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Optically Pumped Quantum Magnetometer Employing Two Components of Magnetic Moment Precession Signal

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Abstract—The new scheme of a combined quantum magnetometric device is proposed that represents a fast M_X magnetometer, in which the phase of M_X signal detection is corrected with respect to the maximum of the variable component of the atomic magnetic moment. The device combines a high response speed ($\tau \le 0.1$ s) with high precision, which is determined by the resolving power of the quantum M_X magnetometer for a time on the order of 100 s. The reproducibility of field measurements is on a level of 2–3 pT.

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Optically pumped quantum magnetometers intended to measure magnetic induction have been known since the 1960s [1, 2]. Their operation is based on the phenomenon of optical pumping and optical detection of the magnetic resonance [3, 4]. Below, the resonance is described in a laboratory coordinate system ZXY with the Z axis parallel to the magnetic field (in this frame, the projection of moment on the equatorial plane rotates with a circular frequency ω equal to that of the applied field) and in a frame $ZX'Y'$ that rotates with the frequency ω around the Z axis, in which slow components $u = M_X\cos(\omega t)$ and $v = M_Y\sin(\omega t)$ of the moment are determined. The M_Z component and the modulus of the radial component M_R are the same in both frames.

Presently, magnetometers exist that employ the detection of either M_Z or M_X components of the magnetic resonance signal [5]. The M_Z magnetometers possess a high precision, while the M_X devices are characterized by a high response speed. However, the readings of M_X magnetometers depend on the phase of detection of the resonance signal: uncertainty $\Delta\varphi$ in the phase setting leads to an error of $\delta B = \Gamma\tan(\Delta\varphi)/\gamma$, where Γ is the halfwidth of the magnetic resonance line and γ is the gyromagnetic ratio for atoms of the working substance. Recently, a method of representation of the magnetic resonance signal has been proposed [6] that makes possible a reliable phase correction under the conditions of significant instability of the field, but this procedure does not allow the field to be measured simultaneously.

Another factor that limits the accuracy of quantum magnetometers (primarily of the M_X magnetometer) is the presence of more than one resonant transition in the Zeeman spectrum of working alkaline atoms. For the M_X type signal, the influence of the wing of an adjacent resonance on the position of the selected resonance line is characterized by the value of $\Delta\omega \cong \alpha\Gamma\Gamma/\Delta$, where $\alpha < 1$ is the relative magnitude of the adjacent resonance and Δ is the distance to the adjacent line ($\Delta \gg \Gamma$). For the M_Z type signal, the influence of the adjacent resonance is much smaller, since it is proportional to $\Gamma(\Gamma/\Delta)^3$.

Several attempts were made to create optically pumped quantum magnetometers that combine M_Z and M_X devices into one instrument so that the M_Z signal could be used for the slow correction of the fast M_X response [7–9]. The present Letter suggests a variant of solving the task of simultaneously ensuring high precision, response speed, and sensitivity. The proposed scheme (M_X–M_R magnetometer) is a tandem, but not in the full sense, since it employs a single cell and only one magnetic resonance. As a reference signal for the slow, precise part of the scheme, we suggest using the signal due to a radial component of the rotating magnetic moment, which occurs in the $0XY$ plane and is called the M_R signal. The squared M_R signal (M_R^2) can be measured using two quadrature detectors [10] so that the result is independent of φ. Note also that the influence of adjacent resonances on the M_R^2 signal as small as that on the M_Z signal.

The shape of the M_R^2 signal is symmetric with respect to the frequency detuning δ [11]:

$$\mathbf{M}_\mathbf{R}^2 = (M_Z^0)^2 V^2 \frac{\Gamma_2^2 + \delta^2}{(\Gamma_2^2 + \delta^2 + 4V^2\Gamma_2/\Gamma_1)^2}, \quad (1)$$

where $4V^2\Gamma_2/\Gamma_1$ is the RF field-induced broadening. The exact position of the center of resonance can be determined using the method of detuning modulation as $\delta_M = \delta + \varepsilon\sin(2\pi\Omega t)$ with a frequency of Ω and a deviation of ε. Detecting the signal at frequency Ω, we

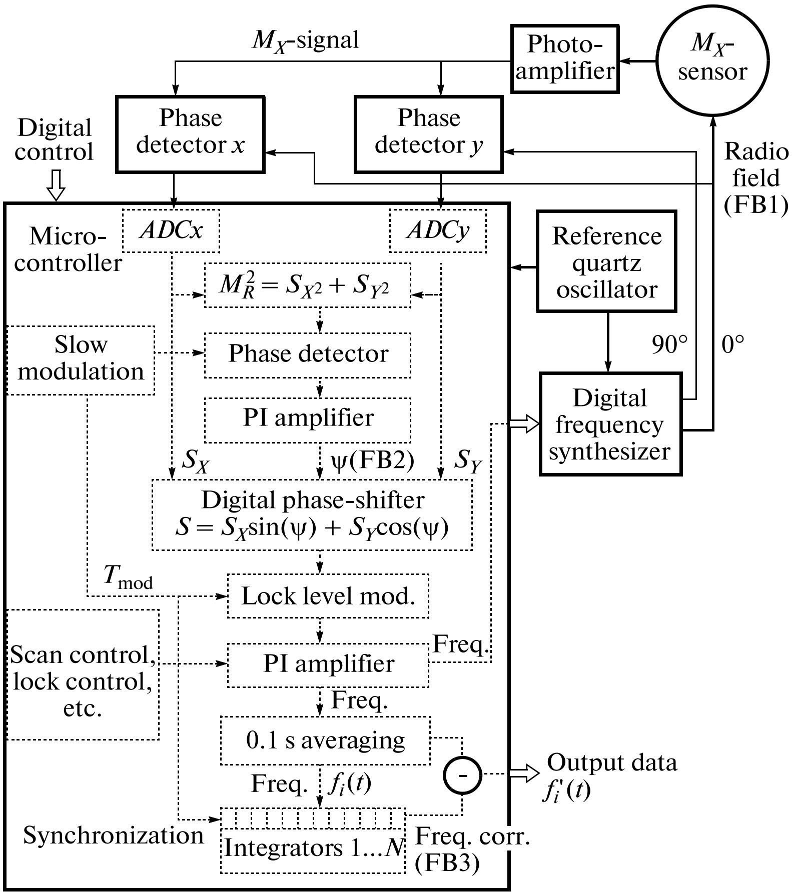

Fig. 1. Block scheme of M_X–M_R magnetometer.

obtain a low-frequency error signal $M_R'^2$. For $\Omega \ll \Gamma$, this signal can be expressed as

$$M_R'^2 = 2(M_Z^0)^2\delta\varepsilon V^2\frac{\Gamma^2 - 2\Gamma_2^2 - \delta^2}{(\Gamma^2 + \delta^2)^3}, \qquad (2)$$

where $\Gamma = \sqrt{\Gamma_2^2 + 4V^2\Gamma_2/\Gamma_1}$ is the resonance line width. We arte interested in determining the dependence of $M_R'^2$ on the uncertainty of phase φ setting, which is related to the frequency detuning as $\delta = \Gamma\tan\varphi$.

In the M_X–M_R magnetometer, the accuracy of phase setting is proportional to the slope of the $M_R'^2$ signal. The maximum slope of this signal is attained for the Rabi frequency V_{opt1} of the RF field, which obeys the condition $4V_{opt1}^2 = (2 - \sqrt{3})\Gamma_1\Gamma_2$. The V_{opt1} value is about half of the frequency $V_{opt} = 1/2(\Gamma_1\Gamma_2)^{1/2}$, which is optimum for the M_X magnetometer. Note that, at $V = V_{opt}$, the $M_R'^2$ signal has a zero slope.

If the frequency detuning δ is modulated directly (as in the M_Z magnetometer), the fast ($t < T_{mod}$) measurement of the magnetic field becomes impossible. For this reason, we have used the modulation of level L of the M_X magnetometer locking for the M_X signal S. In a standard scheme, the feedback (FB1) tends to ensure the condition $S = 0$. In the proposed scheme, the feedback parameters are changed so that it tends to reduce signal S to the established level $-L$ for one half of the modulation period $T_{mod} = 1/\Omega$ and to $+L$ for the other half. Thus, the modulation of both δ and φ is provided, and the M_X magnetometer (whose response speed is two to three orders of magnitude greater than the modulation frequency) keeps following the magnetic field variation at any time interval within T_{mod}. As a result, the M_X magnetometer readings $f_i(t)$ are modulated at a low frequency of Ω. The shape of this modulation is close to rectangular and the front widths are determined by the FB1 characteristic time τ_1. In order to exclude this modulation from $f_i(t)$, we have used an additional feedback (FR3) that separates the modulation-locked component, averages this signal, and subtracts it from $f_i(t)$.

Thus, the proposed scheme introduces two additional feedbacks: FB2 (which corrects the phase shift) and FB3 (which elminates traces of modulation from the instrument readings). The feedback time constants

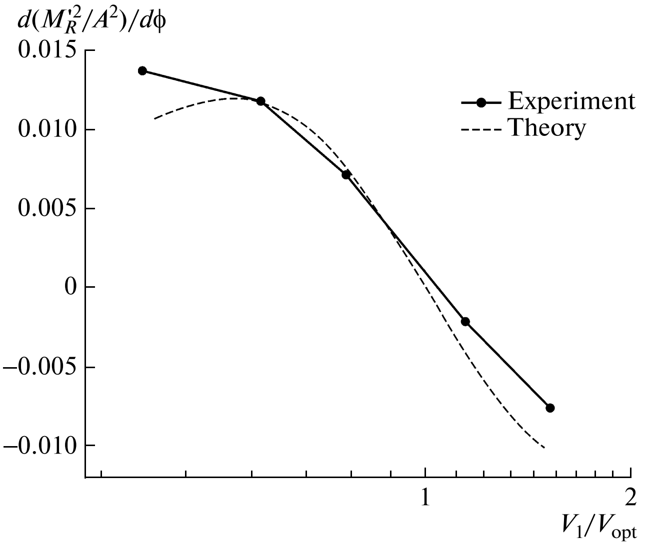

Fig. 2. Dependence of the M_R^2 signal slope on the resonance field power.

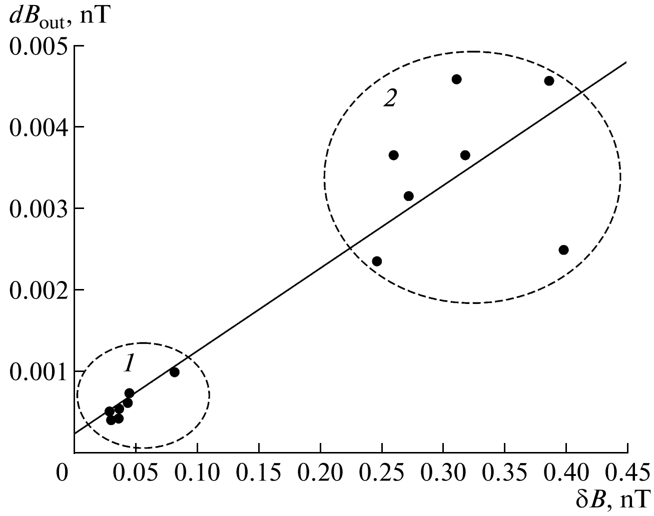

Fig. 3. Plot of the error dB_{out} (in FB2 circuit) versus variation δB of the magnetic field repeatedly measured in the regimes (*1*) with and (*2*) without stabilization.

τ_2 and τ_3 (25–100 s) are determined by the corresponding integrators.

The proposed concept of M_X–M_R magnetometer was experimentally verified using a potassium M_X sensor with matched pumping and probing beams and a digital feedback scheme described in [10]. The feedback algorithm was modified in accordance with the scheme depicted in Fig. 1, the idea of which was considered above. The modulation period was $T_{mod} = 1$ s; the data output rate n was chosen (with allowance for $1/n \gg 2\pi\tau_1$) at 10 s^{-1}, which required implementing $N = nT_{mod}$ program summators that accumulate data on the shape of modulation of the magnetometer output signal for its subsequent correction.

By using a sufficiently fast microcontroller, it is possible to provide a severalfold increase in n. It should be noted that, with the method used to eliminate modulation in the output signal, the system is insensitive to a significant degree with respect to the spectral components of magnetic field within the band $1/T_{mod} \pm 1/(2\pi\tau_3)$ and their odd harmonics. The value of τ_3 is limited from above by the characteristic variation times of parameters in the FB1 circuit; for a stationary device arrangement, these times can be very large and, accordingly, the "dead" zones can be very narrow. In the case of a scheme with fixed parameters, the shape of the modulation signal can be measured separately and this can be used to avoid the appearance of "dead" zones. Naturally, the FB2 and FB3 circuits can be employed with a certain periodicity (e.g., several times a day) rather than constantly.

The experimental measurements were performed within a magnetic screen in a field of ≅45 μT, both with and without the stabilization of the magnetic field. The field inside the screen was measured by a cesium M_Z magnetometer. The magnetic resonance line halfwidth at a working intensity of the pumping light was $\Gamma = 0.9$ nT, the amplitude of the resonance signal was $S_{max} = 181$ ADC units, and the variation sensitivity was 0.5 pT at $\tau = 0.1$ s.

Figure 2 shows the theoretical and experimental dependences of the M_R^2 signal slope on the resonance RF field power. As can be seen, there is good agreement between theory and experiment.

The accuracy of the phase setting in a system with control is determined by the ratio of the M_R^2 signal slope ($dM_R^2/d\varphi$) to the level of shot noise in the light. A simple estimation of the absolute error for the proposed magnetometer can be obtained proceeding from the fact that the maximum (peak to peak) M_R^2 signal at $\Delta\varphi$ amounts to 800 $(ADC^2\ units)^2$ at a noise level of 4.2 $(ADC^2\ units)^2$ (root mean square). Therefore, the absolute error for $\Gamma \approx 1$ nT will not exceed 5 pT at a measurement time of $\tau = 0.1$ s.

In order to directly assess the reproducibility of magnetometer readings, we have repeatedly measured the value of a stabilized phase under conditions of a large forced phase detuning and its correction by the FB3 circuit. The steady-state phase value was measured at $t > \tau_2$. The measurements were performed inside a magnetic screen both with and without stabilization of the magnetic field. In the former case, the variation of the stabilized phase was 1.1×10^{-3} rad, whereas in the latter case it amounted to 1.8×10^{-3} rad. For the given line width, the reproducibility of field measurements was 1.5 and 2.4 pT (r.m.s.), respectively.

Magnetic field variations at the modulation frequency (about 1 Hz) and its odd harmonics influence the accuracy of phase setting. Figure 3 shows a plot of the magnetic field measurement error dB_{out} (recalculated from variations of the stabilized phase) versus variation δB of the measured magnetic field, where the two groups of points correspond to the regimes with and without stabilization of the magnetic field. As can be seen, there is a linear relation of $dB_{\text{out}} = [(0.24 \pm 0.29) + (10 \pm 0.1)\delta B] \times 10^{-3}$.

Thus, we have proposed, implemented, and experimentally verified the scheme of a combined magnetometric device—an optically pumped quantum M_X–M_R magnetometer. In this device, the classical fast M_X magnetometer is supplemented by a slow, high-precision M_R magnetometer operating on the same atoms in the same optical scheme. The prototype device showed a response speed of ten readings per second at a reproducibility of measurements on a level of 2–3 pT (r.m.s.).

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REFERENCES

1. C. Cohen-Tannoudji and A. Kastler, in *Progress in Optics*, Ed. by E. Wolf (North-Holland Publ. Co., Amsterdam, 1966), Vol. 5.
2. W. Happer, Rev. Mod. Phys. **44**, 169 (1972).
3. A. Kastler, J. Phys. Radium **11**, 255 (1950).
4. F. Bitter, Phys. Rev. **76**, 833 (1949).
5. E. B. Aleksandrov and A. K. Vershovskii, Usp. Fiz. Nauk **179**, 605 (2009) [Phys. Usp. **52**, 573 (2009)].
6. A. K. Vershovskii and E. B. Aleksandrov, Opt. Spektrosk. **100**, 17 (2006) [Opt. Spectrosc. **100**, 12 (2006)].
7. A. H. Allen and P. L. Bender, J. Geomagn. Geoelectr. **24**, 105–125 (1972).
8. E. Pulz, K.-H. Jäckel, and H.-J. Linthe, Meas. Sci. Technol. **10**, 1025 (1999).
9. E. B. Aleksandrov, M. B. Balabas, A. K. Vershovskii, and A. S. Pazgalev, Zh. Tekh. Fiz. **70** (7), 118 (2000) [Tech. Phys. **45**, 931 (2000)].
10. A. K. Vershovskii and A. S. Pazgalev, Zh. Tekh. Fiz. **76** (7), 108 (2006) [Tech. Phys. **51**, 924 (2006)].
11. F. Bloch, Phys. Rev. **70**, 460 (1946).

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