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New optic system for low mass ^{199}Hg ion clock

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Abstract. The necessity of modernization of quantum frequency standards (QFS), atomic clocks, which are used in satellite navigation and telecommunication systems, is substantiated. The main goal of all QSC upgrades is to improve the metrological characteristics. In the case of its use on moving objects, its dimensions, weight and power consumption also become important characteristics. The new developed optic system has been applied to low mass ion clock prototype. With its help it has become possible to significantly take up short term stability and temperature coefficients. The prospects for using this design in various moving objects are considered.

Keywords: time scale, optical system, mercury ions, atomic clock, stabilization, automatic frequency control

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Новая оптическая система для малогабаритных атомных часов на ионах ртути-199

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Аннотация. Обоснована необходимость модернизации квантовых стандартов частоты (КСЧ) – атомных часов, которые используются в спутниковых навигационных и телекоммуникационных системах. Основной целью всех модернизаций КСЧ является улучшение метрологических характеристик. В случае применения его на подвижных объектах, также важными характеристиками становятся его габариты, вес и энергопотребление. Разработанная новая оптическая система была применена к прототипу ионных часов с малой массой. С его помощью удалось значительно улучшить кратковременную стабильность. Рассмотрены перспективы использования данной конструкции в различных подвижных объектах.

Ключевые слова: шкала времени, оптическая система, ионы ртути, атомные часы, стабилизация, автоподстройка частоты

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Introduction

In the modern world, generators of highly stable oscillations (frequency standards) are used by humanity to solve various problems [1–5]. The highest accuracy among them is possessed by quantum frequency standards, which are actively used to solve various problems [6–11]. One of these tasks is related to ensuring a stable reference oscillation on a moving object [1, 6, 8, 12–17]. For various reasons, atomic clocks used in satellite systems experience a frequency delay, which is compensated during communication with the ground [12–22]. With a long-term absence of communication to adjust the time scale, delays will accumulate [22–26]. This may lead to various problems. For example, fractions of a second might spell the difference between reaching Mars safely and missing it entirely.

In the last years there is a common trend in developing new highly stable frequency standards, because of the growing demand from developing navigation and telecommunication systems [1–5]. Mostly these new designs are cold ion traps or laser-based. Ionic standards have somewhat worse stability indicators, but they compete with standards based on neutral atoms in terms of accuracy, since a single ion in a Paul trap is weakly subject to external perturbations. In addition, ion traps are compact (volume up to 1 dm^3) and less sensitive to the settings of the cooling and interrogating laser fields. In CIS-countries, optical clocks are being created for ultracold strontium atoms with a relative error of part costs at the level of 10^{-17} (VNIIFTRI), and work is also underway on the creation of optical clocks on single ions of ytterbium, aluminum, and neutral thulium atoms.

As it has been mentioned, there are several uses for ultra-stable clocks in space and on Earth that necessitate a tiny package size. Deep-space vehicles, for example, have strong physical size limits for onboard instruments; total spacecraft mass (unfueled) is frequently less than 400 kg, with projected trends toward even less mass. Current paper describes the newly developed optical system for one of these standards, the ion-based Hg-199 for telecommunication and space applications [23, 28, 29]. This device stands from other common “brothers” with its high tolerance to great G-values, which makes it a solid candidate for onboard use.

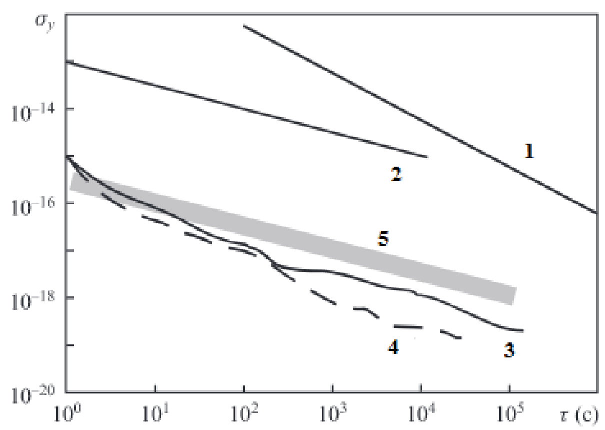

Fig. 1. Clock stability: gas chamber based *1*, ion beam based *2*, femtosecond laser *3*, *4*, optical standards device *5* of the cesium frequency standard

Materials and Methods

We have developed a high-performance $^{199}Hg^{+}$ trapped-ion clock with frequency stability near $2 \cdot 10^{-16}$. The ion-trapping technologies developed for this clock are critical to achieving this level of stability. The ion trap design for the liter clock is be based on “ion-shuttling” between a linear quadrupole and a linear multipole, similar to what is utilized in ground clocks [1, 3]. However, improvements and redesigns in the vacuum and optical systems are required to achieve the 1 to 2 liter size requirement.

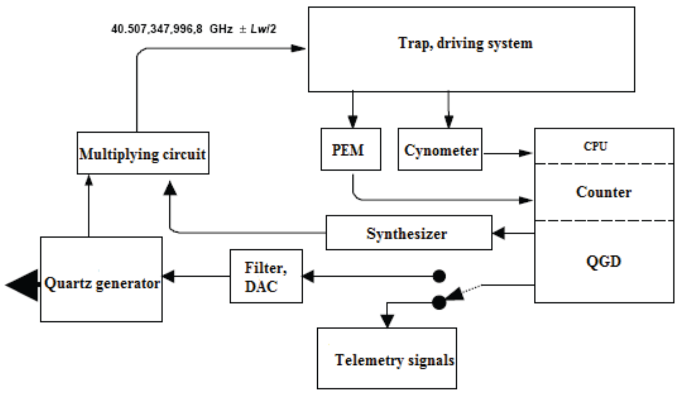

Fig. 2. Block diagram for the developed standard

Optical standards may be the perfect solution for onboard use right now for the high stability, those based on ultracold atoms and femtosecond lasers are too fragile for onboard applications.

The Hg-199 standard conceptually has a negative feedback loop where the magnetic trap provides the controller with information regarding its resonance shift. The photon counter determines time interval τ that could be varied in a certain range depending on deployment conditions: from 1 to 10 seconds, the number of registered photons by PEM: from 10^4 to $5 \cdot 10^5$. The driving system produces processing commands judging by the number of photons emitted with the help of the newly developed algorithm in order to drive the frequency of the main quartz generator and also the power circuits. Voltage output from these circuits passes transformer coils and corrects the magnetic field in the trap in order to ensure stable and precise maintenance of the device. The programmable part consists of CPU, counter and quartz generator driver (QGD), quartz generator itself receives the error signal information and shifts the produced frequency to resonance. The whole work is performed inside the counter and CPU-related parts, thus taking the most crucial tasks, digital and analog circuitry are also separated making it easier for developers to maintain the device as well as further reducing its size.

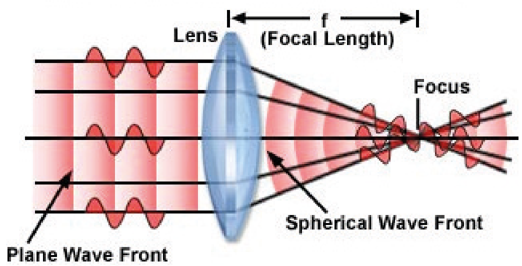

Fig. 3. Wave diagram through a perfect lens

Trap and its containing substance must be preserved at the operating state. Multiplying loop, controlling CPU and the optical system inside the trap are dedicated to this task.

While some optical components of the focusing system act as components that create an image, others are provided for all kinds of transformations of the illuminating beam, and also perform filtering and transmitting functions. The image-forming components of the optical system are considered to be a converging lens (located in or near the illuminator), a condenser, an objective, an eyepiece tube (or eyepiece) and refractive components or a video camera lens. But some of these components are not typically image-forming, and their properties are of primary importance in determining the property of the final microscopic image.

Awareness of the role of individual lenses, the elements that make up the optical system, is considered the main one for understanding the process of formation of a focusing beam in an optical system. A perfect lens is considered to be a simple, image-creating component (Fig. 3):

flawlessly corrected, free of aberrations and focused light into 1 point. A parallel, paraxial beam of light, refracted in a converging lens, is focused at its focal point or focus (it is labeled Focus in Fig. 3). These lenses are often referred to as positive lenses because they help converge a convergent (converging) light beam more sharply and slow down the diverging beam. Light from a point source placed at the focal point of the lens emerges from it in a parallel, paraxial beam (direction from right to left in Fig. 3). The distance between a lens and its focus is called the focal length of the lens, denoted *f* in Fig. 3.

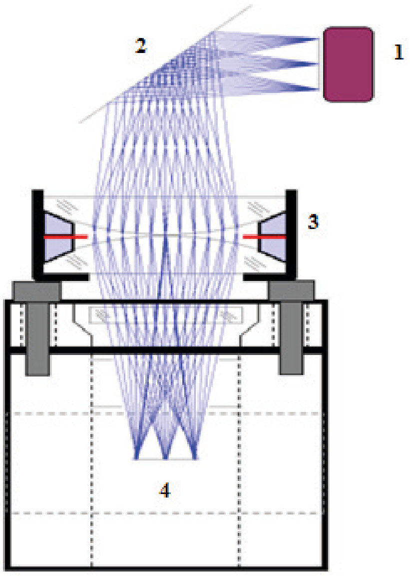

Fig. 4. UV Optical system: source *1*, refractors *2*, focus system *3*, working substance *4*

The optical system that collects appropriate ultraviolet (UV) fluorescence from the trapped Hg ions is crucial for achieving the desired short-term stability. The apparatus depicted in Fig. 4 was conceived and built by us, and it is utilized for both concentrating the source light from a ^{202}Hg lamp onto the trapped ions and capturing fluorescence from these ions. The dielectric-coated folding mirror acts as a dichroic reflector, reflecting 194-nm ion fluorescent light with >95% reflectance and parasitic 254-nm light from a neutral Hg transition with just 10 % reflectance. Because stray light limits the stability, it is critical to remove the 10 stronger 254-nm light from the beam because it is situated inside the UV-sensitive photomultiplier tube's detection band.

This system is integrated with the ion trap assembly. The electronics modules that control the photomultiplier tubes, pulse amplifier–discriminator, and discharge lamp are housed in the same enclosure as the lens, mirrors, and detectors/source. The ground clock used three independently movable optics modules to optimize ion fluorescence, but the single-module approach to the optical package here is different. The three identical optical arms of the integrated optical system described here may be placed on the bench such that their focuses fall in the same place. Since the production and assembly of the optical package have been recently completed, the optical alignment process is just getting started.

Results and Discussion

Fig. 5 shows the dependence of the change in the values of the Allan variance σ*y*(τ) on time τ for the laboratory design of atomic clocks.

The experimental results show that the Allan dispersion σ(τ) satisfies the requirements that apply to the accuracy characteristics of atomic clocks. Studies of the operation of atomic clocks were carried out for 12 days in a temperature chamber.

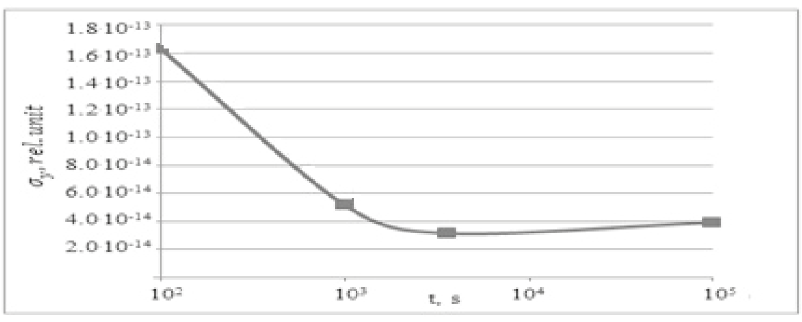

Fig. 5. Plot of Allan variance σ_y versus time *t*

Conclusion

The obtained results have shown that the developed optical systems for the small-sized design of atomic clocks on mercury-199 ions can be used in the basic model for satellite systems. In addition to this design, it is necessary to develop a thermal stabilization unit for the optical part, taking into account the space use of atomic clocks.

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