Study of fiber PM 1550 HP response in the set of thermal field disturbance sensor

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Abstract: - The paper deals with the measurement of polarization preserving fiber response upon the ambient thermal field with different initial temperatures. The principle of fiber sensor of thermal field disturbance detecting measure of fiber response is described theoretically by means of coherency, Jones and Mueller matrices. Measured results in the experiment are processed in graphical form presenting measure of response for given set of sensor. The partial result is depiction of polarization development on the surface of observable Poincaré sphere. Results of fiber response for $\lambda = 1550$ nm are compared with the results of measurements for $\lambda = 633$ nm obtained in previous works.

Key-Words: - Beat length, Coherency matrix, fiber response, state of polarization, observable Poincaré sphere.

1 Introduction

From the beginning of fiber realization in the telecommunication area it got to the big development of theory and practical applications. Almost in the same time there were ideas on the application of fibers also in sensors. Especially polarization maintaining fibers (PMF) have been used in the number of sensor applications. An example could be application in the interferometric sensor of gyroscope [1], [2]. Polarization maintaining fibers were established for exciting of optical radiation to one polarization axis only and maintenance state of polarization along the whole length of fiber. According to the induced birefringence, fibers were applied in sensors, e.g. for measurement of mechanical pressure [3].

Artificial birefringence created by the different thermal expansibility of strength elements towards the fiber cladding reaches high sensitivity on the ambient temperature. For uniform excitation of both fiber axes there is a polarization state change of optical radiation in the fiber output by means of an ambient thermal field disturbance. By the change of polarization state of output optical radiation happens to the immediate detection of thermal field disturbance by the ambient thermal source. High sensitivity of fiber on the outer field led to the idea of PMF application as sensor of thermal field disturbance.

Infant of research work, time development of output polarization fluctuation in PMF PANDA and bow-tie for uniform excitation of both polarization axes were studied. Expressive fluctuation led to the construction of fiber sensor realized and evaluated for $\lambda = 633$ nm, where good polarization properties of He-Ne laser are used. Measurement results validated high sensitivity of sensor upon the ambient thermal field. Disadvantage of this sensor is its construction arrangement using He-Ne laser as source of optical radiation. Hence for elimination of this and also for comparison different properties of used components is now used semiconductor laser with $\lambda = 1550$ nm.

The results of theoretical analysis and partial experiments on the $\lambda = 633$ and 1550 nm were published in previous papers [4], [5], [6]. Two experiments for $\lambda = 1550$ nm have been made there. In the first one the measure of fiber response depending on the distance of ambient thermal source from fiber were studied. In the second one the effect of PMF response on its exposed length were studied. Presented work is an extension of previous experiments and it is focused mainly on the determination of fiber response in both dependences during the excitation by the ambient thermal field with variable initial temperature.
2 Principle of sensor function

The part of PMF in principle can be studied as multiple linear retarder, which contains no partial polarizers and can be described by means of Jones matrix. Output optical radiation from PMF can be described by coherency matrix \( C' \), determined by the unitary Jones matrix of given component \( L \), in this case fiber and coherency matrix of input optical radiation \( C \) according [7]

\[
C' = (LE) \otimes (LE)' = (LE) \otimes (L'E^+) = L(E) \otimes (E^+)L^+ = LCL^+ . \tag{1}
\]

By the decomposition of coherency matrix of output optical radiation we find elements of Stokes vector, enabling to describe the fiber sensor of thermal field disturbance from the optical intensity \( I \) point of view.

To the creation of coherency matrix of output optical radiation we need coherency matrix of input optical radiation and Jones unitary matrix of PMF. For excitation of both polarization axes and any turning of fiber we introduce clockwise polarized optical radiation described by Jones matrix \( J_{RC} \)

\[
J_{RC} = \begin{pmatrix} -i \\ 1 \end{pmatrix} . \tag{2}
\]

Coherency matrix of input optical radiation provides as

\[
C = \langle \mathbf{E} \otimes \mathbf{E}' \rangle = \begin{pmatrix} E_x & E_x' \\ E_y & E_y' \end{pmatrix} = \begin{pmatrix} \langle E_x E_x' \rangle & \langle E_x E_y' \rangle \\ \langle E_y E_x' \rangle & \langle E_y E_y' \rangle \end{pmatrix} . \tag{3}
\]

After substitution of (2) we obtain coherency matrix of circular optical radiation

\[
C_{RC} = \begin{pmatrix} -i \\ 1 \end{pmatrix} \otimes \begin{pmatrix} i \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & -i \\ i & 1 \end{pmatrix} . \tag{4}
\]

Phase delay of linear retarder \( \phi \) we introduce to the Jones matrix of linear retarder with azimuth \( 0^\circ \). By this we obtain common relation of linear retarder as

\[
L = \begin{pmatrix} e^{-i \phi/2} & 0 \\ 0 & e^{i \phi/2} \end{pmatrix} . \tag{5}
\]

Hermitean conjugate (transposed) matrix to the matrix (5) can be expressed as

\[
L^+ = \begin{pmatrix} e^{-i \phi/2} & 0 \\ 0 & e^{i \phi/2} \end{pmatrix} . \tag{6}
\]

By the substitution of matrices (2), (7) a (6) into (1) we obtain coherency matrix of output optical radiation

\[
C_{RC} = LC_{RC}L^+ = \begin{pmatrix} e^{i \phi/2} & 0 \\ 0 & e^{-i \phi/2} \end{pmatrix} \begin{pmatrix} 1 & -i \\ i & 1 \end{pmatrix} \begin{pmatrix} e^{-i \phi/2} & 0 \\ 0 & e^{i \phi/2} \end{pmatrix} . \tag{7}
\]

By the calculation of matrix product from (7) we obtain resultant relation for coherency matrix of output optical radiation

\[
C' = \begin{pmatrix} 1 & -ie^{i \phi} \\ ie^{-i \phi} & 1 \end{pmatrix} . \tag{8}
\]

By the decomposition of (8) on the spin matrices based on the next equation,

\[
C = \frac{C_{xx} + C_{xy}}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{C_{xx} - C_{xy}}{2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} + \frac{C_{xy} + C_{yx}}{2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \tag{9}
\]

we obtain:

\[
C' = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \sin \phi \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} + \cos \phi \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} . \tag{10}
\]

From the relation (10) is clear an assignment of components on the right side of equation to the corresponding components of Stokes vector. Unit matrix corresponds to the component \( S_0 \), component with multiple \( \sin \phi \) corresponds to the \( S_2 \) and component with multiple \( \cos \phi \) corresponds to the \( S_3 \). Distribution of optical intensity \( I \) in the vertical preference is zero according to the definition

\[
S_1 = C_{xx} - C_{yy} .
\]

In the principle of function under consideration, for excitation of both polarization axes by means of the circular polarized optical radiation with no disturbance of ambient thermal field, the phase shift \( \phi \) will be equal zero, corresponding Stokes
component $S_2 = 0$ and in this ideal state we get circular polarized optical radiation in the output of fiber.

In the case of ambient thermal field disturbance by means of outer thermal source the phase shift will be excited with result in the change of output polarization state. This variation of polarization state is proportional to the change of phase shift, expressed by the minimal and maximal value of measured optical intensity $I$.

According to the character of measured quantity, optical intensity $I$, is preferable for next description to use Mueller matrix. Behavior of input circular polarized optical radiation propagating through the sensor under consideration, linear retarder, is expressed by the Mueller matrix as follows

$$
\begin{pmatrix}
S_0 \\
S_1 \\
S_2 \\
S_3
\end{pmatrix} = 
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & \cos \phi & \sin \phi \\
0 & 0 & -\sin \phi & \cos \phi
\end{pmatrix}
\begin{pmatrix}1 \\
1 \\
0 \\
1
\end{pmatrix} =
\begin{pmatrix}
1 \\
0 \\
\sin \phi \\
\cos \phi
\end{pmatrix}.
$$

(11)

The output optical radiation (11) hits the linear polarizer – analyzer with required orientation towards the polarization axes. In the output of polarizer we obtain optical radiation expressed by the Stokes vector

$$
\begin{pmatrix}
S_0' \\
S_1' \\
S_2' \\
S_3'
\end{pmatrix} = 
\begin{pmatrix}
1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 \\
1/2 & 1 & 0 & 1 \\
0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}1 \\
1 \\
+\sin \phi \\
0
\end{pmatrix} =
\begin{pmatrix}
1 \\
0 \\
1/2 + \sin \phi \\
0
\end{pmatrix}.
$$

(12)

From resultant equation it is clear that optical radiation in the output of polarizer – analyzer will be linear polarized with orientation 45° and the change of optical intensity is directly proportional to the change of phase shift in fiber. From (12) is evident that for given arrangement we measure by the photodetector directly value of Stokes element $S_2$. Since the variations of phase shift in fiber and development of polarization state of propagating optical radiation through the fiber, these variations are proportional to the $S_0$ a $S_3$ according to (10). To evaluate these variations we need know only one measured Stokes element $S_2'$ or $S_1'$. Whether $S_2'$ is

$$
S_2' = \frac{1}{2}(1 + \sin \phi) = \frac{1}{2}\left(\sin\frac{\phi}{2} + \cos\frac{\phi}{2}\right)^2.
$$

(13)

Because we measure optical intensity $I$ of Stokes element $S_2'$ and not phase shift, we determine $\phi$ from (13) as

$$
\phi = \arcsin(2S_2' - 1).
$$

(14)

This analysis deals with description of sensor from the outer view. At comparison of PMF response for different wavelengths it is necessary to think over the effect of beat length $L_B$ defined as [7]

$$
L_B = \frac{\lambda}{\Delta n_e},
$$

(15)

where $\Delta n_e$ is difference of effective values of refractive indices for fast and slow axis. For studied PMF and $\lambda = 1550$ and 633 nm we obtain the beat length for comparison as

$$
\Delta n_e(1550) = \frac{\lambda_1}{L_{B1}} = \frac{1550}{5} = 310 \frac{nm}{mm},
$$

$$
\Delta n_e(633) = \frac{\lambda_2}{L_{B2}} = \frac{633}{2} = 316 \frac{nm}{mm}.
$$

(16)

From results we can suppose similar character of induced birefringent area. The difference is in measure of influence of beat length upon the PMF response of the exposed parts of the same length. The measure of beat length effect is analyzed in more detail in [6].

3 Experimental results

The aim of experimental measurement is determination of PMF type PANDA response during its thermal field disturbance by the application of outer thermal source with different initial temperatures. Value of temperature is changed from 50°C to 35°C with the step 5°C. Measurement is realized for two different exposed lengths of fiber. Response of fiber is investigated for three different distances (5, 8 and 11 cm) of source and fiber. Disturbance of thermal field of PMF is realized by means of plastic basin with constant amount of water heated on the defined temperature. Arrangement of work place is shown in fig.1.
Set in sensor block enables exposition of required length of investigated fiber and also to arrange required distance of ambient thermal field from the fiber. Response of fiber for 1 and 3 exposed lengths between cork cylinders were investigated in the made experiment. The distance between the cylinders for one length of winding was 47cm. Used type of laser diode for $\lambda = 1550$ nm was ML 925 B45F. The beat length of fiber PM 1550HP is $L_B \leq 5$ mm. Measured values of optical power were red in the interval 0.5 s by means of power meter GENTEC-E0 P-LINK with Ge photodiode PH78-Ge. The example of measured development of polarization state for given configuration is presented on the fig.2.

The measured results were elaborated in two variants of graphs of phase shift: on the temperature for different distances of thermal source from the fiber and dependence on the distance for selected temperatures. Presented approximations come from measurement on the temperature 50, 45, 40 and 35 [°C] and distance 5, 8 and 11 [cm]. Examples of these distances for one exposed length are shown in fig. 4 and 5, results for three exposed lengths are in fig. 6 and 7.

![Fig. 1 Arrangement of work place [6].](image1)

![Fig. 2 Example of output optical power detected on photodetector for $\lambda = 1550$ nm, 3 exposed lengths of winding, initial temperature 50 °C and 5 cm distance of outer thermal source from PM fiber.](image2)

![Fig. 3 Development of polarization state corresponding to the measured trajectory in fig. 2.](image3)

![Fig. 4 Phase shift dependence upon temperature for one exposed length of winding.](image4)
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References:


