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MEASUREMENT OF POLARIZATION PROPERTIES VARIATIONS OF FIBER SEGMENT UNDER COINCIDENT ACTIVITY OF SEVERAL PHYSICAL EFFECTS

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Abstract − Paper deals with measurement of polarization properties of fibers along incidence of different external effects as temperature, torsion and magnetic field. Study of polarization is important from the polarization dispersion point of view for communication systems and also in the area of interferometric and polarization sensors or general interferometric measurements. Analysis of individual effects is solved theoretically and practically in the series of works. Our contribution solves a relatively short part of fiber, where additionally fluctuation of power between both polarization modes could affect.

Keywords: polarization effects, Jones matrix, Pauli matrix, quaternions.

1. BASIC INFORMATION

During last years we have focused to the study of polarization properties of short fibers (ones of meters) loaded by the deformation (torsion) [1], [3]. Our works have been extended on the study of Faraday effect, mainly for its application on defined influence of fiber polarization properties. Experimental arrangement containing massive solenoid for generation of required magnetic field affects also significant warming of fiber. These temperature variations make necessary automated measurement with defined length of measuring interval, which has been tried to find as compromise with respect to warming along application of magnetic field. The system AMEX [2] developed in our department has been used during experiment. This software enables direct input of measuring parameters to the EXCEL by means of RS 232 bus. This system enables measurement in the time division and also stepping for the case of measurement of dependence of output intensity on the angle of polarizer turning. Next processing with data has been made in EXCEL too.

2. MEASUREMENT OF POLARIZATION VARIATION OWING TO THE EXTERNAL EFFECTS

In contrast to previous experiments where polarization preserving fibers were used, fiber doped by rare earth (Nd^{3+}) has been used for this experiment. It enables to reach corresponding values with sufficient Verdet constant of fiber.

2.1 Measuring work place

The fiber of length approximately 2 m, has been put to the ceramic capillary which limits affect of external environment and geometry of fiber. Input linear polarized radiation launched to the fiber and intensity in two orthogonal directions has been measured in the output. Simplified arrangement of work place is given in the fig. 1, where are: P - polarizer, PD – photodetector, E_I, E_O – electric field intensity in the input and output respectively, I_x, I_y – output intensity of radiation

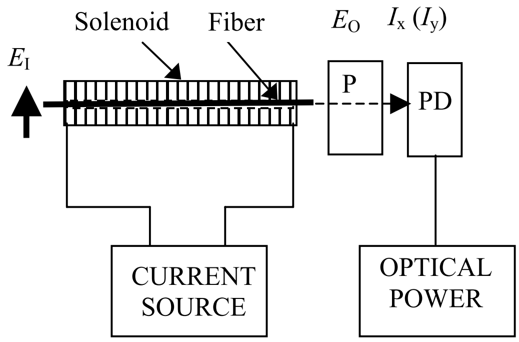

Fig. 1 Arrangement of measuring work place

For output intensity of optical radiation E_O is valid

$$\mathbf{E_O} = \mathbf{JE_I} \tag{1}$$

If fiber is launched by the linear polarized radiation oriented along axes x, so that output intensity can be with respect to unitarity of Jones matrix **J** expressed as

$$\begin{bmatrix} E_{ox} \\ E_{oy} \end{bmatrix} = \begin{bmatrix} a & b \\ -b^* & a^* \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} a \\ -b^* \end{bmatrix} = \\ = \begin{bmatrix} J_{11} \\ J_{12} \end{bmatrix} = \begin{bmatrix} R_{11} \exp j\varphi_{11} \\ -R_{12} \exp(-j\varphi_{12}) \end{bmatrix} \tag{2}$$

where a, b are generally elements of unitary matrix, (a^*, b^* are complex conjugate), in the case of Jones matrix as $J_{ik}=R_{ik}\exp\varphi_{ik}$.

Measured intensities correspond to modules of elements J_{11} and J_{21} of ones matrix. With respect to the unitarity of Jones matrix we know also modules of remaining elements $|J_{11}| = |J_{22}|$, $|J_{12}| = |J_{21}|$. These elements can be measured if the fibre is launched by linear polarized radiation oriented along the axes *y*, too.

Alternative arrangements make possible to determine the phase of Jones matrix elements by calculation from the measured values. Principal problems are in substantial fluctuations of measured values for short fibre. These fluctuations induce

- substantial mistakes, eventually impossibility of their determination regarding to mathematically inadmissible values of goniometrical function,
- comparable values of fluctuations with changes due to outer physical quantity.

Second limitation can be suppressed by the time averaging measurement with automatic measurement system.

As the phases of output radiation have not been measured, additionally we have measured the output intensity as dependence on the angle of polarizer turning from 0 to 360 degrees and we obtained information about output polarization ellipse.

Suppose that result of measurement according to (1) is generally elliptical polarized radiation described by normalized Jones vector

$$J = \begin{bmatrix} \cos R \exp\left(-i\frac{\gamma}{2}\right) \\ \sin R \exp\left(i\frac{\gamma}{2}\right) \end{bmatrix} \qquad (3)$$

where are: R – ratio of components A_y/A_x, corresponding to the maximum values of component E in axes *x, y,* and γ - phase shift of components.

Regarding to unitarity of Jones matrix we can write it as

$$\mathbf{J} = \begin{bmatrix} \cos R \exp\left(-i\frac{\gamma}{2}\right) & -\sin R \exp\left(-i\frac{\gamma}{2}\right) \\ \sin R \exp\left(i\frac{\gamma}{2}\right) & \cos R \exp\left(i\frac{\gamma}{2}\right) \end{bmatrix} \qquad (4)$$

For analysis of this matrix we can use decomposition to the Pauli matrices, or decomposition on the set of quaternions, respectively [4]

$$\mathbf{J} = \cos R \cos\left(\frac{\gamma}{2}\right)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + i \sin R \sin\left(\frac{\gamma}{2}\right)\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} - i \sin R \cos\left(\frac{\gamma}{2}\right)\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} - i \cos R \sin\left(\frac{\gamma}{2}\right)\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \qquad (5)$$

Pauli matrices represent free space and linear retarders $\lambda/2$ for orientation 0° a 45° and circular retarder for 0°.

For observation of outer physical quantities influence it is necessary to determine of R and γ. We can use output ellipse, which can be provided by the measurement. Parametric figure of ellipse with main axes turning by α with respect *x* is in coordinates *x, y*

$$\begin{aligned} E_x(t) &= a \cos\alpha \cos(t-\alpha) - b \sin\alpha \sin(t-\alpha) \\ E_y(t) &= a \sin\alpha \cos(t-\alpha) + \cos\alpha \sin(t-\alpha) \end{aligned} \qquad (6)$$

For intensity of optical radiation it is valid

$$I(t) = E_x^2(t) + E_y^2(t) \qquad (7)$$

By substitution (6) to (7) we obtain $I(t)$ as

$$I(t) = a^2 \cos^2(t-\alpha) + b^2 \sin^2(t-\alpha) \qquad (8)$$

Typical dependences of intensity on the angle α (adequate to polarizer turns) are given in the figure 2 for different length of ellipse axis and figure 3 for different angle of major axis.

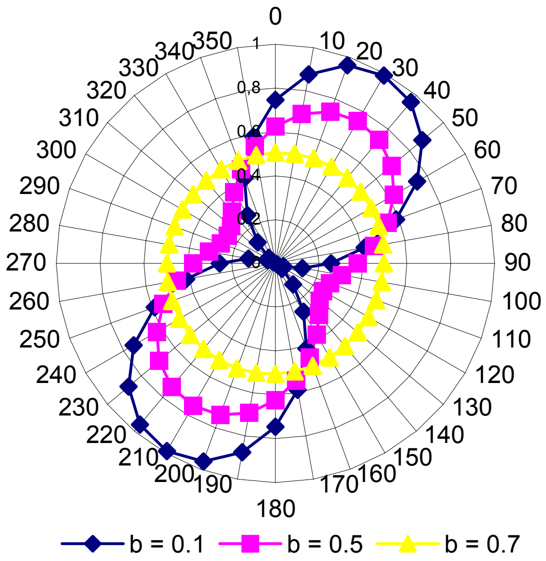

Fig. 2 Theoretical output intensity versus angle (adequate to polarizer turning) for different length *a, b* of ellipse axis by condition $a^2 + b^2 = 1$

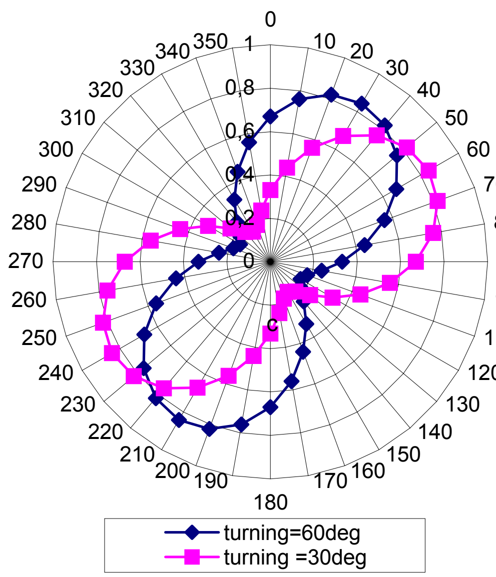

Fig. 3 Theoretical output intensity versus angle (adequate to polarizer turning) for different turning of major ellipse

From these plots we can determine angle of turning and ellipticity, ie. parameters useful for calculation of R and γ from known equations or by the reconstruction of polarization ellipse. Disadvantage of this method comparable to Jones matrix method is impossibility to determine sign of angle γ. It has not to be substantial, if we realize that we trace variations of fiber behavior during study of external quantities effect.

The complex figure has been obtained also by the measurement of all elements of Jones matrix. Some problems are with determination of phases for short fiber even if the measurement in the short time section eliminates fluctuation.

2.2 Results of experiments

A lot of experiments have been made. Effects of magnetic field, torsion and temperature on the polarization properties of fiber have been studied. The results are given in the figures 4 to 7.

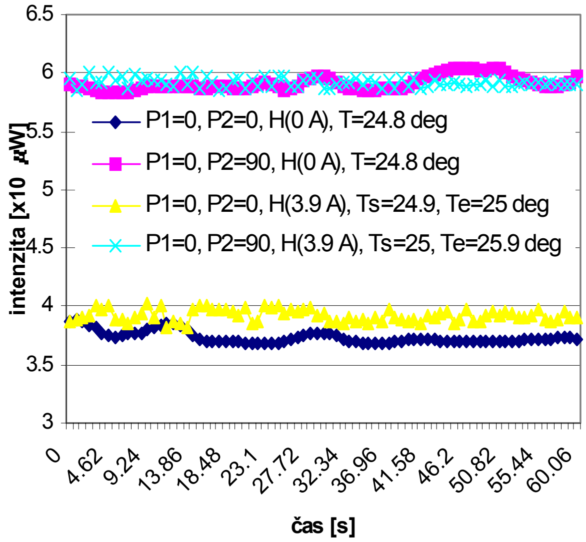

Fig. 4 Time dependence of I_x, I_y for fiber without torsion and for magnetic field corresponding to the current 0 and 3,9 A

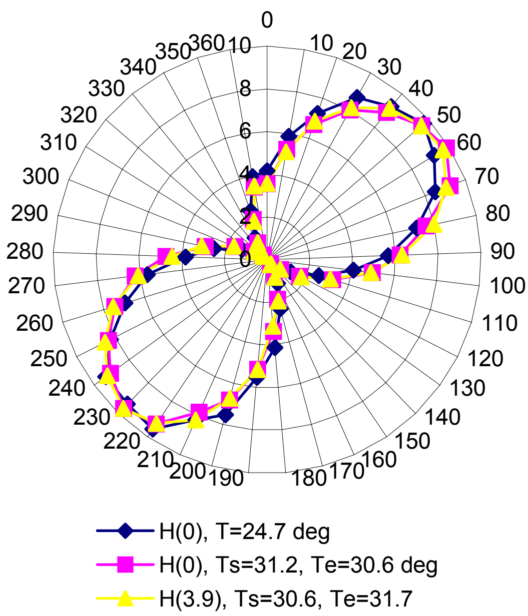

Fig. 5 Output intensity versus angle of polarizer turning

There was happened to substantial fluctuations during measurement of output intensities. It turned out, that these fluctuations could be comparable with variations made by observed quantity. That is why we selected method of automatic measurement [2], susceptible to measure output optical power along the time and make the time average of this power. Interval of measurement has been selected according to the conditions mainly to the possible warming during the magnetic field application. Time interval 60 seconds has been found as suitable.

Magnetic field oriented along axes of fiber was made by the long coil with 9700 turns. Maximum value of coil current was 3,9 A.

Eventual parasitic variation of temperature during measurement has been recorded and it is given in the corresponding figures, T_s is the initial temperature, and T_e is the final temperature. Symbols P1 (input) and P2 (output) introduced in figures 4 and 6 correspond to the setting of input and output polarizers (0°and 90°), respectively. The results given in following figures demonstrate only some measured results. So that plots of intensities I_x, I_y in the axes x and y for input linear polarized radiation in the axes x are given in the figure 4. Fiber is randomly oriented and magnetic field level corresponds to the current equals 0 and 3,9 A. It is evident that fluctuations of measured values are comparable with the magnetic field variations.

Graphs of output intensity versus angle under the similar conditions as in the figure 4 are given in figure 5.

The results are obtained during turning of polarizer in the 10° steps. It is evident a small effect of magnetic field corresponding with results in figure 4. The influence of temperature is more significant than magnetic field. Next figures 4 and 5 are results of similar conditions as before and for fiber loaded by the torsion of 5 turns. From resultant graphs it is evident substantial larger effect of magnetic field on the turning of polarization ellipse. The torsion withal makes the coupling between polarization modes and suppresses the parasitic birefringence of fiber.

Turning of polarization ellipse is possible to see from the graphs.

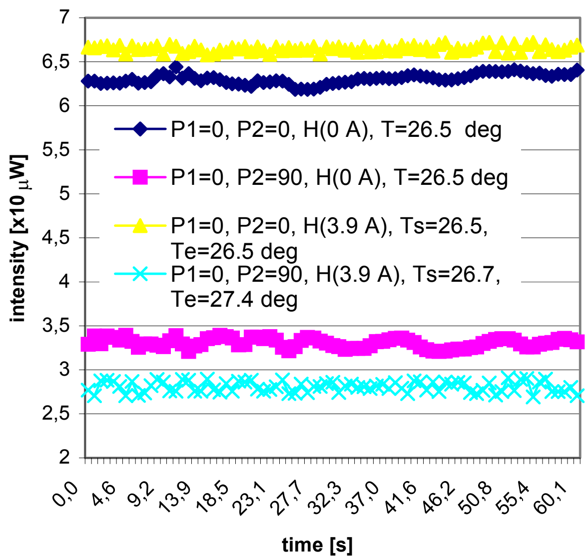

Fig. 6 Time dependence of output intensities I_x and I_y of fiber, subjected by torsion of 5 turns for two values of magnetic field

2.3 Summary of results

Obtained results can be summarized generally to items as follows:

- Faraday effect of fiber is relatively less expressive because of the mild birefringence of measured fiber.
- Faraday effect rapidly increases with torsion of fiber, where the birefringence is depressed.
- Results of measurement are influenced by the temperature, which affects the level of fluctuations and also on the resultant polarization properties of fiber.
- There are variations of output radiation from linear polarization to the elliptical polarization and beat length of fiber is changed by means of torsion for linear polarized input radiation.

Introduced results have been analysed by means of decomposition of the Jones matrix to the Pauli spin and unitary matrices or in the system of quaternions, respectively. Graphs on the fig. 5 and 7 allow to determine the form of polarization ellipse by the comparison of measured results with the calculated results obtained from parametric equations of ellipse. Spin matrices (quaternions) represent retarders $\lambda/2$ for linear polarization with orientation 0°and 45°and circular polarization from the transmission point of view. This analysis enables to consider the influence of separate spin matrix coefficients on the resulted polarization characteristics and to contribute to the understanding of physical changes in optical fiber.

Evolution of polarization (change of ellipticity and angle of major axis) due to the particular effect can be represented on the Poincaré sphere. Relations between spin matrix and coordinates of Poincaré sphere are evident.

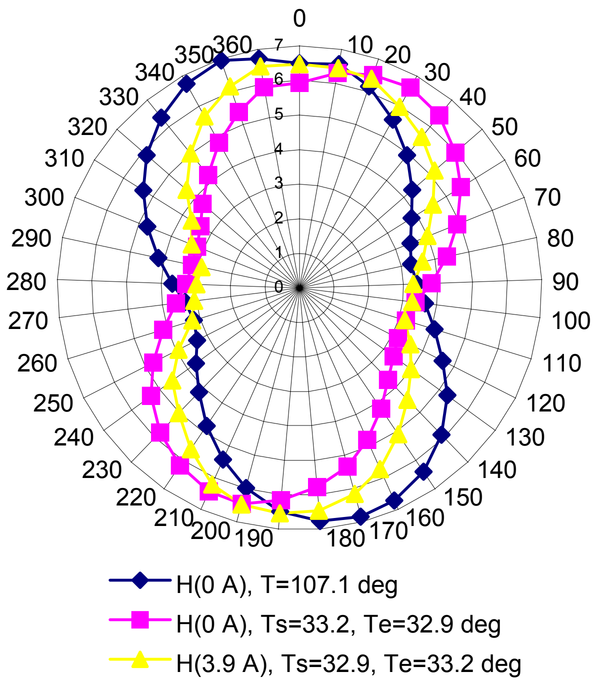

Fig. 7 Output intensity versus angle of polarizer turning of fiber, subjected by torsion of 5 turns for two values of magnetic field and two temperatures

3. CONCLUSIONS

Analysis of measured results shows how external physical effects as deformation, magnetic field and temperature influence the polarization characteristics of optical fiber. This information can be useful e.g. in the design of sensors with single mode fibers. It is resulted that measurement of the short segment optical fibers requires election of suitable measuring method that makes possible to suppress the fluctuation in optical power.

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