Contributed paper

OPTO-ELECTRONICS REVIEW **8**(2), 175–180 (2000)

In-line fibre-optic ellipsometer for sensors application

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Theoretical and experimental analysis of a new fibre-optic ellipsometer in polarimetric configuration is presented. The main idea of a system operation is based on controlled birefringence introducing on a piece of standard single-mode fibre. Estimation of real-time changes in polarisation state parameter, and the ellipsometer measurement have been done for the known induced birefringence. In the paper, research of the constructed in-line system as a new ellipsometer detection system for the fibre-optic sensor application is also presented.

Keywords: ellipsometer, polarimeter, fibre-optic sensor.

1. Introduction

Although the fibre-optic interferometers are equivalent to classical bulk-optic interferometers, the use of fibre-optic elements modifies their actions. The main difference of those two systems is the effect of polarisation properties for the former and coherence properties for the latter ones [1]. Therefore any external perturbation: thermal, mechanical (stress or deformation) and electric (current or voltage) affects condition of light propagation in optical fibre. The changes in propagation conditions generate the changes in guided wave parameters, mainly in its phase. For point-type fibre-optic sensors, the interferometer arms are so short that depolarisation process can be passed over [1] but changes of the state of polarisation (SOP) is the main problem of the system performance. That polarisation sensitivity can be overcome by compensation [2] or can be used as additional source of information. In the latter situation the fibre-optic system is usually called "polarimetric" [3].

The beam separation into two parts with linear orthogonal SOPs is usually used if the external interaction induces only twist of the polarisation azimuth. Then, the intensity measurement by differential method gives information about the twist of the polarisation azimuth [4]. However, the system will interpret the induced SOP ellipticity as additional twist of the polarisation azimuth. To solve this problem, the output light beam is separated into measuring paths with different polarisation properties [5,6]. Other method is based on separation of output beam into two paths for independent phase and SOP measurements [7].

The automatic measurement of SOP for bulk-optic system is proposed in Ref. 8, where only one measurement path changing the input SOP of the investigated medium is employed. This method can be developed by application of SOP modulation technique used for polymer investigation [9]. Both methods can be treated as ellipsometric techniques which have been recognised in classical optics for many years [10], but today they are not implemented in fibre-optic technique.

In this paper, a new in-line fibre-optic ellipsometer in polarimetric configuration (FOPE – fibre-optic polarimetric ellipsometer) is presented. The main idea of the system operation is based on birefringence modulation in a standard single-mode fibre followed by identification of the input SOP changes by a suitable detection of different harmonics of the output signal. From physical point of view, this system is based on the SOP modulation technique presented in [11] where a tunable liquid crystal phase plate has been used as birefringence modulator.

2. Modulation of polarisation state by changes of fibre-optic birefringence

To introduce SOP, modulation transverse force was applied to a standard single-mode fibre, using a piezoceramic transducer (PZT), as shown in Fig. 1. For such kind of interac-

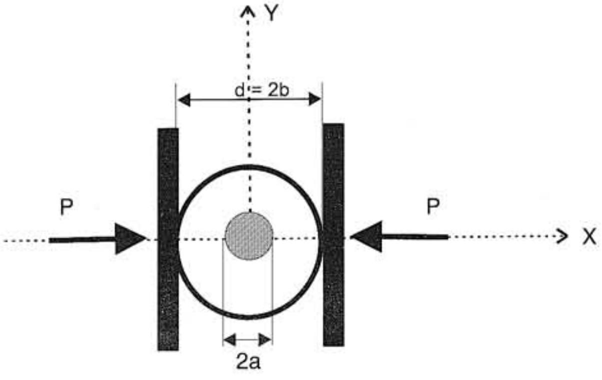

Fig. 1. Scheme of gripping fibre-optic cross-section.

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tion, the external force P (N/m) acts on fibre-optic cladding with the outer diameter d = 2b, which is much bigger than the fibre core radius a.

Then, the propagation constant for the mode with linear polarisation in X and Y direction can be expressed as [12]:

$$\beta_X = \beta + \frac{Pk_0}{d\pi}[2C_2 - 6C_1] + \frac{8Pk_0}{3d\pi}\left[\frac{a}{d}\right]^2[2C_1 - C_2]H(v), \qquad (1)$$

$$\beta_Y = \beta + \frac{Pk_0}{d\pi}[2C_1 - 6C_2] + \frac{8Pk_0}{3d\pi}\left[\frac{a}{d}\right]^2[2C_2 - C_1]H(v), \qquad (2)$$

where β is the solution of the Hondros-Deby characteristic equation for a single-mode optical fibre; C_1, C_2 is the direct and lateral photoelastic constant, respectively; v is the normalised frequency. Moreover, the factor H(v) depends on the fibre-optic parameters as [12]

$$H(v) = 2 + \frac{4(u^4 - w^4)}{(uwv)^2} + \frac{4J_0(u)}{uJ_1(u)}. \qquad (3)$$

For the weak waveguide condition the characteristic equation has the following form [13]

$$\frac{J_k(u)}{uJ_{k-1}(u)} = -\frac{K_k(w)}{wK_{k-1}(w)}, \qquad (4)$$

where $v^2 = u^2 + w^2$, $k \geq 0$, $w^2 = a^2(\beta^2 - n_2^2 k_0^2)$, $u^2 = a^2(n_1^2 k_0^2 - \beta^2)$, k_o is the wavelength in vacuum; n_1, n_2 is the refractive index for the core and cladding, respectively; $J_k(x)$ is the first kind Bessel function of the k-order, $K_k(x)$ is the second kind modified Bessel function of the k-order.

Finally, the fibre birefringence has the following form

$$\Delta\beta = \beta_x - \beta_y = \frac{8Pk_0C}{d\pi}\left[1 - \left(\frac{a}{d}\right)^2 H(v)\right], \qquad (5)$$

where $C = C_1 - C_2$.

Theoretical investigation has shown that the modulation in the range of 2π order is achieved for the force of about 180 N when interaction length is equal to 0.1 m in a squeezer construction shown in Fig. 2. This value is much smaller than fibre durability on force. The photoelastic constant of the fused silica $C = 3.51 \times 10^{-12}$ m²/N, wavelength λ = 0,633 μm, core diameter 2a = 6 μm and outer cladding diameter d = 250 μm were used for calculation [12].

If voltage signal driving the PZT squeezer is $V_0 \sin(\omega t)$, then the phase change is (for linear range of SOP modulator operation)

$$\delta(t) = \delta_0 \sin(\omega t + \phi_0) + \delta_w \qquad (6)$$

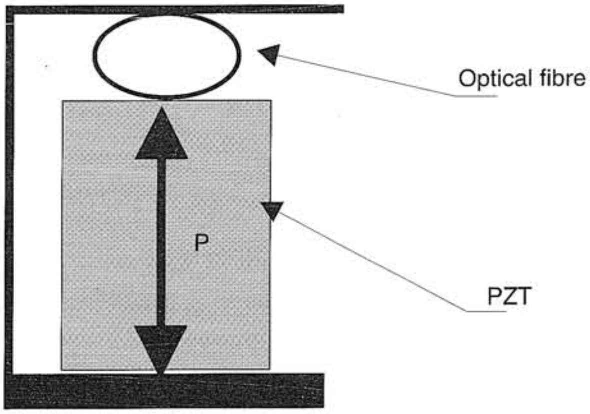

Fig. 2. Scheme of squeezer construction.

where δ_0 is the maximum phase difference between orthogonal field components, ϕ_0 is the initial phase shift between reaction and extracting voltage, δ_w is the phase difference induced by initial stress. It should be mentioned that, for stable thermal condition of squeezer operation, an amplitude of the above phase change linearly depends on the induced birefringence Δβ and the length of interaction L

$$\delta_0 = \Delta\beta L. \qquad (7)$$

3. Construction of fibre-optic polarimetric ellipsometer

The new in-line fibre-optic polarimetric ellipsometer (FOPE) is based on the recently presented system [14] but with improved operation, yielding better accuracy and stability of the measurement. This all-fibre system conception shown schematically in Fig. 3 has been previously presented in the bulk-optic configuration [11].

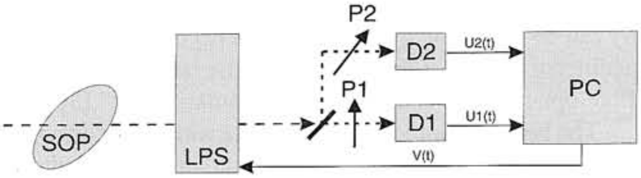

Fig. 3. Scheme of the FOPE system.

The light of an unknown SOP is going through a linear phase shifter (LPS) tuned by the voltage signal V(t). Then it is divided into two parts and goes through the polarisers P1 and P2 oriented with the angle 0 and π/4 with respect to the fast axis of the LPS. The personal computer PC collects the output signals U1(t) and U2(t) from the detectors D1 and D2. The dedicated software program determines the SOP by suitable comparison of the output signals U1(t) and U2(t) with the LPS driving voltage V(t). The Jones matrix calculus has been adopted for mathematical description of the system action to obtain information about SOP parameters [15]. SOP of the input beam is described by the standard Jones' vector

$$E_1 = \begin{bmatrix} \cos\phi \\ \sin\phi e^{j\Delta} \end{bmatrix} \tag{8}$$

where ϕ and Δ stand for the unknown parameters of polarisation ellipse, i.e., the diagonal angle and retardation of orthogonal components of electric field, respectively [10]. Total variation of the SOP requires change of the above parameters in the ranges form 0 to π/2, and from 0 to 2π, respectively.

For ideal system without losses containing 3 dB beam splitter, the Jones vectors of the output beams, before the detectors D1 and D2 have following forms

$$\begin{gathered}\mathbf{E1} = \frac{1}{\sqrt{2}}\mathbf{P}\cdot\mathbf{R}\left(\frac{\pi}{4}\right)\cdot G[\delta(t)]\cdot\mathbf{E}_{in} \equiv \\ \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}\cdot\begin{bmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix}\cdot\begin{bmatrix} 1 & 0 \\ 0 & e^{-j\delta(t)} \end{bmatrix}\cdot\begin{bmatrix} \cos\phi \\ \sin\phi e^{j\Delta} \end{bmatrix}'\end{gathered} \tag{9}$$

$$\begin{gathered}\mathbf{E2} = \frac{1}{\sqrt{2}}\mathbf{P}\cdot\mathbf{R}(0)\cdot\mathbf{G}[\delta(t)]\cdot\mathbf{E}_{in} \equiv \\ \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}\cdot\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}\cdot\begin{bmatrix} 1 & 0 \\ 0 & e^{-j\delta(t)} \end{bmatrix}\cdot\begin{bmatrix} \cos\phi \\ \sin\phi e^{j\Delta} \end{bmatrix}'\end{gathered} \tag{10}$$

where P, R, G are the Jones matrices for linear polariser parallel to OX axis, rotator with the angle π/4 or 0 and retarder with the time-dependent retardation of δ(t) (induced by the LPS at the frequency ω), respectively [15].

Finally, the output signals from the detectors D1 and D2 have the following form

$$U1(t) \propto \mathbf{E1}\cdot\mathbf{E1}^{+} \equiv 0.5U_0\cos^2\phi \tag{11}$$

$$U2(t) \propto \mathbf{E2}\cdot\mathbf{E2}^{+} \equiv 0.5U_0\{1+\sin(2\phi)\cos[\delta(t)-\Delta]\} \tag{12}$$

where the constant parameter U_0 can be determined by integration of the signal U2(t) in time equal to an integer number of the signal period T = 2π/ω

$$U_0 = 2\int_{\tau}^{\tau+mT} U2(t)dt,\ m\in N \tag{13}$$

As one can see, the diagonal angle ϕ can be directly determined from the signal on the D1 detector as

$$\phi = \arccos\sqrt{2\frac{U1}{U_0}}. \tag{14}$$

This is typical polarimetric method widely used in fibre-optic sensor technique.

The second parameter describing the SOP needs more sophisticated method using the U2(t) signal. Adopting the SOP modulation method described above [PZT squeezer used as the LPS, see Eqs. (6) and (7)], the signal from the detector D2 has been formed by the following harmonic components [14]

$$U2(t) = 0.5U_0\left\{1+\sin(2\phi)\left[\begin{matrix}\cos\Delta_1\{J_0(\delta_0)+2\sum\limits_{k=1}^{\infty}J_{2k}(\delta_0)\cos[2k(\omega t+\phi_0)]\}+ \\ \sin\Delta_1\{2\sum\limits_{k=0}^{\infty}J_{2k+1}(\delta_0)\sin[(2k+1)(\omega t+\phi_0)]\}\end{matrix}\right]\right\} \tag{15}$$

where $\Delta_1 = \Delta - \delta_w$. The proper system performance requires the condition $J_0(\delta_0) = 0$ to be fulfilled, therefore the amplitude of the phase modulation δ_0, generated by the PZT squeezer, must be equal to 2.4048. Then, the initial phase shift ϕ_0, described in Eq. (6), generates shift in phase of the output characteristic only. Moreover, only the first three harmonic components of a signal from the detector D2 are important

$$U2(t) = 0.5U_0\left\{1+2\sin(2\phi)\left[\begin{matrix}\sin\Delta_1 J_1(\delta_0)\sin(\omega t+\phi_0)+ \\ \cos\Delta_1 J_2(\delta_0)\sin(2(\omega t+\phi_0)+\pi/2)+ \\ \sin\Delta_1 J_3(\delta_0)\sin(3(\omega t+\phi_0)+\ldots)\end{matrix}\right]\right\} \tag{16}$$

Applying a well-known technique for a detection of the signal harmonics one can easily detect the first three harmonic amplitudes from this detector as

$$U_{\omega} = U_0\sin(2\phi)\sin\Delta_1 J_1(2.4048) \tag{17}$$

$$U_{2\omega} = U_0\sin(2\phi)\cos\Delta_1 J_2(2.4048) \tag{18}$$

$$U_{3\omega} = U_0\sin(2\phi)\sin\Delta_1 J_3(2.4048) \tag{19}$$

Then, during system justify by using the linear polarised light (Δ = 0) the ratio of U_ω to $U_{2\omega}$ signal gives the value of δ_w, and in the end using Eqs. (17) and (18), the second searched parameter of SOP is determined as

$$\Delta = \arctan\frac{J_2(\delta_0)U_{\omega}}{J_1(\delta_0)U_{2\omega}} + \delta_w \tag{20}$$

As one can see, determination of the SOP parameters needs only the two first harmonics of the output signals.

However, the proper system operation assures fulfilment of the condition $\delta_0 = 2.4048$ that plays fundamental role for a system accuracy [14]. Unfortunately, this parameter is time-dependent, so the third signal harmonic is used to stabilise the working point of the system. The ratio of the first-to-third harmonics of the signal from a detector

$$\frac{U_\omega}{U_{3\omega}} = \frac{J_1(\delta_0)}{J_3(\delta_0)} = const \qquad (21)$$

has, as shown in Fig. 4, monotonically decreasing character in respect to amplitude of the phase modulation δ_0. For the system working point this ratio is equal to 2.6088. Thus, if the detected ratio described by Eq. (21) is smaller, the amplitude of signal driving the phase modulator should be decreased and for the bigger detected ratio, the amplitude should be increased. In this way, the amplitude of signal driving the phase modulator is a feedback parameter that should be used to stabilise the working point at the constant value $\delta_0 = 2.4048$.

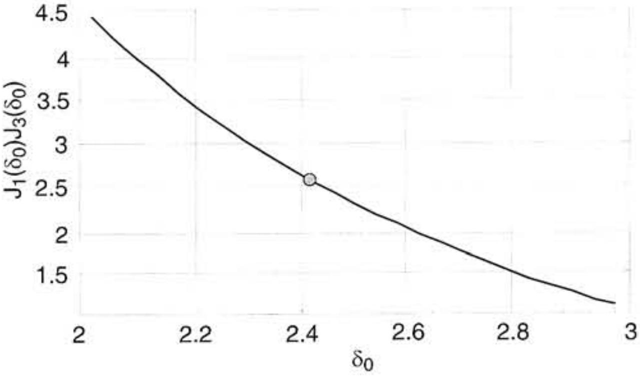

Fig. 4. Dependence of the first and the third Bessel's function ratio vs. their arguments.

4. Experimental results

The constructed FOPE system is shown schematically in Fig. 5. The fibre part of this system contains a piece of standard single-mode optical fibre, the PZT squeezer used as the LPS, a fibre coupler, two in-line fibre polarisers and the systems of three polarisation controllers. First of them PC1 is used for a compensation of birefringence of the fibre before the LPS.

The light with the unknown SOP passing through the LPS is divided by the fibre coupler into two parts that are detected by the polarisation sensitive detectors D1 and D2. The additional polarisation controllers PC2 are used for the final system adjustment, i.e., to assure 0 and $\pi/4$ azimuth angles of the polariser P before the detectors D1 and D2 with respect to the fast axis of the LPS. A lock-in amplifier detects the output signals U1(t), U2(t), and the appropriate signal harmonics. Moreover, it provides the suitable driving signal V(t) for the LPS. Finally, the special programme (for IBM/PC) is used to calculate parameters of polarisation ellipse – SOP as well to control the LPS operation via RS-232 interface driving the lock-in. This calculation is made in real time so the SOP changes can be observed. Application of two polarisation sensitive detectors instead of phase and polarisation sensitive ones described in Ref. 14 and 16 makes possible determination of the SOP parameters changes in all their ranges.

The standard single-mode fibre operating at the wavelength of 635 nm has been used in the constructed system shown in Fig. 6. The PZT squeezer which works at about 100 V and frequency 1.2 kHz has been used as LPS. An EG&G 7260 lock-in amplifier has been used as main electronic equipment. As the output signal from this device, the amplitude of the first three harmonics of the signal has been taken. Additional, the lock-in amplifier gives the intensity-normalised factor U_0 as integral of the U2(t) signal

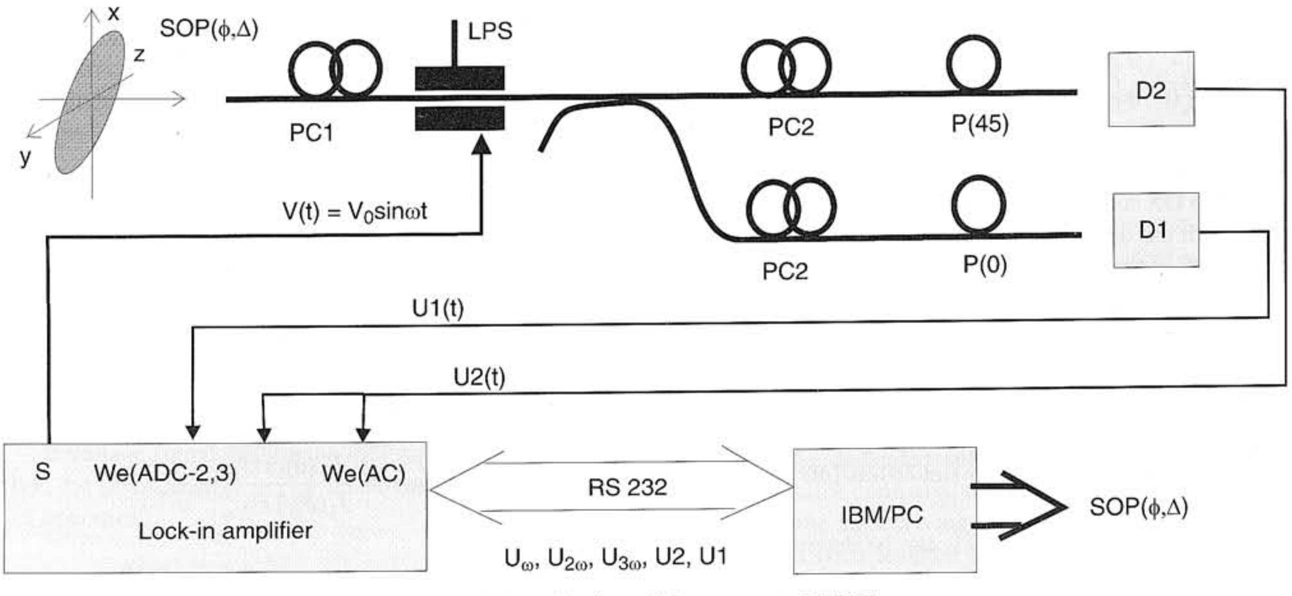

Fig. 5. Schematic view of the constructed FOPE.

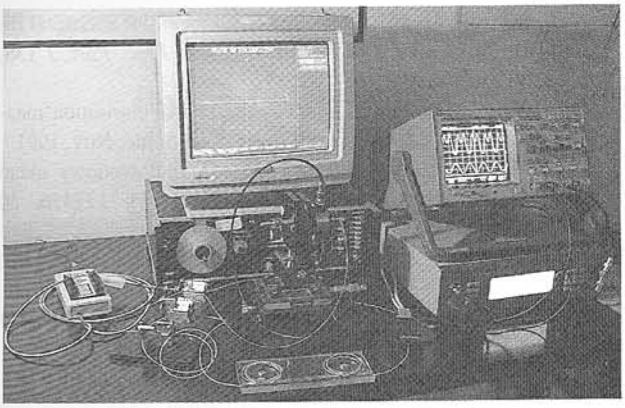

Fig. 6. General view of the FOPE system.

in time equal to ten-fold period $2\pi/\omega$. The same device is also used for a precise control and driving the LPS according to Eq. (21).

The experimental verification of theoretical consideration has been done using the system described above. For this reason the light of various input SOPs, initially measured by the Babinet-Soleil compensator (BSC), has been introduced to the system. Some examples of the detected signal U2(t) from the FOPE are shown in Fig. 7, where the bottom signatures indicated the measured SOP values.

The parameters ϕ and Δ, calculated from Eqs. (14) and (20), have shown that the FOPE is very precise because it gives possibility to measure SOP with the accuracy of 1.0 deg for ϕ and 1.7 deg for Δ. This good accuracy, better than for classical method (using the BSC or a rotational quarter-wave plate and the polariser) is followed by computer method of calculation. The long-term stability of system work has been also investigated. As one can see from Fig. 8, the FOPE system has no good long-term stability, which had main influence on system usefulness. The instability of the PZT work condition gives the problem with taking working point (δ_0 = 2.4048) and is observed as a drift of measurement. Therefore, the feedback loop used in the system should be improved. However, as it can be easily seen from the presented results, a fluctuation of the measured diagonal angle ϕ is two times smaller then the measured retardation of orthogonal components of the electric field Δ which are in the order of 1.4 deg and 3.4 deg, respectively.

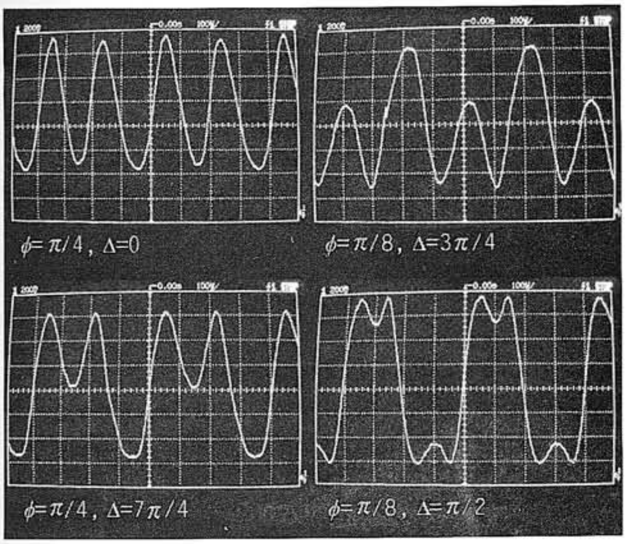

Fig. 7. Detected signals from the detector D2 for different input SOP.

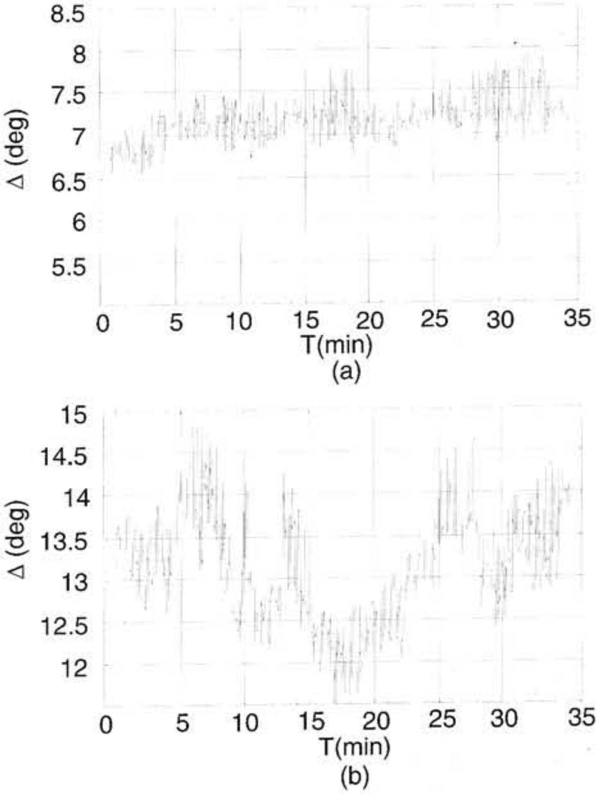

Fig. 8. Stability of the FOPE work. Input SOP measured by BSC was: ϕ = 6.8 deg, Δ = 13.5 deg.

5. Conclusions

The presented in-line fibre-optic ellipsometer ensures a measurement of full-range SOP changes. The main advantage of this system is the lack of rotating parts and compatibility with fibre-optic sensors of interferometric and polarimetric type. Thus, the in-line construction of the FOPE can be easily implemented in fibre links in form of simple and compact devices. The accuracy of determination of polarisation ellipse is ϕ = 1.4 deg and Δ = 3.4 deg in laboratory conditions, so it is similar to previously presented construction which used liquid crystal phase plate. The applied modulation technique gives possibility to perform one measurement within a few dozen of ms, therefore the changes of the SOP can be monitored in real time.

The fibre-optic elements used for the FOPE construction have shown better thermal stability than the presented before liquid crystal ones, but required strong fibre gripping (in the LPS) may cause ageing of the optical fibre. This aspect of system work has probably the main influence on the obtained results of long-term stability investigation. Thus, the construction of this element as well as feedback loop operation should be improved to obtain better stability of system operation.

Acknowledgements

This work has been done in 1999 under financial support of the State Committee for Scientific Research, MUT statutory activity No. PBS-170.

References

1. L.R. Jaroszewicz, *The Polarisation and Coherence Role in a Fibre-Optic Interferometry*, P.L.Q. thesis, MUT, Warsaw, 1996.
2. W.J. Bock, T. Woliński, and T.A. Eftimov, "Polarimetric fibre-optic strain gauge using two-mode highly birefringent fibres", *Pure Appl. Opt.* **5**, 125–139 (1996).
3. J.D.C. Jones, R.P. Tatam, P.A. Leilabady, C.N. Pannell, and D.A. Jackson, "Optical fibre polarimetry", *Proc. SPIE* **630**, 187–193 (1986).
4. E. Udd, *Fibre Optic Sensors: An Introduction for Engineers and Scientists*, John Wiley & Sons, New York, 1991.
5. S. Donati, "Magneto-optical fibre sensors for electrical industry: analysis of performances", *IEE Proc. Part. J* **135**, 372–379 (1988).
6. R. Cross, B. Heffner, and P. Hernday, "Polarisation measurement goes automatic", *Lasers & Optronic*, Nov. 1991.
7. A. Kieżun and L.R. Jaroszewicz, "Światłowodowy układ detekcji fazowo-polaryzacyjnej", Patent PL 177396, 30 Nov., 1999. (in Polish)
8. F. Ratajczyk, "On automatic measurement of birefringent medium properties", *Opt. Appl.* **26**, 227–233 (1996).
9. Y. Shindo, "Application of polarised modulation technique in polymer science", *Opt. Eng.* **34**, 3369–3374 (1995).
10. R.M.A. Azzam and N.M. Bashara, *Ellipsometry and Polarised Light*, North-Holland, Amsterdam, 1977.
11. A. Kieżun, "New polarimetric detection system", *Opto-Electr. Rev.* **5**, 161–166 (1997).
12. J.I. Sakai and T. Kimura, "Birefringence and polarisation characteristics of single-mode optical fibres under elastic deformation", *IEEE J. Quan. Elec.* **QE-17**, 1041–1051 (1981).
13. D. Marcuse, *Theory of Dielectric Optical Wavequides*, New York, Academic Press, 1974.
14. L.R. Jaroszewicz, A. Kieżun, and R. Świłło, "A novel all-fibre ellipsometer", *Proc. SPIE* **3746**, 292–295 (1999).
15. R.C. Jones, "A new calculus for the treatment of optical systems I: Description and discussion of the calculus", *J. Opt. Soc. Am.* **31**, 488–493 (1941).
16. A. Kieżun and L.R. Jaroszewicz, "Polarimetric detection setup for fibre sensors", *Molecular and Quantum Acoustic* **20**, 109–114 (1999).