THE NEW METHOD FOR LIGHT POLARIASATION STATE DETERMINATION AND THEIR APPLICATION FOR MAGNETOOPTICAL EFFECT INVESTIGATIONS

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This work presents the new method that allows determining the ellipse of polarisation. Therefore it allows determining the state of polarisation. This paper also shows how to apply presented method in designing the fiber optic magnetic field sensors.

Keywords: Fiber optic sensors, magnetooptic effects, state of polarisation.

1. INTRODUCTION

There is for magnetic field sensors being able to function under extremely strong electromagnetic interference. Since such circumstances exist inside high power transformers, thus measuring magnetic field intensity in those places is a serious problem. Well-known electric methods of measuring magnetic field, making use of Hall sondes or coils, are very sensitive to electromagnetic interference and being uninsulated. Sparks that appear in electric circuits can lead to explosion of hydrogen issued from the transformer oil.

The optical fiber magnetic field sensors are an interesting alternative for classical sensors since it possesses good insulating properties and can use optical fibers as electromagnetic-insensitive feeding conduits. However, this choice possesses some disadvantages as well. The main problem with this type of sensor is its high susceptibility to temperature or mechanical vibration [1]. The successful solution of the problem will allow performing practically a project of the optical fiber magnetic field sensor [2]. This article deals with an investigation of Faraday's effect in a few quartz fibers.

2. THEORY

Magnetic field can influence light propagation by changing the material properties, which are described by the dielectric constants. This influence modifies real or imaginary part of these constants thus changing the refraction and absorption indices. In case of the Faraday's effect the magnetic field changes real part of dielectric constant tensor and extors thus appearance of circular birefringence. If the material is optically isotropic and does not possess birefringence and eigenabsorption, as a result of the Faraday's effect two rays, with opposite circular polarisation, propagate in the material. There is a difference between refraction indexes of both rays which, in turn, causes to appear some difference of phases between the rays after travelling by them a distance l. This phase difference is equal to [3]:

$$\Delta\psi = 2\Pi\frac{(n'-n'')l}{\lambda} \tag{1}$$

As a result of their interference there arises a linear polarisation at the output being twisted of some angle related to the input polarisation. The twisting angle is equal to [3]:

$$\Gamma = \frac{1}{2}\Delta\psi = \frac{\Pi l(n'-n'')}{\lambda} \tag{2}$$

Basing upon the theory of molecular optic [4] the Faraday's twisting angle can be given as follows [5]:

$$\Gamma = VHl\cos\Theta \tag{3}$$

where:

V -Verdet material constant $\left[\frac{rad}{A}\right]$, H - magnetic field intensity, Θ – an angle between the light wave vector and the vector of magnetic field intensity.

The formula (3) shows that the Faraday's effect reaches its maximum when the angle between the vector of magnetic field intensity **H** and the light wave vector is equal to zero ($\Theta=0^0$). Since both vectors are parallel an effect is named a longitudinal one [5].

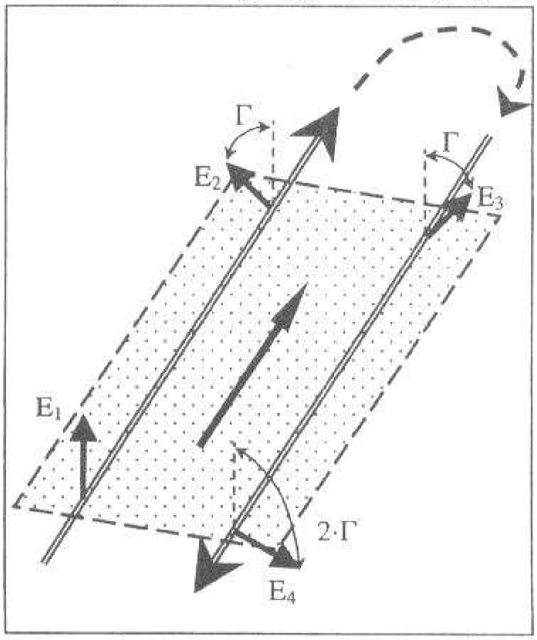

Fig.1. Illustration non-reversible of Faraday effect.

The next property of the effect is its non-reversible. This non-reversibility consists in the absence of twisting reduction when the light propagation changes its direction through

180° (e.g. after reflection). After reversing the light propagation direction the rotation of the polarization plane will be reverse, however the twisting angle, which has arisen before the light direction change, will be still increasing. It is shown on Fig.1.

Summarizing it should be underline, that the Faraday's effect non-reversibility will allow us to multiply easily this effect and to achieve proper sensitivity.

3. MEASURING POSITION

Fig.2 shows the set-up for investigation of Faraday effect in the optical fibers. A light ray with wavelength 670 nm is emited by a laser diode. The ray after passing by the Glan's polarizer enters into fiber being tested. The fiber is wrapped on a special reel and put into the coil (Fig.3.).

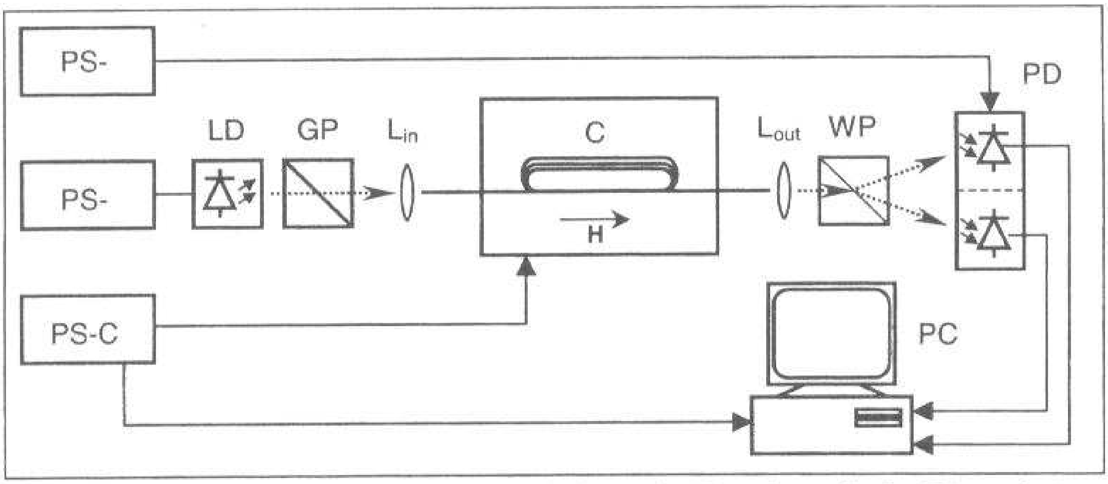

Fig.2. Measurments scheme. *PS-LD – laser diode supply, LD – laser diode, GP – polarizer: Glan prism, L_{in}, L_{out} – lens, MF – magnetic field interaction space, WP – analyser: Wollaston polarizing prism, SP-PD – photodetector supply, PD – photodetectors, PS-C – coil supply, C – magnetic field source: air-core coil, PC – computer.*

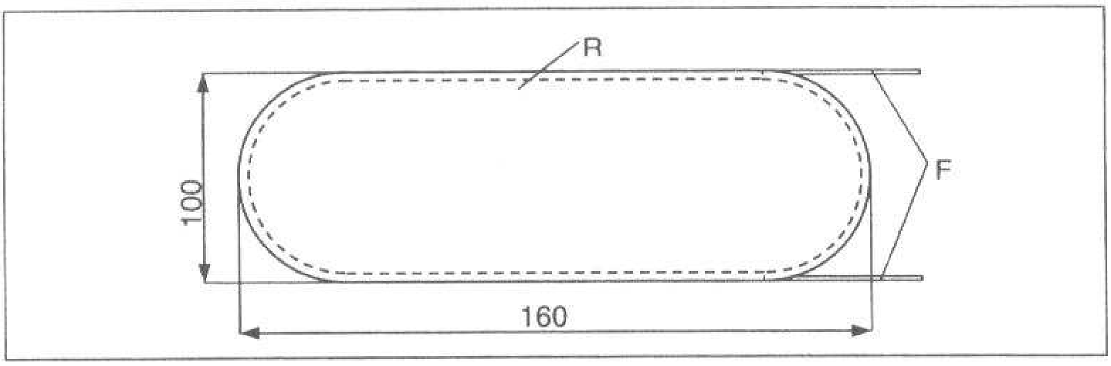

Fig.3. Fiber sensors head. *R – special shape reel, F – fiber being*

As magnetic field source an air-core is used. The coil is provided with a rectangular hole to place inside it the special reel with fiber being tested. The coil is supplied with direct current of the range from 0 to 10 A. For current 10A an average of magnetic field intensity being calculated on the reel surface is about 35 mT.

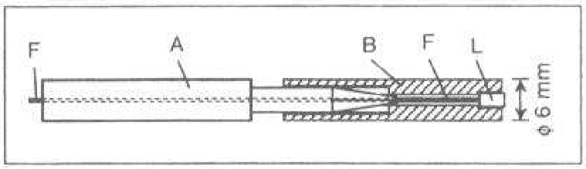

Fig.4. Fiber holder. *A - clamp, B – terminal nut, F – fiber tested, L – SELFOC type lens.*

The second end of the fiber is provided with SELFOC type lens in order to collimate a ray (Fig.4.). The ray after passing the SELFOC comes across the Wollaston prism WP and is split into two rays, which have mutually orthogonal polarisation planes. These rays are detected in the photodetectors. The photodetectors voltages are measured in PC card that is mounted in a computer. All parts being specified are closed in detection chamber as shown on Fig.5. The fiber holder is fixed to the part A of detection chamber. The prism and photodetectors are fixed to the part B of detection chamber. There is a goniometer between those parts in order to twist part B of a given angel relative to part A. Such an arrangement allows to determine the parameters which characterise the ellipse of a polarisation state of the ray leaving the fiber being under investigation.

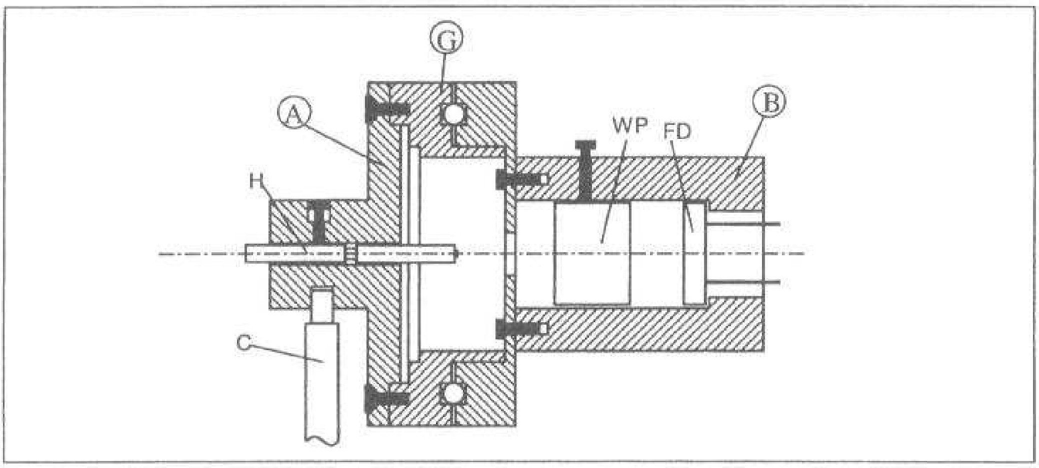

Fig.5. Detection chamber. *A – immobil part, B – mobil part, G – goniometer, WP – Wollaston polarizing prism, PD – photodetectors, C – clamping part A, H – fiber holder with SELFOC type lens.*

4. STATE OF POLARISATION DETECTION METHODS

The aim of polarisation analysis is to define the degree of polarisation, type of polarisation and parameters that define the state of polarisation. As far as a type of polarisation is concerned there are three possibilities: linear, circular and elliptical polarisation. In case of a linear polarisation only the azimuth must be determined and in case of a circular polarisation only the helicity must be determined. In case of an elliptical polarisation one must determine the azimuth, angle of ellipticity and helicity. The typical set-up that is used for polarisation detection is shown on fig.6. It contains the polariser (P) and the quarter-wave plate (λ/4).

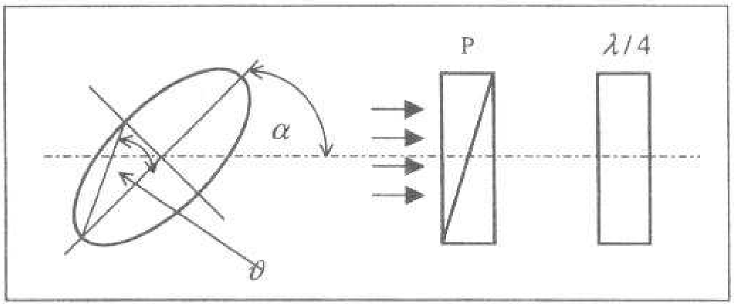

Fig.6. Schematic diagram of measurement set-up used for polarisation state detection [4].

A method being different from the one mentioned above was proposed in [5]. As shown on fig.7, the presented set-up contains a phase shifter (PF), a photodetector (PD), a computer (K) and a polariser, which is positioned at an angle of 45° to the phase shifter fast axis. The liquid crystal plate takes the role of the phase shifter in which the phase shift between the eigenwaves depends on an attached voltage. The phase shifter takes the role of a compensator. The signal from photodetector is registered by A/D card that is placed in PC computer. From the character of the signal intensity variation, as a function of voltage attached to PF, one can determine parameters that characterise the ellipse of polarisation.

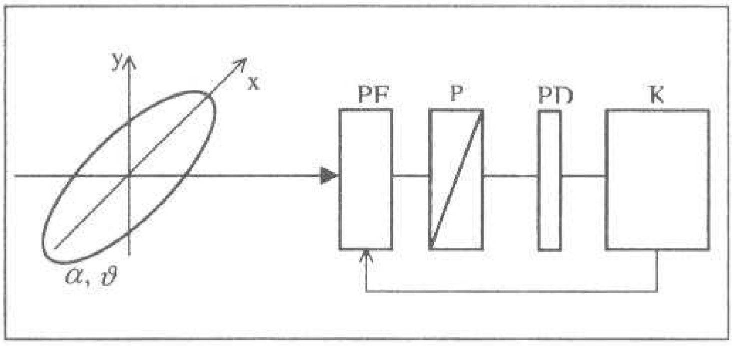

Fig.7. Schematic diagram of measurement set-up used for polarisation state detection, that is using phase shifter [5].

Method proposed in this paper allows determining the azimuth α and a modulus of an ellipticity angle $|\vartheta|$. Measured values of voltage U_{PD1} and U_{PD2} are appropriately equal to parameters m_x^2 and m_y^2 of the ellipse of polarisation that is shown on fig.8. In order to

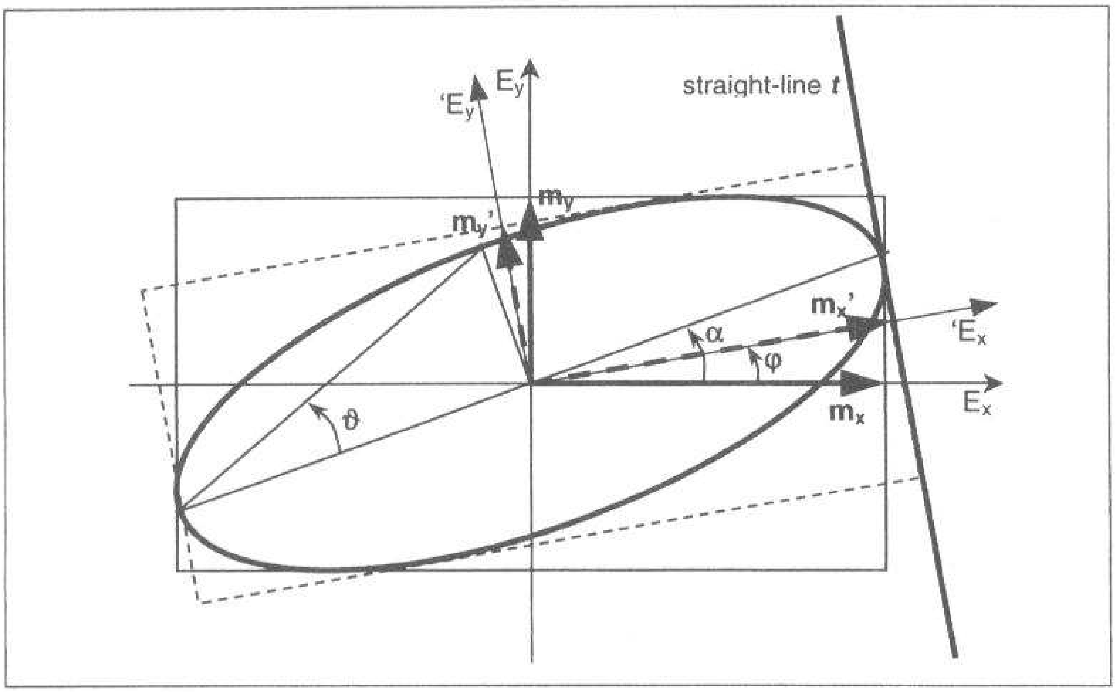

Fig.8. Determination of a straight-line **t** that is tangent to the ellipse of polarisation.

determine the state of polarisation the measurement of values U_{PD1} and U_{PD2} should be achieved twice. The first measurement should be done when the axis of polarisator overlap with axis of co-ordinate system E_x,E_y. The next step is to twist the polarisator and achieve the second measurement in order to obtain U'_{PD1} and U'_{PD2} values. The twist angle must be different from $90^0, 180^0$ and 270^0. Drawing the line ***t*** that is tangent to ellipse of polarisation one could determine the $\cos\delta$ of investigated polarisation state, where the δ is the phase difference between two orthogonal, line polarised waves that come from break-up the elliptical polarised wave. The equation of line ***t*** is given [6]:

$$E_y = -E_x \operatorname{ctg}\varphi - \frac{m'_x}{\sin\varphi} \tag{4}$$

The ellipse of polarisation equation in co-ordinate system E_x,E_y is given:

$$\left(\frac{E_x}{m_x}\right)^2 - \frac{2E_xE_y}{m_xm_y}\cos\delta + \left(\frac{E_y}{m_y}\right)^2 = \sin^2\delta \tag{5}$$

Solving simultaneously eq. 5.2 and eq. 5.1, with condition that ellipse and line ***t*** have only one common point, the value of $\cos\delta$ might be obtained.

$$\cos\delta = m_x^{'2} - m_x^2\cos^2\varphi - \frac{m_y^2\sin^2\varphi}{m_xm_y\sin 2\varphi} \tag{6}$$

The values of voltage on photodetectors are in direct proportion to electric field intensity square. Therefore the eq. 6 might be rewrite [6]:

$$\cos\delta = U'_{PD1} - U_{PD1}\cos^2\varphi - \frac{U_{PD2}\sin^2\varphi}{\sqrt{U_{PD1}U_{PD2}}\sin 2\varphi} \tag{6a}$$

The next step is to obtain α and $|\vartheta|$ from equations that connect theses values with $\cos\delta$ [5]:

$$\alpha = 0.5 arctan(\mathrm{tg}\, 2\beta \cos\delta) \tag{7}$$

$$\vartheta = 0.5 arc\sin(\sin 2\beta \sin\delta) \tag{8}$$

As a result of putting eq.6a into eq.7 and eq.8, the equations connecting α and $|\vartheta|$ with values of measured voltages are obtained:

$$\alpha = 0.5 arctan\left(\frac{2\cdot[\sqrt{U_{PD1}U_{PD2}}(U'_{PD1} - U_{PD1}\cos^2\varphi)\sin 2\varphi - U_{PD2}\sin^2\varphi]}{(U_{PD1} - U_{PD2})\sin 2\varphi}\right) \tag{9}$$

$$|\vartheta| = 0.5 arc\sin\left(\frac{2\sqrt{U_{PD1}U_{PD2}}(U_{PD1} - U_{PD2})}{(U_{PD1} - U_{PD2})^2 + 4U_{PD1}U_{PD2}}\sqrt{1 - \left(U'_{PD1} - U_{PD1}\cos^2\varphi - \frac{U_{PD2}\sin^2\varphi}{\sqrt{U_{PD1}U_{PD2}}\sin 2\varphi}\right)^2}\right) \tag{10}$$

The presented method allows determining the value of $\cos\delta$. Since $\cos\delta$ is not heterovalued in interval $(0;2\pi)$, this method does not allow to determine the helicity of the investigated polarisation state.

5. RESULTS OF MEASUREMENTS

The monomode, step-index fiber was investigated. It had the following parameters: core diameter $d_{core} = 5\mu m$, cladding diameter $d_{clad.} = 125\mu m$, and coating diameter $d_{coat.} = 245\mu m$. The length of the fiber being under influence of magnetic field was equal $l = 7.22m$. The linearly polarised light excited the fiber. The optical power associated with orthogonal polarisation planes, as a function of magnetic field's intensity *H*, was measured at the end of the fiber. On the basis of these measurements the values α and $|\vartheta|$ was calculated. Calculated results are burdened with uncertainties that arise from uncertainties of voltage measurements and define the angle φ. Where intensity of magnetic field is equal zero the azimuth is also equal zero. Therefore values of α are equal the angle of polarisation plane twist Γ. The dependence between Γ and B is shown on fig. 9. The dependence between $|\vartheta|$ and B is shown on fig. 10.

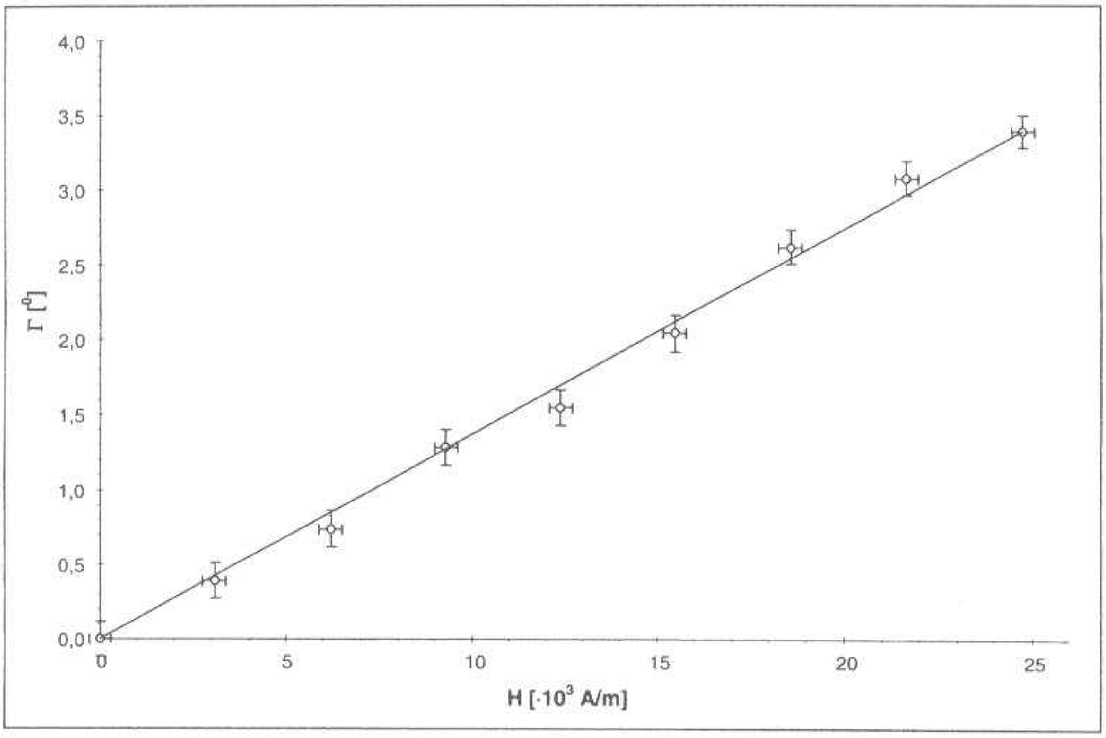

Fig.9. The polarisation plain twist angle as a function of magnetic field intensity.

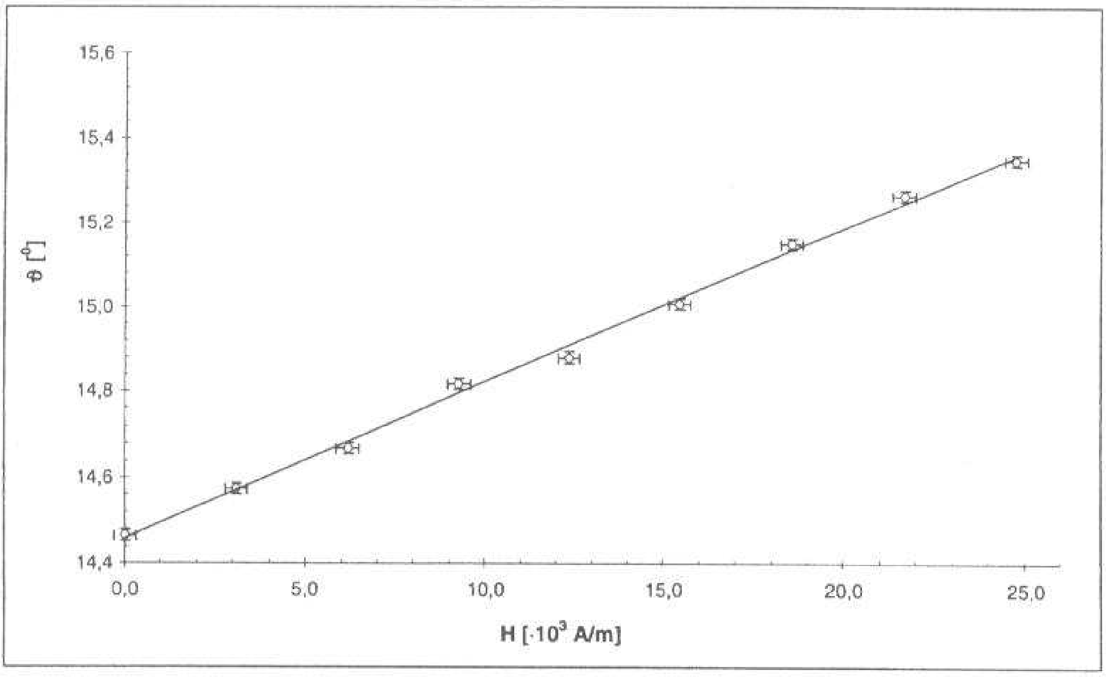

Fig.10. The ellipticity of polarisation state at the end of the fiber, as a function of magnetic field intensity.

6. CALCULATIONS AND CONCLUSIONS

The measurements show that the azimuth depends linearly on magnetic field's intensity, therefore the linear function was fitted to the measurement points at Γ(B) plot. The fit was done using Gaussian iterative method. The fitting coefficient is equal $a=(2.45\pm0.08)\cdot10^{-6}\frac{rad\cdot m}{A}$. The value of Verdet constant was calculated based on fitting coefficient. If the Verdet constant is defined in the way: $\Gamma=VHl$ then it is equal:

$$V=\frac{a}{l} \tag{11}$$

Placing the suitable values one obtains: $V=(0.34\pm0.01)\cdot10^{-6}\frac{rad}{A}$

Small changes of an angle of ellipticity $|\vartheta|$ indicate that the residual linear birefringence exists in the fiber. Magnetic field produces the circular birefringence in optical fiber. If the value of linear birefringence in such fiber is enough small, the azimuth of polarisation state will depend linearly on magnetic field's intensity. The high value of linear birefringence associated with optical fiber causes the dependence $\alpha(B)$ is non-linear (for example if the fiber is wrapped on the shape of small radius). It should be emphasise that quartz fiber is very sensitive to changes of stress, so the measurement set-up must be isolated from mechanical vibrations. This feature causes that simple monomode fiber is not proper for sensor application. Designing the magnetic field optical fiber sensor should be based on fibers that are insensitive to mechanical vibrations and stress.

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7. LITERATURE

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