# Nonlinear Optical Phenomena in Iron Oxide Containing Magnetic Nanocolloids

**A. V. Prokofiev**[1,2], **V.M. Petrov**[1], **I. V. Pleshakov**[1,2], **and A. V. Shamray**[1,2,3]

[1]St.-Petersburg Polytechnic University, St.-Petersburg, Russia
[2]Ioffe Institute, St.-Petersburg, Russia
[3]ITMO University, St.-Petersburg, Russia

**Abstract**— Nonlinear optical properties of magnetic liquids (ferrofluids) are discussed in this work. The experiments were performed on a series of samples with different concentration of magnetite. By the method of $z$-scan it was demonstrated that the materials has a strong nonlinearity, primary determined by the thermal mechanism. The obtained data can be used in optoelectronic devices, where the ferrofluid employed as an active element.

## 1. INTRODUCTION

In present work the peculiarities of optical behavior of magnetic colloids (ferrofluids) are discussed. These materials are solutions of magnetic nanoparticles, suspended in a carrier fluid, and exhibiting a number of specific physical properties, [1]. Ferrofluids have been studied since the 1960s but still remain an important research object because new physical phenomena are constantly revealed in them. These substances find different applications, for example, they are considered to be promising for biomedical purposes, [2, 3]. The other important trend it the area belongs to the optical devices, where ferrofluid can be used as an active element. The operation of such systems is based on the magneto-optic effects which have pronounced features in solutions of magnetic particles. There are optoelectronic devices in which the interaction of light with the material occurs at large lengths. These are fiber-optic systems with a ferrofluid-filled microstructure, [4–7]. It can be expected that under certain conditions nonlinear properties of ferrofluids will manifest themselves in them, which is important from not only practical but also fundamental point of view. Our task was to investigate the nonlinear response of bulk ferrofluids under the action of external magnetic field.

## 2. SAMPLES AND EXPERIMENTAL TECHNIQUE

We studied the samples based on kerosene and water solutions of magnetite ($Fe_3O_4$), prepared by using the technology which gives nanoparticles with an average size of about 10 nm. They were synthesized from the solution of $FeCl_3$ and $FeSO_4$ by precipitation with ammonia water and subsequent filtering, washing, drying and separation. To provide an optical transparency, the samples were diluted from the initial concentration (several percent) to 0.02–0.2 vol. % of the solid phase content. The samples were fabricated as thin layers (100 μm) of the liquid, placed between two glass plates.

The measuring technique was chosen to be $z$-scanning [8], involving displacement of the sample along a focused laser beam. Fig. 1 shows an arrangement of experiment. The setup included a compact electromagnet which produced a magnetic field $H$ of 0–500 Oe or permanent magnet with $H = 1$ kOe. H, applied to the sample, was perpendicular to the light beam.

The light polarization could be either parallel or perpendicular to the field. The magnet could move together with the sample along the beam, thus passing through the region with the maximum optical energy concentration. As a radiation source, a Nd:YAG-laser was used (the second harmonic, $\lambda = 532$ nm).

In order to increase the signal-to-noise ratio the modulation method, utilizing chopper and lock-in amplifier, was employed as it is indicated in Fig. 1. The iris diaphragm, placed in the far field diffraction zone, permitted to detect the light in two regimes: with closed aperture, when the standard $z$-scan pattern was registered [8], and with open aperture, when the total light energy, passed through the sample, was collected.

## 3. RESULTS OF THE EXPERIMENT

Example result of the experiment with the closed aperture is shown on Fig. 2. Here the following parameters were used: the initial power of light radiation $P_0 \approx 0.6$ mW, the focus distance of lens $f = 6$ cm, focused Gaussian beam waist radius $w_0 \approx 25$ μm. It can be seen that the maximum

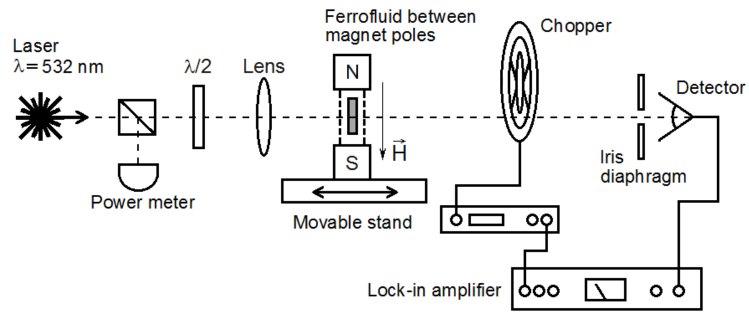


Figure 1: Experimental setup. The sample with the magnet is mounted on the stand, which can move along the optical beam ($z$ axis) near the focus of lens.

relative light intensity considerably exceeds the intensity in the region where the sample is far enough from the focus. The $z$-scan curves typical of the defocusing nonlinearity were obtained. The efficient third-order nonlinear refractive index $n_2$ was estimated to be $\approx -4.4 \times 10^{-7}$ m$^2$/W, which was rather high. The predominant contribution into the refractive index nonlinearity is likely to come from thermal effects owing to a high absorption at 532 nm. The graphs show that the magnetic field affects the transmission of the sample so that the light with the polarization parallel to $H$ is absorbed to a greater degree than in the case of the perpendicular polarization orientation relative to the field. The latter can be explained by the phenomenon of induced magneto-optical dichroism which is known to exist in ferrofluids, [9]. At the minimum, however, the difference disappears. It can be supposed that the effect of the thermal lens formed in the sample in this case is so strong that the dependence of the intensity on polarization becomes indistinguishable.

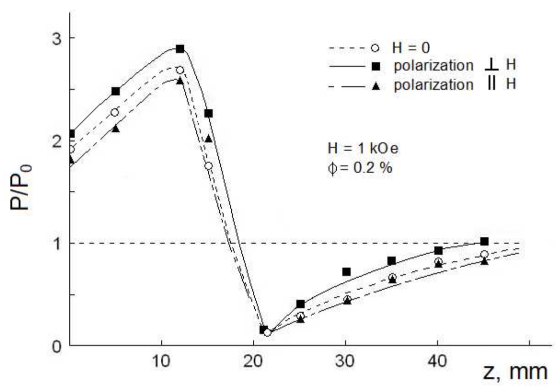


Figure 2: The case of closed aperture. Relative detected optical intensity vs sample translation distance along $z$ axis for the different orientations of the light polarization in respect to the magnetic field (kerosene-based sample).

Figure 3 shows the result of the experiment with an open aperture. The laser power in this experiment was somewhat higher, about 14 mW, and the lens had $f = 12$ cm, the beam waist radius $w_0 \approx 50$ µm. The radiation was collected in the photodetector by an additional lens placed behind the sample. The decrease in the intensity of the light transmitted through the substance as the sample approached the lens focus (a minimum in the $P/P_0$ curve existed even in the absence of magnetic field) was likely to be due to negative thermal diffusion which led to a growth of a particle concentration in the region of the beam, which, in its turn, increased the optical energy absorption and scattering.

As can be seen from Fig. 3, the magnetic field exerts different influences on the behavior of laser beams with different polarizations. The effect can be attributed to specific features of scattering. The field gives rise to formation of agglomerates of magnetic particles which are extended along the field and participate in the thermomagnetic convection which depends on the polarization orientation relative to the agglomerates. Since the latter create a scattering medium, the intensity of the radiation transmitted through the material becomes dependent on its polarization. This is confirmed by the presence of the dynamic pattern observed in the region of the light spot.

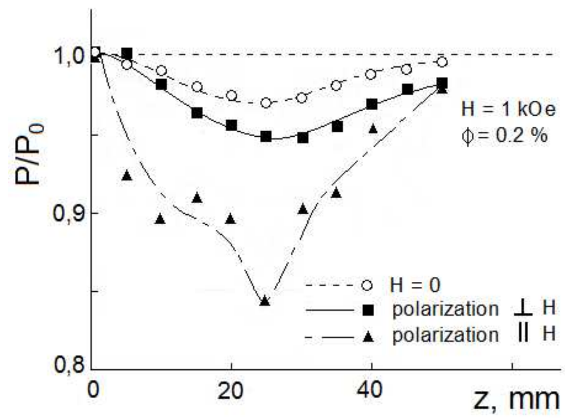


Figure 3: The case of open aperture. Relative detected optical intensity vs sample translation distance along $z$ axis for the different orientations of the light polarization (kerosene-based sample).

The conformable results were obtained for the solutions of different $\phi$ as well as for water solutions of $Fe_3O_4$.

## 4. CONCLUSION

To summarize, it has been shown that the $z$-scanning technique reveals strong optical nonlinearity of diluted magnetite-based ferrofluids. It was found that the magnetic field exerted an influence on the nonlinear characteristics of the materials, which can be attributed to the formation of agglomerates of nanoparticles. The field dependent effects related to the light scattering were also observed. In our opinion, the results of work can find an application in such area as optoelectronics for elaboration of magnetically controlled elements.

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