Influence of external effects on the polarization properties of the fibers

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Abstract: - Paper deals with the measurement of polarization properties of fibers in the incidence of different external effects as temperature, torsion and magnetic field, applied on the rare earth (Nd³⁺) doped fiber. 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, distributed sensors or general interferometric measurements. Analysis of individual effects is solved theoretically and practically in the series of works. Presented contribution solves a relatively short part of fiber, where additionally fluctuation of power between both polarization modes could affect.

Key-Words: - fiber segment, polarization, torsion, magnetic field, temperature, Jones matrix, Faraday effect

1 Introduction
During last years some activities have been focused on the study of polarization properties of short fibers (ones of meters) loaded by the deformation (torsion) [1]. These works have been extended also on the study of Faraday effect. Experimental arrangement containing a long solenoid for generation of required magnetic field affects also significant warming of fiber. This paper monitors the effect of magnetic field, deformation by torsion and temperature on the polarization properties of active Nd⁺⁺ doped fiber, which can be interesting for application of such fiber in sensors and active optical components.

2 Measurement of polarization variation owing to the external effects
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 is launched to the fiber and intensity of radiation passing through the polarizer for its different turning has been measured in the output. An arrangement of work place is given in the fig.1, where are: P - polarizer, Eᵢ, Eₒ – electric field intensity in the input and output respectively, Iₒ – output intensity of radiation for turning of polarizer Θ. 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.

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 serial 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.

![Fig. 1 Arrangement of measuring work place](image-url)
2.1. Effect of magnetic field

During excitation of fiber by the linear polarized radiation it happens the rotation of polarization vector about angle $\Phi$ by the Faraday effect. For homogenous magnetic field $H$, made by the coil with $N$ windings and flowing current $I$ it is valid

$$\Phi = VNI$$

where $V$ is Verdet constant (for silica $V = 3,3 \times 10^{-4}$).

For active fiber the value of Verdet constant could be greater. Magnetic field applied on the fiber is created by the coil with some sections of winding with maximum number of 9700 and maximum value of current equals 3.9A.

Maximal Faraday effect can be obtained with application of isotropic fiber. But fiber used for experiment shows considerable anisotropy. Properties of fiber has been observed by the measurement of output intensity of optical radiation in the range from 0 to 360° and launching by the linear polarized radiation in the range from 0 to 180°.

![Fig. 2 Dependence of output intensity for fiber loaded by torsion (5 turns) on the angle of polarizer rotation](image)

Owing to the anisotropy, the effect of magnetic field on the rotation of polarization on the output of fiber has been very small, mainly in the case of excitation of one from the linear eigenvectors, where this effect has been in the level of measurement sensitivity. Substantially better result has been obtained with application of fiber loaded by the torsion. In the fig. 2 we can show dependence of output intensity of Nd³⁺ fiber (SG 302) with torsion made by the 5 turns of fiber face, for two values of magnetic field intensity corresponding to the current 0A and 3.9A. From the figure we can find that the effect of magnetic field is not irrelevant. The reason is evidently by the creation of coupling between originally linear polarization modes, which depress effect of linear birefringence by the transfer of power. It is possible to think about the creation of circular birefringence during the torsion, but for 5 turns and length of fiber (2m) this effect is insignificant.

A substantial effect of temperature on the polarization properties of fiber has been observed during the measurement. In the fig. 2 we can see also output intensity for two different temperatures for the case without magnetic field. From the figure is clear that tendency of output polarization rotation is the same for the temperature and magnetic field, so that temperature can introduce substantial error of measurement. This effect of temperature on the properties of Nd³⁺ doped fiber leads to the effort of more detailed observation of temperature influence.

2.2. Effect of temperature

At the analysis of temperature effect we come from the reality, that fiber has some anisotropy. Under certain referential temperature for example $T=20\,^\circ C$, the phase shift between polarization modes is given by the equation

$$\Delta \phi_0 = \phi_y - \phi_x = (n_y - n_x)kL = \Delta nkL,$$

where are:
- $k$ - wave vector for vacuum,
- $L$ - length of fiber,
- $n$ - refractive index.

Variation of phase shift with temperature can be determined with consideration of cancellation of fiber extension, which has insignificant effect on the output polarization. Change of phase shift with temperature will be as follows

$$\delta \Delta \phi = \frac{d\Delta n}{dT} kL \Delta T.$$

Total phase shift $\Delta \phi$ at the end of fiber is given by the addition of both components

$$\Delta \phi = \Delta nkL + \frac{d\Delta n}{dT} kL \Delta T.$$

Isotropic fiber for $\lambda=633$ nm, 2m of length has been measured as reference specimen duly with no temperature dependence. Contrary to isotropic fiber, our Nd³⁺ doped (SG 302) shows expressive temperature dependence.

Since in the frame of previous works we have dealt with the problems of torsion effect on the polarization properties of fiber, we have observed also contemporary influence of temperature and torsion on Nd³⁺ doped fiber Measurement has been done for temperatures in the
range from 20 to 100°C and torsion from 1 to 10 turns (steps have been the whole turns to achieve the same excitation in the input). Measured dependence of ellipticity at the end of fiber as function of torsion (in turns) and for two temperatures is given in the fig. 3. Curve of ellipticity is practically the same with the fact that temperature shifts the curve to bigger torsion. From the figure it is clear that ellipticity decreases with increasing of torsion, i.e. fiber, by its properties, is getting near the isotropic fiber. This also corresponds to the pieces of knowledge given in part about analysis of magnetic field effect.

![Fig. 3 Dependence of ellipticity on the torsion for 20°C and 80°C and fiber SG 302](image)

Interesting results have been obtained for suitable combination of torsion and temperature. During 1, 2 and 3 turns we can find the temperatures (in the concrete 30, 85, 25°C), where relatively precision circular polarization will be in the output of fiber. Accurate value of temperature we can take from intersection of output intensities for selected angles. For example in the fig. 4 there are output intensities for one turn and angles from 0° to 150° with the step equals to 30°.

![Fig. 4 Dependence of output intensity on the temperature for 1 turns’ torsion and select angles of polarizer](image)

It means that fiber can be described by the linear polarization eigenvectors form an angle 45° regarding to the vector of linear polarized field excitation. If we suppose that principle polarization states will be preserved for given torsion of 1 turn, we can decide that change of temperature from 30°C to approx. 75°C made conversion from circular to the near linear polarization and the phase shift between principle polarization states equals π/2. Similar results could be obtained also for torsion of 2 and 3 turns. For bigger torsion and selected input polarization we obtain conversion of near linear to elliptic polarization or vice versa and circular polarization does not form. But we can consider, that for these torsions it is possible to find input polarization in the position 45° regarding to the principle polarization states and the behavior of fiber would be near to the quarter-wave plate.

Polarization properties of fiber we can describe by the Jones matrix, which giving dependence of \( E_I \) and \( E_O \) vectors respectively:

\[
E_O = JE_I
\]

(5)

Development of polarization along the length of fiber with knowledge of eigenvectors or polarization eigenmodes it is possible to represent on the Poincaré sphere. Mutual relation of Jones matrix and representation on the Poincaré sphere flows from the possibility of decomposition of Jones matrix \( J \) to the spin matrices, or to the corresponding set of the matrix 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].

\[
J = \begin{bmatrix}
\xi_0 + i\xi_3 & \xi_2 - i\xi_1 \\
-\xi_2 + i\xi_1 & \xi_0 - i\xi_3
\end{bmatrix} = \\
\xi_0 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + i \xi_1 \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} + \xi_2 \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} + \xi_3 \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}
\]

(6)

where, it is valid that \( \Sigma \xi_i^2 = 1 \).

Relation with Poicaré sphere goes from the fact that vectors of quaternions recommend to the coordinates of Poicaré sphere in 3D Stockes space. In the standard
form these vectors are as follows

\[
\begin{bmatrix}
\frac{\sqrt{2}}{2} & 1 \\
0 & 1 \\
\end{bmatrix}
\quad \text{and} \quad
\begin{bmatrix}
\frac{\sqrt{2}}{2} & -1 \\
0 & 1 \\
\end{bmatrix}
\]

for \(\lambda/2\) (45°),

\[
\begin{bmatrix}
\frac{\sqrt{2}}{2} & i \\
0 & 1 \\
\end{bmatrix}
\quad \text{and} \quad
\begin{bmatrix}
\frac{\sqrt{2}}{2} & -i \\
0 & 1 \\
\end{bmatrix}
\]

for \(\lambda/2\) (circ.), \[1\] and \[0\] for \(\lambda/2\) (0°).

In the case of torsion given by 1, 2 or 3 turns corresponding to the temperature and launching by the polarized light in the direction of axes x, fiber behaves as retarder rotated by the angle equals 45°. Its Jones matrix we can write in the normed form and to decompose into matrix quaternions (spin matrices)

\[
\mathbf{J}_{45}(\lambda/4) = \frac{1}{\sqrt{2}} \begin{bmatrix}
1 & i \\
1 & 1 \\
\end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix}
1 & 0 \\
0 & 1 \\
\end{bmatrix} + \frac{i}{\sqrt{2}} \begin{bmatrix}
0 & 1 \\
1 & 0 \\
\end{bmatrix}
\]

(8)

These matrices represent free space and linear retarder \(\lambda/2\) rotated by the 45° with eigenvector

\[
\begin{bmatrix}
\frac{\sqrt{2}}{2} \\
0 \\
\end{bmatrix}
\quad \text{resp.} \quad
\begin{bmatrix}
\frac{\sqrt{2}}{2} \\
0 \\
\end{bmatrix}
\]

which correspond to the linear polarization of \(\pm 45°\) on the Poincaré sphere (see fig. 5). With launching by the horizontal polarization (point H - 0°), linear polarization varies by the temperature to the elliptical, which corresponds to the shift of point A, describing polarization on the circle, walking through the point H and lying in the plain perpendicular to the axis, recommended to the polarization eigenmodes, in our case \(S_1(\xi_1)\), i.e. join of point for 45° and \(-45°\).

As example also other case of polarization development and the same launching of linear polarization for polarization modes X and X' are given by the dash line. In our specific case we can find the shift of point \(A = f [\alpha(T)]\) along the circle about \(\pi/2\), as flows from the coefficient \(i\) in the equation (8), i.e. polarization in the output is transformed to the circular. In this case we can describe the development of polarization along the fiber by the effect of temperature on the base of knowledge about the input and output and the known trajectory on the Poincaré sphere and with known parameters of fiber to determine the effect of temperature to the polarization properties of fiber. We can expect similar relation also for different values of torsion and also for different orientation input linear polarization.

3 Conclusion

In the continuation with the previous study of torsion and magnetic field effects on the properties of rare earth doped fiber, the analysis and measurement has been extended to the combinations of these effects with the effect of temperature. It turned out, that influence of temperature together with torsion are dominant in fiber, where some birefringence, though parasitic, exists. The reason of presented results can be as for application of active fibers in sensors, where given properties can be functional. Also it is suitable for cases, where these properties can be parasitic and they can affect the resultant parameters of system.

Fig. 5 Projection of the polarization evaluation on the Poincaré sphere in the Stockes space

Contemporary incidence of temperature and torsion enables to analyze the polarization properties of fiber and thereby properties of special fibers. In this direction it is possible to focus also further works in deeper investigation of real properties of rare earth fibers.

4 Acknowledgement

This work has been supported by the Research Plan FVT 0000403: "Development, integration, administration and security of communication and information systems (C4I2) in NATO environment", of Ministry of Defense, Czech Republic.

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