Influence of the dynamic Stark effect on long-term frequency stability of a self-oscillating magnetometer with laser-pumped alkali atoms

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Abstract. This paper presents the results of investigation Stark shift effect influence on the long-term stability of a dual scheme of quantum magnetometers. Such scheme allows suppressing Stark shift components when a certain pumping light polarization is applied. As a result, long-term stability of a quantum sensor increases. However, when low-frequency (LF) and microwave fields are attached to a single vapor cell a coherence circulation in hyperfine structure of alkali atoms takes place. Physical origin of this effect is associated with the so called “dressed” atom theory, when atom is “dressed” by LF field. It yields in multiphoton absorption and resonance frequency shift. First estimates for this shift based on density matrix evolution formalism are provided in the paper.

1. Introduction

One of the most important parameters of the quantum magnetometer with laser pumping is its precision, which is limited by flicker noise at long observation time [1]. This limitation is closely coupled with laser source spectrum instability. Intensity and frequency variations of the pumping light cause Stark shift (or Light Shift effect) of the measured frequency. In alkali atoms such a shift can be described by three components – scalar, vector and tensor [2], which normally act simultaneously that complicates their independent measurement and limits optical pumping regime optimization, when Light shift effect is minimized. In the paper this problem is resolved comparing two Rb⁸⁷ vapor cell magnetometers measurements. One of them was based on a low-frequency (LF) spin oscillator principle, while the second one was built as a passive microwave spectrometer with a resonance frequency lock loop [3].
2. Experiment

A simplified scheme of the experimental setup is shown on Figure 1.

![Experimental setup diagram](image)

**Figure 1.** Experimental setup: 1 - beam splitter, 2,3 - circular polarizers, 4,5 - the mirrors. The constant magnetic field is oriented along the 0Y axis, spin oscillator linearly polarized RF field oriented along the axis 0Z.

The most significant feature of the setup is a single optical pumping source and a photodiode detector, which is used for both resonances registration – microwave signal and LF signal of the spin oscillator. Division of the signals was then provided with a LF filter in a microwave channel, which allowed microwave double resonance signal at modulation frequency of a reference oscillator to pass. This detection technique is common for classical radio-frequency (RF) atomic frequency standards. The possibility of a certain light shift component detection in the experiment follows from the fact that on microwave transitions all three components of the light shift act together, whereas on LF transitions of the self-oscillating magnetometer only vector and tensor components exist. This specific feature of the two magnetometers dual scheme allows to determine weighted impact of each light shift component correctly and estimate the influence of their mutual compensation on the long-term stability of the resonance frequency while changing pumping light polarization. Similar estimates were provided when a working magnetic field was measured as an error signal in the microwave channel and as a frequency offset of Mx-magnetometer. After that differential signal of magnetic field variations was processed in terms of Allan deviation. These dependences analysis allows to conclude, that Allan deviation increases with the law \((t^{n-1})^{1/2}\), where \(n\) varies within \(2.4 - 2.6\) due to measurement error.

Experiment showed that self-oscillating magnetometer long-term stability is strongly dependent on the hyperfine structure states coupling, which is induced by microwave transitions. In this case mutual effect of the microwave and LF signals takes place. This effect is not related to magnetic field variations and appears in frequency shifts of the spin oscillator when fixed microwave field intensity shifts are presented. In the work [5] it is noted that physical nature of such frequency shifts is associated with coherence circulation between magnetic sublevels of an alkali atom “dressed” by spin oscillator LF field. Absolute value of this shift strongly depends on magnetic-dipole transition number and reaches its maximum at 0-0 microwave transition, which is commonly used in atomic frequency standards.
In accordance with quantum theory of the “dressed” atom [6], simultaneous action of the LF and microwave fields on alkali atoms yields in multiphoton absorption and reemission of LF field quants, and probing microwave field absorption. The spectrum of microwave transitions between the sublevels of the hyperfine structure takes the form of the central and side groups of satellite lines. The centers of absorption line groups are spaced from the hyperfine transition 0-0 central series frequency by a multiple of the LF field frequency. As an example, arrows on Fig.2 show the possible microwave transitions between the hyperfine structure sublevels of alkali “dressed” atom with a nuclear spin of 3/2 for the center and the first two satellites of the side lines in the case of a significant excess of the radio frequency \( \omega \) over Larmor frequency \( \omega_0 \) and line DC and alternating LF and microwave fields orientation (so called \( \sigma \pi \) fields configuration).

**Figure 2.** The spectrum of microwave "dressed" alkali atom transitions with a nuclear spin equal to 3/2, \( \sigma \pi \) RF field configuration.

In contrast to the embodiment of the microwave spectrum, shown in Figure 2, the experiment with the dual magnetometer scheme corresponds to the resonance case when \( \omega \approx \omega_0 \). At the same time the spectra of the central and lateral satellites lines series overlap, which results in an increase in the magnetic sublevels with different values of the total angular momentum of the atom coupling. For example, in this case and in accordance with Figure 2 at 0-0 resonance frequency transitions, indicated in Table 1 are induced simultaneously. In the second column of the table probabilities of the corresponding transitions up to the 2\(^{\text{nd}}\) order Bessel function are indicated.
Table 1. Microwave transitions probabilities, F=1, m_F ↔ F=2, m_F, σ RF fields configuration.

| Transitions | Probability of the transition |  |
|-------------|-------------------------------|---|
| F=1, m_F = -1 ↔ F=2, m_F =1 | 3/64 $[J_0(\omega_1/\omega) - J_0(3\omega_1/\omega)]^2$ | |
| F=1, m_F = 0 ↔ F=2, m_F =0 | 1/64 $[J_0(\omega_1/\omega) + 3J_0(3\omega_1/\omega)]^2$ | |
| F=1, m_F = 1 ↔ F=2, m_F =0 | 1/128 $[J_1(\omega_1/\omega) + 3J_1(3\omega_1/\omega)]^2$ | |
| F=1, m_F = 0 ↔ F=2, m_F =1 | 3/32 $[J_1(3\omega_1/\omega)]^2$ | |
| F=1, m_F = -1 ↔ F=2, m_F =2 | 3/256 $[J_1(3\omega_1/\omega) - 3J_1(\omega_1/\omega)]^2$ | |
| F=1, m_F = 1 ↔ F=2, m_F =1 | 3/64 $[J_2(\omega_1/\omega) + 3J_2(3\omega_1/\omega)]^2$ | |
| F=1, m_F = 0 ↔ F=2, m_F =2 | 3/128 $[J_2(3\omega_1/\omega) - 3J_2(\omega_1/\omega)]^2$ | |

The weight contribution of the transitions indicated in Table 1 depends on the population difference between the magnetic sublevels. Laser pumping of the small size resonance cell with antirelaxation wall coating in the magnetometers dual scheme experiment was carried out on the D_2 line of electric-cyclic transition F = 2 ↔ F’ = 3. For this case when circularly polarized light pumps the atoms of the working substance (Rb$_{87}$), the system of stationary equations of the density matrix evolution in the balance approximation has the following form:

$$
\begin{align}
\sigma_{11} &= \sigma_{22} = \sigma_{33} = 0.125, \\
\sigma_{44} &= 0.125 - 0.165 \Gamma^* \sigma_{44}, \\
\sigma_{55} &= 0.125 + 0.075 \Gamma^* \sigma_{44} - 0.432 \Gamma^* \sigma_{55}, \\
\sigma_{66} &= 0.125 + 0.09 \Gamma^* \sigma_{44} + 0.324 \Gamma^* \sigma_{55} - 0.648 \Gamma^* \sigma_{66}, \\
\sigma_{77} &= 0.125 + 0.108 \Gamma^* \sigma_{55} + 0.576 \Gamma^* \sigma_{66} - 0.6 \Gamma^* \sigma_{77}, \\
\sigma_{88} &= 0.125 + 0.072 \Gamma^* \sigma_{66} + 0.6 \Gamma^* \sigma_{77}, \\
\sum \sigma_{mn} &= 1,
\end{align}
$$

where $\Gamma^*$ is a ratio of the rates of optical pumping and atoms relaxation processes.

Figure 3 presents the results of diagonal elements of the density matrix calculation in function of the $\Gamma^*$ parameter.

Figure 3. The diagonal elements of the density matrix as a function of the parameter $\Gamma^*$ for Rb$^{87}$ atoms (F=2 ↔ F’=3) in case of paraffin-coated cell, $\sigma \pi$ RF field configuration.
The end resonance was observed in the experiment with two magnetometers when the applied fields had \(\sigma\sigma\) configuration with the constant magnetic field orientation perpendicular to the vector of LF and microwave fields. In this case, the probability of the end resonance magnetic dipole transition \(F = 1, m_F = 1 \leftrightarrow F = 2, m_F = 2\) is proportional to \(3/64 [J_2 (2\omega_1 / \omega)]^2\). The experimental value of the Bessel functions arguments mentioned above does not exceed 0.1. In this case, taking into account the statistical weight of the corresponding population difference, ratio of the probabilities of inducing magnetic dipole transitions at a frequency of 0-0 and end resonance transitions is of the order of \(10^2\) in the range of the \(\Gamma^\ast\) from 1 to 5, which has good correlation with experimental data.

3. Conclusions
The analysis carried out in the paper allows to identify further ways of improving the metrological characteristics of quantum devices based on magnetic resonance in optically oriented atoms [7, 8], as well as to expand the functionality of the technique of simultaneous observations of the LF and microwave transitions for different isotopes of the alkali atoms used in atomic clocks and quantum magnetometry.

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