Quantum autonomous magnetic field sensor

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Abstract. A new design of a quantum sensor based on a ferrofluid cell for recording variations in the magnetic field is considered. The possibility of determining the position of the magnetic object in the zone of placement of a quantum sensor by changing the structure of the diffraction pattern of laser radiation is established. The results of experimental studies are presented.

1. Introduction

One of the tasks of applied physics is the development of devices for detecting various magnetic objects by measured magnetic field parameters [1-4]. These objects can be located both in a stationary and mobile state. Moreover, the measurements of the magnetic field parameters must be carried out with a high degree of reliability in different conditions: geographic, seismological, etc. Also in a complex magnetic environment, in the presence of a large number of interference of various kinds [3, 5, 7]. The among all types of developed magnetometers and sensors for monitoring the parameters of the magnetic field the quantum magnetometers are have the greatest versatility for carrying out measurements and the best indicators for measuring accuracy and sensitivity [1-8].

At present, the marine mobile magnetic objects detection is actual task. For the detection of mobile offshore facilities, a large number of different instruments have been developed. For example, devices that measure the variation in pressure fluctuation in the field of a non-uniform sea wave. According to this change, the presence of a mobile marine object in a given area is determined [8]. Fiber-optic antennas, radar stations and acoustic sensors are also used to detect mobile objects [9]. All of them have advantages and disadvantages. Of particular interest are devices that can operate in an off-line mode. But, such devices are subject to rather stringent requirements in various areas (the complexity of their detection, high noise immunity, continuous operation of at least 12 months on an autonomous power source, etc.). In addition, the device must have a high degree of reliability in terms of identifying the position of the object itself in a given area (for example, when solving security tasks or eliminating unauthorized intrusion). None of the devices in operation meet the above requirements. Therefore, the search for possible solutions to the task is extremely urgent and in demand.

2. Quantum sensor and measurement technique.

The paper considers one of the possible solutions to the task at hand - the creation of a quantum sensor based on a ferrofluid cell made of quartz glass. Previous studies have shown that in the case of placing a ferrofluid cell in a magnetic field, nanoparticles of a ferromagnetic liquid are located on magnetic field lines, forming transparent and non-transparent zones [11, 12]. As a magnetic fluid, it is most expedient to use an aqueous solution of single-domain hematite nanoparticles with a concentration concentration...
of 0.054 with a surfactant (surfactant) tetramethylammonium hydroxide. For laser radiation with \( \lambda = 613 \) 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 [11, 12]. The use of these cells makes it possible to investigate the structure of the force lines of various magnetic systems [11-14]. If the ferrofluid cell is located in a weak uniform magnetic field (for example, with an induction of \( B_0 = 0.206 \) mT and an inhomogeneity of \( 10^{-5} \) cm\(^{-1}\)), which is created by special inductors. Then the diffraction pattern from the laser radiation transmitted or reflected from the cell is detected with a photodetectors [13]. The resulting picture relative to the central maximum is symmetric [11, 12].

In fig. 1, as an example, the scheme for the propagation of laser radiation through a ferrofluid cell located in a magnetic field B is shown. The structure of the magnetic field lines in this case is controlled by the diffraction pattern from the laser radiation transmitted through the ferrofluid cell [11, 12]. At the boundaries \( d \): air-glass media, glass-magnetic fluid, magnetic liquid-glass and glass-air - refraction of laser radiation is taken into account. It is established that the intensity of doubly reflected laser radiation from the boundaries of media sections (glass-magnetic fluid and glass-air) to the formation of a diffraction image in the transmitted radiation has no significant effect. In the experiment, the photoreceiver (screen 3) is placed at a distance \( L \) from the side face of the ferrofluid cell. In its plane, a diffraction image is recorded. The position of each maximum on the screen relative to its center (point 0) will be determined by the diffraction order \( k \) and depends on the period of the diffraction grating \( d_r \) formed. In this case, the transparent faces of the cell are located perpendicular to the laser radiation incident on them and the lateral planes of the inductor. In addition, the transparent faces of the cell are parallel to the force lines of the magnetic field that are created by the coils of inductance.

**Figure 1.** 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 fluid layer in the direction perpendicular to the magnetic field with the thickness equal to \( d_r \); 3 - the screen.
In the case of a permanent magnet with induction $B_m$ (imitation of the motion of a magnetic object), the position of the central maximum shifts next to the inductance coils, the shape of the maxima changes to a diffraction pattern, and its symmetry is violated. In fig. 2 as an example, the type of diffraction pattern recorded by the camera located in the zone where the screen 3 was located (fig. 1) is presented. In fig. 2a 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. 2.b - corresponds to one of the moments of motion next to the inductance coils of the magnetic object. Diffraction patterns in fig. 2 are presented after computer processing.

![Diffraction patterns](image)

**Figure 2** (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.

The result obtained in fig. 2 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 has changed significantly, the symmetry of the diffraction pattern has disrupted. The conducted experiments and the results of their analysis showed that the information presented in this form is not very convenient for the operation of electronic systems. A quantum sensor will be placed on an autonomous object, for example, an underwater buoy. Therefore, the term in the diffraction pattern is chosen and along it (along the width or height of the diffraction cell) a distribution of the intensity $I$, the recorded laser radiation, is constructed. In fig. 3, as an example, the distribution data in the diffraction pattern for the laser radiation transmitted through the ferrofluid cell is presented. In one case, the magnetic object was absent in the zone of placement of the inductor with a ferrofluid cell. In the other case (fig. 3b) he 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 3.** The dependence of the intensity I on the distance between the force lines 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 have shown that the change in the position and amplitude of the maxima in the recorded diffraction pattern (fig. 2b) depends on the trajectory and speed of the magnetic object relative to the position of the ferrofluid cell in the solenoid. In addition, a number of features related to the geometric arrangement of the plane in which a diffraction image was recorded in a quantum sensor, relative to the direction of the magnetic field lines of the mobile object, and also the size and type of nanoparticles in the ferromagnetic liquid from which the cell was made was established. In addition, during the experiments it was established that electromagnetic radiation when scanning the radiation pattern of various types of radar stations, which are currently used to solve various problems in water areas [10]. Do not cause distortions in the structure of the force lines in the ferrofluid cell that would correspond to the finding near it a magnetic object. This shows the high degree of noise immunity of the quantum sensor developed by us.

3. Conclusion
The obtained results show that the method developed by us with the use of a quantum sensor on a ferrofluid cell allows us to determine the presence of a magnetic object in the zone of its location as a result of changes in the structure of the recorded diffraction pattern of laser radiation. For the reliability of determining the presence of a mobile magnetic object in a given zone, it is necessary to install three quantum sensors that detect the change in the magnetic field lines in three planes. This completely eliminates the measurement error. The developed quantum sensor and the electronics necessary for its operation have a high compactness. Low power consumption of the quantum sensor and electronics allows them to operate continuously in an autonomous mode from the batteries (depending on the battery life) 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.

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