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Promising Quantum-Optical Technologies for Satellite Navigation Challenges

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Abstract. Accuracy of navigation and positioning provided by signals of global navigation satellite systems is largely determined by the frequency standards installed on board of satellites. In recent years, there has been a rapid development of new quantum-optical technologies using compact and frequency-stable laser systems, femtosecond frequency generators, ultracold atoms and ions. Optical methods of information reading off and processing provided by an atomic system were developed. This resulted in significant reduction of a relative frequency instability of ground-based frequency standards down to 18th decimal digit. A number of successful European suborbital launches demonstrated a possibility of application of some of the technologies in the space segment. The paper provides a brief overview of the latest achievements in this field and possibility of its development in Russia.

Keywords: laser cooling, ultrastable atoms and ions, ion Paul trap, femtosecond synthesizers of optical frequencies, stabilized laser, optical clock

1. Introduction

Global navigation satellite systems (GNSS) have become an integral part of our life: it is difficult to imagine sea and air navigation, traffic, and cargo transportation without them. The demand in exact positioning and synchronization is constantly growing, covering agriculture, forest and mining industry, data transmission, and fundamental science. The main objective of development of any national GNSS system is the increase in accuracy and reliability of positioning of the consumer.

One of the key factors defining the quality of functioning of GNSS is the accuracy and stability of a time signal formed by the onboard synchronizer (OS). Thus, at a daily relative error of frequency of the onboard standard in 1×10^{-14}, the corresponding error of positioning along the direction on the satellite will make about 0.25 m. There is, however, a set of the factors influencing the characteristics of the signal delivered to the consumer [1] and leading to decrease in accuracy. To achieve target characteristics and obtain in the long term decimeter accuracy, within the Federal Target Program "GLONASS of 2012–2020", a wide complex of problems touching all segments of the system including the onboard frequency standard (OFS) is being solved. Today OFS of the GLONASS system is based on microwave standards using a bunch of atoms of caesium and on a rubidium cell.

As it is noted in the report [2], one of the important problems of development of the GLONASS system is decrease in daily relative instability of OFS to 5×10^{-15} by 2020, and in the long term up to 1×10^{-15}. Achievement of these indicators employing the existing caesium or rubidium standards is actually impossible in view of a number of fundamental restrictions.

In the short term as a part of OFS, passive hydrogen mazer tests are planned [3]. Passive hydrogen mazers with a daily instability of frequency $< 1 \times 10^{-14}$ have proved themselves onboard GALILEO satellites [4] and in ground tests in Russia [5]. In its turn, an active hydrogen mazer has been successfully functioning more than 6 years onboard the Spektr-R spacecraft [6]. Considering a significant progress in developments of hydrogen mazers including for space applications (thus, within the Millimetron project, active hydrogen standards with instability $< 1 \times 10^{-15}$ are created), their use when developing promising navigation satellite systems is a relevant task.

Other important direction is creation of the onboard optical frequency reference (OOFR). Transition from a microwave ($f = 10^{10} - 10^{11}$ Hz) to optical ($f = 10^{14} - 10^{15}$ Hz) range of frequencies leads to an essential, on several orders, increase in relative stability of the oscillator, since it is defined by its *Q-factor:* $Q=f/\delta f$ (f is the transition frequency, and δf is the resonance width). Atoms in the optical range have a number of metrological (clock) transitions with a natural spectral width much less than 1 Hz. Methods of laser cooling [7] and capture of atoms [8] and ions into traps [9] allow one to solve two important problems. First, interaction time with the exciting field can be increased up to several seconds that provides the Fourier-limited spectral width of resonance up to $\delta f = 1$ Hz without increase in physical sizes of a system. Secondly, due to localization of a cold ion on the sizes much less than the length of light, linear Doppler effect and effect of return are nullified and also actually a full isolation from undesirable external fields and collisions is provided.

Today a relative instability and an error of frequency of optical standards of frequency at the level of units of the 18th sign after a comma both on the neutral atoms taken into optical lattices [10] and on single ions is demonstrated [11]. We will note that such values are shown only when checking standards directly in the optical range in extremely stable external laboratory conditions. To illustrate the last, it is enough to estimate the Doppler effect, which arises at extension, for example, of a metal platform with a characteristic size of 1 m, on which optical elements are placed. If change of temperature makes only 1 degree per hour, then the contribution of the Doppler effect when reflecting from one mirror will be up to 4×10^{-17}. It is also necessary to consider gravitational red shift of frequency (1×10^{-16}/m) and a set of other systematic effects having a significant effect at such level of accuracy [12]. It is obvious that reduction of the size of a system and toughening of service conditions leads to decrease in characteristics. Nevertheless, for the transported sample about 1 m3, a daily instability of frequency at the level of 10^{-17}–10^{-16} is quite achievable and is already shown by a number of laboratories [13, 14]. We will note that this indicator approximately much surpasses the instability of the best samples of active hydrogen mazers and commercially available microwave clocks of a fountain type [15].

Of course, there is a question of a possibility to transfer perspective technologies of photonics on board the spacecraft. It is interesting to note that if about ten years ago such ideas belonged to the section of "science fiction", then today a number of the successful launches, which have shown functionality, at least, regarding quantum and optical technologies including the femtosecond synthesizers of optical frequencies (FSOF) [16], stabilized lasers [17], and also the systems for a deep laser cooling and Bose condensation of rubidium atoms onboard the spacecraft is already carried out [18]. In fact, the essential difficulty arising during creation of any optical standard of frequency is a large number (usually about 10) various laser systems, which frequency of radiation has to be tuned on the line of transitions in an atom. It is required as for cooling and capture of atoms and ions, and for control of internal quantum states. Under such conditions, a spectral width of radiation of laser systems has to be 0.01–1 MHz with a similar accuracy of tuning. Support of operability of lasers is a difficult task; the number of failures often does not ensure a reliable functioning of optical frequency standards even on an interval of several hours.

Emergence of erbium and ytterbium fiber-optical lasers with diode pumping (continuous and femtosecond) [19, 20] and also a wide line of semiconductor lasers (Fabry–Pérot, with the distributed feedback, on quantum holes, quantum and cascade, etc.) blocking a very wide spectral range from infrared to ultraviolet has significantly increased compactness and reliability of laser systems. New reliable schemes of stabilization of frequency of semiconductor lasers on the external resonator [21] are developed that allows using them in the conditions of strong external indignations without change of the wavelength of generation. There was a break in methods of stabilization of frequency of the so-called "clock lasers" interrogating metrological transition in the laser. Compact, reliable systems based on the external ultrastable Fabry–Pérot interferometer providing relative instability of frequency of the laser at the level of 10^{-16}–10^{-15} per 1 sec (that corresponds to the subhertz spectral width of the line) are created [22, 23].

One of the fundamental factors, which have provided real horizons of applying optical clocks as OOFR was creation of FSOF based on the fiber-optical femtosecond laser with a passive mode synchronization [24]. In the papers [25, 26] it has been shown that FSOF allows one to transform optical frequency to radio-frequency range making only an insignificant contribution to a relative instability of frequency at the level of units of the 19th sign. An opportunity to use high characteristics of stability of a clock laser connected on the frequency to an optical resonance in an atom, in the range available to the consumer (1–10 GHz) has opened. Progress of the production technology of FSOF in Europe (Menlo Systems company) enabled one to carry out two successful suborbital launches with a compact (22 kg) FSOF onboard in 2015 and 2017 [16]. It is possible to consider that the issue of an onboard FSOF is solved at the basic level and further only efforts to increase the reliability and compactness of the system are required. In Russia, similar works are conducted by the Avesta company.

The last question, which it would be desirable to mention in Introduction, belongs to the choice of atomic or ionic system for a perspective OS. In spite of the fact that optical standards on neutral atoms in optical lattices show several somehow best characteristics of stability due to a big (up to 10^5) amount of the interrogated atoms [10] in comparison with standards on single ions [11], the last are preferable. First, the depth of potential of an ionic trap is several eV (several tens of thousands kelvin) that allows one to hold long, up to months, a single ion in a trap [27]. The main mechanism of losses are collisions with background gas in the vacuum chamber, leading to a recharge and loss of an ion. Secondly, the design of an ionic trap is much more compact and does not demand delicate adjustments of optical bunches. In the third, a lower stability of ionic clock on short times of averaging (in comparison with the clocks on neutral atoms) is not considered a restriction at designing of OS for the navigation satellite. Disadvantages are a high sensitivity to electric fields (delicate control of potentials on electrodes is required), a rather low level of a signal of a luminescence from a single ion and inaccessibility of ultraviolet transitions in some ions [28, 29].

The essential motivating factor is creation of transported optical clocks on an ion Ca+ of 0.5 m^3 showing a relative instability in 10^{-16} per one day [14]. Moreover, a cooperation of the German institutes and companies (PTB, Toptica, Menlo Systems) has begun development of the transported clocks on a single ion of Yb^+ [30]. The similar project has been started in France [31].

In 2017, the Ministry of Education and Science of the Russian Federation supported the project 14.610.21.0010 "Development of the generator of ultrastable reference signals of frequency on cold ions of ytterbium to increase by times the accuracy of geopositioning, space navigation, and formation of new segments of mass demand in the market of applications of global satellite navigation", which task is creation a compact (1 m^3) standard of frequency on a single ion of ytterbium. To realize this task, the consortium of key performers of RSS-LPI RAS-Skoltech- Institute of Laser Physics, Siberian Branch of the Russian Academy of Sciences-Avesta, where an industrial partner JSC "RSS" plays a defining role in coordination of participants to solve a problem of transition to an onboard prototype of OFS is created. The complex of new solutions in the field of photon and quantum and optical technologies, electronics, and control systems is required. The principle of functioning of optical clocks on a single ion Yb$^+$ will be presented in the article and key approaches to their realization will be discussed.

2. Main principles of operation of optical clocks on the single ion Yb$^+$

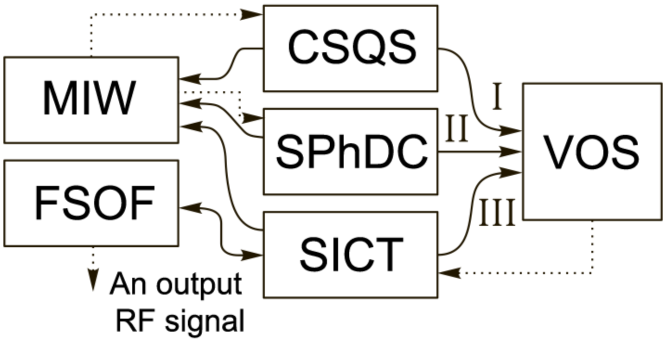

Fig. 1. A general scheme of OOFR. VOS is the vacuum optical spectroscope; CSQS is the control system of quantum states; SPhDC is the system of photoionization and Doppler cooling; SICT is the system of interrogation of clock transition; FSOF is the femtosecond generator of optical frequencies; MIW is the measuring instrument of wavelengths based on the Fizeau interferometer.

The optical frequency reference on the single ion Yb+ consists of three main units. The reference generator (the single ion Yb+) is in the vacuum optical spectroscope (VOS) representing a vacuum chamber with an ionic trap, the equipment for its loading and compensation of external fields and also an optical system for registration of a signal of fluorescence of an ion under the influence of the cooling laser radiation. The second component of the optical frequency standard is a laser system, which in turn, is divided into three parts: a control system of quantum states (CSQS), system of photoionization and Doppler cooling (SPhDO), and the system of interrogation of clock transition (SICT). The third main unit consists of the measuring instrument of lengths of waves based on the Fizeau interferometer (MIW) and also the femtosecond synthesizer of optical frequencies (FSOF) and is responsible both for stabilization of frequency of laser sources (MIW, FSOF) and for transfer of stability and accuracy of the standard from optical range in radio-frequency (FSOF).

SPhDC forms laser radiation on the lengths of waves of 369.5 nanometers and 398.9 nanometers, which provides (together with the laser from CSQS radiating on the wavelength of 935 nanometers) laser cooling of the particles taken in VOS, loading of ions into a trap by means of photoionization of neutral atoms 171Yb and also reading of the result of initiation of clock transition by means of a method of quantum jumps. CSQS provides radiation on the lengths of waves of 935 nanometers and 760 nanometers for preparation of a necessary quantum condition of an ion before the interrogation of its clock transition and short circuit of a cooling cycle. A sufficient accuracy of stabilization of frequencies of laser radiation of CSQS and SPhDC units is 2 MHz and can be realized by means of MIW. To do that, a small part of their radiation is brought to the last. By means of the built-in PID controller, MIW stabilizes frequencies of CSQS and SPhDC lasers.

SICT is an optical system providing radiation for initiation of clock transition of an ion based on a laser source, which frequency on short times (less than an interrogation period of an ion) can be stabilized concerning a mode of a highly stable Fabry–Pérot interferometer or relative to FSOF (which in itself can also be stabilized relative to a similar highly stable resonator that increases fault tolerance of a system). A typical short-term instability of frequency of radiation of SICT is 2 · 10-15 (1–10 sec). A long-term stability of frequency of SICT and of the whole standard in general is provided with stabilization relative to clock transition in an ion.

A general scheme of operation of the optical frequency standard consist in the following sequence. At first in the trap, which is a part of VOS, the ion 171Yb+ is taken. After that, it is cyclically exposed to laser cooling to minimize a shift of frequency of clock transition and is prepared in an initial quantum state. After that, there is an excitement and reading off clock transition that allows one to stabilize SICT radiation frequency relative to transition frequency in an ion. SICT frequency is divided by means of FSOF, which provides an output radio-frequency signal of the frequency standard. A short-term stability of such standard at the same time is defined by a highly stable resonator stabilizing SICT or FSOF, and a long-term one is determined by the frequency of clock transition of an ion which relative instability can reach units of the 17th sign.

2.1. Paul trap

The fact that ions have an electric charge, other than zero, considerably facilitates their capture and localization. Interaction with an electric field permits one to hold ions by means of radio-frequency fields in so-called Paul traps [9]. The trap represents a combination of electrodes to which constant and radio-frequency potentials are attached (with the frequency ranging from 1 to 100 MHz). These electrodes create variable non-uniform potential close to quadrypolar. Thus, in three-dimensional Paul traps, which are usually in the foundation of optical ionic standards of frequency, the configuration of electrodes has an axial symmetry and the potential created by them in the center of a trap is close to the one described by a formula (1):

$$\Phi(r,z,t)=\frac{U_{dc}+V_{ac}\cos(\omega t)}{r_0^2+2z_0^2}(r^2-2z^2). \quad (1)$$

where U_dc is the constant component of the potential; V_ac is the amplitude of the variable component; ω is the circular frequency of the variable potential; r_0 and z_0 are the typical dimensional parameters of the potential determined by the certain geometry of electrodes. Fig. 2 depicts the configuration of electrodes, which enables one to provide the potential close to the one set by a formula (1), and at the same time providing good optical access to the center of a trap that is important for implementation of an effective laser cooling, manipulation of a quantum condition of an ion, and also reading off its state is presented. Here, a variable potential with an amplitude V_ac≈250 V is put to two electrodes-edges located along a trap axis, and hollow cylindrical electrodes surrounding them are grounded.

The movement of a charged particle in the potential set by a formula (1) is described by Mathieu equations. The analysis of these equations of the movement shows that at certain values of amplitude Vac and frequency of tension ω on the electrodes of the trap, the ion keeps close to the center of the trap [32]. Its movement time can be presented as a superposition of a rather slow (secular) movement of an ion in a harmonious pseudopotential close to the point where an amplitude of fluctuations of an electric field becomes zero and fast small fluctuations of an ion with the frequency of the field of a trap, which are called a micromovement. Since the micromovement is the necessary harmonic oscillations of a particle in the field of a trap, its amplitude is proportional to the amplitude of fluctuations of the holding field in this point of a trajectory of the secular movement of an ion.

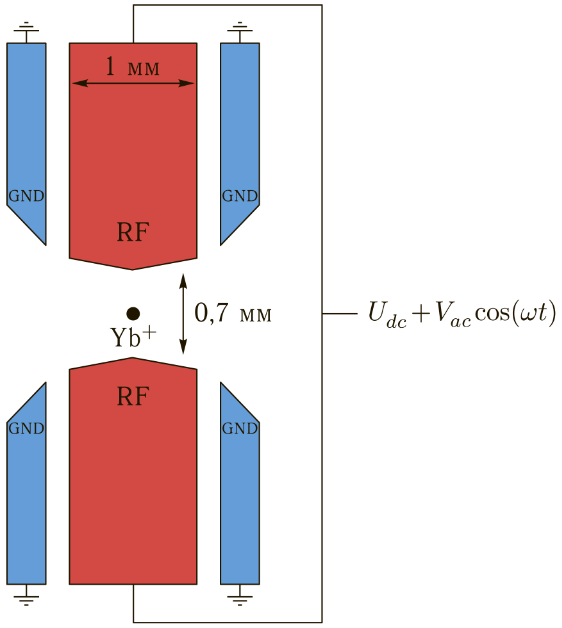

Fig. 2. A sketch of a 3D Paul trap. A variable potential is put to the electrodes-edges defined by RF, and cylindrical electrodes (GND) located concentrically around radio-frequency are grounded.

Important features of ionic traps are a big depth of a potential hole (up to several eV) that allows one to take into them ions even at the room temperature without preliminary cooling and also the fact that an ion is localized close to the point where the amplitude of the holding field becomes zero. The last leads to the fact that the frequency of clock transition of a particle is poorly subject to shift because of the Stark effect and also to minimization of shift because of the Doppler effect of the second order connected with the existence of the micromovement. The size of the area of localization of single ions in such traps in the presence of laser cooling is several tens of nanometers that leads to realization of the Lamb Dicke regime [33], this means to a full suppression of the Doppler effect of the first order. In addition, the effect of return, which in case of free atoms leads to splitting and asymmetry of the line of clock transition, is suppressed.

It is important to note that an effective suppression of the Stark and Doppler shifts of the second order is reached only in case the potential of a trap is close to the one described by a formula (1). If in the field of capture, for example, there are parasitic static electric fields, then the minimum of pseudopotential will be shifted to the area with a nonzero amplitude of an electric field that will lead to a considerable strengthening of the influence of the effects described above on the frequency of clock transition. For this reason, the design of traps also usually provides the existence of several compensating electrodes, which allow one to eliminate parasitic fields. Methods of search of optimum parameters of the compensating fields are in detail described, for example, in [34].

Loading of an ion in a trap can be carried out by means of shock ionization of atoms of ytterbium by an electron beam or by photoionization directly in the field of the capture of a trap. For this purpose, for several seconds the atomic oven in the form of the tube filled with metal ytterbium and supplied with the electric heater, which creates an atomic bunch passing through the center of a trap and also an ionization source (a laser of photoionization or an electron beam) is turned on. Photoionization is more preferable, since it provides loading only of ions of this element and isotope and also as unlike an electron beam, its using does not lead to emergence of parasitic charges near a trap.

Time of life of ions in a trap due to the high level of a vacuum (<10-10 mbar) and a deep depth of potential is usually several days. At the same time, the main channel of losses is exchange of an ytterbium ion charge with atoms of background gas at collisions. In case of loss of an ion that can be revealed on lack of fluorescence of a particle under the influence of the cooling radiation during several cycles of cooling, the ion is repeatedly loaded into a trap that takes about a second and has no significant effect on characteristics of stability.

2.2. Laser system

The OOFR major element are the laser sources providing radiation for cooling of an ion, photoionization, manipulation of a quantum condition of a particle and initiation of clock transition. These sources have to be constantly tuned to the corresponding lines of transitions in an ion, stable and compact. Today the most stable and reliable sources are fiber lasers with the distributed feedback [35]. Fiber lasers generate only in the narrow range of lengths of waves (1530–1560 nanometers for the lasers alloyed by ions of erbium [37]; 1030-1050 nanometers for the lasers alloyed by ions of ytterbium. Semiconductor lasers with the distributed feedback [38] (for example, made by Polyus, 780 nanometers and 850 nanometers) and with vertical resonators [39] also have a high stability of frequency. Unfortunately, the majority of the listed types of lasers generate in the ranges of lengths of the waves (taking into account the second harmonica) differing from necessary for quantum manipulations with an ytterbium ion in a trap (369 nanometers, 398 nanometers, 739 nanometers, 760 nanometers, 871 nanometers, and 935 nanometers).

Perspective laser sources including for use in space applications are semiconductor lasers with an external resonator. They have a wide range of reorganization of a wavelength, high stability of frequency, and narrowness of a range of radiation. Their compactness, simplicity of a design and operation have made them the main laser sources in spectroscopic laboratories in the world today, and laser diodes available today block a considerable part of the near infrared, visible and near ultraviolet area of a range. The design of commercially available diode lasers has high reliability [40].

The majority of the semiconductor lasers used today with the external resonator are manufactured either according to the Littrov scheme [41], or according to the Littman scheme [42]. In both schemes, the resonator of the laser is formed by the back reflecting surface of the diode and the reflecting element, and the discrimination of lengths of waves providing single-frequency generation by a diffraction lattice. At the same time, reorganization of the laser is carried out by the change of the length of the resonator and the angle of diffraction of a lattice. The main lack of these schemes is a high sensitivity of the laser to an adjustment of the reflecting element.

It is more preferable to use in OOFR the scheme offered in [43] and represented in Fig. 3, where the reflector of the cat's eye type is used, and the interferential filter is employed for discrimination of lengths of waves. A peculiarity of a reflector of the cat's eye type which is implemented by means of a lens and a mirror located in its focal plane is reflection of a bunch precisely in the opposite direction. It reduces sensitivity of the scheme to vibrations and changes of temperature. Tuning of frequency to an atomic resonance is carried out by change of current of the laser, temperature, and turn of the interferential filter by means of a piezoactuator.

A pilot study of lasers of this kind confirms their high stability. Power of radiation is 5–50 MW depending on the wavelength, and the spectral width of the line is about 1 MHz (depends on a resonator length).

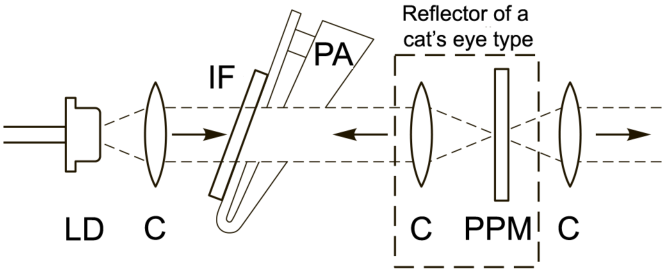

Fig. 3. The scheme of the semiconductor laser with the external resonator based on the interferential filter (IF) and the reflector of a cat's eye type. Here LD is the laser diode, C is the collimator, PA is the piezoactuator, PPM is the partially passing mirror.

After passing of a number of optical elements (insulators, optical-acoustic modulators, polarizing optics), radiation is brought to optical fiber and goes to VOS. Such scheme reduces sensitivity of a design to adjustments and vibrations.

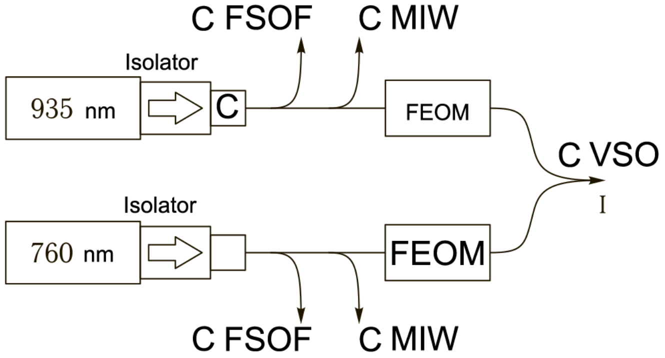

Fig. 4. The laser control system of quantum states (CSQS) based on diode lasers with the external resonator (Fig. 3). C is the collimator; FEOM is the fiber electro-optical modulator; FSOF is the femtosecond generator of optical frequencies; continuous thick lines are the optical fibers; MIW is the measuring instrument of wavelengths based on the Fizeau interferometer.

CSQS includes two lasers with the lengths of waves of 935 nanometers and 760 nanometers (Fig. 4). The laser of 935 nanometers serves for hashing of density of population $^2D_{3/2}$ - and $^3[3/2]_{1/2}$ - of levels. When applying of the cooling radiation, an ion can break up in a metastable $^2D_{3/2}$ state and drop out of a cooling cycle. To return the studied ion to a cycle of cooling, the excitement into $^3[3/2]_{1/2}$- state is made. The laser of 760 nanometers serves for hashing $^2F_{7/2}$- and $^1[3/2]_{1/2}$- of levels. This communication is necessary for a fast return of an ion to an initial state in case of transition to metastable level $^2F_{7/2}$-. In view of existence of superthin splitting, modulation of frequency of radiation, which is implemented based on fiber electro-optical modulators (FEOM), is necessary. Stabilization of frequency of CSQS lasers can be made both by means of FSOF, and by means of MIW.

SPhDC consists of three lasers: two with the wavelength of 369.5 nanometers and one with the wavelength of 398.9 nanometers. Two lasers of 369.5 nanometers are used for Doppler cooling and preparation of an initial condition of the studied ion. The frequency of these lasers differs by 14.75 GHz for an effective excitement two superthin components of the main state. The laser of 398.9 nanometers is used for ytterbium photoionization. All lasers in the SPhDC system are equipped with the fiber optical-acoustic modulators (FOAM) for a possibility of a fast inclusion and switching off radiation. The frequency of SPhDC lasers is stabilized by means of MIW or FSOF.

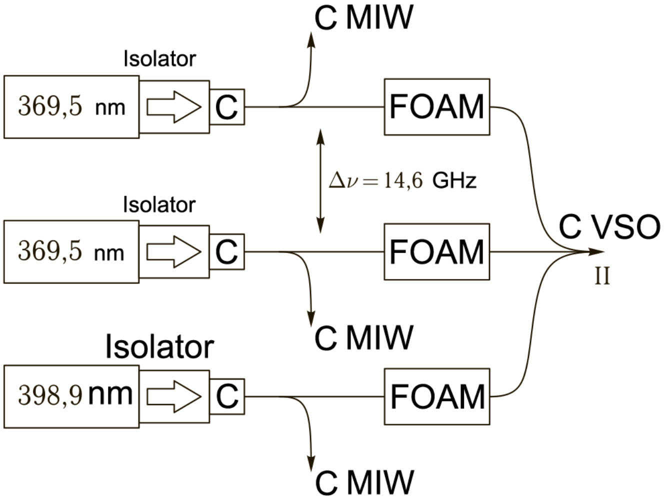

Fig. 5. A laser system of photoionization and Doppler cooling (SPhDC). Radiation is carried out by means of diode lasers with the external resonator in the scheme with the interferential filter (Fig. 3). C is the collimator; FOAM is the fiber optical-acoustic modulator; continuous thick lines are the optical fibers; MIW is the measuring instrument of wavelengths based on the Fizeau interferometer.

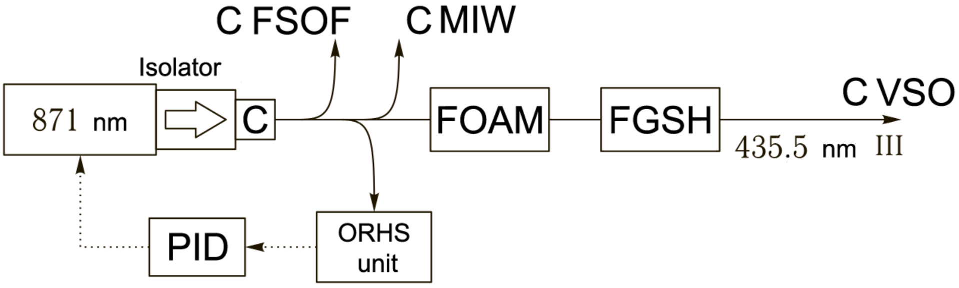

Fig. 6. A system of interrogation of clock transition (SICT). Radiation is performed by means of a diode laser with the external resonator (Fig. 3). C is the collimator; FAOM is the fiber optical-acoustic modulator; FGSH is the fiber generator of the second harmonica; ORHS is the optical resonator of high stability; PID is the proportional-integrated-differential controller; continuous thick lines are the optical fibers; dashed lines are the electric signals; MIW is the measuring instrument of wavelengths of based on the Fizeau interferometer.

In the system of interrogation of clock transition (SICT, Fig. 6), the radiation of the diode laser on the wavelength of 871 nanometer passes, at first, through the fiber optical-acoustic modulator for a possibility of reorganization of the frequency with a 100 MHz band, and then through the fiber generator of the second harmonica based on a periodically polarized nonlinear crystal [44] where the frequency of laser radiation doubles. Then on optical fiber radiation is brought to VOS. A part of radiation on the wavelength of 871 nanometer is split off for calibration of a wavemeter and stabilization of the frequency of repetition of FSOF.

2.3. Clock laser and reading off information from a single ion

For stabilization of the SICT laser on short times (1–10 sec), the ultrastable optical Fabry–Pérot interferometer, which consists of the resonator body (RB) and two mirrors with a dielectric covering fixed at end faces of a working body by the method of optical contact, is used. Mirrors and a body of the resonator are made of the glass of a special grade of with a zero coefficient of thermal expansion (Ultra Low Expansion – ULE). The optical resonator is placed in the vacuum chamber for reduction of the influence of fluctuations of the index of refraction and ambient temperature.

To stabilize the frequency of the laser relative to own frequency of the resonator, the Pound–Drever–Hall (PDH) technique is used [45]. The schematic diagram of such binding is represented in Fig. 7. Radiation of the stabilized laser on fiber is delivered to the electron-optical modulator and is modulated in phase then is reflected from ORHS and the reflected signal is detected by the photo diode. At the same time, the complex coefficient of reflection of radiation from the resonator depends on frequency. The signal from a photo diode collides with a modulation signal. The signal of beats gains dependence on a laser frequency, where at the coincidence of the frequency of the laser to ORHS resonance frequency the signal is equal to zero.

It should be noted that by means of such equipment, it is possible to stabilize the frequency of both diode and fiber lasers [22, 46]. In case of stabilization of the frequency of the fiber laser, after it one usually installs an optical-acoustic modulator, and a servo-signal for compensation of the noise of a phase of the laser goes to it as the frequency of such lasers unlike semiconductor ones cannot be quickly modulated by means of pump current. The target relative instability of frequency of SICT is $2 \cdot 10^{-15}$ (1 sec) that it is enough for a stable interrogation of an ion and is confirmed by a series of experiments [47, 48].

To read off information on initiation of clock transition in ions, the method of quantum jumps (Fig. 8) is usually used. It is that after a cycle of initiation of clock transition (Fig. 8, I), an ion is irradiated with the cooling radiation on the wavelength of 369.5 nanometers. At this moment, registration of a signal of fluorescence of an ion by means of the photoelectronic multiplier begins. If during initiation of clock transition the ion has passed into a state $^2D_{3/2}$, then an ion will not reradiate the photons of 369.5 nanometers (Fig. 8, IIa). If initiation of clock transition is not happened, the signal of fluorescence of an ion will be observed (Fig. 8, IIb). This scheme allows one to carry out stabilization of frequency of the interviewing laser of clock transition on transition frequency in an ion.

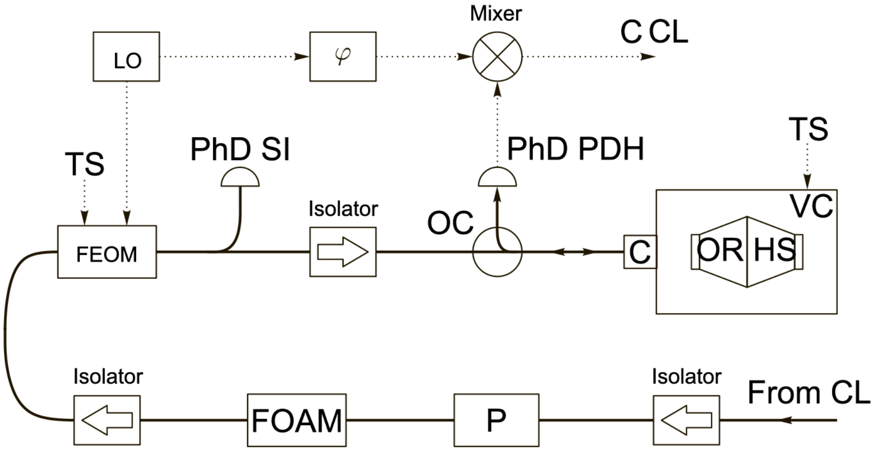

Fig. 7. The knot of the optical resonator (OR) of high stability. CL is the clock laser; P is the fiber polarizer; FOAM is the fiber optical-acoustic modulator; FEOM is the fiber electro-optical modulator; TS is the loop of temperature stabilization; PhD SI is the photo diode of intensity stabilization; OC is the fiber optical circulator; PhD PDH is the photo diode in the scheme of the Pound–Drever–Hall (PDH); C is the collimator; ORHS is the optical resonator of high stability; VC is the vacuum chamber; LO is the local oscillator; ϕ is the phase shifter; continuous thick lines are the optical fibers.

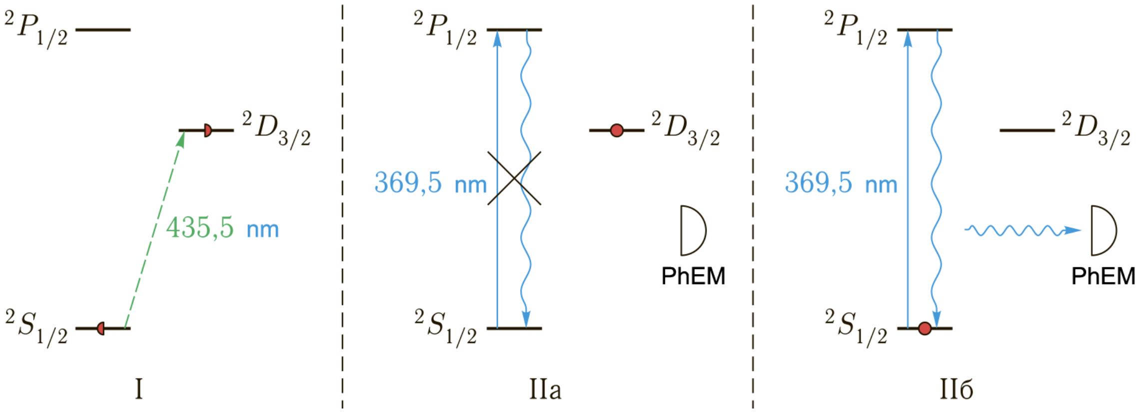

Fig. 8. Reading off quantum information from an ion. I is the initiation of clock transition; IIa is the lack of fluorescence upon transition of an ion to a state 2D3/2; IIb is the detecting of fluorescence in case of not initiation of clock transition. PhEM is the photoelectronic multiplier.

2.4. Femtosecond synthesizer of optical frequencies

The most important element of the optical standard of frequency is FSOF. Clock transition in an ion and mode of the ultrastable resonator regarding which the SICT laser is stabilized from stability of the standard in the optical range of frequencies. At the same time, practical applications demand a highly stable and exact reference point of frequency in the radio-frequency range. FSOF carries out transfer of accuracy and stability of the standard from optical range in radio-frequency.

To create of OOFR based on ions of ytterbium, it is supposed to use FSOF based on the femtosecond fiber laser with a passive synchronization of modes with the supercontinuum generator. The range of such laser source stretches within 1000–2000 nanometers. A feature of such system is that the range consists of a set of equidistant longitudinal laser modes, which frequencies are set by the formula $f_n=f_{CEO}+n\times f_{REP}$, where f_{CEO} is the frequency of a shift of a wave package relative to the carrier, f_{REP} is the frequency of repetition of impulses of the laser (f_{CEO} and f_{REP} are usually in the range of 50–250 MHz), *n* is the number of a mode [49]. In the range of wavelengths

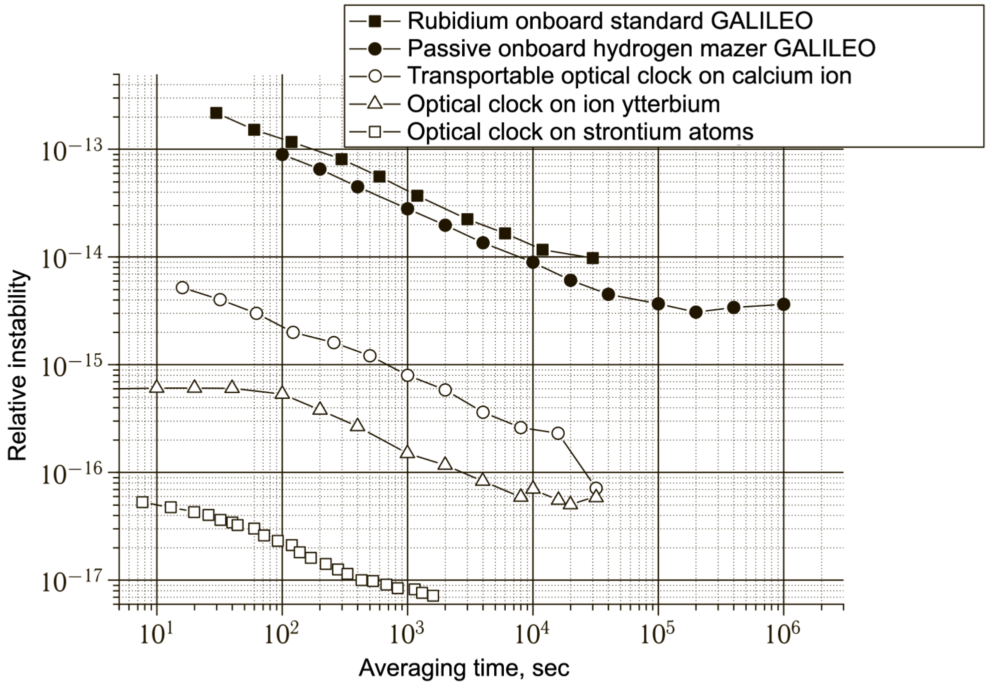

Fig. 9. Relative instability (the Allan variance) of various atomic standards of frequency depending on averaging time: the rubidium onboard standard used on the GALILEO [56] satellites, a passive onboard hydrogen maser for the GALILEO [56] satellites, the transported optical clock on a single ion 40Ca+ [14], optical clock on a single ion 171Yb+ [59], optical clock based on the atoms 87Sr in an optical lattice [10].

less than 1000 nanometers, transformation to the second harmonica with the use of nonlinear crystals of PPLN (periodically polared lithium niobate crystal) are usually applied to employ FSOF.

Thus, FSOF carries out transformation of frequencies from radio-frequency range in optical and vice versa without loss of characteristics of stability [50]. The onboard realization of FSOF was performed by the Menlo-Systems company and successfully tested onboard the suborbital device in 2016 [16]. In Russia, the Avesta company is engaged in production of fiber FSOF; FSOF laboratory systems are also created in LPI RAS and Institute of Laser Physics, Siberian Branch of the Russian Academy of Sciences.

Creation of FSOF with f_{CEO} frequency (the no offset scheme, $f_{CEO} = 0$) expelled from structure of a range is perspective. It is reached by nonlinear process of the generation of differential frequencies (GDF) between two sites of initial FSOF [51–53]. Such scheme facilitates stabilization of FSOF relative to optical reference points of frequency and transfer of their stability and accuracy in the radio frequency range [54].

During creation of ytterbium OOFR, it is planned to use a fiber FSOF that by means of nonlinear transformations provides output radiation on the wavelengths near 871 nanometers (the SICT oscillator frequency) and 1560 nanometers. Stabilization of FSOF on short times will be carried out by means of a highly stable fiber laser radiating on the wavelength of 1560 nanometers. A long-term stability of FSOF is provided by binding to the frequency of clock transition in an ion by means of SICT. FSOF will possess a radio-frequency output of 1 GHz.

3. Conclusion

The revolutionary changes, which have happened in the last decade in the field of synthesis of highly stable signals of frequency, have led to an unconditional priority role of quantum and optical technologies on the horizon of the next 10 years both in land and in onboard systems [55]. Today optical clock surpass caesium fountains in indicators concerning instability and an error by order of magnitude (Fig. 9) and continue to evolve towards the increase in compactness, reliability, and improvement of characteristics.

Undoubtedly, creation of a prototype of a reliable and compact OOFR device integrating the listed technologies and modules is the most difficult scientific and technical task. Apart from a scientific component, its realization in onboard option requires development of a line of technologies of photonics (solid-state radiators, fiber-optical components, electron-optical elements of technology of drawing coverings). The submitted project opens an opportunity to integrate the existing scientific and technological reserve and on its basis to make the objective roadmap of development of this direction in Russia.

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