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"Current – polarization-dependent loss" optical fibre sensor

Abstract. *The study briefly discusses the Faraday magneto-optic effect, design and working principle of the polarimetric current sensor and the polarization-dependent loss. The study presents a concept of a "current – polarization-dependent loss" optical fibre sensor for current measurement in power lines. A method for measuring polarization loss using optical reflectometer is presented. Test results on the effect of GeO2 dopant in a single-mode optical fibre core, wavelength and optical fibre length on the polarization loss are presented. The conclusions on selecting the optical fibre and wavelength in the design of a "current – polarization-dependent loss" optical fibre sensor are formulated.*

Streszczenie. *W pracy krótko scharakteryzowano magnetooptyczne zjawisko Faradaya, budowę i zasadę działania polarymetrycznego czujnika natężenia prądu oraz tłumienie zależne od polaryzacji. Zaprezentowano koncepcję światłowodowego przetwornika „prąd – tłumienie zależne od polaryzacji", który może być wykorzystany do pomiaru natężenia prądu w liniach elektroenergetycznych. Omówiono metodę pomiaru tłumienia polaryzacyjnego przy użyciu reflektometru optycznego. Przedstawiono wyniki badań dotyczących wpływu stężenia molowego domieszki GeO2 w rdzeniu światłowodu jednomodowego, długości fali świetlnej oraz długości włókna światłowodowego na wartość tłumienia polaryzacyjnego. Sformułowano wnioski dotyczące doboru włókna światłowodowego i długości fali świetlnej do realizacji światłowodowego przetwornika „prąd – tłumienie zależne od polaryzacji". (**Światłowodowy przetwornik „prąd – tłumienie zależne od polaryzacji")***

Keywords: optical sensor, optical current sensor, single mode optical fibre, polarization- dependent loss, Farady effect, light polarization, optical time domain reflectometer, Lagrange interpolation
Słowa kluczowe: czujnik światłowodowy, światłowodowy czujnik natężenia prądu, światłowód jednomodowy, tłumienie zależne od polaryzacji, magnetooptyczne zjawisko Faradaya, polaryzacja światła, reflektometr optyczny, interpolacja Lagrange'a

Introduction

For the last several years, polarimetric sensors with optical fibre coil have been used for measuring current in power lines. An advantage of this solution is that the sensors can be installed directly on the phase conductors of the power lines without any interruptions to the current circuit. However, the polarimeter used for measuring the angle of rotation of the plane of polarization (polarisation angle) are expensive.

A polarimetric current sensor with metrological properties as shown in [1,2,3,4] is based on the magneto-optic effect (Faraday effect). The external magnetic field generated by the electrical current flowing through the conductor changes the angle of rotation of the plane of polarization of light transmitted in optical fibre of the sensor coil (Fig. 1.).

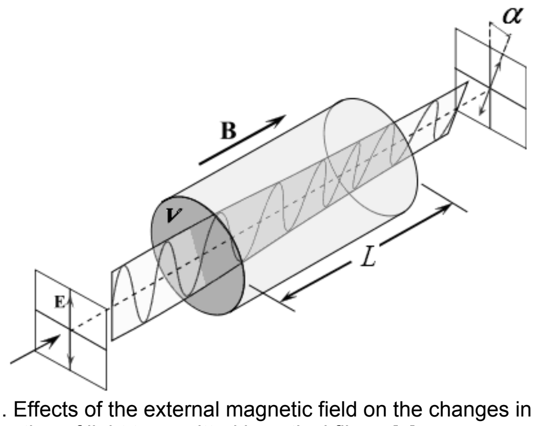

Fig. 1. Effects of the external magnetic field on the changes in polarization of light transmitted in optical fibres [5]

Optical fibre is optically inactive, which means that if no external magnetic field is present, the polarization of light transmitted in optical fibre will not change. It becomes optically active when the external magnetic field is generated – the angle of rotation of the plane of polarization changes in accordance with the following Faraday equation [5,6,17,19,20]:

(1) $$\alpha = V \cdot L \cdot B \ [\mathrm{rad}]$$

where: V – Verdet constant (proportionality factor) $\left[\frac{\mathrm{rad}}{\mathrm{T \cdot m}}\right]$, L – path on which light interacts with the magnetic field $[\mathrm{m}]$, B – magnetic field induction $[\mathrm{T}]$.

The Verdet constant in (1) is an empirical value that represents the material as a proportionality factor between the magnetic constraint and the glass response. For a typical oxide glass – a diamagnetic, the Verdet constant has a positive value and is low [1,2,4,5,6,7,17,19,20]. It is also strongly correlated with wavelength and weakly correlated with temperature [1,2,4,5,6,7,8,9,17,19,20].

For a polarimetric current sensor (Fig. 2.), with an optical fibre coil $L = N \cdot l = N \cdot 2 \cdot \pi \cdot R$, any change in the light polarization angle can be described as [1,2,3,4,5]:

(2) $$\alpha = V \cdot \mu_0 \cdot I \cdot N \ [\mathrm{rad}]$$

where: $\mu_0 = 4 \cdot \pi \cdot 10^{-7} \left[\frac{\mathrm{V \cdot s}}{\mathrm{A \cdot m}}\right]$ – magnetic permeability of vacuum, I – electric current in the conductor [A], N – number of turns in the optical fibre coil.

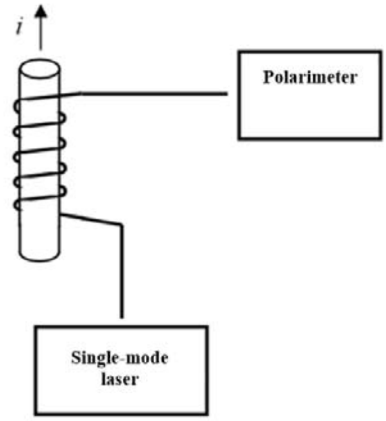

Fig. 2. Block diagram of the polarimetric current sensor with optical fibre coil [10]

As discussed above, the polarimeter used for measuring the angle of rotation of the plane of polarization of light is an expensive instrument increasing the cost of the sensor itself. The cost can be reduced by replacing the polarimeter with an optical time domain reflectometer (OTDR) [11,12,13] to measure the polarization-dependent loss (PDL).

Magnetic field around a conductor, in accordance with the magneto-optical effect (Faraday effect), changes the angle of rotation of the plane of polarization of light transmitted in optical fibre of the sensor coil. It generates a polarization-dependent loss describing the relationship between the introduced losses (transmitted optical signal loss) and the optical signal polarization. The electric current in the phase conductor of the power line can be determined based on the received signal strength (at the sensor output) measurement.

Polarization-dependent loss

Loss is a quantity defining a decrease in electromagnetic power (energy decrease) between two points at a specific wavelength [11,12,14]. If the optical fibre is not affected by the external magnetic field and no waveguide losses occur (macrobendings and microbendings), the total loss is due to the material losses only [11]. If the optical fibre is affected by the external magnetic field, the total loss is an algebraic sum of the material loss and polarization-dependent loss [12].

Polarization-dependent loss of the optical signal describes the level of changes in optical fibre loss at different states of polarization of the transmitted light wave [12]. The total loss at the optical fibre without any waveguide losses can be defined as follows:

$$A = A_M \pm A_{PDL} \text{ [dB]} \quad (3)$$

where: A_M – material loss [dB], A_{PDL} – polarization-dependent loss [dB]. The polarization-dependent loss can also be considered an uncertainty of the total loss measurement.

The most common method to measure the polarization-dependent loss of the optical signal is to evaluate the loss at randomly selected states of polarization, which is a variant of the loss evaluation in all states of polarization (all-states method) [12]. The method has the following properties:

- changes in the optical power at the output of the tested component (optical fibre) with changing states of the output signal polarization are evaluated. The states of light polarization are selected at random,
- a polarization controller (polarizer) with a known angle of rotation of the plane of polarization is installed between the light source (laser) and the tested component (optical fibre),
- loss in the tested component (optical fibre) is measured using an optical reflectometer. A characteristic of the relationship between the loss of the tested component (optical fibre) and the state of polarization (angle of rotation of the plane of polarization) of the transmitted light wave was determined based on the measurement results.

Experimental test results

The tests included a series of measurements of loss in single-mode telecommunication optical fibres (G.652 – standard optical fibre and G.657A1 – resistant to bending optical fibre, according to ITU-T) at different angles of rotation of the plane of polarization of light wave (different states of polarization of optical signal.) The measurements were carried out using Yokogawa AQ7280 optical time domain reflectometer. Polarization of the transmitted light wave was determined using a THORLABS FPC031 fibre polarization controller.

Five angles of rotation of the plane of polarization -90°, -45°, 0°, +45°, +90° were used during the tests. The measurements were carried out for the second optical window (1310 nm) and the third optical window (1550 nm). In accordance with the guidelines for the measurement of the transmission parameters of optical fibres, loss was measured in both directions, and the results were arithmetically averaged [11,12,13], to find the value of optical fibre loss at different angles of polarisation A_α [dB].

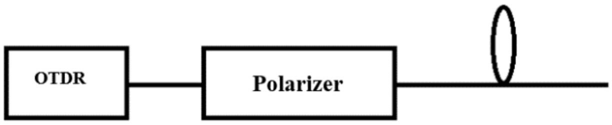

Fig. 3. A diagram of the measuring system for evaluating the effects of angle of rotation of the plane of polarization on the optical fibre loss. Loss measurement using an optical reflectometer – two-point method (TPA or 2PA) [author's own results]

Table 1. Loss measurement results for G.652 optical fibre, length 100 m at different angles of rotation of the plane of polarization for the second and third optical window using optical reflectometer – two-point method (TPA or 2PA) [author's own results]

Angle of rotation of the plane of polarization of light α [°]	Optical fibre loss at different angles of rotation of the plane of polarization of the transmitted light wave [dB]					
	for the second optical window			for the third optical window		
	A_{k1}	A_{k2}	A_α	A_{k1}	A_{k2}	A_α
-90	1.787	2.31	2.049	2.237	2.202	2.220
-45	2.106	2.207	2.157	2.183	2.663	2.423
0	2.544	2.335	2.440	2.308	2.332	2.320
+45	2.211	2.440	2.326	2.460	2.298	2.379
+90	2.035	2.311	2.173	2.214	2.045	2.130

Table 2. Loss measurement results for G.652 optical fibre, length 400 m at different angles of rotation of the plane of polarization for the second and third optical window using optical reflectometer – two-point method (TPA or 2PA) [author's own results]

Angle of rotation of the plane of polarization of light α [°]	Optical fibre loss at different angles of rotation of the plane of polarization of the transmitted light wave [dB]					
	for the second optical window			for the third optical window		
	A_{k1}	A_{k2}	A_α	A_{k1}	A_{k2}	A_α
-90	2.210	2.236	2.223	3.268	3.128	3.198
-45	2.499	2.779	2.639	3.249	3.209	3.229
0	2.353	2.376	2.365	3.245	3.313	3.279
+45	2.258	2.462	2.360	3.274	3.305	3.290
+90	2.320	2.493	2.407	3.235	3.243	3.239

Table 3. Loss measurement results for G.652A1 optical fibre, length 100 m at different angles of rotation of the plane of polarization for the second and third optical window using optical reflectometer – two-point method (TPA or 2PA) [author's own results]

Angle of rotation of the plane of polarization of light α [°]	Optical fibre loss at different angles of rotation of the plane of polarization of the transmitted light wave [dB]					
	for the second optical window			for the third optical window		
	A_{k1}	A_{k2}	A_α	A_{k1}	A_{k2}	A_α
-90	2.318	2.013	2.166	2.403	2.340	2.372
-45	2.172	2.154	2.163	2.226	2.184	2.205
0	2.109	2.017	2.063	2.252	2.393	2.323
+45	2.133	2.274	2.204	2.457	2.165	2.311
+90	1.987	1.978	1.983	2.423	2.386	2.405

The results were normalized to the loss at 0° angle of rotation of the plane of polarization (no effects of the magnetic field on the transmitted light wave) based on an average loss (Table 1÷3) in optical fibre at different angles of rotation of the plane of polarization of the transmitted light wave. The polarization-dependent loss was determined. The following relationship was used:

(4) $A_{PDL\alpha} = A_\alpha - A_0$ [dB]

where: A_α – average optical fibre loss at the angle of rotation of the plane of polarization α [dB], A_0 – average optical fibre loss at the 0^o angle of rotation of the plane of polarization [dB]. Tables 4 to 6 show the results.

Table 4. Polarization-dependent loss measurement results for G.652 optical fibre, length 100 m for the second and third optical window using an optical reflectometer – two-point method (TPA or 2PA) [author's own results]

Angle of rotation of the plane of polarization of light α [°]	Polarization-dependent loss $A_{PDL\alpha}$ [dB]	
	for the second optical window	for the third optical window
-90	-0.391	-0.101
-45	-0.283	0.103
0	0.000	0.000
+45	-0.114	0.059
+90	-0.267	-0.191

Table 5. Polarization-dependent loss measurement results for G.652 optical fibre, length 400 m for the second and third optical window using an optical reflectometer – two-point method (TPA or 2PA) [author's own results]

Angle of rotation of the plane of polarization of light α [°]	Polarization-dependent loss $A_{PDL\alpha}$ [dB]	
	for the second optical window	for the third optical window
-90	-0.142	-0.081
-45	0.275	-0.050
0	0.000	0.000
+45	-0.004	0.011
+90	0.042	-0.040

Table 6. Polarization-dependent loss measurement results for G.657A1 optical fibre, length 100 m for the second and third optical window using an optical reflectometer – two-point method (TPA or 2PA) [author's own results]

Angle of rotation of the plane of polarization of light α [°]	Polarization-dependent loss $A_{PDL\alpha}$ [dB]	
	for the second optical window	for the third optical window
-90	0.103	0.049
-45	0.100	-0.118
0	0.000	0.000
+45	0.141	-0.011
+90	-0.080	0.082

The results (Table 4÷6) were interpolated (Lagrange interpolation) with a quartic polynomial [15,18] to obtain a full characteristic of the relationship between the polarization-dependant loss in the optical fibre and the angle of rotation of the plane of polarization of the transmitted light wave (processing characteristics). The following interpolation polynomials were obtained:

- for G.652 optical fibre, length 100 m and the second optical window:

(5) $$W_{1,II}(A_{PDL\alpha}) = 9{,}455\cdot10^{-9}\cdot A_{PDL\alpha}^4 - 1{,}952\cdot10^{-7}\cdot A_{PDL\alpha}^3 - 1{,}172\cdot10^{-4}\cdot A_{PDL\alpha}^2 + 2{,}273\cdot10^{-3}\cdot A_{PDL\alpha}$$

- for G.652 optical fibre, length 100 m and the third optical window:

(6) $$W_{1,III}(A_{PDL\alpha}) = -9{,}541\cdot10^{-9}\cdot A_{PDL\alpha}^4 - 1{,}829\cdot10^{-9}\cdot A_{PDL\alpha}^3 + 5{,}932\cdot10^{-5}\cdot A_{PDL\alpha}^2 - 4{,}852\cdot10^{-4}\cdot A_{PDL\alpha}$$

- for G.652 optical fibre, length 400 m and the second optical window:

(7) $$W_{2,II}(A_{PDL\alpha}) = -1{,}198\cdot10^{-8}\cdot A_{PDL\alpha}^4 + 6{,}781\cdot10^{-7}\cdot A_{PDL\alpha}^3 + 9{,}094\cdot10^{-5}\cdot A_{PDL\alpha}^2 - 4{,}473\cdot10^{-3}\cdot A_{PDL\alpha}$$

- for G.652 optical fibre, length 400 m and the third optical window:

(8) $$W_{2,III}(A_{PDL\alpha}) = 3{,}760\cdot10^{-10}\cdot A_{PDL\alpha}^4 - 7{,}316\cdot10^{-8}\cdot A_{PDL\alpha}^3 - 1{,}051\cdot10^{-5}\cdot A_{PDL\alpha}^2 + 8{,}204\cdot10^{-4}\cdot A_{PDL\alpha}$$

- for G.657A1 optical fibre, length 100 m and the second optical window:

(9) $$W_{3,II}(A_{PDL\alpha}) = -9{,}551\cdot10^{-9}\cdot A_{PDL\alpha}^4 - 2{,}414\cdot10^{-7}\cdot A_{PDL\alpha}^3 + 7{,}872\cdot10^{-5}\cdot A_{PDL\alpha}^2 + 9{,}389\cdot10^{-4}\cdot A_{PDL\alpha}$$

- for G.657A1 optical fibre, length 100 m and the third optical window:

(10) $$W_{3,III}(A_{PDL\alpha}) = 6{,}574\cdot10^{-9}\cdot A_{PDL\alpha}^4 - 1{,}637\cdot10^{-7}\cdot A_{PDL\alpha}^3 - 4{,}516\cdot10^{-5}\cdot A_{PDL\alpha}^2 + 1{,}509\cdot10^{-3}\cdot A_{PDL\alpha}$$

The characteristics of the relationship between the polarization-dependent loss and the angle of rotation of the plane of polarization of light transmitted in optical fibre as a function of wavelength and optical fibre length (Fig. 4 and 5) were determined for the tested optical fibres in MathCAD based on the quartic Lagrange interpolation polynomials (5÷10).

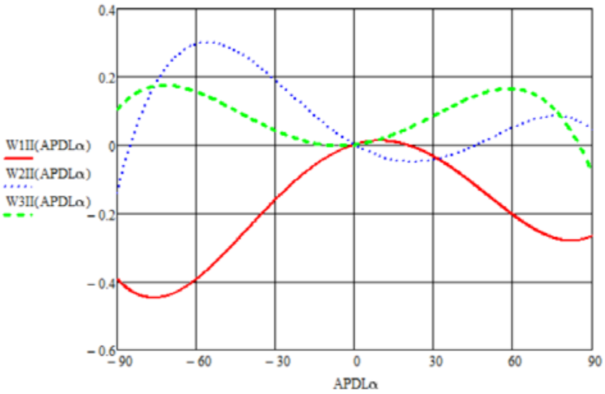

Fig. 4. Polarization loss in optical fibre: G.652, length 100 m – W1II(APDLα); G.652, length 400 m – W2II(APDLα); G.657A1, length 100 m – W3II(APDLα); as a function of angle of rotation of the plane of polarization for the second optical window [author's own results]

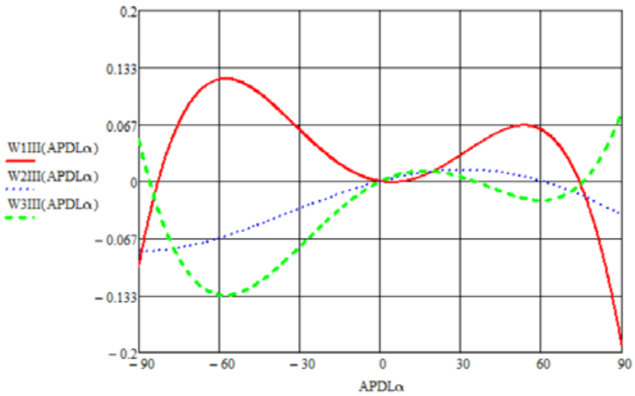

Fig. 5. Polarization loss in optical fibre: G.652, length 100 m – W1III(APDLα); G.652, length 400 m – W2II(APDLα); G.657A1, length 100 m – W3II(APDLα); as a function of angle of rotation of the plane of polarization for the third optical window [author's own results]

Conclusions

The test results showed that the optical fibre loss depends on the material used (material loss) and the polarization of the transmitted light (polarization-dependent loss).

The analysis of the characteristics (Fig. 4 and 5) show that the polarization-dependent loss depends on the wavelength (optical window), optical fibre length and the optical fibre standard (GeO_2 dopant content in the core.) The following relationships can be determined:

- for the optical fibre standard (G.652), an increase in optical fibre length increases the polarization loss at constant wavelength,
- for the optical fibre standard (G.652 or G.657A1), an increase in wavelength decreases the polarization loss at constant optical fibre length,
- for different optical fibre standards, an increase in GeO_2 molarity in the optical fibre core (G.652 – 4.582 M%, G.657A1 – 3.617 M% [2, 16]) increases the polarization loss at constant wavelength and constant optical fibre length.

It shows that the polarization loss can be used in the design of “current - polarization-dependent loss” optical fibre sensors. The polarization losses are determined using a reflectometric method presented in the study.

The polarization loss and the angle of rotation of the plane of polarization of light transmitted in optical fibre must be determined based on the performance characteristics of the sensor to measure the current. The angle, in accordance with the Faraday magnetic-optical effect depends on the current, Verdet constant for the optical fibre and the optical fibre length. The measured current can be determined using a modified equation (2).

Table 7. Verdet constant for single-mode optical fibres for the second and third optical window [1,2,4,5,16]

Single-mode optical fibre standard	**Verdet constant for single-mode optical fibre** $V\left[\frac{\mathrm{rad}}{\mathrm{T\cdot m}}\right]$	
	for the second optical window	**for the third optical window**
G.652	4.3784	5.4579
G.657A1	4.3716	5.4498

The polarization loss measurement accuracy depends on the accuracy of the optical refractometer. Also, the polarization must be identified when measuring the alternating currents. The analysis of the characteristics (Fig. 4 and 5) shows that in the second optical window, the measurements can be carried out using 100 m long G.652 optical fibre and 400 m long G.652 optical fibre. For the third optical window, the measurements can be carried out using 400 m long G.652 optical fibre and 100 m long G.657A1 optical fibre. In both cases, the optical fibre length must be chosen in accordance with (2) to obtain the angle of rotation of the plane of polarization between approx. -15^{o} (-0.262 rad) to approx. $+15^{o}$ (+0.262 rad).

During construction of the “current – polarisation-dependent loss” optical fiber sensor, its processing characteristic should always be determined, because this type of characteristic is not standardized for this type of sensors.

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