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SLOW AND FAST MAGNETO-OPTICAL RESPONSE OF MAGNETITE NANOPARTICLES SUSPENSION

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ABSTRACT. DC magnetic field applied to Fe_3O_4 nanoparticle suspension affects its light scattering. Time dependent variations in the light intensity transmitted through a suspension are observed after the magnetic field is switched-on. Two types of variations can be distinguished. Fast response takes less than millisecond while slow variations occur at the time interval from seconds to hundreds of minutes. Possible mechanisms of these variations are discussed.

1. Introduction

Iron oxide (Fe_3O_4, magnetite) nanoparticles are of great interest due to their wide biological applications [1]. Most of these applications require suspensions of nanoparticles in biocompatible liquids, water in particular. The colloids of subdomain paramagnetic particles dispersed in a liquid carrier are termed ferrofluids. Ferrofluids exhibit a number of interesting magneto-optical phenomena. Suspended magnetic nanoparticles subjected to the external magnetic field form linear structures resembling thin chains and filaments oriented along the field resulting in a diffraction of incident light beam [2]. In this paper we

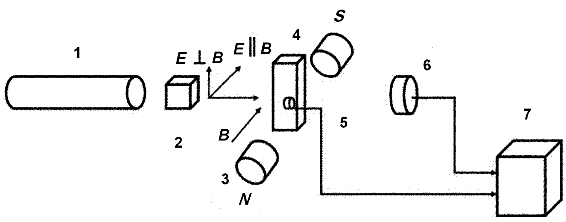

Figure 1. Experimental set-up. 1 - He-Ne laser, 2 - Glan-Thompson prism, 3 - DC electromagnet, 4 - sample cuvette, 5 - Hall probe, 6 - photodetector, 7 - computer.

present the results of transmission coefficient measurements recorded with high temporal resolution for the light beam perpendicular to the magnetic field (transverse geometry) and polarization plane being orthogonal and parallel to the applied magnetic field (Fig. 1).

2. Materials and Methods

An aqueous suspension of Fe_3O_4 (magnetite) nanoparticles was synthesized according to the procedure described by Massart [3]. The average size of the particles was found to be 10 nm from TEM measurements. Volume fraction of the suspension was determined by thermogravimetric analysis and amounts 0.0012. A standard 10 mm spectrophotometer glass cuvette poured with Fe_3O_4 colloid was placed between the poles of a DC-operated magnet. The magnetic flux density was measured by Hall probe and ranged within $0 \ldots 0.72$ Tesla. A He-Ne laser with a 632.8 nm wavelength was served as a light source. All experiments were performed at ambient temperature.

3. Results and Discussions

Time evolution of the relative transmission coefficient of Fe_3O_4 nanoparticle suspension or ferrofluid after applying the magnetic field is shown in Fig. 2. Relative transmission

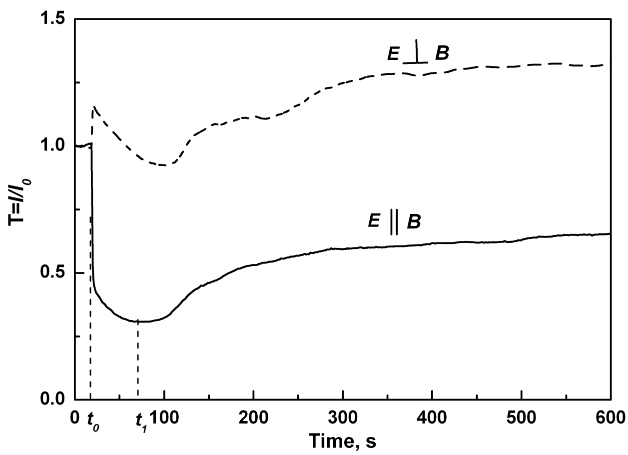

Figure 2. Slow variations of relative transmission coefficient of iron oxide nanoparticle suspension for both orthogonal (dashed) and parallel (solid) orientations of polarization plane. Magnetic flux density is 0.72 Tesla.

coefficient T is defined by the ratio of the transmitted light intensity after the magnetic field was applied to that one without the magnetic field. A well pronounced minimum is observed on each kinetic curve. The appearance of this minimum can be explained in terms of chain formation composed from the magnetite nanoparticles oriented along the external magnetic field.

Figure 3 depicts fast variations in both the intensity of transmitted light and the magnetic field flux density recorded at high sampling rate. As it is clearly seen from the figure the fast optical response after switching on the magnetic field does not exceed 1 ms. According to [2] the intensity of light I that is transmitted through a ferrofluid with thickness x is given by

$$I = I_0 \exp - \frac{4\pi}{\lambda} Im\,(n)\,x, \tag{1}$$

where λ is the wavelength of light, n is the refractive index of ferrofluid. The latter may be introduced as follows

$$n_{||} = \mu \left\{1 + 2\pi N \left[\alpha_o + (\alpha_e - \alpha_o)\, L\,(\xi)\right]\right\} \tag{2}$$

$$n_{\perp} = \mu \left\{1 + 2\pi N \left[(\alpha_e + \alpha_o)/2 - (\alpha_e - \alpha_o)\, L\,(\xi)\,/2\right\}\right] \tag{3}$$

where μ is the index of refraction of carrier fluid (water), N is a concentration of nanoparticles, α_e, (α_o) is the polarizability of the particle parallel (perpendicular) to the optic axis, $L(\xi) = coth(\xi) - \xi^{-1}$ is the Langevin function with $\xi \equiv mH/k_B T$, m is the magnetic moment of a particle, H is a magnetic field strength, k_B is the Boltzmann constant. From the analysis of (1) - (3) follows that transmissivity of iron oxide ferrofluid exposed to the magnetic field depends on orientation of polarization plane with respect to the direction of magnetic field. It was experimentally found that the effect weakens with the decrease of nanoparticle concentration until it vanishes for pure water.

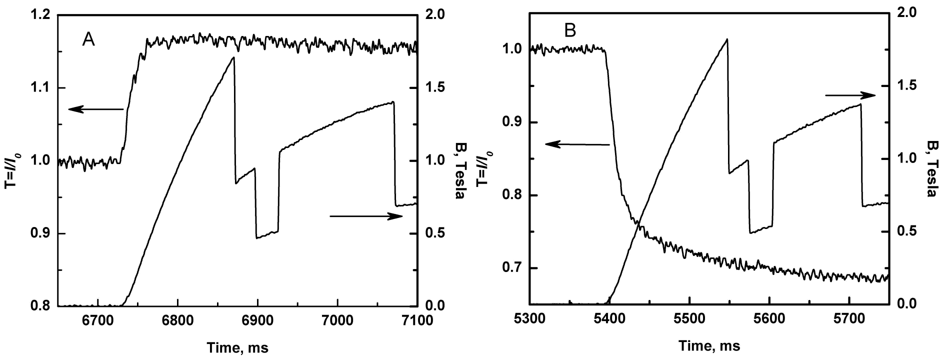

Figure 3. Fast magnetically induced variations of relative transmission coefficient. Panel A - polarization plane orthogonal to the magnetic field, B - parallel to the magnetic field. The magnetic field undergoes ringing before it reaches stable value due to a feedback with controller.

Two different processes take place when the magnetic field is applied to the superparamagnetic nanoparticles suspended in a medium. They are Néel process when the magnetic moment within a nanoparticle orients along the magnetic field and Brown process which is the rotation of the particle itself in the carrier. The characteristic times associated with each process are substantially different. It amounts $\sim 10^{-9}$ s for Néel process and $\sim 10^{-5}$ s for Brown one respectively. Observed phenomenon is a strong argument that fast optical response of magnetite ferrofluid is due to the arrangement of magnetic moments according to the applied magnetic field, no particles aggregation is involved. To distinguish between the relative contributions of both processes additional experiments are required.

4. Conclusions

It was experimentally found that the intensity of light transmitted through an aqueous suspension of magnetite nanoparticles varies after the external magnetic field is applied. Slow variations in the time span of ~ 10 s $\ldots \sim 100$ minutes is a consequence of aggregation of the nanoparticles due to magnetic interactions between them. Fast variations with characteristic time about 1 ms are caused by either particles rotation or by the reorientation of the magnetic moment inside a nanoparticle according to the direction of the external magnetic field. This makes iron oxide nanoparticles an appealing platform for high-speed magneto-controlled optical devices. Understanding of the interaction of light with magnetite nanoparticles in a presence of the magnetic field is also of great fundamental interest.

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