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A DUAL-BEAM METHOD FOR STUDYING THE INHOMOGENEITY INDUCED BY LASER RADIATION IN A MAGNETIC FLUID

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Abstract. In the paper, a new method of experimental study based on the induction of a so-called thermal lens (TL) by the focused high-level laser radiation has been put forward for magnetic fluids. This TL is a region with a spatially changing refractive index, which occurs due to the redistribution of the nanoparticle concentration in the material and the thermal expansion of the carrier fluid. This region was illuminated by the low-level light emission of an auxiliary laser. The optical response of the medium was recorded as diffraction patterns formed from each of these two beams. The shape of the diffraction pattern in the auxiliary beam was shown to depend on the angle at which it was directed to the TL. The diffraction spot sizes were found to depend on the strength of the applied external magnetic field.

Keywords: magnetic fluid, laser radiation, thermal lens, light-induced inhomogeneity, diffraction pattern

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ДВУХЛУЧЕВОЙ МЕТОД ИССЛЕДОВАНИЯ НЕОДНОРОДНОСТИ, ИНДУЦИРОВАННОЙ ЛАЗЕРНЫМ ИЗЛУЧЕНИЕМ В МАГНИТНОЙ ЖИДКОСТИ

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Аннотация. В статье предложен новый метод экспериментального исследования магнитной жидкости, основанный на эффекте индуцирования в ней так называемой тепловой линзы под действием высокоинтенсивного сфокусированного лазерного излучения. Такая линза – это светоиндуцированная неоднородность, и она представляет собой область с пространственно-изменяющимся показателем преломления, которая формируется в результате перераспределения концентрации наночастиц в жидкой среде и теплового расширения жидкости-носителя. Указанная область просвечивается световым пучком вспомогательного лазера малой интенсивности. Оптический отклик среды регистрируется в виде дифракционных картин, образующихся от каждого из двух лазерных пучков. Установлено, что размеры дифракционных пятен зависят от напряженности приложенного внешнего магнитного поля.

Ключевые слова: магнитная жидкость, лазерное излучение, тепловая линза, светоиндуцированная неоднородность, дифракционная картина

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Introduction

Magnetic fluids, which are colloids whose solid phase is a magnetically ordered material, find diverse different practical applications [1, 2]. They are also of interest for research: for example, recent studies considered the behavior of such fluids embedded in biological systems [3–5] and other complex media [6-8]. Optoelectronic devices (modulators, sensors, tunable filters, etc.) with an active medium based on magnetic fluids are considered in many works [9–12].

A key factor to take into account in exploiting the optical properties of these substances is that a high-intensity laser beam alters the concentration of magnetic nanoparticles. This effect can be attributed to several mechanisms, the primary one being thermal (see [13] and references therein). A change in concentration leads to a change in the refractive index n and the appearance of a lens-like inhomogeneity in the sample, the so-called thermal blooming or thermal lensing (TL), on which the light diffracts. This is in fact a type of self-diffraction. TL under high-intensity laser radiation is characteristic for many materials, in particular, it has been observed in magnetic fluids [14, 15].

The common technique for studying TL is focusing a laser beam in a medium, measuring the diffraction of the same beam on the inhomogeneity induced by it. The information obtained from such experiments is essential both for developing photonics devices and for understanding the nature of the processes occurring in such systems.

Since laser radiation induces TL and diffracts on it, its characteristics (power, beam shape, etc.) cannot be varied without it modifying the object studied.

In this paper, to study the effect of thermal lensing, we propose to use an auxiliary low-intensity laser illuminating the induced inhomogeneity at a certain angle. The advantage of this approach is independent probing of the studied object.

Experimental

Samples. The samples were made from a commercial magnetic fluid with a solid fraction consisting of magnetite nanoparticles with an average diameter of about 10 nm. The solvents were kerosene and water with added organic oils and stabilizers (surfactants that prevent aggregation). They were diluted with the appropriate carrier to concentrations φ = 1–3 vol.%. The fluid was placed in a cell with the thickness d = 60 μm.

Experimental setup. Fig. 1 shows a diagram of the experimental setup. The primary light source (a helium-neon laser) had a wavelength of 633 nm and a power of 17 MW. Its radiation was focused on the sample with a lens; according to estimates of focal spot size, the optical irradiance in it was 18 MW/m^2. Radiation from an auxiliary semiconductor laser with a wavelength of 660 nm

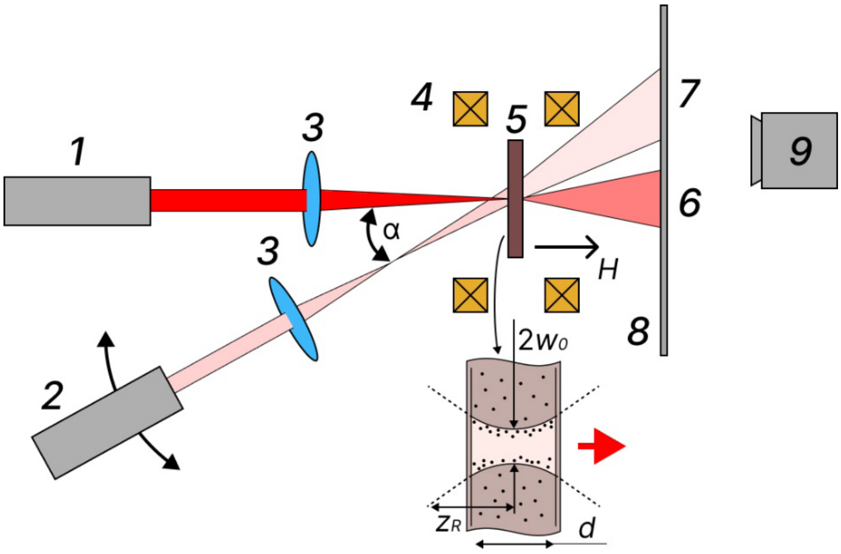

Fig. 1. Schematic of experimental setup: primary and auxiliary lasers *1*, *2*, respectively; focusing lenses *3*; electromagnet *4*; cell *5* with sample; diffraction spots *6*, *7* from primary and auxiliary beams, respectively; screen *8*, digital CMOS (Complementary Metal-Oxide-Semiconductor) camera *9*
Inset: region of laser beam focused on the sample, with the waist parameters

and a power of 12 MW was focused onto the sample. The irradiance from this laser beam on the inhomogeneity induced by the primary laser did not exceed 4 kW/m^2 (by our estimate), i.e., it could not have any significant influence on it. Each of the two beams formed its own diffraction pattern on the translucent screen located behind the cell.

The cell with the magnetic fluid was placed in an electromagnet generating field with the strength H orthogonal to its plane, variable from zero to 60 kA/m.

The dimensions of the TL were estimated assuming its boundary is approximately defined by the caustic (see inset in Fig. 1); the parameters characterizing the laser beam waist were used: its diameter at the beam focus $2w_0$ and the Rayleigh length z_R. They were calculated using well-known formulas, equaling 35 and 900 μm, respectively, for the geometry of our optical circuit. Since the thickness of the cell d is much smaller than the Rayleigh length z_R, we assumed that the inhomogeneity had an approximately cylindrical shape with a diameter of about 35 μm and a length of 60 μm.

Results

Several series of diffraction patterns were obtained in the experiments under different conditions and for different samples (Fig. 2).

Pronounced diffraction patterns appearing as concentric rings were observed in both beams for the kerosene-based magnetic fluid (see Fig. 2,*a*), which were noticeably influenced by the application of the magnetic field (see Fig. 2,*b*). The spot in the auxiliary beam was elongated, and an increase in the angle α led to an increase in its ellipticity (see Fig. 2,*c*). The spot sizes in water-based samples were much smaller than in the kerosene-based samples (Fig. 2,d shows an image obtained at about three times the screen distance from the cell). It is evident that the diffraction rings are poorly resolved (the diffraction pattern from the auxiliary beam, located on the right in Fig. 2,*d*, is magnified by several times for clarity). For this reason, only the results obtained for kerosene-based samples are given below.

The size D of the diffraction patterns depended on the magnetic field strength H, while the variation in this size can be conveniently characterized by a normalized parameter

$$Q(H) = D(H)/D_0,$$

where $D(H)$, D_0 are the average diameters of the outer ring of the diffraction spot at field strength H and at $H = 0$, respectively.

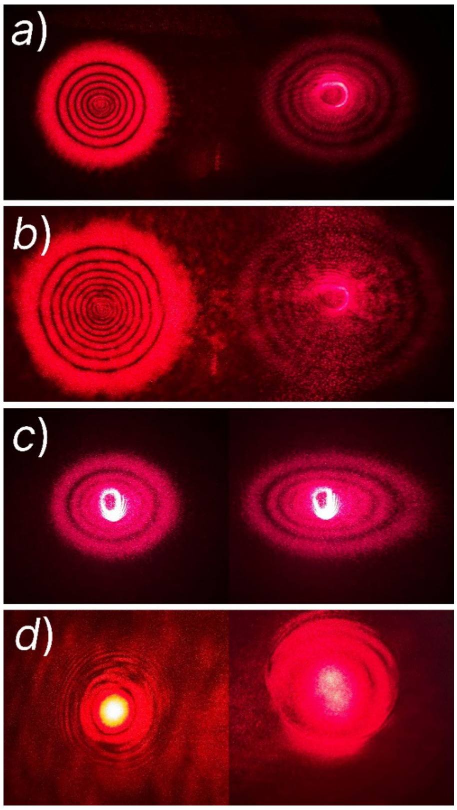

Fig. 2. Examples of diffraction patterns from different samples under different conditions: samples based on kerosene, φ = 2 vol.% (*a*–*c*) and water, φ = 3 vol.% (*d*); applied magnetic fields *H* = 0 (*a, c, d*) and *H* = 56 kA/m (*b*); images from primary (left) and auxiliary (on the right) beams are shown (*a*,*b*,*d*); angle α (see Fig. 1) was equal to 20°. The difference in Fig. 2,*c*: here both images are from auxiliary beams: at α = 35° on the left and at α = 55° on the right

The dependences of *Q* on the magnetic field strength for some concentrations φ are shown in Fig. 3. The angle α was chosen small here so that the elliptical distortion of the response in the auxiliary beam was negligible. It can be seen that the shapes of the *Q*(*H*) curves for the responses in the primary and auxiliary beams coincide. The concentration dependences *Q*(φ) are shown in Fig. 4, illustrating the increase in the relative size of diffraction spots with increasing concentration.

Discussion

Analyzing the obtained experimental results, we can interpret them as follows. If a cylindrical inhomogeneity induced by radiation from the primary laser is placed in an additional radiation field from the auxiliary laser directed to the axis of the main laser at an angle, then another diffraction pattern similar to the primary one should appear on the screen; this is in fact exactly what is observed. The diffraction spot from the auxiliary beam becomes more elliptical with increasing angle α between the axes of the two lasers, which correlates with the elongation in the projection of the cylindrical inhomogeneity under side illumination, so that the number of resolved rings in the diffraction pattern decreases.

Since the size of the diffraction patterns is much smaller in the case of the water-based magnetic fluid, it is logical to assume that the characteristic size of TL in them should be estimated as larger than in kerosene-based samples. This assumption is consistent with the results obtained in [13], finding that such magnetic fluids tend to form large nanoparticle aggregates under laser radiation, significantly exceeding $2w_0$ (beam waist diameter).

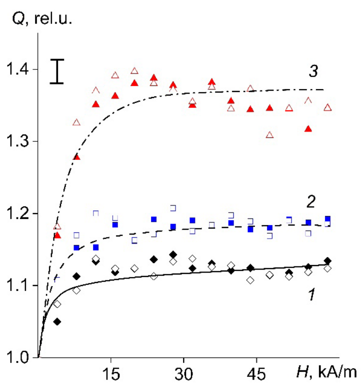

Fig. 3. Dependences of relative sizes of diffraction spots on magnetic field strength in kerosene-based magnetic fluids at different concentrations φ, vol.%: 1.0 (curve *1*), 1.5 (*2*), 3.0 (*3*)

Data are shown for primary (shaded symbols) and auxiliary (unshaded symbols) laser beams at angle α = 20°

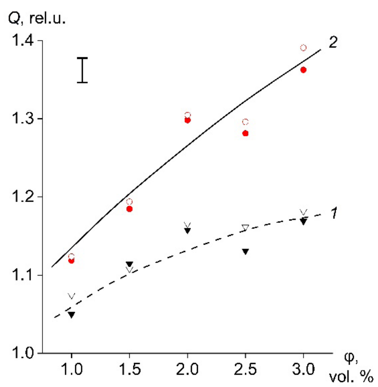

Fig. 4. Concentration dependences of relative sizes of diffraction spots in kerosene-based magnetic fluids at magnetic field strengths *H* = 4.0 kA/m (*1*) and 16 kA/m (*2*)

Data are shown for primary (shaded symbols) and auxiliary (unshaded symbols) laser beams

The behavior of optical responses in the magnetic field is qualitatively explained by the properties of magnetic fluids. It is known that chain-like aggregates arise in them under the influence of magnetic fields, with the diameters ranging from units to several tens of micrometers (for liquid media, where kerosene or water are solvents and the magnetic field strength H is more than 8 kA/m) [16, 17]. These sizes of the aggregates are comparable to the diameter $2w_0$, i.e., the inhomogeneity induced by laser radiation is commensurate with the magnetically induced aggregate. It is natural to assume that the shape of this object does not radically change upon application of the magnetic field. However, the spatial distribution of particles (and the refractive index $\boldsymbol{n}$ associated with their concentration [17]) in the object is transformed due to dipole interaction of magnetic moments aligned with the vector of the magnetic field. An increase in the divergence of the laser beam passing through the TL was observed in kerosene-based samples with increasing magnetic field strength, indicating a decrease in the size of the TL.

Evidently, the graphs of the functions $Q(H)$ for different concentrations φ are almost similar, reaching saturation at a magnetic field of about 15 kA/m (see Fig. 3). The value of the field strength at saturation we obtained differs from the values typical for magnetic fluids, however, it is in good agreement with the data on the dependence of the refractive index n on the field strength H [17]. The diffraction patterns of water-based magnetic fluids are almost independent of the magnetic field. This likely happens because the structure formed in the is larger and denser than in kerosene-based samples [13].

Conclusion

Based on our findings, we can conclude that using auxiliary laser beams to probe light-induced inhomogeneities in magnetic fluids can serve as an effective method for characterizing their physical properties. Its advantage is that inhomogeneities induced by high-intensity radiation can be probed independently using a weak laser beam.

Within the proposed approach, such inhomogeneities can be probed without altering the conditions under which they form, only tuning the auxiliary laser's illumination parameters.

REFERENCES

1. **Scherer C., Figueiredo Neto A. M.,** Ferrofluids: properties and applications, Braz. J. Phys. 35 (3A) (2005) 718–727.

2. **Oehlsen O., Cervantes-Ramнrez S. I., Cervantes-Avilés P., Medina-Velo I. A.,** Approaches on ferrofluid synthesis and applications: Current status and future perspectives, ACS Omega. 7 (4) (2022) 3134–3150.

3. **Socoliuc V., Avdeev M. V., Kuncser V., et al.,** Ferrofluids and bio-ferrofluids: Looking back and stepping forward, Nanoscale. 14 (13) (2022) 4786–4886.

4. **Monteserнn M., Larumbe S., Martнnez A. V., et al.,** Recent advances in the development of magnetic nanoparticles for biomedical applications, J. Nanosci. Nanotechnol. 21 (5) (2021) 2705–2741.

5. **Imran M., Alam M. M., Khan A.,** Advanced biomedical applications of iron oxide nanostructures based ferrofluids, Nanotechnology. 32 (42) (2021) 422001.

6. **Yerin C., Belykh S.,** Magnetic emulsions as prospective magneto-optical media, IEEE Trans. Magn. 58 (2-1) (2022) 4600704.

7. **Pleshakov I. V., Alekseev A. A., Bibik E. E., et al.,** Magnetic nanoparticles in solid matrices: Formation and fixation of structures, induced by magnetic field, Nanosyst. Phys. Chem. Math. 14 (5) (2023) 544–548.

8. **Yerin K. V., Vivchar V. I.,** Transmission spectra of diluted and concentrated magnetite colloids in liquid dielectrics, J. Appl. Spectrosc. 90 (7) (2024) 1205–1211.

9. **Zhao Y., Zhang Y., Lv R.-Q., Wang Q.,** Novel optical devices based on the tunable refractive index of magnetic fluid and their characteristics, J. Magn. Magn. Mat. 323 (23) (2011) 2987–2996.

10. **Hao Z., Li Y., Pu Sh., et al.,** Ultrahigh-performance vector magnetic field sensor with wedge-shaped fiber tip based on surface plasmon resonance and magnetic fluid, Nanophotonics. 11 (15) (2022) 3519–3528.

11. **Han Sh., Pu Sh., Hao Z., et al.,** In-line temperature-compensated vector magnetic field sensor with side-polished fiber, Opt. Lett. 48 (17) (2023) 4504–4507.

12. **Dave V., Mehta R. V.,** Diffraction of laser light by a ferrocell and ferrofluid layers: A comparison, Optik. 311 (Sept) (2024) 171925.

13. **Pleshakov I. V., Alekseev A. A., Bibik E. E., et al.,** Effect of laser radiation on magnetite nanoparticles in deposited ferrofluid, Nanosyst. Phys. Chem. Math. 15 (3) (2024) 346–351.

14. **Du T., Yuan S., Luo W.,** Thermal lens coupled magneto-optical effect in a ferrofluid, Appl. Phys. Lett. 65 (14) (1994) 1844–1846.

15. **Sharma P., Alekhya V. V., Pathak S., et al.,** A novel experimental approach for direct observation of magnetic field induced structuration in ferrofluid, J. Magn. Magn. Mat. 534 (Sept) (2021) 168024.

16. **Prokof'ev A. V., Pleshakov I. V., Bibik E. E., Kuz'min Yu. I.,** An optical investigation of the geometric characteristics of aggregates formed by particles of magnetic fluid, Tech. Phys. Lett. 43 (2) (2017) 194–196.

17. **Horng H. E., Hong Ch.-Y., Yang S. Y., Yang H. C.,** Designing the refractive indices by using magnetic fluids, Appl. Phys. Lett. 82 (15) (2003) 2434–2436.

СПИСОК ЛИТЕРАТУРЫ

1. **Scherer C., Figueiredo Neto A. M.** Ferrofluids: properties and applications // Brazilian Journal of Physics. 2005. Vol. 35. No. 3A. Pp. 718–727.

2. **Oehlsen O., Cervantes-Ramнrez S. I., Cervantes-Avilés P., Medina-Velo I. A.** Approaches on ferrofluid synthesis and applications: Current status and future perspectives // ACS Omega. 2022. Vol. 7. No. 4. Pp. 3134–3150.

3. **Socoliuc V., Avdeev M. V., Kuncser V., Turcu R., Tombбcz E., Vékбs L.** Ferrofluids and bio-ferrofluids: Looking back and stepping forward // Nanoscale. 2022. Vol.14. No. 13. Pp. 4786–4886.

4. **Monteserнn M., Larumbe S., Martнnez A. V., Burgui S., Francisco M. L.** Recent advances in the development of magnetic nanoparticles for biomedical applications // Journal of Nanoscience and Nanotechnology. 2021. Vol. 21. No. 5. Pp. 2705–2741.

5. **Imran M., Alam M. M., Khan A.** Advanced biomedical applications of iron oxide nanostructures based ferrofluids // Nanotechnology. 2021. Vol. 32. No. 42. P. 422001.

6. **Yerin C., Belykh S.** Magnetic emulsions as prospective magneto-optical media // IEEE Transactions on Magnetics. 2022. Vol. 58. No. 2 (Part 1). P. 4600704.

7. **Pleshakov I. V., Alekseev A. A., Bibik E. E., Dudkin V. I., Kudryashova T. Yu., Karseeva E. K., Kostitsyna T. A., Medvedeva E. A.** Magnetic nanoparticles in solid matrices: Formation and fixation of structures, induced by magnetic field // Nanosystems: Physics, Chemistry, Mathematics. 2023. Vol. 14. No. 5. Pp. 544–548.

8. **Ерин К. В., Вивчарь В. И.** Спектры пропускания разбавленных и концентрированных коллоидов магнетита в жидких диэлектриках // Журнал прикладной спектроскопии. 2023. Т. 90. № 6. С. 843–849.

9. **Zhao Y., Zhang Y., Lv R.-Q., Wang Q.** Novel optical devices based on the tunable refractive index of magnetic fluid and their characteristics // Journal of Magnetism and Magnetic Materials. 2011. Vol. 323. No. 23. Pp. 2987–2996.

10. **Hao Z., Li Y., Pu Sh., Wang J., Chen F., Lahoubi M.** Ultrahigh-performance vector magnetic field sensor with wedge-shaped fiber tip based on surface plasmon resonance and magnetic fluid // Nanophotonics. 2022. Vol. 11. No. 15. Pp. 3519–3528.

11. **Han Sh., Pu Sh., Hao Z., et al.** In-line temperature-compensated vector magnetic field sensor with side-polished fiber // Optics Letters. 2023. Vol. 48. No. 17. Pp. 4504–4507.

12. **Dave V., Mehta R. V.** Diffraction of laser light by a ferrocell and ferrofluid layers: A comparison // Optik. 2024. Vol. 311. September. P. 171925.

13. **Pleshakov I. V., Alekseev A. A., Bibik E. E., Ilichev I. V., Prokof'ev A. V.** Effect of laser radiation on magnetite nanoparticles in deposited ferrofluid // Nanosystems: Physics, Chemistry, Mathematics. 2024. Vol. 15. No. 3. Pp. 346–351.

14. **Du T., Yuan S., Luo W.** Thermal lens coupled magneto-optical effect in a ferrofluid // Applied Physics Letters. 1994. Vol. 65. No.14. Pp. 1844–1846.

15. **Sharma P., Alekhya V. V., Pathak S., Jain K., Tomar P., Basheed G. A., Maurya K. K., Pant R. P.** A novel experimental approach for direct observation of magnetic field induced structuration in ferrofluid // Journal of Magnetism and Magnetic Materials. 2021. Vol. 534. 15 September. P. 168024.

16. **Прокофьев А. В., Плешаков И. В., Бибик Е. Е., Кузьмин Ю. И.** Оптическое исследование геометрических характеристик агрегатов, образованных частицами магнитной жидкости // Письма в Журнал технической физики. 2017. Т. 43. № 4. С. 26–31.

17. **Horng H. E., Hong Ch.-Y., Yang S. Y., Yang H. C.** Designing the refractive indices by using magnetic fluids // Applied Physics Letters. 2003. Vol. 82. No. 15. Pp. 2434–2436.

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