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Magnetic field source for dark mode spectroscopy

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The paper is focused on the study of two-dimensional magnetic field distribution used for the analysis of the samples containing magnetically active films by means of dark mode spectroscopy (DMS). The design of proposed electromagnet for in-plane magneto-optic configuration and the magnetic field model computation are presented together with the results obtained from magnetic field distribution measurement.

Keywords: dark mode spectroscopy, magnetic field.

1. Introduction

The paper is oriented on the design problems related to the dark mode spectroscopy (DMS) of layered systems with magnetic films. It is a well-known fact that magnetic field has an influence on the light propagating in the layered media containing magnetically ordered thin films. In our case, magnetic garnet films deposited on non-magnetic substrates are considered. The theory of electromagnetic radiation propagation in layered media has been described in details in the literature – for example see [1–3]. Magneto-optic experiments can be divided in two groups according to the orientation of external magnetic field with respect to the sample surface. In one case, the vector of external magnetic field is perpendicular to the sample surface, in the other case it lies in the sample surface. The latter is referred to as an in-plane configuration.

As to the study of in-plane magnetic field influence on light guided in a thin film system using DMS [4, 5], the generator of 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. DMS experimental setup

The measuring setup is composed of two units – the optical part and magnetic part. The whole measuring apparatus is placed on an optical table board in order to damp

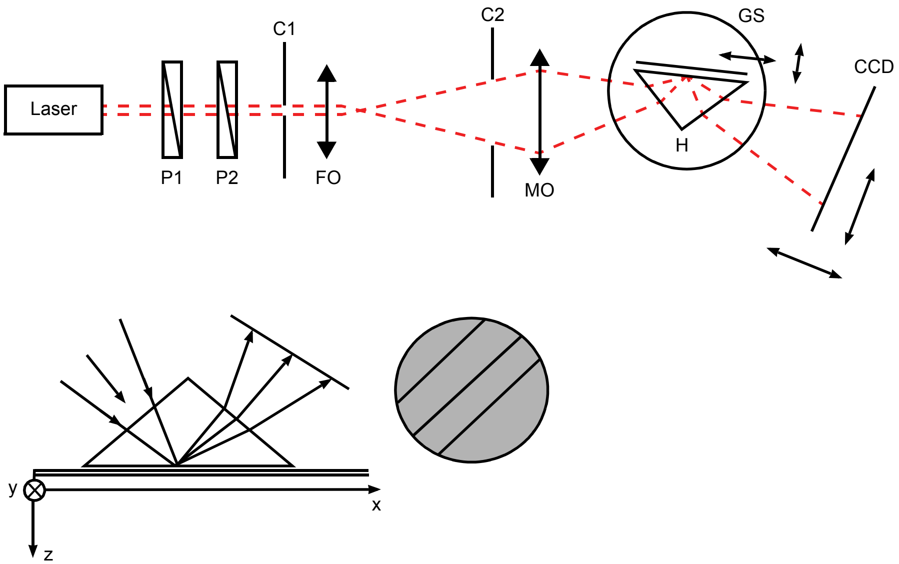

Fig. 1. Measuring apparatus for DMS. P1, P2 – polarizers, C1, C2 – shutters, FO – lens, MO – microscope objective lens, H – coupling prism, GS – rotation table, CCD camera.

mechanical vibrations, because the measuring method is sensitive to them. The optical part is schematically represented in Fig. 1, where the pass of the light beam is represented schematically.

A magnetic field generator for the study of light propagation in 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 resulting field is controlled via the coil currents. 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 details of the setup can be found in Fig. 3

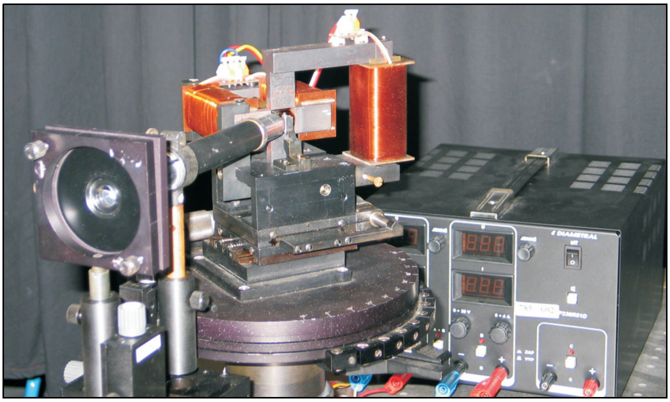

Fig. 2. Magnetic field source setup for DMS.

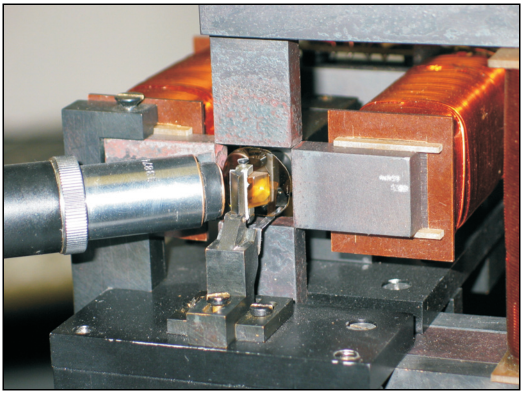

Fig. 3. Details of pole extensions of magnetic field source for DMS.

where the sample is clearly seen together with the excitation prism and launching optics.

In order to fulfill all the requirements of the method, a special electromagnet had to be designed. The design of the magnetic field source had to respect the size of studied samples (20×20×8 mm). Because the field homogeneity had to be kept in perpendicular direction as well, the pole extension thickness was proposed to be 8 mm. The result is the magnetic circuit with 20×8 mm size cross-section, made from 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 copper enameled wire with 0.67 mm diameter with total number of 1414 windings for each magnet circuit. The coils are designed for standard maximal current density 4 A/mm^2 in the used conductors.

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

3. Study of magnetic field by modeling supported by ANSYS program

Creating a mathematical model of electromagnets, results from Maxwell equations [7]. The solution of the equation system can be simplified by introducing new values, vector potential **A** and scalar potential φ. The vector **B** can be expressed as a vector potential rotor:

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{1}$$

By substituting (1) into Maxwell equations and using identity, the relation is obtained:

$$\mathbf{E} = -j\omega\mathbf{A} + \nabla\varphi \tag{2}$$

Here j is the imaginary complex unit and ω is angular frequency. By combining (1) and (2), and the follow-up modification, we obtain:

$$\Delta \mathbf{A} + k^2 \mathbf{A} - \nabla \left[\nabla \cdot \mathbf{A} - \mu(\sigma + j\omega\varepsilon)\varphi \right] \tag{3}$$

where Δ is Laplace operator, ∇ is Hamilton operator (nabla), μ is medium permeability, σ is electric conductivity, ε is medium permittivity, and

$$k^2 = \mu(\sigma + j\omega\varepsilon)\varphi \tag{4}$$

The scalar function φ may have a random progression [8, 9]. We choose it so that

$$\varphi = \frac{\nabla \cdot \mathbf{A}}{\mu(\sigma + j\omega\varepsilon)} \tag{5}$$

Then, Equation (3) simplifies to the form:

$$\Delta \mathbf{A} + k^2 \mathbf{A} = 0 \tag{6}$$

This equation represents the wave equation for vector potential.

For a solution of 2D propositions it is advantageous to use the vector potential, whereas for 3D propositions, the scalar potential is better. ANSYS program applies transformation for the solution [7]

$$\mathbf{B} = \nabla \times (\mathbf{N_A})^T \mathbf{A_e} \tag{7}$$

where $\mathbf{N_A}$ is the form function, $\mathbf{A_e}$ defines the magnetic vector potential and T is the hash function.

While designing the model of magnetic field sources, at first the calculation with the help of FEM (finite element method) was performed. ANSYS program for solving FEM method on IBM SP/2 computer was used for the calculation. The model of the 3D scheme of magnetic field source for DMS is shown in Fig. 4.

4. Magnetic field mapping

The task of all measurements was to determine various parameters of a magnetic field source proposed for in-plane DMS experiments. The first three measurements were performed using LOHET II probe connected to the digital voltmeter. The measuring 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, 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)

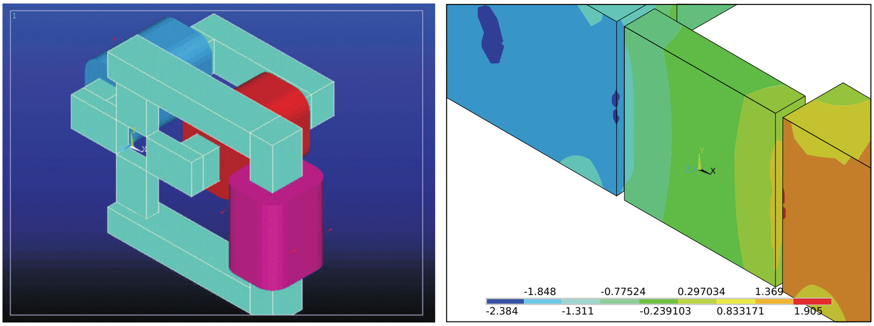

Fig. 4. Model of 3D scheme of the magnetic field source for DMS.

had to be used in subsequent measurement, even if the data had to be recorded manually (no digital interface). The results were the in-plane magnetic field maps for various positions of the perpendicular coordinate (see Fig. 4 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.

The experimental results obtained using LOHET II probe are depicted in Fig. 5. It is clearly seen that the magnetic field distribution in the Fig. 5**a** looks quite "rough". Based on these preliminary results, it was decided to anneal the core of the magnet.

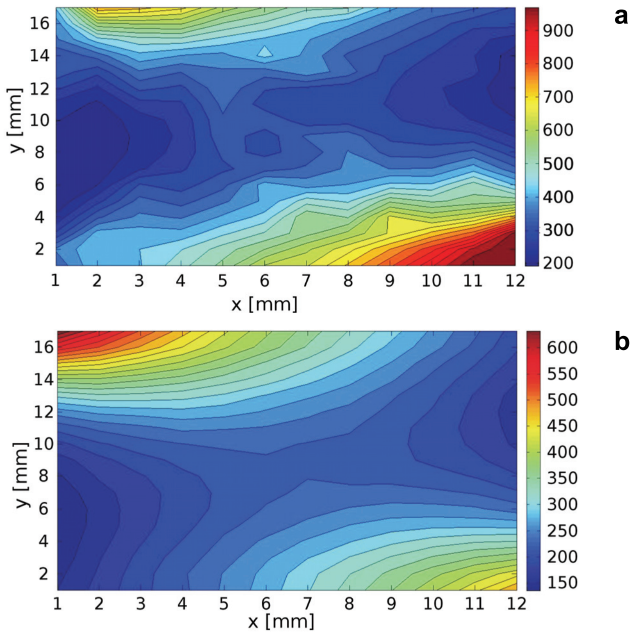

Fig. 5. Distribution of B_x in the measured sample area: before annealing (**a**), after annealing (**b**). $I_1 = –0.11$ A, $U_1 = 0.9$ V vertical coil; $I_2 = –0.9$ A, $U_2 = –0.8$ V horizontal coils ($z = 3$ mm).

The procedure was the following: two-hour ramp from 20 °C to 800 °C, two-hour annealing at 800 °C and eight-hour linear ramp cooling from 800 °C back to room temperature. The result can be seen in Fig. 5**b**. The annealing of the cores helped greatly to improve the homogeneity of magnetic field.

Magneto-optic in-plane experiments can be roughly divided into 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 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 used soft magnetic material.

The high current density in the coil winding resulted in excessive thermal load of the coils. By this reason, thermal dependence of electromagnetic parameters of coils was studied. At the next measurement, current was led into the coils and temperature

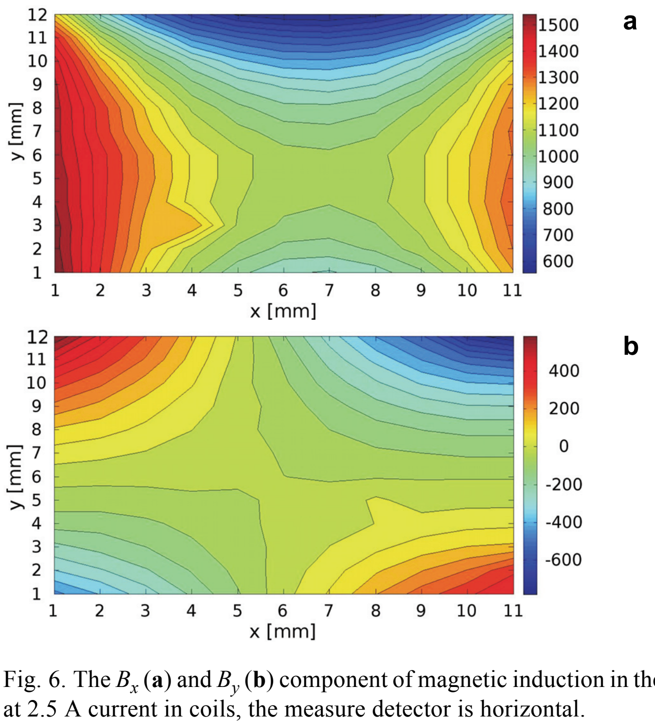

Fig. 6. The B_x (**a**) and B_y (**b**) component of magnetic induction in the measured area in the depth z = 3 mm at 2.5 A current in coils, the measure detector is horizontal.

was recorded each 15 seconds. The temperature was observed for a period of 195 s. Under the same conditions, the influence of current on-and-off switching was observed. The effect of temperature as well as of permanent switching on-and-off was found to be insignificant. While measuring with high current ($I = 2.5$ A), we cooled the coils with the help of a fan. Nevertheless, it was possible to work for 15 minutes at maximum, with the follow-up switching-off for 60 min.

The main task of the whole analysis was to determine the in-plane magnetic field distribution, which is crucial for the proper understanding of magneto-optic DMS experimental results. The studied in-plane area was restricted to 10×10 mm (x, y) square in the center of the magnetic circuit. The example of the results can be seen in Fig. 6, where the components B_x (Fig. 6**a**) and B_y (Fig. 6**b**) 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 1 mm probe movement step in both directions and both coils were fed by the dc current of 2.5 A.

5. Conclusions

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 magnetic field obtained from the measurement differ from the values obtained by modeling 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 center of the measured area between the pole extensions in the area of 5×5 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 observation of the required parameters of the magnetic field during DMS experiments.

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