QUANTUM FREQUENCY STANDARDS AND MAGNETOMETERS OF THE HIGHEST STABILITY BASED ON A PRINCIPALLY NEW EXCITATION METHOD OF A COHERENCE SIGNAL

E. N. Pestov

Independent Researcher, St. Petersburg, RUSSIA
E-mail: infra-balt@peterlink.ru

ABSTRACT

It is shown that in the present state of development of precision quantum devices, the limitations on their long-term stability increase reside in the method itself of the resonance signal excitation with the $H_1\cos\omega t$ harmonical field , which produces forced oscillations regime. The design of new types of frequency standards and magnetometers based the method of "impact excitation of the phase coherence" is proposed. This method offers a means of eliminating many causes of instability and slow drift of the standard frequency ω_0. The method makes it possible to set up the regime of free oscillations at the resonance eigenfrequency $< \omega_0 >$ and to obtain the highest medium- and long-term stability. This method enables the development of frequency standards without microwave resonators and frequency synthesis circuits. The results of the research work and development of a ^{133}Cs magnetometer with a free oscillation regime is presented. It is pointed out that hydrogen frequency standards and proposed potassium standards with laser pumping are most practical for setting up a *free oscillation regime*.

impact excitation, coherence signal, stability, frequency standard, quantum magnetometer, forced oscillations, free oscillations, regime, eigenfrequency

1. INTRODUCTION

Conceptually for realization of high absolute accuracy and stability of quantum frequency standards and magnetometers, short-term and long-term, the researchers usually base on the certain set of physic-technical parameters

$$P\ (f_0,\ S/N,\ \Delta f,\ \gamma,\ \sum \delta f_i) \qquad (1)$$

where $f_0 = \omega_0 / 2\pi$ - central resonance frequency of atoms, S/N - a signal to noise ratio, Δf - a resonance width, γ - the gyromagnetic ratio, $\sum \delta f_i$ ($\delta f_i = \delta\omega_i / 2\pi$) - frequency shifts of the centre of the unperturbed resonance from influence of many factors determined by physical and technical parameters of the "atom + field " system.

In the usual opinion, it is this set of *static* parameters P (…) that is basic and sufficient to estimate limiting short-term instability and accuracy of the concrete frequency standard or magnetometer. It is known that for increase of the accuracy characteristics of quantum devices the researchers go on a way of increase of values f_0, S/N, γ, reduction of a resonance width Δf and frequency shifts $\sum\delta f_i$ of a various origin. On the basis of the stated concept, by application of laser pumping, detecting and the cooling of atoms, new types of quantum frequency standards were realized: on atomic beam tube with isotopes ^{133}Cs [Ref. 1] and ^{87}Rb [Ref. 2], gas cells with ^{87}Rb [Ref. 3], atomic fountain [Ref. 4] and ion trap [Ref. 5]. As a result of intensive investigations to the present time in the frequency standards absolute accuracy $\sim 10^{-15}$ and the short-term instability $\sim 10^{-14} \cdot \tau^{-1/2}$ have been achieved. {It is necessary to note such a new type of quantum magnetometer as a spin-exchange Cs-He magnetometer [6]. Nowadays this magnetometer has the least systematic error ≤ 0.03 nT and is intended for the National Metrological Centres [Ref. 7].} However, the long-term instability (for $\tau > 10^4$ s) which is the main parameter for the frequency standards in the time keeping regime is worse than the short-term stability on the order and more. The achievement of a higher long-term stability remains a problem as the drift of reference frequency f_0 unpredictable on a sign and value is observed.

2. DESTABILIZING FACTORS CAUSED BY A FIELD $H_1 \cos \omega t$

The destabilizing factors in quantum devices are the frequency shifts $\sum\delta f_i$ whose nature and values are carefully investigated. {In particular, the complex experimental researches of frequency shifts $\delta f_i\ (I, \pm\sigma, \theta, H_1, t^0)$ were executed for quantum magnetometers on the alkaline metals atoms: ^{133}Cs [Ref. 8], ^{87}Rb [Ref. 9] and potassium isotopes, ^{39}K and ^{41}K [Ref. 10]}.

For the frequency standards the investigations of frequency shifts δf_i will be carried out more widely and intensively in connection with a variety of the physical schemes of the standards and shifts themselves. The investigations have shown that some shifts can be compensated and others can be reduced to a minimum or stabilized in time.

At the present accuracy level the greatest attention is given to frequency shifts $\delta f_i\,(H_1)$ connected with amplitude and phase of a resonant field H_1 such as: phase shifts in the Ramsey resonator; shifts from a pulling of resonant frequency f_0 by the neighbouring transitions; shifts from spectrum components connected to frequency synthesis and their phase fluctuations; shifts from inhomogeneous of the field distribution H_1 on an entrance and output of the resonator, its spatial distribution; modulatently-parametrical shifts; Bloch-Siegert shift $\delta\omega^{(2)}$ dependent from a field amplitude H_1, and others. Besides these frequency shifts depend on the atom velocity distribution. Thus the resonant field $H_1 \cos\omega t$, on the one hand, creates phase coherence in atom's spin-system carring out a useful role, on the other hand, it opens up and accumulates many kinds of system errors which in result become additiveless. The greate efforts put by the researchers for minimization of these shifts result in significant *technical complication* of systems. However, appreciable increase of the long-term stability does not occur, the slow drift of a resonance is kept.

In the last works [Ref. 11] Pestov E. and Chirkov A. show that they have managed to *explain the physical nature* of long-term instability. They have found out the dynamic (drift) correction $\boldsymbol{\delta\omega^{(1)}}$ to the resonant frequency ω_0 in the first order of a field amplitude of H_1 at harmonic excitation which shows the existence of the **slow** *regular* **drift** (with the large period) in system ″atom + field″, and this drift *can not be eliminated technically*.

Thus the main obstacle in ways to achievement of high long-term stability is the *method itself of resonance signal excitation* based on creating of **forced** *oscillations* in quantum system under the action of a resonant field $H_1 \cos \omega t$ (or $E_1 \cos \omega t$ in laser standards).

Radically to solve a problem of increase of long-term stability the principally new excitation method of quantum transitions - **without a resonant phasing field $H_1 \cos \omega t$** - allows essentially which the *regime* of **free oscillations** realizes. In this case the frequency shifts stated above and the slow drift are totally excluded. This method is stated below.

3. IMPACT EXCITATION METHOD OF A COLLECTIVE PHASE COHERENCE

3.1 Physical mechanism for the phase coherence excitation in quantum system

{The stated method of macroscopic coherence excitation without action of a resonant field H_1 on quantum system was offered and was carried out experimentally by author long enough, in 70's years [Refs 12, 13]. However, this method was paid no attention to by the scientific circles.}

At study of reactation rate of the magnetic moment components of spin-system on external influences the author has come to a conclusion that the phase part of a coherence signal (or undiagonal part of a density matrix) can react to them almost instantly. This statement was verified experimentally and has proved to be true [Ref. 12]. The new induction method of collective phase coherence is to affect on a quantum system with a population inversion by single δ - function video-pulses of the magnetic field $\mathbf{H}_{x,y,\delta}$ (or electrical $\mathbf{E}_{x,y,\delta}$) of duration $\tau_\delta << T_0$ where T_0 - oscillations period of quantum transition.

The field acting along axis X is written as:

$$\mathbf{H}_{x,\delta} = H_{1,\delta} \cdot \mathbf{e}_x \cdot \delta(t - t') \qquad (2)$$

where $H_{1,\delta}$ is the amplitude of the δ -function pulse, $\mathbf{e}_x$ is a unit vector, ort; $\delta(t - t')$ is a delta function; $\tau_\delta = (t - t')$, T_0 - frequency period of quantum transition.

This kind of a coherence excitation at which the energy of system does not vary is carried out within the framework of the law of system total pulse conservation. The method is as natural as the traditionally used excitation by a harmonic field $H_1 \cos\omega t$ which is carried out within the framework of the energy conservation law $\Delta E_{2,1} = \hbar\omega_0$ and is characterized by inertial property [Ref. 14].

3.2 Principal features of the method [Refs 12, 14]

Let's note some basic features of the method named as "impact excitation of phase coherence":

1. The collective phase coherence is introduced in quantum system *instantly* within the time $\tau_\delta << T_0$.
2. The organizer of a phase coherence is a *δ - like video-pulse* of the field $\mathbf{H}_{x,y,\delta}$ (or of a $\mathbf{E}_{x,y,\delta}$). In this case the coherence is induced by affecting with δ - video pulse on initial spins' phases φ_i but not on the current phases $\Phi_i = \omega_0 t + \varphi_i$ of a wave function as at traditional harmonic excitation by a field $\mathbf{H}_1(x, t)$.
3. The affecting on a system δ - video-pulse is the single coherence operator in phase space and creates a zero difference $\Delta\varphi_{1,2}$ between the initial phases of the interfering sublevels |1 > and |2 >. This difference is strictly fixed in terms of the coordinates $(x, y, t' + \tau_\delta)$

$$\Delta\varphi_{1,2}(x, y, t' + \tau_\delta) = 0 \qquad (3)$$

4. The excitation of phase coherence by the $\mathbf{H}_{x,y,\delta}$ video-pulse involves in the interference process *all absorption spin contour.* Thus the **free–oscillation** signal $S_{x,y,\delta}(t)$ at an average on ensemble resonance eigenfrequency $< \omega_0 >$ is generated with an amplitude larger (by a factor of $1.5 \div 2$) than that one in the traditional case of excitation by a harmonic field $\mathbf{H}_1(x, t)$ which selectively "cuts off" only some of the spins from the absorption contour near the central frequency f_0.

4. FREE OSCILLATION REGIME IN QUANTUM DEVICES

4.1 Investigation results

This paper submits the results of investigations and realization of the "impact excitation of the phase coherence" method and *regime of free oscillations* on an example magnetometer with optical pumping of ^{133}Cs atoms using an *interrupted* and *continual* signal.

In Fig. 1 the function block diagram of a quantum Cs magnetometer is given.The sensitive sensor is executed under the known circuit: 1 - spectral lamp, 2 – contour coil of the high-frequency generator 3 with capacity regulation by means a photodetection circuit 4 for stabilization of pumping light, 5 - lens, 6 - π -polarizer, 7 - circular λ/4 polarizer (σ^+ or σ^-),
8- absorption cell containing ^{133}Cs atomic gas, 10 -photodiode
The circuit of the electronic block differs from the traditional one for an self-oscillation regime. It contains: 11- the signal amplifier, 12 – frequency divider (carries out the function of a phase memory cell), 13 - the former of single δ - like current pulses i_δ (is connected to the inductance coil 9 for short circuit of the feedback circuit).

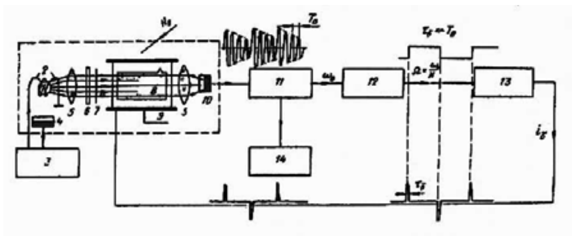

Fig.1 Cs-He magnetometer function diagram

The constant field $\mathbf{H}_0(z,y)$ is directed under a corner ~ 45^0 to axes Z and Y, the optical axis of the sensor coincides with an axis Y, and the video-pulse $\mathbf{H}_{x,\delta}$ acts on an axis X.

4.1.1 Regime with the interrupted free oscillation signal

For this case the connection between units 12 and 13 is broken off. From the former 13 the single current pulses i_δ are fed to the inductance coil 9 in which the video-pulses $\mathbf{H}_{x,\delta}$ of the form (2) are appeared. The duration of a video-pulse $\mathbf{H}_{x,\delta}$ is $t_\delta < 1/4\ T_0$. After action of a pulse the ^{133}Cs atoms generate the free oscillation signal $S_{y,\delta}(t)$ on Zeeman transition frequency $< \omega_0 >$ in a state $| F = 4 >$

$$S_{y,\delta}(t) = S_{max} \cdot \cos(< \omega_0 > t) \cdot \exp(- t/\tau_2) \qquad (4)$$

decreasing on amplitude with relaxation time $\tau_2 >> \tau_\delta$.

In the oscillogram of Fig. 2 the occurrence process of a free precession signal $S_{y,\delta}(t)$ from action of the first and second video-pulses $\mathbf{H}_{x,\delta}$ is shown; $\tau_\delta < 0.3\ \mu s$, $T_0 \leq 6\ \mu s$, $\omega_0 / 2\pi \approx 180$ kHz.

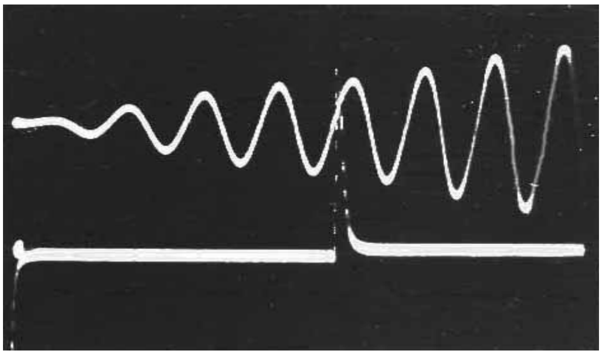

Fig. 2. Oscillogram showing dynamics of occurrence of a free precession signal of the ^{133}Cs atoms from action of the 1-st and 2-nd magnetic video-pulses.

The steepness of gradual increase of a signal amplitude during 4 - 5 precession periods is conditioned by the chosen amplifier bandwidth about 50 kHz. When using the ^{133}Cs magnetometer amplifier with a bandwidth ~ 250 kHz the first half-cycle had much larger signal amplitude.

The oscillogram in Fig.3 illustrates the free precession signal from action of a single video-pulse.

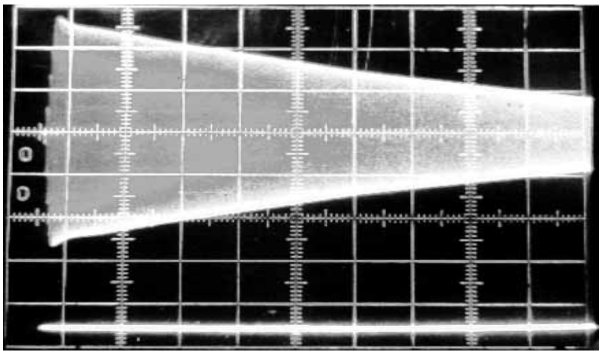

Fig. 3. Oscillogram of the free precession Cs atoms signal from action of one magnetic video-pulse with optimum amplitude for magnetometer with a faltering signal (time scale: one crate on a horizontal axis corresponds to 1 ms).

The relaxation time is τ_2 ~ 8 ms. If after the time τ_2 in the coil 9 a video-pulse $\mathbf{H}_{x,\delta}^{(2)}$ with the opposite polarity to the precession, applies the signal almost instantly will disappear up to a noise level. The time of a total signal disappearance also is connected to an amplifier band-width. The time pause τ_p can be established equal ~ (10÷20) μs. Further the signal can again be started by a single video-pulse $\mathbf{H}_{x,\delta}^{(1)}$ up to its maximal amplitude.

Despite the signal interruption such a magnetometer keeps high quick-operatence. At relaxation time τ_2 ~15 ms the modern circuitry allows to make 5 counts and to generate one averaged measurement with an count error ~ 0.001 nT in a digital form. Thus for 0.1 s it is possible to carry out 5 averaged measurements, and for 1 s - 50 measurements.

The signal in such magnetometer is completely free from the action of an electronic feedback circuit with the harmonic field $H_1\cos\omega t$ and represents the *signal of the eigenoscil-lation regime* distinguished from all other regimes by the property of the *best stability*.

4.1.2 Circuit with a continuous signal of the free precession

In this case connection between units 12 and 13 is closed, Fig. 1. The loop of positive feedback is closed. At inclusion of the button "start" on the unit 13 a single video-pulse $\mathbf{H}_{x,\delta}^{(1)}$ arises which sets the beginning to oscillations. The divider of frequency keeps memory of a signal phase and sets a factor of division K which determines an time interval between two following pulses τ_δ.

The oscillogram of a *continuous signal of free atom precession* of the Cs magnetometer is given in Fig. 4. Each subsequent pulse τ_δ acted through 256 precession periods T_0 ($T_0 = 2^8$).

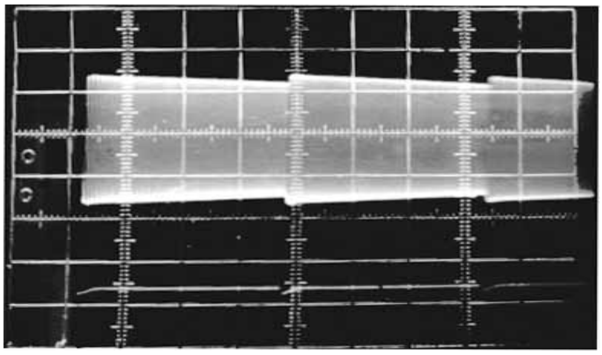

Fig. 4. Oscillogram of a continuous free precession signal in the quantum ^{133}Cs magnetometer.

Quantum magnetometer in such free oscillation regime has the highest long-term stability in relation to traditional magnetometers with a continuous signal.

5. APPLICATIONS OF THE NEW METHOD

The considered excitation method carries *universal* character and opens up the possibility of developing of highly stable atomic frequency standards with a continuous free oscillation signal induced *without the Ramsey resonator* and without a system for synthesizing the frequency of the resonant micro-wave field. The frequency standards of such type should have the best stability and accuracy as most of the insta-bility factors are excluded from them [Ref. 15].

Now the frequency standards on the *hydrogen atoms* are closest to realization of a device on this coherence excitation principle. (The creation of a video-pulse with duration < 1 ns does not represent of principle difficulties).

Other perspective standards are the standards on potassium isotopes (^{39}K and ^{41}K) having lower than hydrogen the reference transition frequency f_0, accordingly, 461.7 MHz and 254.0 MHz. Despite it the potassium standards with a free oscillation regime and laser pumping can become competing on stability with the modern hydrogen standards. At the same time on dimensions and weights such standards will be less than hydrogen ones on the order and more.

6. CONCLUSION

1. The investigation results show that at the present stage the further increase of the long-term frequency stability of quantum standards is limited by the method itself of resonance signal excitation with using a harmonic resonant field sy ${}_1$t enωt at which the forced oscillation regime is realized.

2. The suggested principally new method of "impact excitation of phase coherence" in quantum system by the δ - like video-pulse of magnetic field $\mathbf{w}_{x,\delta}$s sy ${}_{1,\delta} \cdot \mathbf{i}_u \cdot \delta(t - t')$ allows to realize a free oscillation regime at the resonant eigenfrequency $< \omega_0 >$ distinguished by the best stability.

3. A physical nature and conditions of formation of stable free oscillations are considered. The offered excitation method has realized in quantum ^{133}Cs magneto - meters.

4. On the basis of this method a concept and schemes are developed for building the atomic frequency standards and other quantum devices including such ones which do not contain resonators and circuits for synthesis of microwave signals. Evidently, in such standards there will be no frequency shifts (and time drift) related to the H_1 field and the resonator [Ref. 15].

5. The results of works [Refs 16, 11] show that for achievement of the best long-term stability of frequency standards (and magnetometers) it is necessary to execute the additional criteria at the choice of a type of quantum systems irrespective of an oscillation regime. (These questions will be stated further).

REFERENCES

1. B.Boussert, G.Lucas-Leclin, F.Hamouda, and et al. “Frequency Perfornances of a Miniature optically pumped Cesium Beam frequency standard”. IEEE Trans. Ultrason., Ferroel. and Freq. Contr. **46**, 366 (1999); **47**, 449 (2000); **48** (2001).

E. de Clercq and A. Makdissi. “Current Status of the LPTF Optically Pumped Cs Beam Standard” . Symp. on Freq. Standards and Metrology. Ed. J.C.Bergquist. World Scientific (1996).

2. A.G.Gevorkyan, A.N.Bessedina, and A.B.Bassevich. “Prospects for development GLONASS spaceboard atomic beam frequency standard with laser pumping”. [^{87}Rb].Proc. IEEE Internat. Freq. Contr. Symp. (FCS), USA, p. 97 (1993).
A.N.Besedina, A.B.Bassevich, A.G.Gevorkyan et al. Rubidium atomic beam frequency standard with laser pumping and detection”. Proc. 5th Russian Symposium “Metrology, Time and Space”, Moscow, VNIIFTRI, p. 344 (1994).

3. G.Milety, P.Thomann. “Study of the S/N performance of passive atomic clocks using a laser pumped vapor”, Proc. 9th Eur. Freq.and Time Forum (EFTF), p.217(1995)

4. S.Jefferts, D.Meekhof, J.Shirley, T.Parker. “Accuracy evaluation of a cesium fountain primary frequency standard at NIST”. IEEE Instr. and Meas.,**50**,507 (2001).

5. D.Prestage, R.Tjoelker, G.J.Dick, and Maleki, “ Ultra-stable Hg^+ trapped ion frequency standard”. J. Mod. Optics **39**, 221 (1992).

5. E.V.Blinov, R.A.Zhitnikov, and P.P.Kuleshov. Zh. Tech. Fiz., **49**, 588 (1979).

7. E.N.Pestov, D.E.Pestov, V.A.Ryabkov, and V. Shifrin. “Cs-He optically pumped magnetometer – the reference gauge of magnetic induction for National Metrological Centres”, *in Proc.* 16th European Frequency and Time Forum (EFTF), St. Petersburg, (2002).

8. E.I.Dashevskaya,, A.N.Kozlov, and E.N.Pestov, “M_z –signal frequency shifts of the ^{133}Cs magnetometer in the geomagnetic field” . (Sbornik statei, Frunze: Ilim), 91 (1968) [in Russian).

9. E.I.Dashevskaya,, A.N.Kozlov, and E.N.Pestov, “M_z –signal frequency shifts of the ^{87}Rb magnetometer in the geomagnetic field”, 3-d scientific Conference of IZMIRAN, Moscow, IZMIRAN, p. 314 (1971).

10. E.N.Pestov. “Experimental investigations of the frequency shifts of magnetometers using optical orientations of potassium isotopes ^{39}K and ^{41}K”, Abstracts of the 2-nd All-Union Conference on the Physical Foundations of Quantum Magnetometry, Saransk, 13 (1973).

11. E.N.Pestov and A.G.Chirkov. “New results obtained when investigating a nature of long-term instability in quantum frequency standards and magnetometers. Non-removable resonance drift,” *in Proc.* 16th European Frequency and Time Forum (EFTF), St. Petersburg, (2002).

12. E.N.Pestov, “Method for exciting quantum systems”, Patent Declaration n s 1 605 621/26-25, VNIIGPE, Moscow, 1970 [in Russian].

13. E.N.Pestov. “Quantum magnetometer”, Author’s certificate U.S.S.R. 352 240, 30 April 1971 [in Rus.].

14. E.N.Pestov. “Induction of collective phase coherence in a quantum system without a resonant phasing field”, JETP Lett., **55**, No 1, 19 (1992).

15. E.N.Pestov and A.N.Besedina. Russian Patent No. 2 062 537, 25 May (1992).

16. E.N.Pestov. Proc. 4th International Conference “Physical Metrology 2000”, St.-Petersburg, SPGU, p. 106 (2000).