

Optical fibre current sensor for electrical power engineering

K. BARCZAK*

Department of Optoelectronics, Silesian University of Technology, 2 Krzywoustego St., 44-100 Gliwice, Poland

Abstract. The paper presents the experimental results of the investigations of optical fibre current sensors with an external transformation. The head of the sensor is made of the glass which has a high value of the Verdet constant. The sensor was built on the glass bar (with high value of the Verdet coefficient), polarisers, plastic optical fibres, a light source and a detector module. The paper deals with magnetic field measurements of two types of electrical current conductors: a typical conductor with circular cross-section and a busduct. Output signals from the optical current sensor were displayed on the digital oscilloscope and memorized in μ Comp for a further analysis. This type of sensor was investigated on a laboratory stand and on an electrical power line which included conductor where the high intensity electric current flow. The constructed optoelectronic current sensor was tested for detection of current with intensity of the order of 200 A, with an accuracy of a few percent. Practically, the upper border of the current detection by means of this sensor is much higher.

Key words: the magneto optic effect, optical fiber current sensors, polarimetric sensors.

1. Introduction

Systems of electrical power automatic control engineering are subjected to incessant changes and modifications. Due to the development of analogue and digital electronics nowadays the most modern devices of these systems are just digital devices. Also electric transducers of measured quantitative have undergone qualitative changes. Optical transformers of the current making use of the magneto optic phenomenon belong to the unconventional transformers. Presently, they are being more and more implemented in electric power systems. Measurement signals, after their optical detection are the voltage signals with a low values and can be easily transformed into digital form. This is a considerable advantage of digital devices in automatic control engineering. The presented paper suggests applying optical fibre sensors of the magnetic field with external transformation as measurement sounders of the optoelectronic current transformer. Such sensors have been successfully investigated and produced for already two years at the Department of Optoelectronics at the Silesian University of Technology in Gliwice, Poland. The idea of applying optical fibre sensors of the magnetic field with external transformations using new magneto optic materials is a new approach to this problem. The development of optoelectronic transformers of the current basing on new optical materials characterized by adequate magneto optic properties require the combined endeavours of experts dealing with power measurements and those dealing with optical sensors. The aim of the investigations is to construct a prototype of a device which may be adapted to controlling systems in order to assess its actual possibilities of being applied in power automatic control engineering.

2. Optical fibre magnetic field sensor with external transformation – development and investigation

An optoelectronic transformer is a device, whose measurement head is constructed entirely of insulating materials (organic glass and polymers). The structure of the measuring probe of the transformer is similar to that of the so-called electrical current sensors [1] applied in electrical power engineering (Fig. 1), in which air coils or based on open ferromagnetic coils are used. The principle of their operation is based on inducing voltage in the coil, affected by the magnetic field arising around the conductor due to the current passing in it. Such a solution permits to simplify the construction of the transformer, because the insulation ensures a sufficient distance between the coil and the conductor of the current. The necessity of the keeping such a distance between the coil and the conductor of the current involves two undesirable effects:

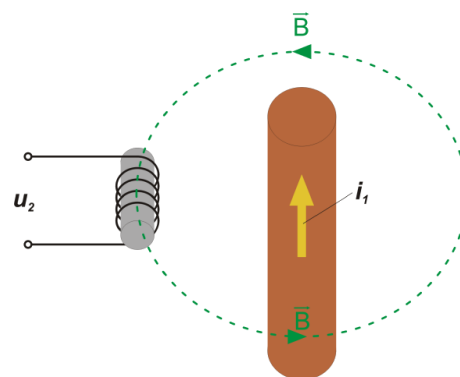


Fig. 1. Current sensor based on open ferromagnetic coils

*e-mail: kamil.barczak@polsl.pl

- reduces its sensitivity and
- increases the share of magnetic fields resulting from other currents flowing in its vicinity.

This is of still more importance in three phase currents, for which the transformers are designed.

The optoelectronic transformers are deprived of these restrictions. The optical measuring probes may be placed rather close to the conductors of the current, without disturbing the distribution of the magnetic fields. Consisting fully insulating material, the optical transformers warrant operational safety. There is still another advantage resulting from the application of the optoelectronic transformers, viz. the possibility of non-invasive measurements. The idea of constructing a measuring probe for the optoelectronic current transformer is to be seen in Fig. 2.

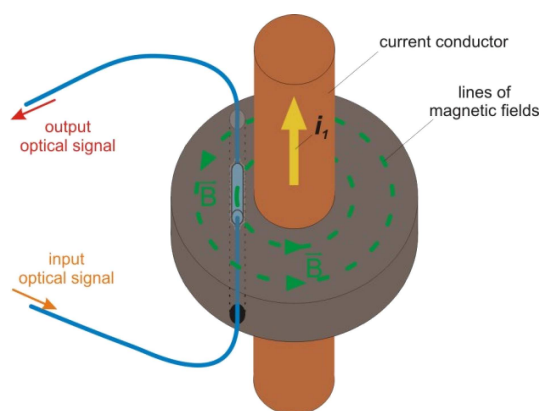


Fig. 2. Optical fiber measurement probe for optoelectronic current transformers

The subject matter concerning current transformers in electrical power engineering has dealt with world-wide literature [1, 2].

Current transformers are used to measure primary currents in electric power systems. Without the knowledge of the instantaneous primary current it is impossible to control the power system and to protect it in the case of a failure. Transformers provide fundamental information about the state of operation of the whole system and its respective elements. Literature provides information concerning many investigations dealing with the topic of optoelectronic current transformers and voltage covering the last forty years [3, 4]. Up to now, however, a so-called “optical current transformer” has been realised by only some firms world-wide. Its application in a real energy system is still rare [5, 6]. The existing solutions are focused on the application of optical fibres as sensor elements in measurement systems. It has also been suggested to take measurements in the systems optical sensors with external transformation [7, 8]. Thanks to the continuous progress, including systems automatic control engineering in electrical power engineering, optical fibre sensors are becoming more and more popular. Their future share in power systems will depend on their metrological properties, their price, simplicity and compatibility with traditional devices ensuring safety.

Important advantages of waveguide sensors applied in electrical power engineering are their following properties:

- non-electrical output signal, providing information about the measured quantity,
- the possibility of application in difficult atmospheric conditions,
- the possibility of non-invasive (remote) measurements,
- inconsiderable geometrical dimensions and small mass,
- insensibility to disturbances in the electromagnetic field,
- the possibility of cooperation optical fibre systems applied in communication.

At the Department of Optoelectronics at SUT for more than ten years investigations have been under way concerning magneto-optically sensitive waveguides [9–19]. For two years already investigations have been run concerning so-called volumetric optoelectronic sensors of the magnetic field with optical fibre inputs [16]. Sensors of this kind are classified as so-called waveguide sensors with external transformation [15,20].

Actually both sensors with internal and external transformation are being intensive developed [18–24]. In the case of sensors with internal transformation the magneto-optically sensitive element is the optical fibre itself. In the case of sensors with external transformation, however, the magneto-optically sensitive element is the volumetric element consisting of magneto-optical glass. As far as sensors of the magnetic field are concerned, in recent years investigations have been focused mainly on sensors with external transformation. The latest fundamental results of investigations [20, 21, 23] indicate promising properties of sensors in which special kind of glass have been used. These investigations (Fig. 3) are being carried out at the Department of Optoelectronics and Lighting Technology at the Bialystok University of Technology, (Poland).

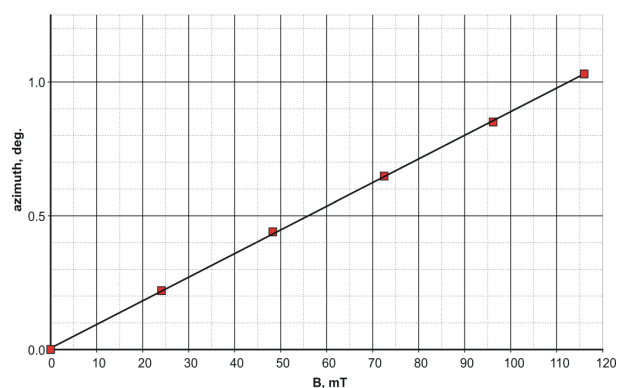


Fig. 3. Exemplary measurements of the magneto-optic effect in glass, applied in a waveguide sensor of the magnetic field

An optical fibre sensor of the magnetic field with external transformation was successfully applied in investigations concerning the distribution of the magnetic fields in electromagnetic devices [16]. The structure of this sensor and its corresponding investigations has been presented in Fig. 4.

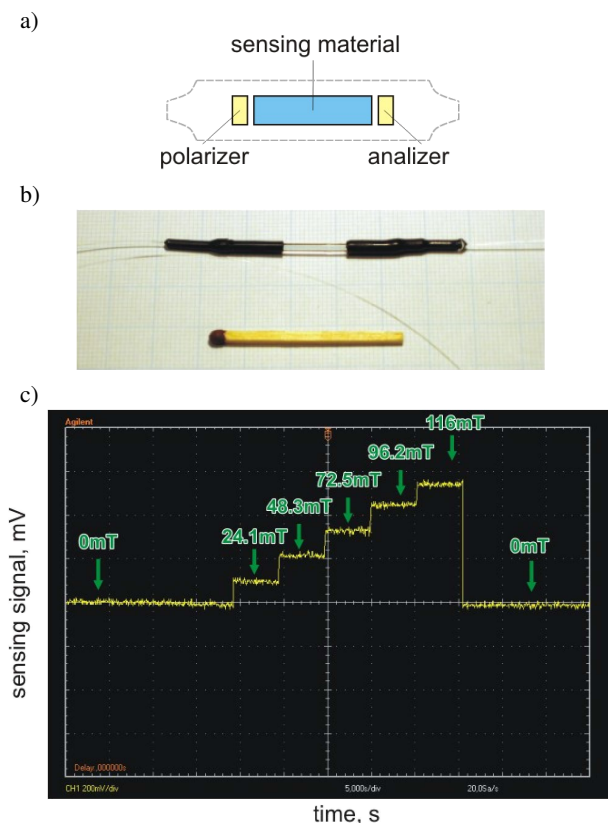


Fig. 4. Optical fibre sensor of the magnetic field with external transformation constructed at the Department of Optoelectronics at SUT. a) diagram of the structure; b) view of the sensor; c) signal from the sensor as a function of the external magnetic field

Some type of these sensors have been constructed, differing from each other in the way of excitation and the magneto-optically sensitive material.

3. Optical fibre current sensors with external transformation

In the presented solutions, specially elaborated glass characterized by a high value of the Verdet constant was applied. The search for glass matrices warranting adequate magneto-optic properties resulted in the selection of many glass-creating materials. The most promising ones include glass on the groundmass (matrix) of the oxides of heavy metals – HMO (Pb, Bi) as well as telluric glass. The choice of these materials results from the higher optical polarizability of ions of heavy metals [15, 21–23].

Basing on experience gathered in the course of investigating of the magnetic field sensors, a test probe was constructed for measurements of the electrical current in a conductor (Fig. 5).

Analyses of the distribution of the magnetic field around the conductor with electrical current has shown that for values of the current intensity equal to 1000 A values of the magnetic induction B in the area of the sensor amounts to about 10 mT. The prepared measurement head had been previously tested with using a current exciter in the laboratory of the firm Energopomiar-Elektryka in Gliwice.

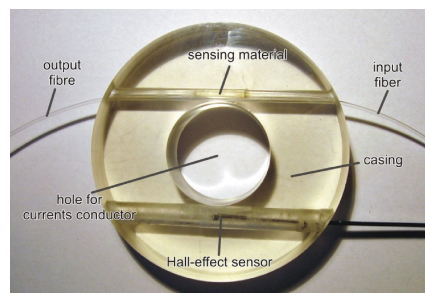


Fig. 5. Probe for the measurements of electrical current containing an optical magnetic field sensor with external transformation

The optical magnetic field sensor with external transformation was also tested in laboratory conditions at the Department of Optoelectronics at SUT. The test stand comprises an air-core coil, and autotransformer, a light source, a photodetector and a digital oscilloscope (Fig. 6). At this stage of investigations special systems were accomplished with a light source and a photodetector adapted for work with magneto-optic sensors provided with waveguide inputs. These elements were placed in compact and light casings. Such solutions increased the portability of the whole measurement system, which permitted to carry out measurements in conditions approximate to actual ones. The elaborated sensors were tested in an alternating magnetic field, the source of which was a air-core coil supplied with alternating current from an electrical supply network (50 Hz). Figure 7 illustrates an exemplary signal sent out by the optical sensor as well as the signal flowing through the coil.

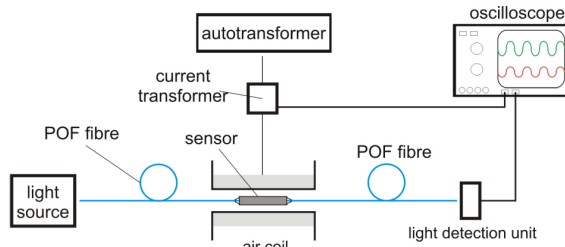


Fig. 6. Scheme of the test stand for measurements of optical magnetic field sensor, the alternating magnetic field displaying a frequency of 50 Hz

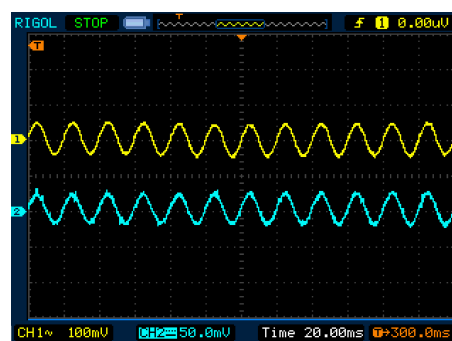


Fig. 7. Investigations concerning a optical magnetic field sensor with external transformation in an alternating magnetic field with the value 11 mT and network frequency. The first channel (upper signal, in yellow colour) – voltage signal from the sensor, the second channel (bottom signal, blue) – signal of the current in the coil from the shunt 10 m Ω

The maximum rms value of induction of the magnetic field amounted to 11 mT.

Reiterated investigations carried out in this system proved an absolute repeatability of measurements. The response time of the sensor to change of the magnetic field with a power network frequency is almost instantaneous. The physical mechanism of the magneto-optic phenomenon indicates that the response times do not exceed 10^{-9} sec. Thus, both the second and the fifth harmonic of the current flow (important in electroenergetic systems) can be measured without deformations and without any delay.

Due to the geometry of the optical sensor, its finite geometrical dimensions, the distribution of the magnetic field around the live conductor had to be analyzed. The aim of these analyses was to choose the seal wire with the proper geometry. The chosen seal wire had a rectangular cross-section. Conductor with a circular cross-section was also considered (Fig. 8). Figure 8a presents the distribution of the magnetic field along the axis "x", situated crosswise to the busway at a distance of 1 mm above it (Fig. 8b). The diagram in Fig. 8c presents for the sake of comparison the distribution of the magnetic fields

along the axis "x" situated transversely to a circular conductor (Fig. 8d). For the sake of comparison the distance of the axis "x" from the conductor was assumed to be 7.3 mm, basing on the assumption that the axis "x" is situated 1 mm above the conductor (with the same cross-section).

The diagram 8a and 8c show that the conductor with a rectangular cross-section generates a more uniform value of the component tangent to the axis "x" of the magnetic field, than the circular conductor. It is that component of the magnetic field which is responsible for the Faraday effect in the sensory material situated along the axis "x". Conclusions drawn from this analysis resulted in the elaboration of a somewhat modified head of the sensor together with a special holder for the busway. The modified sensor is shown in Fig. 9.

The sensor head prepared in this way tested in the laboratory, applying a seal wire in form of a busway (with rectangular cross-section). The measurements concerned currents within the range from 240 A to 600 A root-mean-square value. The seal wire operated under short-circuit conditions, i.e. at low (safe) voltages. The test stand is presented in Fig. 10. Its block diagram is similar to the diagram shown in Fig. 6.

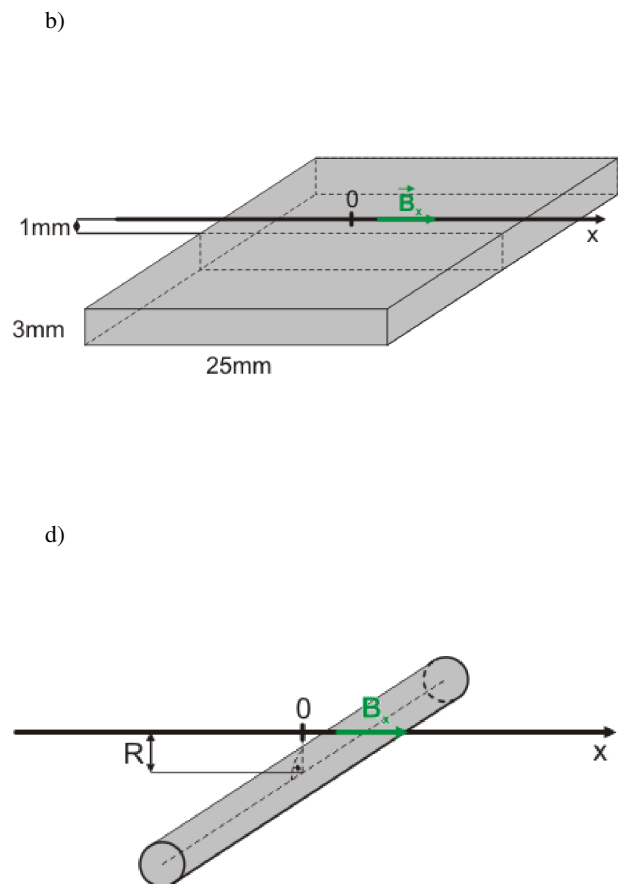
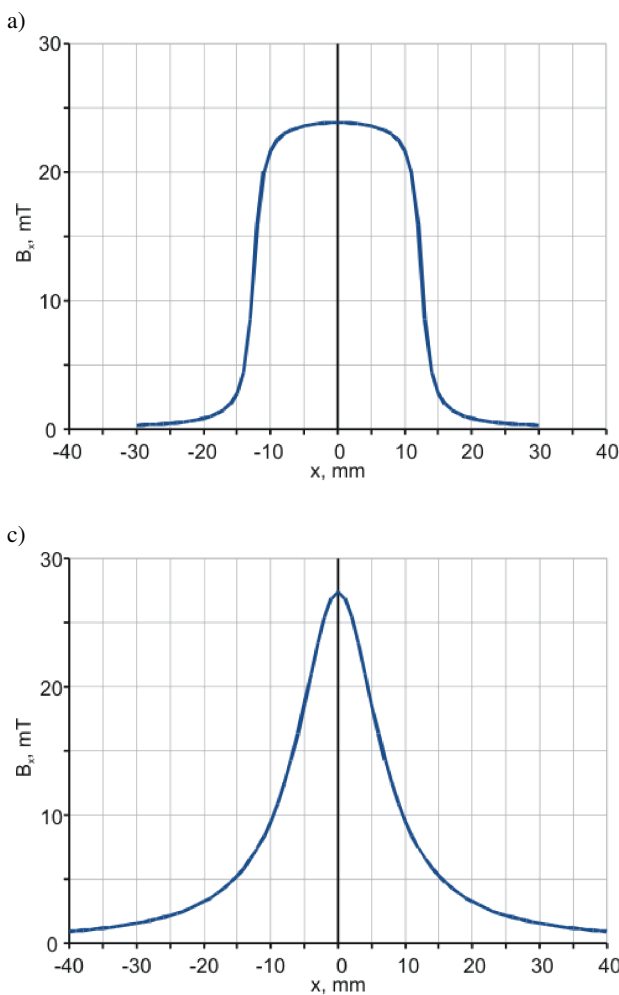


Fig. 8. Analysis of the distribution of the magnetic field in the case of a conductor with a rectangular and circular cross-section. The calculations concern a current of 1000 A flowing through the conductor

Optical fibre current sensor for electrical power engineering

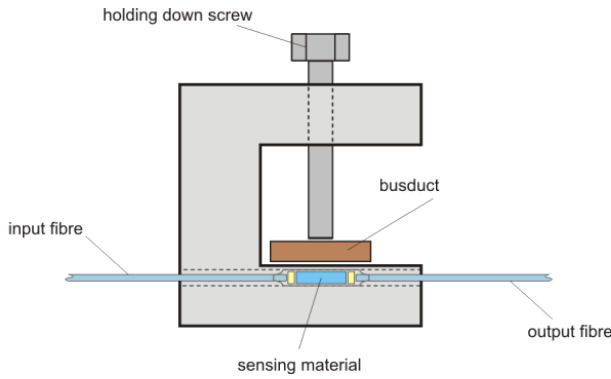


Fig. 9. The head of the optical fibre sensor with external transformation and the seal wire in form of a busway

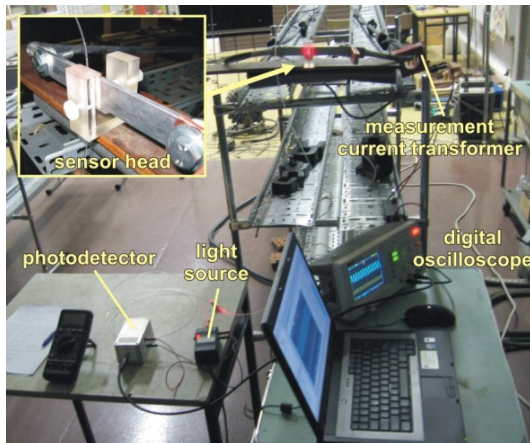


Fig. 10. Current optical fibre sensor stand

The results of the measurements have been gathered in Fig. 11. The horizontal axis contains the maximum values of the current flowing through the seal wire, and the vertical axis is the maximum values of the voltage signal emitted by the optical fibre current sensor. The obtained results confirm the good metrological properties of the constructed optoelectronic sensor, which can detect currents with intensity of the order of 200 A and less with an accuracy of only a few percent.

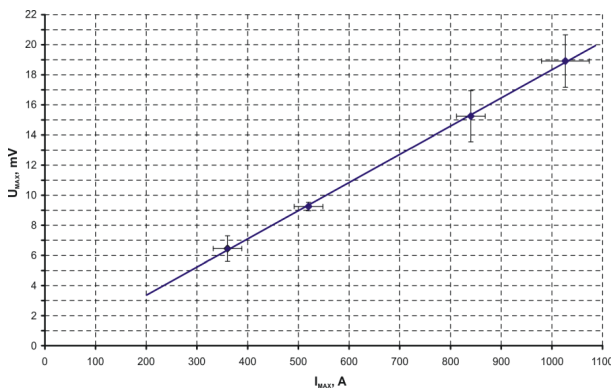


Fig. 11. Optical fibre sensor with external transformation and a busway seal wire. Maximum value of the sensor signal as a function of the maximum value of the current flowing through the busway

4. Conclusions

The investigations dealt with in this paper ought to permit the application of optical fibre sensors of magnetic fields with an external transformation as a measuring probe of optoelectronic current transformers. This system is characterized by a simple and stable construction and insensibility to all mechanical vibrations. The effect of mechanical vibrations on the operation of optical fibre current sensors is characteristic for solutions employing optical fibre loops. The presented sensors (with an external transformation) ensure a large freedom of their applications and permit to apply a modular structure of the whole transformer. Such a construction permits also to construct a measuring probe not in the form of a closed loop. This is an important advantage which allows installing the transformer in the course of the normal operation of the power line without the necessity to switch off. In the demonstrator of the optoelectronic current transformer for power systems several fundamental modules are to be distinguished, viz.:

- magneto optic measuring probe (optical fibre current sensor);
- sending-receiving module of optical signals;
- matching (adopting) module to devices of the electric power network;
- supply module.

The construction of such a transformer has been presented schematically in Fig. 12.

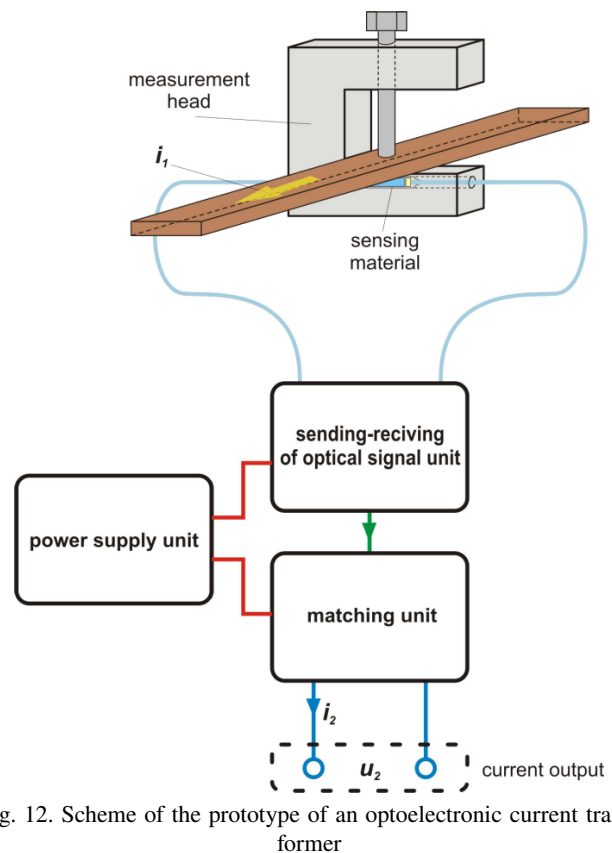


Fig. 12. Scheme of the prototype of an optoelectronic current transformer

The electronic module of the elaborated systems will be placed at a safe distance from the electric power line, and they will be held on the electrical ground of the earth. Actually, the tests of the systems have been operating.

Acknowledgments. The work was partially sponsored by the State Committee for Scientific Research (NCBiR) within the grant N R01 034 06/2009.

REFERENCES

- [1] A. Wiszniewski, *Current Transformers in Electrical Power Engineering*, WNT, Warsaw, 2006, (in Polish).
- [2] S. Koszmider, J. Olak, and Z. Piotrowski, *Current Transformers*, WNT, Warsaw, 2006, (in Polish).
- [3] Z.P. Wang, S.Q. Zhang, and L.B. Zhang, "Recent advances in optical current-sensing techniques", *Sensors and Actuators A* 50, 169–175 (1995).
- [4] K. Kurosawa, "Optical current transducer using flint glass fiber as the faraday sensor element", *OFS* 11, 134–139 (1996).
- [5] K. Bohner, T.P. Gabus, and H. Brandle, "Temperature and vibration insensitive fiber-optic current sensor", *ABB Corporate Research* 1, CD-ROM (2000).
- [6] *Digital Instrument Transformers*, www.nxtphase.com (2011).
- [7] N. Itoh, K.B. Rochford, H. Minemoto, and S. Ishizuka, "High frequency response of optical magnetic field sensors using rare-earth iron garnet films", *Tech. Digest, 13th OFS Conf.* 1, 370–373 (1998).
- [8] M.N. Deeter, "Fiber-optic Faraday-effect magnetic-field sensor based on flux concentrators", *Applied Optics* 35 (1), 154–157 (1996).
- [9] T. Pustelny, K. Barczak, K. Gut, and J. Wójcik, "Special optical fiber type d applied in optical sensor of electric currents", *Optica Applicata* 34 (4), 531–539 (2004).
- [10] C. Tyszkiewicz and T. Pustelny, "Differential interferometry in planar waveguide structures with ferromagnetic layer", *Optica Applicata* 34 (4), 507–514 (2004).
- [11] K. Barczak and T. Pustelny, "Magneto-optic properties of special optical type D fibers", *Journal de Physique IV* (137), 15–18 (2006).
- [12] T. Pustelny, C. Tyszkiewicz, and K. Barczak, "Optical fiber sensors of magnetic field applying Faraday's effect", *Optica Applicata* 33 (2–3), 469–475 (2003).
- [13] K. Barczak, T. Pustelny, A. Szpakowski, and M. Blahut, "Experimental and theoretical investigation concerning the magnetic effects in special D-type fibers", *Journal de Physique IV* (129), 85–90 (2005).
- [14] T. Pustelny and M. Grabka, "Photonic-crystal fibres with suspended core – theoretical investigations", *Acta Physica Polonica A* 116 (3), 385–388 (2009).
- [15] K. Barczak, T. Pustelny, D. Dorosz, and J. Dorosz, "New optical glasses with high refractive indices for applications in optical current sensors", *Acta Physica Polonica* 116 (3), 247–249 (2009).
- [16] K. Barczak, T. Pustelny, Z. Zycki, and T. Blazejczyk, "Optical fibre magnetic field sensors for monitoring of the state of work of electric motors", *Acta Physica Polonica A* 116 (3), 250–253 (2009).
- [17] T. Pustelny, E. Maciak, Z. Opilski, and M. Bednorz, "Optical interferometric structures for application in gas sensors", *Optica Applicata* 37 (1–2), 187–194 (2007).
- [18] K. Barczak, T. Pustelny, D. Dorosz, and J. Dorosz, "Polarization maintaining fibers for application in magnetic field measurements", *Eur. Physical J. Special Topics* 154, 11–14 (2008).
- [19] T. Pustelny, J. Ignac-Nowicka, and Z. Opilski, "Optical investigations of layered metalphthalocyanine nanostructures affected by NO₂ applying the surface plasmon resonance method", *Optica Applicata* 34 (4), 563–572 (2004).
- [20] N. Itoh, H. Minemoto, D. Ishiko, and S. Ishizuka, "Commercial current sensor activity in Japan", *OSA Technical Digest Series, 17th OFS Conf.* 16, 92–95 (2007).
- [21] E.P. Golis, M. Reben, J. Wasylak, and J. Filipecki, "Investigations of tellurite glasses for optoelectronic devices", *Optica Applicata* 38 (1), 163–169 (2008).
- [22] P. Struk and T. Pustelny, "Design and numerical analyses of the planar grating couplers", *Bull. Pol. Ac.: Tech.* 58 (4), 509–512 (2010).
- [23] D. Dorosz, "Glasses from the system PbO-Bi₂O₃-Ga₂O₃-BaO the properties and tendency to crystallization", *Proc. of SPIE* 5775, 264–267 (2005).
- [24] A. Zajac, D. Dorosz, M. Kochanowicz, M. Skórczakowski, and J. Swiderski, "Fibre lasers – conditioning constructional and technological", *Bull. Pol. Ac.: Tech.* 58 (4), 491–520 (2010).