# Enhancing current sensor sensitivity using faraday effect with multiple reflections in magneto-optical crystals

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**Abstract.** This paper develops and studies a sensor element mock-up based on the Faraday effect with multiple reflections. The authors show that as the length of the optical path in a magneto-optical crystal increases, it prompts the increase in the current sensor sensitivity. The paper also establishes the correspondence of the current waveform and the optical response of the sensor mock-up. It is shown that in developed sensor, the output signal magnitude directly correlates with the magnetic field induction.

## 1 Introduction

As the production capacities grow and the alternative electricity types are being introduced, there appears a growing need for a means to better analyze the electric grid state. Such analysis is only possible when information on current and voltage parameters at any grid point is available promptly, at a high speed, large range and with a low measurement error. In this case, the researchers are particularly hopeful about the use of optical technologies in the electric power industry related to the use of new sensor types and the possibility of transmitting information over optical fiber.

Current sensors are one of the measuring components operating according to new optical principles; their development was in the focus of researchers' great efforts. Compared to conventional transformers, optical current sensors are compact and convenient, lightweight, easy to install, insensitive to electromagnetic noise and providing a wide range of measurements, as well as long-range signal transmission [1].

Optical current sensors operate based on the Faraday effect, which consists in rotating the polarization plane of linearly polarized light as impacted by a magnetic field. The polarized light passes through a magneto-optical sensing element, which is commonly placed around a current conductor. Thus, light travels along the magnetic field which is current-induced. In general, two types of methods based on the Faraday effect are used to detect current in a conductor, i.e. polarimetric and interferometric methods.

A polarimetric sensor measures the polarization state of the radiation transmitted through the active element [2, 3]. An interferometric sensor maintains the system polarization state using a phase modulator [4, 5].

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According to the type of the active elements used, one can distinguish fiber-optic sensors as well as the sensors based on volumetric magneto-optical materials. In the latter case, the sensing element may have the form of a block (square, triangular, etc.) surrounding a conductor with a current [6].

An important parameter of the sensors is the resistance to external conditions such as vibrations and temperature gradients. The sensors based on the magneto-optical effect are characterized by high resistance to these influences and interference. Magneto-optical properties of materials also have a significant impact on the quality of the sensor performance [7].

The sensitivity of sensors based on magneto-optical materials is determined by the material and the length of the light path inside. Since the selection of materials with magneto-optical properties is limited, the most effective method to increase the sensors' sensitivity is to adjust the length of the light path through the active medium.

The purpose of this research is to develop a prototype sensor element to measure the magnetic field based on magneto-optical glasses and crystals using a scheme of multiple reflections of a light beam inside the active element.

## 2 Theoretical rationale of the sensor design

The rotation of the polarization plane, and, consequently, the response to the magnetic field and current, occurs in the active element of the sensor part of the optical current transformer.

In a homogeneous field and an isotropic medium, the magnitude of the rotation angle is proportional to the optical path covered in the active element:

$$\theta = VB_{\parallel}L\,, \tag{1}$$

where $V$ is the Verdet constant; $B_{\parallel}$ is induction of a magnetic field parallel to the light flux; $L$ is the length of the path covered by the light beam in the active element.

In the case when the field is not homogeneous, or deviations from the parallelism of the force lines and the beam path are observed, at each point of the active element, to obtain the elementary angle of rotation, only those components of the magnetic field intensity vector that lie along the path of beam propagation should be considered. Thus, for the adequate and effective performance the magnetic field sensor requires a geometry that provides, if possible, for the uniformity of the magnetic field and the parallelism of its force lines with the path passed by the light beams.

Based on formula (1), to increase the sensitivity of the magnetic field sensor, it is necessary to create a special geometry of the active element to increase the path length in the magneto-optical material. Magneto-optical crystals and glasses are generally cylinder- or parallelepiped-shaped objects. An increase in their length increases the path of radiation passing through them. However, in this case, a magnetic field inhomogeneity occurs at the ends of the active element, and it becomes higher with the increase in the length of the optical element. In addition, the cost of magneto-optical glasses and crystals increases dramatically depending on their size. In some cases, special requirements may arise to the dimensions of the sensor unit optical part, and it is difficult to use dimensional magneto-optical material. Based on this, the most promising is the use of small crystals with multiple passage of active radiation through them; and due to this the use of the radiation entire volume in the sensor is additionally obtained. Thus, the possible schemes of the active element of the magnetic field sensor can be divided into single- and multi-pass.

The simplest design of a magnetic field sensor is a configuration with a single magneto-optical crystal having such a length at which the inhomogeneities of the magnetic field at its ends are insignificant. Within this scheme the light beam propagates along the magneto-optical element parallel to the magnetic field lines. With the appropriate crystal length, the field is characterized by high uniformity.

The application of the above scheme is justified when it is necessary to carry out measurements in strong fields. The limitations of this scheme are related to the short path length in the active material. To increase the sensitivity of a single-chip circuit, a geometry with multiple reflections of the optical beam in the crystal can be proposed, Figure 1.

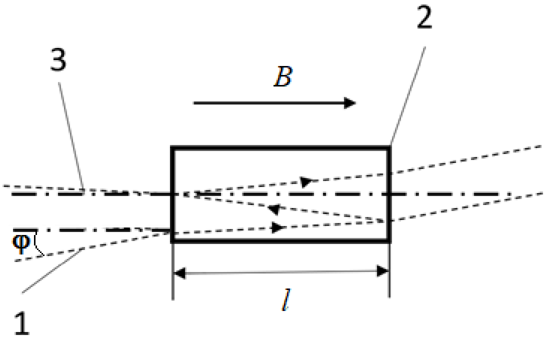

**Fig. 1.** Optical diagram of a sensor element in a single-chip design with multiple reflections: 1 – light beam; 2 – magneto-optical element; 3 – axis of the magneto-optical element.

In this scheme, the possibility of reflecting a beam from the interface of a magneto-optical element with the external environment is realized. To increase the reflection coefficient, it is possible to use thin-film reflective coatings. In terms of geometry, the crystal axis is located at a small angle φ to the magnetic field intensity vector. The length of the path traversed by the beam in this scheme can be determined by the following formula:

$$L_{pt} = 3l \,/ \left(1 - \frac{\sin^2 \varphi}{n^2}\right)^{1/2}, \tag{2}$$

where $n$ is the refractive index of the magneto-optical element.

To define the coordinate of the crystal width where the radiation will yield on the same surface, one can use the following formula:

$$d_{pt} = 3l \,/ \left(n^2 - \sin^2 \varphi\right)^{1/2}. \tag{3}$$

Here one should also consider the diameter of the beam incident on the radiation crystal.

## 3 Experimental studies of optical response in a scheme with multiple reflections

An active TGG crystal was used to measure the optical response in a multiple reflection scheme. A semiconductor laser with a wavelength of 632 nm was used as the radiation source. Glan-Taylor prisms were used as polarizers. The active element was located in the coil to create a uniform magnetic field at an angle of 3 degrees with respect to the light beam. The radiation receiver was the FEU-100. The measurements of the magnitude of the magnetic field induction were carried out using a standard teslameter sensor.

The measurement technique was based on the zero method. The sample was placed between two polarizers oriented so that the radiation intensity at the photodetector was close to zero (minimal). When the current was turned on, an increase in the signal intensity at the photodetector was observed due to the rotation of the plane of linearly polarized radiation passing through the sample. The difference in the analyzer's reading after and before switching on the current is precisely the Faraday rotation angle.

Figure 2 shows the dependence of the rotation angle of the radiation polarization plane on the magnitude of magnetic induction in single-pass and multi-pass versions of the active element.

As can be seen from Figure 2, the dependencies are linear. The linear dependence indicates that it is the Faraday effect being measured in the experiment, and that the materials demonstrate the expected optical properties.

From the dependencies obtained in Figure 2, it is possible to determine the Verdet constant for the material studied in different versions. Use the formula (4):

$$V = \tan(\alpha) / l, \tag{4}$$

where $\tan(\alpha)$ is the tangent of the angle of inclination of the dependence of the rotation angle on the magnetic field induction, defined as the ratio of the inclination angle to the magnitude of the magnetic induction; $l$ – the length of the magneto-optical material.

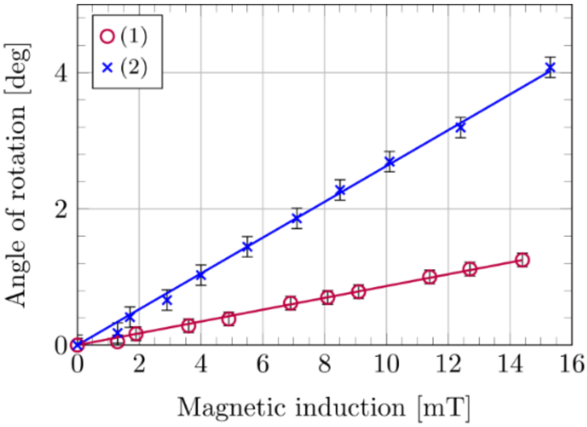

**Fig. 2.** Dependence of the rotation angle of the radiation polarization plane on the magnitude of the magnetic induction of the field induced by a conductor with a current: 1 – single light passage; 2 – three-fold passage of light.

The designs with single and multiple pass of light radiation have the same Verdet constant which amounts to 129.1 *rad* / (*Tl·m*). The increase in the steepness of the dependence curve is associated with an increase in the length of the optical path inside the crystal due to reflection from the end walls. This makes it possible to increase the sensitivity of the magnetic field sensor by a multiple of the increase in the length of the optical path. In particular, when the number of internal reflections increases up to two, the steepness of the dependence curve increases 3 times, which leads to the same increase in sensitivity.

The considered scheme makes it possible to increase the efficiency of the magnetic field sensor, is compact and stipulates for the use of one magneto-optical crystal, which results in the cost savings at the production of a magnetic field sensor. However, the sensitivity in this scheme is limited by the crystal length. In addition, it requires a highly collimated laser beam and precise alignment of the active element.

## 4 The layout of the sensor element and its study

To make a mock-up of an optical current transformer, a polarimetric scheme was used, Figure 3.

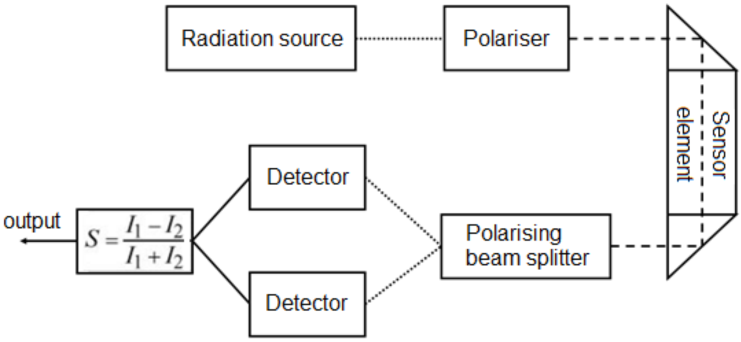

**Fig. 3.** Dependence of the rotation angle of the radiation polarization plane on the magnitude of the magnetic induction of the field induced by a conductor with a current: 1 – single light passage; 2 – three-fold passage of light.

A feature of this scheme is the use of a polarization beam splitter that separates the beam which passed through the magneto-optical element into two beams with orthogonal states of linear polarization. The use of this scheme allows neglecting the fluctuations and changes in the radiation flux from the source [8]. The value of the useful signal proportional to the angle of Faraday rotation (at small angles, when $\sin 2\theta = 2\theta$) in this scheme is defined by the formula:

$$S = \frac{I_1-I_2}{I_1+I_2} = 2\theta \tag{5}$$

where $I_1$ and $I_2$ are the photo detector output signals.

During the experimental part of the research work, a mock-up of a sensor element based on a magneto-optical TGG crystal was developed. The sensor element of an optical current transformer consists of two parts: magnetic and optical, Figures 4 and 5, respectively.

**Fig. 4.** The magnetic part of the sensor element.

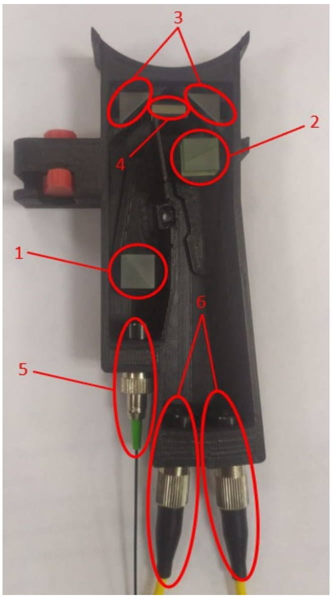

**Fig. 5.** Optical part of the sensor element.

The magnetic part of the sensor element is a ferrite core, which serves as a magnetic field concentrator in the gap where the active element is placed. The gap is 2.5 cm.

The optical part of the sensor element consists of: 1 – Glan prism, 2 – Wollaston prism, 3 – dielectric coated mirrors, 4 – magneto–optical TGG crystal, 5 – collimator with an optical input, 6 – collimators for an optical output.

Figure 5 shows the appearance of the optical part of the sensor element with the optical components installed.

In the left part of the optical component of the sensor element, there is a laser radiation input and a mount for a fiber-optic collimator. Next, a Glan-Taylor prism is installed in the adjustment plate for alignment. The rotary mirrors and magneto-optical crystal are rigidly fixed. The Wollaston prism is located on the right side of the optical component of the sensor element and is mounted in the adjustment plate. There are also two radiation outputs on the right side. After adjustment, it is possible to fix the prisms with a retainer. The right and left parts of the optical component of the sensor element are separated by a light-absorbing partition to avoid radiation from the formation channel into the registration channel.

Figure 6 shows the oscillograms of the current and the signal obtained using the developed sensor layout.

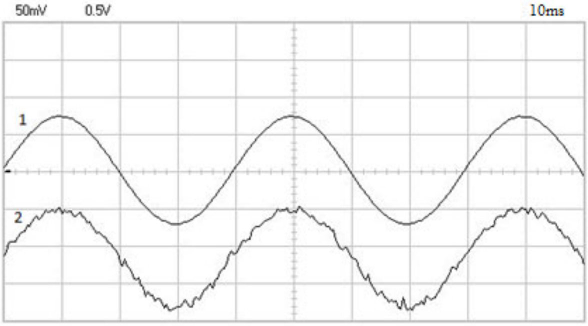

**Fig. 6.** Waveforms of current (1) and optical sensor signal (2).

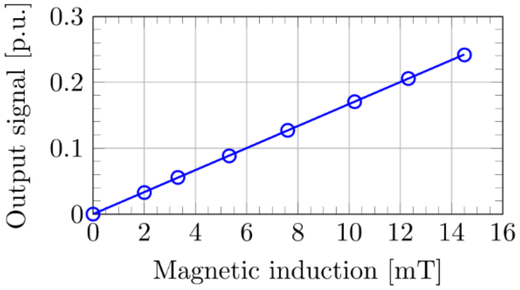

**Fig. 7.** Dependence of the output signal of the optical current transformer layout on the induction of a stationary magnetic field.

As can be seen from this figure, there is a good match between the current waveform and the sensor mock-up.

Figure 7 shows the dependence of the output signal of the optical current transformer layout on the induction of a magnetic field. As Figure 7 shows, one can observe a close to direct dependence of the output signal on the induction of the magnetic field. The straight-line nature of this dependence indicates the consistency in the efficiency of measuring the magnetic field by the developed layout in the specified range of magnetic field induction. For the assembled mock-up, the effective sensitivity was 17.5 p.u./mT.

## 5 Conclusion

The authors studied an active element with multiple reflection of a light beam on the efficiency of a magnetic field sensor based on the Faraday effect. The results obtained indicate that the chosen design contributes to an increased length of the optical path, while not requiring an increase in the size of the crystal itself. This approach made it possible to increase the sensitivity of the sensor three times compared to traditional schemes.

This increase in sensitivity opens up opportunities for the development of high-precision and compact devices used to measure the magnetic field. Improved sensors based on the Faraday effect can be used in modern monitoring systems, where accurate and reliable identification of magnetic field parameters is a key factor. Thus, such sensors can be used in a variety of fields, including scientific research, industry and medical diagnostics, providing improved measurement efficiency and accuracy.

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