MAGNETOOPTIC TECHNIQUE FOR LOCAL MEASUREMENT AND OBSERVATION OF MAGNETIC FIELD

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ABSTRACT

A new technique for observation and quantitative measurement of local magnetic field using special transparent magnetooptic indicator films has been developed. This technique allows for observation and local field measurements with a spatial resolution of 1 µm and sensitivity of 0.1 G. In UME this technique is used both for industrial applications, like characterization of magnetic cards, as well as for research on novel magnetic materials.

Magnetooptic technique for observation and measurements of local magnetic fields is based on the Faraday rotation of light polarization in magnetic field. When polarized light passes through magnetic field, its polarization plane rotates proportionally to the field strength and the path travelled by the light:

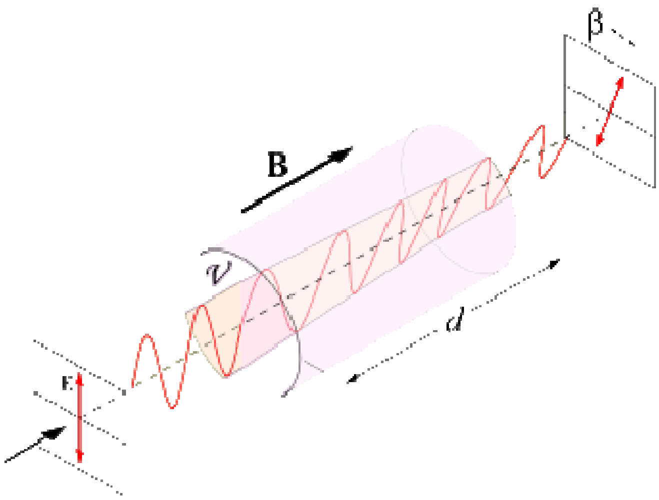

Fig. 1. Schematic representation of Faraday effect

$\beta = VBd$, where β is the angle of polarization rotation, B is the magnetic field strength, and d is the distance travelled by light. Proportionality coefficient V is called Verdet constant. This constant is a characteristic of the medium the light passes through. For vacuum or air Verdet constant is very small resulting in very low magnitude of the Faraday rotation. For glass it is larger but still very small. There are various ways to increase Verdet constant, for example doping glass with bismuth increases it substantially. But even in that case the resulting Faraday rotation is about 1 degree per centimeter in the field of 1 kG, which is still not sufficient for direct visualization of the Faraday effect.
At the Magnetism Lab of UME we use yttrium-iron garnet films to obtain stronger Faraday rotation. Yttrium-iron garnet (YIG) is a ferrimagnetic material, i.e. it is a magnet but with a more complicated microscopic structure than regular ferromagnetic materials (ferrimagnetic materials have several

magnetic sublattices). A specific feature of IYG is that it is transparent to visible light, i.e. it is a transparent magnet. Therefore, it can be used as a magnetooptic indicator for magnetic field observation. To use YIG as a magnetooptic indicator, it is produced in the form of thin films (several microns thick) grown epitaxially on transparent gallium gadolinium substrates. To further increase the magnitude of the Faraday effect, YIG films are doped with bismuth. The resulting Faraday rotation is several degrees per micrometer in the field of about 100 G. This Faraday rotation exceeds by several orders of magnitude the respective value in any other transparent medium. That is why YIG films can be used as magnetooptic indicators.

Generally, YIG films produced for research purposes have an out of plane anisotropy. That means that the magnetization in the film is directed perpendicular to its plane. Such films are not very suitable to be used as indicators because they are divided into magnetic domains, which would obscure the image to be observed. For our observations we use specially produced films with in-plane anisotropy, i.e. in the absence of external field the magnetization vector of the film is confined within its plane. If a perpendicular field is applied (Fig.2), the magnetization vector deviates from the plane thus resulting in Faraday rotation in the light passing through the film.

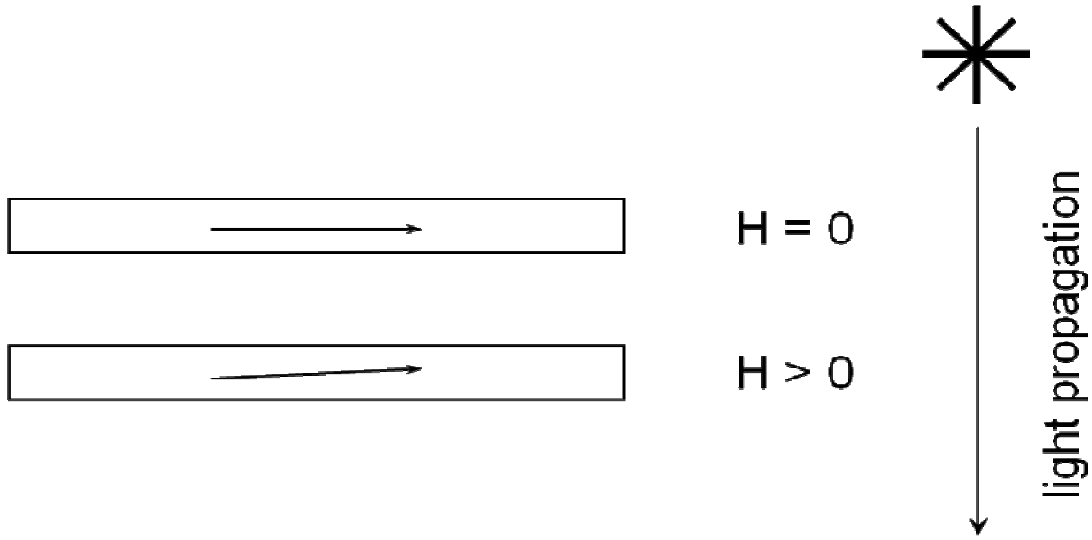

Fig. 2. Magnetization direction in in-plane YIG films

To visualize magnetic field distribution in any magnetic sample, IYG film is placed directly onto the sample. As mentioned above, the local magnetization vector in the in-plane IYG film rotates towards the local external field. Thus, the magnetization distribution in the indicator film will reflect that in the sample under study (Fig.3).

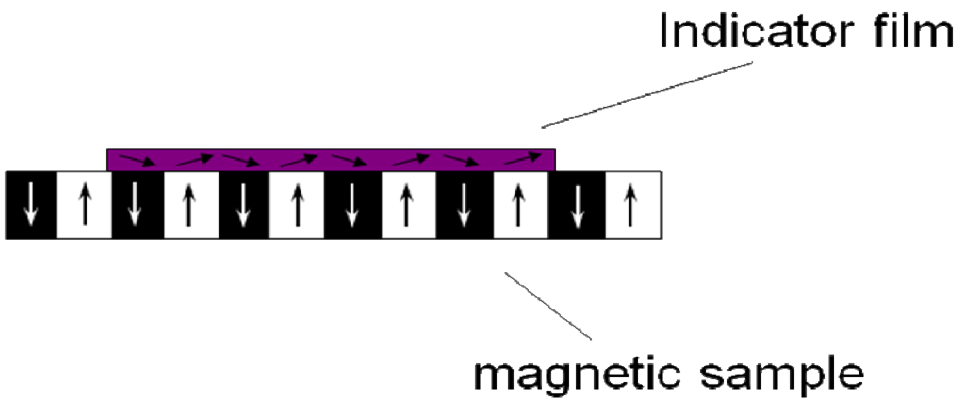

Fig. 3. Magnetization variation in in-plane YIG films placed on top of inhomogeneous magnetic sample.

As described above, deviation of the local magnetization in the indicator film will result in Faraday rotation of the light polarization, which can be observed in a polarizing microscope. The whole setup is shown schematically in Fig.4:

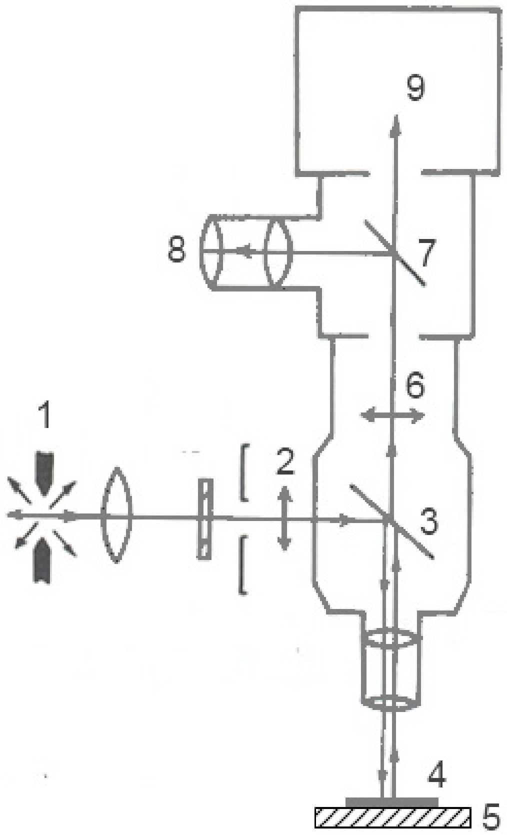

Fig.4. Scheme of the magnetooptic setup

Light beam from the source one becomes polarized after passing through the polarizer 2. Then it reflects from a semi-transparent mirror 3 and reaches the YIG indicator film 4 placed on top of the sample 5. There is a mirror layer deposited underneath the indicator film, thus the light reflects back, passes again through the semi-transparent mirror 3 and then through the second polarizer (called analyzer) 6. Polarizers 5 and 6 are aligned perpendicular to each other (crossed position), as a result in the absence of Faraday rotation no light can pass through the second polarizer 6. However, if the light experiences Faraday rotation in the indicator film, its polarization plane turns away from the initial direction and thus some light can pass through the analyzer 6. The stronger the Faraday rotation the more light passes through the analyzer. Thus, areas with stronger local magnetic field will be visualized as brighter areas in the image.

As an example of magnetooptic image, in Fig. 5 we show magnetic recording in a telephone card. Green and yellow lines are the bits of information with local magnetic field directed out of the plane either up or down. The difference in the color arises due to the optical dispersion of the Faraday rotation (i.e., the dependence of its magnitude of the light wavelength). To achieve this difference in color the polarizers have to be slightly uncrossed (not exactly perpendicular to each other), so that the two opposite directions of Faraday rotation become nonequivalent.

The spatial resolution of this technique is about 1 µm, the sensitivity (lowest detectable field) is 0.1 G. The field range depends on the indicator film. While the most sensitive indicator films can be used up to about 500 G, there are films that can operate up to 3 kG.

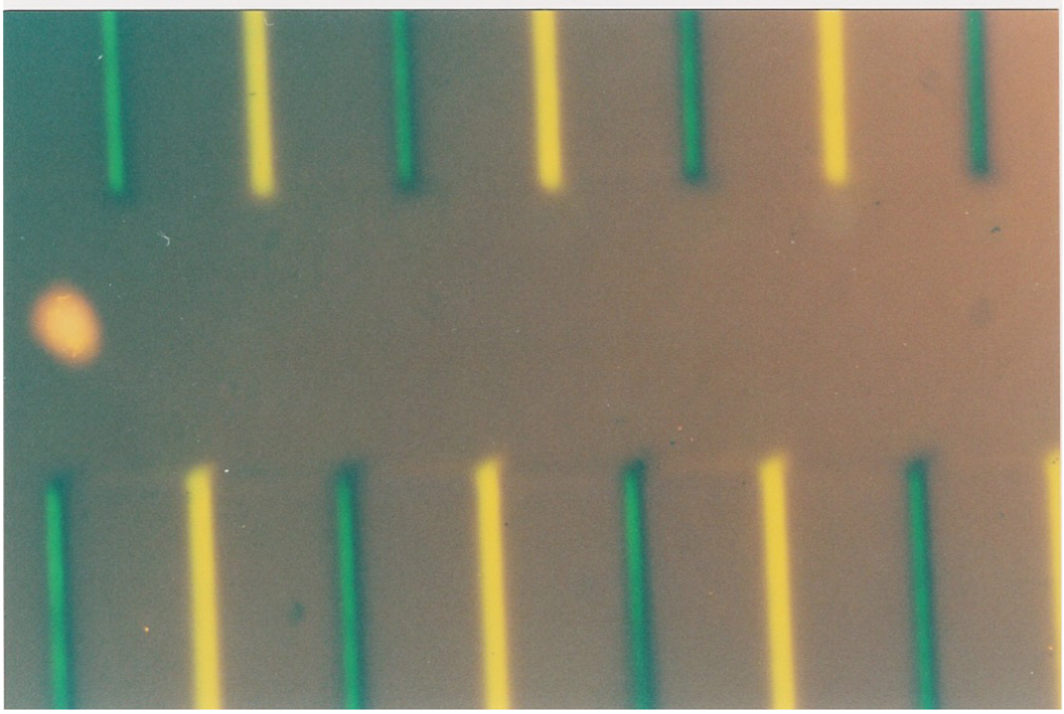

Fig. 5. Magnetooptic image of magnetic recording in a phone card.

As shown in Fig. 4, after passing through the semi-transparent mirror 7, the light gets split into two parts. One goes to the eyepiece for visual observation, the other goes to the photomultiplier where the light intensity is measured. Thus, by measuring the light intensity, one can get quantitative mapping of the local magnetic field. However, the intensity of the light passing through the second polarizer is not linear with respect to the Faraday rotation (and thus to the magnetic field). This makes it difficult to convert the light intensity into magnetic field strength. To solve this problem, we developed a special Faraday modulator. Faraday modulator represents a small solenoid with another indicator film inside, placed between the mirror 3 and the analyzer 6 in the microscope. There is no mirror layer on that piece of indicator film, so that the light freely passes through it. A small AC voltage is applied to the solenoid so that a small AC field is generated. This field results in additional periodic (AC) Faraday rotation. The amplitude of the AC filed is chosen such that the amplitude of this AC Faraday rotation φ_0 is much smaller than the Faraday rotation at the sample β, so that it can be considered as small modulation. To understand the effect of this modulation, let us write down the expression for the light intensity. As light is an electromagnetic wave, its intensity is proportional to the square of the electric field amplitude in the wave:

$$I = KE^2, \qquad where\ K = \frac{c\varepsilon_0}{2}\ is\ a\ constant$$

After passing through the analyzer 6, the electric field amplitude is $E = E_0 sin\beta_0$, where the total Faraday rotation β_0 is a sum of the constant Faraday rotation at the sample β and the AC rotation in the modulator φ: $\beta_0 = \beta + \varphi \cdot sin\omega t$. Thus,

$$I = KE_0^2 sin^2(\beta + \varphi_0 sin\ \omega t)$$

Having in mind that both β and φ_0 are small and $\varphi_0 << \beta$ so that the quadratic term in φ_0 can be neglected, the above equation can be simplified as:

$$I = KE_0^2\beta^2 + 2KE_0^2\beta\varphi_0 sin\ \omega t$$

The first term in this sum is constant and the second one is an AC component of the light intensity I which, as one can see, depends linear on the Faraday rotation β and thus on the local magnetic field. Thus, instead of measuring the DC light intensity, one can measure the AC signal using lock-in technique. Apart from converting a quadratic signal to a linear one, it has another advantage that the lock-in technique allows one to filter out the noise in the signal. As a result, local AC field with an amplitude as small as 0.1 G can be measured with a spatial resolution of 1 μm.

Due to the linearity of this measurement technique, its calibration is very simple. It is enough to take measurements in a homogeneous field with a known magnitude to calculate the conversion factor between the signal and the field values. As an example, in Fig. 6 we show a quantitative profile of the local magnetization of the telephone card from Fig. 5. The measurement was taken by scanning the sample in the microscope using a stepping motor.

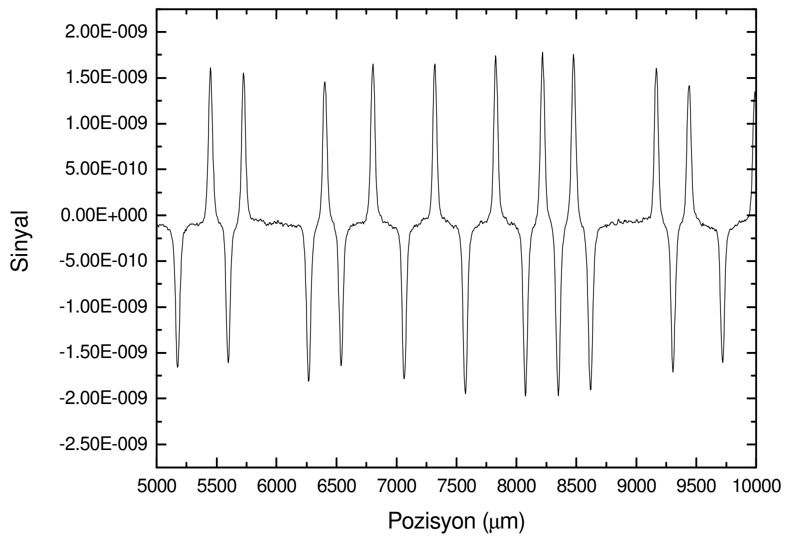

Fig. 6. Magnetooptic image of magnetic recording in a phone card.

Apart from its locality, the magnetooptic technique has another advantage, which is its fast response. The response time of the indicator films is determined by the magnetization dynamics and is below 0.1 μs. Thus very fast dynamic processes can be observed. This makes this technique very useful not only for practical applications, like characterization of phone cards in the example above, but also for R&D studies on new promising materials.

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Born in 1966 in Moscow/Russia. Graduated from Moscow Institute of Steel and Alloys in 1989. In the same year started to work as a researcher at the Institute of Solid State Physics, Russian Academy of Sciences. Received a PhD degree in physics in 1994. Starting from 1998 works in the Laboratory of Magnetism at TÜBİTAK Ulusal Metroloji Enstisüsü (UME), currently with the status of Head Senior Researcher.