THz Frequency Counter based on a Semiconductor-Superlattice Harmonic Mixer with 4-Octave Measurable Bandwidth and 16-Digit Precision

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1. Introduction

THz frequency counters with high precision and wide measurable range are vital for the establishment of a *THz molecular clock* using ultracold molecules [1] as well as various THz applications. Here, a broadband and high-precision THz counter based on a semiconductor-superlattice harmonic mixer (SLHM) was developed, and its frequency uncertainty and instability over four-octave THz range were investigated by complementary methods: comparison of two THz frequencies determined using two independent counters and direct measurement of a known frequency generated from a highly stabilized THz-quantum cascade lasers by a single counter [2]. In addition, detailed research study regarding the higher-harmonics generation of a local oscillator (LO) for the SLHM revealed the maximum frequency that our THz counter can measure.

2. Experimental Results

The Allan deviations of the SLHM-based THz counter at the averaging time τ of 1 s are summarized in Fig. 1(a). These deviations at each measured frequency ν_{THz} dropped to the 10^{-17} level within $\tau = 10^4$ s. The fractional frequency offset and uncertainty at each ν_{THz} were less than 4.6×10^{-17} and below 9.6×10^{-17}, respectively (Fig.1 (b)). Although there exists a slight frequency offset at 654 GHz and 2020 GHz, the developed THz counter is capable of determining the absolute THz frequency with an uncertainty of less than 1×10^{-16} over the four-octave range from 120 GHz to 2.8 THz.

Figure 1 (c) plots the power of the LO harmonics in the semiconductor superlattice as a function of the harmonic number *k*. The harmonics with k > 23 were difficult to observe under our experimental condition. Thus, the maximum possible frequency to be measured by our THz counter is approximately 3.7 THz when the highest 22 th harmonic is generated from the LO signal at 170 GHz. Further analysis derived that a cw-THz source oscillating at 3.7 THz (DUT) must have an output power of at least 1.9 mW for accurate rf-beat frequency counting with the SNR of more than 25 dB.

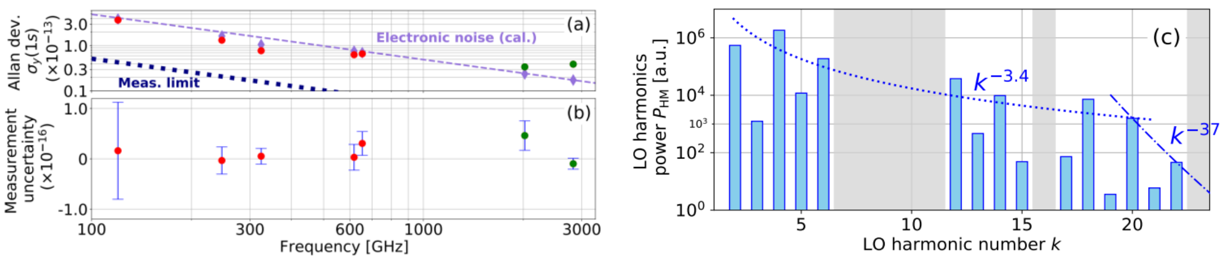

Fig. 1. (a) Summary of fractional frequency instabilities at 1 s averaging time (circles), and (b) measurement uncertainties of the SLHM-based THz counter. (c) Relative power spectrum of the LO harmonics in the semiconductor superlattice. The gray areas have no data owing to the lack of proper THz sources.

3. Conclusion

We have developed a broadband and high-precision THz frequency counter based on a semiconductor-superlattice harmonic mixer. Its comprehensive characterization showed a measurement uncertainty of less than 1×10^{-16} over a four-octave THz range. This compact and easy-to-handle THz counter operating at room temperature is suitable for many THz applications requiring a wide measurement range without a bulky cryogenic apparatus.

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Providing an auditing service with the OpenTTP

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1. Introduction

The Open Traceable Time Platform (OpenTTP) [1, 2, 3] project was conceived by the National Measurement Institute, Australia (NMIA) from their experience in providing remote services to a diverse group of clients over many years, combined with their desire to share this knowledge in an affordable way. These services include providing traceability for frequency standards in calibration laboratories, but also providing traceable time of day and auditing of network time devices.

We present the setup and performance of the OpenTTP at the National Metrology Institute of Malaysia (NMIM) where it is used to provide an auditing service to a number of clients via a secured network. The auditing service that was built around the OpenTTP satisfies the regulator's digital timestamp certification requirements for the accuracy of Network Time Protocol (NTP) timestamping servers.

2. The NTP auditing service

The regulator for time stamping services in Malaysia requires that these services are traceable to Malaysian Standard Time to within ± 1 second [4]. While this is an easy requirement to satisfy, none of the service providers could provide credible evidence that they complied. NMIM was approached to develop a solution to satisfy the regulator but no resources were provided for the project. As the NMIM was one of the OpenTTP partners this was used to develop a pilot project.

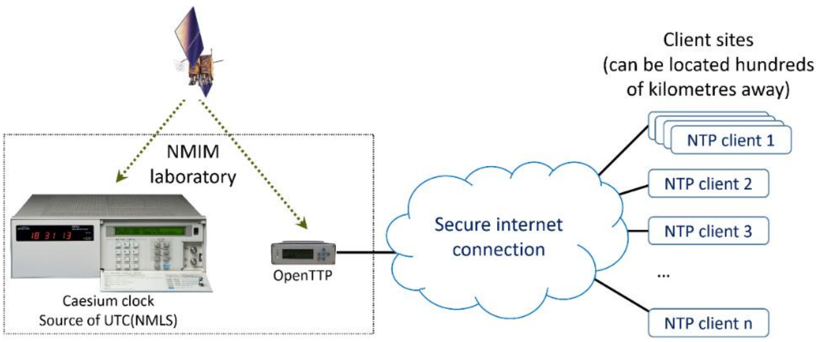

Fig. 1. OpenTTP NTP auditing setup.

We present the details and outcomes of the pilot project, and the service that was established for time stamping authorities. We also present plans for improving the OpenTTP and expanding the services that it can be used for.

3. Conclusion

The auditing service based on the OpenTTP enables NMIM to offer an effective solution at low cost for the regulator's digital timestamp certification requirements. The OpenTTP project has fostered collaboration between NMIM and NMIA that has led to future plans for improvement of the OpenTTP and its software.

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Microwave Frequency Generation up to 70 GHz Using Er-Doped Fiber Optic Frequency Comb

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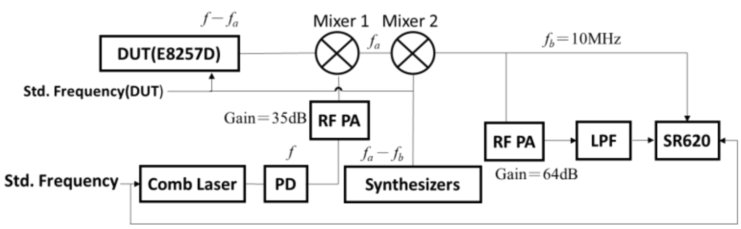
1. Introduction

Frequency calibration measurement refers to the use of a standard frequency instrument to obtain the relationship between the values delivered by a device under test with those of a frequency standard. The use of standard frequency instruments for calibration can ensure the reliability of measured results. The National Time and Frequency Standard Laboratory of Chunghwa Telecomm Laboratories has established an optical frequency measurement technology that can be traced back to the national frequency standard. The standard frequency measurement system is constructed by reducing the optical frequency to the microwave frequency, and the fiber comb laser is the main core equipment of this technology. The experimental results can be measured to 70 GHz.

2. Main Body

The fiber comb laser converts the light signal into the electrical one with repetition frequency of 500MHz through a photodetector, and we select and connect the electrical signal (f) with the DUT one (f-fa) to the mixer 1 to complete the first frequency beat. Then we connect the synthesizers output (set to fa-fb) with the first beat frequency signal (fa) to the mixer 2, and complete the second frequency beat to obtain the output signal fb (10MHz). After the fb signal passes through the power amplifier and low-frequency filter, it is connected to the SR620 for frequency stability measurement. (shown in fig.1)

The measurement data is recorded one point per second for a total of 1000 points. The current measured frequency is 70 GHz, and the frequency stability can reach about 9.0E-13. (shown in fig.2)



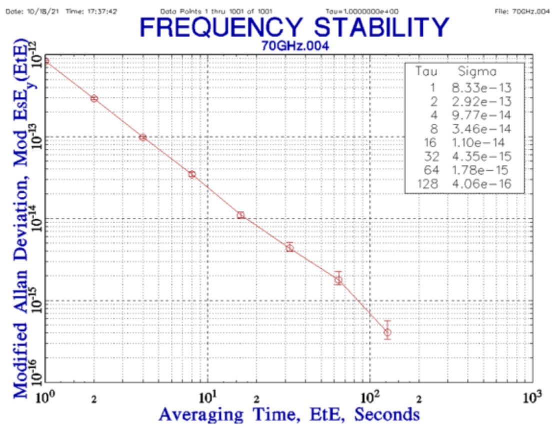


Fig. 1. Experimental setup

Fig. 2. 70GHz frequency stability

3. Conclusion

Using the characteristics of the high repetition rate of the optical comb laser, the optical frequency is reduced to the microwave frequency, which can be used for the development of high-frequency measurement technology. At present, the frequency stability and accuracy of the generated 70 GHz have met our requirements for providing calibration services. For the rapid development of high-frequency instruments in the future, it is necessary to establish high-frequency traceability standards.

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Characterization and upgradation of indigenously developed telephone time dissemination system

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1. Introduction

CSIR-NPL(NPLI) disseminates time via satellite and internet. In this paper we have presented the complete characterization of the FonOclock time dissemination system (indigenously developed) in order to evaluate and improve the performance of the system. Currently, the system provides a synchronization accuracy of +/- 10ms w.r.t UTC(NPLI). In this paper we discuss about the second stage development of the system where we aim to achieve better accuracy. Therefore, our focus is to study the various uncertainty aspects associated and further improve its synchronization accuracy. Also, In 1992 N. Moriya et. al. from Japan have demonstrated and claimed that a synchronization accuracy within ±1ms was achieved [1].

2. Characterization, calibration and upgradation of the FonOclock system

FonOclock system has been indigenously developed which transmits time and date information to the receivers upon receiving a call. The clock of the transmitters needs to be synchronized accurately and constantly from a standard source which is being done by 1PPS of UTC(NPLI). In order to distribute 1PPS of UTC(NPLI) to different transmitters, an indigenously developed 1PPS distribution amplifier was used. To measure the lag in 1PPS imparted by the distribution amplifier and the transmitter, 1PPS was characterized at two different stages. The average time difference was calculated to be 32ns and the standard deviation of time difference was calculated to be 0.1ns which is quite low as compared to synchronization accuracy. It was observed that the low quality soft modem causes data buffer which majorly contributes to the uncertainty. Hardware modification of the system is done in order to improve the synchronization accuracy, where the system has been interfaced with high quality hard modems where we see less data buffer which is expected to improve uncertainty. Also, the drift of the 16MHz crystal oscillator was estimated to be approx. 285μs/s. A program was developed in embedded C in order to correctly define the frequency of the oscillator in the main controller. The program varies and optimizes timer/counter value in MCU. The frequency drift w.r.t 1PPS UTC(NPLI) at different timer/counter values are shown in fig 1(a). The oscillator was calibrated approx. up to 2μs/s. Hence the drift has been drastically improved.

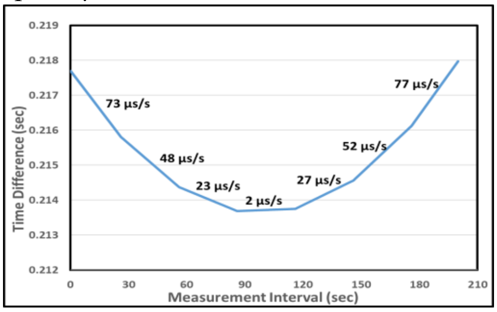

Fig. 1. (a) Time difference of 1PPS between the transmitter and receiver in free running condition with different frequency correction (b) MAX232 circuit interfaced between the FonOclock receiver and the modems

3. Conclusion

A complete characterization of the system was done and the oscillator was calibrated using embedded C which showed a drastic improvement in the drift. The hardware of the system was upgraded. The system software needs to be upgraded in order to achieve much better synchronization accuracy.

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Timing Traceability Links between Two Timescales

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1. Introduction

Indian Standard Time (IST) is generated by the IST generation system, generally called as Timescale at CSIR-National Physical Laboratory (CSIR-NPL). IST is defined as UTC (Universal coordinated Time) + 5:30 hours. We have an IST generation system which is the direct link to UTC, which has long term stability through GNSS. CSIR-NPL is a standard organization, provides the actual time to the country through various modes [1-2]. It is, therefore a crucial requirement to have a redundant time generation system to strengthen the existing primary system, which is continuously operating and contributing to International Atomic Time (TAI) since 2011. In order to ensure incessant availability of IST, we established a redundant time generation system in a new building premise. In order to make both the timescales comparably close to each other, the timing traceability has been established through RF, Optical and GNSS links. In this paper, we report the timing traceability link [3] between these two timescales.

2. Integrating two timescales using different links

Precise timekeeping, dissemination and synchronization are the crucial requirements from the ages. The CSIR-National Physical Laboratory (CSIR-NPLI) accomplishes this necessity by maintaining the national timescale of India identified as UTC (NPLI). It provides the time dissemination services across the country. To fulfill the increasing demands of time synchronization services, CSIR-NPL has established a redundant timescale which is comparable to the primary time scale and integrated these two timescales using RF cables, Optical fiber cables and GPS links over the approximate distance of 250 m. The basic set up of time and frequency transfer through RF and optical physical links between Primary (TSA) and Backup timescale (TSB) are shown in Fig.1. The traceability of UTC for TSB is established through UTC (NPLI).

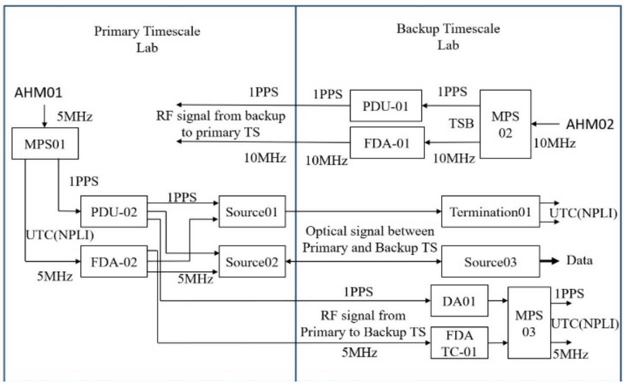

Fig.1 Physical links between primary and backup timescale

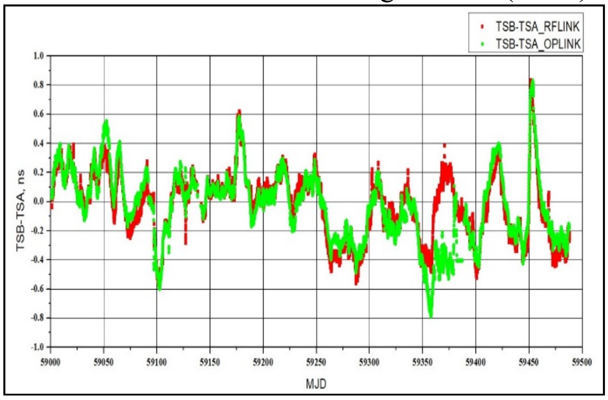

Fig.2 Difference between two timescales using RF and optical Link from 1st June, 2020 to 30th Sep., 2021

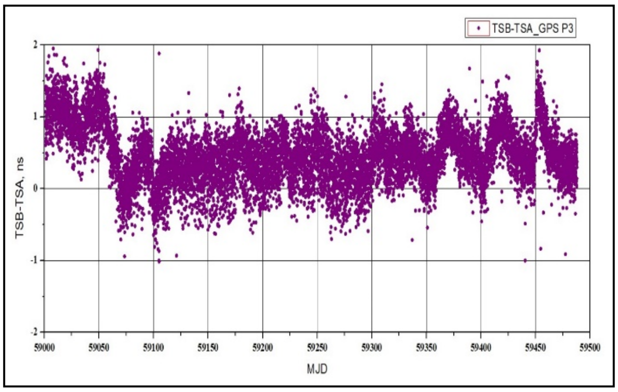

Fig.3 Difference between two timescales using common view GPS P3, from 1st June, 2020 to 30th Sep., 2021

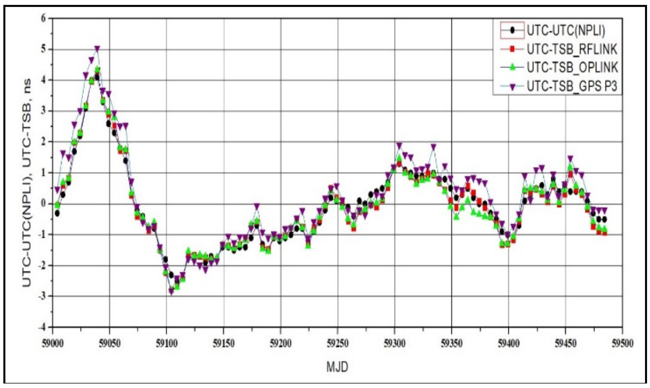

Fig.4 Performance of UTC-TSA and UTC-TSB, from 1st June, 2020 to 30th Sep.,2021

Fig.2 shows the difference between two timescales using RF and optical links. We also have the traceability of backup timescale using common view GPS technique using GTR51 receivers both sides as shown in Fig.3. We observe that the difference between both the timescales (TSB-TSA) is ±1 ns. Which depicts that TSB is well steered to TSA. The performance of both TSA and TSB is shown in Fig.4 with the reference of UTC i.e.±5 ns.

3. Conclusion

CSIR-NPL has developed a redundant timescale and established the UTC timing traceability through UTC (NPLI).We have observed that TSB is within ±1 ns to TSA.

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Novel approach to synchronize National Informatics Centre (NIC) network with IST over IOT framework

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1. Introduction

National Knowledge Network of National Informatics Centre (NIC-NKN) has the mandate to provide a national seamless hi speed internet network. A novel methodology has been proposed to synchronize the NIC-NKN(Delhi and Hyderabad center) with Indian Standard Time (IST) maintained by NPLI over NTP protocol. To establish the stratum 1 synchronization at these two locations, methodology based on IOT framework along with a unique Stratum 1 NTP architecture supported by a pre-calibrated Rubidium frequency source was proposed. This paper presents the successful commissioning of said architecture in the IOT framework.

2. Synchronization of NIC-NKN network

It is extremely important to synchronize national and state data centers of NIC-NKN involved in management of IT infrastructure of Central Ministries/Departments over heterogeneous networks functioning with a speed of multi-gigabits per second. This network connects R & D institutions/organizations, national universities and medical institutions. also network connectivity over optical fibre cable is provided to state government secretariats with hub connectivity to the central government. Hence synchronizing this network backbone of Digital India Mission was of crucial importance A novel methodology was proposed to NIC-NKN which suggest that by adopting basic architecture of Internet of Things (IOT), their two centers, located at National Data Centre (NDC), New Delhi and Disaster Recovery Centre (DRC), Hyderabad will be synchronized to IST using Network Time Protocol (NTP) architecture [1]. The architecture proposed is based on a pre-calibrated Rb frequency standard, multichannel GNSS receiver and a dedicated high end NTP server as shown in figure1. These two centers are now successfully synchronized. For the first time IOT architecture (with M2M communication) based IST synchronization was implemented, details of which will be presented in the paper. With a limited degree of programmability and customization in the network architecture of NIC-NKN, the synchronization of IST has been achieved with offset ranging from 0.3 to 0.5 milliseconds and jitter in few microseconds. The architecture was designed around four major components working at different layers. The major components of this architecture are sensor/actuators, smart devices, gateways, middleware devices and application.

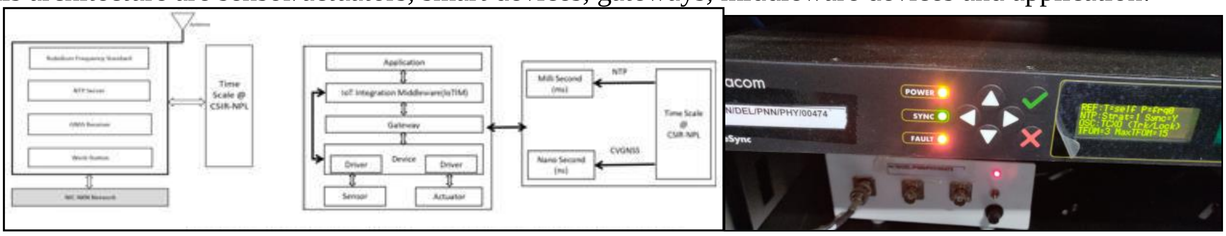

Figure 1 Successful deployment as stratum1NTP server at NIC, New Delhi.

3. Conclusion

This paper paved the way for upcoming IOT applications of the nation which required critical real time synchronization as well as established a successful architecture deployed using NTP protocol and CVGNSS technologies. The future of research might be useful to address the requirement of various timing solution in a cost effective way for multiple applications like, Certifying Authorities, Banking, Telecommunication, Stock exchange, VOIP and ISPs etc.

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Automatic Frame Selection for Calibration of Stopwatches based on Video Totalize Method

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1. Introduction

At SCL, a video totalize method for calibration of stopwatches by utilizing high speed video recordings and a synchronous counter was developed [1]. The stopwatch under test, is running side-by-side with a reference synchronous counter. Their readings are recorded by a high speed camera and used for comparison (Fig. 1). Appropriate video frames from the video clips where the readings of the stopwatch change, known as the transition frame, should be selected. Currently the transition frame was selected manually by the operator. As new cameras with higher frame rates become available (1000 fps and more), frame selection by human is getting more difficult due to the large data size. Scanning through a large number of frames by human is tedious and error-prone. To cope with these challenges, a new method to select video frames objectively and automatically using image processing techniques is proposed.

2. Description

The proposed method consists of two major stages, (1) detection of change of reading, (2) selection of transition frame. First of all, user selects the key digit where the change of reading can be detected. The software then locates the seven segments individually and computes their luminance. The average intensity levels per segment are plotted against time (Fig. 2a) for a video clip captured at 1000 fps for around 4.5 s.

Fig. 1. Calibration of stopwatches

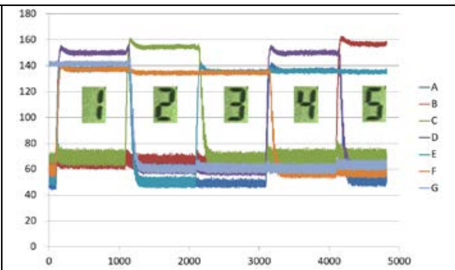

Fig. 2a. Intensity change per segment

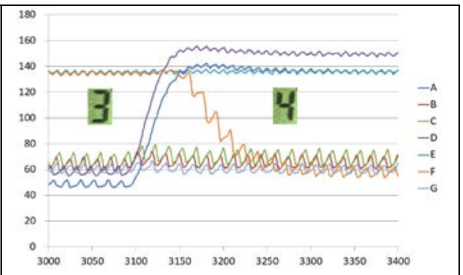

Fig. 2b. Changing from digit 3 to 4

A particular change from the digit 3 to 4 is shown in Fig. 2b. There are several segments involved (segments A and D turning off followed by segment F turning on) but the first one that changes should be regarded as the start-of-change. Once the start-of-change is located it is necessary to determine which particular frame is the transition frame. For rising edges, it can be characterized by the 10 % and 90 % levels of the signal dynamic range. The frame at the 10% level can be selected as the transition frame. The algorithm is applied on the videos recorded at the beginning and the end of the calibration of stopwatches. To reduce the uncertainty, the same type of transition, e.g. the turning off of segment D in the transition of the key digit from 3 to 4, should be selected in both cases.

3. Conclusion

In this paper, a method for the selection of video frames for the calibration of stopwatches based video totalize method is proposed. It provides an objective approach to select video frames automatically using image processing techniques, which can be particularly useful when processing a large number of video frames captured by very high speed cameras.

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A narrow-linewidth and frequency-stabilized laser at the telecom wavelength for the realization of an 'optical H-maser'

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Optical clocks using optical lattice and single-ion trap technologies have reached levels of stability and accuracy that surpass the performance of the best Cs fountain atomic clocks by orders of magnitude. Several optical clocks using different technologies and atomic species [1] are recommended by the International Committee for Weights and Measures (CIPM) as secondary representations of the ‘second’. To compare and evaluate such different optical clocks, it is important to develop an optical version of H-maser, which has a much better short-term stability than that of an H-maser and can be continuously operated. Furthermore, such an 'optical H-maser' is preferable to be operated at the telecom wavelength for the application of delivering optical clock signals over optical fiber networks.

Recently, we have developed an iodine-stabilized laser at telecom wavelength using a dual-pitch periodically poled lithium niobate waveguide for wavelength conversion [2]. This laser use iodine lines at 514 nm as frequency references, close to the third harmonic frequency of the telecom frequency standard of acetylene (see Fig. 1).

1) We can reach a laser frequency instability of 1×10^{-13} at 1s, which is already better or equivalent to that of the H-maser, using a telecom laser and a 30-cm-long iodine cell in the spectrometer.

2) We have experience with an iodine stabilized Nd:YAG at 532 nm using a 2-m-long iodine cell with a frequency instability of 1×10^{-14} at 1s.

3) Since the telecom laser has a larger frequency noise compared to the Nd:YAG laser, laser linewidth narrowing for the telecom laser is necessary for achieving a good short-term stability.

4) With a 2-m-long iodine cell and the narrower iodine absorption linewidth at 514 nm, we should be able to reach a frequency instability at a level of a few $\times10^{-15}$ at 1 s for a new telecom frequency-stabilized laser under development.

5) The developed iodine-stabilized telecom laser using a 30-cm-long iodine cell can be continuously operated and is now installed in an Astro-comb for astronomical observation.

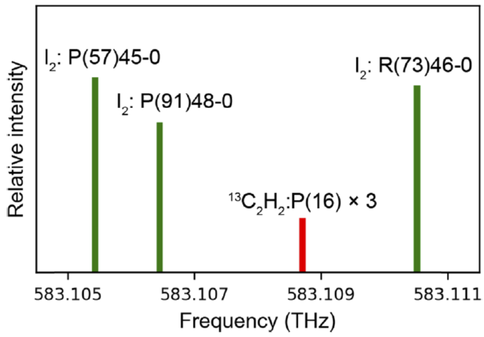

Fig. 1. Frequency atlas of the I_2 absorption lines at 514 nm near the third harmonic frequency of the P(16) transition $^{13}C_2H_2$ at 1542 nm.

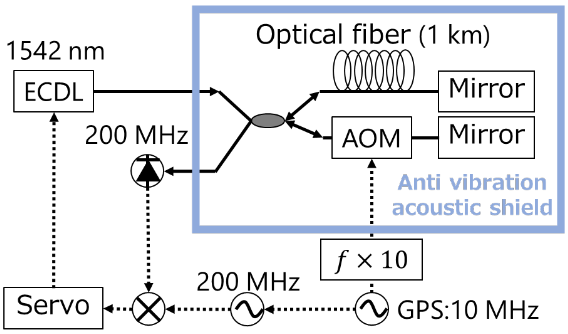

Fig. 2. An interferometer using optical fibers for laser linewidth narrowing.

This is a joint research project with K. Ikeda, D. Akamatsu, Y. Goji, R. Kato, M. Yoshiki, M. Nishihara and K. Yoshii at Yokohama National University (YNU), and M. Wada, S. Okubo, K. Kashiwagi and H. Inaba at the National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST). This work is supported by the Japan Society for the Promotion of Science (JSPS) (KAKENHI 18H03886).

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Sr optical lattice clocks at NIM

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1. Introduction

In order to improve the accuracy of time and frequency metrology, and contribute to the redefinition of the SI second, two Sr optical clocks are being developed at National Institute of Metrology(NIM). The experimental apparatus, the systematic frequency shift evaluation and the absolute frequency measurement will be introduced.

2. Experiment and evaluation

Sr1 began to be developed in 2006 on NIM Hepingli Campus. It was equipped with a clock laser which has a 10 cm reference cavity. The first evaluation was made in 2015 with a total uncertainty of 2.3E-16[1]. Sr1 then was improved in recent years. with a total uncertainty of 2.9E-17 evaluated in 2020. Its absolute frequency is traced to the ensemble of primary and secondary frequency standards published in the Circular T bulletin by BIPM through a satellite link.[2]

The Sr2 experimental apparatus was started to built in 2017 on NIM Changping Campus. In order to improve its stability, a clock laser with a 30 cm reference cavity was developed. The clock laser has a frequency stability of ~2E-16 @ 1 s[3]. Special care has been taken to improve the temperature homogeneity of the environment of the atoms to control the black body radiation shift. The total uncertainty of Sr2 is 8.9E-18, which is evaluated in 2021.

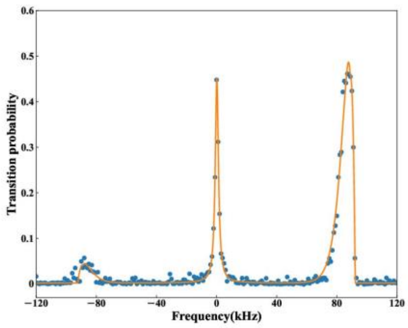

Fig. 1. The sideband-resolved spectroscopy of Sr1

3. Conclusion

Two Sr optical lattice clocks are being developed at NIM. The systematic uncertainties have been evaluated. Comparisons of the two clocks with a 54 km fiber link is planned in the near future.

[1] Lin Y-G, Wang Q, Li Y *et al.* Chin. Phys. Lett. **32** 090601 (2015).
[2] Yige Lin, Qiang Wang, Fei Meng *et al.* Metrologia **58** 035010 (2021).
[3] Ye Li, Yige Lin, Qiang Wang *et al.* Chin. Opt. Lett. **16** 051402 (2018).

On-chip optical frequency reference with a self-stabilized soliton microcomb

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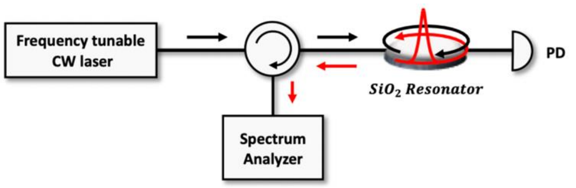
1. Introduction

Next generation high precision sensors require field-deployable accurate references. Quantum enhanced sensors and distributed network sensors are particularly of concern since referencing to accurate frequency sources is essential to the sensor performance. We present ongoing research at KRISS and KAIST regarding the development of an atomic transition referenced chip-based optical frequency synthesizer. Particularly, we report a new scheme for generating a soliton microcomb through stimulated Brillouin scattering(SBS) along with the fabrication of a chip-scale Rb vapor cell for 2-photon spectroscopy. [1]

2. Main Body

Microcombs have gathered great interest due to their potential for the miniaturization of optical frequency combs which are now essential components for frequency standard generation. While soliton microcombs significantly reduce the form factor and overall complexity of traditional frequency comb systems, further simplification is desired for portability in a practical sense. Nonlinear processes such as SBS can occur with high efficiency in ultrahigh-Q microresonators which can compensate for thermal shifts eliminating the need for external feedback for stable soliton generation. Specifically, we employ two modes from different mode families in a 5.98 mm diameter silica wedge resonator which are used to indirectly pump the soliton mode through SBS processes. As the pump laser is tuned towards cavity resonance the coupled power increases and the combined cavity shift including thermal and Brillouin frequency shifts permit the generation and stabilization of deterministic solitons without any external feedback. Single-solitons with pulse widths of ~350 fs, repetition rates of 11 GHz, and phase noise levels of -137 dBc/Hz at 100 kHz were generated and measured. Remarkably, the free-running laser pumped soliton was sustained for several days after being unlocked due to drifts in the laboratory environment. The SBS microcomb system is in preparation to be locked to a chip-scale Rb atomic cell for further development of an integrated optical frequency synthesizer.



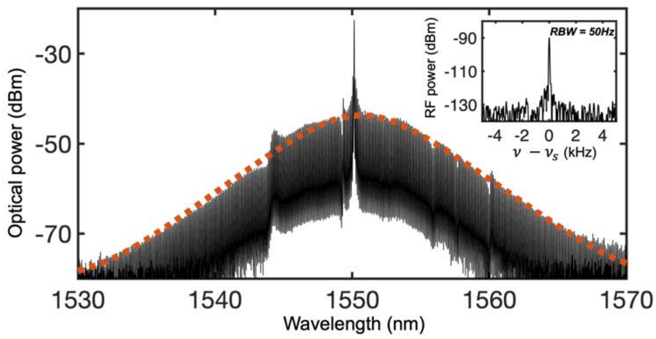


Fig. 1. Microcomb generation setup (left) and optical spectrum of back-scattered frequency comb (right). The optical spectrum is fitted with a sech^2 envelope and the RF spectrum measured with 50Hz RBW is shown in the inset.

3. Conclusion

We present collaborative research at KRISS and KAIST to develop a chip-based optical frequency synthesizer referenced to on-board atomic vapor cells for reliable frequency distribution to high precision sensors.

[1] I. H. Do *et al.*, Optics Letters **46**, 1772 (2021).

Contribution to International Atomic Time by the nearly continuous operation of an Yb optical lattice clock

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Optical clocks such as single ion optical clocks and optical lattice clocks are promising candidates for a redefinition of the SI second. Towards the redefinition, several Sr and Yb optical lattice clocks have recently started to contribute to International Atomic Time (TAI) [1]. TAI is a global timescale computed by the Bureau International des Poids et Mesures (BIPM). The calibration of TAI is made by evaluating the frequency difference between TAI and primary and secondary frequency standards averaged over a month. While the operation of Cs and Rb fountain clocks typically covers more than 80 % of a one-month evaluation period, most of the optical lattice clocks are operated for only a shorter period. The calibration accuracy of TAI by the optical lattice clock is usually limited by the uncertainty due to the dead time of the optical clock.

At National Metrology Institute of Japan (NMIJ), we have developed an Yb optical lattice clock (NMIJ-Yb1) which can run nearly continuously for a long period [2]. In 2020, this clock has been adopted as a secondary frequency standard that is allowed to calibrate TAI. We evaluate the frequency of TAI by (i) measuring the frequency difference between the Coordinated Universal Time of NMIJ (UTC(NMIJ)) and NMIJ-Yb1 and (ii) using a satellite link between UTC(NMIJ) and TAI. From October 2019 to September 2021, NMIJ-Yb1 was operated for 330 days and contributed to TAI [1]. The uptime for the operating period of 330 days was 83.9 %. Figure 1 shows an example of the operation record showing the performance of NMIJ-Yb1. In this example, the operation of NMIJ-Yb1 covered 94.5 % of an evaluation period of 30 days, which enabled us to reduce the uncertainty resulting from the dead time to a negligible level (low 10^{-17}).

In this presentation, we will report the details of the clock apparatus for realizing the nearly continuous operation and an up-to-date systematic evaluation of NMIJ-Yb1.

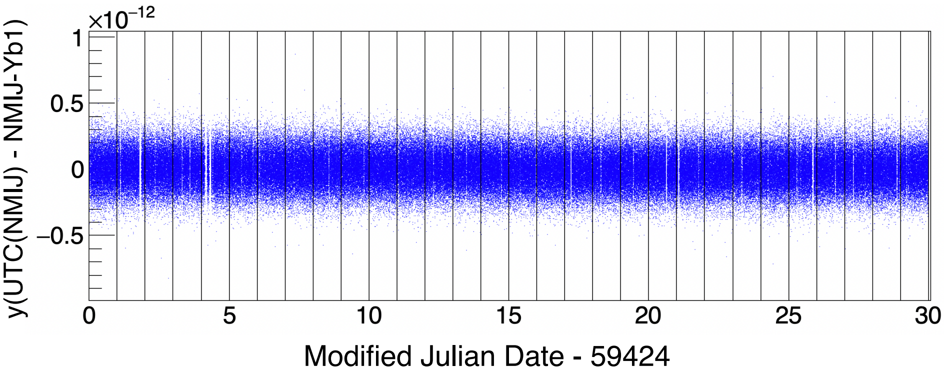

Fig. 1. Fractional frequency difference between UTC(NMIJ) and NMIJ-Yb1 (y(UTC(NMIJ) – NMIJ-Yb1)) measured during a period of 30 days from the Modified Julian Date 59424 (29 July 2021). The data point corresponds to a 6.8 s average.

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[1] BIPM Circular T https://www.bipm.org/en/bipm/tai/

[2] T. Kobayashi *et al*., Metrologia **57**, 065021 (2020).

The Navigation with Indian Constellation and its applications in Time Transfer

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Abstract

The Navigation with Indian Constellation (NavIC) also known as Indian Regional Navigation Satellite System (IRNSS), is a constellation of seven satellites placed in geostationary and geosynchronous orbits along with the associated ground segment. This entire system has been realized by the Indian Space Research Organization (ISRO) and has been made fully operational since 2018. It is able to provide independent position, navigation and timing (PNT) services over the Indian region and the surrounding area extending up to 1500 km beyond its geopolitical boundary. The ground segment of NavIC consists of navigation centres linked with a number of one-way and two-way ranging stations and a precise timing facility called the IRNSS Network Timing (IRNWT) facility. In this talk we propose to describe the NavIC system in some detail.

Precise time plays a crucial role in any satellite navigation system for providing PNT services. Consequently, a major metrological application of NavIC is to provide Time & Frequency calibration with very high accuracy. To ensure traceability to the national reference, UTC (NPLI), and through it to the apex reference, UTC, the IRNWT is linked with the National Physical laboratory, India (NPLI) using Common-view (CV) and Two Way Satellite Time and Frequency Transfer (TWSTFT) techniques.

The time transfer accuracies provided by the NavIC system are very encouraging and we shall discuss typical results.

Intercontinental frequency link via broadband very long baseline interferometry

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1. Introduction

Very long baseline interferometry (VLBI), as one of the space geodetic techniques, has similar potential for long distance time and frequency (T&F) transfer as GNSS observation, which is now widely used. With the aim of frequency transfer, we have developed transportable VLBI stations (2.4-m diameter) equipped with an advanced wide band (3-14 GHz frequency) receiver and high speed (16 GHz) sampling digitizer. These new technologies overcome the disadvantage in sensitivity due to the small antenna. This improved sensitivity and the precise group delay gained by the wide frequency range enabled intercontinental VLBI observation between the small antenna pair [1].

2. Intercontinental Frequency Link

We successfully demonstrated an intercontinental frequency link among INRiM (Istituto Nazionale di Ricerca Metrologia), INAF (National Institute for Astrophysics) and NICT (National Institute of Information and Communications Technology). Yb optical lattice clock at INRiM in Italy and Sr optical lattice clock at NICT in Japan were compared by VLBI and GPS techniques in the period from Oct. 2018 to Feb. 2019. The VLBI observation demonstrated accuracy superior to the GPS technique. It obtained the frequency ratio (Yb/Sr) between Yb and Sr clocks separated by over 9000 km distance as the fractional deviation $(R\text{-}R_0) / R_0 = 2.5(2.8)\times 10^{-16}$ from the ratio R_0 of the currently recommended frequency values (Fig.1) [2].

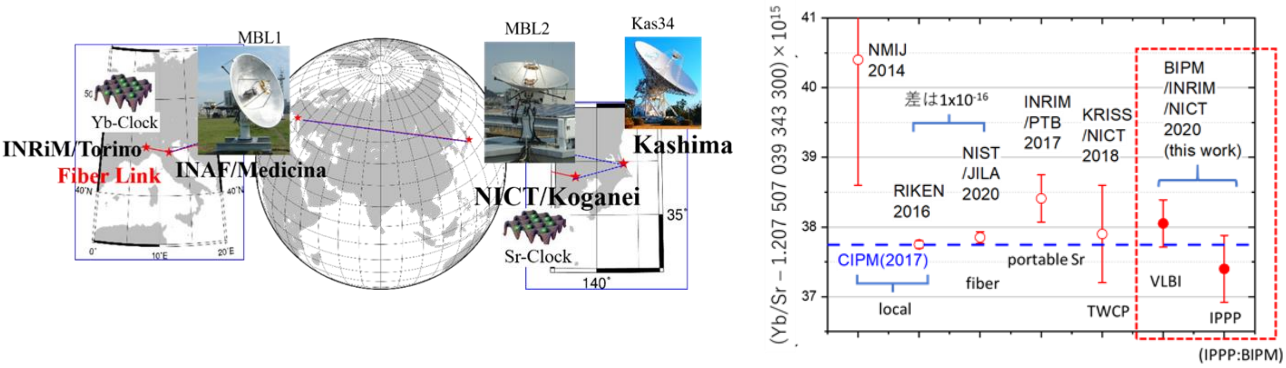

Fig. 1. Left: Yb and Sr optical lattice clocks at INRiM (Torino, Italy) and at NICT (Koganei, Japan) were compared over about 9000 km distance via VLBI observations. The Kashima 34-m antenna participated in the VLBI observations of a small-diameter antenna pair to boost the signal-to-noise ratio. Right: Frequency ratio Yb/Sr obtained by VLBI and GPS(IPPP) in this experiment.

3. Conclusion

This measurement demonstrates the potential of broadband VLBI for high-accuracy frequency links over Earth-scale distances. Similar broadband VLBI techniques such as VGOS (VLBI Global Observing System) have been promoted for geodetic applications by the International VLBI Service for Geodesy and Astrometry (IVS). Collaboration between geodesy and metrology communities will be a key to future high accuracy global frequency links.

[1] M.Sekido, K. Takefuji, H. Ujihara *et al.*, J. Geod. **95,** 41, (2021).
[2] M. Pizzocaro, M. Sekido, K. Takefuji *et al.*, Nat. Phys. **17**, 223-227, (2021).

GNSS time transfers in the national positioning infrastructure

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1. Introduction

GNSS geodetic receivers are installed nationwide as permanent reference stations to continual observe GNSS signals for geodetic survey determinations including: crustal-deformation monitoring, land surveying, airborne mapping, water vapour estimations, atmosphere remote sensing and military uses. NIMT also operates and contributes GNSS measurements with the insertions of external frequency signals coincided with an official civilian time scale of UTC(NIMT) in order to maintain and provide national timescale services to this infrastructure. Timing solutions are determined from selected four ground stations to estimate their receiver timing accuracies and stabilities using a GNSS common-view technique for remote clock comparisons.

2. GNSS common-view time transfer

The comparisons of these GNSS reference stations and UTC(NIMT) is accomplished through common-view GNSS time transfer using GPS, GLONASS, BDS, Galileo and QZSS satellites. The time offset at the receivers is set to aligned with GPS time (GPST) so that receiver positions and clock offset can be calculate and do not need to consider the system time differences between different GNSS constellations. Obtained GNSS measurements in RINEX files are converted into the common GNSS generic time transfer standard (CGGTTS) results using software tools provided by the BIPM.

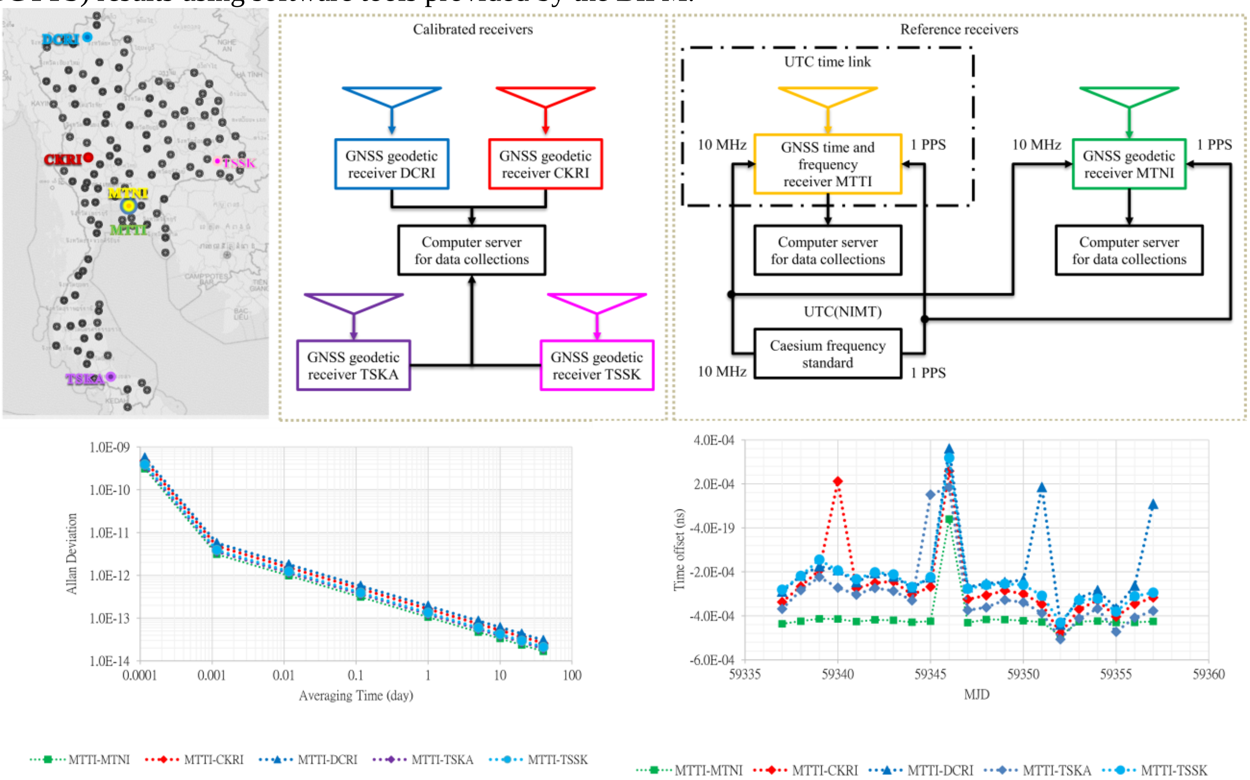

Fig. 1. Measurement schemes and comparisons results between MJD 59337 to 59357 (3 to 23 May 2021)

3. Conclusion

Monitoring time differences employed on at the active GNSS control stations with respect to UTC(NIMT) are achieved at 0.3 ps and the stability of better than 0.1 ps as demonstrated in computed Allan deviation in 1 day. Occurred simultaneously jumps in computed time differences at every stations on MJD 59346; 12 May 2021, have to be further investigated and corrected in order to improve the synchronisation performances and alignment to UTC(NIMT) within the GNSS national positioning and timing infrastructure in Thailand.

[1] P. Defraigne, GNSS Time and Frequency Transfer (Springer handbook of GNSS) 1335, ISBN: 978-3-319-42926-7 (2017).