Frequency Measurement Capability of a Fiber-Based Frequency Comb at 633 nm

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***Abstract*—A fiber-based frequency comb has been developed to measure the frequency of a 633-nm iodine-stabilized laser at the National Metrology Institute of Japan (NMIJ). The measured frequency was consistent with the previous results measured with a Ti:sapphire-based comb. The NMIJ comb was shipped to Australia for the validation of the measurement capability of the National Measurement Institute, Australia (NMIA) and NMIJ combs using a common microwave reference and a common optical frequency. Consequently, the frequency consistency of the two combs was approximately 8×10^{-17}. Furthermore, we demonstrate that an absolute mode number of the comb can easily and clearly be determined by using the two combs.**

***Index Terms*—Frequency measurement, frequency stability, frequency synthesizers, gas lasers, optical fiber lasers.**

I. Introduction

THE OPTICAL frequency comb was invented at the end of the 20th century and has been an indispensable tool for linking microwave and optical frequencies [1], [2]. For example, the optical frequency measurement of frequency-stabilized lasers is required for the realization of the meter. In particular, the iodine-stabilized helium–neon ($HeNe/I_2$) laser operating at 633 nm is the most popular wavelength standard for realizing the meter. Many national metrology institutes (NMIs) have been operating the $HeNe/I_2$ laser as a national standard of length, and the frequency measurement of $HeNe/I_2$ lasers is a special task in the field of length standards [3], [4]. However, careful alignment, special discharge tubes, and regular international comparisons are required to keep the precise frequency of $HeNe/I_2$ lasers.

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The recent developments in fiber-based frequency combs (fiber comb) enable us to link the optical frequencies to the microwave frequency standards with high reliability. The fiber comb has become ubiquitous in this field because of its compactness and cost effectiveness [5], [6]. A 633-nm laser phase locked to the comb has a potential to be a length standard. Metrology applications require high reliability and quality systems for measurement instruments. Therefore, validating the measurement capability of the fiber combs is an important issue from a metrological point of view.

Recently, one of the fiber combs developed by the National Metrology Institute of Japan (NMIJ) was shipped to the National Measurement Institute, Australia (NMIA) to validate the measurement capability of the fiber combs of NMIA and NMIJ at 633 nm [7]. In this paper, we describe the fiber comb developed by NMIJ to measure 633-nm lasers, the frequency measurement of $HeNe/I_2$ lasers at NMIJ, and the results of the measurement capability validation of the NMIJ and NMIA comb. Furthermore, we demonstrate a technique for the mode-number determination of the combs using two fiber combs, which is necessary to determine the absolute frequency of the laser locked to the comb.

II. Fiber Comb Developed by NMIJ to Measure 633-nm Lasers

The design of our fiber comb system is similar to our past experiment [8]. Here, we mainly describe the differences from that system.

The mode-locked fiber laser is pumped by a 980-nm laser diode via a wavelength-division-multiplexing coupler. The pump power is typically 200 mW. The full-width at half-maximum of the spectrum and the repetition rate (f_{rep}) of the laser are 40 nm and 50.5 MHz, respectively. The erbium fiber in the laser cavity is approximately 90 cm long and is wound on a drum-type piezo actuator to stabilize f_{rep}. The net dispersion of the laser cavity is estimated to be $+0.006 \pm 0.005$ ps^2. Thirty percent of the circulating power is coupled out of the cavity and equally distributed to two parallel erbium-doped fiber amplifiers (EDFAs) [9]. The total output power is approximately 5 mW. Each EDFA is pumped by a 980-nm laser diode from its output side with a power of 400–450 mW (backward pumping only). The first EDFA is used to detect f_{rep} and f_{CEO}. The second EDFA is used to detect the beat note (f_{beat}) between the frequency comb and a 633-nm iodine-stabilized laser. Each EDFA generates an average output power of 50–65 mW, which corresponds to a pulse energy of 1.0–1.2 nJ, by using an optimal amplification method [10].

A 20-cm non-polarization-maintaining highly nonlinear fiber (HNLF) is spliced to the output of the first EDFA. The output continuum from the HNLF covers a wavelength range of 950 nm to more than 2150 nm and is used to detect f_{rep} and f_{CEO}. The entire generated continuum is launched into a periodically poled lithium niobate (PPLN) crystal with an aspheric lens; the component at 2040 nm is doubled and mixed with the component at 1020 nm. The optical paths for 1020 and 2040 nm are compensated with a 20-cm single-mode fiber after the HNLF. A 1020-nm optical bandpass filter is inserted to eliminate the other wavelength components of the comb. A signal-to-noise ratio of 40 dB at 300-kHz resolution was obtained for the f_{CEO} beat detection [8]. With regard to the second EDFA, we use a 10-cm length of HNLF to broaden the spectrum, extract the 1266-nm component of the comb, and frequency double with a PPLN crystal to generate a comb in the 633-nm region to measure the HeNe/I_2 laser. We were able to obtain a signal-to-noise ratio of 35 dB at 300-kHz resolution in the 633-nm beat detection, which is of sufficient quality to properly count its frequency.

III. Frequency Measurements of 633-nm Iodine-Stabilized Lasers at NMIJ

The NMIJ has maintained the HeNe/I_2 lasers as the national standard of length for over 20 years. The laser frequency has been maintained by using a group of identical lasers. In addition, we have intermittently measured their frequencies since 2001. We have measured them with a Ti:sapphire-based comb until 2005 and with fiber combs since 2006. Furthermore, the NMIJ has participated in international comparisons between HeNe/I_2 lasers every few years to validate their correctness. In this section, we describe the frequency measurements of HeNe/I_2 lasers with a Ti:sapphire-based comb before and after the international comparison of HeNe/I_2 lasers in 2004 and describe the measurements with a fiber comb in 2006.

The two comb frequencies f_{rep} and f_{CEO} are phase locked to the RF references synthesized from an H-maser linked to the Coordinated Universal Time (UTC). The optical frequency is calculated from the equation $f_{\text{optical}} = n \times f_{\text{rep}} \pm f_{\text{ceo}} \pm f_{\text{beat}}$, where n is a mode number (which is an integer that must be determined). The signs of f_{ceo} and f_{beat} are determined by checking the increase or decrease of f_{beat} when f_{rep} or f_{ceo} is increased under the condition of locking f_{ceo} or f_{rep}, respectively. We use universal counters (Agilent Technology 53132A) to count f_{rep}, f_{CEO}, and f_{beat}. The counters were operated with an external arming to synchronize them. We employed ratio counting by using a frequency divider to check that the frequency is properly counted. The f_{beat} signal was filtered, amplified, and divided into three signals. One of these signals was frequency divided by ten and used for the ratio counting. The second beat signal was also used for the ratio counting, and the last signal was used for the frequency counting. In these measurements, we excluded the anomalous frequencies, which were indicated by a ratio count that was not exactly 10. f_{rep} and f_{CEO} were also simultaneously measured to check them, but the set values for the frequency synthesis were used to calculate the optical frequencies because the counter resolution is much coarser than the actual frequency fluctuation for f_{rep}, and the frequency fluctuation of f_{CEO} is much smaller than the fluctuation of f_{beat}.

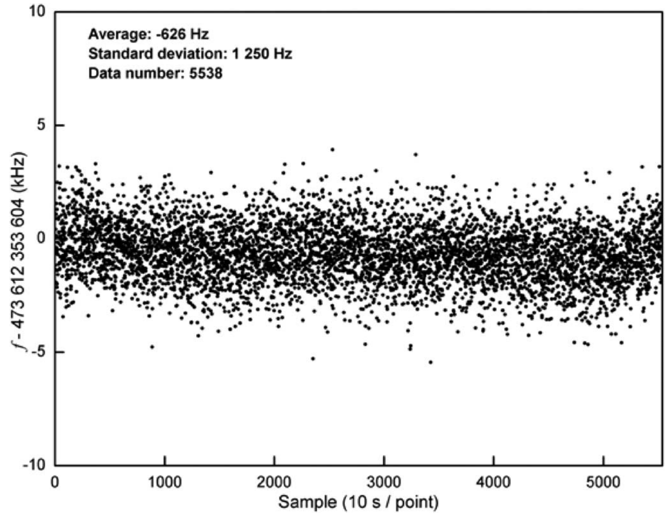

Fig. 1. Measurement results of the HeNe/I_2 laser N1 using a fiber comb.

TABLE I
Measurement Results of HeNe/I_2 Lasers P4 and O3. The Mean Frequency on Each Day Is $(473\,612\,353\,604 + \Delta f)$ Kilohertz. The Value in the Brackets Is the Standard Deviation

Date	Laser	Data points	Δf	Comb
8 Oct. 2004	P4	436	-2.9 (0.9)	Ti:sapphire
14 Oct. 2004	O3	10	+1.1(1.5)	-
25-30 Oct. 2004	APMP LK-11			
10 Nov. 2004	O3	1000	+2.7 (0.9)	Ti:sapphire
18 Nov. 2004	O3	441	+3.6 (1.1)	Ti:sapphire
25 Sep. 2006	N1	5538	-0.6 (1.3)	Fiber

In 2004, we had measured the frequencies of HeNe/I_2 lasers with a Ti:sapphire laser-based comb system before and after the international comparison. The specifications of the comb are described in [11]. First, the frequency of the HeNe/I_2 laser P4 was measured at NMIJ on October 8, 2004. The frequency of P4 was transferred to the HeNe/I_2 laser O3 at NMIJ before the comparison. O3 was shipped to Beijing and took part in the international comparison of HeNe/I_2 lasers APMP LK-11 [12], [13]. Finally, the absolute frequency of O3 was measured again at NMIJ on October 10 and 18 after the comparison. The frequency of O3 was consistent with the other participating lasers, i.e., within several kilohertz in the comparison. Our measurements at NMIJ before and after the comparison were also consistent with the results in the comparison. These results supported the international comparison. In 2006, we measured the frequency of the HeNe/I_2 laser N1 with our fiber comb at NMIJ before shipping to Australia. The measurements were so reliable that we could obtain a long and almost continuous data run, as shown in Fig. 1. Table I shows the results of the measurements in 2004 and 2006. The measurement runs consisted of 441–5538 blocks of 10-s measurements. The values in the brackets in Table I are the standard deviation of the measurement values (averaging time: 10 s). The typical standard deviation was 1 kHz. The optical frequency of the HeNe/I_2 lasers agreed with the Comité International des Poids

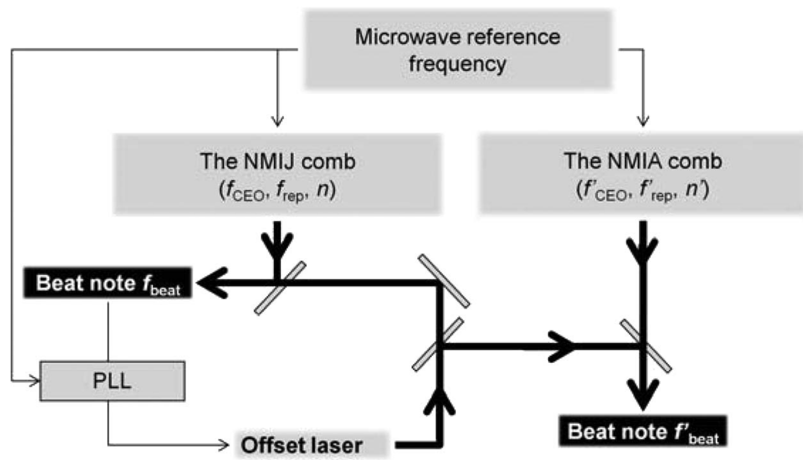

Fig. 2. Diagram of the measurement capability validation of combs. An offset laser is locked to the NMIJ comb and measured with the NMIA comb. The beat frequencies between the offset laser and each comb are simultaneously counted.

et Mesures (CIPM)-recommended frequency of within 4 kHz. This shows that the fiber comb measurements are consistent with the CIPM-recommended value and the results using the Ti:sapphire-based comb. Furthermore, these results also show a measurement capability of our comb systems with microwave references.

IV. Measurement Capability Validation of NMIA and NMIJ Comb

The comb technique enables us to directly measure the optical frequency from the UTC. Therefore, there is the possibility that we can avoid the time-consuming international comparisons of HeNe/I_2 lasers. In that case, however, we need to internationally validate the measurement capability of the comb for guaranteeing international consistency. The most direct way to validate the capability of the comb to compare a common optical frequency and a common microwave frequency is to compare two independent combs. If the capability is sufficiently better than the uncertainty of the microwave reference, then the measurement capability of the comb is dominated by the microwave reference.

In November 2006, one of the fiber combs developed by NMIJ was shipped to NMIA to perform a measurement capability validation of the NMIA and NMIJ fiber combs at 633 nm. The fiber combs are suitable to be shipped abroad because they are much more compact and robust than Ti:sapphire-based frequency combs.

We show the experimental setup of the capability validation of the fiber comb to compare a microwave and an optical frequency in Fig. 2. The NMIA comb is based on a commercial fiber comb, which is capable of measuring the optical frequency between 600 and 2000 nm. The amplified fundamental source (1560 nm) is frequency doubled and then broadened with a photonic crystal fiber. The NMIJ comb was described in the previous section. In this experiment, an offset laser was phase locked to the NMIJ comb, and the laser frequency was measured with the NMIA comb. The NMIA and NMIJ combs were locked to a common H-maser. The syntheses of $f_{\rm rep}$ for these combs were similar to our past experiment [11].

We used the set frequencies of the phase locking ($f_{\rm rep}$, $f'_{\rm rep}$, $f_{\rm CEO}$, and $f'_{\rm CEO}$) and the measured frequencies ($f_{\rm beat}$ and $f'_{\rm beat}$) for the optical frequency calculation. We counted the phase-locked $f'_{\rm beat}$ for the frequency calculation because the frequency fluctuation is somewhat large (approximately 5 kHz at 1-s averaging) since the control bandwidth of the offset laser was narrow (approximately 5 Hz) [14].

We simultaneously counted $f_{\rm beat}$ and $f'_{\rm beat}$ with a dead-time-free counter (Menlo Systems FXM). Due to the different equipment available for the comb validation, we checked the beat frequencies by using two counters for counting each beat note instead of using the ratio counting scheme.

We excluded anomalous frequencies (with a frequency difference of more than 0.5 Hz) in the frequency measurements. The synthesized and measured laser frequencies $f_{\rm synthesized}$ and $f_{\rm measured}$ are

$$f_{\rm measured} = N \cdot f_{\rm rep} \pm f_{\rm CEO} \pm f_{\rm beat} \qquad (1)$$

$$f_{\rm synthesized} = M \cdot f'_{\rm rep} \pm f'_{\rm CEO} \pm f'_{\rm beat} \qquad (2)$$

where N and M are the mode numbers of the NMIJ and NMIA combs, respectively. The determination of the signs of $f_{\rm CEO}$, $f'_{\rm CEO}$ and $f_{\rm beat}$, $f'_{\rm beat}$ were described in the previous section. In the case of using two combs, the mode number can be determined by slightly changing $f_{\rm rep}$, as described in the next section.

The frequency difference ($f_{\rm measured} - f_{\rm synthesized}$) is shown in Fig. 3 (inset). The average of the difference frequencies was 38 mHz, which corresponds to a fractional frequency offset of 8.1×10^{-17}. The corresponding Allan deviation is shown in Fig. 3. The Allan deviation was 4.1×10^{-13} for a 1-s averaging and improves to $2.2{-}3.4 \times 10^{-16}$ after 10 000 s. These stabilities are similar to the results described in [15].

These results show that the NMIA and NMIJ combs agree with each other at a level of 8×10^{-17} in the measurement of the 633-nm lasers. This is significantly lower than the uncertainty of the microwave frequency reference and of the UTC itself. Therefore, the capability of each comb to carry out an absolute measurement of an optical frequency is limited

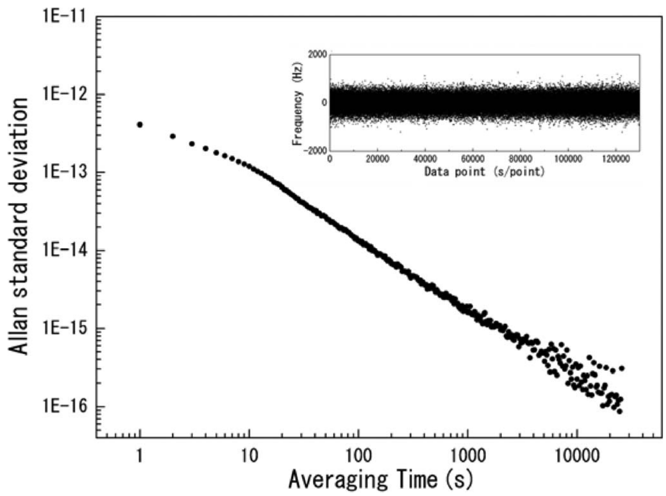

Fig. 3. Frequency differences between two combs (inset) and corresponding Allan deviation.

in practice by the accuracy of the local reference and of its comparison to UTC $(> 10^{-15})$.

V. Mode-Number Determination of Comb

If the laser frequency is previously known with an uncertainty that is much smaller than $f_{\rm rep}$, then we can easily determine the mode number of the comb by fitting an appropriate integer. However, when we measure an unknown laser or lock a laser frequency to a comb mode such as in the validation previously described, we need to independently determine the mode number. Two fundamental studies have previously been reported. The first approach is to detect the variance of $f_{\rm beat}$ when $f_{\rm rep}$ is changed [16]. This method requires a large tuning range of $f_{\rm rep}$ for most of the lasers stabilized on the molecular absorption, which needs a moving stage in the fiber laser cavity and a difficult observation of the beat note crossing over many comb modes. Another approach is to solve the simultaneous equations by using two combs without changing $f_{\rm rep}$ [17]. This method requires two combs with a very close $f_{\rm rep}$, which also needs a moving stage in one of the two mode-locked fiber lasers to put $f_{\rm rep}$ of that laser close to $f_{\rm rep}$ for the other laser. In this paper, we demonstrate another practical method to determine the mode number by using two combs. The basic principle is same as [16]. The key point of our approach is to simultaneously count the beat notes between the measured laser and each comb to eliminate the frequency fluctuations of the laser.

Assume that the frequency of the measured laser is $f + \delta f$, where f is a constant, and δf_1 and δf_2 are the frequency fluctuations at each time span. When measured with a comb, $f + \delta f$ can be written as

$$f + \delta f_1 = N \cdot f_{\rm rep} \pm f_{\rm CEO} \pm f_{\rm beat1}. \tag{3}$$

When we change $f_{\rm rep}$ by $\Delta f_{\rm rep}$, the laser frequency can also be written as

$$f + \delta f_2 = N \cdot (f_{\rm rep} + \Delta f_{\rm rep}) \pm f_{\rm CEO} \pm f_{\rm beat2}. \tag{4}$$

Therefore, N can be written as

$$N = \frac{(f_{\rm beat1} - f_{\rm beat2}) + (\delta f_2 - \delta f_1)}{\Delta f_{\rm rep}}. \tag{5}$$

We have to estimate the mode number N from only $(f_{\rm beat1} - f_{\rm beat2})/\Delta f_{\rm rep}$ because $(\delta f_2 - \delta f_1)$ is unknown. The last term in (5) tells us that a high stability (small δf_1 and δf_2) or a large $\Delta f_{\rm rep}$ is required to precisely determine the mode number N.

On the other hand, we can measure the laser frequencies of (3) and (4) by simultaneously using a second comb with the repetition rate unchanged, i.e.,

$$f + \delta f_1 = M \cdot f'_{\rm rep} + f'_{\rm CEO} + f_{\rm beat3} \tag{6}$$

$$f + \delta f_2 = M \cdot f'_{\rm rep} + f'_{\rm CEO} + f_{\rm beat4}. \tag{7}$$

The integer M is the mode number of the second comb. The unknown fluctuation term $(\delta f_1 - \delta f_2)$ can be eliminated by combining (3), (4), (6), and (7). Consequently, we can obtain N from

$$N = \frac{(f_{\rm beat1} - f_{\rm beat2}) + (f_{\rm beat4} - f_{\rm beat3})}{\Delta f_{\rm rep}}. \tag{8}$$

In practice, the frequencies of the microwave reference and the frequency synthesis system of $f_{\rm rep}$ also fluctuate. We can eliminate the microwave reference fluctuation by using a common microwave reference for the two combs. As a result, the viability of this method does not depend on the frequency stability of the measured laser or the microwave reference. In addition, it can be applied to both the case of measuring a laser frequency stabilized on a molecular absorption line and to phase locking a laser to a comb mode as described below.

In practice, the direct measurement of $(f_{\rm beat1} - f_{\rm beat2})$ in (8) is often difficult because $f_{\rm rep}$ and the other beat signals sometime interfere with the beat note counting, and the RF bandpass filter chooses the frequency range of the beat signal. We propose a concrete procedure described below to make this measurement easier for the frequency counting system and for the operator. Fig. 4 shows the frequency relations between the comb mode and the measured laser in this procedure. Here, we assume a particular set of sign relationships. An offset laser is phase locked to a mode of the NMIJ comb. We change $f_{\rm rep}$ of the measuring comb (the NMIA comb here). A beat signal at approximately 30 MHz $(f_{\rm beat1})$ was first measured with the NMIA comb. Another beat signal at 10.7 MHz $(f_{\rm beat3})$ was also simultaneously measured with the NMIJ comb. The beat note was then shifted and again measured at approximately 30 MHz $(f_{\rm beat2})$ by changing $f_{\rm rep}$ of the NMIA comb by $\Delta f_{\rm rep}$. Another beat signal at 10.7 MHz $(f_{\rm beat4})$ was also simultaneously measured with the repetition rate of the NMIJ comb unchanged. When the signs of $f_{\rm beat3}$ and $f_{\rm beat4}$ of (6) and (7) are positive, we can calculate the frequency change of the Nth mode of the comb as $f_{\rm rep} - f_{\rm beat1} - f_{\rm beat2} + f_{\rm beat3} - f_{\rm beat4}$.

Table II shows our results. In this experiment, we obtained appropriate beat note frequencies by setting $f_{\rm rep} =$ 99 999 825 Hz and $\Delta f_{\rm rep} = 8$ Hz. From these values, $N\Delta f_{\rm rep} = f_{\rm rep} - f_{\rm beat1} - f_{\rm beat2} + f_{\rm beat3} - f_{\rm beat4} = 37\,889\,094.0\ (2.3)$ Hz,

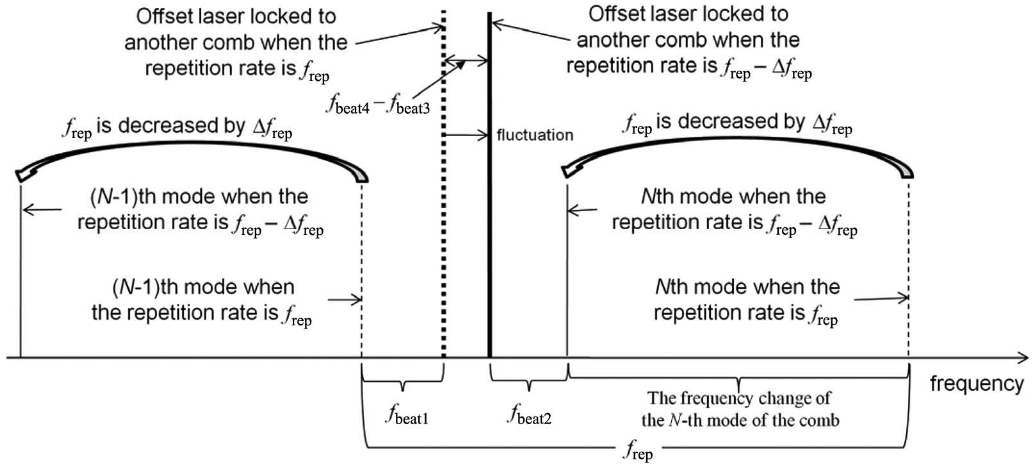

Fig. 4. Frequency relations between the comb mode and the measured laser in mode-number determination.

TABLE II
FREQUENCY MEASUREMENT RESULTS

	average (Hz)	Allan deviation at 1000 s averaging (Hz)	averaging time (s)
f_{rep}	99 999 825 (set)	-	-
Δf_{rep}	8 (set)	-	-
f_{beat1}	30 304 285.32	3.2	1000
f_{beat2}	31 806 453.60	7.1	1000
f_{beat3}	10 700 006.47	2.8	1000
f_{beat4}	10 699 998.51	7.2	1000
f_{beat1} - f_{beat3}	19 604 278.85	1.3	1000
f_{beat2} + f_{beat4}	42 506 452.11	0.77	1000

and we can obtain $N = N\Delta f_{\rm rep}/\Delta f_{\rm rep} = 4\,736\,136.75\,(0.29)$. As a result, the mode number N was identified as 4 736 137. The mode number of another comb can also be identified from the absolute frequency of the offset laser.

The residual frequency instability mostly originates from the synthesizers that were used for the repetition rate frequency synthesis, and there is the possibility of some improvement here. In addition, the instability reduces with the integration time τ, which is proportional to $1/\tau$. In this measurement, although we counted frequencies for 50 000 s to calculate the Allan deviation at 1000-s averaging, this result shows that the determination itself only needs 1000 s or less. Furthermore, the averaging time can be shortened if we allow a larger $\Delta f_{\rm rep}$. For example, it is less than 100 s if $\Delta f_{\rm rep}$ is 80 Hz.

VI. CONCLUSION

We have shown that fiber combs have the capability to compare a microwave frequency and an optical frequency at 633 nm with an uncertainty of 8×10^{-17}, which is better than the uncertainty of the best microwave reference. Therefore, the measurement capability of the comb is determined by the microwave reference. In addition, we have demonstrated a method to determine the number of the comb mode used in the beat note detection. We could easily determine the mode number by changing $f_{\rm rep}$ by only 8 Hz.

The uncertainty of the conventional HeNe/I_2 laser is at the 10^{-11} level, which is perfectly adequate for length metrology. However, the fiber comb has several advantages. The fiber combs have been simple and robust year by year. Their robustnesses are already beyond the HeNe/I_2 lasers; they have been almost continuously operated for more than two years in our laboratory, and the lifetime of the fiber comb is estimated to be much longer than the HeNe/I_2 laser. In addition, the fiber combs do not need international comparisons carried out by transporting the reference standards, as the microwave frequency standards are already compared through international time and frequency transfer for the generation of UTC. Therefore, the combination of an offset laser with a fiber comb has the possibility of being a practical source for a length standard. The NMIJ actually has a plan to replace the Japanese length standard from HeNe/I_2 lasers to fiber combs in 2009.

This "comb-stabilized laser" does not require any iodine cell or complicated adjustments to keep a precise frequency and is compatible with the existing optical systems such as the length interferometers used with HeNe/I_2 lasers. This technique is available for applications using multiplex lasers such as a polychromatic interferometer. Furthermore, such a stabilized laser can be used anywhere there is a local microwave reference frequency traceable to UTC, for example, via signals from the Global Positioning System.

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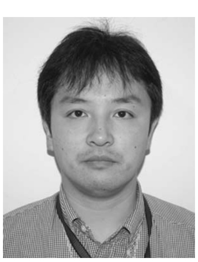

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Jun Ishikawa, photograph and biography not available at the time of publication.

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