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Interferometric determination of opto-mechanical properties of fibres

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A fibre manipulation device is designed, constructed and used to study the dependence of birefringence on strain in the case of polymer fibres. This device is used with the Pluta polarizing interference microscope to determine the mean refractive indices and birefringence of fibres under strain. For each value of strain the area enclosed under the interference fringe shift is considered to represent the optical path difference integrated across the area of the fibre. This device enables one to study stretched, twisted and rotated fibres and can be fitted easily to the interference microscope stage without obstructing its operation. Microinterferograms are given for illustration.

1. Introduction

The changes in the optical anisotropy and orientation in polymer fibres by stress can be evaluated interferometrically by the measurement of refractive indices and birefringence of these fibres. These optical properties provide parameters that characterize the structure of the polymer on the molecular level. Stretched fibres can be tested by the measurement of the optical anisotropy of these fibres. DE VRIES [1] studied the relation between the birefringence and the draw ratio of some synthetic fibres.

Both double-beam and multiple-beam interferometry were applied to the measurement of refractive indices and birefringence of fibres (cf., FAUST [2], BARAKAT and EL-HENNAWI [3], PLUTA [4], HAMZA [5], and HAMZA et al. [6], [7]). Recently we used, in this laboratory, multiple-beam Fizeau fringes to study the optical anisotropy in polypropylene fibres as a function of the draw ratio (cf., HAMZA and coworkers [8], [9]).

Many devices used for handling the fibre during microscopic examination to rotate the fibre around its axis, stretch or twist the fibre, were reported (cf., BANKY and SLEN [10], COLLINS [11], MCKEE [12], and BEEVERS [13]).

When using the interference microscope with fibres of irregular cross sections, it is preferable to use the area under the fringe shift to represent the optical path difference integrated across the area of the fibre (cf., SIMMENS [14], and HAMZA [5]).

The aim of this work is to construct a fibre manipulation device for the optical microscope stage and to use this device in the measurement of refractive indices and birefringence of nylon 6 fibres, under strain, interferometrically using the PLUTA [15] and [4] polarizing interference microscope.

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2. Theoretical considerations

The mean value of the refractive index of the fibre is calculated from the totally duplicated images of the fibre, using the Pluta polarizing interference microscope [4], [15]. The following expression (cf., HAMZA [5]) is used:

$$n_a = n_L + \frac{F\lambda}{hA} \tag{1}$$

where n_a – mean refractive index of the fibre for light vibrating parallelly or perpendicularly to the fibre axis; n_L – refractive index of the immersion liquid; F – area enclosed by the fringe shift, for light vibrating parallelly or perpendicularly to the fibre axis; λ – wavelength of light used; h – interfringe spacing; and A – mean cross-sectional area of the fibre.

The mean birefringence Δn_a of the fibre can be determined from the values of the refractive indices for plane polarized light vibrating parallelly and perpendicularly to the fibre axis; $\Delta n_a = n_a^{\parallel} - n_a^{\perp}$.

Considering the nonduplicated image of the fibre, using Pluta polarizing interference microscope, the birefringence can be calculated from the formula

$$\Delta n_a = \frac{F\lambda}{hA} \tag{2}$$

where F – area enclosed under the fringe shift using nonduplicated image of the fibre.

3. Experimental results and discussion

i) Fibre manipulation device for the interferometric determination of refractive indices and birefringence of fibre under strain:

In order to measure dynamically both the refractive indices and the birefringence for the fibre under stretching, twisting or rotation, using an interference microscope, a fibre manipulation device is designed. It is shown in Fig. 1. This device consists simply of three units. The first unit is a stretching unit which consists of a steel base plate (1), 500 mm long 200 mm wide. Four sliding bars (2, 2′, 3 and 3′) are supported with the metallic base plate by four fixed bars (4, 4′, 5 and 5′), which are used for guiding the motion of two movable brackets (6 and 7). Every bracket moves on two sliding bars to ensure satisfactory smooth and parallel movement to each other. The system is provided with a special bar (8), which is fixed in the centre of the base plate (1). This bar is threaded as two halves.

The first half is working as a left hand thread and the second is a right hand thread. Two threaded nuts (9 and 10), welded with the brackets (6 and 7), are used to move these brackets by rotating the threaded bar (8). At the two ends of the bar (8) there are two wheels which are used to rotate the threaded bar causing the two sliding brackets to approach or to move away from each other, respectively

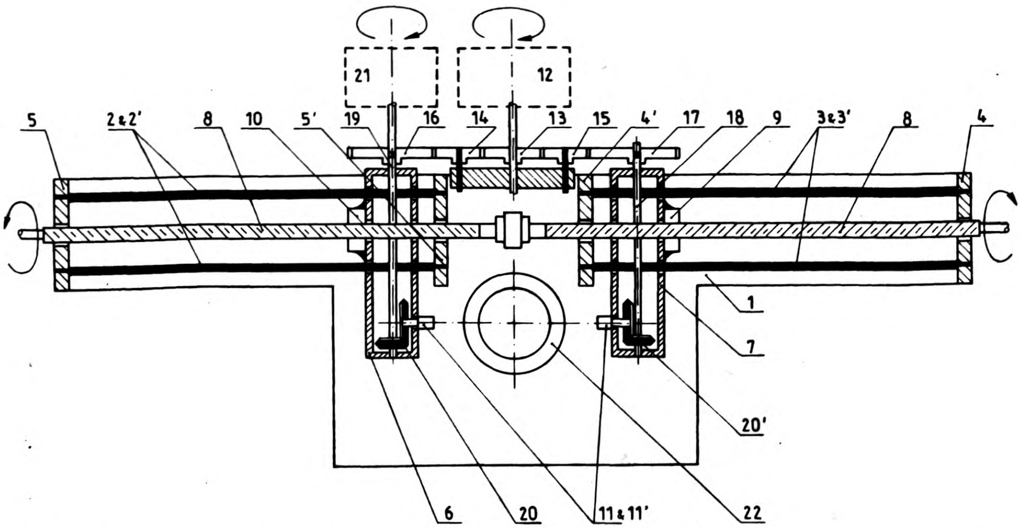


Fig. 1. Schematic diagram of the fibre manipulation device for opto-mechanical measurements of fibres under scattering, rotation or twisting, using the interference microscope (for explanation see text)

according to the anticlockwise or clockwise, direction of rotation. At the end of every bracket, there is a small round clamp (11 and 11′) used for fastening the two ends of the tested fibre by an adhesive. The moving of the two brackets causes a simultaneous stretching of the fibre from both its ends. In this case the measurements on the tested fibre can be performed at the same point of the investigated sample.

The second unit of this fibre manipulation device is used to rotate the fibre. It consists of a reduction gear box (12), which is connected with a three idle gears: one driver (13) and two intermediate gears (14 and 15). The rotation is transferred from the gear box (12) and the driver gear (13) to the driven gears (16 and 17), which are fixed on the vertical round bars (18 and 19). Every bar is ended with a group of two bevel gears (20 and 20′). By this group the vertical rotation will be translated to a horizontal one to facilitate the rotation of the tested fibre around its axis.

The third unit is used to twist the fibre. This unit consists of a reduction gear box (21) mounted with the vertical round bar (19). To rotate one end of the tested fibre relative to its other end, it is important to create a small gap between the intermediate gear (14) and the driven gear (16). This can be done by turning the threaded bar (8) clockwise for one complete turn, to cutout the contact between the driven gear (16) and the intermediate gear (14).

When fitting the fibre ends with the round clamps (11 and 11′), the utmost care should be taken during the fixation and straightening the sample so that the fibre be not stretched, because of strain birefringence which will be introduced with stretching the fibre. In order to determine the initial fibre length, the fibre is fully straightened and measured by an accurate vernier. The system may then be transferred to the microscope stage. A piece of a microscope slide may be arranged on a suitable jig (22) fixed in the centre between the two clamps (11 and 11′), and a cover glass added to the fibre which is immersed in a suitable liquid. The microscope is adjusted to ensure suitable illumination.

ii) Application of the device to the measurement of refractive indices and birefringence of fibres under strain:

Figures 2 **a**, **b** and **c** are microinterferograms showing the totally duplicated images of a sample of nylon 6 fibre with three different draw ratios 1.17, 1.5, and 2.0, respectively, using Pluta microscope. White light is used. The refractive index of the immersion liquid $n_L = 1.5445$ at 30.5°C. The fringe displacements in the upper image of the fibre are caused by the difference in $(n_a^{\parallel} - n_L)$, whereas in the other image the fringe displacement is due to the refractive index difference $(n_a^{\perp} - n_L)$. Using Eq. (1) the mean refractive indices $n_a^{\parallel}$ and $n_a^{\perp}$ of nylon 6 fibres are determined; the birefringence $\Delta n_a = n_a^{\parallel} - n_a^{\perp}$ is also determined at different values of draw ratio.

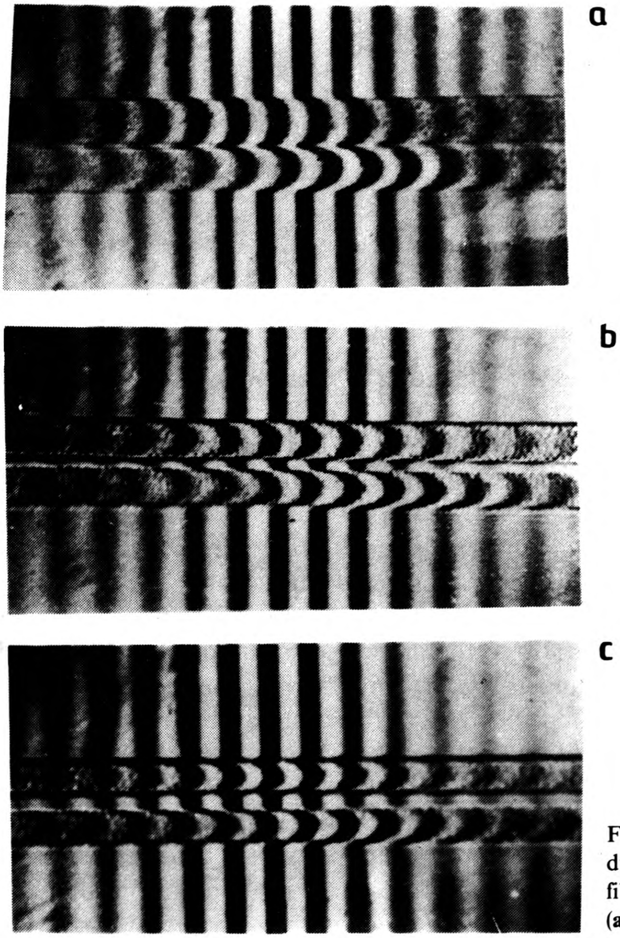


Fig. 2. Microinterferograms for the totally duplicated images for a sample of nylon 6 fibres, using white light (draw ratios: 1.17 (**a**), 1.5 (**b**), and 2 (**c**))

Figures 3 **a**, **b**, **c** and **d** are microinterferograms showing differentially sheared

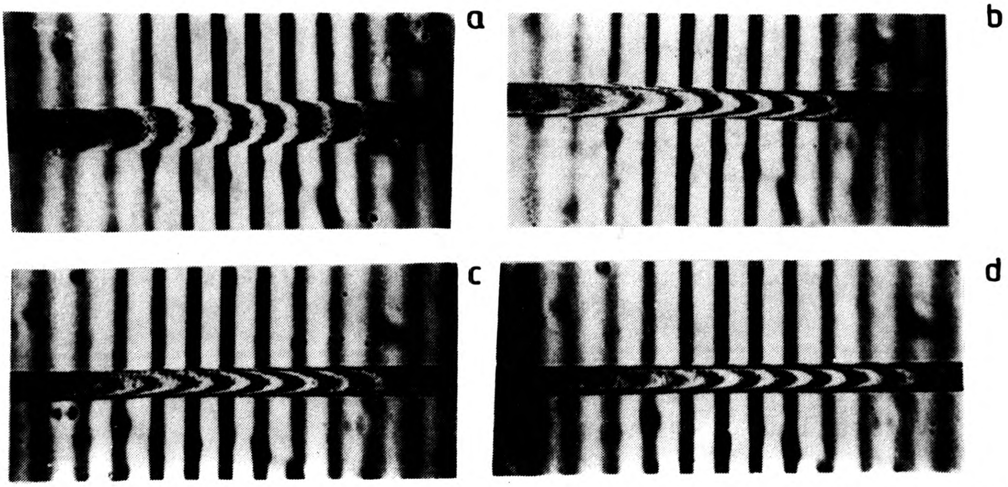


Fig. 3. Microinterferograms of the differentially sheared images for a sample of nylon 6 fibres (draw ratios: 1 (**a**), 1.83 (**b**), 2.33 (**c**) and 3.17 (**d**)). White light is used

images for another sample of nylon 6 fibres at four different values of draw ratios 1, 1.83, 2.33, and 3.17, respectively, using white light.

Figure 4 gives an interferogram of non duplicated images for a sample of the tested nylon 6 fibre before stretching. Monochromatic light of wavelength 546.1 nm is used. The refractive index of the immersion liquid $n_L = 1.5445$ at 30.5°C. From this figure $A = 1.329 \times 10^{-3}$ mm^2, $F_{\Delta n} = 6.925 \times 10^{-4}$ mm^2 and $h = 0.029$ mm, therefore, $\Delta n = 0.009$.

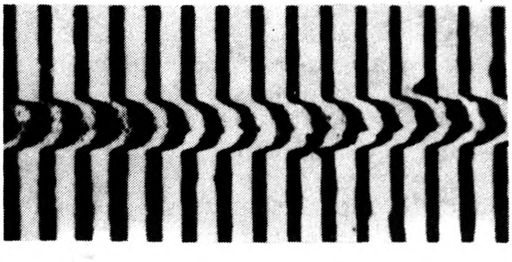


Fig. 4. Interferogram of the differentially sheared image of the fibre, using monochromatic light of the wavelength 546.1 nm

Figures 5 **a** and **b** represent totally duplicated images for a sample of nylon 6 fibres at two different values of draw ratio, 1.83 and 2.83, respectively. Monochromatic light of wavelength $\lambda = 546.1$ nm is used, $n_L = 1.5445$ at 30.5°C. In each of the Figs. 5 **a** and **b** the fringe displacement in upper image of the fibre is caused by the difference $(n_a^{\parallel} - n_L)$, whereas in the other image the fringe displacement is due to the refractive index difference $(n_a^{\perp} - n_L)$.

From Figures 2–5 it is clear that on stretching the fibre the area enclosed under it is changed.

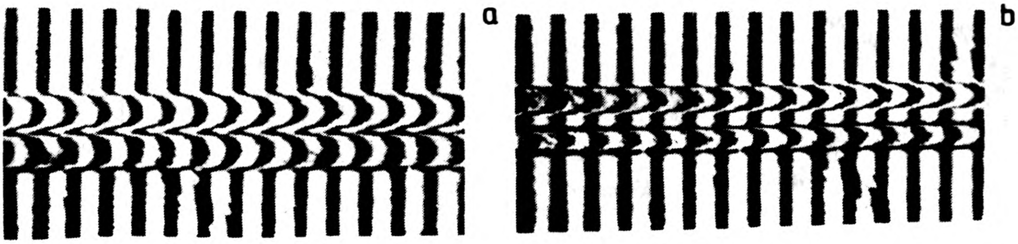


Fig. 5. Microinterferograms for the totally duplicated images for a sample of nylon 6 fibres at draw ratios: 1.83 (**a**) and 2.83 (**b**). Monochromatic light of wavelength $\lambda = 546.1$ nm is used

The Table gives the values of the mean refractive indices and the birefringence calculated from Figs. 5 **a** and **b**.

Refractive indices and birefringence of nylon 6 fibres ($n_L = 1.5445$, $T = 30.5°C$, $h = 0.029$ mm and $\lambda = 546.1$ nm)

Figure	Draw ratio R	Area of transverse section $\times 10^{-3}$ mm^2 A	Area enclosed under the fringe shift $\times 10^{-4}$ mm^2		Average refractive index and the birefringence		
			$F^{\parallel}$	$F^{\perp}$	$n_a^{\parallel}$	$n_a^{\perp}$	Δn_a
5 **a**	1.83	0.658	6.232	6.578	1.562	1.526	0.036
5 **b**	2.83	0.348	5.886	4.847	1.576	1.518	0.058

Figure 6 shows the relation between $n_a^{\parallel}$, $n_a^{\perp}$ as a function of birefringence Δn_a. The birefringence was found to be directly proportional to the refractive index $n_a^{\parallel}$, being inversely proportional to the refractive index $n_a^{\perp}$. White light was used in this experiment.

Extrapolation to zero birefringence gives the average value of the refractive index in the isotropic state $n_{iso} = 1.540$. This value coincides with the average value of n_{iso} calculated from the formula $n_{iso} = \dfrac{n^{\parallel} + 2n^{\perp}}{3}$ and equal to 1.539.

The birefringence Δn_a, calculated from the totally duplicated images as a function of draw ratio, is given in Fig. 7, while the relation between Δn_a calculated from the non duplicated images, and the draw ratio is shown in Fig. 8.

It is clear from these figures that the birefringence (Δn_a) varies with the draw ratio R according to the following differential relation, due to DE VRIES [1]

$$\frac{d(\Delta n)}{d \ln R} = m + p\Delta n. \tag{3}$$

By integrating Eq. (4)

$$\Delta n = \frac{c}{p} R^p - \frac{m}{p} \tag{4}$$

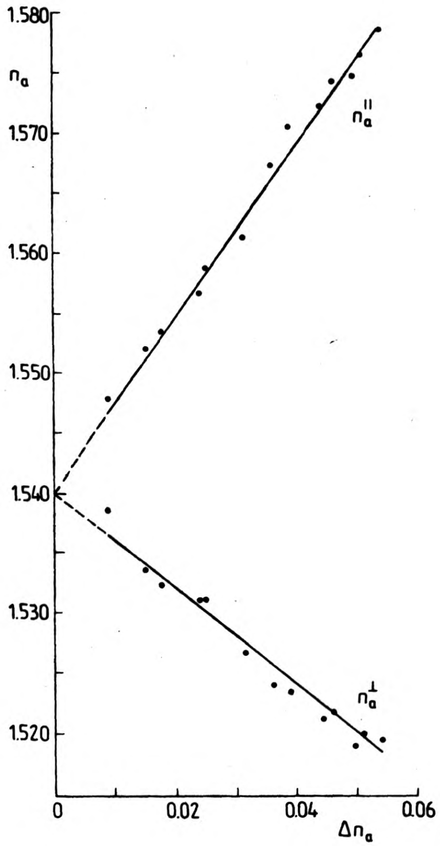


Fig. 6. Variation of the mean refractive indices $n_a^{\parallel}$ and $n_a^{\perp}$ with the birefringence

where c, p and m are parameters characterize the deformation process, their values for nylon 6 fibres have been obtained, namely: $c = 0.1056$, $p = -1.343$ and $m = 0.101$.

The experimental values of the birefringence fitted to the values derived from Eq. (4) are shown in Figs. 7 and 8 (dashed lines).

4. Conclusions

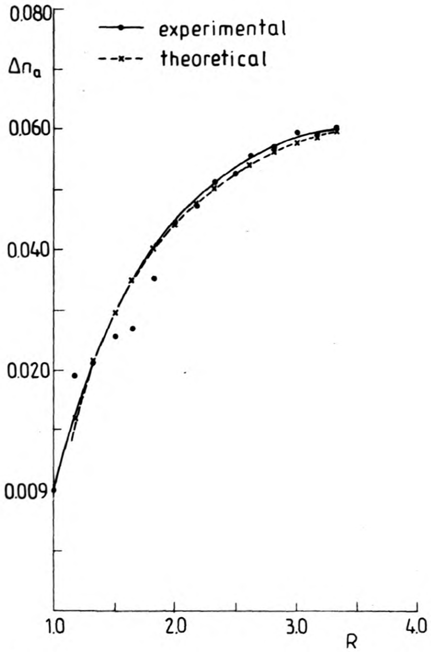
The described device realizes the following tasks:

i) It can be fitted conveniently to the stage of the polarizing interference microscope without obstructing its operation.

ii) It presents the fibre under test in the object plane of the interference microscope during the time the required experiment is performed.

iii) The fibre can be: a) stretched along its axis, b) rotated around this axis or c) twisted by fixing its one end and rotating the other one.

The two-beam microinterferometric technique, with the application of the described device, gives a clear understanding of the mechanism of the fibre stretching



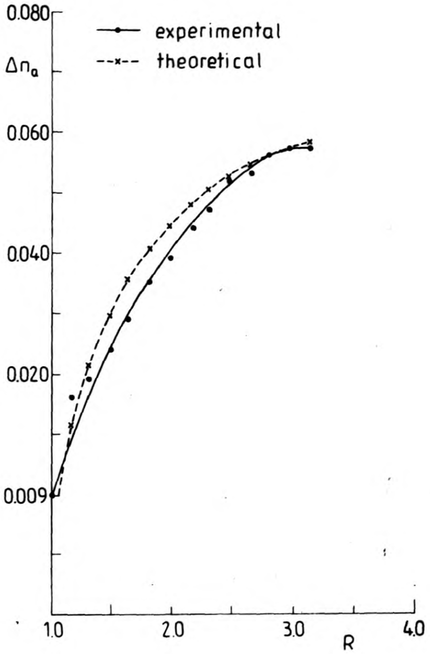


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Fig. 7. Mean birefringence measured from the totally duplicated images as a function of draw ratio. Solid curve represents the actual measurements, the fitted line being indicated by broken curve

Fig. 8. Relation between the mean birefringence, measured from the differentially sheared images, and the draw ratios. The actual measurements are indicated by the solid curve, while the broken curve represents the fitted values

and its effect on the molecular orientation within the fibre. The following conclusions may be drawn:

1. The interferometric technique gives valuable information about the changes of the optical properties of the stretched fibres. This information helps the characterisation of these fibres and the adjustment of the drawing processes of fibres.

2. The birefringence of nylon 6 fibres is directly proportional to $n_a^{\parallel}$, and inversely proportional to $n_a^{\perp}$ values. This result means that during stretching the fibre chains become oriented in the direction of stretching (parallel to the fibre axis).

3. With the increasing stretching of the fibre its birefringence increases at a constant rate, and then it levels off.

4. This device, combined with the Pluta microscope, provides an easy and quick method for studying the opto-mechanical properties of fibres. It is very useful when fibres with high refractive indices are measured or when an immersion liquid of refractive index differs remarkably from that of the fibre. The measurement errors of the values of refractive indices and the birefringence cannot be smaller than 0.003–0.001, when the diameter of the fibre is about 30 μm and determined with an accuracy of about 1 μm (cf., PLUTA [4]).

References

[1] De Vries H., J. Polym. Sci. **34** (1959), 761–78.
[2] Faust R. C., Proc. Phys. Soc. **B65** (1952), 48–61.
[3] Barakat N., El-Hennawi H. A., Text. Res. J. **41** (1971), 391–6.
[4] Pluta M., J. Microsc. **96** (1972), 309–32.
[5] Hamza A. A., Text. Res. J. **50** (1980), 731–4.
[6] Hamza A. A., Sokkar T. Z. N., Kabeel M. A., J. Phys. D, Appl. Phys. **18** (1985), 1773–80.
[7] Hamza A. A., Sokkar T. Z. N., Kabeel M. A., J. Phys. D, Appl. Phys. **18** (1985), 2321–8.
[8] Hamza A. A., Kabeel M. A., J. Phys. D, Appl. Phys. **20** (1987), 963 8.
[9] Hamza A. A., Fouda I. M., El-Farahaty K. A., Helaly S. A., J. Mater. Sci. (submitted).
[10] Banky E. C., Slen S. B., Text. Res. J. **27** (1957), 417–8.
[11] Collins J. D., J. Sci. Instrum. **40** (1963), 198–9.
[12] McKee A. N., Doctor's Thesis, University of Leeds, 1967.
[13] Beevers R. B., *Experiments in Fibre Physics*, Butterworths, London 1970, p. 152–5.
[14] Simmens S. C., Nature **181** (1958), 1260–1.
[15] Pluta M., Optica Acta **18** (1971), 661–75.

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Интерферометрическое определение оптомеханических свойств оптических волокон

Сконструирован прибор для установки оптических волокон и применен для исследования зависимости двойного лучепреломления, вызванного напряжениями в случае полимерных волокон. Этот прибор был употреблен вместе с поляризационно-интерференционным микроскопом Плюты для определения средних коэффициентов преломления и двойного лучепреломления волокон, вызванного напряжениями. Для каждого значения напряжение поля, в котором наступает сдвиг интерференционной линии спектра считается как представляющее разность оптических дорог, интегрированную по поле волокна. Этот прибор дает возможность исследовать растягиваемые, скручиваемые и вращаемые волокна и можно его легко припасовать к столику интерференционного микроскопа без помех в его действии. Для иллюстрации помещены микроинтерферограммы.