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Quantum analyzer of force lines structure at magnetic fields

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Abstract. A new method for studying the structure of the field lines of the magnetic systems of various configurations. The optimum parameters of ferrofluid cells and laser light for different research variants of force lines structure in the area between the poles of the magnetic system are determined. The results of experimental studies, which allow to define the change $\Delta B$ inhomogeneity of the magnetic field over the cross section of the magnetic system and to carry out its adjustment to the minimum $\Delta B$ in real time are represented.

1. Introduction.

One of the important problems of fundamental physics is the study of the lines of force of the magnetic field structure [1-4]. The greatest difficulties arise in the case of power lines investigation between the poles of the magnetic structure of the system, especially in fields with high induction $B > 1$ T [3, 5-7]. Most imaging methods of single magnet lines of force (sawdust, arrow, etc.) can not be used in the interpolar space of the magnetic system or allow to display only the average change in the magnetic field inhomogeneity $\Delta B$ (e.g., films, etc.), but not the structure itself of the power lines [2, 3, 5, 7, 8].

The use of different measurement sensors (such as Hall or nuclear magnetic resonance (NMR), etc.) give in most case the information about the induction value $B$ in the measurement area [7-11]. When using sensors based on NMR are used the line width permits to determine the inhomogeneities $\Delta B$ in the volume from which the NMR signal is recorded. But any movement of considered sensors for measuring inhomogeneities in the interpolar space will be associated with a high mistakes of determining the coordinates of their location between the poles. The placement of a grid of these sensors (except NMR) allows to determine the nature of the change in the average heterogeneity along one direction, but it is impossible to draw a picture of the lines of force on the basis of these measurements [2, 3, 5, 7, 9]. In [3] we have presented experimental results showing the ability to study the structure of the magnetic field lines with ferrofluid cells and laser radiation. The results obtained in [3, 6], and further conducted experiments allowed to choose the optimal parameters of the ferrofluid cell (type of material from which it is made, the thickness of the magnetic fluid layer in the direction of laser radiation $d_k$, composition of magnetic field, etc), and the laser radiation wave length $\lambda$.

2. Experimental setup and method for studying the structure of magnetic field lines.

Based on our experiments on different ferrofluid cells with different magnetic fluids it has been found that for the study of the structure of the force lines of the magnetic field is most advisable to use...
A ferrofluid cell made of quartz glass with two transparent parallel faces or with one face for various cases of studies. This is due to the peculiarities of different configurations of magnetic systems, in the interpolar space of which the structure of the lines of force is investigated. For the first variant of the cell $d_k = 1$ mm for the second one - $d_k \approx 3$ mm. As the magnetic fluid in two variants of cell structure the most appropriate is to apply an aqueous solution of single-domain nanoparticles of hematite with a bulk density of 0.054 with a surface active agent (surfactant) tetrametilamoniya hydroxide [6].

Taking into account the various restrictions on placement of ferrofluid cells, as well as the possible impact on her laser radiation in the interpolar space, it was found that in order to explore the magnetic field inhomogeneity nature change along three directions and to build on these results the volume picture of force lines structure taking into account all peculiarities of the magnetic system, it is necessary to use ferrofluid cells of two considered variants. In one case, a diffraction pattern is recorded from the laser radiation transmitted through it with $\lambda = 613$ nm - a cell with two transparent faces is used. In the other two - from reflected laser radiation on a structure of nanoparticles of a magnetic fluid, which is a similarity of the diffraction grating [3]. For these two cases, a cell with one transparent face is applied. To record these diffraction patterns, experimental setups have been developed and assembled, and relationships have been obtained that allow the results of measurements to determine the period of the diffraction grating (the distance between the lines of force in the plane of incidence of the laser radiation on the ferrofluidic cell).

In Fig. 1 is a block diagram of an experimental setup for recording a diffraction pattern from a laser radiation transmitted through a ferrofluidic cell.

![Figure 1](image_url)

**Figure 1.** Structural scheme of experimental setup 1 – semiconductor laser; 2 – aperture; 3 – lens; 4 – ferrofluid cell; 5 – magnetic system; 6 – polarizer; 7 – camera; 8 – computer.

The procedure for measuring the period of the diffraction grating $d_r$, which corresponds to the distance between the lines of force of the magnetic field, in this case partially corresponds to the classical scheme for studying the diffraction pattern from a multi-slit lattice. The difference in the case under consideration is the presence of a transparent layer (glass walls of a ferrofluidic cell) with a thickness $d_1$ and a layer thickness of a magnetic fluid $d_2$. In Fig. 2 is a represented diagram of the propagation of laser radiation beams in a ferrofluidic cell placed in a magnetic field.
Figure 2. Scheme of propagation of laser radiation rays in a ferrofluidic cell when a diffraction pattern is recorded in transmitted light: 1 - walls of a ferrofluidic cell; 2 - magnetic fluid layer in the direction perpendicular to the magnetic field with the thickness equal to \( d \); 3 - the screen.

It was shown in [3, 6] that nanoparticles of a magnetic fluid in a magnetic field are placed on its lines of force, forming transparent and opaque zones in the ferrofluidic cell for laser radiation with a period of \( d \). If, at a distance \( L \) from the center of the ferrofluid cell, the screen 3 (camera) is placed, then it will form a diffraction image in the laser radiation transmitted through the cell. The position of each maximum on the screen relative to its center (point O) will be determined by the diffraction order \( k \), \( d \), and \( \lambda \). And also by the distance to the screen \( L \) and the divergence angle of the laser radiation \( \theta \). For two adjacent maxima their position on the OY axis already was determined. As well as also the value of the additional displacement \( \Delta y_k \) along the axis OY, which is formed due to the refraction of radiation at the boundaries of the magnetic fluid - glass and glass - air. It was found that at distances of \( L = 20 \) cm, which were used in the experiment, the value of \( \Delta y_k \) is infinitesimal compared to the distance between two adjacent maxima \( \Delta Y \). To determine the given distance \( \Delta Y \), using the conditions for obtaining the maxima of the diffraction pattern, the following relation was obtained:

\[
\Delta Y = \lambda L (k_2 \frac{L}{\sqrt{d_2^2 - k_2^2 \lambda^2}} - k_1 \frac{L}{\sqrt{d_1^2 - k_1^2 \lambda^2}})
\]  

(1)

Where \( L \) – distance between the ferrofluid cell and camera, \( k_1 \) and \( k_2 \) - an integer representing the propagation-mode of interest.

By measuring \( \Delta Y \) from the diffraction image recorded by camera 7 (Fig. 1), for each diffraction order in accordance with (1), the value \( d_1 \) is determined, which makes it possible to determine establish the distance between the lines of force of the magnetic field. Constructing the dependence of the change \( d_1 \)
on the distance between the poles of the magnetic system, we can determine the degree of spatial inhomogeneity of the magnetic field.

To study the spatial structure of magnetic field lines using a diffraction pattern in the reflected laser radiation, an experimental setup was developed and assembled, that is shown in Fig. 3.

**Figure 3.** Structural scheme of experimental setup 1 – semiconductor laser; 2 – aperture; 3 – lens; 4 – ferrofluid cell; 5 – magnetic system; 6 – polarizer; 7 – camera; 8 – computer.

In the studies carried out, the ferrofluidic cell 4 with one transparent face is used. The wavelength of the laser radiation is \( \lambda = 515 \text{ nm} \). In the Fig. 4 is represented a diagram of the propagation of laser radiation beams in a ferrofluidic cell placed by a magnetic field when conducting studies in reflected light. For the recorded diffraction pattern in the reflected light, the positions of the diffraction maxima on the OY axis were determined and was also determined the magnitude of their displacement \( \Delta y_k \) were also determined due to the presence of refraction of laser radiation at the boundaries of four media: air - glass, glass - magnetic fluid, magnetic fluid - glass, glass - Air (Figure 4). During the calculations, the screen 3 (camera) supposed to be was located at the distance \( L = 15 \text{ cm} \) from the ferrofluid cell. The laser radiation was fed to the ferrofluidic cell at point A at an angle \( \alpha_1 = 45^0 \). Then, after refraction, on the cell walls the radiation was incident on a diffraction grating formed by nanoparticles with the period \( \text{dr} \). The structure of the diffraction grating begins at a very small distance \( d_k \) from the inner wall of the ferrofluid cell. The performed calculations showed that the deflection \((\alpha_1 - \alpha_2)\) of laser radiation emitted from the ferrofluidic cell at point B (after all 4 refractions) from the direction of the beam at point C (the classical diffraction case in reflected radiation) is less than \( 0^030' \), and the displacement \( \Delta y \) is less than \( 10^{-3} \text{ mm} \). Therefore, when determining the position of the diffraction maxima along the OY axis in the reflected laser radiation, these values do not have a significant effect on the measurement result.
Figure 4. Scheme of propagation of laser radiation rays in a ferrofluidic cell when a diffraction pattern is recorded in reflected light: 1,3 - walls of the ferrofluidic cell; 2 - the layer of the magnetic fluid with equal to d, the thickness the direction perpendicular to the magnetic field; 4 - the screen.

The obtained diffraction pattern allows, with an error of not more than 1%, to determine the distance between neighboring maxima $\Delta Y$ (Fig. 4). The value of $\Delta Y$ can also be determined using the relation obtained by us:

$$
\Delta Y = \frac{d_k}{d_r} \cdot \left[ \frac{t_1}{1 - \frac{t_1^2}{d_r^2}} - \frac{t_2}{1 - \frac{t_2^2}{d_r^2}} \right] + d_1 \cdot n_m \cdot \left[ \sqrt{1 - \frac{t_1^2}{d_r^2}} \cdot \sqrt{\frac{n_c^2 - n_m^2}{1 - \frac{t_1^2}{d_r^2}}} - \sqrt{\frac{n_c^2 - n_m^2}{1 - \frac{t_2^2}{d_r^2}}} \right] + L \cdot \left[ \frac{n_c^2 - n_m^2(1 - \frac{t_1^2}{d_r^2})}{1 - (n_c^2 - n_m^2 (1 - \frac{t_1^2}{d_r^2}))} - \frac{n_c^2 - n_m^2(1 - \frac{t_2^2}{d_r^2})}{1 - (n_c^2 - n_m^2 (1 - \frac{t_2^2}{d_r^2}))} \right]
$$

(2)

$$
t_1 = (2k_1 + 1) \cdot \lambda/2; \ t_2 = (2k_2 + 1) \cdot \lambda/2
$$

(3)
where \( n_m \) – the refractive index of a magnetic fluid, \( n_c \) – refractive index of the transparent glass wall of the cuvette, \( d_k \) – distance from the cell wall to the first layer of nanoparticles in a magnetic fluid that forms a diffraction grating, \( k_1 \) и \( k_2 \) – orders of diffraction maxima (\( k_2 > k_1 \)).

The experiments carried out showed that in the case when the angles of incidence of the laser radiation are significantly different from 45°, disregarding the displacements \( \Delta y_k \), connected by the refraction of laser radiation at four media boundaries, can not be ignored. This greatly complicates the calculation, as well as the carrying out of the experiment itself. Measuring the distance between the maxima of the diffraction pattern \( \Delta Y \), which is recorded with the help of a special chamber 7 (Fig.3), it is possible to calculate with the help of (2) the value of \( d_r \) the diffraction grating in the zone of its location in the interpolar space of the magnetic system. It allows to determine the structure of its lines of force for the two planes of the magnetic system.

3. Results and its discussion.

In Figure 5, as an example, a diffraction pattern (after computer processing) of the laser radiation transmitted through the cell in the direction perpendicular to the induction of the magnetic field \( B \) is presented.

![Figure 5 (a, b). The diffraction pattern of the laser radiation in the case of the magnetic fluid placing: (a) in a uniform magnetic field; (b) in an inhomogeneous magnetic field.](image)

The resulting diffraction image allows to determine visually the degree of inhomogeneity of the magnetic field in terms of the structure and relative location of the diffraction maxima. By selecting the line mode on the laptop screen, it is possible to determine with a high accuracy the distance between the neighboring maxima of the diffraction pattern, as well as the position of the central peak in magnitude of the amplitude of the peaks in the diffraction image.

Conclusion

Realizing measurements of the \( d_r \) values in three planes of the magnetic system using with two types of ferrofluidic lattices, it is possible to construct a 3D (volumetric) picture of the magnetic field lines in the inter-polar space of the magnetic system. Such an image of the configuration of the field lines can not be obtained even when calculating the magnetic field fields. In addition, the obtained result makes it possible to adjust the magnetic system to the minimum value of the magnetic field inhomogeneity in real time by the changing of the character of the recorded diffraction pattern.

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