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The effect of a thermal lens at double-beam laser action on a magnetic fluid

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A light-induced inhomogeneity in the form of a lens of thermal nature in a magnetic fluid, which is a colloidal solution of magnetite, has been studied using two laser beams. The application of this scheme made it possible to independently observe the occurrence of a feature in the area of an intense laser beam by recording a diffraction pattern in an additional weak probing beam. It was found that the size of the diffraction patterns formed in each of these rays depends on the magnetic field.

Keywords: magnetic fluid, ferrofluid, thermal lens.

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Magnetic fluids (ferrofluids) have been known since the 1960s and have found numerous applications in a wide variety of fields over the past decades [1]. These unusual materials are still being studied today, and their new properties and additional possibilities for practical application are still being discovered. Specifically, the medical aspects of this research have been discussed widely in recent years [2–5], and the prospects for fabrication of optoelectronic devices (magnetic field sensors, modulators, tunable filters, etc.) based on such materials have been examined [6–11].

The optical characteristics of ferrofluids depend on the magnetic field, which makes them promising for use as controlled photonic elements. The analysis of such modulation of their optical response is still relevant. Along with other mechanisms, thermal effects have a significant influence on this response. A convenient tool for studying them is the observation of a thermal lens, which has been experimented with in, along with other dispersed systems, magnetic fluids [12,13]. It was demonstrated that a lens may be characterized as a region with a refraction index varying in a complex manner. This region forms in a focused laser beam due to thermally induced redistribution of the concentration of colloidal particles (an inhomogeneity regarded as an equivalent concave lens emerges in a Gaussian beam [13]). In all cases, the recorded and analyzed response was a diffraction pattern shaped by the interaction of the beam with the object it generated.

In the present study, a setup with two lasers was used to devise a method for independent scanning of a thermal lens. One laser (hereinafter referred to as the excitation laser) was focused on the sample, and the other (probing laser with a reduced radiation power density at the sample) was directed at an angle to it.

The diagram of the setup is shown in Fig. 1. A He−Ne laser with an emission wavelength of 633 nm and an output power of 17 mW was the excitation one. Its beam was concentrated at the sample by a lens. The power density in the focal region was close to $1.8 \cdot 10^7$ W/m^2. The probing laser was directed at angle $\alpha = 20^\circ$ to the excitation one and was a laser diode with a wavelength of 660 nm and a power of 12 mW. It was focused outside the sample in such a way that the power density in its light spot, combined with the inhomogeneity induced by the first laser, did not exceed $4 \cdot 10^3$ W/m^2 (i.e., was insufficient to a exert a significant influence on the refraction index distribution). A response in the form of two diffraction patterns was observed on the screen. The setup allowed for the application of external magnetic field H produced by Helmholtz coils and oriented perpendicular to the sample plane. It could be varied within the range of 0−750 Oe.

The sample was placed in a plane-parallel optical cell with a thickness of 60 μm and was a kerosene-based colloidal

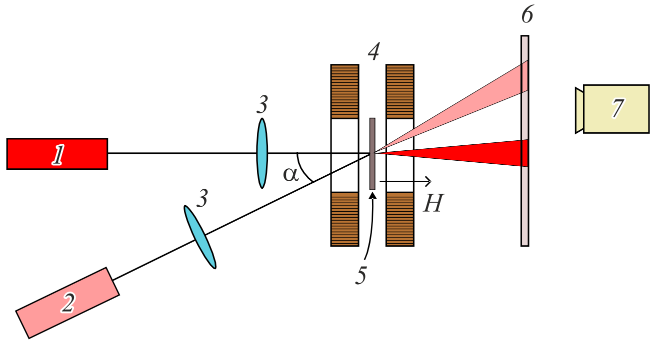

Figure 1. Experimental setup for double-beam study of the thermal lens effect. *1* — Excitation laser, *2* — probing laser, *3* — focusing lens, *4* — Helmholtz coils, *5* — sample, *6* — screen, and *7* — camera.

solution of magnetite Fe_3O_4 (a commercial ferrofluid with polymer stabilization and up to 22 vol.% of added organic oil). The magnetic material particles had an approximate size of 10 nm. The same substance was used in [14] (note that the effect of interaction of nanoparticles with a laser beam was examined in this study). The initial concentration of the solid phase (N) was 18 vol.%; in experiments, the fluid was diluted to $N = 1-3$ vol.%.

Figure 2 shows an example of diffraction patterns for the sample with $N = 2$ vol.% at two field values: $H = 0$ and 700 Oe (Figs. 2, a and b, respectively). The light spots observed in two beams are generally similar with well-resolved concentric rings. However, they have certain subtle differences: while their characteristic sizes are approximately equal, the spot from the probing beam has slightly larger dark gaps between the rings; in addition, it has a near-elliptical shape with estimated eccentricity $e \approx 0.53$. The application of the field induces an increase in the size of spots and the number of rings, while the ellipticity of the spot from the probing beam decreases ($e \approx 0.47$).

The dependences of relative sizes of the diffraction patterns on H are shown in Fig. 3 (D is the diameter of the outer ring and D_0 is the diameter of the outer ring at $H = 0$). The field dependences for the excitation (Fig. 3, a) and probing (Fig. 3, b) beams are closely similar. It is evident that the concentration of the magnetic fluid has a strong influence on the magnitude of D variation; at all N, the approximate similarity of curves $D(H)/D_0$, which reach saturation approximately at $H = 200$ Oe, is preserved.

It is evident that the mechanism of formation of the diffraction pattern in the excitation beam is no different from the phenomena of this kind discussed earlier. The spot formed by the probing beam is the result of diffraction at the feature produced by radiation of the excitation laser. Lateral

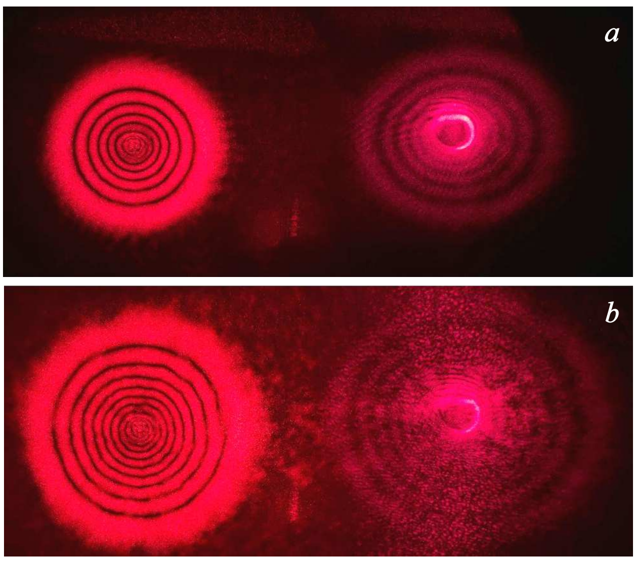

Figure 2. Diffraction of the excitation (left) and probing (right) beams for the sample with a magnetic phase concentration of 2 vol.% at $H = 0$ (a) and 700 Oe (b).

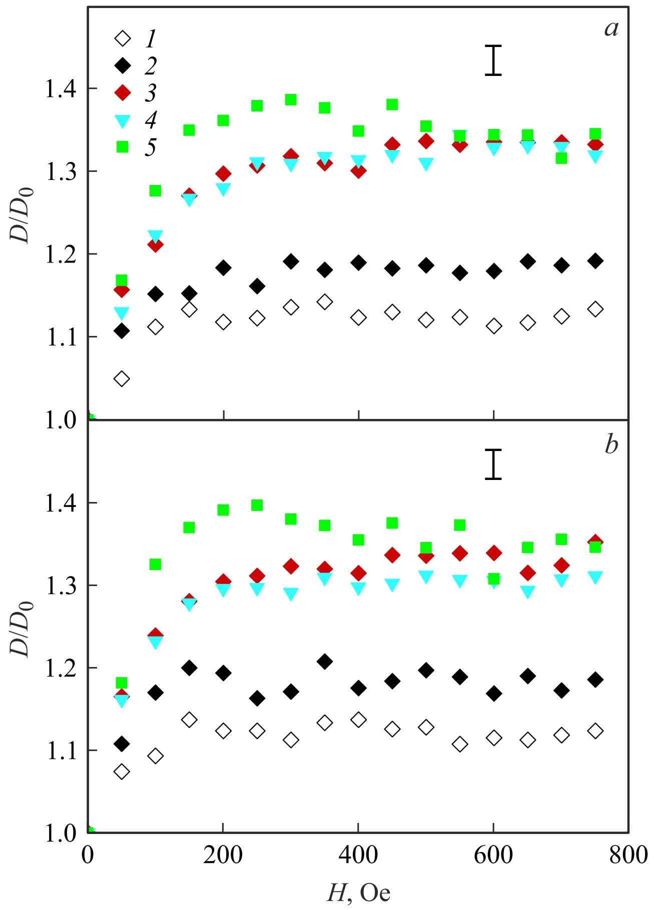

Figure 3. Dependence of the diffraction spot size in the beams of excitation (a) and probing (b) lasers on the magnetic field. N, vol.%: *1* — 1.0, *2* — 1.5, *3* — 2.0, *4* — 2.5, and *5* — 3.0.

illumination of this object (in the present case, at a small angle) yields a generally similar image, which is slightly altered compared to the main one. The size of the region in the bulk of the sample where the radiation power of the excitation laser is concentrated may be estimated using the known expressions for beam diameter at the lens focus $2w_0$ and Rayleigh length z_R. The values corresponding to the parameters of our optical circuit are $2w_0 \approx 35\,\mu$m and $z_R \approx 900\,\mu$m. It is evident that the extent of the structure formed by light is limited by the thickness of the cell; i.e., its characteristic dimensions are $\sim 35 \times 60\,\mu$m. It is fair to assume that the elongation of this object is reflected in the elliptical shape of the diffraction spot originating from the probing beam.

It is known that refraction index n of ferrofluids increases with magnetic field strength [15]. This is what causes the changes in diffraction patterns observed when H is applied. Treating the light-induced inhomogeneity as a concave lens with certain specified parameters, one may obtain a reduction in its focal length with an increase in $n(H)$ (i.e., obtain an increase in divergence angle of the laser beam and, consequently, D). While this simplified description provides an explanation for the observed effects at a qualitative level, it leaves out other processes occurring in the system. Specifically, the features of behavior of a ferrofluid under the application of H must be taken into account. Aggregates forming in the magnetic field are comparable in size to the region bounded by the caustic. The latter is most likely combined with a single aggregate, producing a feature with a complex spatial distribution of nanoparticles. Orienting magnetic moments, the magnetic field drives their convergence due to the dipole interaction and, consequently, induces an increase in N, which causes an increase in n. Note also that the thermal mechanism is, in all likelihood, not the only one contributing to the formation of this inhomogeneity. Other possible ways of interaction of nanoparticles with light are also known (see, e.g., [14] and references therein).

The saturation of $D(H)/D_0$ dependences, which occurs much earlier than is recorded in the magnetization curves, is consistent with the results obtained for $n(H)$ in [15], where the growth of n was reported to slow down significantly starting from $H \approx 150-200$ Oe. The change in ellipticity of the diffraction spot in a strong field is probably associated with the fact that the radial size of the thermal lens increases with an increase in concentration of nanoparticles of the solid phase that form it.

Thus, a method for obtaining data on a thermal lens induced in magnetic fluids by laser radiation was proposed. The method expands the possibilities of experimental approaches to this phenomenon and was used to perform a preliminary study of the magnetic behavior of this type of inhomogeneity in a magnetite-containing ferrofluid.

Conflict of interest

The authors declare that they have no conflict of interest.

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