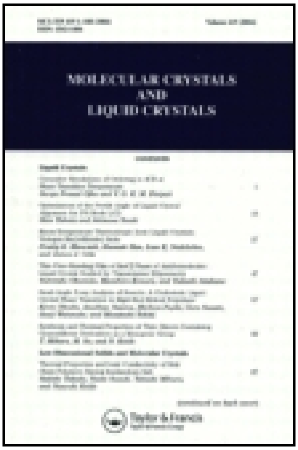

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LC Vision: The Application to Magnetic Material Domains Investigations

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The information about local changes of H-field detecting domain structures or magnetic inhomogeneities on the surface of magnetic materials is important for science and high technology. It may be obtained with thin layers (≈1 μm) of oriented NLCs and polarizing microscope. In the paper we summarize the universal application of LC vision to magnetic domains investigation in mineralogy, metallography and optical technology. In mineralogy the objects of investigation were the sections of rocks with inclusions of ferromagnetic minerals. On the surface of materials applied for storage devices such as $(YLa)_3Fe_5O_{12}$ *thin films being grown on the substrate of* $Gd_3Ga_5O_{12}$ *the labyrinthical, striped and cylindrical domain structures were observed in the case when the vector of H-field is parallel to optical polarization vector. The domains on the surface of thin amorphous Co based alloy ribbons were investigated using NLC materials with improved value of magnetic anisotropy. The NLC technique results were compared with the results obtained with magnetic emulsion technique.*

Keywords: liquid crystal; magnetic anisotropy; magnetic domains; polarizing microscope; visualization

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INTRODUCTION

Our paper is devoted to non-display application of LCs. The thin NLC layers (1 μm) applied on the surface under investigation as a free film and observed in polarizing microscope are being used in the science and high technologies for local H-field inhomogeneities detection on the surface of different materials [1]. The initial order in NLC is the physical basis for the visualization of H-fields. This order may be disturbed by H-field that may be used for its visualization on the sections of different materials. In the paper we summarize the universal application of LC vision for magnetic domains investigation in mineralogy, optical technology and metallography. The NLC technique was compared with traditional magnetic emulsion method.

THEORY

The fundamental mechanism of NLC orientation under the influence of H-field was first explained by famous Russian physicist V. K. Freedericksz [2–4]. He proved the threshold character of NLC deformations and gave their description as nonlinear equation in the flat layer of NLC [3]:

$$k\frac{\partial^{2}\varphi}{\partial x^{2}} - \chi_{a}H^{2}\sin\varphi\cos\varphi = 0 \tag{1}$$

φ – angular deviation caused by H-field; k – elasticity coefficient; χ_a – magnetic anisotropy.

He also found the expression for H-field threshold H_{th} and layer thickness h_{th}:

$$H_{th}h_{th} = \pi\sqrt{k/\chi_{a}} \tag{2}$$

The effect described by Eq. (2) was called in scientific literature as Freedericksz transition that may be used for local H-field inhomogeneities detection on the surface of different materials. Later the theory of elastic bend and splay deformations in NLCs was developed for the case of two-dimensional director fields **L**(x, y) in closed curvilinear cells exposed to inhomogeneous magnetic fields [5].

The idea of LC vision is based on the director orientation **L** correlation with the direction of local **H**-field. Director **L** tends to coincide with the direction of **H**-field, realizing the spatial distribution along the NLC layer of the intensity of transmissive (or reflective) polarized light. As the result the optical pattern appears, visualizing the distribution of magnetic field on the boundary surface. The gradients of light intensity ∇I are proportional to the gradient of reflection coefficient ∇n that are proportional to the angular gradients $\nabla \varphi$. The relations between these parameters are established with well-known equations.

The theoretical aspects of the NLC behavior in inhomogeneous H-fields were discussed in [5–8]. As was established by V. K. Freedericksz the NLC orientation in the magnetic field is determined by its susceptibility $\chi_{ik} = [(\chi_{||} + 2\chi_{\perp})/3] > 0$ described by the second order tensor

$$\chi_{ik} = \chi_{\perp}\delta_{ik} + \chi_a(\mathbf{L_i L_k}), \tag{3}$$

$\chi_{||}$, $\chi_{\perp}$ are diamagnetic susceptibilities parallel and perpendicular to the NLC director **L**, $\chi_a = \chi_{||} - \chi_{\perp}$, and δ_{ik} is the Kronker symbol.

In NLC the diamagnetic anisotropy has only positive values within the range from 0.3 to $1.04 \times 10^{-9}\ \mathrm{m^3\,mol^{-1}}$ [6], though **H**-field tends to orient the director along its lines of force. When the field strength **H** is enough to surmount the NLC elastic forces, the director reorients and a new stationary equilibrium is set (Freedericksz transition).

If the NLC molecules are oriented homeotropically to the substrate surface, the magnetization vector will lie in the same plane with the director and only the bend deformations are possible. In accordance with moments **L** and **H** equilibrium [7]:

$$(\mathrm{K}_1 - \mathrm{K}_3)\ \mathbf{L} \times \text{grad div } \mathbf{L} + \mathrm{K}_3\mathbf{L} \times \Delta^2\mathrm{L} + \chi_a(\mathbf{LH})(\mathbf{L} \times \mathbf{H}) = 0 \tag{4}$$

K_1, K_3 – are NLC elastic modules along axes x, y. For many NLCs $\mathrm{K}_1 = \mathrm{K}_3$. Let φ and ψ be the angles between y and **L**, y and **H** respectively. Then the moment equilibrium equitation can be written in the form

$$\Delta^2(2\acute{\alpha}) - (\chi_a/\mathrm{K}\mathbf{H}_2)\sin 2\acute{\alpha} = 0, \tag{5}$$

where $\acute{\alpha} = \varphi$ and ψ; $K = K_1 = K_2$.

This equation is valid for fields of any strength, which allows the NLCs to be considered as the media whose deformations unequivocally map the magnetic field topography at each point of the surface. In this case we didn't take into consideration the influence of the surface anchoring energy.

EXPERIMENTS

Two main particularities of NLCs are used in LC vision: smooth and local changes of phase delay in the layer. The recording of NLC local deformations becomes possible when the deformed layer is illuminated in the transparent or reflective mode and the arising interference pattern is studied with crossed polarizers. Three different cases of magnetic domains investigation in mineralogy, optical technology and metallography are discussed. In all cases the NLC technique was compared with the results obtained with magnetic emulsion technique.

A. Visualization of Magnetic Domains in Minerals

The study of mineral magnetic field topography is commonly conducted using either magnetic emulsion or Faraday effects [9]. Figure 1 shows the comparable images of the same sample of pyrrhonist surface decorated with magnetic emulsion and NLC.

Although both methods visualized the similar domain structure the character of the information obtained is essentially different. The emulsion method gave an implicit picture of domain distribution that required additional laborious investigations for interpretation. LC vision gave not only additional information about structural

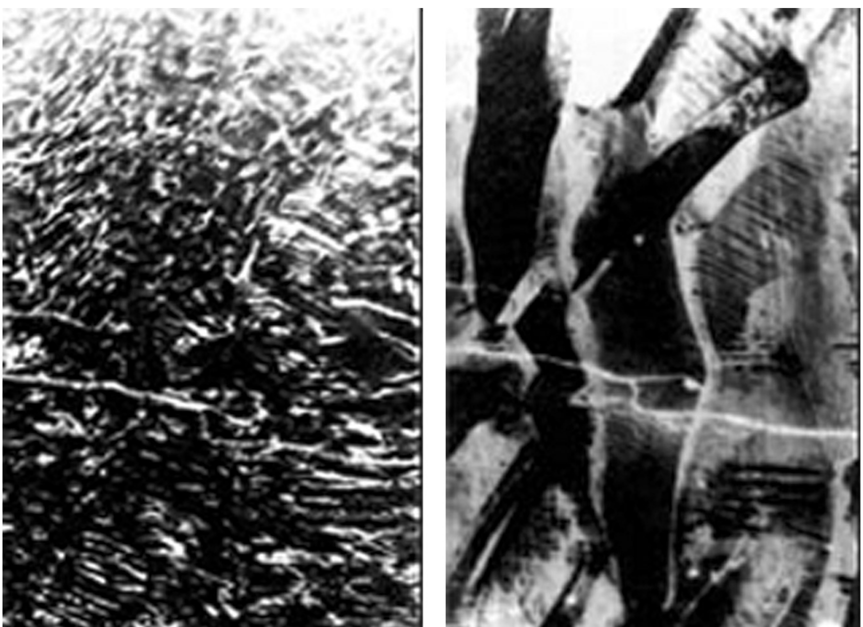


FIGURE 1 Magnetic domains at pyrrhonist surface decorated with magnetic emulsion (left) and MBBA:EBBA (right); T = 20°C, magnification 300×.

inhomogeneities of the sample but also presented magnetization direction at every surface point within the bounds of separate blocks, grains and other parts [8]. At every block the domain directions have regular orientation and the whole picture receive the clear interpretation.

The relation between geological structure and magnetic characteristics of minerals is still the subject of deep investigations. Figure 2 illustrates the possibilities of LC vision as a new tool for study magnetic properties of minerals, for example magnetic domains in magnetite from different deposits.

Figure 2 reveal two primary directions of domains orientation on the surface of magnetite from Kolsky peninsula deposit: parallel to the planes of structural stripes and at the angle 45°. LC vision opens new possibilities in detecting the past changes of Earth magnetic field orientation. This may be examined by visualizing samples paleomagnetism fixed in accordance with the period of their formation.

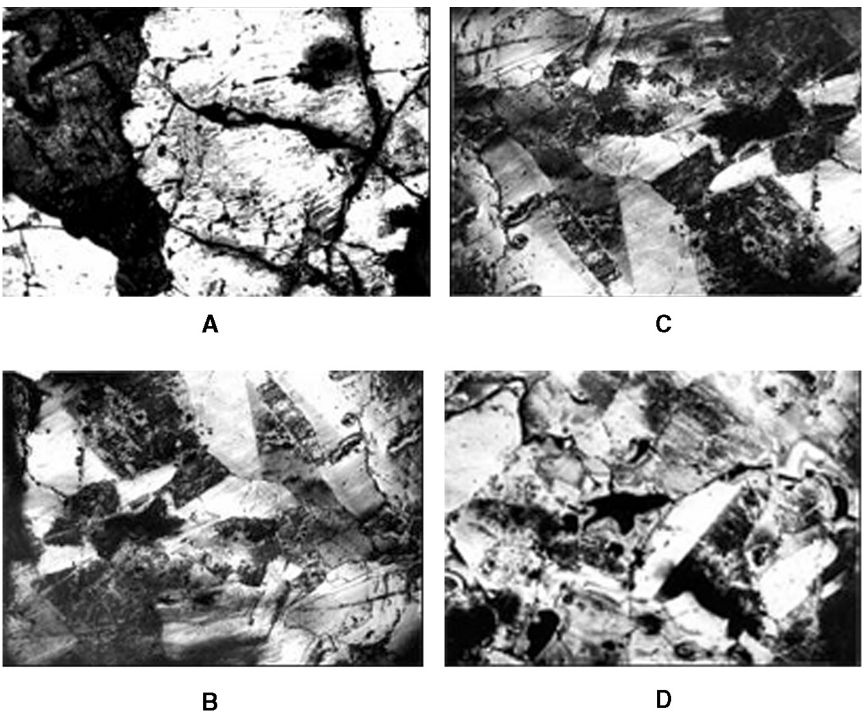


FIGURE 2 Domains in magnetite from Kovdorsky deposit (Kolsky peninsula) [A, B] and Lermontovsky deposit (Kolsky peninsula) [C, D]. MBBA:EBBA, 100×, T = 20°C.

B. Visualization of Magnetic Domains in Materials for Storage Devices

Double layers of ferrogarnet $(YLa)_3Fe_5O_{12}$ thin films being growth on the substrate of $Gd_3Ga_5O_{12}$ are used for storage devices with high density of recording information, based on cylindrical magnetic domains (CMD). The magneto optical defects in domains order may be the reason of defects in storage device functions. That is the reason for visualizing and study of CMDs.

The vector of **H**-field in the films may have parallel or perpendicular orientation to optical polarization vector **P**. In the case $\mathbf{H} \perp \mathbf{P}$, the visualizationof CMDs may be realized with Faraday magneto optical effect. When vector of **H**-field is parallel to optical polarization vector the domains cannot be visualized with Faraday method. In this case CMDs may be visualized only with NLCs. The Figure 3 pictures illustrate domain pattern detected with LC vision: stripe (1), labyrinth (2) and cylindrical (3) domain structures.

It was demonstrated that regular domain structures was disturbed by local magnetic inhomogeneities.

C. Visualization of Magnetic Domains in Thin Amorphous Co Based Alloy Ribbons

Thin amorphous Co based alloy ribbons are used for **H**-fields protection as new material for safety screens. The magnetic structure of amorphous films strongly depends on its manufacture technology. For detecting magnetic structure both emulsion and NLC methods were applied.

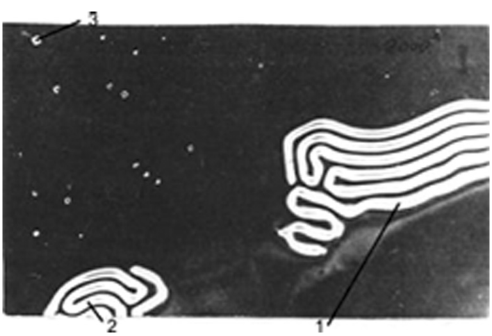


FIGURE 3 Domain pattern detected with NLC: stripe (1), labyrinth (2) and cylindrical (3) domain structures. T = 20°C, 5CB, 2000×.

It was established that the size of magnetic domains in the thin amorphous Co based alloy ribbons was less than the resolution of optical microscope. The initial constant H-field was additionally applied to increase the domain size. The patterns of magnetic domains visualized with both methods are shown on Figures 4 and 5 and gave mainly the similar results. The regions with magnetic domains were visualized only on small part of the sample surface. The detecting of domains took long period of exposition: one or two days. There also were some differences in obtained information.

The magnetic emulsion visualized domains with different orientation and two scale size 1 and 10 μm (Fig. 4).

NLC visualize different colors of domains that means the deferens of local H-field intensity. The domains size was between 1 and 20 μm. The different domains orientation means the presence of many magnetic inhomogeneities on the surface of samples. In comparison with emulsion method LC vision may be used as metrological technique for determination the intensity of magnetic field for individual domains.

The threshold of H-field of individual domain that leads to NLC molecules orientation may be calculated from its balance with polar anchoring energy with the surface. The value of anchoring energy is 10^{-2}–10^{-3} erg/cm^2 [1].

Well known organic diamagnetic liquid crystals like MBBA have $\Delta\chi < 120\ 10^{-6}$ cm^3/mol. [10]. For decreasing the period of exposition and increasing H-field sensitivity the new rare earth-containing liquid crystal with large magnetic anisotropy $\Delta\chi$ have been synthesized [11]. The metallomesogen containing rare earth ion with higher value of $\Delta\chi$ were oriented by H-field of domains in fraction of seconds. At a present

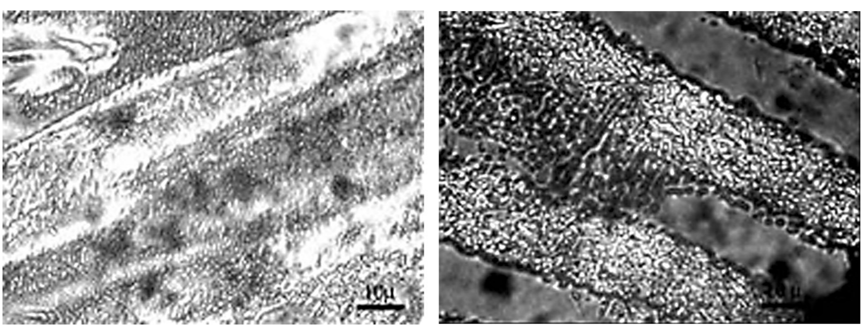


FIGURE 4 The patterns of magnetic domains visualized with emulsion method, T = 20°C.

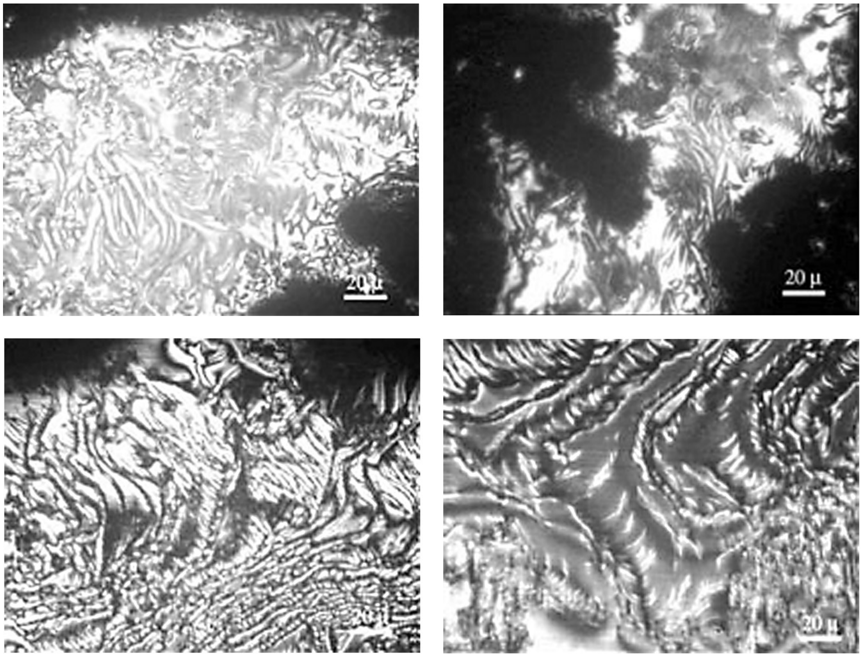
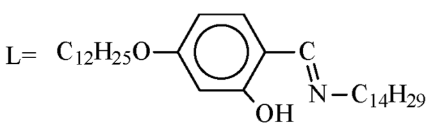
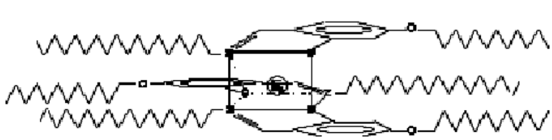


FIGURE 5 The patterns of magnetic domains visualized with NLCs, MBBA:EBBA, T = 20°C.

work we used the complex of Schiff's base with Tb(III) – $L_3Tb(C_{12}H_{25}SO_4)_3$ [12]. The general view on the ligand and complex structures are presented below:





These substances have transition temperatures Cr 84 Sm 115 I and high magnetic anisotropy $\Delta\chi = -22800 \cdot 10^{-6} cm^3/mol$. Due to the large magnetic anisotropy, they can be easy aligned by an external magnetic field. Another very interesting and promising feature of this class of

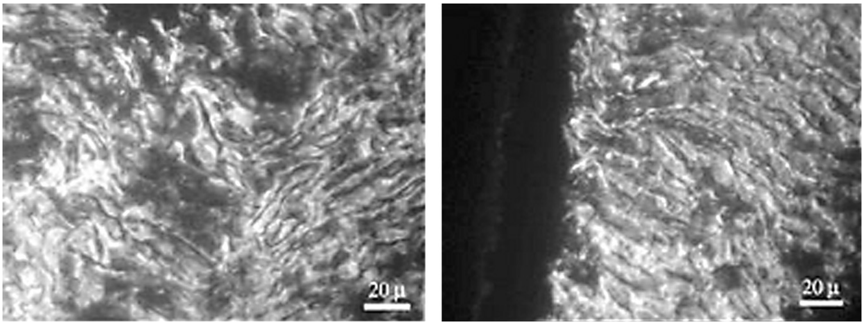


FIGURE 6 The patterns of magnetic domains visualized with $L_3Tb(C_{12}H_{25}SO_4)_3$.

compounds is their ability to super cooling. After cooling of the sample from mesophase to the ambient temperature they contain the texture that exhibited at high temperature. It gives new opportunities for recording domains pattern.

Figure 6A show the domain structure visualized with SmLC. Being cooled to crystalline phase (Fig. 6B) the material may record the image of magnetic domains in solid phase. The domains image may be saved in crystalline phase for a long time revealing storage effect.

Our calculations revealed that new material has the advantages in H-field visualization time of four orders and sensitivity of one order. The value of H-field energy at the interface of LC-magnetic material is approximately $1 \cdot 10^{-1}\,\text{erg/cm}^2$, that more than one order higher the value of LC anchoring energy.

CONCLUSION

LC vision demonstrated its efficiency in visualizing inhomogeneous magnetic fields or domains on the surface of minerals, storage devices, thin Co based alloy ribbons for safety screens and other magnetic materials. The advantage of LC vision in comparison with magnetic emulsion method is the possibility to visualize magnetic domains at the same time with visualizing structural inhomogeneities of the material.

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