. 6(a, b, and c), the following equation can be obtained:

$$\frac{\left[\frac{1}{\lambda_1^2} - \frac{1}{\lambda_2^2}\right]}{\left[\frac{1}{\lambda_1^2} - \frac{1}{\lambda_3^2}\right]} = \frac{(n_{L1} - n_{L2}) + \frac{1}{2t}(m_1(\lambda_1 - \lambda_2) + q_1\lambda_1 - q_2\lambda_2)}{(n_{L1} - n_{L3}) + \frac{1}{2t}(m_1(\lambda_1 - \lambda_3) + q_1\lambda_1 - q_3\lambda_3)} \tag{7}$$

This equation can be used for light vibrating parallel and perpendicular to the fiber axes. By using Eq. 7, the initial interference order

m_1 can be calculated. By substituting the value of m_1 in Eq. 6, the spectral dispersion curves of highly oriented fibers can be determined.

EXPERIMENTAL RESULTS AND DISCUSSION

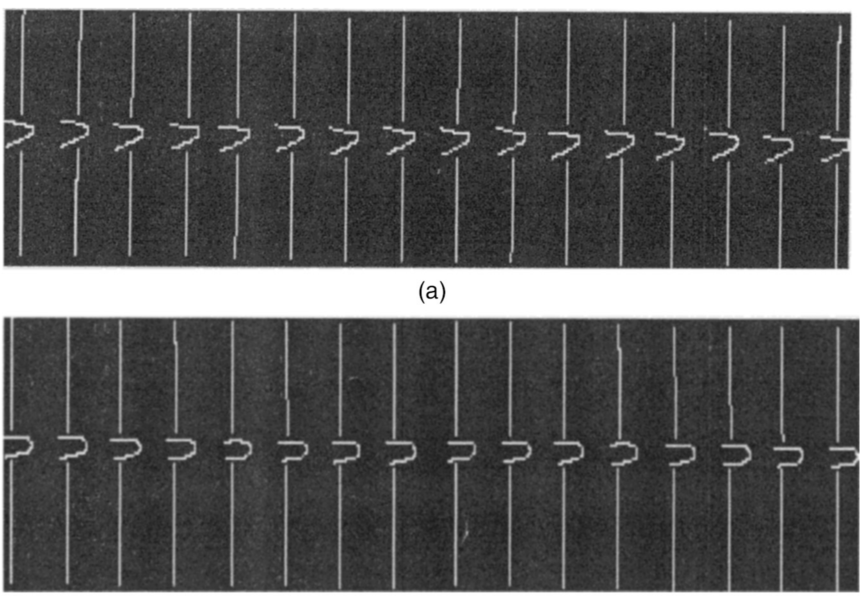
The suggested method is applied to measure the initial interference order of highly oriented PEN [poly(ethylene 2,6-naphthalene-dicarboxylate) fibers, 1000 denier/248 filaments, PEN-Q50M4] using multiple-beam Fizeau fringes in transmission. The method depends on measuring the increment of current interference order with respect to initial interference order at the wavelengths values of monochromatic light used. The spectral dispersion curves of highly oriented PEN fiber are determined. The obtained results are compared with those obtained by the VAWI technique to confirm the results of the suggested method.

Determination of the Spectral Dispersion Curves of Highly Oriented PEN Fiber Using the Suggested Method

Barakat and El-Hennawi [5] describe an optical set-up for producing multiple-beam Fizeau fringes in transmission. The wedge interferometer consists of two circular optical flats of flatness $\pm 0.01\,\mu m$, the inner surface of each flat is coated with highly reflecting, partially transmitting silver layer. An immersion liquid is dropped onto the fiber, which is fixed on the lower face of the silvered liquid wedge interferometer. The wedge angle is adjusted to produce sharp parallel bright fringes on a dark background, so that the interference fringes in the liquid region are normal to the fiber axes. The micrometer eyepiece is used to measure the interfringe spacing b and the distance z at any elevated wavelength of monochromatic light used.

The spectral dispersion curves of highly oriented PEN fiber were determined using this method. The fiber is fixed in the wedge interferometer, sharp bright fringes on dark background are obtained. The visibility of the fringes inside the fiber depends on the optical path difference between the fiber and its surrounding medium. The refractive indices of the immersion liquids used are 1.647 and 1.458 for light vibrating parallel and perpendicular to the PEN fiber axes, respectively. The wavelengths of the monochromatic light used are 589.3, 578, and 546.1 nm. A deviation of the fringe shift inside the fiber is obtained due to the difference in the refractive indices between the immersion liquid and the fiber used. The interfringe spacing b, the distance ΔZ and hence the parameter q are measured at any wavelength of monochromatic light used using Eq. 4.

The obtained microinterferograms of multiple-beam Fizeau fringes in transmission for PEN fiber are threshold, enhanced and converted into binary image to identify the contour line, which is analyzed via software program [12]. Figures 2(a, b) and 3(a, b) show contoured line microinterferograms of PEN fiber for light vibrating parallel and perpendicular to the fiber axes at wavelengths 578 and 546.1 nm, respectively. From these microinterferograms it is clear that the fringe shifts are large and the connection between the fringe and the surrounding medium fringe is difficult to be detected. The initial interference order m_1 and refractive indices $n^{\parallel}$ and $n^{\perp}$ are calculated using Eqs. 7 and 3, respectively. Table 1 gives the results of refractive indices $n^{\parallel}$ and $n^{\perp}$ of highly oriented PEN fibers at the used wavelengths using the suggested method. The obtained results for the refractive indices $n^{\parallel}$ and $n^{\perp}$ at three different wavelengths are extrapolated using Cauchy's formula to obtain other values over the visible range of spectrum. Figures 4 and 5 give the spectral dispersion of refractive indices $n^{\parallel}$ and $n^{\perp}$, respectively, of highly oriented PEN fiber using the suggested method.



(a)

(b)

FIGURE 2 Microinterferograms of multiple-beam Fizeau fringes in transmission with contour line of a PEN fiber for light vibrating (a) parallel and (b) perpendicular to the fiber axis, at the wavelength 578 nm.

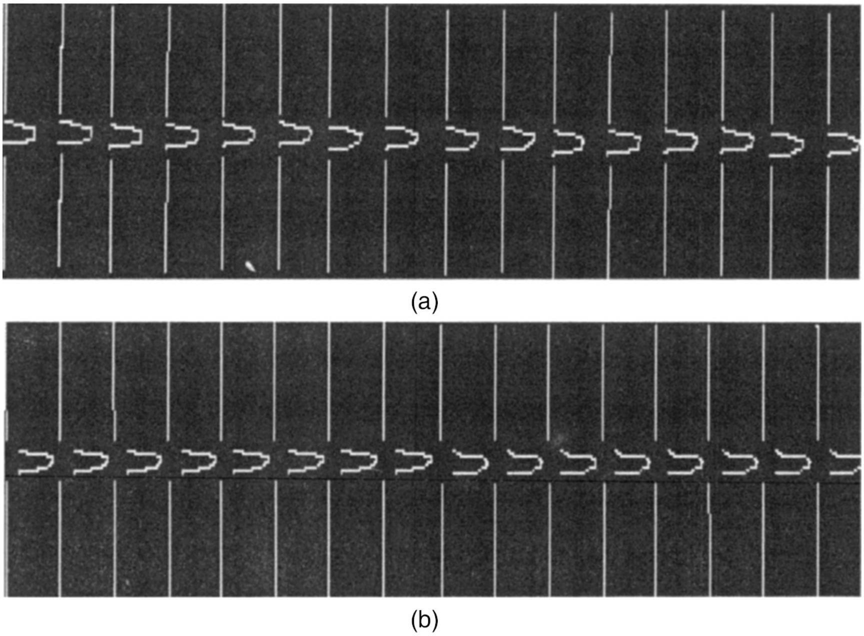


FIGURE 3 Microinterferograms of multiple-beam Fizeau fringes in transmission with contour line of PEN fiber for light vibrating (a) parallel and (b) perpendicular to the fiber axis, at the wavelength 546.1 nm.

Determination of the Spectral Dispersion Curves of Highly Oriented PEN Fibers Using the Conventional VAWI Method

To confirm the results obtained using the suggested method, the conventional VAWI technique was used. The Biolar double polarizing refracting interference microscope [13,14] is especially suitable for

TABLE 1 The Dispersion of Refractive Indices $n^{\parallel}$ and $n^{\perp}$ of PEN Fibers of Thickness $t = 19.76\,\mu m$ Using the Suggested Method

s	Wavelength λ_s(nm)	Increment		Interference order		Refractive index	
		$q_s^{\parallel}$	$q_s^{\perp}$	$m_s^{\parallel}$	$m_s^{\perp}$	$n^{\parallel}$	$n^{\perp}$
1	589.3	0.570	0.155	22.570	7.155	1.9827	1.5658
2	578.0	1.108	0.400	23.108	7.400	1.9844	1.5676
3	546.1	2.538	0.936	24.538	7.936	1.9888	1.5735

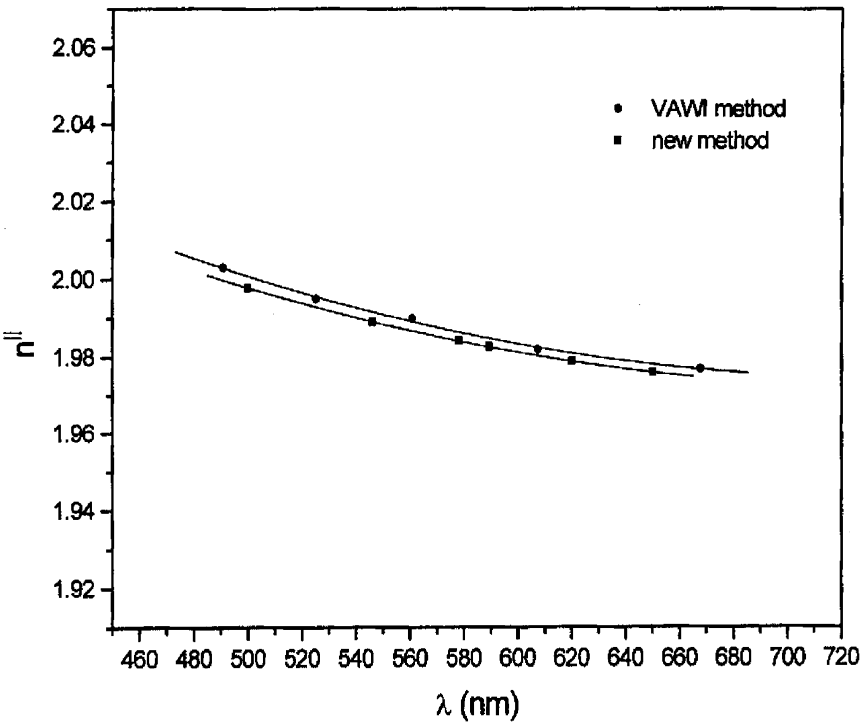


FIGURE 4 The spectral dispersion of refractive index $n^{\|}$ of PEN highly oriented fiber using the suggested method and conventional VAWI technique.

microinterferometry of birefringent fibers using the VAWI technique. A tungsten halogen light source (12 V/100 W) is recommended, from which monochromatic radiation of continuously variable wavelength is extracted by transverse sliding of the wedge interference filter. The Biolar microinterferometer enables the wavelength of monochromatic light to be measured because there is a constant relation between the interfringe spacing b and the wavelength λ of the light entering the optical system.

The conventional VAWI technique [8,9] was used to measure the spectral dispersion of highly oriented PEN fibers. The fiber was fixed on a glass slide and immersed in a suitable liquid of refractive index 1.434 at temperature 30°C. Then, the fiber was placed on the object plane of the Biolar interference microscope [13,14]. The interference pattern has two images for light vibrating parallel and perpendicular to the fiber axes. Varying the wavelength of light used by moving the interference filter from red to blue regions of the visible spectrum, the

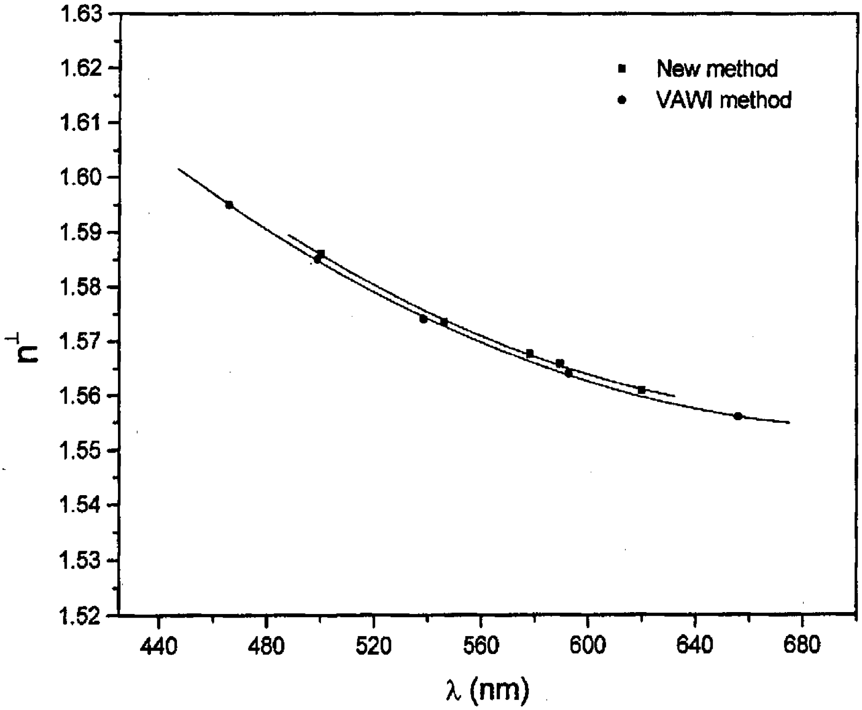


FIGURE 5 The spectral dispersion of refractive index $n^{\perp}$ of PEN highly oriented fiber using the suggested method and conventional VAWI technique.

positions of coincidences and anticoincidences of the fringe shifts with the medium fringes are obtained. The initial interference order is calculated using the following equation [8]:

$$m'_1 = q'_s \frac{b_s}{b_1 - b_s} \tag{8}$$

where the subscripts $s = 1, 2, 3, \ldots$ denotes the coincidence and anticoincidence number and $q_s = 0.5, 1, 1.5, \ldots$ (for $s = 1$, $q_s = 0$) and $m_s = m'_1 + q'_s$.

Figure 6(a–h) shows microinterferograms of coincidences and anticoincidences positions of PEN fiber for light vibrating parallel to the fiber axis (Figure 6[a–d]) and perpendicular to the fiber axes (Figure 6[e–h]). The wavelength of light is measured using the calibration graph [2] at the positions of coincidences and anticoincidences. The spectral dispersion of refractive indices $n^{\parallel}$ and $n^{\perp}$ can be calculated

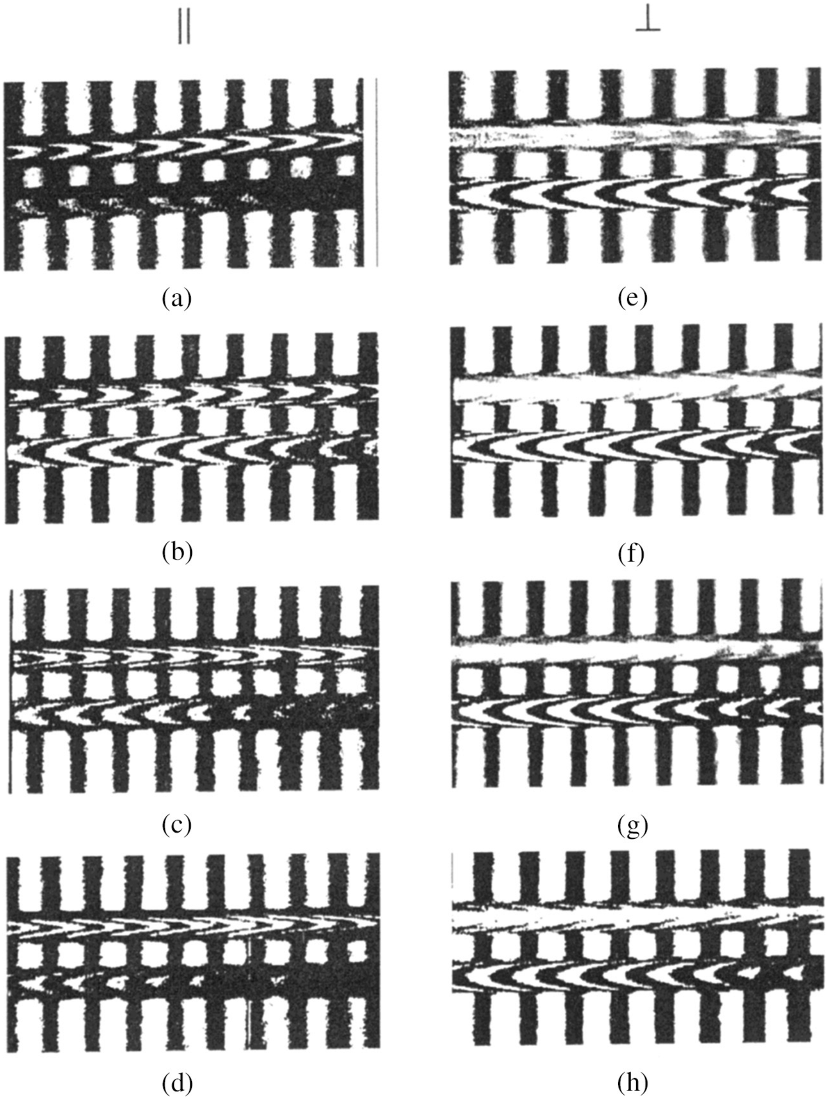


FIGURE 6 Microinterferograms of coincidences and anti-coincidences positions of PEN fiber for light vibrating parallel (a–d) and perpendicular (e–h) to the fiber axes.

using the following equation [8]:

$$\delta'_s = (n^i_s - n^i_L)t = m'_s \lambda_s \tag{9}$$

TABLE 2 The Dispersion of Refractive Index $n^{\parallel}$ of PEN fibers of Thickness $t = 19.76\,\mu m$ Using the VAWI Method

s	q_s	b_s (μm)	m_1 (b)	λ_s (nm)	m_s	δ_s (μm)	$n^{\parallel}$
1	0	233.5	0	667.74	10	6.677	1.977
2	1	211.0	10.23	608.33	11	6.692	1.982
3	2	193.0	9.50	560.8	12	6.730	1.990
4	3	179.5	9.97	525.15	13	6.827	1.998
5	4	166.5	9.94	490.82	14	6.872	2.007

where i denotes to the state of polarization of the light used (parallel $\parallel$ or perpendicular $\perp$ to the fiber axis) and n_L is the refractive index of the immersion liquid.

Tables 2 and 3 give the results of refractive indices $n^{\parallel}$ and $n^{\perp}$ of highly oriented PEN fiber using the conventional VAWI technique. Figures 4 and 5 give the spectral dispersion of refractive indices $n^{\parallel}$ and $n^{\perp}$ of PEN highly oriented fibers. From these figures it is clear that the results of the spectral dispersion using the suggested method are in a good agreement with those obtained using VAWI technique.

The obtained results show that the suggested method is a quick and easier method for measuring the spectral dispersion of highly oriented fibers than traditional multiple-beam technique. Using the traditional multiple-beam technique, highly oriented fibers give large optical path length difference and the connection between the fringes crossing the fiber and the immersion liquid medium is not clear, so it is difficult to measure the initial interference order and the spectral dispersion of these fibers. The suggested method gives a theoretical consideration for measuring the initial interference order and gives more accurate results for measuring the spectral dispersion of highly oriented fibers. This is due to the fringes produced by multiple-beam interferometric technique being bright and sharp (see Figures 2 and 3). Also, the optical path difference produced by this technique is twice that

TABLE 3 The Dispersion of Refractive Index $n^{\perp}$ of PEN fibers of Thickness $t = 19.76\,\mu m$ Using the VAWI Method

s	q_s	b_s (μm)	m_1 (b)	λ_s (nm)	m_s	δ_s (μm)	$n^{\perp}$
1	0	229.0	0	655.86	3	1.968	1.554
2	0.5	205.0	4.27	592.48	3.5	2.074	1.564
3	1	184.5	4.14	538.35	4	2.153	1.574
4	1.5	169.5	4.27	498.75	4.5	2.244	1.585
5	2	157.0	4.36	465.74	5	2.329	1.595

produce by VAWI technique. The accuracy in the measurement of the spectral dispersion using the suggested method depends on the accuracy in the measurement of the refractive index using multiple-beam technique. The errors in measuring refractive indices for light vibrating parallel and perpendicular to the fiber axis using multiple-beam technique are ± 0.0007 (cf. Reference [15]) and, using conventional VAWI technique, they can not be better than .0052 (cf. Reference [16]).

CONCLUSIONS

Using the traditional multiple-beam technique, highly oriented fibers give large optical path length difference and the connection between the fringes crossing the fiber and the immersion liquid medium is not clear, so that it is difficult to measure the initial interference order and the spectral dispersion of these fibers using the traditional technique. The suggested method overcomes these difficulties. Mathematical formulae are derived for measuring the initial interference order of highly oriented fibers using multiple-beam Fizeau fringes in transmission. To confirm the results obtained by the suggested method, the conventional VAWI technique is used to measure the spectral dispersion of these fibers. The results obtained using the two methods are in good agreement. The suggested method gives more accurate results for measuring the spectral dispersion of highly oriented fibers. This is due to the fringes produced by multiple-beam interferometric technique being bright and sharp. Also, the optical path difference produced by this technique is twice that produce by VAWI technique.

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