UDC 550.868.08+621.398

QUANTUM SENSOR WITH IMPROVED METROLOGICAL CHARACTERISTICS

P.V. Mokrenko[1], I.T. Strepko[2]

[1] *Lviv Polytechnic National University 12, S.Bandera St., Lviv, 79013, Ukraine*
[2]*Ukrainian Academy of Printing 19, Pid Holoskom St., Lviv, 79020, Ukraine*

In our time, automation systems have widely used the constant current quantum converters in frequency, the main element of which is the quantum sensor (QS), which uses optical pumping and optical recording of magnetic resonance of alkali metal atoms (Cs-133, Rb-87, etc.).

The work presents the developed by authors designs of quantum sensors with increased metrological characteristics over a long period of time when changing the outside temperature in a wide range due to the removal of the heating of the absorption cell by electric means and its implementation by thermal convection of the inert gas from the spectral lamp and the establishment of a uniform temperature for all elements of the quantum sensor and the reduction of heat dissipation from the internal volume of the sensor body.

Having analyzed the existing quantum sensors operating in autoclaving mode, the authors have suggested a method of shock excitation of phase coherence of spin-systems oriented by resonant light and based on it, a differential constant current quantum converter into a frequency with high metrological characteristics has been constructed, which are presented in the paper.

***Keywords**: quantum sensor, electronic paramagnetic resonance, thermal stabilization, spin system, spectral lamp, coherence, metrological characteristics.*

Introduction. In the known quantum sensor (QS) that use the optical orientation of the magnetic moments μ_i of alkali metal atoms, it is necessary to stabilize not only the luminous flux of a spectral lamp, but also to maintain the absorption cell temperature in a given working interval, since the change in the temperature of the cell changes the amplitude of the magnetic signal resonance [1]. For example, the temperature of a cesium absorption cell of ≈20cm^3 should be maintained at about 30^{o}C, and the temperature of the spectral lamp is ~110^{o}C.

The intensity of the luminous flux of a spectral lamp can be simply stabilized by adjusting the power of a high frequency generator in a feedback loop which contains an additional photocell or thermal gauge and which is constructively located near the light source [2, 3].

The heating of the absorption cell (AC) is performed by alternating current transmission through a bifilar winding that is coiled on an isolated frame, in the middle of which AC is located, or high-frequency heating of a special carbon fabric, which surrounds the absorption cell.

The disadvantages of such systems of heating of the AC of paralogue quantum sensors are the following factors that influence the deviation of conversion:

- the effect of high-frequency energy of high power, which heats the cell, on the precession of atoms;
- the need to have a separate heating cell path (RF generator, regulator, heater, etc.);
- availability of two separate control systems for temperature control of the cylinder of a spectral lamp and for absorption cells.

Presenting main material. In order to eliminate the measurement deviation from the heating system of the AC and simplify the system, we [4] developed the thermostabilization of the quantum sensor, by placing it in a metallic nonmagnetic cylinder with a corrugated surface, with a slit in the cavity and covered with thermal insulation plastics. Thermal heaters for temperature control are installed on the inner surface of a metal cylinder which is heated directly by heat radiation from a spectral lamp and with assistance of metal rods in a cylinder which are heated by high frequency currents of the excitation generator of a spectral lamp.

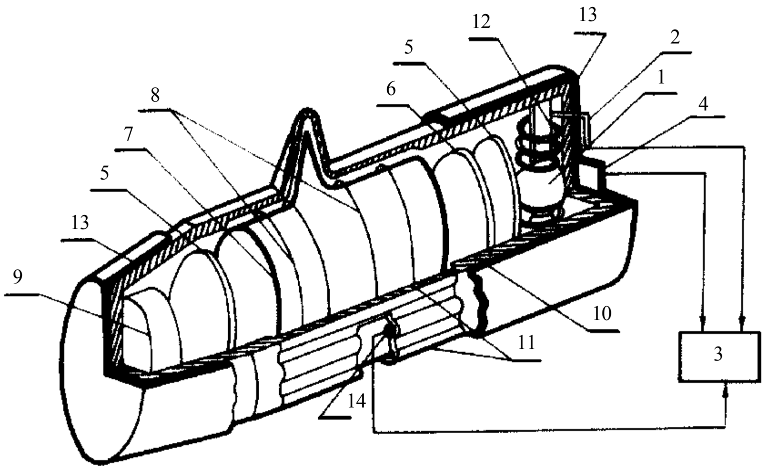


Fig. 1. Construction of thermostabilized QS

In Fig. 1. thermostabilized quantum sensor [4], developed by us, is presented. It contains: SL 1 with vapors of the working substance of alkali metal which is placed in the coil 2 of the oscillation circuit of the RF generator 3; control photodiode 4; focusing lenses 5; polarizer 6; absorption cell 7; Radio Frequency Coil (RFC) 8; photodetector 9; a metallic non-magnetic cylinder consisting of a glass 10 connected to a corrugated surface 11; metal rod 12; heat insulator 13 and a temperature gauge 14. The principle of the sensor is similar to one discussed in [5].

In the developed sensor we switched from the active heating system to the passive through the use of heat of a spectral lamp 1 and high-frequency heating of a non-magnetic cylinder (with high thermal conductivity) of 10 cylinder. In this case, the spectral lamp 1 is equivalent to a «spherical furnace» heated to a temperature of ~110°C.

In this way, the heating of the absorption cell is carried out on the one side with the heating of the metal cylindrical cup 10 due to the thermal emission of the spectral lamp and since the extension of the metal cylinder is a coffered metal surface 11 that is covering the AC, the heat is transferred from the heated cylinder 10 to the cell 7, and on the other - due to the high-frequency heating of the metal rods 12 which leads to additional heating of the cylinder 10 and to the transfer of heat to the cell and finally due to the convection of hot air from the spectral lamp. To reduce the cooling of the cylinder surface, external layer is covered with a thermal insulating plastic 13. When establishing the thermodynamic equilibrium inside the volume of the metal cylinder, when the temperature inside it reaches a given value, further stabilization of the temperature is carried out only by adjusting the power of the RF generator using a thermal gauge 14 located on the internal cylinder surface.

Laboratory experiments performed with the sensor, developed by us, showed, that a metal cylindrical copper cup with an internal diameter of ≈ 25 mm (diameter of the sphere of a spectral lamp ≈ 11 mm), a length of ≈ 30 mm and covered outside with a heat-insulating plastic was heated to a temperature of ~60 ° C (at ambient temperature of the environment is ~10 ° C). The design of the quantum sensor has reduced by half the power consumed by the network and increased the signal-to-noise ratio. However, this sensor is characterized by a temperature gradient in the volume of the AC.

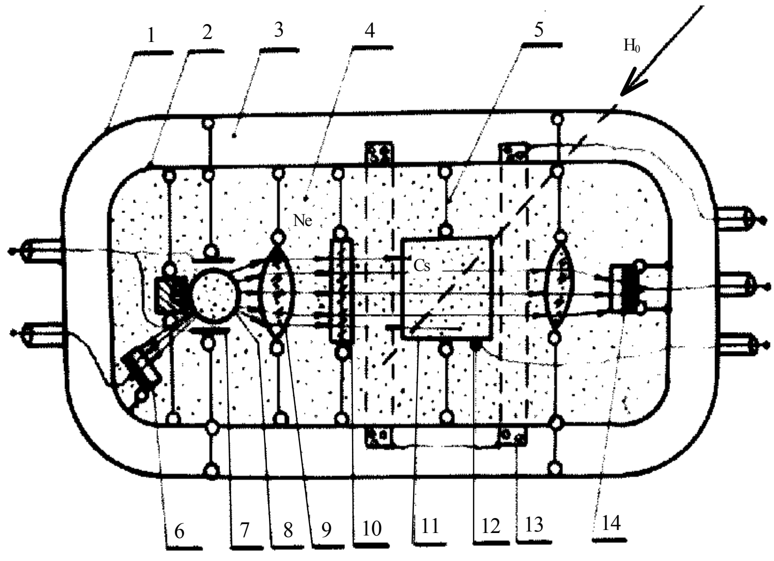


Fig. 2. Design of the QS with the increased metrological characteristics

In Figure 2. a new version of quantum sensor with optic pumping [6,7] is presented. It allows to significantly improve its metrological characteristics over a long period of operation and in a wide range of changes in the external temperature.

The quantum sensor is hermetic, its body consists of the outer 1 and inner 2 walls separated by a vacuum gap 3, and the internal volume of the body is filled with inert gas 4. In the middle of the case on stretchers 5 the following sensor elements are fastened: the control photodiode 6, the cover of the capacitor 7, a spectral lamp 8, a focusing lens 9, a circular polarizer 10, an absorption cell 11, heaters 12, Helmholtz radio frequency rings 13, photodiode 14. The principle of this sensor is similar to the sensor described in [7-8]. To perform both the heating of the cell and the establishment of a single temperature for all elements of the quantum sensor we use the heat of the spectral lamp 8 (when burning it is heated to$\approx 110^{o}$C), and inert gas 4 is additionally pumped into inert volume of the body till a certain pressure is established. The gas is heated from the cylinder of a spectral lamp, and due to heat convection, a single temperature is set in the middle of the case. The pressure of the inert gas is selected so that the absorption cell does not overheat. To provide effective thermal convection from a heated spectral lamp, the elements of a quantum sensor are fixed with the help of rod stretch marks 5 to the inner wall 2 of the body. Constancy of temperature in the middle of the body of the sensor is set due to maintaining the constant intensity of burning of the spectral lamp, and hence, its temperature. This is provided directly by the regulation circle with control photodiode 1. The dual walls 1 and 2 of the sensor body are separated by a vacuum gap 3 that creates thermal insulation for a quantum sensor in a wide range of external temperature changes.

The use of the proposed quantum sensor with optic pumping allows to increase the stability of its metrological characteristics over a long work period of time and in a wide range of external temperature changes due to:

- elimination of electric heating of the cell and its implementation due to the thermal convection of inert gas from the cylinder of a spectral lamp;
- the establishment of a homogeneous(single) temperature (due to convection) for all elements of a quantum sensor;
- eliminating the influence of external conditions (temperature, humidity, etc.) and reducing the dissipation of heat from the internal volume of the sensor body;
- the maximum value of the amplitude of the precession signal for a single-beam quantum sensor is observed at an angle 45^0 between the optical sensor axis and the direction of the magnetic field vector H_o.

Differential quantum sensor with improved metrological characteristics

The above quantum sensors, which operate in the mode of self-oscillation, have the disadvantages inherent to any tuned generator: the difficulty of adjusting the phase and performing the phase balance in the operating frequency range; the instability of the phase in the feedback ring when the temperature changes and over time due to the aging of the elements, and so on. [2,3,7]. These disadvantages are especially noticeable when measuring small increments of a direct current (magnetic field) by quantum sensors, executed on the differential scheme using as a registrar of a phase meter, for which it is necessary to set the initial phase difference $\Delta\varphi_o=0$ between the frequencies ω_1 and ω_2 sensors. For these reasons, differential quantum devices of this type are difficult to implement.

To eliminate the above-mentioned shortcomings was made possible by using the shock excitation method of phase coherence of spin-systems oriented by the resonant light proposed by us [8]. Investigation of a one-channel variant of a quantum magnetometric sensor with shock excitation [8,9] showed the promise of such a method and its extension to other schemes.

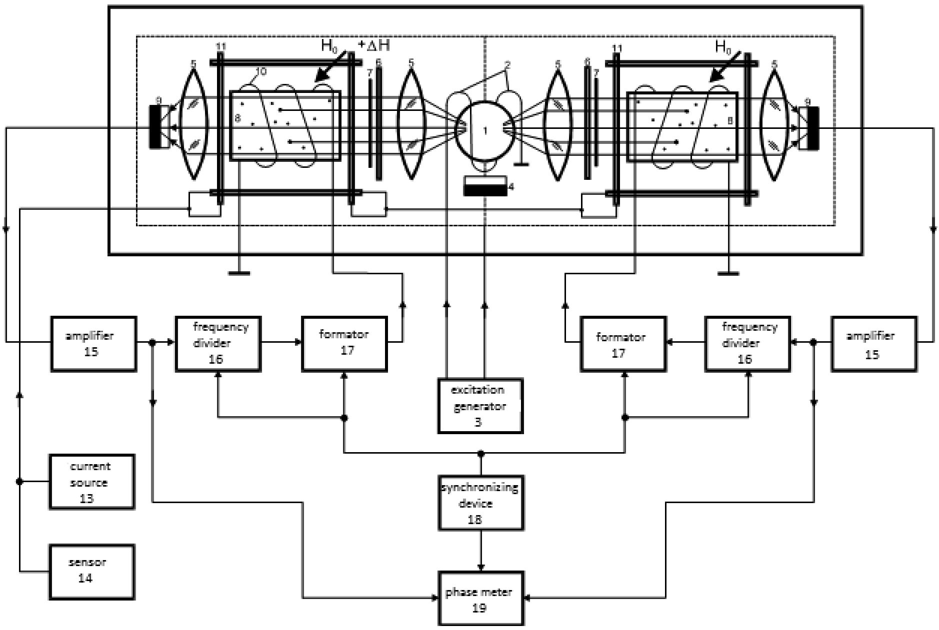


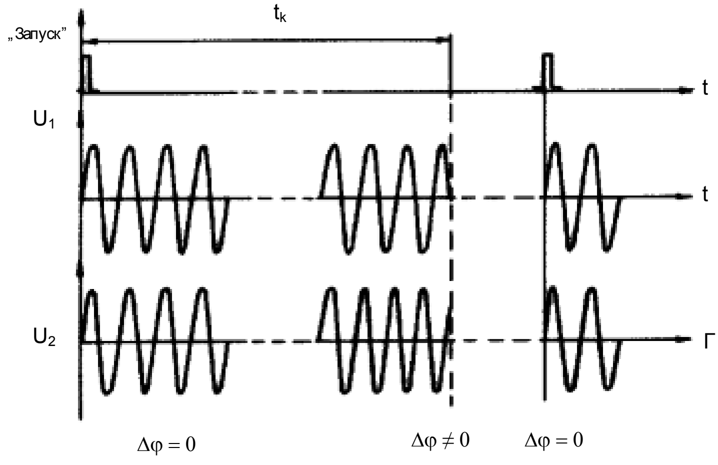
Fig. 3. Functional diagram of differential quantum converter

We have suggested and developed a differential scheme of a quantum current meter, which is presented in Fig. 3. The scheme has the feature that the feedback circuits of quantum sensors are performed according to the shock excitation scheme with the frequency divider and pulse shaper, which are connected to the program-synchronizing device. This scheme automatically fulfills the condition $\Delta\varphi_o=0$ between frequencies of quantum sensors ω_1 and ω_2 at each synchronous pulse action. The device (Fig. 3) contains: one spectral lamp 1 located in the circuit 2 of the generator 3; control photodiode 4; focusing lenses 5; polaroid 6; optical $\lambda/4$ phase rotators 7; absorption cells 8, covered with paraffin; photodetectors 9; radio frequency coils 10; ring systems 11 and protective multi-layer combined magnetic screen 12. To create the reference magnetic field H_o is the current source 13, and as a primary measuring transducer of a controlled quantity X in the current of Ix - a sensor 14 whose output is connected to the ring system 11. The feedback circuits have precession signal amplifiers 15, frequency dividers 16, and formers 17 that are connected to the program sync device 18. Outputs of the amplifiers are connected to the recording device 19, in which the phase meter or frequency meter is used.

The principle of the optical part of the quantum transducer sensors is analogous to that discussed earlier, so let us dwell in more detail on the functioning of the feedback loop. Signal at frequency $\omega_o=\gamma H_o$ is removed from the photodiode 9 and enters the input of the amplifier 15, and from the output of the latter is fed through a frequency divider 16 to form the short video pulses of current (video pulse duration τ_i<T_o, де T_o - period of the frequency of the precession signal), the output of which is connected to the radio frequency coil 10, which forms the video pulses of the magnetic field. They affect the spin system of the atoms of the absorbing cell 8 and come in the phase to the magnetic moment $M_\perp(x,y)$, because they are produced by the phase of the same precession signal $M_\perp(x,y)$. The self-oscillating process in this SCG differs in great stability in time, since it has the nature of free oscillations.

The work of the entire device as a whole consists in the fact that the measured value X with the help of the sensor 14 is converted into a constant current of them, which is brought to the ring system 11. From the flow of this current in the center of the annular system, a uniform magnetic field is created that affects the spin system of atoms and changes the frequency of the precession of the latter. The registration of the frequency of precession and its change is carried by the photodetector 9, the signal from which comes to the input of the amplifier. The outputs of the amplifiers 15 in both channels are connected to the recording device 19.

To register large changes of currents it is enough to measure the output frequency of the sensors by a frequency meter and obtain an unambiguous result - the controlled quantity has changed or not. Particularly simple this can be noticed if the coil, on which the controlled current flows, covers only one sensor, and the second is always in a constant bearing field H_o and it has an output frequency $\omega_{вих}$=const.



$$\begin{cases} Cs^{133} \\ C = 0{,}01\dfrac{Erst}{mA} \\ \Delta\varphi = 1^o \\ \Delta i = 1*10^{-9}A = 1nA \end{cases}$$

Fig. 4. Timing diagram of the work of a differential QS

When registering small changes in currents and, therefore, frequencies, it is necessary to apply more accurate methods of measuring the frequency. In this case, in the role of the registrar 19, a phase tube can be used as a device that compares two frequencies to a great degree. For its work it is necessary that at the initial time of measurement $t_в$ phase difference between frequencies ω_1 and ω_2 sensors equal to zero, that is $\Delta\varphi_o=0$ (see timing diagrams of Fig. 4). This is precisely what is accomplished by a program-synchronizing device 18 that produces single pulses and connected to dividers and formers of the feedback loop. Synchronous pulse reduces frequency dividers 16 and simultaneously triggers formers 17, providing a condition $\Delta\varphi_o=0$. This same pulse can be used to set the start of counting in the registrar 19 at one-time measurements if the digital frequency meter or digital phase meter is used as the registrar. The end time of the reference (measurement time $t_в$) can be set either by the registration device itself 19, or by the software-synchronizing device 18.

If the registrer uses a phase meter, and a program-synchronizing device provides $\Delta\varphi_o=0$, then during the measurement $t_в$ possible run-off phase $\Delta\varphi>0$. Let this run of the phase during the measurement $t_в=1c$ is $\Delta\varphi=2\pi=360^o$. Moreover, the phase meter allows you to visually perform a counting with an accuracy of 1o, which corresponds to a change in the magnetic field $0.3\gamma/360^o=10^{-8}E$ (for a spin system of atoms of cesium-133 1γ = 1 нТ or 10^{-5} E). Having executed the annular system, in which the controlled current is started, with a constant $C=1\gamma$/мкА (the last is very easy to execute) we obtain that the visual countdown by the phaser with accuracy up to 1^o corresponds to a change in the controlled current by an amount equal to 1 нА.

Conclusions. The suggested thermostabilized quantum sensor, in which the heating of the elements of the circuit is carried out by the heat of a spectral lamp, has allowed to reduce the consumption power twice and increase the metrological characteristics of the sensor in a wide range of changes in the temperature of the surrounding environment.

The shock excitation of phase coherence [10] was used by us in constructing a high-precision quantum converter.

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УДК 550.868.08+621.398

КВАНТОВИЙ ДАВАЧ ІЗ ПОКРАШЕНИМИ МЕТРОЛОГІЧНИМИ ХАРАКТЕРИСТИКАМИ

П.В. Мокренко[1], І.Т. Стрепко[2]

[1]Національний університет «Львівська політехніка»
вул. С. Бандери, 12, Львів, 79013, Україна
[2]Українська акдемія друкарства вул. Під Голоском, 19, Львів, 79020, Україна
i_strep@ukr.net

В наш час в системах автоматики спостерігається широке застосування квантових перетворювачів постійного струму в частоту, основним елементом яких є квантовий давач, що використовує оптичне накачування і оптичну реєстрацію магнітного резонансу атомів лужних металів (Cs-133, Rb-87 та ін.).

В роботі розглядаються розроблені авторами конструкції квантових давачів з підвищеними метрологічними характеристиками протягом тривалого часу роботи при зміні зовнішньої температури в широкому діапазоні за рахунок усунення обігріву комірки поглинання електричним способом і здійснення його шляхом теплової конвекції інертного газу від спектральної лампи і встановлення однорідної температури для всіх елементів квантового давача та зменшення розсіювання тепла із внутрішнього об'єму корпусу давача.

Проаналізувавши існуючі квантові давачі, які працюють в автоколивальному режимі, автори запропонували метод ударного збудження фазової когерентності спін-систем, орієнтованих резонансним світлом і на його базі побудували диференціальний квантовий перетворювач постійного струму в частоту з високими метрологічними характеристиками, які наведені в роботі.

***Ключові слова**: квантовий давач, електронний парамагнітний резонанс, термостабілізація, спін-система, спектральна лампа, когерентність, метрологічні характеристики.*

Стаття надійшла до редакції 10.03.2018
Received 10.03.2018