Demonstration of the nearly continuous operation of an $^{171}\text{Yb}$ optical lattice clock for half a year

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Received 3 May 2020, revised 16 June 2020
Accepted for publication 22 June 2020
Published 2 November 2020

Abstract
Optical lattice clocks surpass primary Cs microwave clocks in frequency stability and accuracy, and are promising candidates for a redefinition of the second in the International System of Units (SI). However, the robustness of optical lattice clocks has not yet reached a level comparable to that of Cs fountain clocks which contribute to International Atomic Time (TAI) by the nearly continuous operation. In this paper, we report the long-term operation of an $^{171}\text{Yb}$ optical lattice clock with a coverage of 80.3% for half a year including uptimes of 93.9% for the first 24 days and 92.6% for the last 35 days. This enables a nearly dead-time-free frequency comparison of the optical lattice clock with TAI over months, which provides a link to the SI second with an uncertainty of low $10^{-16}$. By using this link, the absolute frequency of the $^{171}\text{Yb}$ $^1\text{S}_0-^3\text{P}_0$ clock transition is measured as 518 295 836 590 863.54(26) Hz with a fractional uncertainty of $5.0 \times 10^{-16}$. This value is in agreement with the recommended frequency of $^{171}\text{Yb}$ as a secondary representation of the second.

Keywords: optical lattice clock, SI second, frequency metrology

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

1. Introduction

Over the last 20 years, optical clocks such as single ion optical clocks and optical lattice clocks have been rapidly improved and some of the research groups have made remarkable progress in developing optical clocks with fractional frequency stabilities and uncertainties at the $10^{-18}-10^{-19}$ level [1–8], which is better than primary Cs fountain microwave clocks. These achievements have stimulated discussion regarding a redefinition of the second in the International System of Units (SI) [9–12].

With the aim of redefining the SI second, the absolute frequencies of optical clocks have been measured by many groups and used to determine the recommended frequencies of secondary representations of the second [11]. The absolute frequency can be directly measured referenced to a Cs fountain clock if it is locally available in the laboratory [13–20]. When a local Cs clock is not available, the absolute frequency can be measured using a satellite link to International Atomic Time (TAI). TAI is a global timescale computed by the Bureau International des Poids et Mesures (BIPM). BIPM provides the frequency difference between TAI and the SI second averaged over a month. Therefore, the continuous comparison of an optical clock with TAI for a month is desirable in terms of linking to the SI second without additional uncertainty resulting from the dead time. A long-term comparison is also needed to reduce the uncertainty arising from the satellite link [21]. Since optical lattice clocks have commonly been
operated intermittently, previous works have mostly employed stable local flywheels (e.g., an ensemble of hydrogen masers) that reach the $10^{-16}$ level to bridge the gaps in the operation of the lattice clocks [22–25]. A few groups have reported the nearly continuous operation of Sr optical lattice clocks with uptimes of 93% for 10 days, 83% for three weeks [19], and 84% for 25 days [26]. Regarding an ion clock, the operation of an Yb$^+$ clock with 76% uptime for 25 days has been reported [27].

The continuous operation of an optical clock is essential for the calibration of the frequency of TAI as a secondary representation of the second [11] as well as the absolute frequency measurement. A robust optical clock is also important for new applications including tests of fundamental physics [15–17, 24, 28–32], relativistic geodesy [33, 34], and the generation of a stable local timescale [18, 35–37].

The main challenge as regards realizing the continuous operation of an optical lattice clock is to stabilize the frequencies of several light sources including an optical frequency comb to allow the comparison of the optical clock and a microwave standard. So far, we have developed multi-branch erbium-doped-fiber-based frequency combs that can run continuously for long periods [38]. By stabilizing the frequencies of many light sources to the comb, we have constructed a simple and reliable laser system for clock experiments [39]. We have also developed a relocking scheme [40] for optical phase locking. These techniques should greatly assist the realization of the continuous operation.

In this paper, we report the operation of an $^{171}$Yb optical lattice clock with a coverage of 80.3% for half a year (185 days) including uptimes of 93.9% for the first 24 days, 86.4% for the second 27 days, 80.4% for the third 30 days, 72.7% for the fourth 35 days, 82.6% for the fifth 25 days, and 92.6% for the sixth 35 days. Using a single hydrogen maser with its stability limited by a flicker floor of $2 \times 10^{-15}$, we reduce the uncertainty in the link between the Yb clock and the SI second to the low $10^{-16}$ level, and measure the absolute frequency of the Yb clock transition.

2. Experimental setup

Figure 1 is a schematic diagram of the experimental setup. The setup for the Yb optical clock is similar to that reported in our previous paper [41]. The clock utilizes the $^1S_0-^3P_0$ clock transition at 578 nm of $^{171}$Yb atoms trapped in an optical lattice operated at the magic wavelength [42] of 759 nm. The 578 nm light was generated by the second harmonic generation (SHG) of an external cavity diode laser (ECDL) emitting at 1156 nm [43]. The lattice light at 759 nm was provided by a titanium-sapphire (Ti:S) laser (M squared, SolStIS-4000-SRX-R). Before loading the atoms to the optical lattice, two-stage laser cooling with the $^1S_0-^1P_1$ transition at 399 nm and the $^1S_0-^3P_1$ transition at 556 nm was carried out to decrease the temperature of the atoms to several tens of microkelvins. The 399 nm light was generated by an injection-locked 399 nm diode laser with an automatic relocking mechanism [44]. A seed light for the injection locking was provided by the SHG of a 798 nm ECDL [45]. The 556 nm light for the second stage cooling was prepared by the SHG of a 1112 nm light from a fiber laser (NKT Photonics, Koheras) with a semiconductor optical amplifier. All the SHG processes were performed with single-pass periodically poled LiNbO$_3$ waveguides.

The 1112 nm fiber laser and the 1156 nm ECDL were phase locked to a narrow linewidth fiber comb (Fiber comb 1 in figure 1) [46, 47]. This comb was phase locked to a master Nd:YAG laser at 1064 nm, which was stabilized to an ultra-low expansion (ULE) cavity by using the Pound-Drever-Hall method. To compensate for the narrow capture range of optical phase locking, a recently-developed relocking scheme [40] was incorporated in the phase locking of the comb to the master laser and the phase locking of the 1112 nm and 1156 nm lasers to the comb. The 798 nm ECDL and the Ti:S laser were stabilized to another fiber comb (Fiber comb 2 in figure 1) by frequency locking with an electrical delay line [48], which ensured a large capture range. Fiber comb 2 was referenced to UTC(NMIJ), the physical realisation of Coordinated Time maintained by the National Metrology Institute of Japan, which is generated by a hydrogen maser and an auxiliary output generator to add an arbitrary frequency offset.

The Yb optical lattice clock was operated with a cycle time of about 1.7 s. Yb atoms effused from an oven were decelerated with a Zeeman slower and cooled in first-stage cooling for about 1.2 s and then further cooled in second-stage cooling for 275 ms. In the present work, a window heated at 204 °C was installed inside a vacuum chamber in the path of the Zeeman slower beam to prevent the atomic beam from coating the viewport. The atoms were then loaded into a vertically oriented one-dimensional optical lattice and spin-polarized with the $^1S_0-^3P_1$ transition at 556 nm for 20 ms. A Rabi $\pi$ pulse resonant on the clock transition was then applied for 40 ms. The atomic population and the excitation probability were deduced using a laser-induced fluorescence signal by the $^1S_0-^1P_1$ transition at 399 nm, and repumping on the $^3P_0-^3D_1$ transition at 1389 nm induced by a free-running distributed feedback laser. The excitation probability was used to calculate frequency corrections applied to an acousto-optic modulator (AOM), which steers the frequency of the clock laser to the atomic transition. The atomic transition was split into two Zeeman components $m_F \pm 1/2$ by applying a bias magnetic field of 65 µT. The clock laser probed the two components alternatively and was stabilized to each component independently.

Fiber comb 2 was also used to measure the frequency of the Yb clock against UTC(NMIJ). To transfer the stability of UTC(NMIJ) to the comb without degradation, we mixed the 7th harmonics of the repetition rate frequency $f_{rep} \sim 121.8$ MHz with a 900 MHz signal which was generated by the 90-fold frequency multiplication of a 10 MHz signal from UTC(NMIJ). The 90-fold multiplication was realized by using 4 multipliers with multiplication factors of 2, 5, 3, and 3. The resulting output frequency from the mixer $\delta \sim 47$ MHz was phase locked to a synthesizer referenced to UTC(NMIJ). After stabilizing the comb to UTC(NMIJ), the beat frequency between the clock laser and the comb was measured by using a zero dead-time frequency counter.
3. Demonstration of the nearly continuous operation

The frequency of the Yb optical lattice clock was measured against UTC(NMIJ) during a half-year period from the Modified Julian Date (MJD) 58 754 (28 September 2019) to MJD 58 939 (31 March 2020). The Yb clock was operated in six measurement campaigns with uptimes summarized in table 1. Figures 2 (a) - (f) respectively show the fractional frequency differences between the Yb clock and UTC(NMIJ), denoted by \( y(Yb - UTC(NMIJ)) \), in the first-to-sixth campaigns. \( y(Yb - UTC(NMIJ)) \) is given by

\[
y(Yb - UTC(NMIJ)) = \frac{f_a(Yb) - f_a(UTC(NMIJ))}{f_n(Yb) - f_n(UTC(NMIJ))} = \frac{f_a(Yb)}{f_n(Yb)} - 1 \tag{1}
\]

where \( f_a(X) \) denotes the actual (nominal) frequency of \( X \). The approximation is valid when \( f_a(X) - f_n(X) \ll f_n(X) \). Here we chose \( f_a(UTC(NMIJ)) = 10 \text{ MHz} \) and \( f_a(Yb) = f_{\text{CIPM}}(Yb) = 518295836590863.6 \text{ Hz} \), which is the CIPM (Comitè International des Poids et Mesures) recommended frequency of \( ^{171}\text{Yb} \) [11]. The uptime was calculated by using \( N_{\text{valid}}T_{\text{cycle}}/T_{\text{total}} \), where \( N_{\text{valid}} \) is the number of valid data points, \( T_{\text{cycle}} \) the clock cycle time (~1.7 s), and \( T_{\text{total}} \) the total period of the measurement. We discarded data that included the following events: (i) large excursions in the phase-locked frequencies that can occur during the relocking procedures; (ii) cycle slips in the frequency counting; and (iii) low excitation probabilities of the clock transition that lasted for a sufficiently long period.

The clock was mostly unattended during the full campaign period. Several experimental parameters such as the number of trapped atoms, the Zeeman splitting, the excitation probability of the clock transition, and the beat frequencies between the lasers and the combs, were monitored remotely. A data acquisition computer automatically sent an email alert to operators when one of the experimental parameters was outside the normal range. In the first campaign (see figure 2 (a)), to demonstrate almost dead-time-free operation (\( \geq 90\% \) uptime per day), we always carried out manual tuning as soon as we received the email alert. Significant reductions in the uptime were caused by rare events such as the passage of a typhoon at MJD 58 770 and the failure of a diode laser used in fiber comb 1 at MJD 58 778. In the second to sixth campaigns (see figures 2 (b)-(f)), manual recovery was not always performed at night to demonstrate that a large uptime can also be achieved with

### Table 1. Uptimes of the Yb optical lattice clock.

| Campaign | MJD       | Period (days) | Uptime (%) |
|----------|-----------|---------------|------------|
| 1        | 58 754 − 58 778 | 24           | 93.9       |
| 2        | 58 787 − 58 814 | 27           | 86.4       |
| 3        | 58 814 − 58 844 | 30           | 80.4       |
| 4        | 58 844 − 58 879 | 35           | 72.7       |
| 5        | 58 879 − 58 904 | 25           | 82.6       |
| 6        | 58 904 − 58 939 | 35           | 92.6       |
| Total    | 58 754 − 58 939 | 185          | 80.3       |
minimum human effort. Large gaps from MJD 58 831 to MJD 58 834 in the third campaign were caused by the shutdown of the air conditioners for facility maintenance. In the fourth campaign, a diode laser used in fiber comb 2 failed, which caused a large downtime from MJD 58 873 to MJD 58 875. At MJD 58 877, we stopped the clock operation and carried out a systematic evaluation of the microwave synthesis (See section 5).

Figure 3 shows the distribution of interrupting events that occurred during the full campaign period. The number of interrupting events were counted according to the email alert history. We could basically link the email history to the types of interruptions, but could not link some events due to a lack of records. These events are indicated by ‘No record’ in figure 3. The clock operation was mostly interrupted by acoustic noise from a drainage pump in the facility (26% of the total number of interruptions), the instability of the injection locking (12%), mode hopping of the Ti:S laser (11%) and the 1156 nm ECDL (9%), and a small number of trapped atoms (8%). Earthquakes (6%) stopped the Yb clock mostly by disrupting the lock of the 798 nm diode laser. The other relockable light sources were resistant to small magnitude earthquakes. The other factors that interrupted the operation included rapid frequency drifts of the ULE cavity after the air conditioners were shutdown (MJD 58 831 to MJD 58 834) and temporarily halting of the data acquisition computer.

Figure 4 shows the number of interrupting events in each campaign. Most of the interruptions occurred with a small number (≲ 10) in each campaign except for the Ti:S laser (blue square), a small number of trapped atoms (green square), and a drainage pump (red square). The lock of the Ti:S laser failed frequently especially in the second campaign. This problem was partially solved in the following campaigns by cleaning the mirrors used to introduce the pump laser beam and improving the signal-to-noise ratio of the error signal for the frequency locking to the comb. From the second campaign, the number of atoms trapped in the optical lattice gradually decreased (see section 4), which increased the occurrence of lock failures. From the end of the third campaign, the Yb clock was frequently interrupted by a drainage pump, which had been installed in the facility during the third campaign. The pump generated acoustic noise for about 30 minutes once a day when it drained water. During this period, the excitation probability of the atomic transition became almost zero due to the broadening of the clock laser linewidth.

Figure 2. Fractional frequency of the Yb clock relative to UTC(NMIJ) (γ(Yb – UTC(NMIJ))) and the uptime per day in the (a) first, (b) second, (c) third, (d) fourth, (e) fifth, and (f) sixth campaigns. The blue point corresponds to a 6.8 s average, the red point a 10^3 s average, and the gray point in (f) a 30 s average. T_{link} indicates the period employed to calculate the frequency difference between UTC(NMIJ) and TAI. The data in the shaded region in (e) were not used for the calculation due to a large excursion of the phase of UTC(NMIJ) at MJD 58 896.
4. Frequency stability and uncertainty of the optical lattice clock

We evaluated the frequency stability of the Yb optical lattice clock by comparing it with our Sr optical lattice clock [49]. Figure 5 shows the Allan deviation of the frequency ratio Yb/Sr which was improved with a slope of $1.0 \times 10^{-14}/\sqrt{(\tau/s)}$ and reached low $10^{-16}$ in several thousand seconds. Figure 5 also shows the frequency stability of UTC(NMIJ) relative to the Yb clock, which was calculated from the data of the first campaign (see figure 2 (a)). During this campaign period, the frequency offset of the auxiliary output generator for UTC(NMIJ) was constant.

Table 2 lists the systematic shifts and uncertainties of the Yb optical lattice clock obtained in the first campaign. The uncertainty evaluation is mostly based on our previous evaluation [41]. The density shift and the servo error differed slightly depending on the data obtained in each campaign.

The lattice induced light shift was estimated using a model [50–52] that includes the contributions from the dominant electric-dipole ($E_1$) polarizability, the multipolar ($M_1$ and $E_2$) polarizability, and hyperpolarizability [53]. To calculate the
shift using this model, the effective trap potential depth $V_e$, which is less than the maximum trap depth $V_0 = 450 E_r$ due to the radial motion of the atoms, and the average vibrational quantum number $\langle n \rangle$ were estimated by sideband spectroscopy of the clock transition [54]. The obtained values were $V_e = 342(28) E_r$ and $\langle n \rangle = 2.1(6)$. The frequency of the lattice laser was stabilized at $\nu_L = 394798263$ MHz. To find the $E1$ polarizability coefficient $a$ and the $E1$ magic frequency $\nu_{E1}$, we have previously measured the light shift as a function of the frequency of the lattice laser [41], and fitted the obtained data with the light shift model [51]. To estimate the variation of $a$ and $\nu_{E1}$ resulting from the systematic uncertainty of the fixed parameters in the light shift model ($V_e$, $\langle n \rangle$, and the multipolar and hyperpolarizability shifts), we have employed a Monte Carlo method in which the fittings were repeated with different permutations of the fixed parameters. Since the distribution of $a$ obtained from many fittings was asymmetric and had a very long tail mainly due to a relatively large uncertainty in our estimation of $V_e$, we have previously calculated a mean value of $a$ by removing rare events in the tail. Here, we employed a value of $a$ that was determined with center values of the fixed parameters. The uncertainty of $a$ was estimated from a 68% coverage interval of the distribution of $a$. The same method was applied to the estimation of $\nu_{E1}$. We obtained $a = 0.020(13) \text{ mHz/E}_r$ and $\nu_{E1} = 394798244(25) \text{ MHz}$, which agreed with our previous estimation [41] and the values reported by other groups [25, 52, 53, 55]. Finally, the light shift was estimated to be $3.4(33.1) \times 10^{-17}$ with $a$, $\nu_{E1}$, $\nu_L$, $\langle n \rangle$, $V_e$ estimated here, and the sensitively coefficients for the multipolar and hyperpolarizability shifts used in our previous evaluation [41].

The blackbody radiation (BBR) shift was estimated to be $-263.8(20.8) \times 10^{-17}$, which includes the contribution from the vacuum chamber and the atomic oven considered in our previous evaluation [41] and also that from the newly-installed heated window at 204 °C. To include this new contribution,
the BBR shift induced by the heated window was calculated using a model [56] in which the atoms are located at the center of a stainless-steel sphere with an emissivity of 0.1. The radius of the sphere is equal to the distance between the atoms and the heated window (~140 mm). The BBR photons at 204 °C are provided from a small portion of the sphere’s surface with its area equal to that of the heated window seen by the atoms (~260 mm²). This model takes into account the diffuse reflection of the BBR photons on the stainless-steel wall, which increases the effective solid angle by a factor of ~10 compared with the geometric solid angle. With the sensitivity coefficient [57, 58], the calculated shift due to the heated window was $-1.8 \times 10^{-16}$. This shift value was also conservatively taken as an uncertainty.

The density shift was estimated from the atomic density in each campaign. The blue points in figure 6 show the atomic density data. The density decreased with a time scale of ~10 days largely due to a reduction in the transmission efficiency of the 399 nm light through the optical fiber and the output power of the 1112 nm semiconductor amplifier. Some of these components were replaced (see the caption of figure 6) when we could not keep the stabilization of the clock laser to the atomic transition. The status of the stabilization was confirmed by monitoring the Zeeman splittings and the excitation probabilities (see pink and green points in figure 6). The short-term (a few days) fluctuation of the density was mainly caused by variations in the spectral purity of the injection locking, the polarization rotation of the cooling lasers through the optical fiber, and pointing instabilities of the cooling beam at 399 nm induced by an AOM or a damaged optical fiber. In the first campaign (see blue points in figure 6 (a)), the mean value of the atomic density was $3.6(1.6) \times 10^{14}$ m$^{-3}$. The uncertainty of $1.6\rho$ was estimated from the standard deviation. We also added an uncertainty of ~10% to the estimation of the density according to the fluctuation of the 399 nm probe beam. With our sensitivity coefficient [41] and a scaling of the trap volume with $V_0^{3/2}$ [4], the shifts were determined as $-8.3(6.4) \times 10^{-17}$, $-4.9(3.4) \times 10^{-17}$, $-5.7(4.1) \times 10^{-17}$, $-3.9(3.0) \times 10^{-17}$, $-4.5(3.5) \times 10^{-17}$, and $-5.3(3.7) \times 10^{-17}$ in the first, second, third, fourth, fifth, and sixth campaigns, respectively. We observed that the mean excitation probability changed from 0.42 to 0.50 after the air conditioners were shutdown (MJD 58 831 to MJD 58 834) (see figure 6 (c)). We attributed this to a variation of the spin-polarization efficiency due to a large frequency change of the ULE cavity. This can change the shift coefficient, since the density shift depends on (i) the excitation probability mostly due to the p–p wave interaction [59–61] and (ii) the impurity of the spin-polarization [6, 60]. Based on the measured results of reference [60], we estimated that in our relatively low atomic density, the change due to those effects is negligibly small compared with the uncertainty in our evaluation.

The second-order Zeeman shift was estimated from the Zeeman splitting measured in each campaign (see pink points in figure 6). In the first campaign, the mean value of the splitting was 268(3) Hz, where the uncertainty was estimated from the standard deviation. The shift was found to be $-5.2(3) \times 10^{-17}$ using our sensitivity coefficient [41]. The mean splitting value was almost constant (268 – 270 Hz) during the entire campaign period.

The probe light shift was calculated to be $4(2) \times 10^{-18}$ from the shift value of reference [6] and the fact that the laser intensity adjusted for the π pulse was inversely proportional to the time duration of the pulse.

The servo error was estimated by averaging the differences between the excitation probabilities of the high- and low-spectral shoulders for the data obtained in each measurement campaign. The servo errors were estimated to be $-4.7(1.1) \times 10^{-17}$, $-4.8(1.0) \times 10^{-17}$, $4.6(10.8) \times 10^{-17}$, $-2.8(1.2) \times 10^{-17}$, $-6.0(0.9) \times 10^{-17}$, and $-4.1(1.4) \times 10^{-17}$ in the first, second, third, fourth, fifth, and sixth campaigns, respectively. The relatively large uncertainty of $10.8 \times 10^{-17}$ in the third campaign arose from the rapid frequency drifts of the ULE cavity after the air conditioners were shutdown (MJD 58 831 to MJD 58 834).

### 5. Uncertainty of the frequency comparison by the comb

To evaluate the uncertainty of the comb-based frequency comparison between the Yb clock and UTC(NMIJ), we compared fiber comb 2 (see figure 1) with another comb (fiber comb 3, not shown in figure 1) that was independent except for the 10 MHz reference signal of UTC(NMIJ). These combs had independent setups for the microwave synthesis including the 90-fold frequency multiplication. We simultaneously measured the frequency of an acetylene-stabilized laser at 1.5 μm against UTC(NMIJ) by using these two combs, and calculated the frequency difference between the combs. In the first measurement from MJD 58 712 to MJD 58 713, the fractional frequency difference (fiber comb 2 - fiber comb 3) was found to be 9.7 × 10$^{-17}$, which was the average of the frequency difference data obtained for ~10$^5$ s. Figure 7 shows the Allan deviation calculated from the frequency difference data. The Allan deviation is likely limited by a flicker floor of low 10$^{-16}$ at averaging times $\tau \geq 10^4$ s. By fitting the Allan deviation with a function which includes the white phase, the white frequency, and the flicker frequency noise components, the flicker component was estimated to be 1.6 × 10$^{-16}$. In
Figure 7. Allan deviation calculated from the frequency difference between two independent combs except for the reference signal of UTC(NMIJ). The blue curve indicates the fit of a function which includes the white phase, the white frequency, and the flicker frequency noise components.

Figure 8. Fractional frequency of the Yb clock referenced to the SI second ($y(Yb - SI)$) obtained in each campaign. The error bar is given by the total statistical uncertainty for each campaign. The solid red line indicates the weighted mean, the dashed blue lines indicate the total statistical uncertainty in the full period, and the dashed red lines indicate the total uncertainty including the systematic uncertainties.

Table 3. Uncertainty budget for the absolute frequency measurement of the $^{171}$Yb clock transition.

| Effect                                      | First campaign ($\times 10^{-16}$) | Full period ($\times 10^{-16}$) |
|---------------------------------------------|------------------------------------|---------------------------------|
| Statistics                                  |                                    |                                 |
| Yb                                          | 0.07                               | 0.03                            |
| Dead time in Yb – UTC(NMIJ)                 | 2.0                                | 0.6                             |
| Dead time in TAI – SI                       | 1.6                                | 0.4                             |
| UTC(NMIJ) – TAI satellite link              | 2.3                                | 0.8                             |
| TAI – SI                                    | 0.9                                | 0.4                             |
| Statistics total                            | 3.6                                | 1.8                             |
| Systematics                                 |                                    |                                 |
| Yb                                          | 4.0                                | 4.0                             |
| Microwave synthesis                         | 2.2                                | 2.2                             |
| TAI – SI                                    | 1.1                                | 1.1                             |
| Gravitational red shift                     | 0.6                                | 0.6                             |
| Systematics total                           | 4.7                                | 4.7                             |
| Total                                       | 5.9                                | 5.0                             |

6. Absolute frequency measurement

Since UTC(NMIJ) was continuously compared with TAI via a satellite link (see figure 1), the frequency of the Yb clock referenced to the SI second $y(Yb - SI)$ can be deduced from the data $y(Yb – UTC(NMIJ))$ in figure 2 by the relationship,

$$y(Yb - SI) = y(Yb – UTC(NMIJ)) + y(UTC(NMIJ) – TAI) + y(TAI – SI),$$

where $y(UTC(NMIJ) – TAI)$ and $y(TAI – SI)$ denote the fractional frequency differences between (i) UTC(NMIJ) and TAI and (ii) TAI and SI, respectively. These values are provided in Circular T [63], which is a monthly report issued by BIPM. Since BIPM only computes $y(UTC(NMIJ) – TAI)$ for 5-day intervals, we chose a 25-day period (MJD 58754 – MJD 58779), a 30-day period (MJD 58784 – MJD 58814), a 30-day period (MJD 58814 – MJD 58844), a 35-day period (MJD 58844 – MJD 58879), a 20-day period (MJD 58879 – MJD 58884 and MJD 58899 – MJD 58904), and a 35–day period (MJD 58904 – MJD 58939) for the second-to-sixth campaigns, respectively, to calculate the average value of $y(UTC(NMIJ) – TAI)$. These periods are indicated by $T_{link}$ in figure 2. In the fifth campaign, a 5-day period from MJD 58894 to MJD 58899 (see the shaded region of figure 2 (e)) was excluded, since a large excursion of the phase of UTC(NMIJ) occurred during maintenance of the hydrogen maser at MJD 58896. Figure 8 shows the $y(Yb – SI)$ value obtained for each campaign.
The choice of the period $T_{\text{link}}$ causes an uncertainty due to the dead time in the comparison of the Yb clock and UTC(NMIJ). This dead time uncertainty was calculated by using a numerical simulation described in reference [64]. The simulation generated time series data of the frequency according to the noise characteristics: $1 \times 10^{-12}/(\tau/s)$ for the white phase modulation, $7 \times 10^{-14}/\sqrt(\tau/s)$ for the white frequency modulation (FM), $2 \times 10^{-15}$ for the flicker FM, and $4 \times 10^{-24}/\sqrt(\tau/s)$ for the random walk FM. These noise parameters were chosen to reproduce the typical stability of UTC(NMIJ) (see green curve in figure 5). We generated two hundred time series patterns and calculated the standard deviation between the frequency averaged over the entire 25-, 30-, or 35-day period and the mean frequency for the time during which the Yb clock was operated. This standard deviation corresponds to the dead time uncertainty. The dead time uncertainties were estimated as $2.0 \times 10^{-16}$, $3.0 \times 10^{-16}$, $3.3 \times 10^{-16}$, $3.3 \times 10^{-16}$, $1.1 \times 10^{-16}$, and $8 \times 10^{-17}$ for the first, second, third, fourth, fifth, and sixth campaigns, respectively. A frequency correction arose from the dead time when the frequency steering of UTC(NMIJ) was carried out. We added corrections of $-9.9(2) \times 10^{-18}$, $-1.0(9) \times 10^{-16}$, and $7.9(5) \times 10^{-17}$ in the third, fifth, and sixth campaigns, respectively.

In addition, the uncertainty resulting from the dead time when we compare TAI and SI arises from the fact that BIPM calculates the $y(\text{TAI} - \text{SI})$ value based on an evaluation with primary and secondary frequency standards for 25, 30, or 35 days, whereas our measurement period $T_{\text{link}}$ did not fully cover the evaluation period of BIPM in the first and fifth campaigns. This uncertainty was estimated to be $1.6 \times 10^{-16}$ in the first campaign, and $4 \times 10^{-17}$ in the full period based on the stability of the Echelle Atomique Libre (EAL) given in Circular T: $1 \times 10^{-15}/\sqrt(\tau/d)$ for the white FM, $0.35 \times 10^{-15}$ for the flicker FM, and $0.2 \times 10^{-16}/\sqrt(\tau/d)$ for the random walk FM. The statistical and systematic uncertainties of $y(\text{TAI} - \text{SI})$ were calculated from the total uncertainty of $y(\text{TAI} - \text{SI})$ and the systematic uncertainties of the primary and secondary frequency standards reported in Circular T. During the present half-year period, the frequency of TAI was calibrated by using the following frequency standards: Cs thermal beam clocks (PTB-Cs1 and PTB-Cs2 [65]), Cs fountain clocks (SYRTE-F01, SYRTE-F02, SYRTE-FO0M [66], PTB-CSF1, PTB-CSF2 [67], SU-CsF02 [68], and NIM5 [69]), a Rb fountain clock (SYRTE-FORB [70]), and a Sr optical lattice clock (NICT-Sr1 [35]). Since Circular T only provides the total uncertainty of $y(\text{TAI} - \text{SI})$, the systematic uncertainty of $y(\text{TAI} - \text{SI})$ was estimated using the systematic uncertainties and weights of the individual frequency standards based on a method described in reference [71]. The estimated systematic uncertainty of $y(\text{TAI} - \text{SI})$ changed between $1.1 \times 10^{-16}$ and $1.2 \times 10^{-16}$ during the half year period. We adopted an average value of $1.1 \times 10^{-16}$ for the full campaign period. The statistical uncertainty of $y(\text{TAI} - \text{SI})$ was calculated with the above systematic uncertainty to reproduce the total uncertainty given in Circular T. The statistical uncertainty ranged between $0.8 \times 10^{-16}$ and $1.5 \times 10^{-16}$, and decreased to $4 \times 10^{-17}$ in the full campaign period.

Table 3 summarizes the uncertainties for the absolute frequency measurement. The statistical uncertainty of the Yb clock was calculated using the stability of the Yb/Sr ratio measurement (see figure 5) with the duration of the operation. The satellite link uncertainty in $y(\text{UTC(NMIJ)} - \text{TAI})$ was calculated to be $2.3 \times 10^{-15}$ for $T_{\text{link}} = 25$ d, $2.0 \times 10^{-16}$ for...
with a relative uncertainty of 5.5. Obtained from Circular T. With our data Rb fountain clock (SYRTE FORb) second. For example, during the present half-year period, a measurement of the frequency ratios at the 10\( \times 10^{-16} \) level indicates that the uncertainties calculated with the actual duration of the period. Without the large gap (indicated as ‘none’ in figure 5), the expected dead time was calculated as 580 during the full campaign period. This was obtained by counting the number of time gaps of more than 1 minute in the frequency data (figure 2). Since the Yb clock was operated with a 80.3% uptime for 185 days, the mean number of interruptions per hour was 580/(0.803 × 185 × 24 h) = 0.16 h\(^{-1}\). To estimate the probability of the occurrence of \( n \) interrupting events in an interval of \( T \) hours, we employed a Possion distribution,

\[
P(n, T) = \frac{(0.16 T)^n e^{-0.16 T}}{n!}.
\] (3)

To calculate the expected uptime, the typical time for manually restarting the operation is needed. Figure 10 shows a histogram of the recovery time, which was obtained from time gaps in the frequency data (figure 2). Excluding long gaps exceeding half a day, the mean recovery time was 0.72 hours. The expected dead time during a 16-hour period of human work was then calculated as \( \sum_{n=0}^{\infty} nP(n, 16) \times 0.72 h = 1.8 h. \) During an 8-hour night period, the operation is stopped after one interrupting event. In this case, the expected dead time is calculated as \( \int_0^8 \frac{(1-P(0,T))}{T} (8 - T) dT = 3.5 h. \) The uptime per day was therefore expected to be 78%.

To consider the optimum conditions for the operation, we carried out a simulation of the dead time uncertainty as a function of the clock uptime (see figure 11). In this simulation, the dead time was homogeneously distributed for a 30-day period, except for a large time gap of \( T_{gap} = 1 – 5 d \) in the middle of the period. Without the large gap (indicated as ‘none’ in figure 11), the dead time uncertainty falls below 10\( \times 10^{-16} \) for uptimes of \( \geq 80\% \). When the clock operation is stopped for \( T_{gap} = 1 – 5 d \), the uncertainty no longer reaches below 10\( \times 10^{-16} \) even though the uptime for the overall period is \( \geq 80\% \). This indicates that the uncertainties calculated with the actual duration of the clock operation are mostly determined by the instabilities of UTC(NMIJ) during the large gaps. When we take into account the fact that the uncertainty of the absolute frequency measurement is limited by the systematic uncertainties of the Yb clock and the microwave synthesis (the combined uncertainty is 4.6 \( \times 10^{-16} \)), it may be enough to reduce the dead time uncertainty to \( \sim 2 \times 10^{-16} \). In this case, the optimum condition is to operate the clock every day with a
moderate uptime of $\sim 50\%$. This is well below our expected uptime (78\%, see above). It should be noted that daily repetition of the startup and shutdown of the clock increases human effort, and thus it is better in practice to let the clock run continuously.

Previous studies have demonstrated a theoretical or experimental improvement in local timescales by steering flywheel oscillators to intermittently operated lattice clocks [18, 35–37]. In these methods, the stabilities of the timescales are limited by the fluctuations of the flywheels during the dead time of the clocks, and thus can be further improved by continuous operation. An analysis for our local timescale will be presented in a future publication.

The performance at the present level can make a significant contribution to the search for new physics. For example, local position invariance has been tested by looking for an annual variation of the gravitational red shift of atomic clocks [15, 24, 28]. As demonstrated in previous experiments that utilized continuously running fountain clocks and hydrogen masers [79], the continuous operation contributes to reduce the statistical uncertainty in a relatively short term, resulting in a stringent limit on violation of local position invariance. In our case, this experiment can be carried out by comparing the Yb clock with a local Cs fountain clock [80] or a hydrogen maser. Another example is that transient variations of the fine structure constant resulting from the passage of dark matter may be observed in a global network of optical clocks [30]. The detection of the transient effects relies on correlations in the frequency data of worldwide clocks running simultaneously [81]. To obtain a large amount of temporally overlapped data from laboratories worldwide, it is highly desirable that the participating clocks are capable of running continuously for a long period. The continuous operation also makes it possible to search for dark matter interactions on long timescales that could not be studied in previous experiments [81, 82].

In conclusion, we have demonstrated the nearly continuous operation of an Yb optical lattice clock with an uptime of 80.3\% for half a year. This enabled us to link the Yb clock to the SI second with an uncertainty of $2.4 \times 10^{-16}$, and to determine the absolute frequency of the Yb clock transition with a total uncertainty of $5.0 \times 10^{-16}$. The present performance demonstrates that the robustness of optical lattice clocks can reach a level comparable to that of Cs fountain clocks. This work constitutes an important step towards the redefinition of the SI second.

Acknowledgments

We thank H Katori, M Takamoto, and H Imai for providing information on their vacuum systems, and S Okubo for technical assistance. We are indebted to national metrology institutes for their efforts in operating the primary and secondary frequency standards and making the data available in Circular T. We dedicate this article to the memory of T Suzuyama, who passed away on Jul. 4th, 2020. This work was supported by Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Number 17H01151, and 17K14367, and JST-Mirai Program Grant Number JPJMI18A1, Japan.

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References

[1] Chou C W, Hume D B, Koelemeij J C I, Wineland D J and Rosenband T 2010 Frequency comparison of two high-accuracy Al$^+$ optical clocks Phys. Rev. Lett. 104 070802
[2] Bloom B J, Nicholson T L, Williams J R, Campbell S L, Bishop M, Zhang X, Zhang W, Bromley S L and Ye J 2014 An optical lattice clock with accuracy and stability at the 10$^{-18}$ level Nature 506 71–5
[3] Ushijima I, Takamoto M, Das M, Ohkubo T and Katori H 2015 Cryogenic optical lattice clocks Nat. Photon. 6 185–9
[4] Nicholson T L et al 2015 Systematic evaluation of an atomic clock at 2 $\times$ 10$^{-18}$ total uncertainty Nat. Commun. 6 6896
[5] Huntemann N, Sanner C, Lipphardt B, Tamm C and Peik E 2016 Single-ion atomic clock with 3 $\times$ 10$^{-18}$ systematic uncertainty Phys. Rev. Lett. 116 063001
[6] McGrew W F et al 2018 Atomic clock performance enabling geodesy below the centimetre level Nature 564 87–90
[7] Brewer S M, Chen J-S, Hankin A M, Clements E R, Chou C W, Wineland D J, Hume D B and Leibrandt D R 2019 27Al$^+$ Quantum-Logic Clock with a Systematic Uncertainty below 10$^{-18}$ Phys. Rev. Lett. 123 033201
[8] Bothwell T, Kedar D, Oelker E, Robinson J M, Bromley S L, Tew W L, Ye J and Kennedy C J 2019 JILA SrI optical lattice clock with uncertainty of 2.0 $\times$ 10$^{-18}$ Metrologia 56 66004
[9] Gill P 2011 When should we change the definition of the second? Philos. Trans. Roy. Soc. A 369 4109–30
[10] Hong F-L 2016 Optical frequency standards for time and length applications Meas. Sci. Technol. 27 082002
[11] Riehle F, Gill P, Arias F and Robertson L 2018 The CIPM list of recommended frequency standard values: Guidelines and procedures Metrologia 55 188–200
[12] Lodewyck J 2019 On a definition of the SI second with a set of optical clock transitions Metrologia 56 055009
[13] Campbell G K et al 2008 The absolute frequency of the 87Sr optical clock transition Metrologia 45 539–48
[14] Lemke N D et al 2009 Spin-1/2 optical lattice clock Phys. Rev. Lett. 103 060801
[15] Le Targat R et al 2013 Experimental realization of an optical second with strontium lattice clocks Nat. Commun. 4 2109
Godun R M et al 2014 Frequency Ratio of Two Optical Clock Transitions in $^{171}\text{Yb}^+$ and Constraints on the Time Variation of Fundamental Constants Phys. Rev. Lett. 113 210801

Hunttemann N, Lipphardt B, Tamm C, Gerginov V, Weyers S and Peik E 2014 Improved limit on a temporal variation of $m_F/m_0$ from comparisons of $^{171}\text{Yb}^+$ and Cs atomic clocks Phys. Rev. Lett. 113 210802

Grebing C et al 2016 Realization of a timescale with an accurate optical lattice clock Optica 3 563–9

Lodewyck J et al 2016 Optical to microwave clock frequency ratios with a nearly continuous strontium optical lattice clock Metrologia 53 1123–30

Pizzocaro M, Thoumany P, Rauf B, Bregolin F, Milani G, Clivati C, Costanzo G A, Levi F and Calonico D 2017 Absolute frequency measurement of the $^1S_0^+\text{P}_0$ transition of $^{171}\text{Yb}$ Metrologia 54 102–12

Panfilo G and Parker T E 2010 A theoretical and experimental analysis of frequency transfer uncertainty, including frequency transfer into TAI Metrologia 47 552–60

Tanabe T et al 2015 Improved frequency measurement of the $^1S_0^+\text{P}_0$ clock transition in $^{87}\text{Sr}$ using a Cs fountain clock as a transfer oscillator J. Phys. Soc. Jpn. 84 115002

Hachisu H, Petit G, Nakagawa F, Hanado Y and Ido T 2017 SI-traceable measurement of an optical frequency at the low $10^{-16}$ level without a local primary standard Opt. Express 25 8511–23

McGrew W F et al 2019 Towards the optical second: verifying optical clocks at the SI limit Optica 6 448–54

Pizzocaro M, Bregolin F, Barbieri P, Rauf B, Levi F and Calonico D 2019 Absolute frequency measurement of the $^1S_0^+\text{P}_0$ transition of $^{171}\text{Yb}$ with a link to Int. Atomic Time Metrologia 57 035007

Hill I R, Hobson R, Bowden W, Bridge E M, Donnellan S, Curtis E A and Gill P 2016 A low maintenance Sr optical lattice clock J. Phys. Conf. Ser. 723 012019

Baynham C F A et al 2017 Absolute frequency measurement of the $^3S_1/2\rightarrow^1S_1/2$ optical clock transition in $^{171}\text{Yb}$ with an uncertainty of $4 \times 10^{-16}$ using a frequency link to international atomic time J. Mod. Opt. 65 585–91

Blatt S et al 2008 New Limits on Coupling of Fundamental Constants to Gravity Using $^{87}\text{Sr}$ Optical Lattice Clocks Phys. Rev. Lett. 100 140801

Safronova M S, Budker D, DeMille D, Jackson Kimball D F, Derevianko A and Clark C W 2018 Search for new physics with atoms and molecules Rev. Mod. Phys. 90 025008

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

Weisł o P, Morzyński P, Bober M, Czygan A, Lisak D, Ciurył o R and Zawada M 2016 Experimental constraint on dark matter detection with optical atomic clocks Nat. Astron. 1 0009

Takamoto M, Ushijima I, Ohmae N, Yahagi T, Kokado K, Shinkai H and Katori H 2020 Test of General relativity by a pair of transportable optical lattice clocks Nat. Photon. 14 411–15

Takano T, Takamoto M, Ushijima I, Ohmoe N, Akatsuka T, Yamaguchi A, Kuroishi M H, Miyahara B and Katori H 2016 Geopotential measurements with synchronously linked optical lattice clocks Nat. Photon. 10 662–6

Grott j et al 2018 Geodesy and metrology with a transportable optical clock Nat. Phys. 14 437–41

Hachisu H, Nakagawa F, Hanado Y and Ido T 2018 Months-long real-time generation of a time scale based on an optical clock Sci. Rep. 8 4243

Milner W R et al 2019 Demonstration of a timescale based on a stable optical carrier Phys. Rev. Lett. 123 173201

Yao J et al 2019 Optical-Clock-Based Time Scale Phys. Rev. Applied 12 044069

Inaba H et al 2006 Long-term measurement of optical frequencies using a simple, robust and low-noise fiber based frequency comb Opt. Express 14 5223–31

Hisai Y, Akamatsu D, Kobayashi T, Okubo S, Inaba H, Hosaka K, Yasuda M and Hong F-L 2019 Development of 8-branch Er: fiber frequency comb for Sr and Yb optical lattice clocks Opt. Express 27 6404–14

Kobayashi T, Akamatsu D, Hosaka K and Yasuda M 2019 A relocking scheme for optical phase locking using a digital circuit with an electrical delay line Rev. Sci. Instrum. 90 103002

Kobayashi T, Akamatsu D, Hisai Y, Tanabe T, Inaba H, Suzuyama T, Hong F-L, Hosaka K and Yasuda M 2018 Uncertainty Evaluation of an $^{171}\text{Yb}$ Optical Lattice Clock at NMIJ IEEE Trans. Ultrason. Freq. Control 65 2449–58

Katori H, Takamoto M, Pal’chikov V G and Ovsiannikov V D 2003 Ultrastable optical clock with neutral atoms in an engineered light shift trap Phys. Rev. Lett. 91 173005

Kobayashi T, Akamatsu D, Hosaka K, Inaba H, Okubo S, Tanabe T, Yasuda M, Onae A and Hong F-L 2016 Absolute frequency measurements and hyperfine structures of the molecular iodine transitions at 578 nm J. Opt. Soc. Am. B 33 725–34

Saxberg B, Plotkin-Swing B and Gupta S 2016 Active stabilization of a diode laser injection lock Rev. Sci. Instrum. 87 063109

Kobayashi T, Akamatsu D, Nishida Y, Tatabe T, Yasuda M, Hong F-L and Hosaka K 2016 Second harmonic generation at 399 nm resonant on the $^3S_0^+\text{P}_0$ transition of ytterbium using a periodically poled LiNbO$_3$ waveguide Opt. Express 24 12142–50

Iwakuni K, Inaba H, Nakajima Y, Kobayashi T, Hosaka K, Onae A and Hong F-L 2012 Narrow linewidth comb realized with a mode-locked fiber laser using an intra-cavity waveguide electro-optic modulator for high-speed control Opt. Express 20 13769–76

Inaba H et al 2013 Spectroscopy of $^{171}\text{Yb}$ in an optical lattice based on laser linewidth transfer using a narrow linewidth frequency comb Opt. Express 21 7891–6

Hisai Y, Ike K, Sakagami H, Horikin T, Kobayashi T, Yoshii K and Hong F-L 2018 Evaluation of laser frequency offset locking using an electrical delay line Appl. Opt. 57 5628–34

Akamatsu D, Inaba H, Hosaka K, Yasuda M, Onae A, Suzuyama T, Amemiya M and Hong F-L 2013 Spectroscopy and frequency measurement of the $^{87}\text{Sr}$ clock transition by laser linewidth transfer using an optical frequency comb Appl. Phys. Express 7 012401

Katori H, Ovsiannikov V D, Marmò S I and Palchikov V G 2015 Strategies for reducing the light shift in atomic clocks Phys. Rev. A 91 052503

Nemitz N, Ohkubo T, Takamoto M, Ushijima I, Das M, Ohmoe N and Katori H 2016 Frequency ratio of Yb and Sr clocks with $5 \times 10^{-15}$ uncertainty at 150 seconds averaging time Nat. Photon. 10 258–61

Nemitz N, Jrgensen A A, Yanagimoto R, Bregolin F and Katori H 2019 Modeling light shifts in optical lattice clocks Phys. Rev. A 99 033424

Brown R C et al 2017 Hyperpolarizability and Operational Magic Wavelength in an Optical I. Phys. Rev. Lett. 119 253001

Blatt S, Thomsen J W, Campbell G K, Ludlow A D, Swallows M D, Martin M J, Boyd M M and Ye J 2009 Rabi spectroscopy and excitation inhomogeneity in a one-dimensional optical lattice clock Phys. Rev. A 80 052703

Kim H, Heo M-S, Lee W-K, Park C Y, Hong H-G, Hwang S-W and Yu D-H 2017 Improved absolute
frequency measurement of the $^{171}$Yb optical lattice clock at KRISS relative to the SI second Jpn. J. Appl. Phys. 56 050302
[56] Middelmann T, Lisdat C, Falke S, Vellone Winfred J S R, Riehle F and Sterr U 2011 Tackling the blackbody shift in a strontium optical lattice clock IEEE Trans. Instum. Meas. 60 2550
[57] Sherman J A, Lemke N D, Hinkley N, Pizzocaro M, Fox R W, Ludlow A D and Oates C W 2012 High-accuracy-high-accuracy measurement of atomic polarizability in an optical lattice clock Phys. Rev. Lett. 108 153002
[58] Beloy K et al 2014 Atomic clock with $1 \times 10^{-18}$ room-temperature blackbody stark uncertainty Phys. Rev. Lett. 113 260801
[59] Lemke N D, von Stecher J, Sherman J A, Rey A M, Oates C W and Ludlow A D 2011 $p - \omega$ wave cold collisions in an optical lattice clock Phys. Rev. Lett. 107 103902
[60] Ludlow A D, Lemke N D, Sherman J A, Oates C W, Quéméner G, von Stecher J and Rey A M 2011 Cold-collision-shift cancellation and inelastic scattering in a Yb optical lattice clock Phys. Rev. A 84 052724
[61] Lee S, Park C Y, Lee W-K and Yu D-H 2016 Cancellation of collisional frequency shifts in optical lattice clocks with Rabi spectroscopy New J. Phys. 18 033030
[62] Nakajima Y et al 2010 A multi-branch, fiber-based frequency comb with millihertz-level relative linewidths using an intra-cavity electro-optic modulator Opt. Express 18 1667–76
[63] BIPM 2020 Key products of the BIPM time department https://www.bipm.org/en/bipm/tai/
[64] Yu D-H, Weisse M and Parker T E 2007 Uncertainty of a frequency comparison with distributed dead time and measurement interval offset Metrologia 44 91–6
[65] Bauch A 2005 The PTB primary clocks CS1 and CS2 Metrologia 42 S43–S54
[66] Guéna J et al 2012 Progress in atomic fountains at LNE-SYRTE IEEE Trans. Ultrason. Ferroelectr. Freq. Control 59 391–409
[67] Weyers S, Gerginov V, Kazda M, Rahm J, Lipphardt B, Dobrev G and Gibble K 2018 Advances in the accuracy, stability and reliability of the PTB primary fountain clocks Metrologia 55 789–805
[68] Blinov I Y, Boiko A I, Domnin Y S, Kostromin V P, Kupalova O V and Kupalov D S 2017 Budget of Uncertainties in the Cesium Frequency Frame of Fountain Type Measurement Techniques 60 30–6
[69] Fang F et al 2015 NIM5 Cs fountain clock and its evaluation Metrologia 52 454–68
[70] Guéné J, Abgrall M, Clairon A and Bize S 2014 Contributing to TAI with a secondary representation of the SI second Metrologia 51 108–20
[71] Hachisu H, Petit G and Ido T 2016 Absolute frequency measurement with uncertainty below $1 \times 10^{-15}$ using Int. Atomic Time Appl. Phys. B 123 34
[72] Kohno T, Yasuda M, Hosaka K, Inaba H, Nakajima Y and Hong F-L 2009 One-Dimensional Optical Lattice Clock with a Fermionic $^{171}$Yb Isotope Appl. Phys. Express 2 072501
[73] Yasuda M et al 2012 Improved Absolute Frequency Measurement of the $^{171}$Yb Optical Lattice Clock towards a Candidate for the Redefinition of the Second Appl. Phys. Express 5 102401
[74] Park C Y et al 2013 Absolute frequency measurement of $^3\text{So}(F = 1/2) - ^3\text{P}_0(F = 1/2)$ transition of $^{171}$Yb atoms in a one-dimensional optical lattice at KRISS Metrologia 50 119–28
[75] Akamatsu D, Yasuda M, Inaba H, Hosaka K, Tanabe T, Onae A and Hong F-L 2014 Frequency ratio measurement of $^{171}$Yb and $^{87}$Sr optical lattice clocks Opt. Express 22 7898–905
[76] Takamizawa A, Yanagimachi S, Tanabe T, Hagimoto K, Akamatsu D, Yasuda M, Inaba H, Hosaka K, Tanabe T, Onae A and Hong F-L 2014 Atomic Time Metrologia 50 1069-1075
[77] Rabi spectroscopy New J. Phys. 16 18
[78] Fujieda M et al 2018 Advanced satellite-based frequency transfer at the 10$^{-18}$ level IEEE Trans. Ultrason. Ferroelectr. Freq. Control 65 973–8
[79] Akamatsu D, Kobayashi T, Hisai Y, Tanabe T, Hosaka K, Yasuda M and Hong F-L 2014 Dual-mode operation of an optical lattice clock using strontium and ytterbium atoms IEEE Trans. Ultrason. Ferroelectr. Freq. Control 65 1069-1075
[80] Peil S, Crane S, Hansen J L, Swanson T B and Ekstrom C R 2013 Tests of local position invariance using continuously running atomic clocks Phys. Rev. A 87 010102 R
[81] Takamizawa A, Yanagimachi S, Tanabe T, Hagimoto K, Hirano I, Watabe K, Ikegami T and Hartnett J G 2015 Preliminary evaluation of the cesium fountain primary frequency standard NMIJ-F2 IEEE Trans. Instum. Meas. 64 2504–12
[82] Wcislo P et al 2018 New bounds on dark matter coupling from a global network of optical atomic clocks Sci. Adv. 4 eaau4869
[83] Roberts B M 2019 Search for transient variations of the fine structure constant and dark matter using fiber-linked optical atomic clocks New. J. Phys. (accepted) http://doi.org/10.1088/1367-2630/abaace