Peculiarities of registration of magnetic field variations by a quantum sensor based on a ferrofluid cell

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Abstract. Device makes it possible to study the structure of the magnetic field lines, to determine the uniformity of the field in various magnetic systems, etc. In addition, our studies using a developed quantum visualizer have made it possible to establish the degree of influence of various factors on the homogeneity of the structure of the magnetic field lines. The experimental results obtained by us made it possible to develop the design of an autonomous quantum sensor for recording variations in the magnetic field, which are created, for example, by a moving magnetic object.

1. Introduction

At present, the development of new instruments and devices for monitoring the parameters of the magnetic field under various conditions (geographic, seismological, etc.), as well as the modernization of the used ones, is an urgent task of applied physics [1-7]. The development of new models of magnetometers and sensors for measurements in systems (from permanent magnets, electromagnet, solenoid, etc.), which create various magnetic fields, is also in demand. The greatest difficulties arise in the study of the structure of magnetic field lines, especially in the interpolar space of magnetic systems. The various types of magnetometers currently in use [1-9] do not allow these studies to be carried out. The developed magnetometers or sensors are mainly constructed to solve a narrow range of specific problems, since measurements need to be carried out with high accuracy. It should be noted that among all types of magnetometers and sensors, quantum devices [2, 3, 7-13] have the greatest universality and the best parameters for measuring accuracy and sensitivity for monitoring magnetic field parameters. Therefore, they found the greatest application in various spheres of human activity. One of which is the determination of the presence of a mobile magnetic object in the marine aquatorium.

A large number of instruments and devices have been developed to detect mobile marine objects in the ocean and sea areas. For example, a device that measures the variation of the pressure fluctuation in the field of a non-uniform sea wave. This change determines the presence of a mobile marine object in a given area [14]. Fiber-optical antennas, radar stations and acoustic sensors are also used to detect mobile objects in marine areas [15, 16]. All of them have advantages and shortcomings.

Recently, the most interesting devices are those used for monitoring the movement of magnetic objects in a given area of the sea, which can operate in an autonomous mode. These devices are
subject to fairly strict requirements from different criteria (the complexity of their detection, high noise immunity, continuous operation of at least 12 months with an autonomous power source, etc.). In addition, these devices must have a high degree of reliability from the point of view of identifying the presence of the object itself in a given zone (for example, when solving security tasks or eliminating unauthorized intrusion). Now none of the devices in operation satisfies the above mentioned requirements. Therefore, the search for solutions of the problem is extremely urgent and in demand. One of the possible solutions to this problem is presented in our work.

2. Features of registration of variations of a magnetic field by the quantum sensor.

The new construction of the quantum visualizer was considered in [17-19]. The use of this device makes it possible to study the structure of the magnetic field lines, to determine the uniformity of the field in various magnetic systems, etc. In addition, our studies using a developed quantum visualizer have made it possible to establish the degree of influence of various factors on the homogeneity of the structure of the magnetic field lines. The experimental results obtained by us made it possible to develop the design of an autonomous quantum sensor for recording variations in the magnetic field, which are created, for example, by a moving magnetic object. A block diagram of the quantum sensor is represented in fig. 1.

![Block diagram of an autonomous quantum sensor](image)

**Figure 1.** Block diagram of an autonomous quantum sensor: 1 - semiconductor laser; 2 - laser power supply; 3 - the coil of inductance; 4 - stabilized current source; 5 - ferrofluidic cell; 6 - a specialized camera; 7 - processing scheme; 8 - data transmission scheme; 9 - power supply; 10 - the battery.

The main element by which the variation of the magnetic field is recorded is the ferrofluid cell 5. As the magnetic liquid, it is most expedient to use an aqueous solution of single-domain hematite nanoparticles with a concentration of 0.054 with a surfactant tetramethylammonium hydroxide. Previous studies have shown that in the case of placing a ferrofluid cell in a magnetic field, nanoparticles of a ferromagnetic liquid are located along magnetic field lines. For laser radiation with \( \lambda = 613 \text{ nm} \), passing through a ferromagnetic liquid placed in a cell, this configuration of nanoparticles is similar to a diffraction grating. The period of this lattice is determined by the distance between the
force lines of the magnetic field [17-19]. The use of these cells makes it possible to investigate the structure of the force lines of various magnetic systems [17-19]. If the ferrofluid cell is located in a weak uniform magnetic field (for example, with an induction of \( B_0 = 0.206 \text{ mT} \) and an inhomogeneity of \( 10^{-5} \text{ cm}^{-1} \)), which is created by special inductors, then the diffraction pattern from the laser radiation transmitted or reflected from it being, recorded by a specialized camera appears to be symmetric, relative to the central maximum is symmetric in nature.

As a result of our investigations, we established the peculiarity of measuring the period of the diffraction grating \( d_r \), which corresponds to the distance between the force lines of the magnetic field. In contrast to the classical consideration of the position of diffraction maxima and minima in a ferrofluid cell, when determining them, it is necessary to take into account the thickness \( d_1 \) of the transparent walls of the ferrofluid cell and the thickness of the magnetic liquid layer \( d_2 \) in it.

In addition, the earlier experimental results made it possible to establish one more feature. The degree of contrast of the diffraction pattern from the laser radiation transmitted through the ferrofluid cell is several times higher than in the recorded diffraction pattern in the reflected radiation. This means that the sensitivity of the quantum sensor operating on the diffraction pattern from the transmitted radiation through the ferrofluid cell to variations in the external magnetic field will be higher.

Therefore, it is preferable to use a diffraction pattern from the laser radiation transmitted through the cell in the quantum sensor to record the variations of the magnetic field. In Fig. 2 shows a diagram of the propagation of laser radiation through a ferrofluid cell in a magnetic field \( B \).

**Figure 2.** Scheme of propagation of laser radiation rays in a ferrofluid cell when a diffraction pattern is recorded in transmitted light: 1 - walls of a ferrofluid cell; 2 - magnetic liquid; 3 - screen.

Laser radiation (\( \theta \leq 0.5 \text{ mrad} \)) is fed perpendicularly to the wall of the ferrofluidic cell 1. These walls are made of quartz glass. Wall thickness \( d_1 = 1 \text{ mm} \). The use of quartz glass makes it possible to minimize the intensity of the reflected laser radiation from the boundaries of the media sections (glass-magnetic fluid and glass-air). In this case, reflected "glare" has an insignificant effect on the formation
of the diffraction image in the past laser radiation. The thickness of the layer of magnetic liquid $d_2$ in the direction of propagation of the laser radiation was 2 mm.

The experiments carried out showed that refraction of laser radiation occurs at the media boundaries (air-quartz glass, quartz glass-magnetic fluid, magnetic liquid-quartz glass, and quartz glass-air). This creates difficulties in obtaining a symmetrical diffraction pattern in the case of a laser radiation incident at an angle to the ferrofluidic cell facet 1.

The position of each maximum on screen 3 (figure 2) relative to its center (point 0) will be determined by the diffraction order $k$, and also depends on the period of the diffraction grating $d_1$ formed in the magnetic field. The value of $d_1$ can be varied with the help of current in the coils of inductance 3 (fig. 1). This allows you to adjust the sensitivity of the quantum sensor to the variations of the magnetic field from moving objects.

In the laboratory model of the quantum sensor (figure 1), a specialized camera 6 is used to register the diffraction pattern. The chamber 6 is placed at a distance $L$ from the side face of the ferrofluid cell, where in fig. 2 the screen is placed.

It should also be noted, that the transparent cell faces for degree increasing of interference pattern contrast, should be located the parallel to the force lines of the magnetic field, which is created by the coils of inductance.

3. Research results and discussion

In the case of a permanent magnet with induction $B_m$ (imitation of the motion of a magnetic object), a shift in the position of the central maximum occurs near the inductor coils, the shape of the maxima in the diffraction pattern changes, and its symmetry is violated. In fig. 3 as an example, the type of diffraction pattern recorded by the camera located in the zone where the screen 3 was located (fig. 2) is presented. In fig. 3.a corresponds to the absence of a magnetic object near the inductance coils in which the ferrofluid cell is located. The magnetic field in the ferrofluid cell is homogeneous. In fig. 3.b - corresponds to one of the moments of motion next to the inductance coils of the magnetic object. Diffraction patterns after computer processing are presented in fig. 3.

![Figure 3](image)

**Figure 3** (a, b). The diffraction pattern of the laser radiation in the case of the magnetic liquid placing: (a) in a uniform magnetic field; (b) in an inhomogeneous magnetic field.

The result obtained in fig. 3 shows that the magnetic field created by the mobile object made a change in the structure of the force lines of the magnetic field of the inductor, in which the ferrofluid
cell is located. The inhomogeneity of the magnetic field in the zone of placement of the ferrofluid cell has changed significantly. The symmetry of the diffraction pattern was violated. The conducted experiments and the results of their analysis showed that the information presented in this form is not very convenient for the work of electronic schemes processing and management.

An industrial (serial) quantum sensor will be placed on an autonomous facility, for example, an underwater buoy. Underwater buoy in its composition has a special radio transmitter or a subversive mechanism with a charge. In the case of distortion in the recorded diffraction pattern (symmetry breaking), a control pulse should act on these devices from block 8 (Fig. 1). This pulse activates the predefined function of the device.

The experiments performed showed that the most optimal solution for studying the nature of distortions in the diffraction pattern is the choice of the line (in width or height) of the diffraction cell. Along this line, the intensity distribution \( I \) of the recorded laser radiation, is constructed. In fig. 4 shows, as an example, the distribution data in the diffraction pattern for laser radiation transmitted through the ferrofluid cell. In the first case, the magnetic object was absent in the zone of placement of the inductor with a ferrofluid cell. In the other case (fig. 4b), it made a move. The intensity distribution \( I \) corresponds to a diffraction pattern fixed at a certain time \( t \). For example, when the distortions in the structure of the force lines in the inductor reached a maximum value.

**Figure 4.** The dependence of the intensity \( I \) on the distance between the lines of force of the magnetic field: a) in a homogeneous field \( B_0 \); b) the magnetic field \( B_m \) from the mobile object is additionally present in the inductor.

The conducted studies showed that the change in the position and amplitude of the maxima in the recorded diffraction pattern (fig. 4b) depends on the trajectory and speed of the magnetic object with respect to the position of the ferrofluid cell in the inductor. The greatest influence on the position of the maxima in the recorded diffraction pattern is exerted by the magnetic field lines of the mobile object, which are located in the same plane with the power lines of the inductor.

In the serial quantum sensor, instead of the camera, the position of the peaks in the diffraction pattern will be recorded using a photodiode array. The information from the photodiode line will be fed to the microcontroller, which will detect changes in the symmetry of the diffraction pattern and issue appropriate control commands to other devices. The use of these elements will make the design of the sensor more compact, since it must be placed in a small hermetic casing of non-magnetic material.

In a real situation is difficult to predict the motion of a magnetic object with respect to the position of the magnetic field lines in which the ferrofluid cell is located. Therefore, in order to eliminate the error in determining the presence of a moving magnetic object in a given zone, it is necessary to use simultaneously for measurements three quantum sensors. In each of the sensors, the change in the...
structure of the magnetic field lines is recorded in one of the three planes. This is another feature of registering the variations of the magnetic field by a quantum sensor.

In addition, as a result of the conducted experiments, it was established that electromagnetic radiation when scanning the radiation pattern of different types of radar stations, which are currently used to solve various problems in water areas [15, 16], do not cause distortions in the structure of the force lines in the ferrofluid cell, which would correspond finding a magnetic object near it. This shows the high degree of noise immunity of the quantum sensor developed by us.

4. Conclusion
The obtained results show that the quantum sensor developed by us on the base of a ferrofluid cell, which considers the established features of registering variations in the magnetic field, makes it possible to determine the presence of a mobile magnetic object in a given zone. The use for this purpose of recorded changes in the structure of the diffraction pattern of laser radiation associated with a change in the magnetic field gradient eliminates the error in the measurement.

It should also be noted that the electronics developed by us for the quantum sensor has a high compactness. Low energy consumption of the quantum sensor and electronics allows the device to operate continuously from stand-alone operation mode (depending on the battery life) up to three years. These characteristics, as well as a high degree of protection against interference, fully meet the requirements for autonomous systems that were considered earlier.

5. References
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