Autocollimating Detectors of Birefringence

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ABSTRACT

The paper describes the devices for measuring the normal-reflection birefringence with using of the photometric, balanced, compensation and interferometric methods. The suggested schemes may be used for research of optical anisotropy in optical recording disks, inner stress in transparent solid body, birefringence of crystals and for the measuring of temperature, pressure, electrical and magnetic field strength.

Keywords:
Polarization, birefringence, polarimetric sensor, optical disks

1.INTRODUCTION

Optical polarization devices for investigating birefringence properties of an object under test in a passing or slantingly reflected beam have as separate parts an optical scheme for formation polarization of a sounding beam and a scheme for analyzing polarization of a light passed through or reflected from an object[1,2]. In the devices with an autocollimational beam path[3] formation and analysis of beam polarization are made by the same optical elements. Owing to superposition of a sounding and inverse beams these devices have the following advantages:

a) due to the double passing of the beam through the object the threshold of sensitivity lowers;

b) if direct access is difficult or impossible distance controlling can be realized;

c) if the object under test is disposed in a hermetically isolated cell for entrance and exit of radiation the same window is used;

d)decrease in the number of optical elements simplifies the device, makes it cheaper and shows us prospects of its further diminishing;

e) the device can easily be adjusted for common use with polarimetric optical-fiber sensors made by a single-fiber scheme;

f) while investigating optical constant high-absorbing anisotropic mediums the conduct of experiment and analysis of results are simplified, the influence of a transition is minimized as well as sensitivity for errors of the incident beam angle.

The autocollimating birefringence detectors suggested and realized by the author of the paper are presented. In particular this detectors are used for measure of birefringence of the optical disks.

2.PHOTOMETRIC DETECTORS OF BIREFRINGENCE

2.1. Photometric detector with linearly polarized probe beam

The photometric method of measurement consists in following. An investigating object is illuminated by a polarized probe beam. Polarization state of the beam changes due to object birefringence. Thus the polarization component appears in reflecting beam which is orthogonal to the polarization vector of the probe beam. The object phase difference and principal plane orientation are defined by means of measurement of the orthogonal and parallel polarization component intensities in the reflecting beam.

The installation scheme with a linearly polarized probe beam[4,5] is shown in Fig.1. This device allows to determine the object phase difference and the principal planes orientations. It does not give enable to define the phase difference sign.

The optical configuration involves a laser I, a polarimetric block II, a modulator III, a control unit (a voltmeter)IV and the specimen V. The modulator should not change the light polarization, and therefore a

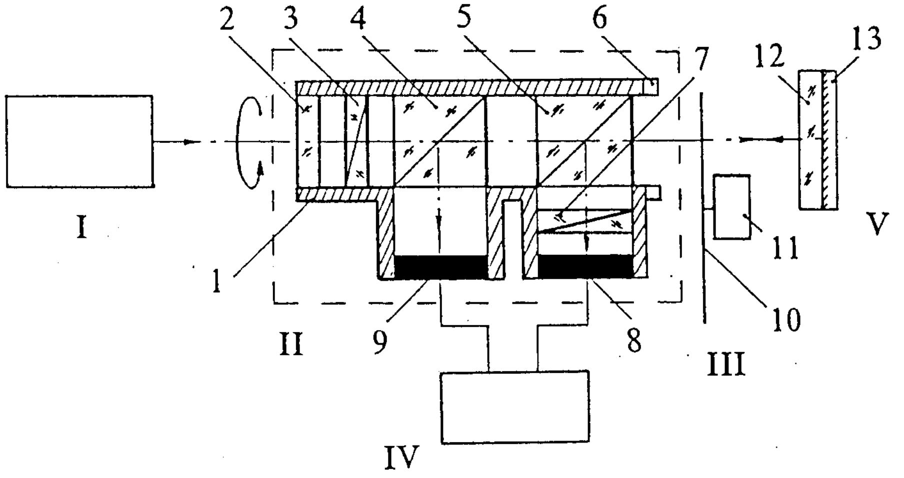

Fig.1. Configuration of the photometric device used a linearly polarized probe beam for measuring birefringence: Laser I, polarimetric block II, modulator III, control unit IV, specimen V. 1- rotating body, 2- λ/4 plate, 3 and 7 - first and second polaroids, 4- semitransparent beamsplitter, 5- polarization beamsplitter, 6- angle-measuring limb, 8 and 9 - first and second photodetectors, 10- chopper, 11- engine 12- transparent layer, 13- reflecting surface.

chopper 10 driven by a engine 11 is used. The best position for the chopper disk is between the polarimetric block and the specimen so that the probe radiation scattered in the polarimetric block is not modulated. A parallel transparent birefringent layer 12 on a reflecting surface 13 can be tested.

The linearly polarized laser beam is fed into the polarimetric block. The beam's polarization plane can be rotated to a required angle by turning the rotating body 1, which contains the λ/4 plate 2, the first polaroid 3, a semitransparent beamsplitter 4, a polarization beamsplitter 5. The output beam intensity remains unchanged.

Then the linearly polarized beam illuminates the specimen which reflects the beam back. If the probe's polarization plane is parallel to one of the principal planes of the object, the reflected beam has the same polarization. When the polarization plane does not coincide with the principal axes of the object, the reflected beam has a different polarization. Hence a component with the polarization perpendicular to that of the probe beams is present in the reflected beam. This component is reflected onto a first photodetector 8 by the polarization beamsplitter 5. Since this beamsplitter with an interference polarization coating is used, an additional polaroid 7 is used to eliminate the small collinear component in the beam reflected from the splitter. A component with the polarization parallel to that of the probe beam passes the polarization beamsplitter and falls on the semitransparent beamsplitter. This splitter reflect a half of the parallel component intensity to the photodetector 9. The intensities of the radiation incident on the photodetectors 8 and 9 are measured by the voltmeter.

The scheme will be described in the Cartesian system of coordinates the X axis of which is parallel to the principal plane of the polarization beamsplitter, which specifies the polarization plane of the probe beam. In the general case the parallel and orthogonal component's intensities in the reflected beam Φ'_x and Φ'_y are given by:

$$\Phi'_x = [\cos^2(\Delta/2) + \sin^2(\Delta/2)\cos^2 2(\psi-\theta)]\, R^2\, \Phi_o\,,$$

$$\Phi'_y = \sin^2(\Delta/2)\sin^2 2(\psi-\theta)\, R^2\, \Phi_o\,. \qquad (1)$$

where Φ_o is the probe beam intensity, R is the amplitude reflection coefficient of the mirror surface of the specimen, Δ is the phase difference introduced into the beam by the transparent layer 12 upon double passage of the radiation, ψ and θ are angular positions of axis of the specimen and the principal plane of the polarization beamsplitter with respect to the zero direction of the device.

Rotating the body 1 the beam component with the perpendicular polarization Φ'_y can be minimized. In this case

$$\psi = \theta + 90^\circ n, \qquad (2)$$

where n is an integer.

Let us align the rotating body so that X axis is at 45° to the fast axis of the specimen, i.e. $\psi - \theta = 45^\circ$. In this position, we have

$$\Phi'_x = cos^2(\Delta/2)\, R^2\, \Phi_o\,,$$

$$\Phi'_y = sin^2(\Delta/2)\, R^2\, \Phi_o\,. \qquad (3)$$

Measuring the parallel and orthogonal component's intensities in the reflected beam, we find the phase difference Δ.

$$\Delta = 2\, tan^{-1} \sqrt{\frac{\Phi'_Y}{\Phi'_X}} + 180^\circ\, m, \qquad (4)$$

where m is an integer.

The probe beam polarization plane may rotate with using of the $\lambda/2$ plate[8] or two $\lambda/4$ plates[6] or the electrooptical polarization rotating device[7] also.

2.2. Photometric detector with circularly polarized probe beam

The installation scheme with a circularly polarized probe beam is shown in Fig.2. This device allows to measure the object phase difference only. It does not give enable to measure the principal planes orientations.

The device works in the following manner. The linearly polarized beam passes the semitransparent and polarization beamsplitters. The polarization plane of the probe beam is parallel to the transmission plane of the polarization beamsplitter. The principal planes of $\lambda/4$ plate are placed at an angle 45° to the beam polarization plane. The $\lambda/4$ plate makes the circularly polarized probe beam. This beam is reflected from the specimen and return passes the $\lambda/4$ plate.

The parallel and orthogonal component's intensities in the reflected beam Φ'_x and Φ'_y will be the following:

$$\Phi'_x = sin^2(\Delta/2)\, R^2\, \Phi_o\,,$$

$$\Phi'_y = cos^2(\Delta/2)\, R^2\, \Phi_o\,. \qquad (5)$$

where Φ_o is the probe beam intensity, R is the amplitude reflection coefficient of the mirror surface of the specimen, Δ is the phase difference introduced into the beam by the transparent layer 9 upon double passage of the radiation, ψ .

Measuring the component's intensities in the reflected beam, we find the phase difference Δ.

$$\Delta = 2\, tan^{-1} \sqrt{\frac{\Phi'_x}{\Phi'_y}} + 180^\circ\, m, \qquad (6)$$

where m is an integer

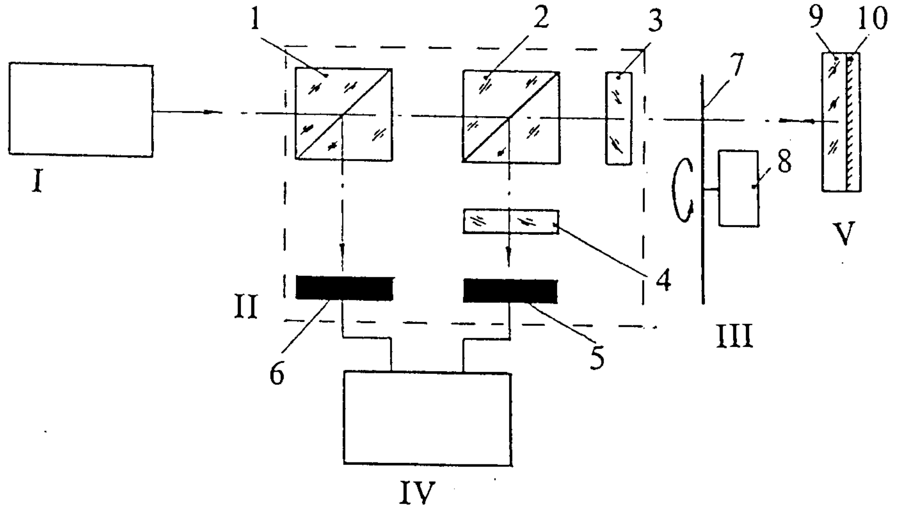

Fig.2. Configuration of the photometric device used a circularly polarized probe beam for measuring birefringence: Laser I, polarimetric block II, modulator III, control unit IV, specimen V. 1-semitransparent beamsplitter, 2- polarization beamsplitter, 3- λ/4 plate, 4- polaroid, 5 and 6 - first and second photodetectors, 7- chopper, 8- engine , 9- transparent layer, 10- reflecting surface.

3.BALANCED DETECTOR OF BIREFRINGENCE

This method is based on compensation of a difference between two orthogonal polarized fluxes which incident on photodetectors. The balanced detector schemes shown in Fig.3. The device enables to determine a phase difference and principal planes orientations.

The scheme will be described in Cartesian system of coordinates the X axis of which is parallel to the principal plane of the second polarization beamsplitter. The balanced detector works in the following manner. The laser probe beam passes the polarimetric block, modulator and illuminates the specimen which reflects the beam back. The reflecting beam falls on the second polarization beamsplitter. A component with Y-polarization is reflected onto the second photodetector by this beamsplitter. A component with X-polarization passes the second beamsplitter and falls on the first polarization beamsplitter. This splitter reflect a part of the X-component to the first photodetector. Photodetectors signals are applied the positive and inverse inputs of the difference amplifier. the amplifier output is coupled with the null indicator input. Besides, the second photodetector may be connected directly to the null indicator.

In the general case the beam fluxes Φ'_1 and Φ'_2 which incident on the first and second photodetectors can be written as:

$$\Phi'_1 = \cos^2\gamma\ \sin^2\gamma\ [\ 1 - \sin^2(\Delta/2)\,\sin^2 2((\psi-\theta)]\ R^2\ \Phi_0\,,$$

$$\Phi'_2 = \cos^2\gamma\ \sin^2(\Delta/2)\,\sin^2 2(\psi-\theta)\ R^2\ \Phi_0. \qquad (7)$$

where γ is the angle between principal planes of first and second polarization beamsplitter, Δ is the phase difference introduced into the beam by the transparent layer 19 upon double passage of the radiation, ψ and θ are angular positions of fast axis of the specimen and the principal plane of the second polarization beamsplitter with respect to the zero direction of the device, Φ_0 is the probe beam intensity if $\gamma=0$, R is the amplitude reflection coefficient of the mirror surface of the specimen.

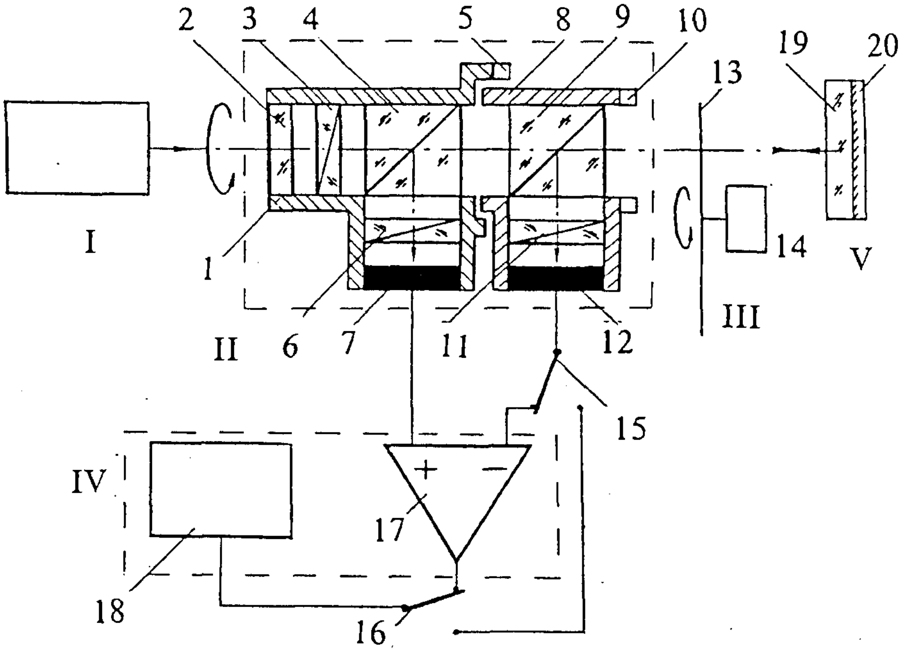

Fig.3. Configuration of the balanced device measuring birefringence: Laser I, polarimetric block II, modulator III, control unit IV, specimen V. 1 and 8 - first and second rotating bodies, 2 - λ/4 plate, 3, 6 and 11- first, second and third polaroids, 4 and 9 first and second polarization beamsplitters, 5 and 10- first and second angle-measuring limbs, 7 and 12 first and second photodetectors, 13- chopper, 14- engine, 15 and 16 first and second commutators, 17- transparent layer, 18- reflecting surface.

Let us align the beamsplitters so that $\gamma=0$ and connect the second photodetector to the null indicator. By rotating the first body with the second body fixed, one can attain minimum of the Φ'_2. In this case

$$\psi = \theta + 90^\circ n, \tag{8}$$

where n is an integer.

We set the second rotating body so that X axis is at 45° to the fast axis of the specimen, i.e. $\psi-\theta = 45^\circ$. In this position, we have

$$\Phi'_1 = \cos^2\gamma \ \sin^2\gamma \ \cos^2(\Delta/2)\, R^2\, \Phi_0,$$

$$\Phi'_2 = \cos^2\gamma \ \sin^2(\Delta/2)\, R^2\, \Phi_0. \tag{9}$$

Furthermore, we couple the second photodetector with the inverse input of the differential amplifier which is connected to the null indicator. Rotating the first body while the second body remains fixed, the fluxes Φ'_1 and Φ'_2 can be balanced if

$$\tan^2(\Delta/2) = \sin^2\gamma. \tag{10}$$

Hence we obtain:

$$\Delta = \tan^{-1}(\sin\gamma) + 180^\circ m, \tag{11}$$

where m is an integer.

4.COMPENSATION DETECTOR OF BIREFRINGENCE

Unlike device which compensate the component whose polarization is collinear with that of the probe beam[3], our device[10] compensates the reflected beam component, which has a polarization perpendicular to that of the probe beam. The optical configuration of our device is shown in Fig.4.

The intensity of the radiation flux of the orthogonal component Φ' in the reflected beam is described by following expression:

$$\Phi' = \{sin(\Delta/2)\, cos2(\varphi-\theta)\, sin2(\varphi-\psi) - cos(\Delta/2)\, sin2(\varphi-\theta)\}^2 R^2 \Phi, \qquad (12)$$

where Φ is the probe beam intensity, R is the amplitude reflectivity of the mirror surface of the specimen, Δ is the phase difference introduced into the beam by the specimen upon double passage of the radiation, φ, ψ and θ are the angular positions of the fast axes of the second $\lambda/4$ plate and the specimen, as well as of the principal plane of the polarization beamsplitter which specifies the polarization plane of the probe beam with respect to the zero direction of the device.

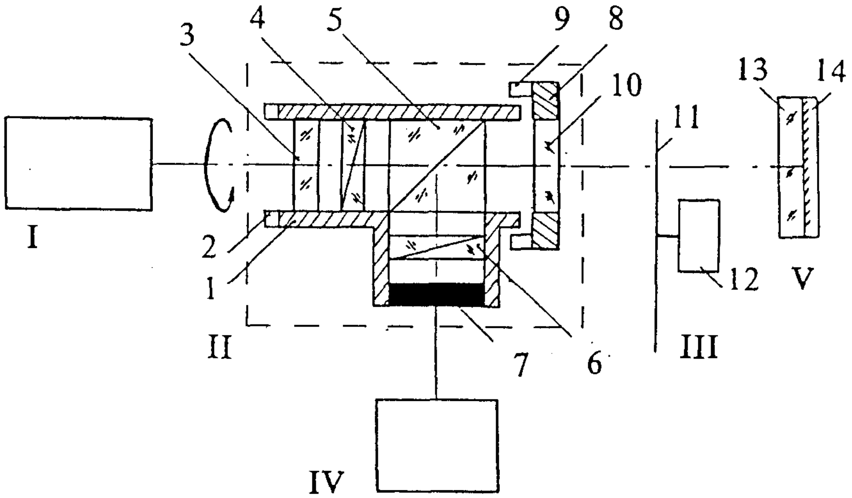

Fig.4. Configuration of the compensation device measuring birefringence: Laser I, polarimetric block II, modulator III, control unit IV, specimen V. 1 and 8 - first and second rotating bodies, 2 and 9 - first and second angle- measuring limbs, 3 and 10- first and second $\lambda/4$ plates, 4 and 6- first and second polaroids, 5- polarization beamsplitter, 7- photodetector, 11- chopper; 12- engine, 13- transparent layer, 14- reflecting surface.

When the principal planes of the polarization beamsplitter and the second $\lambda/4$ plate coincide (i.e., $\varphi = \theta$) Eq.(12) can be put in the following form:

$$\Phi' = sin^2(\Delta/2)\ sin^2 2(\psi - \theta)\, R^2 \Phi, \qquad (13)$$

In this case compensation of the intensity Φ' is achieved by simultaneous rotation of the polarization beamsplitter and the second $\lambda/4$ plate. In the position found, the orientation of the principal planes of the specimen corresponds to the orientation of the principal planes of the polarization beamsplitter.

Furthermore, we install the second λ/4 plate in such a way that its fast axis makes an angle of 45° with the fast axis of the specimen, i.e. $\varphi-\psi = 45°$. In this case

$$\Phi' = sin^2\left[\frac{\Delta}{2}-2(\varphi-\theta)\right]\ R^2\,\Phi, \tag{14}$$

By rotation the polarization beamsplitter with the second λ/4 plate fixed, one can attain compensation of the flux Φ' of the orthogonal component. The difference in the azimuths of the beamsplitter an the second λ/4 plate, latter being in the position found, makes it possible to determine the value of the phase shift of the specimen:

$$\Delta = 4(\varphi - \theta) + 360° m, \tag{15}$$

where m is an integer.

This device enables rather simply to find the fast axis azimuth and phase difference of the reflecting specimen. Besides, due to the compensative method of measuring, a high level of sensitivity is secured. For instance, in our device the threshold of phase difference sensitivity amounts to 0.03°.

5.INTERFEROMETRIC DETECTOR OF BIREFRINGENCE

Suggested interferometric method of birefringence measurement[11] consists in following. A circularly polarized probe beam illuminates the specimen, which reflects the radiation backward. This beam interferes with the circularly polarized reference beam. Comparing the beat amplitudes of the resulting beam polarization components and its phase we shall obtain the phase difference and the principal planes orientations of the specimen.

A scheme of the interferometric detector is present on Fig.5. We shall describe changes of beam polarization states with help of the Cartesian coordinates. The X-axis is the parallel to the polarization plane of the radiation transmitted by a polarization beamsplitter. The principal planes of λ/4 and λ/8 plates, semitransparent and polarization beamsplitters are parallel. The polaroid principal plane makes an angle 45° with the X-axis. An oscillograph is used as a control unit.

The device works in the following manner. The laser beam passes the polaroid and falls on the semitransparent beamsplitter, which divides this beam into probe and reference beams. The probe beam passes the λ/4 plate and becomes circularly polarized. Then the beam falls on the specimen, which reflects it backward. Due to the double passing of the reference beam through λ/8 plate this beam becomes circularly polarized. The reference mirror oscillates along the beam axis with a peak-to-peak more than half wavelength. The reflected reference beam and reflected probe beam are combined by the semitransparent beamsplitter. The polarization components of the resulting beam are divided by the polarization beamsplitter. This components falls on the photodetectors.

The alternating radiation fluxes $\Phi'_{x\sim}$ and $\Phi'_{y\sim}$ which depend upon the phase difference between the probe and reference beams ϕ will be the following:

$$\Phi'_{x\sim}= \sqrt{1+\sin\Delta\sin 2(\psi-\theta)}\ cos(\phi - tan^{-1}\ (\frac{\sin(\Delta/2)\cos 2(\psi-\theta)}{\cos(\Delta/2)+\sin(\Delta/2)\sin 2(\psi-\theta)}))\ R_m R_s\ \Phi_o,$$

$$\Phi'_{y\sim}= \sqrt{1-\sin\Delta\sin 2(\psi-\theta)}\ cos(\phi - tan^{-1}\ (\frac{\cos(\Delta/2)-\sin(\Delta/2)\sin 2(\psi-\theta)}{\sin(\Delta/2)\cos 2(\psi-\theta)}))\ R_m R_s\ \Phi_o. \tag{16}$$

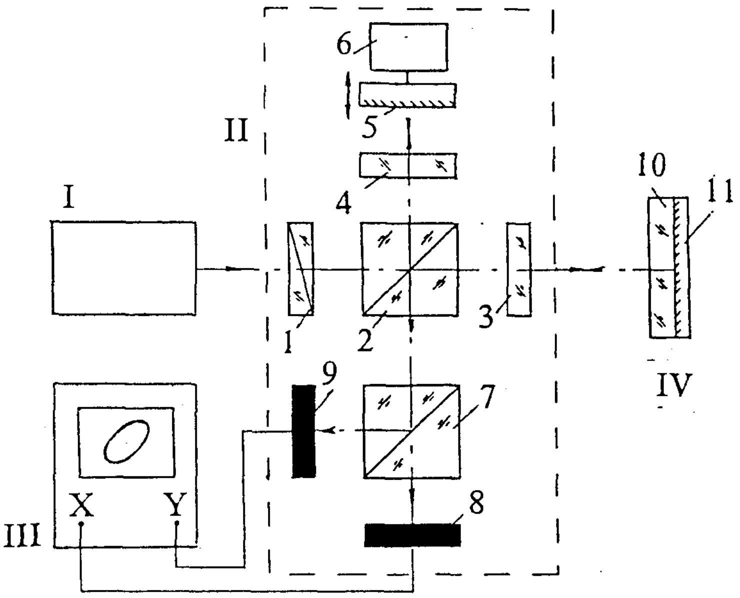

Fig.5. Configuration of the inteferometric device measuring birefringence: Laser I, polarimetric block II, control unit III, specimen IV. 1- polaroid, 2 - semitransparent beamsplitter, 3- λ/4 plate, 4- λ/8 plate, 5- mirror, 6- mirror driver, 7- polarization beamsplitter, 8 and 9- first and second photodetectors, 10-transparent layer, 12- reflecting surface.

where Φ_0 is the initial beam intensity, R_m and R_s are the amplitude reflectivities of the reference mirror and the specimen, Δ is the phase difference introduced into the beam by the transparent layer 12 upon double passage of the radiation; ψ is angular position of fast axis of the specimen with respect to the X axis.

The alternating photodetectors signals are applied the "X" and "Y" inputs of the oscillograph. We can see a Lissajous figure on the oscillograph screen. This figure is an ellipse. Ellipticity ε and major azimuth χ of the ellipse are coupled with the specimen parameters ψ and Δ by following simple formulae:

$$\psi = 45^\circ - \chi$$

$$\Delta = 90^\circ - 2\,\varepsilon. \qquad (17)$$

6.CONCLUSIONS

Finally we underline the principal different peculiarities of the suggested methods. The compensation and interferometric devices enable to determine the value and sign of a phase difference and the principal planes orientations. An advantage of compensation detector is a high precision, while its disadvantage is a long measurement time. Advantages of the interferometric detector are a small measurement time and a possibility of a process evolution control. Its deficiencies are a complicated production and a low precision.

The photometric device with a linearly polarized probe beam and the balanced device allow to define a phase difference value and principal planes orientations. An advantage of the photometric device is a simplicity of production. Advantages of the balanced device are a high precision and linearity of mismatch signal. Its deficiency is a long measurement time.

The photometric device with a circularly polarized probe beam enables to define a phase difference only. Its advantage is a small measurement time, while is disadvantage is a low precision.

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