Strontium optical lattice clocks for practical realization of the metre and secondary representation of the second

Marcin Bober¹, Piotr Morzyński¹, Agata Cygan¹, Daniel Lisak¹, Piotr Masłowski¹, Mateusz Prymaczek¹, Piotr Wcisło¹, Piotr Ablewski¹, Mariusz Piwiński¹, Szymon Wójtewicz¹, Katarzyna Bielska¹, Dobroslawa Bartoszek-Bober¹, Ryszard S Trawiński¹, Michał Zawada¹, Roman Ciuryło¹, Jerzy Zachorowski², Marcin Piotrowski³, Wojciech Gawlik³, Filip Ozimek³ and Czesław Radzewicz³

¹ Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziądzka 5, PL-87-100 Toruń, Poland
² M. Smoluchowski Institute of Physics, Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, St. Lojasiewicza 11, PL-30-348 Kraków, Poland
³ Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Pasteura 5, PL-02-093 Warsaw, Poland

E-mail: zawada@fizyka.umk.pl

Received 23 January 2015, revised 17 March 2015
Accepted for publication 30 March 2015
Published 5 June 2015

Abstract

We present a system of two independent strontium optical lattice standards probed with a single shared ultranarrow laser. The absolute frequency of the clocks can be verified by the use of Er:ﬁber optical frequency comb with the GPS-disciplined Rb frequency standard. We report hertz-level spectroscopy of the clock line and measurements of frequency stability of the two strontium optical lattice clocks.

Keywords: metrology, time and frequency, optical lattice clock

(Some ﬁgures may appear in colour only in the online journal)

1. Introduction

Ultracold neutral atoms in an optical lattice [1] and trapped single-ions [2] are two well-known approaches for development of optical frequency standards.

The $^{1}\text{S}_0 - ^{3}\text{P}_0$ transition in neutral strontium was recommended by the International Committee for Weights and Measures for practical realization of the meter and secondary representation of the second. Although best realisations of the strontium atomic clocks reached accuracy and stability at the $10^{-11}$ level or better [3–7], the International Bureau of Weights and Measures (BIPM) set practical relative uncertainties above $1 \times 10^{-15}$ in case of fermionic isotope $^{87}$Sr [8] and $1 \times 10^{-14}$ in case of bosonic isotope $^{88}$Sr [9].

This conservatism stems from the fact that to calculate the recommended frequency values the BIPM uses the weighted average of independently obtained frequencies and the pool of available strontium optical clocks worldwide is still small. Enlarging this pool is an essential prerequisite for a possible redefinition of the second.

Optical clocks are not only promising candidates for future primary standards, but serve as sensitive probes in such areas as searches for variations of fundamental constants [2, 10–13], relativistic geodesy [14, 15], tests of relativity [16, 17], and searches for dark matter [18].

We developed a system of two independent strontium optical lattice clocks. The system consists of two atomic standards interrogated by a shared ultranarrow laser, prestabilized to a high-Q optical cavity and an optical frequency comb. We demonstrate hertz-level spectroscopy of the clock line and measurements of frequency stability of the standards.
2. Optical lattice standards

A simplified scheme of the system of two optical lattice clocks is depicted in figure 1. The two optical frequency standards (Sr1 and Sr2) are based on the $^1S_0 - ^3P_0$ transition in neutral strontium atoms. Sr1 can operate with bosonic isotope $^{88}$Sr while Sr2 can operate with either bosonic $^{88}$Sr or fermionic isotope $^{87}$Sr isotope. Two clouds of atoms in Sr1 and Sr2 are independently probed by an ultrastable laser with spectral width below 1 Hz. The laser beam is split into two optical paths. The frequencies of both beams are independently locked to the narrow atomic resonances in each standard by a digital lock and acousto-optic frequency shifters. The frequency of the clock transition can be compared with a GPS-disciplined Rb frequency standard by the use of an optical frequency comb.

In both standards atoms are tightly confined in a Lamb-Dicke regime in an optical lattice formed by a standing wave inside an optical cavity. The Lamb-Dicke regime effectively suppresses all motion effects, preventing any Doppler shifts of the measured transition. The lattice is operated at the so-called magic wavelength at which the light shifts of both $^1S_0$ and $^3P_0$ energy levels compensates each others with high accuracy. Moreover, the 1D lattice is oriented vertically. In such orientation tunnelling of atoms between lattice sites is prevented because of small energy differences produced by the Earth’s gravity field between levels in adjacent lattice sites. Since the depth of the optical trap is relatively low, the trap can capture atoms with temperatures significantly below 1 mK. Strontium atoms on the other hand have low vapour pressure and need to be heated in an atomic oven to 500 °C to form an atomic beam. Therefore, a system of a Zeeman slower and two stages magneto-optical trap is needed to load the atoms into the optical lattices. Details of the system are described in the following sections.

2.1. Vacuum chambers

The vacuum setups of Sr1 and Sr2 are presented in figure 2. The long trapping lifetime in the optical lattice requires ultrahigh vacuum conditions. Therefore, the vacuum system is split into two parts connected by a long, thin tube providing efficient differential pumping. The first part contains the atomic oven producing collimated strontium beam and a small cubic chamber which can be used for a 2D magneto-optical trap (MOT) to further collimate the atomic beam. The second part, with a vacuum on the order of $10^{-9}$ mbar consists of a Zeeman slower and the science chamber. The design of the Zeeman slower used in both Sr1 and Sr2 systems is described in detail in [23]. It has a capture velocity of 450 m s$^{-1}$ and produces atoms slowed down to 30 m s$^{-1}$. The flux at the exit of the slower is $3.5 \times 10^9$ s$^{-1}$ at the oven temperature of 460 °C.

The science chamber in Sr1 is made of non-magnetic austenitic 316L stainless steel (Kimball Physics 8.0 Extended Spherical Octagon), while the chamber and its surroundings in Sr2 are made of fortal aluminum alloy and titanium.
(modified version of the chamber described in [24]). All viewports, flanges, nuts, and bolts in the scientific chamber of Sr2 are made of either aluminium or titanium. Carcasses of all coils are made of cooper. Non-magnetic environment is essential for stability of the clock since the $^1S_0–^3P_0$ transition in bosonic strontium is forbidden and a magnetic field is needed to induce a nonzero dipole moment.

2.2. Laser cooling

A simplified level structure of Sr atoms with transitions used in the experiment is presented in figure 3. The cooling process of strontium atoms is performed in two stages: the first is the pre-cooling down to temperatures of a few mK, followed by ultimate laser cooling to temperatures below 10 µK, low enough to capture atoms by the optical lattice trap. The first stage takes place in a blue MOT. For this cooling the strong allowed transition $^1S_0–^1P_1$ is used at 461 nm. Blue MOT beams are detuned 40 MHz below the strontium $^1S_0–^1P_1$ transition and have 23 mm in diameter. To avoid the situation where cooling is interrupted by atoms relaxing to some other metastable states rather than to the ground state, two repumping lasers are used: 679 and 707 nm ($^3P_0–^3S_1$ and $^3P_2–^3S_1$ transitions, respectively). In total, $6–8 \times 10^8$ atoms are loaded into the blue MOT and cooled down to 2–3 mK. The 461 nm lasers in two set-ups consist of one extended cavity diode laser (ECDL), emitting at 922 nm, amplified by two tapered amplifiers (TA) and frequency doubled in the bow-tie cavities (modified Toptica TA-SHG pro systems). The blue light is locked to the $^1S_0–^1P_1$ transition in bosonic $^{88}$Sr using the saturation spectroscopy in a hollow cathode lamp (Hamamatsu L23338NB). The chain of the acousto-optic modulators (AOMs) allows trapping either $^{88}$Sr or $^{87}$Sr atoms in the blue MOTs. The frequencies of the repumping lasers are controlled by the wavelength meter (HighFinesse Angstrom WS-6). The lasers are not locked to any other frequency reference. A 10 kHz frequency modulation is applied to the repumping lasers with the amplitude of $\sim 500$ MHz for $^{88}$Sr and $\sim 4$ GHz for $^{87}$Sr to cover all states to be repumped and to neglect frequency fluctuations in the free running ECDLs. Modulation is applied to both the laser drive current and the laser PZT.

The second cooling stage takes place in a red MOT on the narrow $^1S_0–^1P_1$ transition at 689 nm. The natural width of this transition implies that the trapping laser has to be spectrally narrowed by a lock to a high-finesse optical cavity used as a short-term frequency reference (custom-made by Advanced Thin Films). The design of the cavity and the 689 nm laser...
system is described in details in [25]. In short, the Pound–Drever–Hall (PDH) locking scheme [26] is used to narrow the laser line width well below the width of the \(^1S_0\rightarrow^3P_1\) transition. The cavity mirrors and the 100 mm spacer are made of ultra-low expansion glass. The mirrors are optically contacted to the spacer. The FSR of the cavity is 1.5 GHz and its finesse is \(F = 62800\). The cavity should be insensitive to vibrations, therefore a special design of the cavity is used with the horizontal cylindrical shape. The shape of the cavity is undercut to minimise impact of mechanical noises on the resonance frequencies [27]. The cavity is placed on four viton spherules. The proper choice of the points where the supporting spherules are placed assures immunity to vibrations. The cavity is isolated from the laboratory environment and enclosed in a vacuum chamber placed in another thermal enclosure. The temperature of the enclosure is actively stabilized with an accuracy of 10 mK. The passive vibration isolation platform (Minus K, BM-1) and a steel chamber lined with acoustic damping foam (Novascan NanoCube) assure good mechanical isolation.

The frequency of light from the ECDL (Toptica DL pro) stabilized to the cavity is digitally locked to the atomic \(^1S_0\rightarrow^3P_1\) transition by the acousto-optic frequency shifter. The transition is probed by the saturation spectroscopy technique in a separate vacuum chamber with an oven as a source of the atomic beam similar to the one in the main vacuum systems. The trapping lasers of the red MOTs in Sr1 and Sr2 are the Fabry–Perot diode lasers injection-locked to the light from ultra-stable 689 nm laser. The master-slave system amplifies the power of the red light and filters out any fluctuations of power of the injection laser. These lasers (and all other slave lasers in the experiment) are placed in the mounts originally designed for distributed feedback diodes (Toptica ColdPack) which assures superior thermal stability.

The red MOT beams have a diameter of 6 mm and are superimposed on the blue MOT beams. The magnetic field gradient is lowered from 0.55 T m\(^{-1}\) during the blue MOT phase to 0.03 T m\(^{-1}\) at the beginning of the red MOT phase. Subsequently, the atomic cloud is compressed by linearly ramping the magnetic field up to 0.10 T m\(^{-1}\). The natural width of the \(^1S_0\rightarrow^3P_1\) transition at 689 nm is much smaller than the Doppler width of this transition even at a temperature of a few mK (i.e. the temperature of atoms in the blue MOT). To transfer as many atoms as possible from the blue MOT, in the first phase of the red MOT the narrow red laser beams have to be artificially broadened. A 20 kHz frequency modulation with the amplitude of 1.6 MHz is added by the AOM for that sake.

In the case of \(^{87}\text{Sr}\), a two-color red MOT is necessary, with the \(^1S_0(F = 9/2)\rightarrow^3P_1 (F = 11/2)\) transition for the trapping and cooling process and the \(^1S_0(F = 9/2)\rightarrow^3P_1 (F = 9/2)\) transition (so-called ‘stirring’ frequency [28]) for optical pumping of the ground states.

### 2.3. Optical lattices

In both the Sr1 and Sr2 systems the optical lattices utilize an optical buildup cavities with finesse of around \(F = 120\). In both realizations the mirrors of the cavity are mounted outside of the vacuum chamber. The TEM\(_{00}\) mode of the cavity at a wavelength of 813 nm has a waist of \(w = 152\ \mu\text{m}\) and \(w = 108\ \mu\text{m}\) in Sr1 and Sr2, respectively. The relatively large waists enable reduction of the density of captured atoms and hence the collisional shift of the clock line.

The magic frequency for the \(^{87}\text{Sr}\) and \(^{88}\text{Sr}\) isotopes is known to be 368 554 693(5) MHz [29] and 368 554.58(28) GHz [30], respectively, which is close to the wavelength of 813 nm. The 813 nm light is generated by the ECDL—TA (Toptica TA 100). The required level of control of the lattice-related effects implies that the frequency of the 813 nm laser has to be tuned with the accuracy of 1 MHz. The frequency of the 813 laser is locked to a Fabry–Perot transfer cavity. The cavity itself is referenced to the ultra-stable 689 nm (red MOT) laser stabilised to the \(^1S_0\rightarrow^3P_1\) transition in \(^{88}\text{Sr}\). The frequency of the 813 nm light is further tuned by the AOMs. The light is transmitted and spatially filtered through optical fibers to both Sr1 and Sr2 systems and injected into the cavities surrounding the atomic samples. The length of the cavities is stabilized to the 813 nm light by the PDH lock. The light coupled out from the cavity is observed by a fast photodiode. The photodiode signal is used by the PI controller and the AOMs for stabilisation of the power inside the cavity. The wavemeter used in the experiment (HighFinesse WS6/200) allows one to pre-tune the frequency of the 813 nm laser with accuracy of 200 MHz. More precise tuning has to be done by observing the light-shift of the clock line.

### 3. Ultrastable laser system

An ECDL laser (Toptica DL pro) locked to the TEM\(_{00}\) mode of the high-Q cavity is the short-time frequency reference of the optical standards. The optical scheme of the 698 nm laser system is depicted in figure 4. The following subsections describe areas marked by different colors of the background.

#### 3.1. Ultrastable laser

The heart of the system is the high-Q cavity (Stable Laser Systems, type ATF 6010-4) made of ultra-low expansion glass (ULE). The FSR of the cavity is 1.5 GHz and its finesse is \(F = 300000\). The spacer (100 mm long) is made of the ULE, while the mirrors are made of silica. One of the mirrors is flat, the other one is concave with the radius \(R = 500\ \text{mm}\). Similarly to the 689 nm cavity, the cylindrical shape of the cavity is undercut to minimise impact of mechanical noises on the resonance frequencies. The cavity is placed on four viton spherules on the zerodur support inside the vacuum chamber.

The vacuum in the cavity chamber is on the order of the \(10^{-6}\) Torr. The thermal shielding of the chamber provides passive isolation (thermal conductance of 0.5 W K\(^{-1}\)). The active stabilisation of the temperature (a PID controller and two heaters) has the accuracy of 2 mK. The chamber and the optical set-up which is needed for the PDH lock is placed on the vibration isolation platform (Minus K, BM-1). The damping efficiency
of the platform is in the range between −20 dB and −60 dB for the frequencies of 2 Hz and 100 Hz, respectively. The platform and the chamber are enclosed in the acoustic isolation chamber (Novascan NanoCube) providing isolation on the level of −40 dB. The scheme of the thermal, mechanical and acoustical isolation of the high-Q cavity is sketched in figure 5. Finite thermal stability of our high-Q cavity and small fluctuations of the vacuum pressure in the cavity chamber result in the overall instability of our cavity measured relative to one of the optical standards equals to $3 \times 10^{-15}$ after 10 s, $7 \times 10^{-15}$ after 100 s and $1.5 \times 10^{-14}$ after 200 s. For times longer than 200 s the fluctuations of the cavity start to average.

The yellow area in figure 4 marks the section including the ECDL laser (the spectral width of 50 kHz when free-running) and a scanning confocal Fabry–Perot interferometer (IFP) with a photodiode (PD_IFP) monitoring the single-mode operation of the laser. This section is placed on a low-profile vibration isolation platform (Herzan Onyx-6M) and enclosed in a chamber made of PVC foam. This reduces the acoustic noises from the outside environment and helps to keep the ECDL laser frequency jumps within the range of the PDH lock to the cavity. The light from the ECDL laser is transferred into the cavity chamber by a PM fiber.

Figure 4. The optical scheme of the 698 nm laser. ECDL is the extended cavity diode laser, OI is the optical isolator, EOM is the electro-optic phase modulator, AOM is the acousto-optic modulator, IFP is the scanning Fabry–Perot interferometer, FR is the Faraday rotator, P is the Glan–Taylor polariser, PD_t, PD_IFP, PD_PDH are the photodiodes, CMOS is the CMOS camera, $\lambda/2$ is the half-wavelength plate, $\lambda/4$ is the quarter-wavelength plate.

Figure 5. The scheme of the thermal, mechanical and acoustical isolation of the high-Q cavity.
The blue area in figure 4 marks the optical section needed for locking of the ECDL laser to the cavity mode by the PDH method. An electro-optic phase modulator (EOM) working at 20 MHz adds sidebands to the laser frequency. The power of the incident light is below 10 µW. The fast silicone avalanche photodiode (PDPDH) (Hamamatsu C5658) observes the signal of the beatnote between the light incident on and reflected from the cavity. The beatnote signal is demodulated with the mixer, and the resulting error signal is used by a fast PID regulator (Toptica FALC) to stabilize the frequency and to narrow the spectral width of the ECDL laser by controlling the laser diode current and the length of the ECDL internal resonator.

The gray area in figure 4 contains a complementary metal-oxide semiconductor (CMOS) camera and a silicone photodiode (PD) which are used for monitoring the power and quality of the TEM00 mode of the cavity.

In the green area in figure 4 an AOM in double-pass setup is used for real-time correction of the slow drift (typically less than 0.1 Hz s⁻¹) of the frequency of the cavity modes.

3.2. Doppler cancellation of the fiber-link noises

The light from the ultra-stable laser is transferred to the Sr1 and Sr2 standards and to the optical frequency comb through fibers. Each fiber has a system of active Doppler cancellation of the fiber-link noises to assure the transfer of stable optical frequencies [31]. The complete scheme of the system for the Doppler cancellation is presented in figure 6. The stable frequency of the ultra-stable laser is shifted by ωs in the AOM. The light is subsequently transmitted through a polarisation-maintaining fiber. Small part of the light is reflected, transmitted back through the fiber and AOM and superimposed with a portion of the original beam. The photodiode measures the beatnote of these two beams. The signal from the photodiode (RF) is demodulated in the mixer with the local oscillator signal (LO) from the stable reference oscillator (REF OSC) with the frequency of 2ωs. The output of the mixer is the error signal proportional to the cosine of the phase difference between the original beam and the round-trip beam which passed twice through the fiber and AOM. The error signal through the PI integrator controls the voltage controlled oscillator (VCO). The VCO generates the RF signal for the AOM and with the feedback control PLL loop cancels the phase noises in the optical signal transmitted through the fiber.

3.3. Clock beams in Sr1 and Sr2 standards

In both the Sr1 and Sr2 systems the Fabry–Perot diode lasers are injection-locked to the light from ultra-stable 698 nm laser. The master-slave system filters out any power fluctuations of the injection laser. The residual amount of spectrally broadband amplified spontaneous emission (ASE) of an injection-locked diode is low, since the locked diode operate well above threshold with a strongly saturated gain. Nevertheless, the narrowband interferometric filters with FWHM of the transmission peak below 0.4 nm (custom-made by ATFilms) are placed in the beam to ensure that only the ultra-narrow light will pass to the atoms. The beam is passing the AOM of the digital lock and is injected to the cavity of the optical lattice such that the clock beam is exactly superimposed with the lattice and its waist is much bigger than the size of the sample of atoms.

3.4. Optical frequency comb

The frequency of the clock transition in our experimental setup is measured with a GPS-disciplined Rb frequency standard by the use of an Er:fiber polarization mode-locked optical frequency comb (Menlo FC 1500-250-WG). Its repetition rate equals to 250 MHz and can be changed in the wide range of 2 MHz. To reach the Sr clock transition wavelength, the fundamental output of the laser around 1550 nm is spectrally shifted in the Er:fiber amplifier to ∼1396 nm and subsequently frequency doubled in a periodically-polled lithium niobate (PPLN) crystal, which results in approximately 10 mW of power in 6 nm wide spectrum around 698 nm. The optical frequency comb is fully stabilized to the reference radio frequency source. Additionally, the high bandwidth (>500 kHz) intracavity electro-optic phase modulator (EOM) can be used, which allows phase-locking it to our clock laser as the optical frequency reference. This enables coherent transfer of optical phase between our clock laser and the...
near-infrared telecommunication range at a $10^{-16}$ short-term stability level [32] for future transfer of ultrastable optical frequencies through the fiber networks or referencing high-resolution spectroscopy in that range [33–37].

A new possibility for the absolute frequency measurement of the clocks is opened by installation of a long-distance stabilized fiber optic link connecting our lab to UTC(AOS) and UTC(PL) via the OPTIME network [38]. In this scheme the Er:fiber optical frequency comb will be locked to the RF disseminated via the fiber.

4. Results

To compare the two lattice clocks both standards were tuned to the $^{1}S_{0}^{-3}P_{0}$ transition in the bosonic $^{88}$Sr. Comparing two clocks using the same atomic species assures that no systematic effects have been overlooked in their individual accuracy budget, since the measured frequencies should be the same within the accuracy budgets of both standards.

4.1. The time sequence and interrogation

Lattice clock operates in precisely defined cycles. In each cycle atoms are prepared before the interrogation, then the ultra-stable laser interrogates the clock transition and finally the populations in the ground and excited states are measured, which provides information on the transition probability. The time sequence of one cycle is presented in figure 7. After loading the atoms into the optical trap, the atoms are probed by a single $\pi$-pulse. The electric-dipole $^{1}S_{0}^{-3}P_{0}$ transition in bosonic $^{88}$Sr is forbidden, hence for inducing of the non-zero dipole moment the MOT coils are switched from the anti-Helmholtz to the Helmholtz configuration and a homogeneous magnetic field (up to 26 mT) is applied to the atoms [39].

The absolute probability that the atoms changed their state from $^{3}S_{0}$ to $^{3}P_{0}$ is calculated from the measurements of populations $N_{e}$ and $N_{g}$ of the ground and excited state, respectively, and is equal to $P = N_{e}/(N_{e} + N_{g})$. After the interrogation by the clock light, the population $N_{e}$ is measured by fluorescence imaging with a strong 461 nm transition. All measurements are done by recording the fluorescence images by the electron multiplying CCD camera (Hamamatsu C9100-02).

The pulse of the blue light blows the ground-state atoms out of the lattice trap while the excited atoms are shelved in the dark state for that transition. Sequentially, the 679 and 707 nm repumping lasers pump the excited atoms back to the ground state and their number, $N_{e}$ is measured by the second fluorescence imaging at the 461 nm transition. A third photo which gives the background is made without any atoms in the trap.

4.2. Resolved sideband spectroscopy

In principle, the atoms which have been loaded into the optical trap after cooling in the red MOT have the temperature much lower than the depth of the trap. Therefore, they should mostly occupy lower motional states of the potential. This can be verified by the spectroscopy of the longitudinal sidebands of the clock transition [40]. The clock line $^{1}S_{0}^{-3}P_{0}$, where the motional state $|n\rangle$ is conserved, is accompanied by red and blue sidebands where the motional state decreases ($|n\rangle \rightarrow |n-1\rangle$) and increases ($|n\rangle \rightarrow |n+1\rangle$) by 1, respectively. The atoms in the motional ground state $|n=0\rangle$ cannot contribute to the red sideband transition, hence the longitudinal temperature can be measured via the relative height of the two sidebands. The width of the sidebands provides the transverse temperature in the lattice trap. Additionally, the positions of the sidebands can be used for calibration of the trap depth. An example of the sideband spectrum is presented in figure 8. The measured lattice depth is $U_{0} = 338 \ E_{r} \approx 56 \ \mu K$, where $E_{r} = h^{2}/(2m\lambda^{2})$ is the lattice recoil energy. The fitted expressions for the probability of the transition (see appendix in the [40]) resulted in the longitudinal and transverse temperatures equal to $T_{z} = 2.5 \ \mu K$ and $T_{r} = 30 \ \mu K$, respectively.

4.3. Spectroscopy of the $^{1}S_{0}^{-3}P_{0}$ transition, stability of the strontium optical lattice clocks

An example of the spectroscopy of the clock transition is presented in figure 9. The atoms were interrogated by a 50 ms pulse with an intensity of 400 mW cm$^{-2}$ in the magnetic field of 0.67 mT. A Lorentz function is fitted to the measured data. The measured linewidth (FWHM) is equal to $27(1) \ Hz$ and is mostly limited by the pulse duration.

![Figure 7. The timing scheme of one cycle.](image-url)
To probe each of the standards independently, the clock laser beam is split into two parts and sent to the two standards by separate acousto-optic frequency shifters. The frequencies of the beams are locked to the clock transition with a digital integrator by comparing the absorption signal at the opposite half-width points. The correction is applied sequentially to the driving frequency of AOM. The difference between the corrections in both standards gives the momentary frequency difference between two clocks. The measured frequency stability in fractional units represented by the Allan standard deviation is presented in figure 10. For the average times $\tau$ greater than 60 s the Allan deviation decreased with $\sigma_\alpha(\tau) = 3.41 \times 10^{-14}/\sqrt{\tau}$. This value is close to the $\sigma_\alpha(\tau) = 2.3 \times 10^{-14}/\sqrt{\tau}$ obtained by Katori et al [30, 41] for asynchronous operation of two clocks, a 3D lattice clock with bosonic $^{88}$Sr and a 1D lattice clock with fermionic $^{87}$Sr. The synchronous excitation, which in our system will be implemented in the near future, allowed the Katori group to improve the stability of their bosonic clock to $\sigma_\alpha(\tau) = 4 \times 10^{-16}/\sqrt{\tau}$ [42].

4.4. Preliminary uncertainty budget and relative frequency difference measured between the two standards

We have evaluated the main contributions to the frequency shifts in both standards and compared them in table 1.

![Figure 8](image8.png) Spectroscopy of the longitudinal sidebands of the clock transition. An analytic formula [40] (red) is fitted to the data (black).

![Figure 9](image9.png) Spectroscopy of the $^1S_0-^3P_0$ transition. A Lorentz function is fitted to the measured data. The measured linewidth (FWHM) is equal to 27(1) Hz.

![Figure 10](image10.png) The measured frequency stability (frequency difference between two standards) in fractional units represented by the Allan standard deviation. The dashed (green) line shows the asymptotic stability of $\sigma_\alpha(\tau) = 3.41(27) \times 10^{-14}/\sqrt{\tau}$.

Table 1. Accuracy budget for typical experimental conditions.

| Effects                          | Shift(Uncert.) |
|---------------------------------|----------------|
| Sr1                             |               |
| Quadratic Zeeman                | −132 (37)     |
| Probe light                     | −33.3 (1.5)   |
| Lattice light                   | 0.0 (1.2)     |
| Blackbody radiation             | −2.210 (0.075)|
| Collisions                      | 0.1 (1.0)     |
| DDS and electronics             | 0.00 (0.23)   |
| **Total:**                      | **−167 (37)** |

| Effects                          | Shift(Uncert.) |
|---------------------------------|----------------|
| Sr2                             |               |
| Quadratic Zeeman                | −126 (19)     |
| Probe light                     | −8.1 (1.6)    |
| Lattice light                   | 0.0 (1.2)     |
| Blackbody radiation             | −2.405 (0.075)|
| Collisions                      | 0.1 (1.0)     |
| DDS and electronics             | 0.00 (0.12)   |
| **Total:**                      | **−136 (19)** |

Note: All numbers are in Hz.

To probe each of the standards independently, the clock laser beam is split into two parts and sent to the two standards by separate acousto-optic frequency shifters. The frequencies of the beams are locked to the clock transition with a digital integrator by comparing the absorption signal at the opposite half-width points. The correction is applied sequentially to the driving frequency of AOM. The difference between the corrections in both standards gives the momentary frequency difference between two clocks. The measured frequency stability in fractional units represented by the Allan standard deviation is presented in figure 10. For the average times $\tau$ greater than 60 s the Allan deviation decreased with $\sigma_\alpha(\tau) = 3.41 \times 10^{-14}/\sqrt{\tau}$. This value is close to the $\sigma_\alpha(\tau) = 2.3 \times 10^{-14}/\sqrt{\tau}$ obtained by Katori et al [30, 41] for asynchronous operation of two clocks, a 3D lattice clock with bosonic $^{88}$Sr and a 1D lattice clock with fermionic $^{87}$Sr. The synchronous excitation, which in our system will be implemented in the near future, allowed the Katori group to improve the stability of their bosonic clock to $\sigma_\alpha(\tau) = 4 \times 10^{-16}/\sqrt{\tau}$ [42].

4.4. Preliminary uncertainty budget and relative frequency difference measured between the two standards

We have evaluated the main contributions to the frequency shifts in both standards and compared them in table 1.

Two most important contributions to the budget are the quadratic Zeeman shift and the light shift from the 698 clock laser. Both shifts were evaluated by making two sets of four simultaneous (interlaced) locks to the atomic line with four different values of the magnetic field and four different intensities of the clock laser, respectively. The nonlinear Zeeman shift was calibrated by fitting a quadratic function to the result of the first set of measurements, while the 698 nm light shift was calibrated by fitting a linear function to the result of the second set of data.

The scalar light shift from the 813 lattice laser was evaluated by calculating the shift corresponding to detuning of the lattice light frequency from the magic value [41]. We used the wavemeter accuracy, i.e. 200 MHz, with the coefficient estimated from data in [43].

The shifts induced by the blackbody radiation (BBR) can be described as static shifts with a small dynamic correction [44]. The static contribution is proportional to the differential static polarisability of the two clock states $\Delta \alpha = 4, 07873(11) \times 10^{-39}$ Cm$^2$ V$^{-1}$ [45, 46] and the mean square value of the electric field at temperature $T$ (scales with $T$ like $T^4$). The dynamic contribution of the $5s^2 \, ^1S_0$ ground state is
calculated for the 5s5p $^3P_1$ and 5s5p $^1P_1$ transitions. To calculate the dynamic contribution of the 5s5p $^3P_0$ excited state four transitions are taken into account: 5s4d $^3D_1$, 5s6s $^3S_1$, 5p$^2$ $^3P_1$ and 5s5d $^3D_1$ (see the discussion in [46, 47]). The dynamic correction is calculated following [45] and the transition data are taken from [46, 48].

The temperature of a few crucial points of the vacuum system is monitored during the experiment cycle by MC65F103A thermistors. The acquired data and an accurate model of the vacuum system is used to set a finite elements stationary thermal simulation to obtain the temperature distribution of the system. This simulation is used to calculate the BBR experienced by the atoms. The uncertainty of the shift is evaluated from calculations of the BBR for maximum and minimum temperatures measured in the experiment.

The value of the collisional shift is evaluated by estimating the number of atoms per lattice site. For known lattice waists the atomic density is estimated by measuring the fluorescence intensity of the lattice-trapped atoms with a calibrated photodiode and number of occupied sites with a CCD camera. The frequency shift is calculated following [49]. The uncertainty of this shift is measured by making the set of four simultaneous (interlaced) locks to the atomic line with four different numbers of atoms loaded into the lattice. Since we do not see any shift when varying the atom number, we take the measured data as the upper limit for possible collisional shift.

The last evaluated uncertainty represents the finite resolution of the DDSs driving the AOMs in the frequency chain of the clock lasers.

The relative frequency difference measured between two standards, taking into account the accuracy budget presented above, is equal to 19(42) Hz.

4.5. Absolute frequency measurement of the $^1S_{0}^\rightarrow ^3P_0$ transition

The absolute frequency of the clock transition in our experimental setup can be measured by the use of the Er:fiber optical frequency comb. At this stage of the experiment the optical frequency comb is locked to the GPS-disciplined standard which limits its accuracy to the level of $10^{-12}$ [50]. Within this precision the measured absolute frequency of the clock transition in Sr1 is equal to 429228 066418 300 (580) Hz. This value agrees within its uncertainty with the recommendation of BIPM [9]. We believe that after connecting to the OPTIME network [38] we will be able to calibrate the absolute frequency directly to the hydrogen maser and improve the precision below $10^{-15}$.

5. Conclusion

We have presented preliminary results for spectroscopy of the clock line and frequency stability of the two strontium optical lattice clocks. These standards are interrogated by a shared ultra-narrow laser pre-stabilised to a high-Q optical cavity. The frequency of the clock transition in our experimental setup can be compared with the GPS-disciplined Rb frequency standard by the use of Er:fiber polarization mode-locked optical frequency comb.

In the current state of the experiment, the fluctuations of the relatively high magnetic field, corresponding to the clock transition linewidth of a few tens of Hz, limit stability of our clocks to about $2 \times 10^{-15}$. The accuracy of the Sr2 system, according to our preliminary uncertainty budget, is better than $5 \times 10^{-14}$. Given the BIPM limits are above $1 \times 10^{-14}$ for bosonic clocks, such stability and accuracy are sufficient for our present goals.

The reliable operation and good stability of the setup, allows one to expect good performance of the system after next steps of improvements. In the near future the absolute frequency of the clocks will be verified by the use of the optical frequency comb and a long distance stabilized fiber optic link with UTC(AOS) and UTC(PL) via the OPTIME network [38].

Acknowledgments

The authors would like to thank Dr J Lódewyck and Dr R Le Targat for valuable discussions and help in designing the optical lattice standards. This work has been performed in the National Laboratory FAMO in Toruń and supported by the subsidy of the Ministry of Science and Higher Education. Individual contributors were partially supported by the Polish National Science Centre Projects No. 2012/07/B/ST2/00235, No. DEC-2013/11/D/ST2/02663, No. 2012/07/B/ST2/00251, No. 2012/05/D/ST2/01914 and by the Foundation for Polish Science Projects Start, Homing Plus, and the TEAM Project co-financed by the EU within the European Regional Development Fund.

References

[1] Ido T and Katori H 2003 Recoil-free spectroscopy of neutral Sr atoms in the Lamb-Dicke regime Phys. Rev. Lett. 91 053001
[2] Rosenband T et al 2008 Frequency ratio of Al$^+$ and Hg$^+$ single-ion optical clocks, metrology at the 17th decimal place Science 319 1808
[3] Bloom B J, Nicholson T L, Williams J R, Campbell S L, Bishof M, Zhang X, Zhang W, Bromley S L and Ye J 2014 An optical lattice clock with accuracy and stability at the $10^{-15}$ level Nature 506 71–5
[4] Le Targat R et al 2013 Experimental realization of an optical second with strontium lattice clocks Nat. Commun. 4 2109
[5] Hinkel N, Sherman J A, Phillips N B, Schioppo M, Lemke N D, Beloy K, Pizzocaro M, Oates C W and Ludlow A D 2013 An atomic clock with $10^{-18}$ instability Science 341 1215–8
[6] Falke S, Lemke N, Grebing C, Lipphardt B, Weyers S, Gerginov V, Huntemann N, Hagemann C, Al-Masoudi A and Häfner S 2014 A strontium lattice clock with $3 \times 10^{-17}$ inaccuracy and its frequency New J. Phys. 16 073023
[7] Ushijima I, Takamoto M, Das M, Ohkubo T and Katori H 2015 Cryogenic optical lattice clocks Nat. Photon. 9 185–9
[8] Bureau International des Poids et Mesures (BIPM) 2013 Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the definition of the
second, strontium 87 Atom (f ≈ 429 THz), (France: BIPM, Sèvres)

[9] Bureau International des Poids et Mesures (BIPM) 2009 Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the definition of the second, strontium 88 Atom (f ≈ 429 THz), (France: BIPM, Sèvres)

[10] Peik E, Lipphardt B, Schnatz H, Schneider T, Tamm Ch and Karlshöfn S G 2004 Limit on the present temporal variation of the fine structure constant Phys. Rev. Lett. 93 170801

[11] Fortier T M et al 2007 Precision atomic spectroscopy for improved limits on variations of the fine structure constant and local position invariance Phys. Rev. Lett. 98 070801

[12] Blatt S et al 2008 New limits on coupling of fundamental constants to gravity using 87Sr optical lattice clocks Phys. Rev. Lett. 100 140801

[13] Peik E 2010 Fundamental constants and units and the search for temporal variations Nucl. Phys. B 203–4 18–32

[14] Bjerhammer A 1985 On a relativistic geodesy Bull. Géod. 59 207–20

[15] Delva P and Lodewyck J 2013 Atomic clocks: new prospects in metrology and geodesy Acta Fisica 76 67–78

[16] Schiller S et al 2009 Einstein gravity explorer: a medium-class fundamental physics mission Exp. Astron. 23 573–610

[17] Chou C W, Hum S B, Rosenband T and Wineland D J 2010 The optical lattice and relativity Science 329 1630–3

[18] Derevianko A and Pospelov M 2014 Hunting for topological dark matter with atomic clocks Nat. Phys. 10 933–6

[19] Dicke R H 1953 The effect of collisions upon the Doppler broadening Phys. Rev. 90 1093–9

[20] Takamoto M, Hong F L, Higashi R and Katori H 2005 An atomic clock based on strontium clock J. Phys. Soc. Jpn. 74 044310

[21] Peik E, Lipphardt B, Schnatz H, Schneider T, Tamm Ch and Karlshöfn S G 2004 Limit on the present temporal variation of the fine structure constant Phys. Rev. Lett. 93 170801

[22] Blatt S et al 2008 New limits on coupling of fundamental constants to gravity using 87Sr optical lattice clocks Phys. Rev. Lett. 100 140801

[23] Peik E 2010 Fundamental constants and units and the search for temporal variations Nucl. Phys. B 203–4 18–32

[24] Bjerhammer A 1985 On a relativistic geodesy Bull. Géod. 59 207–20

[25] Delva P and Lodewyck J 2013 Atomic clocks: new prospects in metrology and geodesy Acta Fisica 76 67–78

[26] Schiller S et al 2009 Einstein gravity explorer: a medium-class fundamental physics mission Exp. Astron. 23 573–610

[27] Chou C W, Hum S B, Rosenband T and Wineland D J 2010 The optical lattice and relativity Science 329 1630–3

[28] Derevianko A and Pospelov M 2014 Hunting for topological dark matter with atomic clocks Nat. Phys. 10 933–6

[29] Dicke R H 1953 The effect of collisions upon the Doppler broadening Phys. Rev. 90 1093–9

[30] Takamoto M, Hong F L, Higashi R and Katori H 2005 An atomic clock based on strontium clock J. Phys. Soc. Jpn. 74 044310

[31] Peik E, Lipphardt B, Schnatz H, Schneider T, Tamm Ch and Karlshöfn S G 2004 Limit on the present temporal variation of the fine structure constant Phys. Rev. Lett. 93 170801