Estimation of reducing the impact of the optical lattice spectrum on the optical clock frequency shift

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Abstract. In this paper the method for reducing the shift of the "clock" resonance by the example of ⁸⁷Sr has been described. This shift arises due to the presence in the optical spectrum of the lattice laser of the incoherent component. This component is a traveling wave. It is shown that the effective decrease of the impact on the shift of the "clock" resonance by introducing the interference filter is achieved. This filter was inserted directly into the optical scheme after the laser source. Examples of the optical lattice spectra with and without filter are considered. The estimates of the efficiency ratio of the use of the interference filters to improve the final uncertainty of the optical reference are made. It is shown that the filter reduces the relative uncertainty from the impact of the incoherent component of the optical radiation of the optical lattice by two orders of magnitude. It should help to reduce the lower bound for the total uncertainty limit of the optical frequency clocks down to 10⁻¹⁸.

1. Introduction

Nowadays, the most priority areas of the scientific and technical development, which include the space navigation, geodetic technique, and fundamental research, the precise reference frequency generators are used with metrology purposes. One of such frequency reference is optical lattice clocks (OLC) coupled with femtosecond system. The femtosecond system allows transferring the frequency stability from the optical range to the microwave range. It makes it possible to demonstrate the metrological characteristics that exceed other microwave frequency several times.

Currently, many laboratories around the world have developed optical clocks based on ⁸⁷Sr and ⁸⁸Sr with an uncertainty of 10⁻¹⁶ [1-2] and the estimate of the potential uncertainty limit of 6.9·10⁻¹⁷. The research to create optical clocks is based on the ⁸⁷Sr of a new generation with the declared uncertainty down to 10⁻¹⁸·10⁻¹⁷ and a potential limit of 10⁻¹⁹ [3-5].

In the developed OLC, it was necessary to take measures to eliminate the shortcomings of previous versions. They are the including of the formation of an energy envelope of the optical lattice by the insertion of narrow-band interference filters, the introduction of phase compensation elements (Doppler cancellers, etc.) for long transmission lines between laser systems and the delivery of radiation to time and frequency storage systems. There is also the changing of the design of the vacuum atomic spectrooscope, i.e. adding an internal chamber cooled to cryogenic temperatures to
exclude the impact of thermal radiation on atoms [5], the introduction of systems that extend the time of continuous or quasi-continuous operation [6, 8] to observe and research the new non-periodic factors environmental changes - gravitational potential, earthquakes, etc.

The OLC based on cold atoms consists of the two complementary devices – the high-finesse optical cavity system and the optical spectroscope. The optical spectroscope consists of the vacuum chamber: in this chamber the strontium atoms are cooled and trapped into an optical lattice. In addition, it includes the laser systems for primary and secondary cooling, an optical lattice stabilization system, as well as a cryogenic cooling system for the internal chamber that isolates atoms from external heat flows [5, 8].

The high-finesse optical cavity system consists of a highly stable laser system based on an external cavity, which is made of ultra-low thermal expansion glass, covered by a high-frequency feedback system with frequency-modulated sidebands or a Pound-Drever-Hall system. It operates close to the clock transition frequency and is able to hold it for a certain time.

The selection of the natural line occurs using an optical spectroscope. It is the ultra-narrow-band transition, with respect to which the operating frequency of the optical custodian is corrected. The vapors of isotopes of various rare earth metals, Yb, Tm, alkaline earth metals, for example, Sr, metals Al, Hg can be used as working substances. The most popular and sophisticated, from both theoretical point and practical points of view, is the fermionic isotope of $^{87}$Sr. In its energy structure, there is an intercombination transition of $^1S_0-^3P_0$, the frequency of which is $429\,228\,004\,229\,873.0\ \text{Hz} / 698\,445\,709.612\,754\,4\ \text{fm}$ [7]. This clock transition has a very narrow line width of $\sim 1\ \text{mHz}$. An atom under normal conditions is always impacted by external radiation, magnetic fields and gravity, which disturb the true position of the clock transition; a set of measures is needed to reduce the influence of these disturbances.

2. The factor of the impact on the clock transition shift

The atoms, after several stages of cooling, are captured by a periodic set of potential wells, finally eliminating the Doppler shift to the necessary limit for scanning the clock resonance. This set of potentials is created in an optical cavity. This cavity is placed outside in the plane of the vacuum chamber, where the standing wave is created. Atoms trapped in the optical lattice have a temperature less than 1-10 $\mu$K. The impact of the optical field shifts the position of the clock resonance (Stark shift). This shift considered in [9] is monotonic, but not the same for the ground $^1S_0$ and excited $^3P_0$ levels of the clock transition of the strontium atoms. The values of the wavelengths where the shifts of the ground and exited states coincide appropriate the region of 813 nm and 390 nm (see Figure 1) [9]. The most optimal region for stabilization of the level difference is the region where the dependences of the shifts are flat, and is the wavelength of 813 nm.

However, on the way to achieve the uncertainties at the $10^{-18}$ level, more subtle effects need to be considered. It is necessary to ensure the stabilization of the laser frequency of the optical lattice system at a level of less than a few MHz and the stability of the radiation intensity at a level of less than 10%. One of the direct factors impacting the frequency shift is the presence of two components in the radiation spectrum of the optical lattice radiation being a coherent part, which determines the depth of quantum wells where the cooled atoms are trapped including an incoherent, noise part. The method for eliminating the effect of the influence of the radiation spectrum of the optical lattice or broadening the spectrum of the lattice laser by additional radiation from the Littrow scheme with amplified spontaneous emission from a semiconductor amplifier will be considered below.

During the research, the scheme for the formation of an optical lattice was designed (see Fig. 1). It is based on the use of the modernized laser Toptica TApro 813 nm, the semiconductor optical amplifier and wavelength stabilization using the Angstrom WS-U8 wavemeter [10]. The interference filter (IF) with a spectral width of 0.2-0.4 nm [11] was installed inside of the laser at the output after
the Faraday rotator. The radiation is sent to the two-pass cavity (mirrors M1 and M2) through the optical fiber with optical ports Fiberdocks (FD) and the collimator.

Figure 1. Sketch of the two-pass optical lattice cavity. The operation point of the wavelength is ~813.5 nm. The output optical power of the laser is 2500 mW. This value is held with an accuracy of 1 mW by the laser electronic feedback.

3. Estimation of the ratio of the optical clock transition shifts

Figure 1 shows the scheme for obtaining an optical lattice. The wavelength is controlled by a wavemeter with an accuracy of ± 2 MHz. The tapered amplifier of the laser system provides the output power of 2-2.5 W and is stabilized with an accuracy of 1 mW. Then, through this optical fiber, the radiation is transported into a two-pass resonator, in the waist of which atoms are captured into a set of potential wells.

An optical amplifier is used to increase the optical power of the main laser by two orders of magnitude. A large gain of the semiconductor structure arises the incoherent components of the optical spectrum due to the relative broadband of the amplifier, lying on red and blue detuning of the carrier at a distance of 25-30 nm [12].

In order to reduce the impact of these components on the purity of the spectrum and the geometry of the optical lattice, it was proposed to use an interference filter with a spectral transmission width of 0.2-0.4 nm. Figure 2 shows the spectra of the output radiation of the optical amplifier without a filter-line a and with a filter-line b.

In order to estimate the magnitude of this impact, it is simple to find the relative frequency (field) shift in terms of the atomic polarizabilities and intensities of the elementary spectral regions around the elementary component of the wavelength spectrum. Expression 1 was used [9].

$$N = \frac{h\Delta\nu_0}{h\Delta\nu_{IF}} = \frac{\sum_j \Delta\alpha(\lambda_j) \left(\frac{E_j}{2}\right)^2}{\sum_j \Delta\alpha(\lambda_j) \left(\frac{E_j}{2}\right)}$$

where \(\Delta\nu_0\) is the field shift due to the impact of the optical lattice radiation without using the interference filter; \(\Delta\nu_{IF}\) is the field shift from the lattice radiation using the interference filter; \(\Delta\alpha(\lambda_i)\) is the difference between the polarizabilities of the ground and excited states in the atom at the elementary wavelength \(\lambda_i\) of the emission spectrum; \(E_i\) is the amplitude spectrum.
corresponding to the elementary wavelength; \( h \) is Planck's constant.

By simple calculations with arrays of the data of the intensities, which were obtained from the spectrum analyzer and the values of polarizabilities in [9], it is easy to calculate the shift improvement when using an additional filtering element as an interference filter. To simplify the calculation, it is possible to use the wavelength range determined by the incoherent parts of the spectrum.

It was found that the ratio of the frequency shifts of the clock transition without the interference filter opposite using the filter is higher than 240. The part of the optical lattice intensity of the regular uncertainty budget of the OLC with total uncertainty of \( 10^{-16} \) is not higher than \( 10^{-17} \). It allows one to conclude that the uncertainty can be improved by the factor of 100 and can be at the \( 10^{-19} \) level, i.e. the corresponding contribution to the total uncertainty is also reduced to levels that do not prevent the achievement of the optical clock uncertainty of \( 10^{-18} \).

\[ \begin{align*}
&\text{Figure 2. Output emission spectra of the optical amplifier of the laser with a "magic" wavelength.} \\
&\text{For } ^{87}\text{Sr, the value of this wavelength is } \sim 813.5 \text{ nm. Line a is the radiation spectrum of the optical amplifier, which consists of a coherent narrow-band part and as background - the incoherent part. Line b is the radiation spectrum of the optical amplifier obtained after filtration with the interference filter with a bandwidth of 0.4 nm.}
\end{align*} \]

4. Conclusion

The improving of the part of the total uncertainty of the optical reference frequency by including the interference filter into the design of the optical lattice system is considered. A scheme for obtaining and stabilizing the optical lattice is shown. The estimation of the relative frequency shift due to the effect of the optical lattice intensity in the presence of an interference filter and without it is given. It was shown that the use of this filter reduces the shift, which arises due to the presence of an incoherent component of the optical lattice intensity and the corresponding uncertainty, by more than two orders of magnitude.

References

[1] Nicholson T L et al 2015 Nature Communications 6 6896
[2] Ludlow A, Boyd M, Ye J, Peik E, Schmidt P 2015 Rev. Mod. Phys. 87 637
[3] Ushijima I et al. 2015 Nat. Photon. 9 185-189
[4] Le Targat R et al. 2013 Nat. Commun. 4 2109
[5] Gurov M G, Gurova E G, Rozanov S B 2020 J. Phys.: Conf. Ser. 1661 012140
[6] Gurov M G and Gurova E G 2020 J. Phys.: Conf. Ser. 1661 012097
[7] Bipm https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies. html. (01.02.2021)
[8] Gurov M G Patent RU 2693551 26.11.2018
[9] Hidetoshi K, Takamoto M, Pal’chikov V G, and Ovsiannikov V D 2003 Phys. Rev. Lett. 91 173005
[10] Couturier L, Nosske I, Hu F, Tan C, Qiao C, Jiang Y, Chen P, Weidemüller M 2018 Review of Scientific Instruments 89 043103
[11] Baillard X, Gauguet A, Bize S, Lemonde P, Laurent Ph, Clairon A, Rosenbusch P 2006 OpticsCommunications 266 609–613
[12] Marschall S et al 2010 Optics Express 18 15820-15831