The influence of signals correlation on the long-term stability of a tandem of quantum magnetometers with laser pumping

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Abstract. The results of studies of the long-term frequency stability as a function of the correlation coefficient for a tandem of two quantum magnetometers with laser pumping of ^{87}Rb in wall-coated vapour cell are represented. Measurement scheme includes a low-frequency self-generating magnetometer and a quantum microwave discriminator working at magnetic dipole transitions of radio-optical end state resonance. The difference of synchronously detected signals is processed to determine the Allan variance as a function of averaging time and correlation coefficient of signals. These parameters are essentially dependent both on the pumping light intensity and polarization and the intensity of radio fields that are produced in the working cell.

1. Introduction

The long-term frequency stability of alkali vapor quantum discriminators with optical pumping, which are used in quantum magnetometers and frequency standards, is known to be dependent on technical (flicker) noises caused by slow variations of parameters of such devices (for example, a temperature of the working cell, an alkali vapor pressure, a variation of intensity and spectral composition of pumping light and etc.). The total influence of these noises on the frequency dynamics of self-oscillating device does not allow determining the destabilizing role of different flicker components, which makes it difficult to find new ways of improvement of the metrological of measurement scheme. Nevertheless, numerous studies in this field allow to state that the most important destabilizing factor for such devices are so-called light shifts of the measured frequency, due to the influence of non-resonant components in pumping light spectrum.

2. Frequency stability investigations

The experimental basis of the studies in present work is the magnetic induction meter [1] that consists of a tandem of optically pumped quantum magnetometers (OPQMs), one of which is a low-frequency spin generator; another is a radio-spectrometer with frequency lock loop to the microwave resonance line. The functional scheme of a two-channel system of quantum magnetometers with optical pumping is presented on figure 1.

The external cavity laser Toptica DL-100-L, tuned to the D_2 line of the head doublet of ^{87}Rb atoms, was used as a pumping light source. Figure 2 shows part of the energy spectrum of ^{87}Rb atoms, which corresponds to the D_2 line of the head doublet, where solid arrows in the $S_{1/2}$ ground state indicate

magnetic dipole transitions corresponding to the frequency of the self-oscillating magnetometer and dashed arrows indicate magnetic-field-dependent transitions corresponding to the microwave signal of radio-optical resonance at frequency ν_1 or ν_2, depending on the sign of the circular polarization of pumping light ($\sigma-$ versus $\sigma+$).
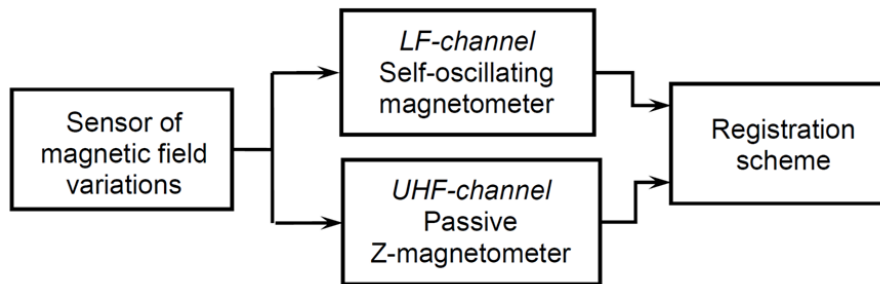

Figure 1. Functional scheme of a two-channel system of quantum magnetometers with optical pumping.
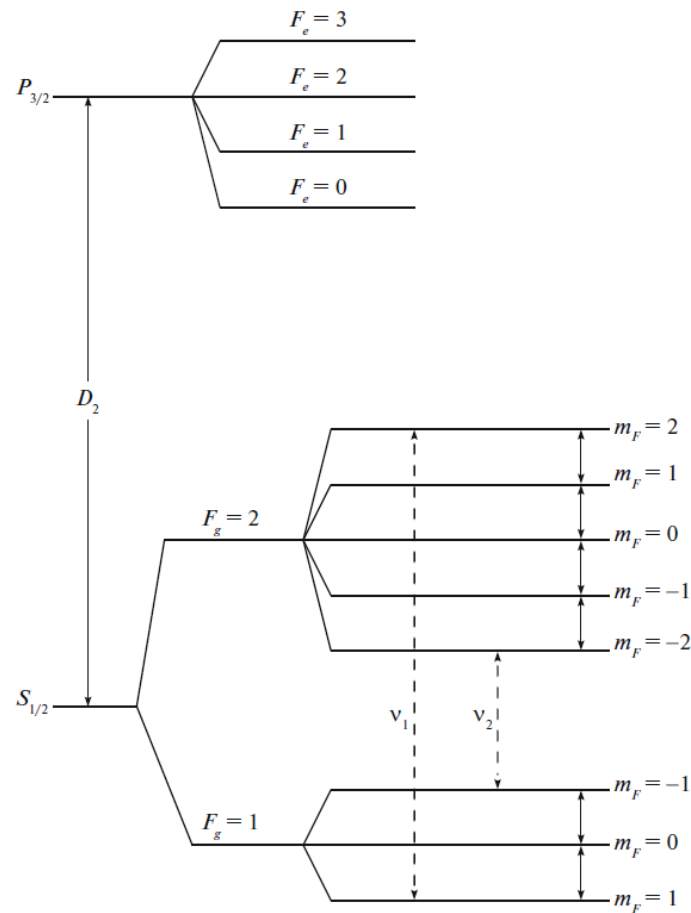

Figure 2. Energy spectrum of alkali metal atoms for the electric-dipole transition of the D_2 line of the head doublet.

The experiments were performed on the laboratory setup of quantum discriminator, based on the set of elements which are commonly used in vapor cell based frequency standards [2]. The laboratory setup is described in detail in [3]. We used the wall-coated 1 cm^3 working cell. The single optical path for the OPQMs tandem was placed in the center of coils, generating the magnetic field with 45° orientation relative to the optical axis. The whole system was placed into two-layer magnetic screen with shielding factor of 10^2 to reduce external magnetic field fluctuations. Resonant microwave field, inducing the transitions in hyperfine structure of rubidium atoms, was created by the traditional scheme of the frequency multiplying of reference quartz oscillator and subsequent amplification of the signal.

The resonance frequency of the self-oscillating magnetometer was determined by a frequency meter with a built-in rubidium frequency standard and processed by a computer, to which the error signal of the microwave channel (proportional to residual variations of magnetic field inside the screen) was also fed, as it was described in [3]. Figure 3 shows the signals from two channels (low-frequency spin generator and UHF radio-spectrometer) and the difference of magnetic field variations detected on the magnetic-field-dependent microwave transition by a self-oscillating magnetometer. The difference of these synchronous variations was reduced to the same scale in magnetic field units and processed to determine the Allan variance depending on the averaging time.
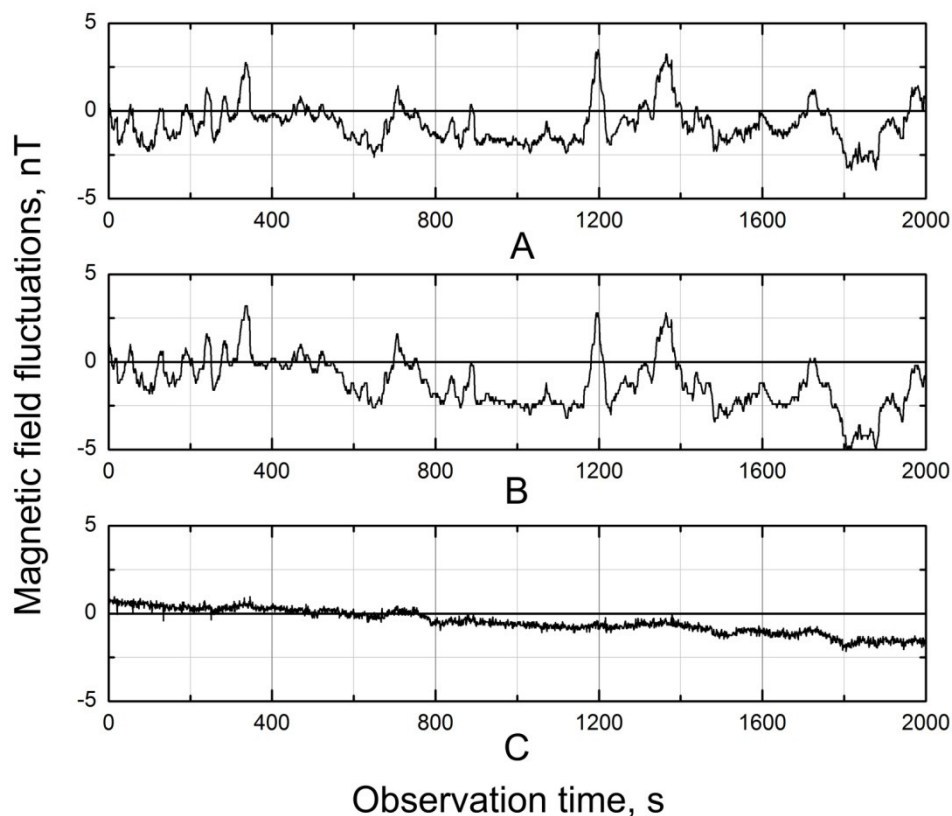

Figure 3. Temporal dependences of the magnetic field variations detected by self-oscillating magnetometer (A) and by radio-spectrometer on the magnetic-field-dependent microwave transition (B). Temporal dependence of the difference of magnetic field variations (C) registered by LF and UHF channels for 0.88 – correlation coefficient, σ+ circular polarization of microwave pumping light.
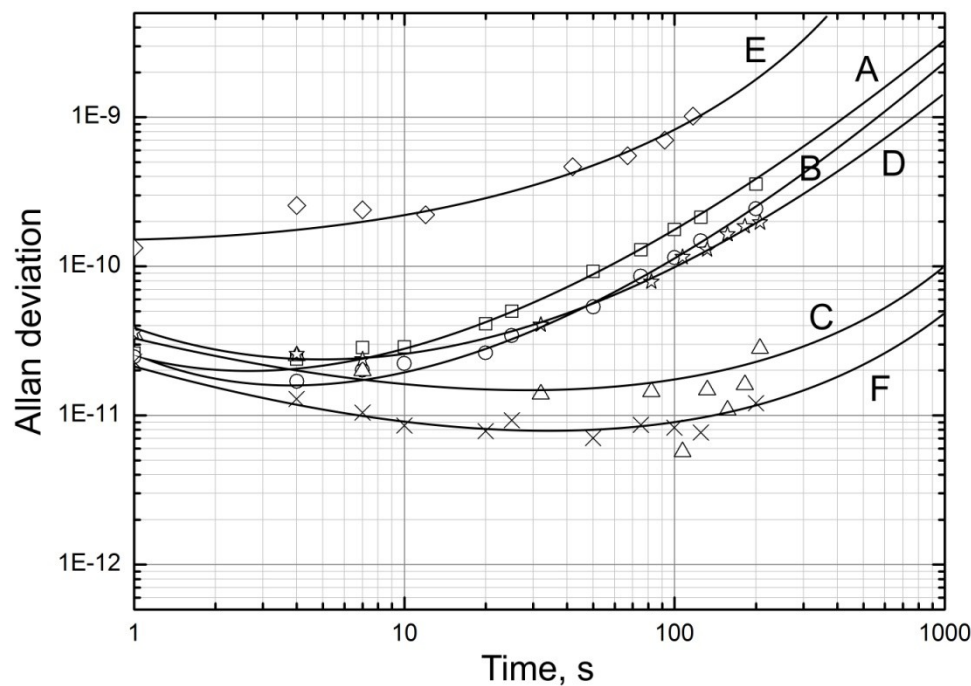
Figure 4. The time dependence of Allan variance for the difference of OPQMs signals. Curves A – F correspond to different signs of the circular polarization of microwave pumping light and various values of correlation coefficient: A – σ+, 0.88; B – σ+, 0.94; C – σ−, 0.99; D – σ−, 0.93; E – σ−, 0.65; F – σ+, 0.99.

During the processing of experimental data there was performed the computation of correlation coefficient, defining the relation between microwave and low-frequency signals, detected in a tandem, which depends on the pumping rate and the intensity of radio fields in the working cell. The value of correlation coefficient was varied in the range between 0.3 and 0.99 depending on the sign of circular polarization of the pumping light, the intensities of applied fields and the power of spin oscillator signal. Figure 4 represents the Allan variance for the difference of frequencies of quantum magnetometers as a function of averaging time.

3. Conclusions

The obtained data lead to the conclusion that mutual compensation of low-frequency flicker noise components in the optically pumped alkali discriminator is possible provided by a correct choice of the direction of circular polarization of the pumping light. This conclusion allows such OPQMs tandem to be considered as an alternative to an atomic clock with a low level of long-term instability. The use of miniature quantum magnetometers based on vertical cavity surface emitted lasers and small-sized alkali vapor cells in OPQMs tandem allows it to be considered as an alternative to miniature atomic clock based on coherent population trapping [4].

Such OPQMs tandem may also be of interest in the development of the magnetic induction meters with laser pumping on D_1 line, where the light shift component, which depends on the magnetic-field orientation relative to the optical axis, becomes significant [5]. The strong light shifts correlation on the microwave and low-frequency transitions, which is implemented in the tandem on the atomic level, gives an opportunity to reduce systematic and orientation errors in quantum magnetometers in conditions of varying intensity and spectral composition of the pump light.

References

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