The interferometric measurement of fiber optic polarizer extincion ratio

Leszek R. Jaroszewicz, Aleksander Kieżun

Institute of Technical Physics, Military University of Technology
ul. Kaliskiego 2, 02-489 Warsaw, Poland

1. Introduction

Polarizing fiber optic elements become commercially obtainable devices nowadays. They are used in coherent telecommunication, as well as in fiber optic sensor systems. The fiber optic polarizer used in those systems may be obtained by different technologies [1 ÷ 3] but usually accomplishes two tasks. First, it polarizes an optical beam emitted by a semiconductor source. Second, it selects one of two polarization modes that propagate in so called single-mode fiber.

This fiber optic element is characterized by the following parameters: losses a defined as a ratio of light intensity on a polarizer output Iout to the input intensity Iin (for linear polarization parallel to the transmission axis of this polarizer) measured in dB:

$$\alpha = 10\log\left(\frac{I_{out}}{I_{in}}\right) \tag{1}$$

and the extinction e defined as a ratio of output maximum intensity I_{max} to output minimum intensity I_{min}:

$$\varepsilon = 10\log\left(\frac{I_{max}}{I_{min}}\right). \tag{2a}$$

In a classic way, those extreme values may be obtained, for instance, by a turn of a polarizer placed behind the studied element. The evaluated extinction may be at the most equal to the extinction of the standard polarizer. The latter value is of order 100 dB for the best volume polarizers [4].

It should be mentioned here that the other definition of extinction ratio is also used. Namely, the extinction is defined as an angle tangent equal to the ratio of shorter to longer axes of polarization ellipse measured behind the polarizer [4]:

$$\tan\varepsilon = \varepsilon = \frac{A_{min}}{A_{max}} \tag{2b}$$

where A_{min} and A_{max} stand for minimum and maximum amplitude of field in the beam behind the polarizer, respectively. As one can see, the best polarizers have extinction $<10^{-5}$ according to this definition [4].

2. The method of estimation of polarizer extinction

In order to estimation of polarizer extinction, an extinction dependence of a drift of fiber optic gyroscope been adopted. This gyroscope is a technical application of the Sagnac interferometer. According to published papers [5] the most fundamental element of the input-output system of the fiber optic gyroscope is the polarizer. Low-frequency disturbances of phase relation between polarization components (characteristic modes of the single-mode fiber) existing in a detection band are direct source of the drift. These disturbances may be eliminated by the polarizer.

Unfortunately, it is not only source of the drift. Slowchange disturbances of external conditions, especially temperature, may also affect on the drift. This effect may be minimized to a level of 0.01 °C/h for $\Delta T < 1$ °C [6]. The Kerr effect, caused by different power levels of waves propagating in opposite directions, is minimized by an application of an input X-type coupler with 50% power division. The effect of an external magnetic field is minimized by a screening of the interferometer.

By making above optimization one can find that the most important factor affecting on the drift level in the Sagnac interferometer-based fiber optic gyroscope in so called minimum configuration (presented in Fig. 1) is a finite level of the polarizer extinction [7].

In the presented system light wave from a semiconductor laser passes by the fiber optic polarizer, which determines one linear polarization state for the propagation in a sensor loop. Then this wave is divided by the coupler into two equal beams propagating in the opposite directions in the sensor loop. These beams are referred in abbreviation as cw and ccw (from clockwise wave and counter-clockwise wave, respectively). An existence of a turn of the sensor loop causes mutual phase shift of these beams, so called Sagnac effect. This phase shift may be determined by a detector after interference beams conjunction in the coupler. The beam returning to the detector passes again by the polarizer. In this way, only this part of the beam, which has the same polarization state as input beam may be extracted. The returning beam is directed to the detector by the coupler connected between the source and the polarizer. The polarization controller system presented in Fig. 1 allows to correct unperfect properties of the sensor loop (it will be described in details later). Phase modulator enables an electronic treatment of the signal by a synchronic detection method.

The optical system acting in such a way may be adopted for studies of polarization properties of fiber optic polarizers as it is described below. For mathematical description we introduce orthogonal coordinates with z-axis parallel to the direction of wave propagation in the single-mode optic fiber (axis along the fiber). We also assume that the light beam going out the source and passing into a fiber optic part of the gyroscope system is described by the Jones vector E_{in} in the form of:

$$E_{in} = \begin{bmatrix} x \\ y \end{bmatrix}, \tag{3}$$

where x and y stand for amplitudes of electric field in two orthogonal directions, perpendicular to the axis of wave propagation, respectively.

On the other hand, the gyroscope loop in case of clockwise wave (cw beam) is described by the Jones matrix in form of:

$$P'_{cw} = \begin{bmatrix} p_{11}(\omega) & p_{12}(\omega) \\ p_{21}(\omega) & p_{22}(\omega) \end{bmatrix}, \tag{4}$$

where indices 1 and 2 correspond to polarization x-mode and ymode of single-mode optic fiber, respectively, while w stands for the a working frequency of the phase modulator.

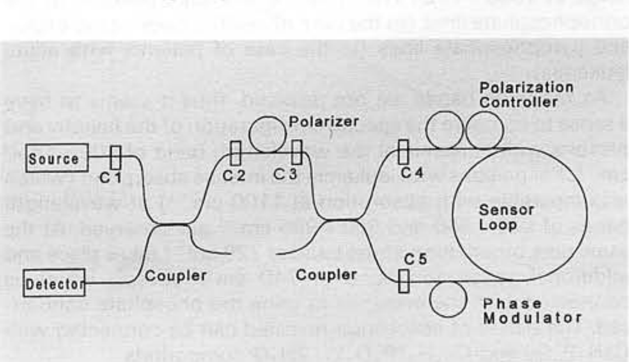

Fig. 1. The minimum configuration of the fiber optic gyroscope based on the Sagnac interferometer; *C1 – C5* – fused connections

For the opposite wave direction (ccw beam) we assume, according to [8], a reversibility of the single-mode fiber, hence:

$$P'_{ccw} = P'^{T}_{cw}. \tag{5}$$

After passing the gyroscope the detected waves that correspond to both propagation directions in the loop (cw and ccw beams) may be described by the following Jones vectors:

$$E_{cw}(\omega) = P'_{cw} e^{j\Delta\Phi/2} E_{in}, \tag{6}$$

$$E_{ccw}(\omega) = P'_{ccw} e^{-j\Delta\Phi/2} E_{in}, \tag{7}$$

where DF stands for the Sagnac phase caused by the rotation.

An interference of waves with amplitudes E_{cw} and E_{ccw}, respectively, produces the detector signal that is a function of the phase shift.

$$\Delta\Phi_D = \arg[<E^{+}_{ccw}(\omega) E_{cw}(\omega)>], \tag{8}$$

where + means Hermite conjungation, while <...> is a time-regard mean value taking into account a spectral distribution of the source.

If the phase is independent on the turn, which is achieved by a proper adjustment of the gyroscope fiber optic loop [9], the phase shift is obtained as an error signal:

$$\Delta\Phi_B = \arg[E^{+}_{in} P'^{+}_{ccw} P'_{cw} E_{in}]. \tag{9}$$

In the above argumentation we have used an identity:

$$P'^{+}_{ccw} = (P'^{T}_{cw})^{*} \tag{10a}$$

and also the fact that elements of Jones matrix of fiber optic gyroscope loop are connected by the following relations:

$$p_{22} = p^{*}_{11},\ p_{21} = -p^{*}_{12}. \tag{10b}$$

In order to study the effect of the polarizer with the extinction e <<1 we describe the polarizer by the Jones matrix that is characteristic for the polarizer with transmission axis parallel to the x-axis:

$$X = \begin{bmatrix} 1 & 0 \\ 0 & \varepsilon \end{bmatrix}, \tag{11}$$

then Jones matrix for cw beam takes the following form [7]:

$$P_{cw} = X^{T} P'_{cw} X \equiv X P'_{cw} = \begin{bmatrix} p_{11} & \varepsilon p_{12} \\ \varepsilon p_{12} & \varepsilon^{2} p_{22} \end{bmatrix}. \tag{12}$$

From this equation one may obtain an expression, which describes the phase error [6]:

$$\tan(\Delta\Phi_B) = \frac{\mathrm{Im}(E^{+}_{we} P^{+}_{ccw} P_{cw} E_{we})}{\mathrm{Re}(E^{+}_{we} P^{+}_{ccw} P_{cw} E_{we})}, \tag{13}$$

which may be transformed to the following form:

$$\Delta\Phi_B = \frac{\mathrm{Im}[\varepsilon(p_{11}p^{*}_{21} - p^{*}_{11}p_{12})xy^{*} + \varepsilon^{2} p_{11} p_{21}(|y|^{2} - |x|^{2})]}{|p_{11}x|^{2} + \varepsilon^{2}|p_{22}y|^{2}} \tag{14}$$

The above dependence shows a relation between phase error DFBand polarizer extinction coefficient e. As one can see, a part of this error is proportional to the e coefficient, while the other part is proportional to its square e_2. Due to high extinction level of fiber optic polarizers studied in the Sagnac interferometer system, terms depending on e_2 may be neglected. Then we obtain:

$$\Delta\Phi_B = \frac{\mathrm{Im}[\varepsilon(p_{11}p^{*}_{21} - p^{*}_{11}p_{12})xy^{*}]}{|p_{11}x|^{*}}, \tag{15}$$

which leads, by the relation (10b) to the form derived by Kinter [9]:

$$\Delta\Phi_B = 2\varepsilon \frac{|y|}{|x|} \frac{|p_{12}|}{|p_{11}|}, \tag{16}$$

where e|y| stands for an amplitude of y-mode extinction by polarizer, while $|p_{12}| = |p_{21}|$ means the amplitude of the wave propagating across the loop along the polarizer x-axis if input wave has been parallel to the y-axis, or vice versa. On the other hand, $|p_{11}|$ means the amplitude of the wave propagating across the loop in x-mode (input and output states are the same).

It is also known that fiber optic gyroscope is described by angular velocity ΔΦ connected with phase shift Ω by the following relation [5]:

$$\Delta\Phi = 2\pi \frac{L \cdot D}{\lambda \cdot c} \kappa \Omega, \tag{17}$$

where L stands for the length of the loop optic fiber, D for the loop diameter, c for light velocity in vacuum, λ for wavelength of the light source and κ for optoelectronic conversion coefficient, which depends on parameters of applied electronic treatment of the signal. Therefore, measured by the system velocity W describes, by Eq. (17), the value of phase shift $\Delta\Phi_B$. The latter parameter is on the base of Eq. (16) a measure of the extinction level of applied polarizer.

Hence, the application of presented system for measurement of extinction level requires an estimation of parameters existing on the right side of the identity (16). Because in the fiber optic gyroscope system, semiconductor lasers coupled with single-mode fiber are used as light sources, one may find from catalogue data that $2\ |y|/|x| \approx 10^{-1}$. The main problem is an estimation of the value of $|p_{12}|/|p_{11}|$ ratio. This problem may be solved by an introduction of the polarization controller (see Fig. 1) which allows for an arbitrary change of the polarization state [10]. In other words, interferometer matrix is modified in such a way that $|p_{12}| = |p_{11}|$. In this case Eq. (16) directly describes extinction level e as the magnitude of phase error. Therefore the limit extinction of the polarizer may be obtained by comparison between Eq. (16) and (17). It should be underlined that used term "limit extinction" means that the extinction of studied polarizer is not lower than obtained by above described method. It is caused by the existence of other sources of phase measurement error (mentioned in the introduction).

3. The measurement of the polarizer extinction ratio

The fiber optic gyroscope system, presented in Fig. 2 and described in details in paper [11], has been applied for studies. Two additional polarization controller systems, in comparison with minimum configuration presented in Fig. 1 have been used in the optical part of a device.

The first polarization controller *PC1*, placed between the *Coup1* and the studied polarizer, allows to obtain maximum adjustment of the input polarization state and the polarizer characteristic and, in this way, minimization of losses in the whole system. The second one *PC3*, placed between the *Coup2*

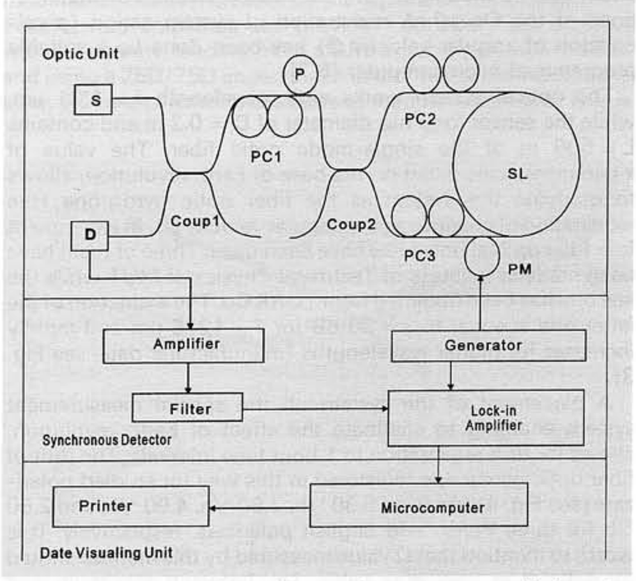

Fig. 2. The scheme of the fiber optic gyroscope applied to the measurement of the extinction ratio of fiber optic polarizer. *PC1 – PC3* – polarization controllers, *S* – source, *D* – detector, *Coup1 – Coup2* – couplers, *SL* – sensor loop, *PM* – phase modulator, *P* – studied polarizer

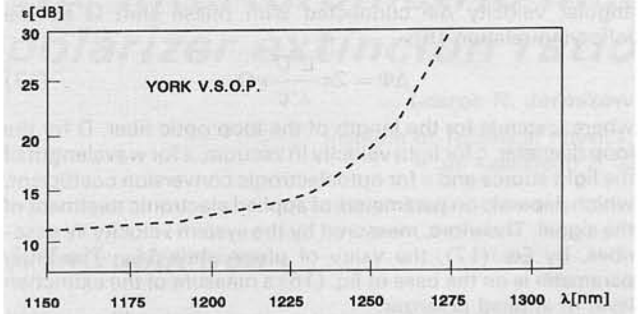

Fig. 3. The dependence of the YORK polarizer extinction on the wavelength (manufacturer data)

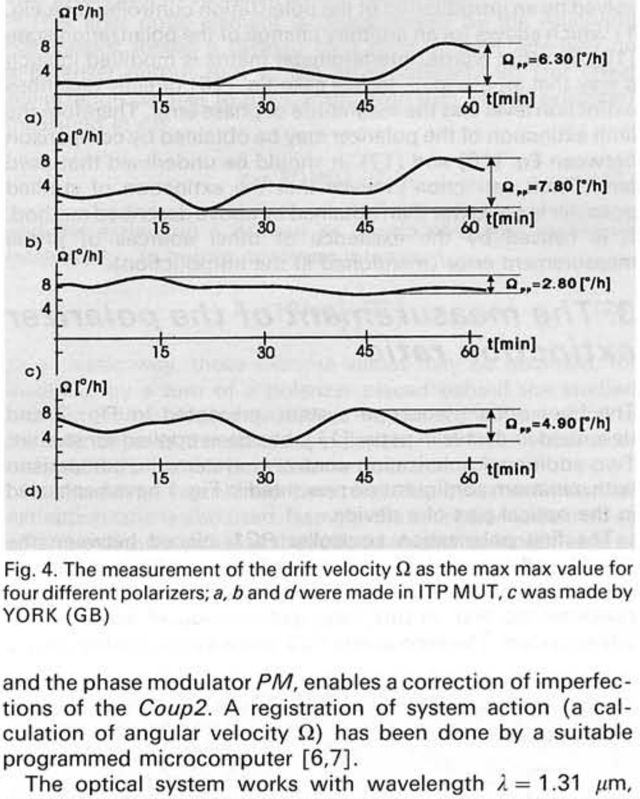

Fig. 4. The measurement of the drift velocity Ω as the max max value for four different polarizers; *a*, *b* and *d* were made in ITP MUT, *c* was made by YORK (GB)

and the phase modulator *PM*, enables a correction of imperfections of the *Coup2*. A registration of system action (a calculation of angular velocity Ω) has been done by a suitable programmed microcomputer [6,7].

The optical system works with wavelength $\lambda = 1.31$ μm, while the sensor loop has diameter of $D = 0.2$ m and contains $L = 500$ m of the single-mode optic fiber. The value of k parameter, calculated on the base of Earth revolution, allows to graduate the system as the fiber optic gyroscope (the registration of changes as the angular velocity Ω). In experiment four fiber optical polarizers have been used. Three of them have been made in Institute of Technical Physics of MUT while the last one has been obtained from YORK Co. The extinction of the latter one is equal to $\varepsilon = 30$ dB for $\lambda = 1275$ nm and rapidly increases for higher wavelengths (manufacturer data, see Fig. 3).

A placement of the system on the special measurement system enabling to eliminate the effect of Earth revolution, allows for drift registration in 1 hour time intervals. The drift of fiber optic gyroscope registered in this way for studied polarizers (see Fig. 4) has been 6.30 °/h, 7.80 °/h, 4.90 °/h, and 2.80 °/h for three Polish and English polarizers, respectively. It is worth to mention that Ω value measured by this method should be defined as max max value, i.e., between maximum and minimum values as it is shown in Fig. 4. Obtained drift values after recalculation on the base of Eq. (17) and (16) give the following values of the extinction level: 33.01 dB, 32.22 dB, 33.98 dB and 36.99 dB, respectively. For those magnitudes the measurement error has been estimated as 0.82 dB, 0.81 dB, 0.85 dB and 0.95 dB, respectively. A quality of band filter, used in the detection part of the system has a crucial effect on this error.

Obtained results are consistent with theoretical expectations and manufacturer measurements. It is worth to mention that the extinction level of Polish polarizers is only twice worse than English polarizer.

4. Summary

The method of extinction level measurement of fiber optic polarizer presented in this work is a new an interesting way to study such the element. The main advantage of this method is a possibility to do measurements in so called in-line system, i.e., without leading out light from the optic fiber. This is especially important in measurements of fiber optic polarizers because their wavelength belongs usually to infra-red range. An application of classic measurement systems involves difficult adjustment of the system. For this reason, approximation method is usually applied, i.e., continuous measurement in the range from 1000 to 1275 nm and then the approximation of obtained curve.

Authors believe that proposed method is the only one allowing for precise estimation of this parameter for wavelength used in fiber optic technology, i.e., 1.30 and 1.55 μm.

This work was supported by Polish State Committee for Scientific Research (Grant No. 2-0173-91-01) and MUT financial support (No. 305). This paper was presented in the poster sesion of NATO Summer-School "Trends in Optical Fibre Metrology and Standards", 27.06-8.07.94, Viana do Castelo, Portugal.

References

1. *J. Hosaka, K. Okamoto, J. Noda*: Single-mode fibre-type polarizer, IEEE J.Quant. Elect., **QE-18** (1982) p.1569.
2. *Yamamoto, T. Kamiya, H. Yanoi*: Characteristics of optical guided modes in multilayer metal-clad planar optical guide with low-index dielectric buffer layer, IEEE J.Quant. Electr., **QE-11** (1975) p. 729.
3. *G. Stewar*: Design of optical polarizers, Proceedings of SIRE Conf, London 1985, p. 9.
4. Optics Guide 5, Melles Griot, Chap. 14, 1991.
5. *R. Ulrich*: Fibre-optic rotation sensing with low drift, Opt .Lett., **5** (1980) p.173.
6. *A. Ostrzyżek*: Doctor Thesis, MUT, Warsaw, 1989.
7. *L.R. Jaroszewicz*: Doctor Thesis, MUT, Warsaw, 1988.
8. *S. Ezekiel, H.J. Ardity*: Fiber optic rotation sensors and related technologies, Springer-Verlag, New York, 1982.
9. *E.C. Kinter*: Polarization control in optical fiber gyroscopes, Opt. Lett., 6, (1981), p.154.
10. *L.R. Jaroszewicz, M. Szustakowski*: The matrix analysis of the polarization transformer, Opt. Applicata, **20** (1990) p. 81.
11. *L.R. Jaroszewicz, A. Ostrzyżek, M. Szustakowski*: The matrix representation of all-fibre gyroscope - numerical calculus and experimental verification, Opto-Electron. Rev., **2** (1993) p. 38.