# HOMOGENEOUS MAGNETIC FIELD SOURCE FOR ATTENUATED TOTAL REFLECTION

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**Abstract**

The paper is focused on the study of two-dimensional magnetic field distribution used for an analysis of samples containing magnetically active films by means of the Attenuated Total Reflection (ATR) method. The design of a proposed electromagnet and the magnetic field model computation are presented together with the results obtained from magnetic field distribution measurement. The ATR method can provide information about a thin film thickness, refractive index, and attenuation in addition to the perfunctory coupling of an optical wave into and off a waveguide [1, 2]. The prism coupling conditions are determined for magnetic structures with induced anisotropy.

The prism – a film coupler is located in the central cavity of a magnetic yoke. By current switching in the coils, we can change the amplitude and magnetic field direction in order to modulate the induced anisotropy in a thin film with magnetic ordering. By the in-plane modulation of the magnetization direction in the samples, we can change the rotation and elasticity of outgoing light.

**Keywords:** Attenuated Total Reflection (ATR), magnetic field, prism coupler

## 1 INTRODUCTION

Currently, magnetic materials are of great interest because they have found wide application in data storage, sensing, and integrated optical devices. An optical waveguide consisting of a magneto-optical (MO) layer can be advantageously used as light nonreciprocal isolators, filters and modulators driven modes. Magneto-optical waveguides are typically designed as an iron garnet layer sandwich or thin ferromagnetic films.

The theory of electromagnetic wave propagation in layered media has been described in literature – see for example [1-3]. Magneto-optical experiments can be divided into two groups according to the orientation of the external magnetic field with respect to the surface of the sample. In one case, an external magnetic field vector is perpendicular to the sample surface, in the latter case it lies in the surface of the sample. This is called a plane configuration.

The Dark Mode Spectroscopy (DMS) method, for which the magnetic field is determined, belongs to the family of ATR methods. The DMS is a technique based on the excitation of guided modes in a planar structure with a prism coupler. The electromagnetic wave interaction of magnetic anisotropic layered structures is carefully described by the 4 x 4 Yeh's matrix algebra [7].

As to the study of in-plane magnetic field influence on light guided in a thin film system using the DMS [4, 5], the generator of the appropriate magnetic field is an essential part of the measuring system. It has to allow changing both the orientation and the magnitude of magnetic induction of the external field in the space occupied by the studied sample [6, 7]. At the same time, it is crucial to keep the field homogenous.

## 2 WORK AIM

The objective was to create a homogeneous magnetic field with variable vector orientation of magnetic induction. The vector variable orientation of magnetic field induction can be obtained between the pole pieces of magnets which are perpendicular to each other, because the change in the orientation vector of the magnetic field is proportional to the change of the direction of the flow of electric current in the coils. Because the space for the measurement samples is large, the magnetic field homogeneity has to be measured. It results in a map of intensity (homogeneous areas), which gives us the necessary position of the measuring points of the sample.

## 3 WORK PROCEDURE

The measuring setup is composed of two units – the optical part and the magnetic part. The optical part is schematically represented in Fig. 1 where the pass of the light beam is represented schematically.

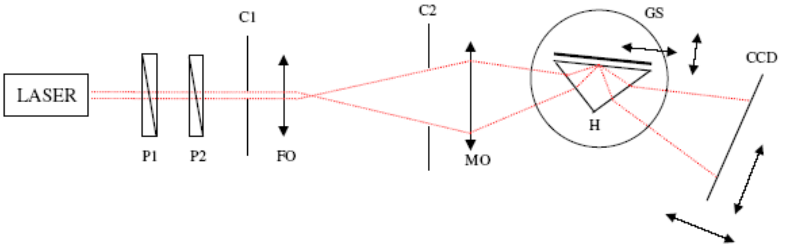


**Fig. 1 Measuring apparatus for Dark Mode Spectroscopy. P1, P2 – polarizers, C1; C2 - shutters, FO - lens, MO - microscope objective lens, H – coupling prism, GS - rotation table, CCD camera.**

A magnetic field generator for the study of light propagation in a magnetic garnet thin film is shown in Fig. 2. It consists of a pair of mutually perpendicular pole extensions and appropriate excitation coils. The intensity and orientation of a resulting field is controlled via the coil currents. The magnetic field intensity distribution is required to be constant in the planes perpendicular to the pole extensions faces, at least in the central part of the measuring area. The detail of the setup can be found in Fig. 3 where the sample is clearly seen together with the excitation prism and launching optics.

In order to fulfil all the method's requests, a special electromagnet had to be designed. The design of the magnetic field source had to respect the size of the studied samples (20 x 20 x 8 mm). Because the field homogeneity had to be kept in a perpendicular direction as well, the pole extension thickness was proposed to be 8 mm. The result is the magnetic circuit with a 20 x 8 mm size cross section, made from a soft magnetic material (AREMA steel). Two coils of the horizontal magnetic circuit (707+707 windings) as well as one coil of the vertical magnetic circuit are wound from a copper enamelled wire with a 0.67 mm diameter with total number of 1414 windings for each magnet circuit. The coils are designed for a standard maximal current density of 4A/mm$^2$ in the used conductors.

The actual study of the magnetic field was realized in two ways. Partly with the help of a supported computational model and partly by the measuring of real magnetic field distribution by means of LOHET II connected to a digital voltmeter and with the METRA gaussmeter (made by METRA Blansko).

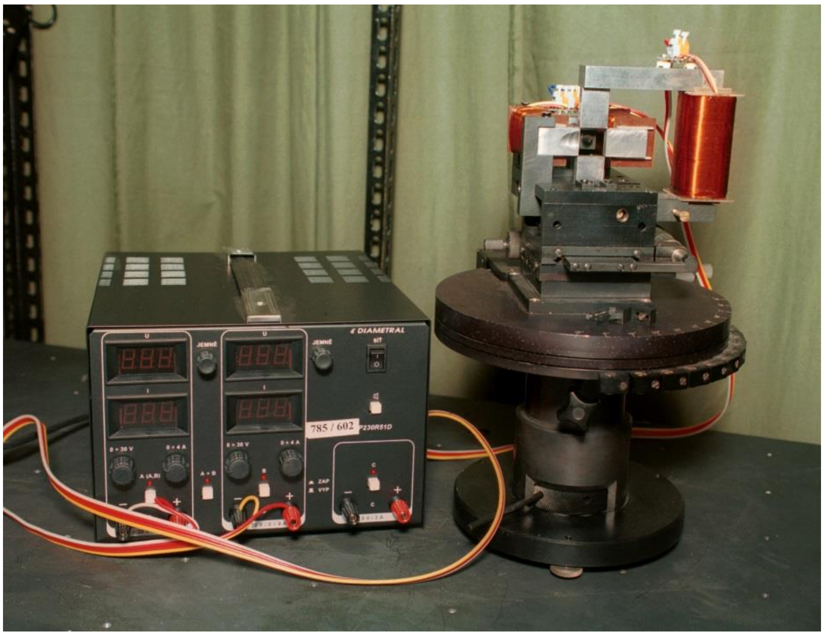

**Fig. 2 Magnetic field source setup**


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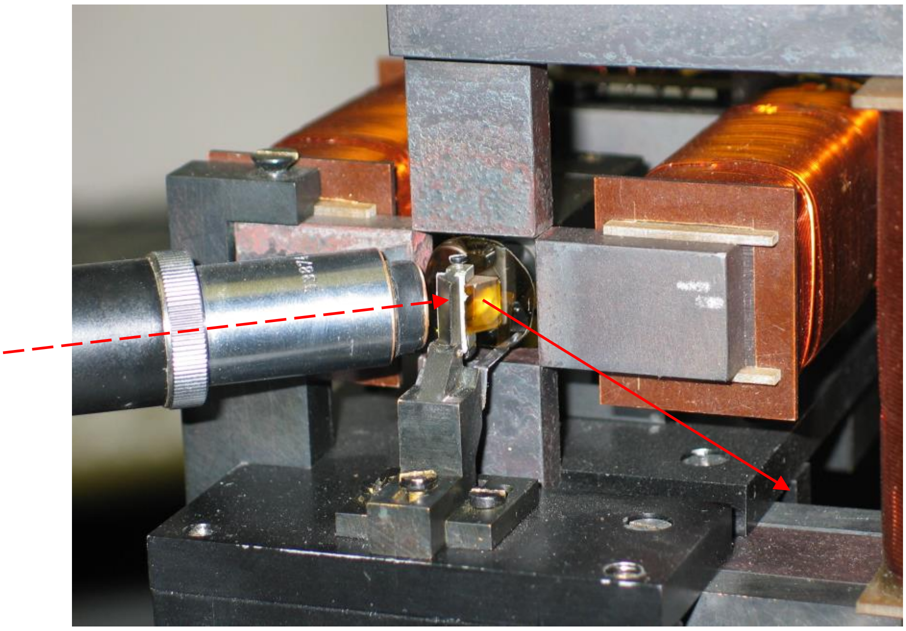

**Fig. 3 Detail of pole extensions of magnetic field source for DMS.**

### 3.1 Magnetic Field Mapping

The main task of the experimental measurement work was to determine various parameters of the proposed magnetic field source. The first three measurements were performed using the LOHET II probe connected to the digital voltmeter. The detection range of the probe was ±0.05 T (for detailed description of the probe parameters see [10]). The advantage of using a simple probe was an easy data acquisition and computer processing of obtained values. On the other hand, the magnetic field intensity excited by the required current I=2.5 A exceeded the measuring range of the probe. That is why the METRA gaussmeter (measurements ranges ±0.2 T, ±0.5 T and ±2 T) had to be used in subsequent measurement, even if the data had to be recorded manually (no digital interface).

The experimental results obtained using the LOHET II probe are depicted in Figs. 5a and 5b. It is clearly seen that the magnetic field distribution in Fig. 5a looks quite 'rough'. Based on the preliminary results, it was decided to anneal the core of the magnet. The procedure was the following: a two-hour ramp from 20 ° to 800 °C, two-hour annealing at 800 °C and an eight-hour linear ramp cooling from 800 °C back to a room temperature. The magnetic field of the magnetic circuit is not quite homogeneous (findings of previous measurements). When annealing changes, the internal structure of the material changes as well, and it affects the homogeneity of the magnetic field [11].

Magneto-optic in-plane experiments can be roughly divided in two categories: pure configurations (longitudinal or transversal), or mixed configurations where the external magnetic field is arbitrarily oriented in the plane of the sample. Considering the first category, only one electromagnet connected to the power source is needed during the measurement. The question is how much the excited magnetic field is influenced by the presence of the pole extensions of the other electromagnet. That is why the next measurements were oriented on the influence of the pole extension remanence. All measurements were performed using the METRA gaussmeter. The vertical electromagnet was used for the excitation of the magnetic field, whereas the horizontal one was switched off. Two cases were considered: in the first case, the power leads of the unused coil were just disconnected, in the second one, the coil was short-circuited. The results of the experiments led to the conclusion that the influence of the residual magnetic field could be neglected and confirmed the suitability of the used soft magnetic material.

### 3.2 Study of Magnetic Field by Modelling Supported by ANSYS Program

A mathematical model of an electromagnet results from Maxwell's equations [7]. The solution of the equation system can be simplified by introducing new values, a vector potential $\mathbf{A}$ and a scalar potential φ. The magnetic flux density vector can be expressed as a vector potential rotor:

$$\mathbf{B} = \nabla \times \mathbf{A}\,. \qquad (3.1)$$

For a solution of 2D propositions, it is advantageous to use the vector potential, whereas for 3D propositions, the scalar potential is better. The ANSYS program applies the transformation for the solution [8]

$$\mathbf{B} = \nabla \times \left(\mathbf{N_A}\right)^{\mathbf{T}} \mathbf{A}_e , \tag{3.2}$$

$$\nabla^T = gradient\ operator = \left[\frac{\delta}{\delta x}\frac{\delta}{\delta y}\frac{\delta}{\delta z}\right]$$

where $\mathbf{N}_A$ is a shape function; $\mathbf{A}_e$ defines a magnetic vector potential and T is a hash function.

## 4 RESULTS AND DISCUSSION

### 4.1 Magnetic Field Mapping

The result of the annealing can be seen in Fig. 4b. The annealing of the yoke helped greatly to improve the homogeneity of the magnetic field. The results were: the in-plane magnetic field maps for various positions of the perpendicular coordinate (see Fig. 6 for orientation). The magnetic field probes were mounted on the computer-controlled step-motor driven x-y translation stages with calibrated actuators. The perpendicular coordinate was measured using the dial gauge.

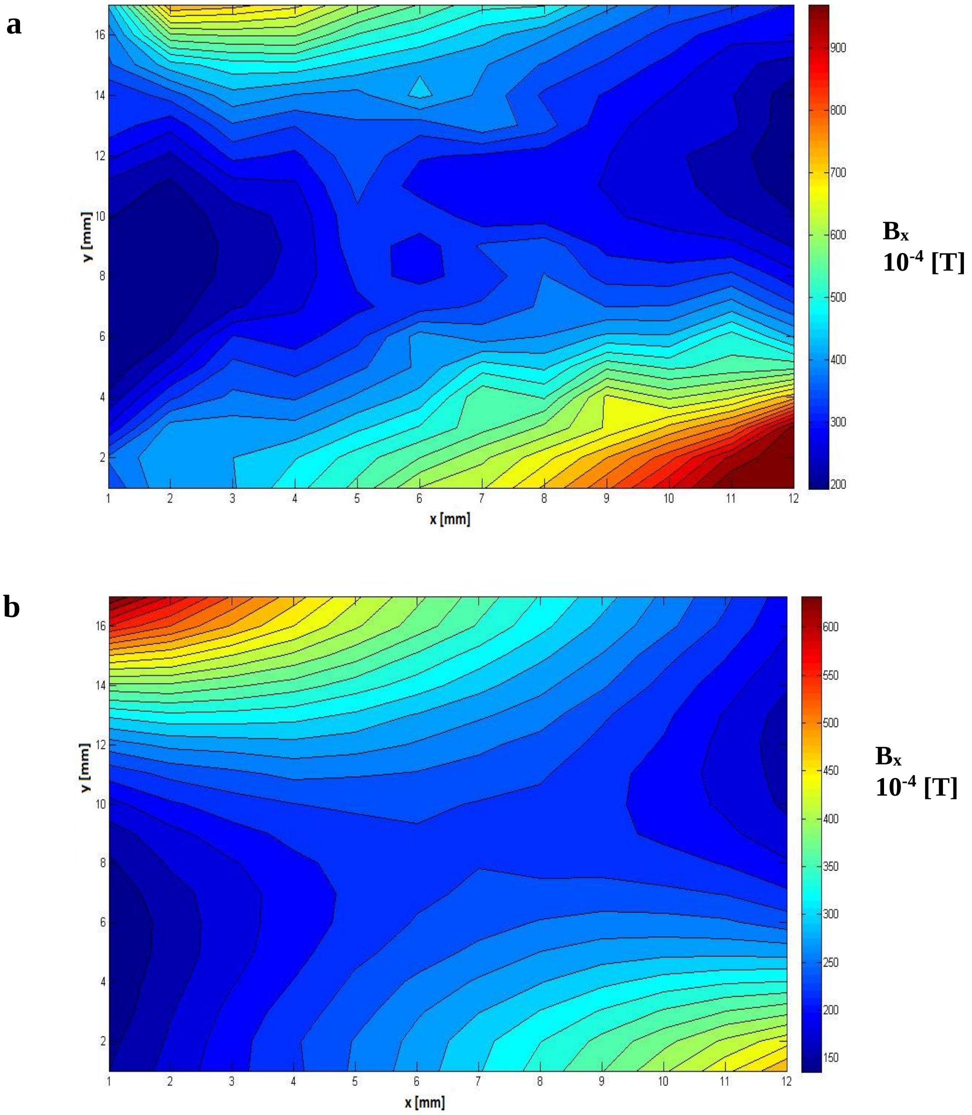


**Fig. 4 Distribution of $B_x$ in the measured sample area: (a) before annealing, (b) after annealing. ($I_1$=-0.11A, $U_1$=0.9V vertical coil; $I_2$= -0.9A, $U_2$=-0.8V horizontal coils), (z = 3 mm).**


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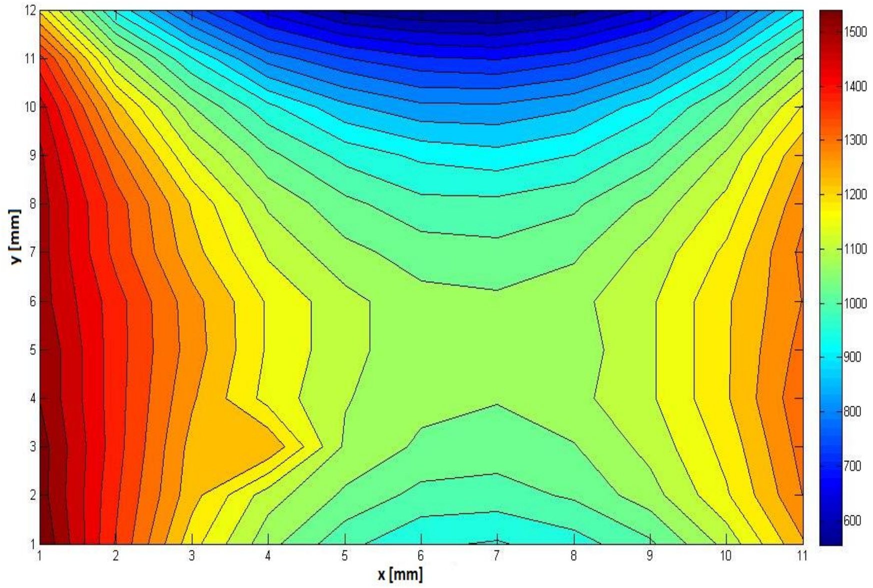
The main task of the experimental work was to determine the in-plane magnetic field distribution, which is crucial for the proper understanding of magneto-optic DMS experimental results. The example of the results can be seen in Fig. 5 where the components $B_x$ (Fig. 5a) and $B_y$ (Fig. 5b) are depicted.

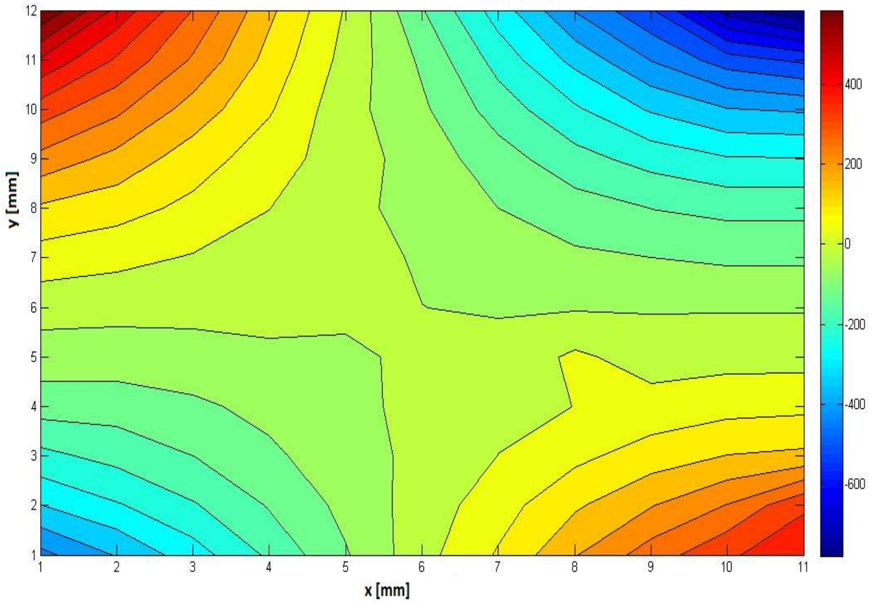
In order to get the information about the perpendicular component of the magnetic field as well, the field mapping was performed for various depths measured with respect to the front plane of the pole extensions. The in-plane magnetic induction components were measured with a 1 mm probe movement step in both directions and both coils were fed by the dc current of 2.5 A.

**a**




**$B_x$**
**$10^{-4}$ [T]**

**b**




**$B_y$**
**$10^{-4}$ [T]**

**Fig. 5 (a) The $B_x$ component of magnetic induction in detail in the measured area in a depth z = 3mm at 2.5 A current in coils, the measure detector is horizontal; (b) the $B_y$ component of magnetic induction in detail in the measured area in a depth z = 3mm at 2.5 A current in coils, the measure detector is horizontal.**

### 4.2 Study of Magnetic Field by Modelling Supported by ANSYS Program

While designing the model of magnetic field sources, at first the calculation with the help of the FEM – Finite Element Method was performed. The ANSYS program for solving the FEM on an IBM SP/2 computer was used for the calculation. The model of the 3D scheme of the magnetic field source for the DMS is shown in Fig. 6.

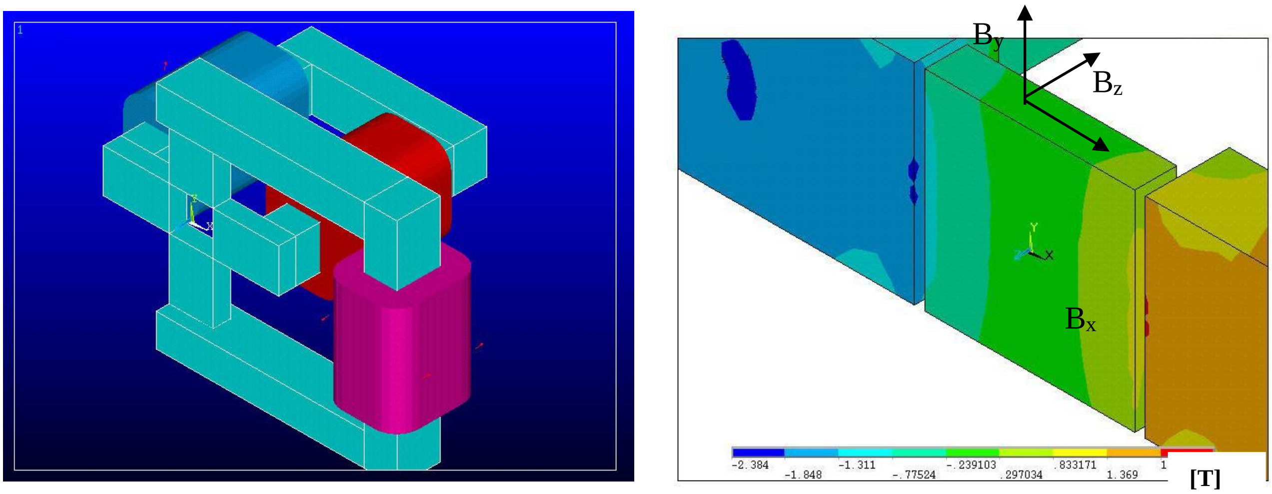



**Fig. 6. Model of 3D scheme of magnetic field source.**

## 5 CONCLUSION

On the basis of the created mathematical model, it is evident that the magnetic field distribution in the whole space between the pole extensions is not homogenous. The values of the magnetic field obtained from the measurement differ from the values obtained by modelling within an order. The differences are partly due to the parameters used in the model. Nevertheless, the magnetic field can be considered to be homogenous around the geometric centre of the measured area between the pole extensions in an area of 5x5 mm and 4 mm along the central axis parallel to z axis.

As to the temperature influence, a significant change of magnetic induction for the given value of the excitation current was not observed. Anyway, it is essential to note that at higher current loading it is necessary to apply forced cooling or to interrupt the work. Overheating of magnets does not influence magnetic induction for current loading of the coils. The construction modification of the extension (the recess for the launching microscope lens) has no fundamental effect on the magnetic field parameters in the sample area.

Positioning of a miniature measuring probe near the measured point (on the thrust tip) appears to be optimal for real time observations of the required parameters of the magnetic field during DMS experiments.

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**REFERENCES**


[1] Tien, P. K., Ulrich, R.: Theory of Prism-Film Coupler and Thin-Film Light Guides, Journal of the Optical Society of America, Vol. 60, No. 10, October 1970, pp. 1325-1337.

[2] Ulrich, R.: Theory of Prism-Film Coupler by Plane-Wave Analysis, Journal of the Optical Society of America, Vol. 60, No. 10, October 1970, pp. 1337-1350.

[3] Višňovský, Š., Yamaguchi, T., Pištora, J. and Postava, K., Beauvillain, P. and Gogol, P.: Unidirectional propagation in planar optical waveguides. Schenk, 2006, ISBN 80-248-1186-3, s.82.

[4] Bárta, O., Pištora, J., Staněk, F., Postava, K.: Magnetic permeability effect on light propagation in planar structures. Proceedings of SPIE, 2000, Vol. 4239, pp. 204-209.

[5] Lesňák, M.: The sours of magnetic fields for magneto optic measurement (in Czech). Jemná Mechanika a optika, 3/2002, s. 79-80.

[6] Bárta, O.: Study of guiding modes in anisotropic andabsorbing planar structures. Ph.D. thesis (in Czech). VŠB – Technical University of Ostrava, 2006

[7] Yeh, P.: Optics of anisotropic layered media: a new 4 x 4 algebram, Surf. Sci., 96, 1980 s. 41-53.

[8] ANSYS, Inc. Theory Reference, www.ansys.com.

[9] Kvasnica, J.: Electromagnetic field theory (in Czech). Praha Academia 1985.

[10] http://uk.rs-online.com/web/search/searchBrowseAction.html?method=getProduct &R=17856

[11] B.D. Cullity,: Introduction to Magnetic Materials, Massachusetts, Addison-Wesley, 1972.