Investigation of polarization properties of fiber segment in thermal field

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Abstract- Paper deals with measurement of polarization properties of fibers in variable thermal 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. Our contribution solves a temperature dependence of polarization in a relatively short part of different types of fibers, where additionally fluctuation of power between both polarization modes could affect. These results can be interesting in the application of fibers in distributed sensors, where partial segments of fiber could be affected by different temperature.

I. Introduction

Investigation of polarization properties is important for applications of fibers in sensors, distributed sensor systems and also in fiber systems for information processing [1]. Parasitic phenomenon affecting the polarization properties is the temperature. It is typically for example if we sense such quantity like magnetic field, mechanical deformation etc. Specific problems are temperature polarization sensors [2], where temperature is the scanned quantity. Parasitic temperature effect can be observed for example during the polarization measurement of fiber loaded by the torsion. Presented results could be useful also in the design process of mentioned temperature sensors, where also fiber can by loaded by the torsion.

II. Experiment

We have investigated short parts of fibers. During the measurement some random fluctuations between polarization modes add to the temperature influence and so the inaccuracies can distort the measurement results. Solution of this effect can be in measurement of values in such suitable selected interval and their averaging. On the other side if we measure for example polarization ellipse in the fiber output, there is necessary to make lot of measurements, which require automation of process. Also period of measurement can be shorted, which is profitable if the fiber is put into the solenoid for creating required thermal field. We have used automatic measuring system AMEX, cooperated with table processor EXCEL for the control of voltmeter and writing of resultant values to the table or graph [4]. Arrangement of components in the measuring work place is given in the Figure 1, where are: P - polarizer, E_I, E_O – electric field intensity in the input and output respectively, I_Θ –intensity of radiation in the output of polarizer. He-Ne laser has been used as source of linear polarized radiation with coupler launching the light into the fiber, and output intensity in dependence on angle of polarizer rotation has been measured by means of a power meter. Required heating of the fiber has been created by means of the long heating coil, providing homogenous thermal field along the fiber placed into the thin ceramic capillary.

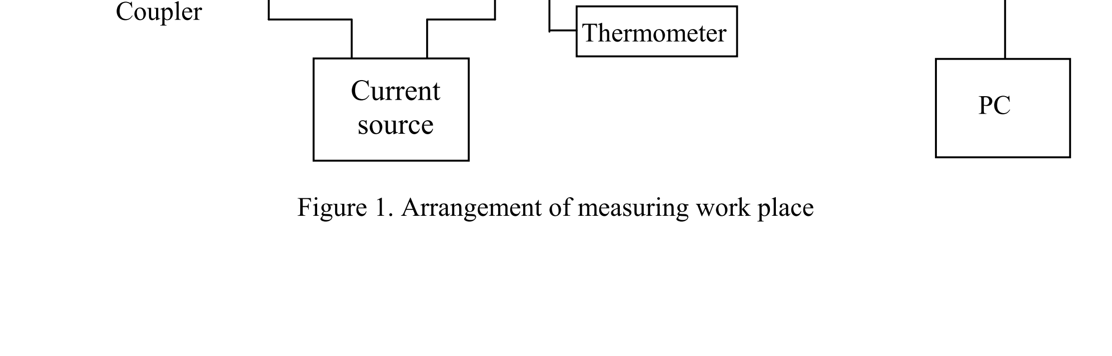

Figure 1. Arrangement of measuring work place

A. Model of fiber in the thermal field

Suppose a short part of fiber with propagation of eigenmodes, loaded by no deformation. Both orthogonal eigenmodes propagate by the different velocity, characterized by difference of refractive indices Δn. The phase shift $\Delta\Phi$ between modes in the end of fiber is given by an equation

$$\Delta\Phi = k\Delta n L\ , \tag{1}$$

where are: $k=2\pi/\lambda$ - wave number, λ - wave length
L – length of fiber.

Temperature variation of phase shift $\Delta\Phi$ can be expressed as

$$\frac{d(\Delta\Phi)}{dT} = k\left(\frac{\Delta n}{n}\frac{dn}{dT}L + \Delta n\frac{dL}{dT}\right). \tag{2}$$

If we consider that variation of length is the same for both modes of short fiber and insignificant in the comparison with beat length, we can neglect the second part of equation, so we obtain (1) as

$$\frac{d(\Delta\Phi)}{dT} = k\frac{\Delta n}{n}\frac{dn}{dT}L \tag{3}$$

Development of polarization depends in this case on the temperature dependence of refractive index n and can be traced from development of polarization ellipse in the output determined to the selected input launching of fiber. More complicated situation will be in fiber loaded by any deformation. Current type of deformation of fibers, which could occur at realization of sensors and other fiber systems, is deformation by the torsion. Resultant effect in this case will depend on the stage of birefringence and the measure of torsion. Along propagation of optical wave we can consider initial polarization modes with probability of coupling each other, or we can find new polarization eigenmodes, corresponding to the new fiber arrangement. For measurement of temperature effect seems to be effective complex polarization ellipse for determined input launching of fiber. For description of fiber we can use Jones matrix **J**, collecting dependence between output and input intensity of electric field $\mathbf{E_O}$ and $\mathbf{E_I}$, respectively.

$$\mathbf{E_O} = \mathbf{J}\mathbf{E_I} \tag{4}$$

Jones matrix **J** is generally unitary matrix and it can be decomposed to the elementary spin matrices, (quaternions), presenting matrix of free space, and wave retarders $\lambda/2$ for linear polarization (with rotation 0°and 45°), and $\lambda/2$ for circular polarization (with rotation 0°) [3].

$$\mathbf{J} = \begin{bmatrix} \xi_0 + i\xi_3 & \xi_2 + i\xi_1 \\ -\xi_2 + i\xi_1 & \xi_0 - i\xi_3 \end{bmatrix} = \xi_0\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + i\left(\xi_1\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} + \xi_2\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} + \xi_3\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}\right) \tag{5}$$

We can assign 3D vector the quaternions, corresponding to the eigenmodes in projection on the Poincaré sphere in the Stockes space and to investigate the development of polarization as function of temperature. Components ξ_1, ξ_2, ξ_3 of the Jones matrix correspond to eigenvector components in Stockes space (S_1, S_2, S_3) as it is shown in Figure 2. Knowledge of the eigenvectors make possible to express an evolution of the polarization in dependence on a phase delay between polarization modes on the Poincaré sphere. For specific input polarization it is possible to express evolution of polarization depending on phase shift as a displacement of the point along a circle. This circle is obtained as a cut of the plane that contains the point of the input polarization and it is perpendicular to the eigenvector.

There are two cases of eigenvectors in the Figure 2:

- the linear polarized eigenvector (H V),
- the elliptical polarized eigenvector (X X′).

It is necessary to emphasize, that two mentioned cases are given only for demonstration.

We suppose that the linear polarization light defined by the direction E is launched into the fiber. During the propagation of light along the fiber, phase shift between polarization modes arises and polarization changes. The point describing the polarization moves for the length of the fiber to the point A or C for linear or elliptical polarization respectively. Owing to the temperature different shift arises too and the point moves along the circle to the point B or D respectively. The movement of this point describes change of the ellipticity and angle of the major ellipse axes. On the contrary from course of the ellipticity and angle of the major axes it is possible to estimate a nature of eigenvectors under scheduled condition.

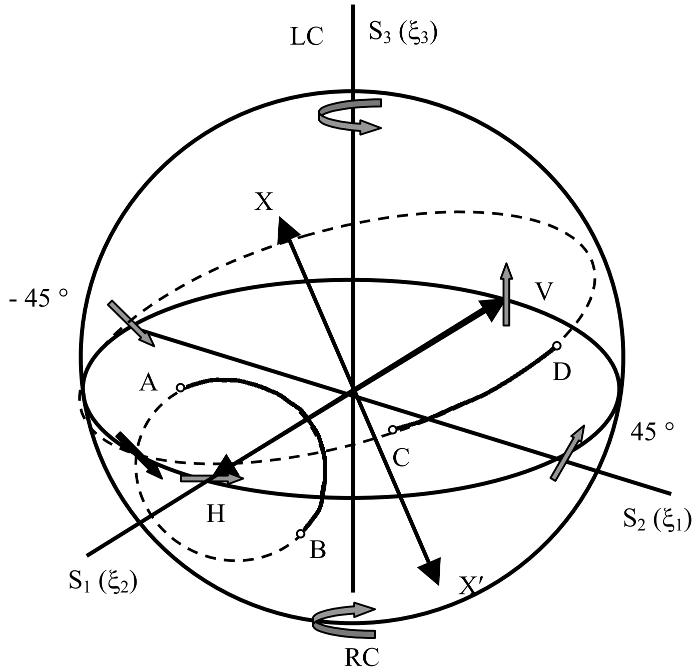

Figure 2. Imagination of the polarization evaluation on Poincaré sphere in Stockes space

Furthermore temperature dependence of polarization optical fiber subjected by torsion has been investigated. Any torsion induces some coupling between initially linear polarization modes. The eigenmodes turn into eliptically polarized modes and direction of the eigenmodes come near to the S_3 (ξ_3) axes. In the extreme, the eigenvectors identify with S_3 (ξ_3) axes and polarization eigenmodes are left and right circular polarized (LC, RC), respectively. The linear polarized light entered this fiber remains linear polarized with changing of direction in dependence on the phase shift. Practical experiences show that we can approach to the state of linear or circular eigenmodes only for systems with high linear or circular birefringence. In the general case the eigenmodes have character of an elliptically polarized radiation.

B. Uncertainty

Fluctuations of measured output power are the main problem of measurement. These fluctuations are caused by coupling between the polarization modes with values in the interval of about 5% around the mean value and changes with frequency of order about 10^{-1} to 10^{0} Hz. Owing to integration time of output voltmeter (only 0,2 ms), the fluctuations exert in the measured value of output optical power. With respect to the number of measurement because of variation of temperature for different torsion, there was not possible to repeat each measurement. In the other side only ellipticity and angle of major axes has been determined, so that incorrect values could be eliminated by the approximation. In addition the direction of the major axes stated as angle of maximum intensity can be confronted with the angle of minimum intensity corresponding with direction of the minor axes. If we consider possible mistakes in determination of maximum with respect to the flat shape of curve in the point of maximum, we can estimate uncertainty in determination of ellipticity about 5% and for the determination of major axes angle about 5°. Obtained results could be improved by the measurement of output intensity with the step of polarizer rotation equalled 5° or 1°.

C. Practical results of measurement and their discussion

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. Some examples of results for Nd^{3+} (type SG) doped fiber is given in Figure 3 to 7.

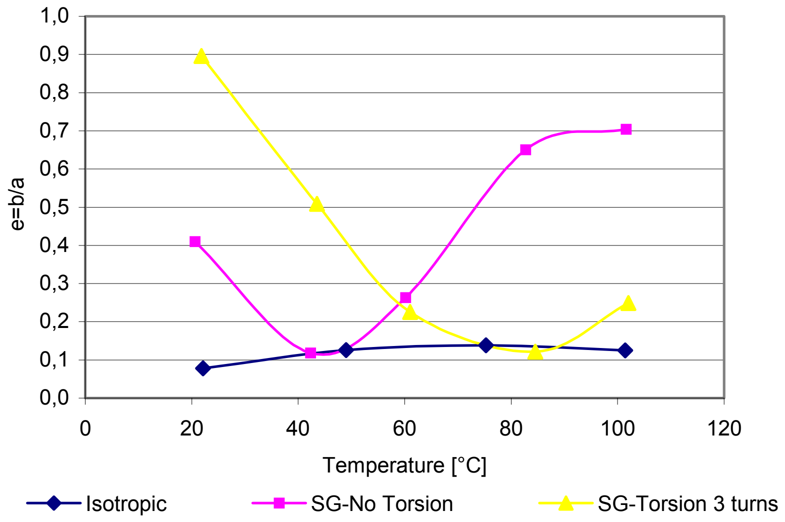

Figure 3. Ellipticity (e=b/a) versus temperature for different fibers – isotropic, Nd^{3+} (mark SG) doped with torsion (3 turns) and without torsion

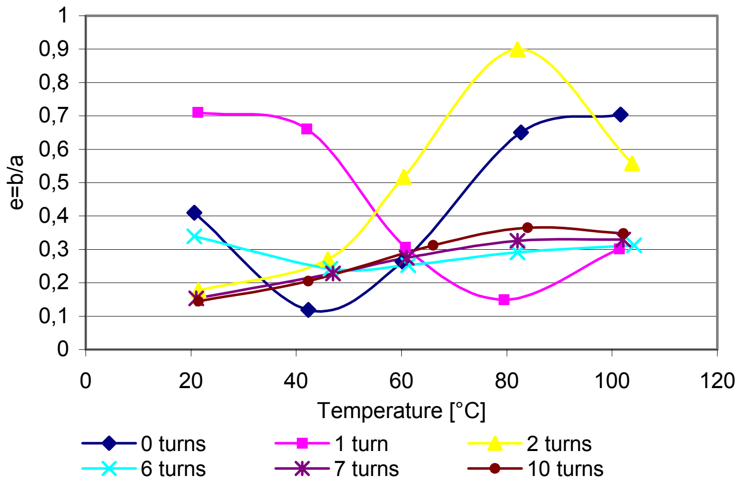

Figure 4. Ellipticity (e=b/a) versus temperature for different torsion (Nd^{3+} doped fiber - mark SG)

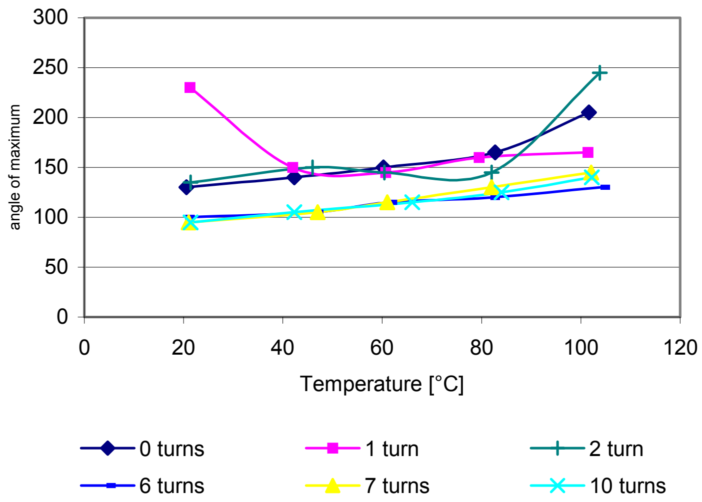

Figure 5. Angle of maximum versus temperature for different torsion (Nd^{3+} doped fiber - mark SG)

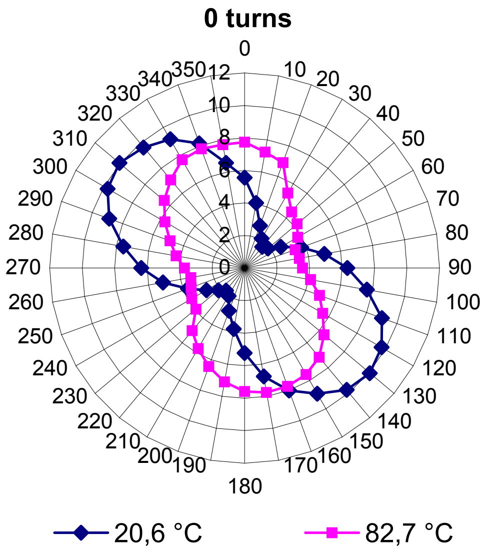

Figure 6. Variation of polarization as function of temperature for fiber SG without torsion

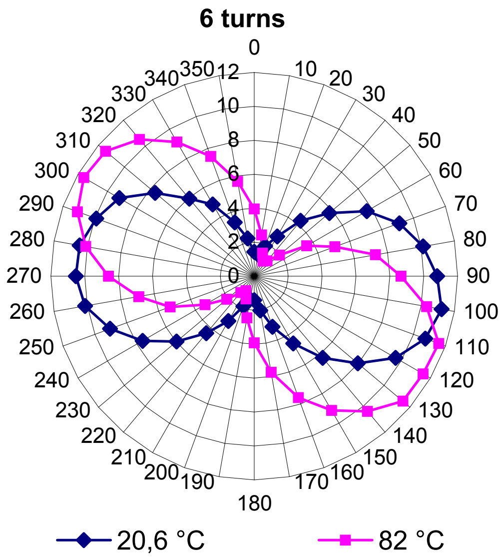

Figure 7. Variation of polarization as function of temperature for fiber SG with torsion

From intensities we found also ellipticity e=b/a, where a, b is the lengths of major and minor axes of polarization ellipse, respectively. For comparison there is also dependence of ellipticity on the temperature for isotropic fiber in the Figure 3. From given graphs is evident, that the temperature affects the output polarization of fiber. As this result corresponds with (3), this dependence rises with increasing of birefringency.

Beside the attempt to interpret changes of the ellipticity and the angle of major ellipse axes by means of the Poincaré sphere it results following:

- As it was expected, the influence of the temperature is negligible for isotropic fiber (Figure 3).
- Owing to weak birefringence of measured fiber (the fiber is produced as homogenous), strong coupling between polarization modes happens and resulted eigenmodes are elliptically polarized. The ellipticity and the angle of major axes change significantly with variation of the temperature. The fact that the ellipticity does not achieve the state of linear polarization (intersection with equator in the Poincaré sphere) indicates that eigenmodes are elliptically polarized and the circular shape of the trace on the Poincaré sphere is deformed. This phenomenon is given by the increasing coupling between the initial polarization modes.

- Torsion of fiber also causes the coupling between polarization modes so that originally linear polarized eigenvectors tend to the axes S_3 (ξ_3) and changes of ellipticity with temperature decreases. From measured results it stands to reason that influence of temperature on the polarization properties of fiber decreases with increased torsion (Figure 4).
- Angle variations of turning of major axes of ellipse decreases with torsion. Dependence on the temperature gets near linear (Figure 5).

These results can be interesting for realization of components and systems using rare earth doped fibers with weak birefringence in the distributed sensors or other systems with active fibers.

III. Conclusions

We have measured dependence of polarization ellipse rotation on the temperature for different parts of fibers (isotropic, birefringent, rare earth doped, etc.). It has been proved that temperature can affect very strong the development of polarization during propagation of optical wave along the fiber and by this way to introduce errors to the sensing quantity. For more complex interpretation it is suitable to use the decomposition of Jones matrix to the spin matrices and projection of polarization development on the Poincaré sphere.

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