FREQUENCY MEASUREMENT OF A 532-NM IODINE-STABILIZED LASER USING AN OPTICAL FREQUENCY COMB LINKED TO UTC(NMIJ)

Kazuhiko KAWASAKI[1], Shinichiro YANAKA[1], Kaoru MIYATA[1], Hajime INABA[2] and Feng-Lei HONG[2]

1 Mitutoyo corporation, 430-1, Kamiyokoba, Tsukuba, Ibaraki 305-0854, Japan, kazuhiko_kawasaki@mitutoyo.co.jp
2 National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305-8563, Japan

Abstract:
We developed an optical frequency comb system (the Mitutoyo comb) synchronized to a rubidium (Rb) based frequency standard oscillator which is linked to the Coordinated Universal Time (UTC) operated by the National Metrology Institute of Japan (NMIJ). We measured the frequency of an iodine stabilized laser at 532 nm which is listed as a wavelength standard for length applications. The frequency measurement results taken by the Mitutoyo comb was compared with the results using another frequency comb system developed by NMIJ (the NMIJ comb). When a common laser frequency was measured by the two systems simultaneously, the frequency difference between these measurement results is 0.17 kHz (6.0×10^{-13}). To investigate the origin of the difference, we measure a common laser by using the two combs referring a common frequency reference, and the difference between these results is 0.1 Hz (3.6×10^{-16}). Therefore, the measurement uncertainty of the Mitutoyo comb is dominated by the uncertainty of the Rb frequency standard.

Keywords: optical frequency comb, frequency standard, frequency measurement

1. INTRODUCTION

Precise length standards can be realized by using frequency stabilized lasers. In Japan, the lasers stabilized to molecular absorption lines operating at 633 nm, 532 nm and 1.5 μm and calibrated periodically can be as the length standards. The frequency of the stabilized lasers can be calibrated by using the optical frequency comb. Therefore, the optical frequency comb invented at the end of 20th century has been an indispensable tool to measure the absolute frequency of lasers using a microwave frequency standard [1-2]. After that, fiber-based frequency comb became an user-friendly and reliable frequency measurement tool [3-5].

In the laser calibration system using optical frequency comb, precise frequency standard oscillator is needed for measurement standard. Thus, optical frequency comb system using a GPS disciplined oscillator (GPS-DO) as a frequency reference has been proposed because of its cost effectiveness [6-7].

In Japan, it is possible to synchronize the frequency standard with the National primary standard of time and frequency of NMIJ using GPS common view technology, that is, UTC(NMIJ-DO) [8]. Additionally, the frequency calibration service of UTC(NMIJ)-DO has been carried out remotely [8].

In this paper, we describe as regards our optical frequency comb referring the UTC(NMIJ)-DO (the Mitutoyo comb). We measured the frequency of an 532-nm iodine stabilized laser. To verify the frequency measurement results, we also measure a common laser by using the Mitutoyo and the NMIJ combs referring a common frequency reference.

2. SYSTEM CONFIGURATION

Figure 1 shows a diagram of the Mitutoyo comb system, which includes an Er fiber oscillator, amplifiers, a highly nonlinear fiber (HNLF) [9], an carrier envelope offset frequency (f_{CEO}) detection part and a beat detection part. The system configuration of the Mitutoyo comb is basically same as the NMIJ comb [3-5].

The Er fiber oscillator is a ring resonator that employs nonlinear polarization rotation as the mode-locking mechanism. A part of the circulating power is coupled out of the cavity and distributed equally to two parallel amplifiers

The first amplifier is used to detect the repetition rate (f_{rep}) and f_{CEO}. The second amplifier is used to detect the beat note fbeat between the frequency comb and a frequency-stabilized laser. The first amplifier is used to detect f_{rep} and f_{CEO} through HNLF and $\mathrm{f_{CEO}}$ detection part. The frequencies of f_{rep} and f_{CEO} are stabilized by a phase lock loop using the reference frequency from a frequency synthesizer. Because the frequency synthesizer is synchronized to the frequency standard oscillator, the accuracy of the reference frequency depends on the accuracy of the frequency standard.

The frequency standard oscillator used for the Mitutoyo comb is a rubidium (Rb) based oscillator. The frequency of the oscillator is compensated precisely by receiving a time signal from a GPS and the information of comparison results between the local frequency standard and the UTC(NMIJ). The residual error is calibrated remotely by comparing with UTC(NMIJ) according to the international rule of a frequency comparison [8]. By this, uncertainty of the local frequency standard is 1.0×10^{-13} in case averaging time is a day. The $\mathrm{f_{CEO}}$ of the Mitutoyo comb is stabilized at 10.7 MHz. The f_{rep} is stabilized about 88.6 MHz. Its frequency is controllable in about 2 kHz range.

The second amplifier is used to detect the beat note f_{beat} between the frequency comb and a frequency-stabilized laser. The output continuum from the HNLF covers 1064 nm wavelength. 532 nm wavelength comb elements which are second harmonics of 1064 nm wavelength comb elements are generated by using a periodically poled lithium niobate (PPLN) crystal. f_{beat} is measured by interfering a frequency–stabilized laser and 532 nm wavelength comb element. Using this measurement result, the absolute frequency of the measured laser can be acquired.

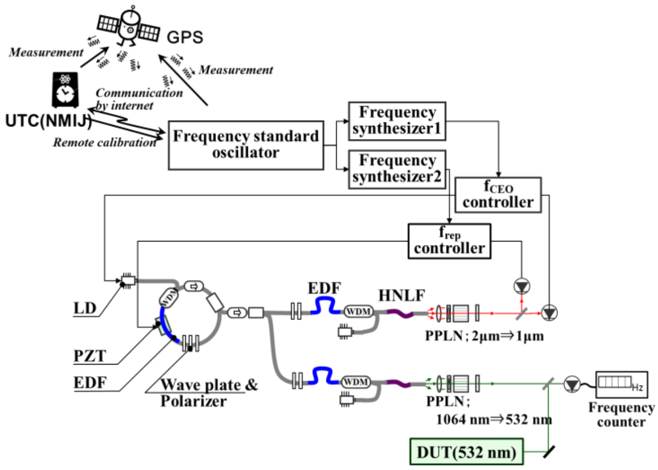


Fig. 1: System configuration of the optical frequency comb system with UTC(NMIJ)-DO (Mitutoyo comb)

3. MEASUTEMT OF A 532-NM IODINE-STABILIZED LASER

We measured the frequency of a 532-nm iodine-stabilized Nd:YVO_4 laser [10] stabilized on the a_{10} component of the R(56)32-0 transition of $^{127}I_2$ for temperature of 15 °C. The measurement results are shown in Fig. 2. The data indicate the results for consecutive 49 807 s with 1 s averaging frequency. The mean and the standard deviation (σ) of the frequency variation for all data were 563 260 223 406.1 kHz and 13.1 kHz, respectively. When the σ is converted into the ratio of it to absolute frequency, it is larger than 2×10^{-11}. The difference of the absolute frequency between the measured value and the recommended value for the optical frequency of the a_{10} component of the R(56)32-0 [11] was 106.9 kHz.

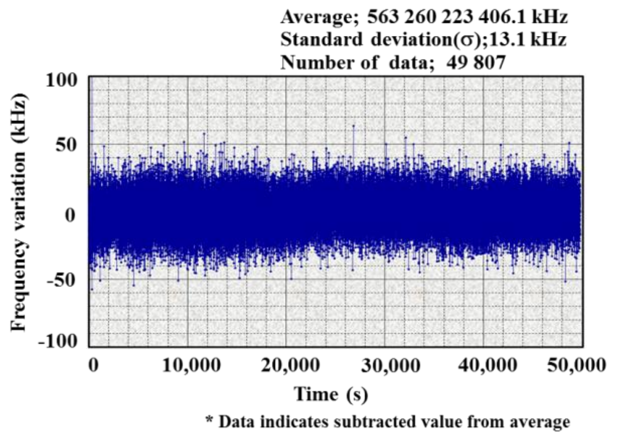


Fig. 2: Frequency measurement results of the iodine stabilized laser using the Mitutoyo comb

4. VERIFICATION OF MEASUREMENT RESULTS

We investigated the cause of the difference between frequency measurements taken by the Mitutoyo comb and the recommended value. It is considered that these are caused by either frequency variation of the measured laser or the optical frequency comb. Frequency variation of an optical frequency comb is caused by the frequency variation of the frequency standard and the capability of the comb stabilization to the reference standard, mainly. These causes also depend on the variation of the measurement environment such as the temperature variation. To identify the causes, we carried the Mitutoyo comb into the NMIJ laboratory.

At first, as shown in Fig. 3, the Mitutoyo comb and the NMIJ comb were stabilized to the same reference frequency standard, and the frequency of a laser was measured by both the combs simultaneously. After this measurement, the values taken by the NMIJ comb were subtracted from the values taken by the Mitutoyo comb. Thereby relative stability between both combs, that is, capability of stabilization of both combs was evaluated. In the measurement, fundamental wave (whose wavelength is 1064 nm) of the Nd:YAG laser developed by the NMIJ [12] was used .

Figure 4 (a), (b) and (c) show measurement results taken by the Mitutoyo comb, taken by the NMIJ comb and the calculation results subtracting (b) from (a), respectively. In (a) and (b), almost same frequency variations are observed. The difference between (a) and (b) can be recognized quantitatively in Fig. 4 (c). The averaging all data for 66 200 s was 0.1 Hz. The standard deviation σ was 0.18 kHz. Subtracting (b) from (a), the width of frequency variation was reduced about one seventh. In consequence, it can be said that the frequency variation in Fig. 5 (a) and (b) was not caused by the comb itself.

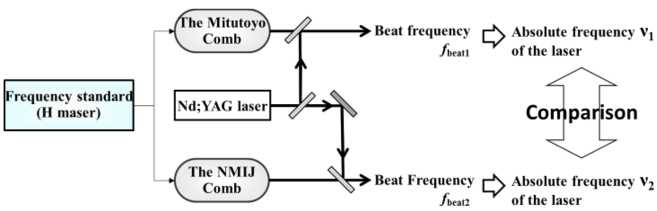
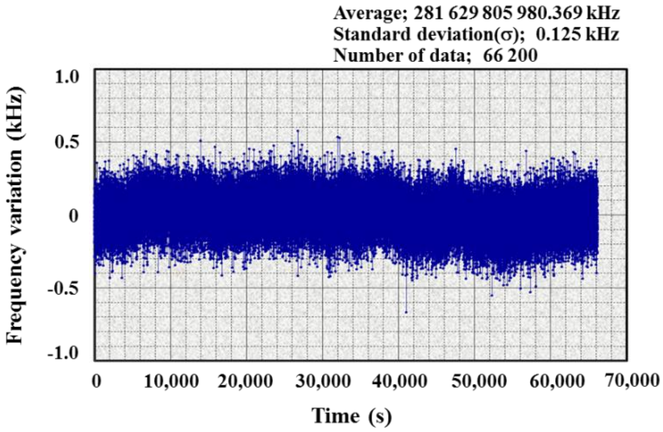
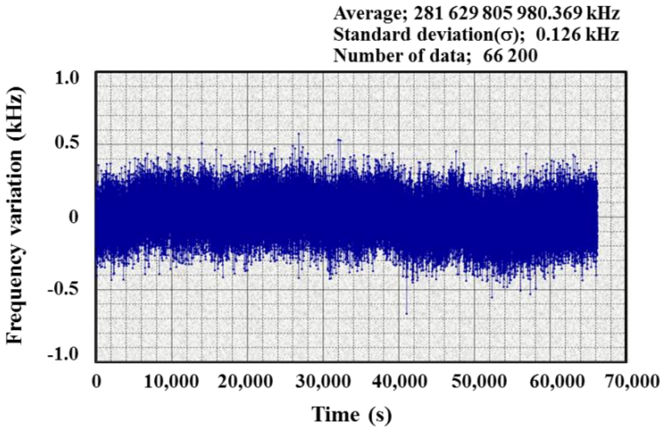


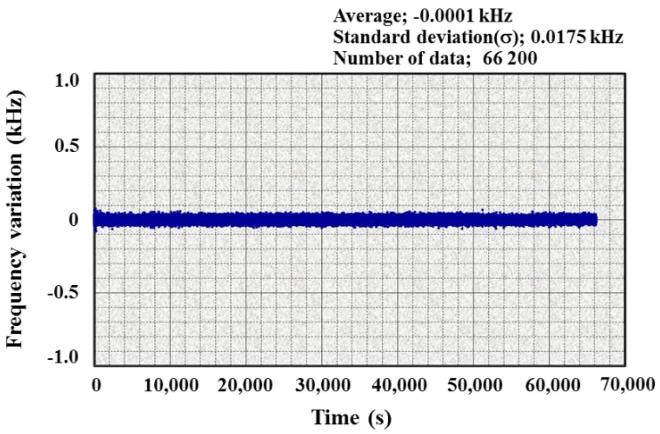
Fig. 3: Comparing measurement results taken by the Mitutoyo comb with the NMIJ comb in case of both combs synchronizing with same frequency standard.



(a) Measured by the Mitutoyo comb



(b) Measured by the NIMJ comb



(c) Difference between (a) and (b)

*** Data indicate values subtracted from averaging all data**

Fig. 4: (a) (b) Frequency fluctuation of the 532-nm iodine-stabilized laser simultaneously measured by the Mitutoyo and the NMIJ comb, (c) Frequency difference between (a) and (b)

Next, as shown in Fig. 5, the Mitutoyo comb was stabilized to the Rb based frequency standard oscillator, and a frequency of the same laser was measured by both the combs simultaneously. After this measurement, subtracting the values taken by the NMIJ comb from the values taken by the Mitutoyo comb, the difference of performances between both comb systems including frequency standard oscillator was verified. As the measured laser, same laser indicated in Fig. 3 was used.

Figure 6 (a) and (b) shows measurement results taken by the Mitutoyo comb stabilized to the Rb oscillator and taken by the NMIJ comb stabilized to the H-maser, respectively. Figure 6 (c) shows values of subtracting (b) from (a). In measurement results taken by the Mitutoyo comb, width of frequency variation became large. In contrast, width of frequency variation taken by the NMIJ combs was almost as same as the one indicated in Fig. 4 (b). In consequence, we conclude that the frequency variations found in Fig. 6 (a), were not caused by the measuring laser but caused by the Mitutoyo comb. Comparing Fig. 3 with Fig. 5, the frequency standard used for frequency stabilization of the optical frequency comb is only different. For this reason, it can be said that the standard deviation (σ) of frequency variation 4.73 kHz found in Fig. 6 (c) was caused by frequency variation of the Rb based frequency standard. In experimental results shown in Fig. 6, the average of difference between both the measurements was 0.17 kHz. It can be considered that this difference is considered to be caused by the performance of Rb based frequency standard synchronized with UTC(NMIJ).

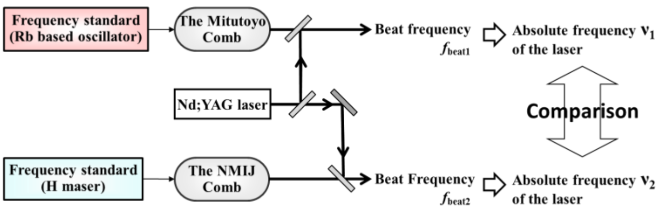
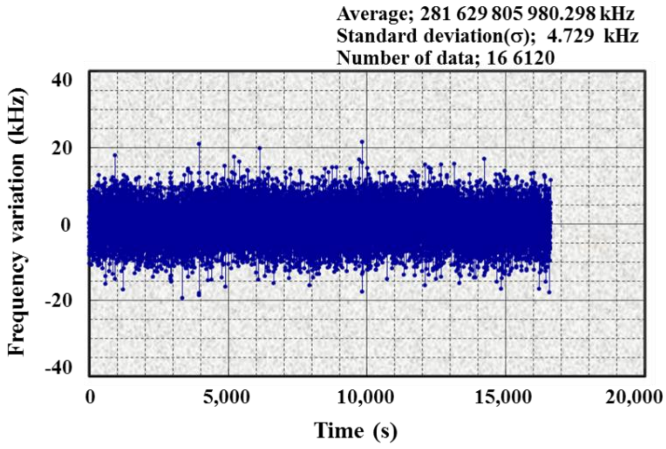
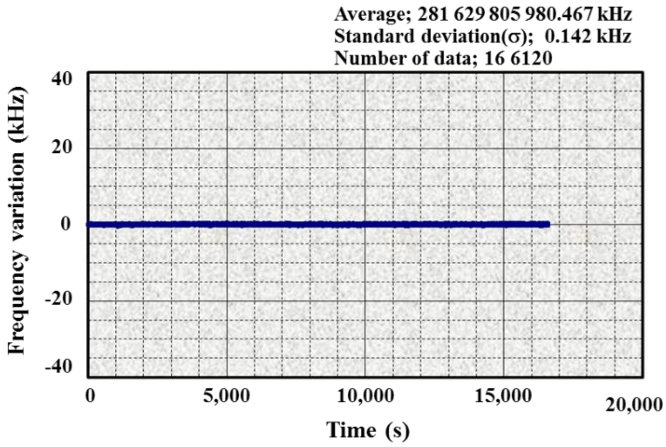


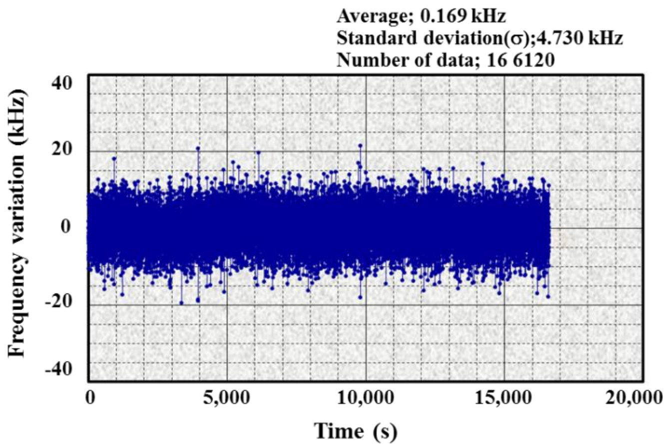
Fig. 5: Comparing measurement results taken by the Mitutoyo comb with the NMIJ comb in case of synchronizing both combs to same frequency standard.



(a) Measured by the Mitutoyo comb



(b) Measured by the NIMJ comb



(c) Difference between (a) and (b)

*** Data indicate values subtracted from averaging all data**

Fig. 6: (a) (b) Frequency fluctuation of the 532-nm iodine-stabilized laser simultaneously measured by the Mitutoyo synchronized to Rb oscillator and the NMIJ comb synchronized to H-maser, (c) Frequency difference between (a) and (b)

5. CONSIDERATION

We have verified that the frequency measurement capability of the Mitutoyo comb is high enough for measuring the 532-nm iodine-stabilized laser, by measuring a common stabilized laser using the Mitutoyo and the NMIJ comb referring a common frequency standard. The frequency fluctuation of the result shown in Fig. 2 was caused by not the frequency comb but the frequency instability of the Rb based frequency standard or iodine-stabilized laser from experimental results shown in Fig. 4 and Fig. 6.

We consider that the causes of the absolute frequency difference (106.9 kHz) between the measurement result and the CIPM recommended value shown in Fig. 2 are as follows.

The Rb oscillator was not cause because its frequency was calibrated remotely and it was demonstrated that its actual frequency shift is less than 1 kHz in optical frequency as shown in Fig. 6(c). Thus, the absolute frequency difference was caused by the frequency shift of the measured laser. The temperature of I_2 cell set in its laser was controlled at 15°C. In addition, the reproducibility of the measured laser is 14.5 kHz in case of turning on/off and is 1.4 kHz/1°C in case of varying environmental temperature [10]. Furthermore, it is considered that frequency shift of the measured laser was caused by optical alignment change with time and so on.

For above reason, we considered that the frequency shift of the measured laser was cause of the absolute frequency difference (106.9 kHz).

5. CONCLUTION

We measured the frequency of a 532-nm iodine-stabilized laser used for length standard laser using an optical frequency comb with the Rb based frequency standard oscillator (Mitutoyo comb). We also measured a common laser by using the Mitutoyo and the NMIJ combs referring a common frequency reference. As a result, we have verified the measurement uncertainty of the Mitutoyo comb is dominated by the frequency instability of the Rb oscillator.

We hope to calibrate laser frequencies at various wavelengths in the near future.

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