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Project of Laser-Pumped Quantum M_X Magnetometer

A. K. Vershovskii
Ioffe Physical Technical Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia
e-mail: antver@mail.ioffe.ru
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Abstract—The possibility of creating a new scheme of a laser-pumped quantum magnetometric device based on a double-beam M_X magnetometer is considered. The proposed system ensures the simultaneous measurement of the modulus of the Earth's magnetic field vector (with an absolute accuracy of 0.02 nT) and two angles of deviation of this vector with an absolute accuracy and sensitivity of not worse than 0.4" (0.1 nT) at a measurement time of $\tau = 1$ s. In contrast to the known analogous systems, the proposed scheme does not require generating additional magnetic fields.

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The principle of operation of most vector magnetometers that employ optically pumped scalar quantum sensors [1, 2] is based on the law of vector summation, according to which the known vectors of various directions are sequentially added to the magnetic induction vector of the field to be determined and the resultant field vector is measured [3]. A series of these measurements allows the unknown vector to be calculated. Using systems that provide the rotation of additional fields [4–6], it is possible to perform measurements in a quasi-continuous regime.

An alternative possibility of using a quantum sensor in vector magnetometry is based on the dependence of the amplitude and phase of a signal in the probing beam modulated at the Larmor frequency in the magnetic M_X resonance on the direction of this beam relative to the field. The originally proposed Fairweather–Usher (FU) scheme [7] ensured a sensitivity of 0.1nT for $\tau = 1$ s and a drift on the order of 2–3 nT per day.

A common disadvantage of almost all magnetometric devices employing systems of additional artificial magnetic fields is the impossibility of absolute measurements, since the contribution due to these additional fields is comparable on the order of magnitude with the measured field and depends on the configuration of magnetic coils and their current—and, hence, on the temperature, humidity, and some other factors.

The present Letter proposes a significant modification of the FU scheme [7], which does not stipulate using any additional magnetic fields and, hence, is capable of absolute measurement of the magnetic field vector components. Here, the absolute measurement implies that (i) the magnetometer measurement is only based upon fundamental constants, (ii) the measuring process does not shift the parameters to be determined, and (iii) referencing to the Earth's coordinate system is possible.

In particular, it is suggested to exclude all the additional magnetic fields (and related coils) from the FU scheme [7]. Instead of the forced return of the measured magnetic field vector **B** toward direction **Z**, it is suggested to vary the direction of laser beam L_Z so that it would follow the vector of the measured magnetic field. This scheme would make it possible to relate the measurement to the Earth's coordinate system by merely changing orientation of the L_Z beam. The role of the M_X sensor in the proposed device can be performed by a potassium magnetometer on an isolated narrow line [8].

Figure 1 shows a block scheme of the proposed device, which employs an M_X sensor and two circularly polarized beams, $L_Z \parallel \mathbf{B}$ and $L_X \perp \mathbf{B}$ with the intensities I_Z znf I_X, respectively. Using a vacuum cell *1* with an antirelaxation coating, it is possible to use laser beams of small (<4 mm) diameter for pumping and detection, which is due to the effective averaging of the laser beam intensity over the cell volume [9]. A system of semiconductor laser stabilization with respect to resonances of saturated absorption in K is described elsewhere [10, 11]. The L_Z beam ensures the optical pumping of alkali metal atoms, while the L_X beam at resonance is modulated due to the interaction with the X component of the atomic moment. The modulated response signal S_{ref}, which bears information on both the modulus of magnetic field and the of M_X resonance phase along the X axis, is used in the oscillation loop of the M_X magnetometer. The quadrupole signals from the output of digital frequency synthesizer *15* (phase-locked to S_{ref} signal) [12] are used as reference signals in detecting the signal of magnetic field deviation along the X and Y axes.

When the L_Z beam is strictly parallel to the magnetic field, its modulation is absent. As the magnetic field deviates by angle Θ, there appears (like in a sin-

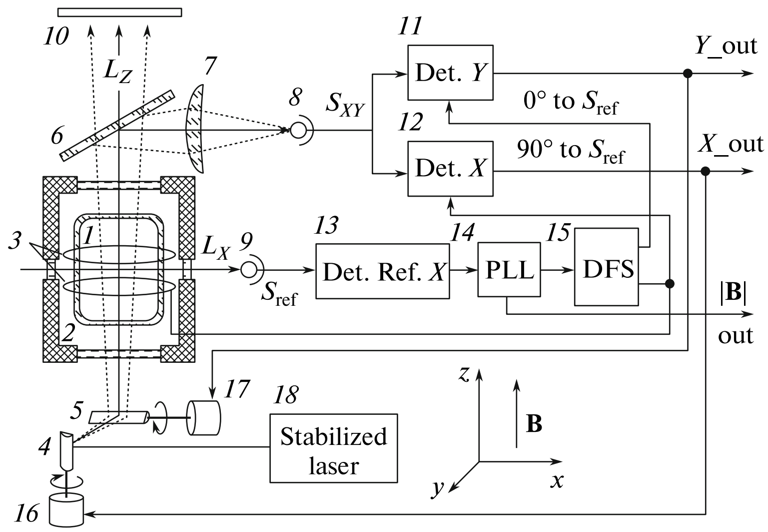

Fig. 1. Block scheme of vector magnetometer: (*1*) cell with K vapor; (2) thermostat; (*3*) RF field coils; (*4*, *5*) rotary mirrors; (*6*) transparent mirror; (*7*) collimator; (*8*, *9*) photodetectors; (*10*) beam position monitor (positioned photoelement); (*11*, *12*) detectors of transverse field components; (*13*) reference (M_X) detector; (*14*) phase locked loop; (*15*) digital frequency synthesizer; (*16*, *17*) piezoelectric motors; (*18*) semiconductor laser stabilized with respect to K-resonance.

gle-beam sensor) the L_Z beam modulation signal at the Larmor frequency. The amplitude S_{XY} of this signal is proportional to sin(Θ)sin(90° – Θ) and its phase depends on the direction of deviation of the magnetic field. The S_{XY} signal can be decomposed into two orthogonal components by lock-in detectors, the signals from which in the FU scheme [7] are fed into the additional coils that compensate for the transverse field variations, while in the proposed variant these signals are applied to the input of the system of L_Z beam positioning, which ensures that this beam is always parallel to the magnetic field vector. These signals also bear information on variations of the angle of the magnetic field vector.

Among the known methods of control over the laser beam direction, the most promising is that employing two rotary mirrors (*4*, *5*, Fig. 1) driven by piezoelectric motors (*16* and *17*, respectively). This scheme can in principle provide the angle of beam rotation $\Theta_{max} = \pm 2°$ (with a resolution of 0.4'' and a response of $\tau_L < 0.1$s) corresponding to the maximum variation of the Earth's magnetic field components; in addition, this device can be made nonmagnetic to a sufficiently high degree. The information on variations of the Θ value can be monitored on the control inputs of piezoelectric motors, but the absolute measurements would require determining the position of the L_Z beam. These measurements can be performed using a positioned four-segment photodetector *10* (or a CCD matrix detector) arranged at any distance from the sensor. This system employs a small fraction of the L_Z beam power transmitted through mirror *6*.

Let us evaluate $\delta B_\perp$—the sensitivity with respect to the transverse components of the magnetic field vector for a response time of 1 s. The maximum response signal S_{XY} is obtained in a position that is standard for a single-beam sensor, that is for Θ = 45°. A minimum angle δΘ that can be measured by the system is determined from the condition

$$\left(\frac{S}{N}\right)_0 \frac{\sin(\delta\Theta)\cos(\delta\Theta)}{\sin(45°)\cos(45°)} = 1, \quad (1)$$

where $(S/N)_0$ is the root-mean-square (r.m.s.) signal-to-noise ratio in the scheme of single-beam M_X magnetometer at Θ = 45° measured for τ = 1 s; so

$$\delta\Theta \cong \sin(\delta\Theta) \cong \frac{1}{2}\left(\frac{S}{N}\right)_0^{-1}. \quad (2)$$

Therefore, in a field of 50 μT, a sensitivity of $\delta\beta_\perp = B\sin(\delta\Theta) = 0.1$ nT is reached at $(S/N)_0 = 2.5 \times 10^5$. Let us compare this value to existing data. Aleksandrov et al. [10, 11] described experiments where a record high sensitivity of $\delta\beta = 1/Q = N\Gamma/S = 2 \times 10^{-15}\ \mathrm{T} \cdot \mathrm{Hz}^{-1/2}$ was achieved with a potassium sensor with the following parameters: vacuum cell diameter, D = 15 cm; pumping intensity, Θ = 45°, $I_0 = 3$ (determined via resonance broadening as $I = (\Gamma - \Gamma_d)/\Gamma_d$, where Γ is the total resonance width and Γ_d is the width in the absence of pumping); laser power, $P \approx 2.5$ μW; cell temperature, T = 42°C; and K atom concentration, $n_0 = 4.77 \times 10^{12}$ (for which the optical density of the cell is $x_0(n, D) \approx 1.6$). The signal-to-noise ratio recalculated for τ = 1 s was $S/N \approx 8.8 \times 10^4$, which was almost three times smaller than the level necessary for attaining the sensitivity claimed in [7]. However, according to formula (2), the sensitivity of angular measurements is independent of Γ and, hence, it can be

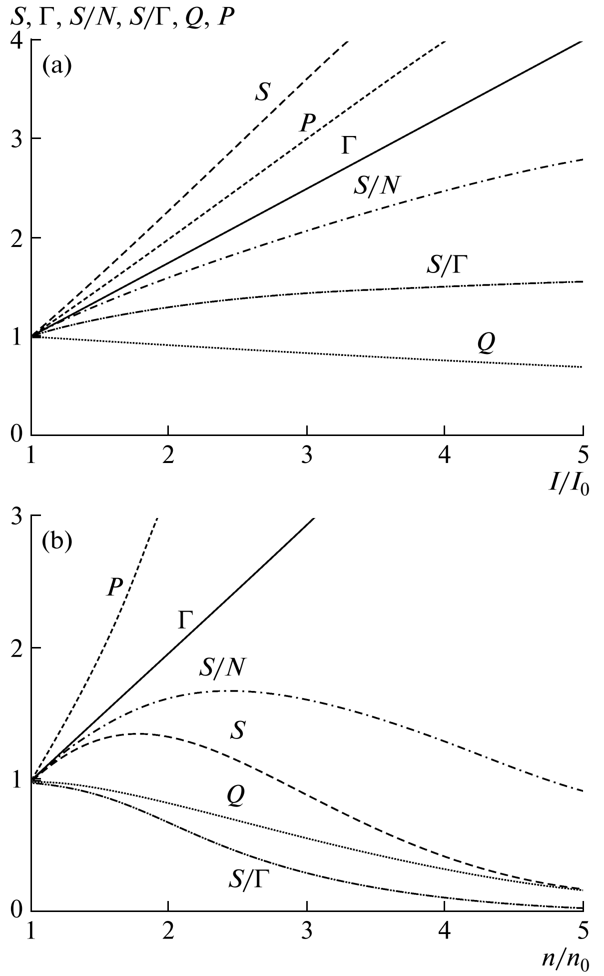

Fig. 2. Plots of the main M_X resonance parameters (S, Γ, S/N, S/Γ, $Q = S/(N\Gamma)$) and required pumping power P versus (a) normalized pumping intensity I/I_0 and (b) normalized K atom concentration n/n_0 (all quantities are normalized to their optimum values with respect to maximum Q).

improved by increasing the intensity I_Z and the concentration $n(T)$ of atoms in the cell.

The expressions for $S(I)$ and $\Gamma(I)$ were obtained in [1, 2], while their generalization for arbitrary pumping parameters was given in [9]. Figure 2 shows the plots of these dependences for $I = I_0$ and $n > n_0$, from which it follows that an increase in n allows the S/N ratio to be increased by a factor of less than 2. In addition, the increase in n is accompanied by rapid growth in the required laser power P that, in turn, leads to a fast increase in the light-induced shifts. Therefore, increasing n seems to be less expedient than increasing I.

A threefold increase in S/N in the vector channel would require an approximately ninefold increase in I_Z. Accordingly, the sensitivity of the M_X sensor would be somewhat reduced and the light-induced and parametric shifts of the M_X resonance would grow by a factor of $(I_Z + I_X)/(I_{Z0} + I_{X0}) = 5$. It is expedient to increase I_Z until (i) light-induced shifts do not exceed the permissible level, (ii) the level of technical laser noises does not exceed the shot noise, and (iii) the sensitivity of modulus measurements exceeds that of measuring components.

Thus, the sensitivity of the vector measurement scheme on a level of 0.1 nT for $\tau = 1$ s can be achieved with a potassium magnetometer [10] at a pumping intensity of $I = 5I_0$ ($P \approx 12$ μW). The M_X sensor in this case is characterized by the sensitivity on a level of 4 fT Hz$^{-1/2}$ and stability on a level of 10 pT. Since the error related to the uncertainty of physical constants is also on a level of 10 pT [13], the absolute accuracy of the M_X sensor can be estimated at about 20 pT.

The process of magnetic field measurement was numerically simulated using a modification of the program described in [6]. The program core was a model of the M_X magnetometer with a resonance parameters described by equations derived in [9] and the M_X resonance amplitude dynamics separately taken into account by introducing a time delay.

The results of numerical simulations fully confirmed the above estimations. Figure 3 shows the Allan diagrams [14] constructed for the models of (*a*) a module scheme [10, 11] and (*b*) a vector magnetometer based on this scheme (for $I = 5I_0$). The diagram (*c*), which was constructed for the same parameters with allowance for the response time of the M_X resonance signal amplitude and the system of L_Z beam positioning, shows a bending at $\tau \approx 0.1$ s. This time approximately corresponds to the expected response speed of the proposed scheme. The diagram (*d*) corresponds to a twofold increase in the concentration of atoms ($n = 2n_0$), which leads (for $I = 5I_0$) to an additional (~3.3-fold) increase in the required P. The diagram (*e*) demonstrates a principal possibility to increase the sensitivity in the X and Y channels up to 0.01 nT for τ = 1 s by increasing the pumping intensity to $I = 100I_0$.

In all cases, a static error of measurement is absent and the accuracy of measurements for a fixed time is determined by the statistical scatter of readings. The only factor that leads to a the appearance of a systematic error in the X and Y channels is a shift of detectors (*11* and *12*, Fig. 1), which must not exceed the relative error of angular measurements, so that $\delta S_{X,Y}/S_{X,Y} < 0.6 \times 10^{-4}$. Neither light-induced shift of the M_X resonance nor errors in the phase setting in the M_X sensor scheme can give rise to a static error in the X and Y channels.

Thus, both analytical and numerical results showed that a magnetometric scheme based on a laser-pumped double-beam M_X magnetometer can ensure the simultaneous measurement of the modulus of the magnetic field vector (with an absolute accuracy of 0.02 nT) and two angles of deviation of this vector with an absolute accuracy and sensitivity of no worse than

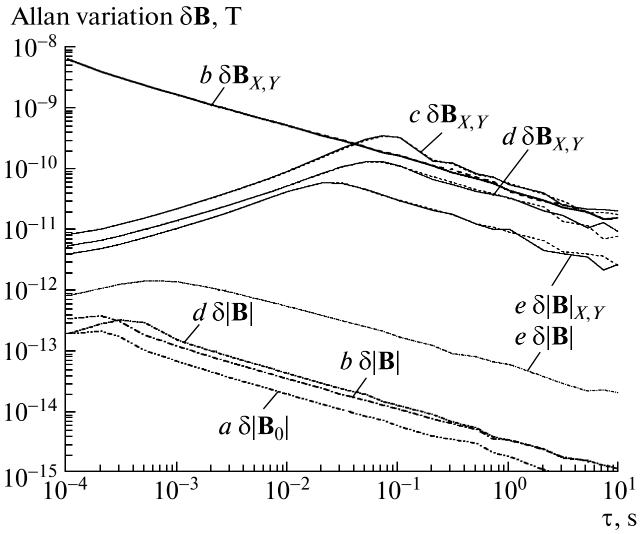

Fig. 3. Allan diagrams of response variance for various models: (*a*) potassium module magnetometer with a 15-cm cell; (*b*) vector magnetometer for $I = 5I_0$ ($I_Z = 9I_{Z0}$, $I_X = I_{X0}$), $n = n_0$; (*c*) same with allowance for the M_X signal dynamics and response time of the system of L_Z beam positioning; (*d*) same for $n = 2n_0$; (*e*) same for $n = n_0$, $I = 100I_0$ ($I_Z = 199I_{Z0}$, $I_X = I_{X0}$).

0.4" (0.1 nT) for a measurement time of $\tau = 1$ s. In contrast to most of the known analogous systems, the proposed scheme does not require generating additional magnetic fields and, hence, is characterized by high absolute accuracy of angular measurements. The accuracy of the proposed scheme is independent of the precision of its positioning in space. It is essentially a meter of the modulus of the magnetic field vector and, simultaneously, a laser monitor of the field direction (i.e., a compass). An additional advantage of the scheme is the absence of generated stray magnetic fields, which makes possible its use in magnetometric observatories jointly with other devices.

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