

closed-loop system stability is achieved. Simulation results demonstrate that control system is able to converge with fine performance.

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## A RELATIVE INFLUENCE OF LOW-FREQUENCY AND MICROWAVE RADIO-OPTICAL RESONANCES IN ALKALI ATOMS VAPOR

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**Abstract:** The paper is devoted to the study of the relative influence of low-frequency and microwave signals of the system of two quantum magnetometers based on simultaneous induction of the spin generator signal on the resonance transition and the  $M_Z$ -signal of the edge

magnetically dependent microwave resonance. The “dressed” atom effect caused frequency shifts of low-frequency and microwave resonances is shown. The frequency shifts ratio of the spin generator to the microwave resonance was between 10 and 100, depending on the experimental conditions. The necessity of the using a circularly polarized low-frequency radio field is shown to reduce the radio-optical resonance frequency shifts caused by the mutual influence of the measuring channels of the magnetometers system.

**Keywords:** quantum magnetometer, optical pumping, frequency stability, alkali atoms, hyperfine structure, frequency shifts.

## **Introduction**

Quantum magnetometers are used for a wide range of physical experiments, measurements of the Earth's magnetic field and its spatial and temporal changes in geophysical and marine applications and the exploration of minerals.

Such systems as the absolute instruments are widely used for magnetic measurements under unfavorable conditions (at high altitudes corresponding to the orbits of ballistic missiles and artificial Earth's satellites). So the problem of measuring the magnetic fields of the solar system planets and interplanetary space has become actual.

Another application of quantum magnetometers is based on their sensitivity to rotation. In this way, it is possible to build quantum gyroscopes on their basis, which are devices that allow to detect the rotation of the body and to determine its angular velocity. This possibility is based on the gyroscopic properties of electrons, atomic nuclei and photons.

The results of a study of the relative influence of the quantum magnetometers system measuring channels are presented below. One of the magnetometers was based on a low-frequency spin generator principle, while the second one was built as passive microwave spectrometer with a resonance frequency lock loop [1].

## **Relative influence of low-frequency and microwave signals**

In the work [2] a research of influence of low-frequency noise on stability of the self-generating magnetometer resonant frequency at

simultaneous registration of a radio optical resonance signal on magnetodependent microwave transition was provided. Similar schemes are applied in the chip-scale atomic clocks using the microwave magnetodependent transition between end magnetic subtotals of a hyperfine structure of a ground state with different values of the complete moment  $F$  of an atom [3].

Unlike [3] where the absorption camera with the extreme high pressure of buffer gas was used, experiments [2] were executed on cells with an anti-relaxational covering, in which so-called luminous shift of resonance frequency played an essential role [4]. Its value depends on the polarization of pumping light and the frequency range of the magnetic resonances observed in hyperfine structure of alkali atoms [2]. At the same time resonant character of the applied radio-frequency fields determines inevitable relative influence of the registered signals.

The paper focuses on exploring the possibility of minimizing the frequency shifts of the measuring module, which are not related to the magnetic field variations and the pumping light. The origin of such shifts is due to the phenomenon of *coherence circulation* between sublevels in the hyperfine structure of the atomic system under the conditions of simultaneous action of microwave and low-frequency fields, causing magnetic dipole transitions between magnetic sublevels of the ground state, i.e. the position of atoms in states with different total moment values. Wherein, in accordance with the concept of a “dressed” atom, a significant contribution can be made to the observed frequency shift by *the change of the g-factor* that determines the scale of the magnetic splitting, as well as the presence of multiphoton transitions, which connect all the magnetic hyperfine structure sublevels to each other.

The scheme of alkali atoms magnetic dipole transitions in the ground state within the concept of a “dressed” atom is shown in Fig.1.

The amplitudes of the microwave transitions probabilities in the energy structure of the “dressed” atom determine the specific contribution of various magnetodipole transitions to the radio-optical resonance signal. The probabilities of microwave transitions  $P$  for different types of resonance (central or edge) are derived taking into account the statistical weight of the transition, which is determined by the population difference between the levels.

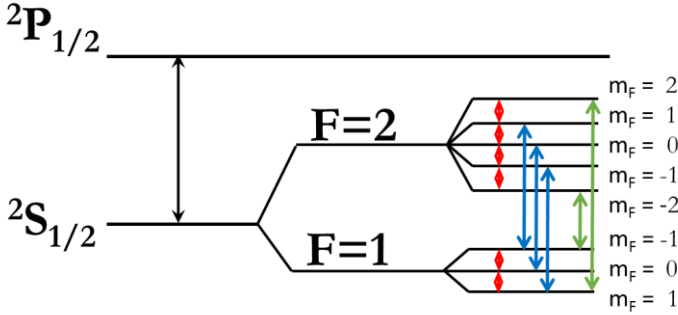


Fig. 1. Magnetic dipole transition of alkali atom ground state. Black arrows – D1 optical pumping line, red arrows – transitions of the spin oscillator, green arrows – microwave edge resonance transitions, blue arrows – microwave transitions in accordance with the concept of the “dressed” atom.

The probability amplitude of such transitions is expressed in terms of the matrix element of the magnetic dipole moment operator  $M$  as

$$\langle F^*, m^* | M | F, m \rangle = \sum_{m_1, m_1^*} D_{m_1^*, m^*}^{F^*} D_{m_1, m}^F J_0 \left[ (m + m_1^*) \frac{\omega_1}{\omega} \right] \langle F^*, m_1^* | M | F, m_1 \rangle \delta_{m_1, m_1^* + q}, \quad (1)$$

where  $D_{m_1^*, m^*}^{F^*}$  and  $D_{m_1, m}^F$  are Wigner functions,  $J_0 \left[ (m + m_1^*) \frac{\omega_1}{\omega} \right]$  are Bessel functions,  $\langle F^*, m_1^* | M | F, m_1 \rangle$  is matrix element of a magnetic dipole transition,  $\delta_{m_1, m_1^* + q}$  is Kronecker symbol, where the index  $q$  takes the value 0 or  $\pm 1$ , depending on the direction of the microwave field vector with respect to the direction of the constant magnetic field,  $\omega_1 = \gamma H_1$  and  $\omega$  are, respectively, the amplitude and frequency of the low-frequency radio field.

Table 1 shows the amplitudes of the transition probability in the central and edge series of the absorption spectrum calculated by Eq. (1) for the magnetic microwave resonances of the “dressed” atom Rb<sup>87</sup>.

The probabilities of P transitions were calculated for microwave resonances of the “dressed” atom in the central and edge series of the absorption spectrum of rubidium-87 for the case of a camera with paraffin covering of the walls.

Table 1. Amplitudes of the transition  $\langle F^*, m_1^* | M | F, m_1 \rangle$  of the atom  $\text{Rb}^{87}$

Transition $\langle F^*, m_1^*   M   F, m_1 \rangle$	Amplitudes of the transition
$m^* = 0, m = -m^*$	$\frac{1}{8} [J_0(\frac{\omega_1}{\omega}) + 3J_0(3\frac{\omega_1}{\omega})]$
$m^* = 1, m = -m^*$	$\frac{\sqrt{3}}{8} [J_0(\frac{\omega_1}{\omega}) - J_0(3\frac{\omega_1}{\omega})]$
$m^* = \pm 2, m = \pm 1$	$\frac{\sqrt{3}}{8} [J_2(2\frac{\omega_1}{\omega})]$

The experimental value of the Bessel function argument given in Table 1 do not exceed 0.1. In this case taking into account the statistical weight of the population differences, the probabilities ratio of magnetodipole transitions with “0-0” frequency and edge resonance is about  $10^2$  for cameras covered with paraffin in the range of  $\Gamma^*$  from 1 to 5, which corresponds to the experimental data.

The relative influence of low-frequency and microwave channels on the intensities of the detected signals is shown in Fig. 2, where experimental recordings of the signal of the self-generating magnetometer and the microwave absorption spectrum of  $\text{Rb}^{87}$  atoms are presented when scanning the frequency of the microwave field.

The nature of the change in the intensity of the signal of the self-generating magnetometer can be explained by the competition of the laser hyperfine pumping process and the process of redistribution of atomic populations caused by the action of the microwave field. It can be seen from Fig. 2 that inducing the edge microwave resonance R1 disrupts the self-oscillations of the self-generating magnetometer (because of atom depolarization), in the case of the edge microwave resonance R2, the intensity of self-oscillations increases, due to the increase in the number of optically oriented atoms interacting with the pumping field.

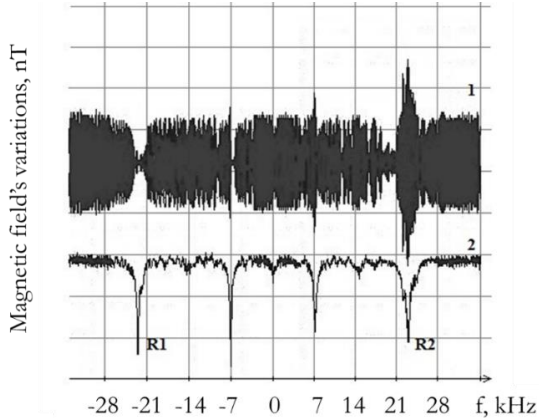


Fig. 2. Recordings of the microwave absorption spectrum and the signal of a self-generating magnetometer on optically oriented pairs of  $\text{Rb}^{87}$  in a magnetic field of  $1 \mu\text{T}$ : 1 – self-oscillating magnetometer signal, 2 – the signal of the absorption radio-optical resonance under conditions of scanning the frequency of the microwave field. The absorption signals of R1 and R2 correspond to edge resonances at transitions between the HFS sublevels,  $F = 1, m_F = 1 \leftrightarrow F = 2, m_F = 2$  and  $F = 1, m_F = -1 \leftrightarrow F = 2, m_F = -2$  respectively.

The role of the coherence circulation in the HFS was tested in two modes of operation: 1) measuring the frequency shifts of the self-generating magnetometer with a fixed frequency detuning of the microwave field; 2) measurement of the shifts in the frequency of microwave resonance for fixed changes in the frequency of the spin generator. The experiment showed a dramatic difference between the relative influence of low-frequency and microwave signals when operating in different modes: with the same artificial deviations, the ratio of the frequency shift of the spin generator to that of the microwave one is  $10\text{--}10^2$ , depending on the experimental parameters.

## Conclusion

It can be stated that in the considered version of the system of two quantum magnetometers, it is preferable to use a circularly polarized low-frequency radio field, which makes it possible to minimize the shifts in the radio-optical resonance frequency caused by the relative influence of the measuring channels.

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