Temporal coherency of LD light measurement by the use a polarimetric fiber-optic strain sensor

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Received June 17, 2009; accepted June 25, 2009; published June 30, 2009

Abstract— In this paper we present a new non-interferometric method of temporal coherency of light measurement. The method is based on the application of a polarimetric fiber-optic strain sensor in which the dynamics of an output signal depends on the degree of polarization and on the same coherency of light coupled to a sensor. The method is particularly useful for measurements of light emitted by diodes for which interferometric methods are very inconvenient. Theoretical analysis of the method is based on the Mueller-Stokes matrix equation modified by an additional depolarization matrix. The method was tested for LD under threshold light.

Temporal coherency of light plays an important role in many optoelectronic devices which apply interference and polarization phenomena. Interferometric methods are commonly used for temporal coherency of light measurements [1-2]. Starting from Michelson's experiments at the end of 19th century the interferometric methods have been used for light emitted by different light sources.

In general, interferometric methods are based on visibility fading measurements of the interference pattern of two light beams from the same source passing through different ways. The methods require relatively long time for difference ways changes between two light beams during measurements. Hence the methods are inconvenient for laser diodes and light emitting diodes working without temperature and wavelength stabilization but with wavelength fluctuations.

On the other hand, optoelectronic devices utilizing the polarization phenomenon like optical fiber giroscopes or polarimetric sensors require the knowledge about temporal coherency of light passing through the fibers. Hence we have dealt with new methods of temporal coherency measurements based on the depolarization phenomenon. We have utilized measurements of the degree of polarization (DOP) which decreases during the propagation of partially coherent light in birefringent media [3,4]. In the paper we present a new depolarization method without the possibility of DOP measurements. The method is based on the application of a polarimetric fiber-optic strain sensor in which the dynamics of an output signal depends on the DOP [5] and in the same temporal coherency of light coupled to a sensor.

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In general, partially coherent light becomes depolarized during propagation through birefringent media. The depolarization effect depends on temporal coherency of light that is characterized by a length of coherence ΔL, length of the medium L, birefringence defined as $\Delta n = \left| n_{fast} - n_{slow} \right|$, as well as the azimuth of light beam polarization versus the fast and slow axes of the birefringent medium [6]. Partially coherent light outgoing from a birefringent medium may be almost totally unpolarized due to the fact that both electric field components of light propagating with different velocities are shifted into different wave packages. In the special case of a single-mode highly birefringent (SM HB) fiber, which is also the type of a birefringent medium, perpendicular electric field components are replaced by LP_{01}^x and LP_{01}^y polarization modes (Fig. 1).

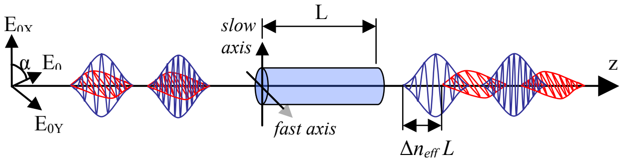


Fig. 1: Length shift $\Delta n_{eff} L$ between LP_{01}^x and LP_{01}^y modes of partially coherent light passing through the HB single-mode fiber with linear birefringence Δn_{eff}

Depolarization in a birefringent medium may be described by the modified Mueller-Stokes matrix equation [6]:

$$\left[\mathbf{S}^{\mathbf{out}}\right] = \left[\mathbf{D}_{\mathbf{C}}\right] \cdot \left[\mathbf{M}\right] \cdot \left[\mathbf{S}^{\mathbf{in}}\right], \quad (1)$$

where [$\mathbf{S^{in}}$] and [$\mathbf{S^{out}}$] are the input and output Stokes vectors, respectively, [**M**] is the Mueller matrix of the medium and [$\mathbf{D_C}$] is the depolarization matrix. The degree of polarization (*DOP*) may be directly calculated from the elements of the Stokes vector [7]:

$$DOP = \frac{I_{polarized}}{I_{total}} = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}, \quad (2)$$

In highly birefingent fibers we can consider the beat length L_B as a good parameter describing fiber birefringence. Beat length L_B is a light propagation distance in the fiber after which the state of polarization is being reconstructed:

$$L_B = \frac{2\pi}{|\beta_x - \beta_y|} = \frac{2\pi}{\Delta\beta} = \frac{\lambda}{\Delta n_{eff}} \qquad (3)$$

where β_x, and β_y are the propagation constants of the orthogonal polarization modes, Δn_{eff} – the effective linear birefringence of the fiber and λ is the central wavelength (in vacuum) of the source spectrum.

During the propagation through a birefringent fiber the length shift $\Delta n_{eff}L$ between polarization modes increases and the degree of polarization diminishes. For Gaussian sources (e.g. light emitting diodes or laser diodes working under threshold) the DOP is specified by the formula [6]:

$$DOP = \sqrt{1 - \frac{4[1-\exp(-2\eta_{Gaussr})]}{\left(\frac{U_{0x}}{U_{0y}} + \frac{U_{0y}}{U_{0x}}\right)^2}}, \quad \eta_{Gauss} = \left(\frac{\lambda \cdot L}{\Delta L \cdot L_B}\right)^2 = \left(\frac{\Delta n_{eff} \cdot L}{\Delta L}\right)^2, \qquad (4)$$

where L, and Δn_{eff} are the fiber length and birefringence, respectively, ΔL is the coherence length of light and U_{0x}, U_{0y} are the amplitudes of LP_{01}^{x} and LP_{01}^{y} modes of the E-M field in the fiber.

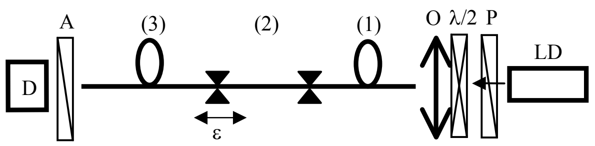


Fig. 2. Polarimetric strain sensor setup: D-detector, A-analyser, O-objective, λ/2-half-wave plate, P-polarizer, LD-laser diode working under threshold, (1), (2), (3)-segments of HB fiber, where segment (2) is under strain: ε.

When the section $L^{(2)}$ of the fiber is elongated, the phase difference between two polarizations of the LP_{01} mode is modulated:

$$\Delta\Phi = \Delta\beta \cdot L^{(2)} \Rightarrow$$
$$\frac{\partial(\Delta\Phi)}{\partial\varepsilon} = \frac{2\pi}{T_\varepsilon} = \frac{\partial(\Delta\beta)}{\partial\varepsilon} L^{(2)} + \Delta\beta \frac{\partial L^{(2)}}{\partial\varepsilon} \qquad (5)$$

where: $\varepsilon = \frac{\delta L^{(2)}}{L^{(2)}}$, $[\varepsilon] = \frac{10^{-3}m}{m} = m\varepsilon$ is relative elongation (strain), T_ε - period of the output signal.

The first component of equation (5) is the change of birefringence, the second component is to be left out because of its two-range lower value.

The change of $\Delta\beta$ indicates the change of beat length:

$$L_B(\varepsilon) = L_{B0}\left[1 + \mathrm{sgn}\left(\frac{\partial(\Delta\beta)}{\partial\varepsilon}\right) \cdot \frac{\varepsilon L_{B0}}{T_\varepsilon L^{(2)}}\right]^{-1} \qquad (6)$$

where L_{B0} is beat length with no strain and value of sgn function is determined by the type of HB fiber (e.g. bow-tie, e-core Andrew). The relation between period T_ε and $L^{(2)}$ does not include beat length: $T_\varepsilon \cdot L^{(2)} = const$.

Depolarization in strained fiber is described by the formula (4) as well, where L_B equals $L_B(\varepsilon)$ from (6).

The measurement carried out in the setup depicted in Fig. 2 is realized with the use of linear initial polarisation coupled with azimuth α=45° versus birefringence axis of the fiber:

$$[\mathbf{S^{in}}] = \begin{bmatrix} S_0^{in} \\ S_1^{in} \\ S_2^{in} \\ S_3^{in} \end{bmatrix} = I_{total}\sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot \begin{bmatrix} 1 \\ \cos 2\alpha \\ \sin 2\alpha \\ 0 \end{bmatrix} = I_{total}\sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix}.$$

Then the polarization state of light coming out directly from the fiber is obtained using the modified Mueller-Stokes formalism [6]:

$$[\mathbf{S^{out}}] = I_{total}\sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot \begin{bmatrix} 1 \\ 0 \\ P_L^{(1)}P_L^{(2)}P_L^{(3)}[(c_1c_2 - s_1s_2)c_3 - (c_1s_2 + c_2s_1)s_3] \\ P_L^{(1)}P_L^{(2)}P_L^{(3)}[(c_1c_2 - s_1s_2)s_3 + (c_1s_2 + c_2s_1)c_3] \end{bmatrix} =$$
$$= [\mathbf{D_C^{(3)}}] \cdot [\mathbf{M}^{(3)}] [\mathbf{D_C^{(2)}}] \cdot [\mathbf{M}^{(2)}] [\mathbf{D_C^{(1)}}] \cdot [\mathbf{M}^{(1)}] I_{total}\sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} \qquad (7)$$

where:

$$[\mathbf{M}^{(i)}] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_i & -s_i \\ 0 & 0 & s_i & c_i \end{bmatrix}, \quad [\mathbf{D_C^{(i)}}] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & P_L^{(i)} & 0 & 0 \\ 0 & 0 & P_L^{(i)} & 0 \\ 0 & 0 & 0 & P_L^{(i)} \end{bmatrix},$$
$$s_i = \sin(\Delta\beta \cdot L^{(i)}), \quad c_i = \cos(\Delta\beta \cdot L^{(i)}), \qquad i = 1, 2, 3.$$

Then, according to the formula (2):

$$DOP_{out} = \frac{\sqrt{(S_1^{out})^2 + (S_2^{out})^2 + (S_3^{out})^2}}{S_0^{out}} = P_L^{(3)}P_L^{(2)}P_L^{(1)}P_{in}. \qquad (8)$$

It is clearly seen that the location of the fiber segment under strain (number 2) has no influence on output *DOP*. In the considered case of azimuth 45° of input linear polarization $DOP=P_{out}$ corresponds to the dynamics of output signal η [5]. Thus, assuming P_{in}=1 in (8) and according to equation (6):

$$\eta = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = P_L^{(1)} P_L^{(3)} \exp\left\{ -\left[\frac{\lambda L^{(2)}}{\Delta L L_{B0}} \left(1 + \frac{\varepsilon L_{B0}}{T_\varepsilon L^{(2)}} \right) \right]^2 \right\} = \qquad (9)$$

$$= const \cdot \exp\left[-\frac{\lambda^2}{\Delta L^2 T_\varepsilon} \varepsilon^2 - \frac{2\lambda^2 L^{(2)}}{\Delta L^2 L_{B0} T_\varepsilon} \varepsilon \right],$$

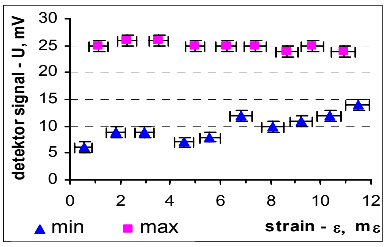
where the constant factor is the contribution from natural fiber birefringence (from all three sections), while the exponential part carries the influence of strain. The square element can be omitted:

$$\eta \propto P_\varepsilon \approx \exp\left[-\frac{2\lambda^2 L^{(2)}}{\Delta L^2 L_{B0} T_\varepsilon} \varepsilon \right] \qquad (10)$$

The experimental setup (Fig.2.) is based on a laser diode (λ=670nm) working under threshold and a single piece of HB-600 birefringent fiber (about 50 cm length without splices).

First, the characteristic of an output signal has to be measured. The setup works as a polarimetric strain sensor (Fig.2). Only maximum and minimum points are noted (Fig 3. a).

a)



b)

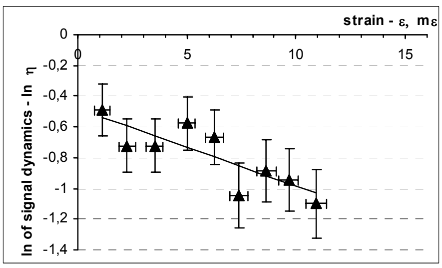


Fig. 3. Experimental data and halfway calculations: (a) output signal extrema, (b) natural logarithm of signal dynamics calculated from extrema. Random uncertainty caused by temperature fluctuations is not marked.

In the first step of analysis the period T_ε of the characteristic is calculated and then the dynamics of an output signal:

$$\eta(k) = \frac{U_k^{\max} - U_{k-1}^{\min}}{U_k^{\max} + U_{k-1}^{\min}}, \qquad (11)$$

where k is the counter of all characteristic points.

Then, due to the fact that a decreasing exponential curve is expected (equation 10), natural logarithm of $\eta(k)$=$\eta(\varepsilon)$ is approximated by a linear relation: $\ln(\eta)(\varepsilon) = a \cdot \varepsilon + b$, where a coefficient corresponds to expression: $-2\lambda^2 L^{(2)} / (\Delta L^2 L_{B0} T)$ due to equation (10). Eventually, the quested length of coherence of a used laser diode is obtained from the formula:

$$\Delta L = \lambda \sqrt{\frac{2L^{(2)}}{(-a) T_\varepsilon L_{B0}}}. \qquad (12)$$

Required data and results of the measurement steps:

λ = (670 ± 0,5) nm L_{B0} = (2,0 ± 0,1) mm $L^{(2)}$ = (88 ± 2) mm
T_ε = (1,22 ± 0,07) mε a = (-0,05 ± 0,02) 1/mε
ΔL = 25 ± 6 μm

Table 1. Final results of the length of coherence measurement: T_ε stands for output signal period versus strain, a is the *DOP* sensitivity for strain coefficient and ΔL is the quested length of coherence of a partially coherent light source.

What is very valuable in the described method of measuring the length of coherence, the experimental setup is very simple. It consists of a single piece of HB fiber with a specified section under strain. Light going out from the fiber passes through the analyser only and hits the detector. The dynamics of signal oscillations generated by means of fiber strain carries all information required to calculate the coherence length of the used light source. The only condition is that temporal coherence of this source must be low enough. Thus, no spatial transformations on a direct output signal are needed, opposite to all interferometric methods. However, the presented implementation of the method needs the same improvement in the case of thermal control or compensation (to reduce random uncertainty) to become useful in practical applications.

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