UNIWERSYTET TECHNOLOGICZNO-PRZYRODNICZY
IM. JANA I JĘDRZEJA ŚNIADECKICH W BYDGOSZCZY
ZESZYTY NAUKOWE NR 257
ELEKTROTECHNIKA 15 (2010) 67-74

USING G.652 TELECOMMUNICATION SINGLE-MODE OPTICAL FIBER FOR A MEASUREMENT COIL OF THE INTERFEROMETRIC CURRENT SENSOR

Sławomir Andrzej Torbus

University of Technology and Life Sciences
S. Kaliskiego 7, 85-796 Bydgoszcz
e-mail: slator@utp.edu.pl

Summary: This article describes benefits of using a G.652 telecommunication optical fibre instead of a multi-mode optical fibre for a measurement coil of the interferometric current sensor. The simulation results were presented for coils with various numbers of turns and made of various optical fibres – a single-mode and multi-mode fibre.

Keywords: Verdet constant, mangeto-optical phenomenon, interferometric current sensor, optical fiber current transformer, single-mode optical fiber, multi-mode optical fiber

1. PHYSICAL PRINCIPLES OF INTERFEROMETRIC CURRENT SENSOR OPERATION

The sensor operation is based on an analysis of the properties of a light wave that propagates through the optical fibre and is transformed when subjected to an external magnetic field generated by a live conductor – energy line.

Optical fibres are not optically active when not exposed to an external magnetic field but become active when a magnetic field is applied – the plane of polarization of a light beam is rotated by a certain angle, this is so-called **Faraday effect** (Fig. 1).

This mangeto-optical phenomenon was discovered by Faraday and described with the following formula [1]:

$$\alpha = V \cdot L \cdot B \tag{1}$$

where:

α – the angle of the plane of polarization rotation [rad],

V – the Verdet constant (proportionality constant) $\left[\frac{\mathrm{rad}}{\mathrm{T \cdot m}}\right]$,

L – the length of the path where the light and the magnetic field interact [m],

B – magnetic flux density $[\mathrm{T}]$.

The Verdet constant in the formula (1) is an empirical value that characterizes the material of the medium as a constant of proportionality between the magnetic excitation and the reaction of glass. Standard types of oxide-based glass – diamagnetic materials have positive and low Verdet constants [1]. Also, as far as diamagnetic materials are concerned, the constant depends to a large extent on the length of a light wave, and to a small extent on the temperature [1].

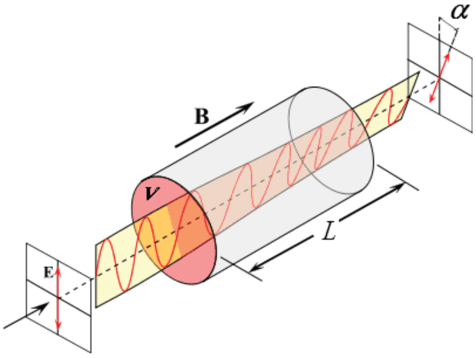


Fig. 1. The influence of an external magnetic field on a change of light polarization [2]

It is possible to describe the relationship between the current in the electric conductor and a change of polarization angle for a single coil of optical fibre with the length of $l = 2 \cdot \pi \cdot R$, where: R – the distance between a fibre coil and the centre of the live conductor (fibre curl radius). In order to do so, the Ampère law must be applied in the integral form:

$$I = \oint_{l=2\cdot\pi\cdot R} H dl = H \cdot l = H \cdot 2 \cdot \pi \cdot R \tag{2}$$

where:

I – current [A],

H – magnetic field strength $\left[\frac{\mathrm{A}}{\mathrm{m}}\right]$.

For a dielectric medium such as a telecommunication fibre, the relationship between the induction and the magnetic field strength may be defined as follows:

$$B = \mu_0 \cdot H \tag{3}$$

where:

$\mu_0 = 4 \cdot \pi \cdot 10^{-7} \left[\frac{\mathrm{V \cdot s}}{\mathrm{A \cdot m}}\right]$ – permeability of vacuum.

On the basis of the above formulas (2) and (3) the following relationship may be described:

$$B = \frac{\mu_0 \cdot I}{2 \cdot \pi \cdot R} \tag{4}$$

The modification of formula (1) using formula (4) shows that for a sensor fitted with an optical fibre with the length of $L = N \cdot l = N \cdot 2 \cdot \pi \cdot R$ a change of light polarization angle may be described with the following relationship:

$$\alpha = V \cdot \mu_0 \cdot I \cdot N \tag{5}$$

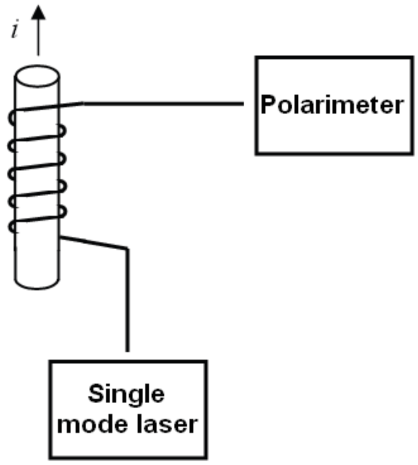


Fig. 2. A block diagram of interferometric fibre sensor

A physical optical waveguide (fibre waveguide, optical fibre) used to construct a measurement coil of the interferometric sensor is made of two layers of silica – SiO_2 that differ in the refractive index. The internal, centrally located layer of glass known as the core is covered by a tightly fitted layer of glass known as the cladding. The core has a higher refractive index – n_1 than the surrounding layer – the cladding with the refractive index – n_2, so that transmission can be carried out on the basis of total internal reflection. Core and cladding diameters of single-mode fibres are standardized. Depending on the type of optical fibre, these are respectively: 5 ÷ 11 µm/125 µm; the diameter of the core of a standard telecommunication fibre is 8 ÷ 9 µm – a standard G.652 step-index profile optical fibre [3]. The standardized diameter of the core of a multi-mode fibre is 50 µm or 62,5 µm, whereas the diameter of cladding is the same as for single-mode fibres – 125 µm.

2. SELECTION OF OPTICAL FIBER FOR A MEASUREMENT COIL OF THR INTERFEROMETRIC CURRENT SENSOR

After determining a polarization angle α with the polarimeter measurement, the equation (5) may be used to determine the current intensity:

$$I = \frac{\alpha}{\mu_0 \cdot V \cdot N} \tag{6}$$

The value of current I (6) is influenced by the Verdet constant V – a parameter characteristic of the type of optical fibre used for the construction of a sensor, and it is described by the Becquerel equation [1]:

$$V = \frac{1}{2} \cdot \frac{e}{m_e} \cdot \frac{\lambda}{c} \cdot \left| \frac{\partial n}{\partial \lambda} \right| \tag{7}$$

where:

$\frac{e}{m_e}$ – specific electronic charge ($1{,}75881962 \cdot 10^{11} \left[\frac{\mathrm{C}}{\mathrm{kg}} \right]$),

λ – wave length $[\mu\mathrm{m}]$,

c – speed of light in vacuum ($c \approx 3 \cdot 10^{8} \left[\frac{\mathrm{m}}{\mathrm{s}} \right]$),

$\left| \frac{\partial n}{\partial \lambda} \right|$ – absolute value of a change of refractive index in relation to wave length $\left[\frac{1}{\mu\mathrm{m}} \right]$.

In the formula (7), $\left| \frac{\partial n}{\partial \lambda} \right|$ is the most interesting element as far as the type optical fibre is concerned, since it describes changes of the refractive index in the core. Those changes may be determined on the basis of the Sellmeier equation [4]:

$$n^2 = 1 + \sum_{i=1}^{3} \frac{a_i \cdot \lambda^2}{\lambda^2 - b_i^2} = 1 + \frac{a_1 \cdot \lambda^2}{\lambda^2 - b_1^2} + \frac{a_2 \cdot \lambda^2}{\lambda^2 - b_2^2} + \frac{a_3 \cdot \lambda^2}{\lambda^2 - b_3^2} \tag{8}$$

where:

a_i, b_i – constants [μm] established empirically for a specific type of glass.

In case of GeO_2 doping, the percentage of the molar concentration of the dope results in an increase of the refractive index in relation to the refractive index of pure glass and therefore the doping is used for the core. The value of indexes a_i and b_i used in the formula (8) for pure silica SiO_2 and for doped silica, depending on the GeO_2 molar concentration are shown in Table 1 [4].

Concentration of GeO_2 dope in the core of standard G.652 telecommunication fibres is approximately 3,1 M%; these are fibres with step-index profile. The concentration of the GeO_2 dope is higher in optical fibres with a more complex refractive index profile (G.653, G.655). The analysis of a multi-mode optical fibre was based on the data from reference sources, namely the Verdet constant for a specific length of a wave [5] ($\lambda = 0{,}63$ μm, V = $4{,}6 \cdot 10^{-6} \ \frac{\mathrm{rad}}{\mathrm{A}} = 3{,}6624 \ \frac{\mathrm{rad}}{\mathrm{T} \cdot \mathrm{m}}$).

Table 1. Indexes a_i and b_i used in the formula (8) [4]

Factors	SiO_2	GeO_2			
		3,1 M%	**5,8 M%**	**7,9 M%**	**13,5 M%**
a_1	0,6961663	0,7028554	0,7088876	0,7136824	0,711040
a_2	0,4079426	0,4146307	0,4206803	0,4254807	0,451885
a_3	0,8974994	0,8974540	0,8956551	0,8964226	0,704048
b_1	0,0684043	0,0727723	0,0609053	0,0617167	0,064270
b_2	0,1162414	0,1143085	0,1254514	0,1270814	0,129408
b_3	9,8961610	9,8961610	9,8961620	9,8961610	9,425478

The value of the derivative relevant for the analysis, following union generalization, has the following form:

$$\frac{\partial n}{\partial \lambda} = -\frac{\displaystyle\sum_{i=1}^{3} \frac{a_i \cdot b_i^2 \cdot \lambda}{\left(\lambda^2 - b_i^2\right)^2}}{\sqrt{1 + \displaystyle\sum_{i=1}^{3} \frac{a_i \cdot \lambda^2}{\lambda^2 - b_i^2}}} \tag{9}$$

where:

a_i, b_i – constants [μm] established empirically for a specific type of glass.

With the derivative of the refractive index in relation to the wavelength (9), its value for a specific wavelength λ may be determined, using data shown in Table 1 for molar concentration GeO_2 at 3,1 M%.

Table 2. Values of the derivative of the refractive index in relation to the wavelength

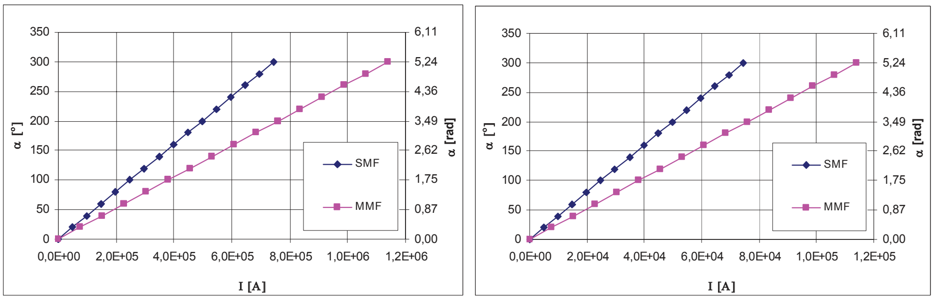
λ	$\frac{\partial n}{\partial \lambda}$ **for the silicon doping** GeO_2 $\left[\frac{1}{\mu m}\right]$
	3,1 M%
0,63 μm	$-0{,}30286 \cdot 10^{-2}$

Using the formula (7) and results of calculations shown in Table 2, the Verdet constant may be determined depending on the wavelength and the molar concentration of the GeO_2 dope in the core of a single-mode fibre. The calculation results obtained for standard wavelengths used for the transmission in single-mode telecommunication optical fibres are shown in Table 3.

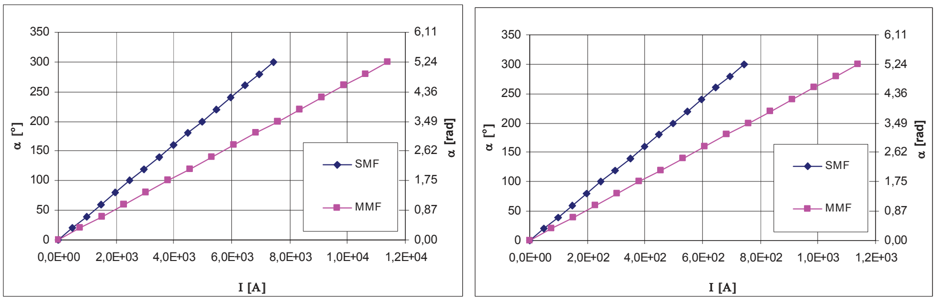
Table 3. Values of the Verdet constant depending on the wavelength and the molar concentration of the GeO_2 dope

λ	V **for the silicon doping** $\mathbf{GeO_2}\left[\frac{\mathrm{rad}}{\mathrm{T\cdot m}}\right]$
	3,1 M%
0,63 µm	5,5932

Having the parameters of the coil made of a single-mode or multi-mode fibre (sensor) – the number of turns of the coil *N*, the Verdet constant of the fibre *V* as well as a measured polarization angle α, it is possible, on the basis of the formula (6), to determine the current in the tested power line. The influence of the above-mentioned parameters of the sensor was determined on the basis of simulations; results of these simulations are presented on diagrams $\alpha = f(I)$.



λ = 0,63 µm and $N = 1$ λ = 0,63 µm and $N = 10$



λ = 0,63 µm and $N = 100$ λ = 0,63 µm and $N = 1000$

Fig. 3. Characteristics $\alpha = f(I)$ depending on optical fibre used and the number of turns of the coil *N*

6. CONCLUSIONS

The new IEC 61850 standard [6] requires that communication in the power system protection and control and monitoring systems of substations is based on communication protocols that comply with the standard. For that purpose, also current transformers must be fitted with ports that enable digital communication with elements of the power system protection and the control and monitoring system. Therefore, it is necessary to seek innovative solutions for protection systems characterized by a quick and precise operation, a simple realization and a possibility to locate these systems in individual segments of the power system and even on individual lines. This is fostered by the progress in fibre-optics, in particular the development of optical fibre sensors and measurement transducers. The subject of the interferometric sensor with a measurement coil made of single-mode G.652 fibre is of relevance at the moment.

In conclusion, the following rules for selection of a single-mode optical fibre, in particular a G.652 fibre, to be used in interferometric current sensor may be formulated:

- the sensor design must eliminate macrobendings [7] that could significantly impair measurements. When constructing a measurement coil of the sensor the above-mentioned recommendations related to telecommunication fibres must be followed. For the G.562 optical fibre, it may be assumed that the length of one turn of 23,6 cm will eliminate the influence of macrobendings,
- if the sensor sensitivity is defined as its capability to detect possibly low currents with specified parameters of the sensor (the number of turns of the coil, the wavelength or the angle of polarization rotation), the use of a measurement coil made of a single-mode G.652 fibre instead of a multi-mode fibre will enhance the sensitivity [8],
- the number of turns of the coil influences the sensitivity. Proportionally to the number of coil turns (6) the sensitivity of the sensor increases, regardless of whether or not the measurement coil is made of a G.652 single-mode fibre or a multi-mode fibre. Therefore, very low currents should be measured by sensors with a very high number of coil turns [8].

BIBLIOGRAPHY

[1] Romaniuk R., 2008. Szkło nieliniowe dla fotoniki. Część 5. Szkła Verdeta-Faradaya. Elektronika 10.
[2] http://pl.wikipedia.org/wiki/Zjawisko_Faradaya.
[3] Recommendation ITU – T G.652: Characteristics of a single – mode optical fibre and cable. 03/2003.
[4] Majewski A., 1991. Teoria i projektowanie światłowodów. WNT Warszawa.
[5] Kaczmarek Z., 2006. Światłowodowe czujniki i przetworniki pomiarowe. Agenda wydawnicza PAK Warszawa.
[6] Lizer M., Szweicer W., Wróblewska S., 2010. Elektroniczne przekładniki pomiarowe – założenia normy i przegląd rozwiązań technicznych. Automatyka elektroenergetyczna 1.
[7] Ratuszek M., 2002. Analiza pomiarów reflektometrycznych sieci światłowodowych dla poszerzonego zakresu długości fal pomiarowych λ = 1310, 1410, 1450, 1550, 1625 nm. Krajowe Symp. Telekomunikacji, Bydgoszcz.
[8] Torbus S.A., Ratuszek M., 2010. The selection method of the single mode telecommunication fiber to the interferometric current sensor depending on the destination areas. SPIE, Wilga.

ZASTOSOWANIE JEDNOMODOWEGO ŚWIATŁOWODU TELEKOMUNIKACYJNEGO G.652 DO REALIZACJI CEWKI POMIAROWEJ W INTERFEROMETRYCZNYM CZUJNIKU NATĘŻENIA PRĄDU

Streszczenie

W artykule pokazano, że preferowane jest stosowanie standardowego światłowodu telekomunikacyjnego G.652 do wykonania cewki pomiarowej interferometrycznego czujnika natężenia prądu, zamiast światłowodu wielomodowego. Przedstawiono wyniki symulacji dla cewek o różnej liczbie zwojów i różnych wartości natężenia prądu dla dwóch różnych typów włókien światłowodowych – jednomodowego i wielomodowego.

Słowa kluczowe: stała Verdeta, zjawisko magnetooptyczne Faradaya, interferometryczny czujnik natężenia prądu, światłowodowy przekładnik prądowy, światłowód jednomodowy, światłowód wielomodowy