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Special optical fiber type D applied in optical sensor of electric currents

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The paper deals with investigation concerning new optical fiber structures type D which may be applied in optical fiber sensors of magnetic field and electric current. These structures have been designed, produced and tested. The results of measurements of the magneto-optic effect and the distribution of mode fields in such optical fibers have been presented, as well as the test stand designed for investigation of magneto-optic phenomena.

Keywords: magneto-optic effects, special optical fibers, optoelectronic sensors, light polarization.

1. Introduction

In the epoch of the development of measuring techniques, when new kinds of sensors and new alternatives of already existing techniques are being developed, also sensors are applied in which magneto-optic phenomena are taken into account. They are equivalents of traditional sensors of magnetic fields and currents, nowadays applied in electrical power engineering on a large scale. Optical fiber sensors of magnetic fields and electric currents inside such devices and electro-energy machines as transformers and electric motors may prove to be a valuable supplement of electrolimit gauges. Conventional solutions are based on the phenomenon of electromagnetic induction and on the Hall effect, *i.e.*, on measurements of the voltage or induced current.

Optical sensors of the magnetic field utilize magneto-optic phenomena, information about the measured quantity being latent in the parameters of the beam of light propagating in the optic medium [1], [2]. Such solutions are of extreme interest in the field of dielectric materials without any metallic elements; they are absolutely safe, permit considerable reduction of the sensor dimension, need not be cooled and are not subject to electromagnetic disturbances. The dielectricity of optical media allows these sensors to be applied inside electro-energy devices while being in operation. At present in this field most buoyantly optical fiber current sensors (OFCS) made of special optical fibers, as well as optical sensors of the magnetic field employing ferrous-yttrium garnets [4], [5] are being developed, which are magneto-optically very sensitive crystals. Both these solutions are based on the Faraday effect, which is most often used in this type of sensors. The present paper is focussed on the search for and investigation on new special kinds of optical fibers to be applied in optical sensors of electric current and the magnetic field, characterized by a high sensitivity. As a result, a new optical fiber structure of type D has been proposed. Such optical fibers have been designed, produced and subjected to extensive tests. This paper presents the results of investigations that have been carried out as well as the parameters of structures being tested and a description of the test stand designed for this purpose.

2. Special optical fiber of type D

The search for new solutions of optical fiber sensors of electric current and the magnetic field has been concentrated on polarized optical fibers, which might change their optical properties in external magnetic field [3], [6], [7]. The elements which introduce a double refraction (birefringence) in the optic path would have to change their values in the optical fiber as a function of the magnetic field.

Based on analyses that have been carried out the authors have concentrated themselves on the construction of a polarized fiber, in which the fading field propagating beyond the core would penetrate the magnetically sensitive zone. As a

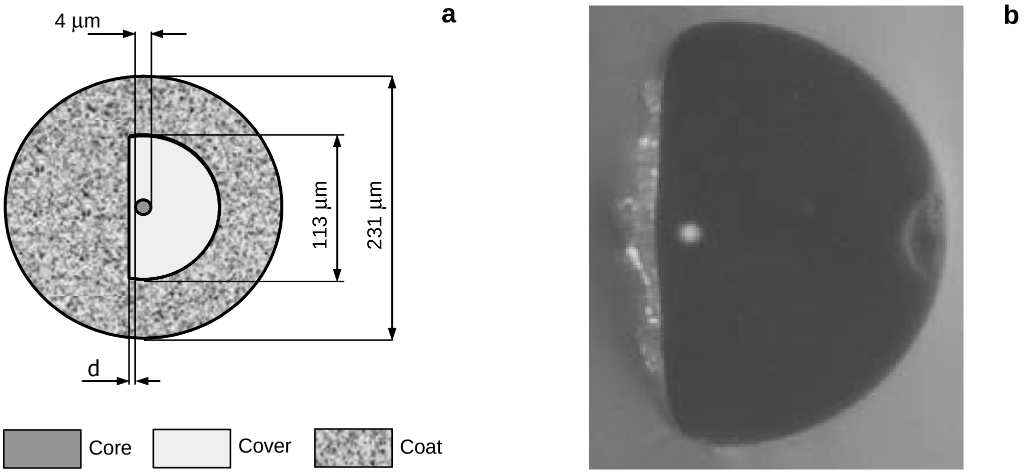
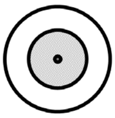
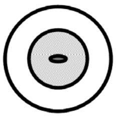
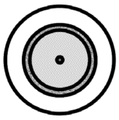
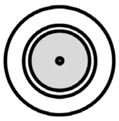
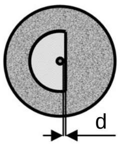
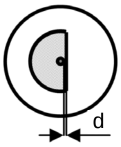


Fig. 1. Cross-section of an optical fiber type D: cross-section (**a**), a photo taken by means of a CCD camera (**b**).

result, a structure of type D has been selected. The single-mode optical fiber type D consists of the core of quartz-glass with a diameter of 4 µm and a jacket with an asymmetric cover (its cross-section looks like the letter D). Inside the cover are particles of ferromagnetic nickel. The theoretical description of the propagation of this kind of light in the structure is rather complicated. Preliminary calculations of such an optical fiber have been carried out in order to determine approximately the geometrical parameters as well as material parameters and their influence on the path of fading of the light wave in the coat. The purpose of preliminary and practically only qualitative calculations was to suggest the distance at which the magnetically sensitive layer ought to be placed, so that the field of the light wave would penetrate into it in order to warrant considerable changes in the polarization plane of light as a function of the external magnetic field. From the physical point of view the optical fiber step-index of type D is due to the lack of a cylindrical symmetry in the cover different from the cylindrical optical fiber step-index, *i.e.*, a system characterized by a different distribution of the electric field of the light wave described by other boundary conditions.

Table. Specification of the optical fibers investigated.

Type of optical fiber	Cross-section	Dimensions [µm]	
Standard step-index S		diameter of the core diameter of coat diameter of the cover cut-off length	4 125 250 0.63
Polarization with an elliptical core E		diameter of coat diameter of the cover cut-off length	125 250 0.63
Step-index with a magnetic coat SM and a standard coating SS		diameter of the core diameter of coat diameter of the magnetic cover diameter of the cover	4 113 136 231
Step-index with a double coating: soft and hard varnish SS		diameter of the core diameter of coat diameter of the first cover diameter of the second cover	4 120 144 231
Type D with a magnetic coating DM K1: $d = 4$ µm K2: $d = 5.6$ µm K3: $d = 6.4$ µm K4: $d = 10.4$ µm		diameter of the core diameter of coat diameter of the magnetic cover (cover – silicon glue with nickel particles)	4 113 231
Type D with a standard DS coating		diameter of the core diameter of coat diameter of the cover	4 113 231

The modification of the distribution of the electromagnetic field in the optical fiber is achieved, for instance, by cutting the coat in the fiber so that the field must reach the boundary between the coat and magnetically sensitive covering [8], [9].

A preliminary analysis has made it possible to determine the geometry of the optical fiber sensor type D, particularly the distance *d* between the core and the coat (Fig. 1). The authors considered it favourable to choose values of the distance *d* within the range of 4–10 µm. As magnetically active material silicon rubber with nickel atoms was employed. The optical fibers were produced in the Laboratory of Optical Fiber Technology at the Faculty of Chemistry, Maria Curie-Skłodowska University in Lublin (Poland). Optical fibers of type D without a magnetic coating have been produced, too, as well as cylindrical fibers with and without a magnetic coat (with a double non-magnetic coating of various hardness). The parameters of the fibers produced have been gathered in the Table.

3. Test stand

For the purpose of investigating the polarization effects, particularly Faraday's effect, a special test stand was constructed, as presented in Fig. 2. This test stand allows automatic measurement of the parameters of the ellipse of the state of polarization (SOP) [10] as a function of external magnetic field. For explicit description of such an ellipse the following two parameters are required: the diagonal angle β and the phase difference δ between the orthogonal states of polarization expressed by the relations [11]:

$$\tan\beta = \frac{m_y}{m_x}, \tag{1}$$

$$\cos\delta = m_x'^2 - m_x^2\cos^2\varphi - \frac{m_y^2\sin^2\varphi}{m_x m_y \sin 2\varphi} \tag{2}$$

where: m_x and m_y denote the amplitudes of orthogonal components of the electric field of light wave, and m_x' is the amplitude of the component rotated through an angle φ ($\varphi \neq 90°$). Therefore, when taking measurements the mobile part of the detection chamber KD (Fig. 2) must be rotated through a given angle [11].

As the source of magnetic field a special coil *C* was used, whose cross-section had an oval shape with a core of air, so that it was possible to insert into the gap a coiled optical fiber of flexure radius amounting to about 70 mm. The maximum intensity of the magnetic field in this coil amounted to 3×10^4 A/m.

In order to explain the effect of stresses in optical fibers also a long coil (0.95 m long) was used, in which the maximum field with a value of the order of 10^4 A/m could be forced.

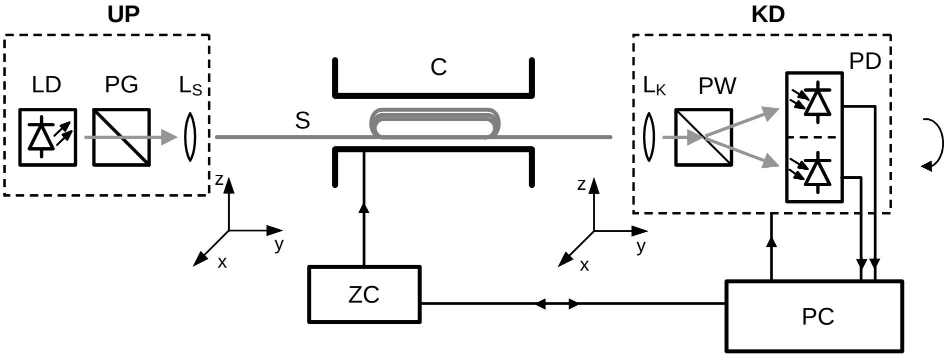


Fig. 2. Block diagram of the test stand (UP – stimulating system of the polarizer and convergent lens, KD – detection chamber with a turn-table and collimating lens, LD – laser diode, PGL – polarizer, Glan prism, L_S – focusing lens, L_K – collimating lens, PW – analyser Wollastone prism, PD – photodetectors, ZC – Coil feeder, C – coil developing the magnetic field, PC – computer with a measuring card, S – optical fiber under investigation).

The turn-table of the detection chamber KD, photodetectors PD and the feeder of the coil ZC are controlled by computer software, owing to which the acquisition of data and the control of the turn of the detection chamber and the current value in the coil are fully automatized.

4. Experimental results

The magneto-optic effect in the optical fibers under study was measured on the presented test stand. The parameters of the ellipse of the state of polarization have been determined and the state of polarization as a function of the intensity of magnetic field H has been investigated. The Faraday effect is a linear one, *i.e.*, there is some proportionality between the rotation angle of the polarization plane and the magnetic field intensity H [10], [12]

$$\alpha = VlH \tag{3}$$

where: l – the length of the structure in the magnetic field, H – the intensity of the magnetic field, V – the so-called Verdet constant, which characterises the sensitivity of the tested structure to action of the magnetic field.

Therefore, every nonlinearity in the relation $\alpha = f(H)$ may indicate the existence of some other effects, *e.g.*, induction of birefringerence due to elastooptic or magnetostrictive phenomena [10]–[13]. The experimental results of these measurements will be used to verify a mathematical model of the light propagation in optical fibers of this kind.

Figure 3 presents experimental results concerning the optical fiber type D, denoted by K2, together with a standard fiber S of the step-index type (*cf.* Table). One may see

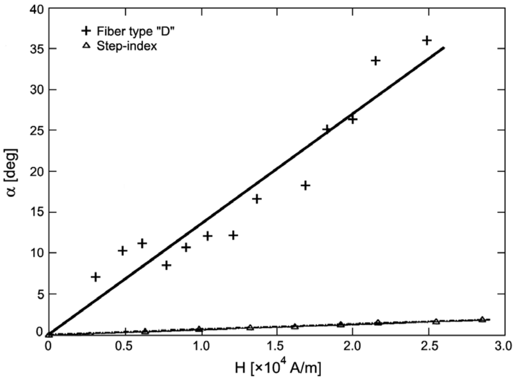


Fig. 3. Azimuth torsion of polarization as a function of the magnetic field in the case of the optical fiber type D with magnetic and standard step-index coatings.

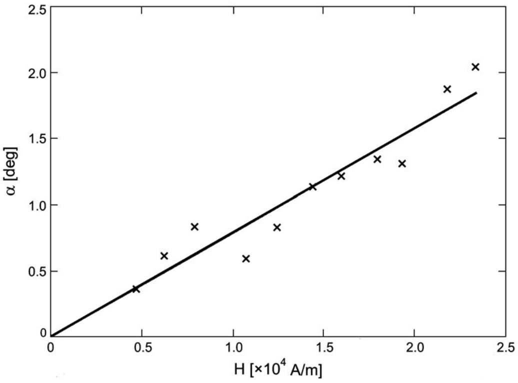


Fig. 4. Azimuth torsion of polarization as a function of the magnetic field in the case of the optical fiber type D with a simple non-magnetic coating.

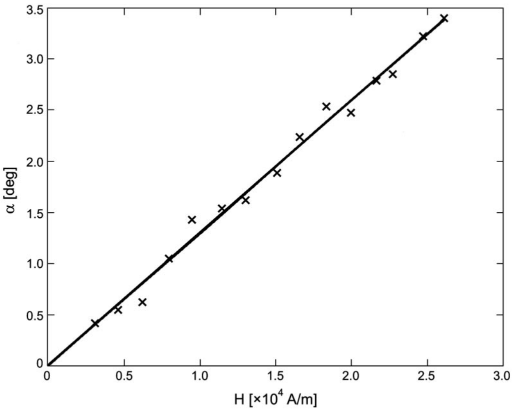


Fig. 5. Azimuth torsion of polarization as a function of the magnetic field in the case of the step-index optical fiber with a double coating: a soft one and a hard one.

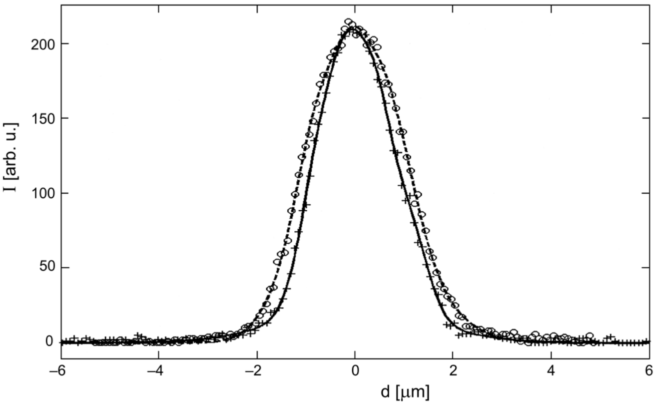


Fig. 6. Distribution of the mode field in the case of an optical fiber type D, denoted by K2.

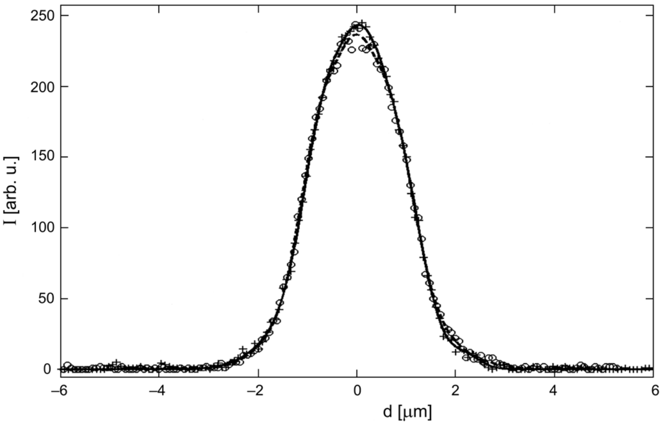


Fig. 7. Distribution of the mode field in the case of a step-index optical fiber with a double SS coating: a soft one and a hard one.

a distinct difference in the sensitivity of the fibers of magnetic field and a value of the Verdet constant nearly by two orders higher in the case of the fiber type D.

Figure 4 presents also the results of measurements of the fiber type D with a simple non-magnetic coating (DS). A similar sensitivity is to be observed as in the case of the standard step-index fiber.

Figure 5 shows changes in the polarization plane as a function of the intensity of the magnetic field determined for the optical fiber step index SS with a double coating (*cf*. Table). In the case of this fiber the value of the Verdet constant exceeds the value of the standard fiber by one order.

Measurements have also been taken of the mode fields of all optical fibers. The measurements were taken in the absence of an external magnetic field. Figures 6 and 7 present results concerning the structures D (*cf*. Fig. 3) and step-index SS with a double coating (*cf*. Fig. 5). In these diagrams measurements of two orthogonal directions have been compared, which in the case of the optic fiber type D were oriented horizontally (in parallel) and vertically to the shearing plane of the coat.

5. Conclusions

Experimental investigations have confirmed a much higher sensitivity (by two orders of magnitude) of special optic fibers type D with a coating containing an admixture of nickel, compared with standard quartz step-index optical fibers. Measurements of the mode fields confirmed the theoretical assumptions that perpendicularly to the field of shear the distribution of the electric field of the wave is distinctly wider than in the parallel direction. This proves a lack of cylindrical symmetry in the distribution of the refraction index in the optical fiber type D. Attention should also be paid to measurements of the step-indexes of an optical fiber with a double coating (Figs. 5 and 7). This is a standard optical fiber with two coating layers, a soft one and a hard one. This difference is responsible for the good linearity of the rotary polarization as a function of the intensity of the magnetic field H. Measurements of the mode field (Fig. 7) display for this optical fiber a very good symmetry in the distribution of the electric field of the optic wave in the fiber. The application of a double coating restricted the double refraction caused by electrooptical effects. These latter ones generally influence the Faraday effect negatively due to deviations from its linearity [13].

It ought to be stressed that the optical fibers type D with the admixtured of ferromagnetic material in the coating are characterized by an extremely high ability to twist the polarization plane in the magnetic field.

Investigation concerning the magnetooptic effects in this kind of optical fibers is rather innovatory and have not been mentioned so far in literature.

Investigation aiming at the development of special optical fibers of type D, as well as optical fibers with a multilayer coating to be applied in sensors of the magnetic field and electric current will be continued.

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