Terahertz Frequency Metrology Based on Frequency Comb

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(Invited Paper)

***Abstract*—Two techniques for terahertz (THz) frequency metrology based on frequency comb, namely, a THz-comb-referenced spectrum analyzer and a continuously tunable, single-frequency continuous-wave (CW)-THz generator, are reviewed. Since the frequency comb enables to coherently link the frequency among microwave, optical, and THz regions, it is possible to establish the THz frequency metrology traceable to time of the SI base units. Using a THz-comb-referenced spectrum analyzer based on a stable THz comb generated in a photoconductive antenna for THz detection, the absolute frequency of CW test sources in the sub-THz and THz regions was determined at a precision of 10^{-11}. Furthermore, a continuously tunable, single-frequency CW-THz generator was demonstrated around 120 GHz by photomixing of an accurately tunable CW laser and a tightly fixed CW laser in the optical frequency region, phase locked to two independent optical combs. The combination of the CW-THz generator with the THz-comb-referenced spectrum analyzer will open the door for establishment of frequency metrology in the THz region.**

***Index Terms*—Frequency comb, frequency measurement, frequency metrology, frequency synthesizers, terahertz (THz) wave.**

I. Introduction

Terahertz (THz) electromagnetic (EM) wave, lying at the boundary between optical and electrical waves, has emerged as a new innovative mode for sensing, spectroscopy, communication, and other applications [1]. Along with recent progress in THz technology, the requirements of THz metrology have increased in various applications [2]. In particular, frequency and power are important quantities to be measured in the metrology because they are fundamental physical quantities of EM waves. The THz frequency metrology can be established by realizing precise frequency measurement equipments (THz spectrum analyzers), signal sources of standard frequency (THz clocks), and accurate, tunable, single-frequency signal generators (THz synthesizers). The establishment of the THz frequency metrology will enable to expand the scope of THz applications based on its high reliability because frequency accuracy in the THz region is relatively lower than that in the optical and electrical regions, namely, "THz gap of frequency metrology." For example, when the THz wave is used as a carrier wave for broad-band wireless communications, its transmission frequency should be highly accurate and stable in order to secure necessary and sufficient bandwidth for broad-band communication without interferences with other applications, such as astronomy or sensing. The THz clocks will be used to generate the accurate and stable transmission frequency. Also, the THz frequency metrology will play an important role in frequency calibration of various types of commercial THz instruments, such as sources, detectors, and systems. The absolute frequency of the THz source is accurately determined by the THz spectrum analyzers, whereas frequency scale of the THz spectrometer is precisely calibrated by the THz synthesizers. The precisely calibrated THz spectrometer increases identification power in spectroscopic applications based on THz spectral fingerprints. For example, high-resolution spectroscopy in gas sensing and astronomy requires high accuracy for determination of the absolute frequency because many absorption lines of molecular gasses exist in the THz frequency range [3].

A spectrum analyzer is a fundamental frequency measurement instrument widely used for RF, microwave, and millimeter waves. However, it is still difficult to use in the THz region although steady efforts are bring made to extend its frequency range. The electrical heterodyne method with a superconductor-insulator-superconductor mixer [4] or a hot-electron-bolometer mixer [5] enables frequency measurement of continuous wave (CW) in the sub-THz and THz regions. Conversely, optical interferometric method can be used as an optical spectrum analyzer in the THz region. However, these methods often require cryogenic cooling of the mixer or detector to suppress thermal noise, which is a major obstacle to practical use. Recently, new types of spectrum analyzers based on harmonic mixing technique with optical frequency comb (OFC) have been proposed and developed, which can measure the absolute frequency and spectral shape of CW-THz wave without the need for the cryogenic

Manuscript received January 30, 2010; revised March 8, 2010 and March 19, 2010; accepted March 24, 2010. Date of publication June 21, 2010; date of current version February 4, 2011. This work was supported in part by the Ministry of Education, Culture, Sports, Science, and Technology of Japan through Grants-in-Aid for Scientific Research under Grant 18650121, Grant 18686008, Grant 20560036, Grant 21360039, and Grant 21650111, in part by the New Energy and Industrial Technology Development Organization of Japan through the Industrial Technology Research Grant Program under Grant 02A51005d, and in part by the Ministry of Internal Affairs and Communications of Japan through Strategic Information and Communications R&D Promotion Programme under Grant 042107005.

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Digital Object Identifier 10.1109/JSTQE.2010.2047099

cooling. One such device is a THz-comb-referenced spectrum analyzer [6], [7] using a frequency comb of photocarriers (PC), namely PC-THz comb, generated in a photoconductive antenna (PCA) for THz detection [8]. By precisely stabilizing a mode-locked frequency of a femtosecond Ti:Sapphire laser and hence the PC-THz comb with a rubidium (Rb) atomic clock, the absolute frequency of CW-THz wave in the sub-THz and THz regions could be measured to a precision of 10^{-11} [6]. Furthermore, a fiber-based, THz-comb-referenced spectrum analyzer has been constructed, which has the advantages of being a portable, alignment-free, robust, and flexible apparatus suitable for practical use [7]. Other types of spectrum analyzers are based on a metal-semiconductor point contact diode [9] and an electrooptic sampling technique [10], using a free-running femtosecond Ti:Sapphire laser. The latter method has been achieved to frequency measurements of a CW CO_2 laser at 28 THz [10].

On the other hand, accurate, stable, and/or tunable single-frequency signal generation is an essential technique to achieve the THz clock and synthesizer. Frequency-stabilized CW-THz sources have been achieved by active control of a THz quantum cascade laser (THz-QCL) [11], [12]; however, it is difficult to tune the frequency in a broad range due to the restricted tunable range of the THz-QCL, typically a few hundreds GHz depending on its band structure [13]. One promising alternative method for widely tunable CW-THz sources is photomixing of two CW near-IR lasers of adjacent wavelengths with a photomixer, such as a unitraveling-carrier photodiode (UTC-PD) [14] or a PCA [15]. However, if the two CW lasers are operated in the free-running mode, it is difficult to generate the accurate and stable frequency in the CW-THz wave. One attractive frequency reference for simultaneous control of two CW lasers is an OFC [16]. A stable millimeter-wave synthesizer has been realized by photomixing two CW lasers locked to an optical comb generator based on an electrooptic modulator [17]. Recently, accurate, stable, phase-locked CW-THz wave has been discretely generated at four different frequencies (0.30, 0.56, 0.84, and 1.1 THz) by photomixing of two CW lasers locked to a single optical comb based on a mode-locked Ti:Sapphire laser [18]. Furthermore, the output frequency was tuned continuously by scanning the frequency interval of the optical comb while locking the CW lasers to the comb; however, the range of continuous tuning was limited to several kilohertz. In the case where the two CW lasers share the same optical comb, when scanning the frequency interval of the comb, the optical frequencies of the two CW lasers change simultaneously. This common-mode change cancels most of the optical frequency change in the two CW lasers. As a result, the continuous tuning range of the CW-THz wave is much smaller than that of the optical frequency in the CW lasers. To increase the continuous tuning range of the CW-THz wave while maintaining high frequency accuracy and stability, a CW-THz generator has been achieved by photomixing of an accurately tunable CW laser and a tightly fixed CW laser in the optical frequency region, phase locked to two independent optical combs [19].

In this paper, we review two techniques for THz frequency metrology based on frequency comb. After describing the coherent link of frequency among microwave, optical, and THz regions achieved by frequency comb techniques in Section II,

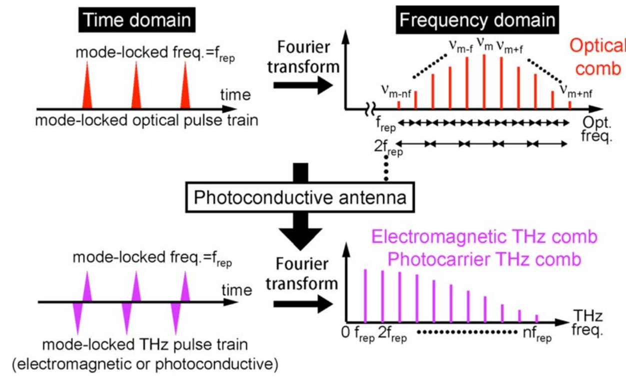

Fig. 1. Optical comb and THz comb.

a THz-comb-referenced spectrum analyzer based on the PC-THz comb and its application for measurement of the CW-THz test sources are presented in Section III [6], [7]. In Section IV, a continuously tunable, single-frequency, CW-THz generator using combination of two independent optical combs with the photomixing technique and its potential for application to a THz clock and synthesizer are demonstrated [19]. Section V then provides conclusions.

II. Coherent Link of Frequency Using Frequency Comb

Fig. 1 shows behavior of optical comb and THz comb in time and frequency domains. A femtosecond mode-locked (fs-ML) laser generates a sequence of pulses that are essentially copies of the same pulse separated by an interval equal to the inverse of the mode-locked frequency of $f_{\rm rep}$. The highly stable fs-ML pulse train is synthesized by a series of frequency spikes regularly separated by the mode-locked frequency $f_{\rm rep}$ in the optical frequency domain. This structure is referred to as a frequency comb. Since the frequency-comb structure can be used as a precision frequency ruler in the optical domain, the fs-ML-laser-based OFC has received a lot of interest as a powerful metrological tool capable of covering the optical region by virtue of precise laser stabilization [16]. Recently, the concept of the frequency comb has been extended to the THz region by combination of the fs-ML pulse trains with the photoconductive process [8]. When a PCA for THz generation is triggered by the fs-ML optical pulse train, a free-space-propagating, mode-locked THz pulse train is radiated from the PCA. This THz pulse train is composed of a regular comb of sharp lines of EM waves in the THz frequency domain, namely, EM-THz comb. On the other hand, when the fs-ML optical pulse train is incident to a PCA for THz detection, a sequence of photoconductive gating is induced in the PCA. Such the photoconductive, mode-locked THz pulse train constructs frequency comb structure of the PC in the THz region, namely, PC-THz comb. In this way, the optical comb is downconverted to the THz region without any change in its frequency spacing. The resulting THz comb is a harmonic frequency comb without any frequency offset, composed of a fundamental component and a series of harmonic components of a mode-locked frequency of $f_{\rm rep}$. This is the biggest difference compared to an OFC having a carrier-envelope offset frequency, which has to be stabilized, and it enables us to achieve simple,

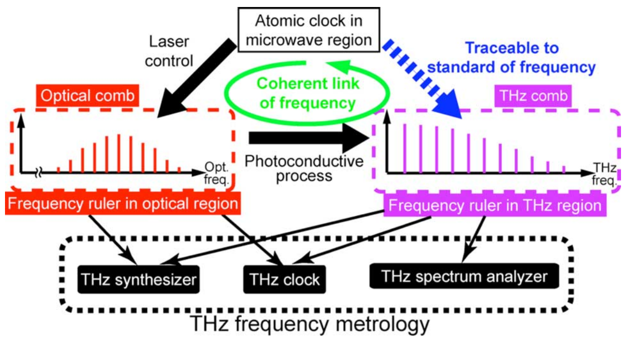

Fig. 2. Coherent link of frequency using frequency comb.

practical THz frequency metrology including stabilization of a THz comb. The THz combs provide attractive features for frequency metrology, namely, simple, broad-band selectivity, high spectral purity, offset free, and absolute frequency calibration. Therefore, if the mode-locked frequency of f_{rep} is well stabilized by the laser control, the THz comb can be used as a precise frequency ruler in the THz region.

Fig. 2 shows the concept of THz frequency metrology based on the frequency comb. Atomic clock in the microwave region has been widely used as a standard of time and frequency. However, it has been difficult to transfer the frequency accuracy of the atomic clock to the optical region due to the large gap of frequencies between the microwave and optical regions. Although such the gap has been bridged by the phase-coherent frequency measurement using the frequency chain [20], it is quite bulky and complicated apparatus. Furthermore, the frequency uncertainty is accumulated while passing through many intermediate oscillators in the chain. Recently, optical comb has emerged as a powerful tool to link the frequency between the microwave and optical regions directly without losing its accuracy by achieving the precise laser stabilization with the atomic clock [16]. Furthermore, the optical comb has been extended to the THz region using the PCA, as shown in Fig. 1 [8]. Here, most important point is that connection of frequency among microwave, optical, and THz regions is based on the coherent process, such as laser control and photoconductive process. This coherent link of frequency enables to maintain the same frequency accuracy in three different regions of EM wave. Therefore, based on the THz comb or optical comb, one can construct the THz frequency metrology, directly connected to a standard of frequency. In this way, THz frequency metrology traceable to time of the SI base units can be established.

III. THz-Comb-Referenced Spectrum Analyzer

A. Principle of Operation

In the field of microwave technology, harmonic mixing technique based on electrooptic sampling has been often used to downconvert microwave spectrum to RF spectrum, using the comb spectrum of the mode-locked laser with a nonlinear detection technique [21], [22]. Futhermore, this technique has been extended to the THz region [10]. We here modified this technique to downconvert THz spectrum to RF spectrum using photoconductive detection. Our THz spectrum analyzer is based on a heterodyne technique, as shown in Fig. 3(a). In this heterodyne method, the PC-THz comb is used as an RF signal with multiple frequencies covering from the sub-THz to THz regions, whereas a measured CW-THz wave works as a local oscillator. Therefore, the moderate power is required for the measured CW-THz wave [6], [7] compared with cryogenic-cooling heterodyne methods. However, combined use of the PCA and the PC-THz comb enables heterodyne mixing covering from the sub-THz to THz regions at room temperature.

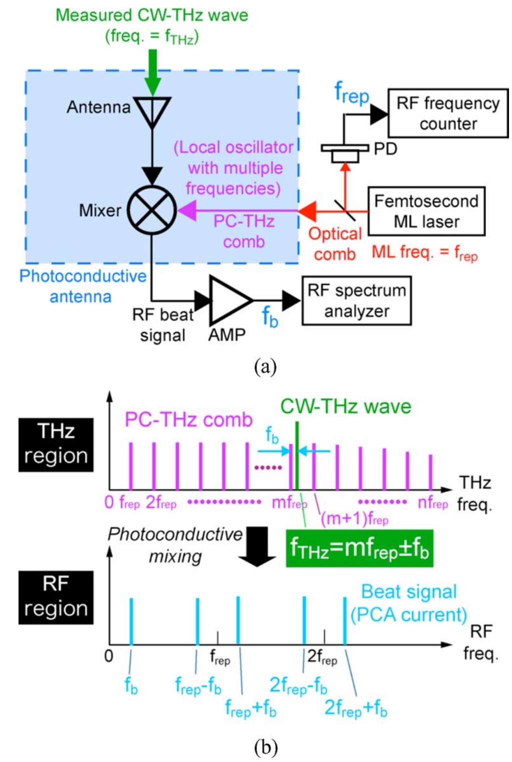

Fig. 3. (a) Principle of THz-comb-referenced spectrum analyzer and (b) corresponding spectral behavior in THz and RF regions.

Consider a PCA detector when an fs-ML laser light (probe pulse with repetition frequency f_{rep}) is incident on the antenna gap of a photoconductive film. Fig. 3(b) illustrates the corresponding spectral behaviors in THz and RF regions. The probe pulse train emitted from the fs-ML laser constructs an OFC in the frequency domain, whose mode spacing is equal to a mode-locked frequency (see Fig. 1). When the PCA is triggered by such pulse train, the PC-THz comb is induced in the PCA. Next, consider what happens when a measured CW-THz wave (frequency $= f_{\mathrm{THz}}$) is incident on a PCA detector triggered by the probe pulse train. The photoconductive mixing process in the PCA generates a group of beat signals between the CW-THz wave and the PC-THz comb in the RF region. Focus on a beat signal at the lowest frequency ($= f_b$), namely, f_b beat signal. Since this f_b beat signal is generated by mixing the CW-THz wave (frequency $= f_{\mathrm{THz}}$) with the *m*th mode of the PC-THz comb (frequency $= mf_{\mathrm{rep}}$) nearest in frequency to the CW-THz wave, f_{THz} is given as follows

$$f_{\mathrm{THz}} = mf_{\mathrm{rep}} \pm f_b. \tag{1}$$

Since f_{rep} and f_b can be measured by RF frequency instruments, f_{THz} can be determined if the value of *m* and the sign of f_b are measured. To this end, the mode-locked frequency is changed from f_{rep} to $f_{\mathrm{rep}} + \delta f_{\mathrm{rep}}$ by adjustment of the laser cavity length with the laser control system. This results in a change of the beat frequency from f_b to $f_b + \delta f_b$. Since $|\delta f_b|$ is equal to $|m\delta f_{\mathrm{rep}}|$, the value of *m* is determined as

$$m = \frac{|\delta f_b|}{|\delta f_{\mathrm{rep}}|}. \tag{2}$$

The sign of $\delta f_b / \delta f_{\mathrm{rep}}$ is opposite to that of f_b. Finally, the absolute frequency of the measured CW-THz wave can be determined by measuring f_{rep}, f_b, δf_{rep}, and δf_b because

$$f_{\mathrm{THz}} = m f_{\mathrm{rep}} + f_b \qquad \left(\frac{\delta f_b}{\delta f_{\mathrm{rep}}} < 0\right) \tag{3a}$$

and

$$f_{\mathrm{THz}} = m f_{\mathrm{rep}} - f_b \qquad \left(\frac{\delta f_b}{\delta f_{\mathrm{rep}}} > 0\right). \tag{3b}$$

B. Experimental Setup

Fig. 4 shows a schematic diagram of the experimental setup. The THz-comb-referenced spectrum analyzer was composed of a home-built, fs-ML erbium (Er)-doped fiber laser (center wavelength = 1550 nm, pulse duration = 40 fs, and f_{rep} = 56 122 206 Hz) [23], a PCA for THz detection, and RF frequency instruments. The mode-locked frequency f_{rep} was stabilized using a laser control system referenced to an Rb atomic clock (Stanford Research Systems FS725 with frequency = 10 MHz, accuracy = 5×10^{-11}, stability = 2×10^{-11} at 1 s). The output of the fiber laser was delivered to a bowtie-shaped, low-temperature-grown InGaAs/InAlAs PCA for a 1550-nm laser light (Menlo Systems GmbH, BT10) by an optical fiber. This results in generation of the PC-THz comb in the PCA equivalent to the Rb atomic clock. The CW-THz wave from a test source propagated in free space through a pair of THz lens (Pax Company, Tsurupica), and was then incident on the PCA. Photoconductive heterodyne mixing between the CW-THz wave and the PC-THz comb in the PCA generates beat signals in the RF region. The f_b beat signal is amplified by a high-gain current preamplifier (bandwidth = 10 MHz and sensitivity = 10^5 V/A) and was measured with an RF spectrum analyzer (Agilent E4402B with a frequency range of 100 Hz to 3 GHz) and an RF frequency counter (Agilent 53132 A with a frequency range to 225 MHz) to determine its spectral shape and center frequency. A portion of the laser light is detected with a photodetector, and its mode-locked frequency (=f_{rep}) is measured using the RF frequency counter. The RF spectrum analyzer and RF frequency counter are synchronized to the Rb atomic clock.

C. Results

1) Test Source Based on Active Frequency Multiplier Chain: The first test source (output power = 4 dBm = 2.5 mW, frequency range = 75–110 GHz, and linewidth < 0.6 Hz) is achieved by combination of an active frequency multiplier chain (AFMC) (Millitech AMC-10-R0000 with multiplication

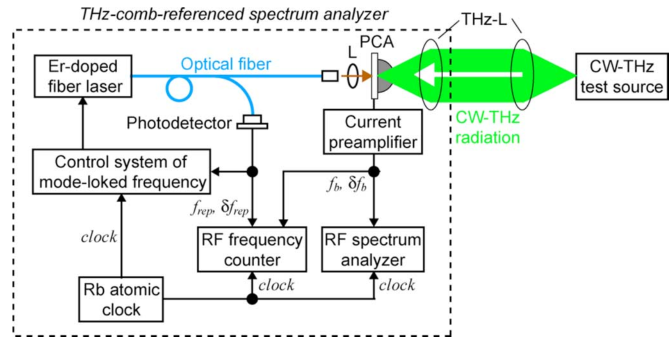

Fig. 4. Experimental setup of THz-comb-referenced spectrum analyzer. L: lens; PCA: bowtie-shaped, low-temperature-grown InGaAs/InAlAs PCA; THz-L: THz lenses.

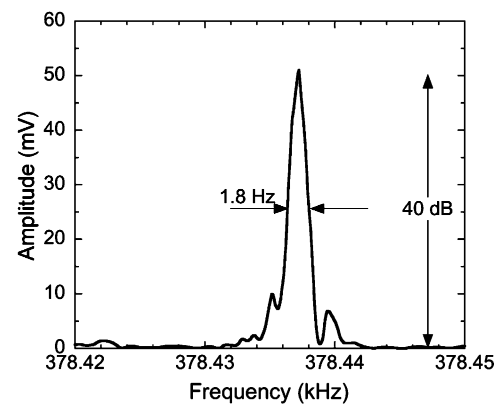

Fig. 5. Spectra of the f_b beat signal of the AFMC source measured by the RF spectrum analyzer (RBW = 1 Hz and sweep time = 690 ms).

factor = 6) and a microwave frequency synthesizer (Agilent E8257D with frequency = 12.5–18.33 GHz), referred to as an AFMC source. Since the frequency synthesizer is synchronized to the Rb atomic clock, output frequency of this AFMC source is accurate and stable. We first evaluated the spectral linewidth of the f_b beat signal when the output frequency of the AFMC source is set to be 100 GHz. Fig. 5 shows a linear-scale spectrum of this signal, measured by the RF spectrum analyzer [resolution bandwidth (RBW) = 1 Hz and sweep time = 690 ms]. The resulting linewidth of the beat signal was 1.8 Hz. This result indicates that each mode of the PC-THz comb has sufficiently narrow linewidth to perform the frequency measurement with high precision. On the other hand, the signal-to-noise ratio (SNR) of the f_b beat signal reached 40 dB. From this SNR and the output power of the test source (namely, +4 dBm = 2.5 mW), the detection limit of the THz power is estimated to −36 dBm, or 250 nW. Comparison of SNR among the f_b beat signals obtained by three different PCAs and electrooptic sampling is given in detail elsewhere [7].

To determine the absolute frequency of the test source, it is necessary to measure the deviation of f_b before and after changing f_{rep}. The initial f_{rep} and f_b values were measured to be 56 122 206.03 and 356 156 Hz as indicated by the blue color in Fig. 6 (RBW = 1 kHz and sweep time = 902 ms). Then, the frequency f_{rep} was changed by δf_{rep} (=+25 Hz), using the laser control system. This resulted in a change of the beat

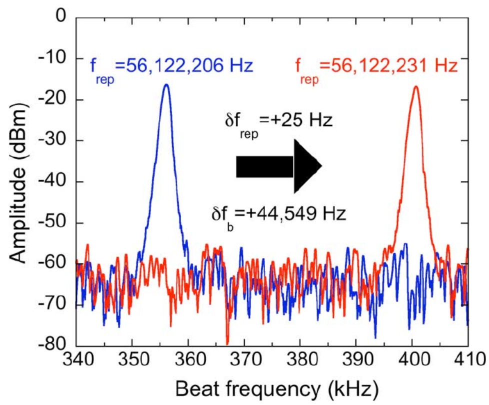

Fig. 6. Spectra of the f_b beat signal when the laser mode-locked frequency ($f_{\rm rep}$) is set at 561 222 06 (blue curve) Hz and 561 222 31 Hz (red curve) (RBW = 1 kHz and sweep time = 902 ms).

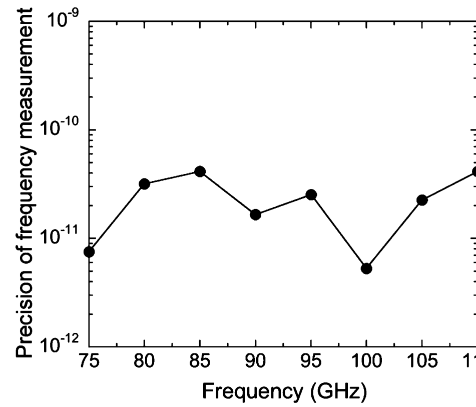

Fig. 7. Precision of frequency measurement in available frequency range of the AFMC source.

frequency by δf_b of 44 549 Hz (see the red color in Fig. 6). Since $|\delta f_b|$ is equal to $|m\delta f_{\rm rep}|$, m is determined as

$$m = \frac{|\delta f_b|}{|\delta f_{\rm rep}|} = \frac{|+44\,549|}{|+25|} = 1781.96 \approx 1782. \quad (4)$$

Since the sign of $\delta f_b/\delta f_{\rm rep}$ (positive in this case) is opposite to that of f_b, the value of $f_{\rm THz}$ was determined as follows:

$$\begin{aligned} f_{\rm THz} &= m f_{\rm rep} - f_b \\ &= 1\,782 \times 56\,122\,206.03 - 356\,156 \\ &= 100\,009\,414\,989.46 \text{ Hz}. \end{aligned} \quad (5)$$

Since the actual set frequency of the AFMC source was 100 009 414 988.9 Hz from the output frequency of the microwave synthesizer, the error between the set and measured frequencies was only 0.56 Hz.

To evaluate the precision of frequency measurement in available frequency range of the AFMC source, we determined the absolute frequency of the source while tuning its output frequency from 75 to 110 GHz at 5-GHz intervals. When precision of frequency measurement is defined as the ratio of the error to $f_{\rm THz}$, the precision for eight different measurement frequencies was shown in Fig. 7. A mean precision of 2.4×10^{-11} was obtained for this source, which is limited by the performance of the Rb atomic clock. The frequency precision will be further improved if we use a frequency standard having higher accuracy, such as cesium atomic clock, optical clock [24], or optical lattice clock [25].

2) Test Source Based on Photomixing of Two Free-Running CW Lasers With UTC-PD: The second test source was produced by photomixing of two CW near-IR lasers at adjacent wavelengths with a UTC-PD [14]. The two CW lasers were external cavity wavelength-tunable laser diodes with an emission wavelength of 1550 nm and operated in free-running mode (Koshin Kogaku Company, LS-601 A-15S1; spectral linewidth $\leq$100 kHz, frequency fluctuation $<$100 MHz/h). The optical frequency difference between them was set to be approximately 120 GHz. The outputs of the lasers were combined using a fiber coupler, amplified with an Er-doped fiber amplifier, and then

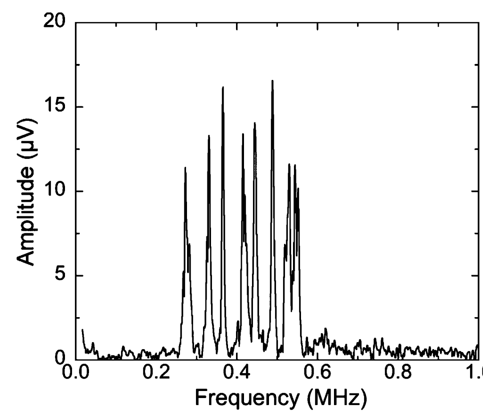

Fig. 8. Spectrum of the f_b beat signal of the photomixing source (RBW = 1 kHz and sweep time = 13 ms).

photomixed by a F-band UTC-PD [Nippon Telegraph and Telephone (NTT) Electronics, available frequency = 90–140 GHz] equipped with a horn antenna. The output power was set to be 100 μW at a frequency of 120 GHz. We used the THz spectrum analyzer for monitoring of the photomixing source. The resulting image of the beat spectrum is shown in Fig. 8 (RBW = 1 kHz, sweep time = 13 ms). Also, a movie of the beat spectrum is given elsewhere [7]. In contrast to the stable AFMC source, the beat frequency of the photomixing source exhibits large fluctuations within a spectral window of 1 MHz. This is because the two CW lasers used for the photomixing are operated in free-running mode without any frequency control.

3) Test Source Based on EM-THz Comb: It is interesting to investigate the applicability of this THz spectrum analyzer to frequencies above 1 THz because frequency range of the two test sources above were limited to the sub-THz region. Unfortunately, we have no available CW test sources in this frequency region. One possible alternative test source is the EM-THz comb radiating from a PCA emitter triggered by a fs-ML laser (see Fig. 1). Because the EM-THz comb is a group of many CW-THz waves having a frequency spacing equal to the laser mode-locked frequency, it can be used as a test source with multiple frequencies ranging from sub-THz to a few THz.

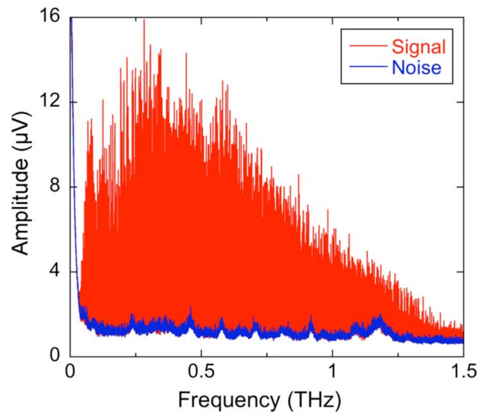

Fig. 9. Spectrum of the EM-THz comb (RBW = 1 kHz and sweep time = 1000 s).

The THz spectrum analyzer was used for capturing the spectrum of the EM-THz comb. Principle and experimental setup of this detection scheme are given in detail elsewhere [7], [8]. The resulting spectrum is shown in Fig. 9 (RBW = 1 kHz and sweep time = 1000 s). The EM-THz comb spectrum was clearly observed over 1 THz. Although it is not so simple to compare the sensitivity between the time-gated sampling measurement in Fig. 9 and the heterodyne measurements in Figs. 5 and 8, the THz spectrum analyzer has sensitivity in the frequencies above 1 THz. The spectral bandwidth of the THz spectrum analyzer should be limited by that of the PCA including characteristics of its photoconductive film and antenna shape, and pulse duration of the fs-ML laser. The spectral sensitivity of the PCA as a THz detector has been previously investigated using THz time-domain spectroscopy, for which a bandwidth of 170 THz was achieved [26]. We consider that the THz spectrum analyzer can be further used for frequency measurement of CW-THz sources oscillating at higher THz frequency, such as THz-QCL.

IV. Continuously Tunable, Single-Frequency CW-THz Generator Referencing Two Independent Optical Combs

A. Principle of Operation

Let us compare the continuous tuning range of photomixing-based CW-THz wave between the previous method, using a single optical comb [18], and our proposed method, using two independent optical combs [19]. We consider the previous method, as shown in Fig. 10(a). Two CW lasers (CWL1 and CWL2) are, respectively, phase locked to two different modes (n_1 and n_2) of a single OFC(frequency interval of comb modes = $f_{\rm rep}$) and are then optically heterodyned by a photomixer to generate CW-THz wave. The frequency of the CW-THz wave ($f_{\rm THz}$) is determined by the optical frequency separation of the two CW lasers. Therefore, it is possible to generate $f_{\rm THz}$ discretely in increments of $f_{\rm rep}$ within the spectral bandwidth of the photomixer by selection of the targeted modes n_1 and n_2. Furthermore, $f_{\rm THz}$ can be tuned continuously by scanning $f_{\rm rep}$ while locking the two CW lasers to the comb. In this case, the range of continuous tuning ($\Delta f_{\rm THz}$) is determined by the product of the scanning

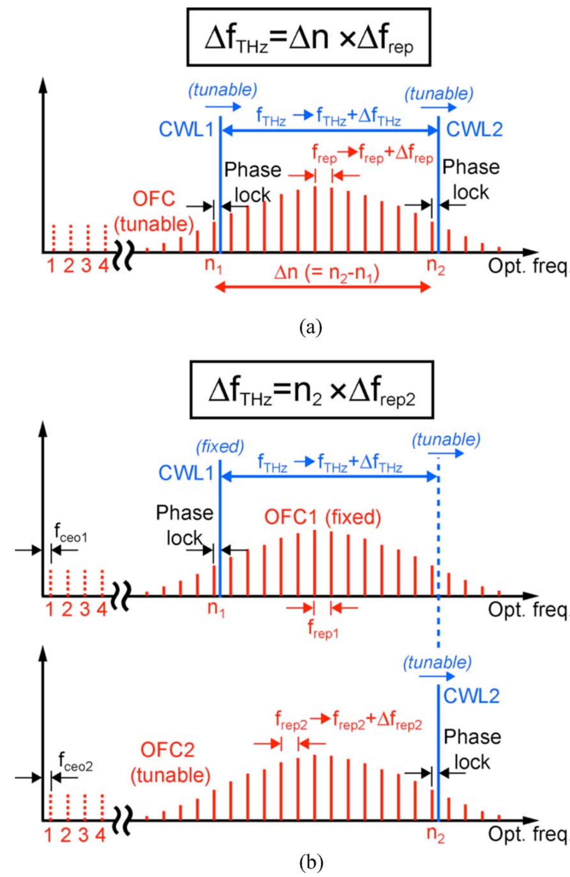

Fig. 10. Continuous tuning of the CW-THz wave based on photomixing of (a) two CW lasers (CWL1 and CWL2) referenced to a single OFC and (b) two CW lasers (CWL1 and CWL2) referenced to two independent optical combs (OFC1 and OFC2).

range of $f_{\rm rep}$ ($\Delta f_{\rm rep}$) and the number of comb lines between the two CW lasers ($\Delta n = n_2 – n_1$). For example, $\Delta n = 20\,000$ when $f_{\rm THz} = 1$ THz and $f_{\rm rep} = 50$ MHz, and $\Delta n = 2000$, when $f_{\rm THz} = 0.1$ THz and $f_{\rm rep} = 50$ MHz. Therefore, when $\Delta f_{\rm rep} = 500$ kHz, which is 1% of $f_{\rm rep}$, $\Delta f_{\rm THz} = 10$ GHz, and 1 GHz, for $f_{\rm THz} = 1$ THz and 0.1 THz, respectively.

In our method, consider that the two CW lasers (CWL1 and CWL2) are, respectively, phase locked to two independent optical combs (OFC1 and OFC2), as shown in Fig. 10(b). We assume that the carrier-envelope offset frequencies ($f_{\rm ceo1}$ and $f_{\rm ceo2}$) of the two combs are fixed by respective laser control. If the repetition frequency of OFC2 ($=f_{\rm rep2}$) is tunable (tunable range = $\Delta f_{\rm rep2}$), whereas that of OFC1 ($=f_{\rm rep1}$) is fixed, the continuously tuning range of the CW-THz wave ($\Delta f_{\rm THz}$) is determined by the product of $\Delta f_{\rm rep2}$ and the comb mode (n_2) to which the CW laser used for tuning (CWL2) is locked. The value of n_2 reaches 3 880 000 when the optical frequency of the CWL2 is 194 THz (corresponding wavelength = 1550 nm) and $f_{\rm rep2}$ is 50 MHz, which is two orders of magnitude higher than the value of Δn for photomixing with $f_{\rm THz} = 1$ THz. Furthermore, when $f_{\rm THz}$ is set to 0.12 THz, as demonstrated in the following experiments, the value of n_2 is three orders of magnitude higher than the value of Δn. In this method, with $\Delta f_{\rm rep} = 500$ kHz, the frequency tuning

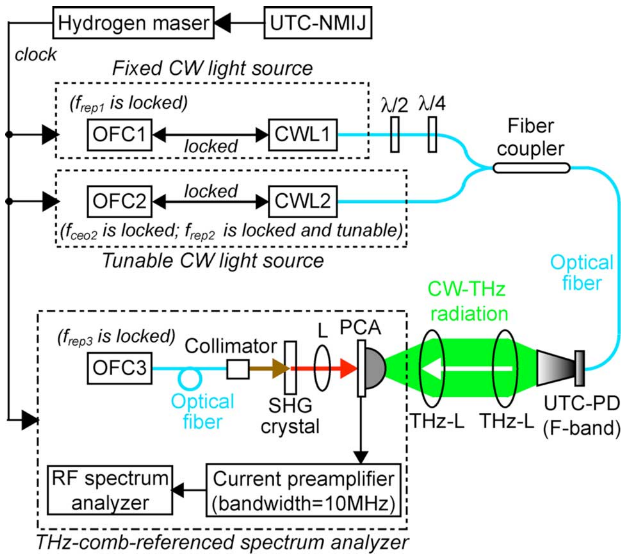

Fig. 11. Experimental setup of continuously tunable, single-frequency CW-THz generator. OFC1, OFC2, and OFC3: OFCs; CWL1 and CWL2: CW near-IR lasers; λ/2: half-wave plate; λ/4: quarter-wave plate; UTC-PD for photomixing; L: lenses; PCA: bowtie-shaped, low-temperature-grown GaAs PCA; THz-L: THz lenses; SHG crystal; UTC-NMIJ.

range of the THz wave, Δf_{THz}, could reach 2 THz. Therefore, our method enables a large increase in the continuously tuning range Δf_{THz} of the CW-THz wave compared with the previous method.

B. Experimental Setup

The experimental setup of the proposed method is shown in Fig. 11. We prepared two CW lasers operating at a wavelength of 1542 nm for photomixing. One was a distributed feedback fiber laser (CWL1; Koheras A/S, Inc., AdjustiK E15-PM), and the other was an external cavity laser diode (CWL2; Optical Comb, Inc., LT-5001). The optical frequency difference between them was set to approximately 120 GHz by using an optical wavemeter (Advantest Corporation, Q8326). CWL1 and CWL2 were, respectively, phase locked to two independent optical combs of home-built, fs-ML Er-doped fiber lasers operating at a center wavelength of 1550 nm (OFC1 with $f_{\mathrm{rep1}} = 48.683$ MHz, and OFC2 with $f_{\mathrm{rep2}} = 51.150$ MHz) [23]. Details of the phase-locking process are given elsewhere [27]. The frequencies f_{rep1}, f_{rep2}, and f_{ceo2} were phase locked to microwave references synthesized from a hydrogen maser linked to coordinated universal time operated by the National Metrology Institute of Japan (UTC-NMIJ). Although f_{ceo1} is also an important parameter for the final characteristics of this CW-THz generator as discussed later, it was not stabilized in the presented system. However, we consider that principle and usefulness of this CW-THz generator can be confirmed even though f_{ceo1} is not stabilized. CWL1, which was phase locked to OFC1, was used as a fixed CW light source in our method, whereas CWL2, which was phase locked to OFC2, was used as a tunable CW light source. In the present system, the optical frequency of n_2 in OFC2 could be continuously tuned over 1.7 THz by making full use of the scanning range of f_{rep2} ($\Delta f_{\mathrm{rep2}} = 450$ kHz). However, continuously tuning range of CWL2 without the mode hopping was limited to 110 GHz due to the stroke of a piezoelectric actuator used to tilt a diffraction grating for wavelength tuning. As a result, the optical frequency of the tunable light source could be continuously tuned over 110 GHz without losing phase locking of CWL2 to OFC2 by varying the repetition frequency over 30 kHz with a variable optical delay line module in OFC2 [27]. If we use another CW laser having broader tunability without the mode hopping for CWL2, it should be possible to extend tuning range of the tunable light source to 1.7 THz. Work is in progress to extend the tuning range over 1 THz.

The outputs of CWL1 and CWL2 were combined with a fiber coupler and then photomixed by an F-band UTC-PD (NTT Electronics, available frequency = 90–140 GHz) equipped with a horn antenna. The polarization of CWL1 was well aligned with that of the CWL2 by adjusting a half-wave plate (λ/2) and a quarter-wave plate (λ/4). The photocurrent of the UTC-PD was set to 6.9 mA by controlling the output powers of CWL1 and CWL2. This resulted in CW-THz wave with an average power of 250 μW at a frequency of 120 GHz.

To evaluate the spectral characteristics of this CW-THz generator, we used a fiber-based, THz-comb-referenced spectrum analyzer [7]. The free-space-propagating CW-THz wave passing through a pair of THz lenses (Pax Company, Tsurupica) was made incident on a bow-tie-shaped, low-temperature-grown GaAs PCA in the THz spectrum analyzer. The PCA was triggered by the second-harmonic-generation (SHG) light (center wavelength = 775 nm) from another repetition-frequency-locked fiber-laser comb (OFC3 with $f_{\mathrm{rep3}} = 49.996$ MHz). This resulted in the generation of a photoconductive self-beat signal of OFC3 in the PCA, namely, a PC-THz comb [8]. The beat current signal from the PCA was amplified by a high-gain current preamplifier (bandwidth = 10 MHz and sensitivity = 10^5 V/A) and was measured with an RF spectrum analyzer. To check the validity of the absolute frequency measured by the THz spectrum analyzer, we also determined the absolute frequency of the CW-THz generator by measuring the optical frequency of two light sources with the optical wavemeter.

C. Results

1) Generation of Frequency-Locked CW-THz Wave: To evaluate the potential performance of this system as a THz clock, we generated frequency-locked CW-THz wave by photomixing two fixed light sources. Here, the combination of CWL2 and OFC2 in Fig. 11 was also used as a fixed light source. The blue curve in Fig. 12 illustrates the linear-scale spectrum of the f_b beat signal, measured by the RF spectrum analyzer (RBW = 10 kHz, sweep time = 189 ms, number of integrated signals = 100). Also, a movie of the beat spectrum is given elsewhere [19]. Compared with the frequency spectrum of the CW-THz wave generated by photomixing of two free-running CW lasers (see Fig. 8), the frequency fluctuation of the CW-THz wave is effectively suppressed in the presented CW-THz generator due to precise stabilization control of two CW lasers based on two optical combs. The linewidth of the CW-THz wave was 1.093 ±

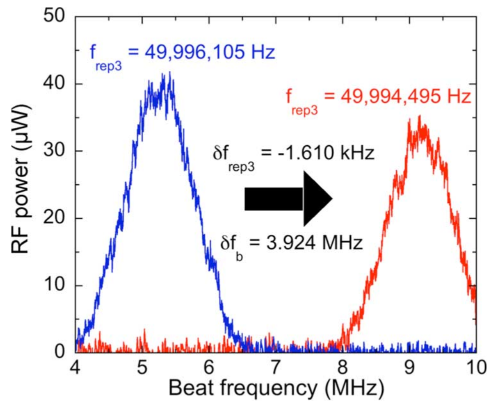

Fig. 12. Spectra of f_b beat signal when f_{rep3} is set at 499 961 05 Hz (blue curve) Hz and 499 944 95 Hz (red curve) (RBW = 10 kHz, sweep time = 189 ms, number of integrated signals = 100).

0.008 MHz when a Lorentzian function was fitted to the spectral shape. CWL1 and CWL2 had linewidths of 0.890 and 1.07 MHz when phase locked to OFC1 and OFC2, respectively. Since the convolution of them gave a linewidth of 0.97 MHz, slight broadening of the linewidth occurred. We consider that the free-running f_{ceo1} was the source of this broadening. The linewidth of the CW lasers used in the present system was limited by the frequency response of piezoelectric transducers used to control their optical frequencies in addition to the spectral linewidth in the free-running mode. Fast feedback control of CW lasers further decreases the linewidth of the CW-THz wave.

To obtain the absolute frequency of the CW-THz wave ($=f_{\mathrm{THz}}$), we measured the deviation of f_b before and after changing f_{rep3}. The initial f_{rep3} was measured to be 49 996 105 Hz with an RF frequency counter. The value of f_b was calculated to be 5.264 MHz by the curve fitting, in which uncertainty of ± 2 kHz was achieved using the regression analysis based on Levenberg–Marquardt algorithm. To determine *m* and the sign of f_b, f_{rep3} was changed by δf_{rep3} ($=-1.610$ kHz). This resulted in a change of the beat frequency by δf_b ($=+3.924$ MHz), as shown in the red curve in Fig. 12. Since $|\delta f_b|$ is equal to $|m\delta f_{\mathrm{rep3}}|$, *m* is determined from

$$m = \frac{|\delta f_b|}{|\delta f_{\mathrm{rep3}}|} = \frac{|+3.924 \times 10^6|}{|-1.610 \times 10^3|} = 2.437 \times 10^3. \quad (6)$$

Finally, because the sign of $\delta f_b/\delta f_{\mathrm{rep3}}$ (negative in this case) is opposite the sign of f_b, f_{THz} was determined as follows:

$$\begin{aligned} f_{\mathrm{THz}} &= m f_{\mathrm{rep3}} + f_b \\ &= 2.437 \times 10^3 \times 4.999\,610\,5 \times 10^7 + 5.264 \times 10^6 \\ &= 121.85\,\mathrm{GHz}. \end{aligned} \quad (7)$$

We next measured the optical frequencies of CWL1 and CWL2 using an optical wavemeter. Since the resulting frequencies were 194.405 46 and 194.526 55 THz, respectively, f_{THz} was 121.09 GHz. Therefore, there was a discrepancy of 760 MHz, or 0.63%, between the THz spectrum analyzer measurement and the optical wavemeter measurement. Since the optical frequency resolution of the wavemeter (=10 MHz) were much smaller than this discrepancy, the error caused by the wavemeter measurement is likely to be negligible. Since the THz spectrum analyzer had the sufficiently high precision of frequency measurement as the demonstrated in the previous section, we estimated the two major components for the uncertainty of the CW-THz generator induced in the THz spectrum analyzer measurement as follows. One component originated in the peak analysis used to determine f_b by the curve-fitting analysis of the spectral shape. The actual uncertainty in this peak analysis was estimated to be 2 kHz for the f_b value of 5.264 MHz, which is caused by the distorted spectral shape and broad linewidth of the beat signal. This causes an error of ± 2 when determining the *m* value based on (6). Therefore, the uncertainty in the peak analysis would lead to an uncertainty of 100 MHz, or 0.083%, in the value of f_{THz} obtained based on (7). The other component was fluctuation of f_{ceo1} because it was not stabilized. To evaluate the fluctuation of f_{ceo1}, we measured the frequency deviation of the f_b beat signal during a 4-min period, which was equal to the measurement time required for the experiment, as shown in Fig. 12, using the THz spectrum analyzer. The resulting frequency deviation was 25.5 kHz. This f_b deviation leads to a deviation of 800 MHz, or 0.65%, in the value of f_{THz} obtained based on (6) and (7). Taking the root-sum-square of these two major components, the total uncertainty was estimated to be 810 MHz, or 0.65%. Therefore, the discrepancy between the THz spectrum analyzer measurement and the optical wavemeter measurement was within the estimated uncertainty of the CW-THz generator. If f_{ceo1} was further stabilized in the same manner as f_{ceo2}, the relative standard uncertainty in the CW-THz generator would be substantially decreased. Further improvement is expected if the linewidth of the CW-THz wave can be narrowed by fast feedback control of the CW lasers. The resulting CW-THz generator can be used as an F-band THz clock with accuracy and stability equal to those of the reference frequency standard used.

2) Generation of Frequency-Tuned CW-THz Wave: The current CW-THz generator can fully cover the available spectral bandwidth of the F-band UTC-PD photomixer because CWL2 achieves continuous tuning of 110 GHz without losing phase locking to the COMB2 [27]. We here show the result of continuous tuning of the CW-THz wave around 121.85 GHz by scanning f_{rep2} at 0.14 Hz intervals. The resulting consecutive spectra of the CW-THz wave are shown in Fig. 13 (RBW = 10 kHz, sweep time = 189 ms, number of integrated signals = 100), in which the horizontal coordinate is scaled by the THz spectrum analyzer. Furthermore, a movie of the beat spectrum is given elsewhere when the output frequency is continuously tuned over 16 MHz [19]. The reason why the amplitude of the THz spectrum decreases as the frequency increases is frequency dependence of the gain in the current preamplifier used in the THz spectrum analyzer rather than decrease of the output power from the UTC-PD.

We fitted their spectral shapes to Lorentzian functions and determined the center frequencies of the CW-THz wave (f_{THz}) in nine consecutive spectra in Fig. 13. The relationship between the change of $f_{\mathrm{rep2}}(\Delta f_{\mathrm{rep2}})$ and that of $f_{\mathrm{THz}}(\Delta f_{\mathrm{THz}})$ is shown by the red color in Fig. 14. A relationship was found in the form $\Delta f_{\mathrm{THz}} = n_2 \Delta f_{\mathrm{rep2}}$, where $n_2 = 3\,757\,241$, with a

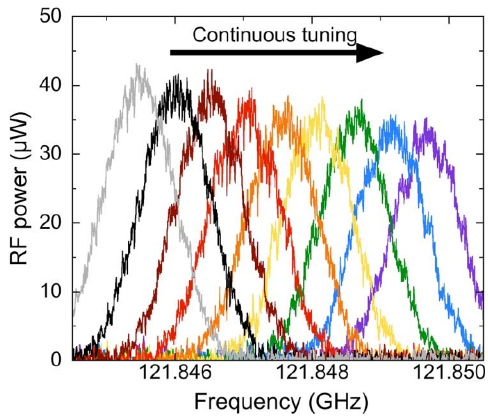

Fig. 13. Continuous tuning of the CW-THz wave around 121.85 GHz by scanning f_{rep2} at 0.14-Hz intervals (RBW = 10 kHz, sweep time = 189 ms, number of integrated signals = 100).

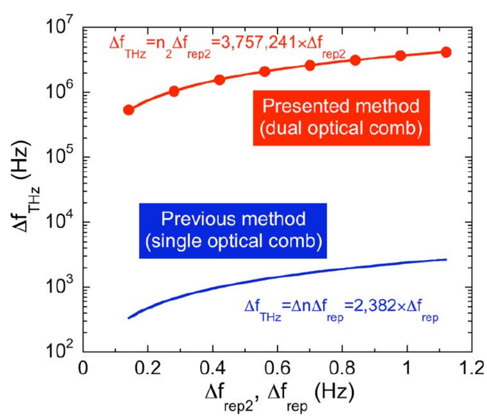

Fig. 14. Relationship between change of f_{rep2} or f_{rep} (Δf_{rep2} or Δf_{rep}) and that of f_{THz} (Δf_{THz}) for the presented method, using a dual optical comb, and the previous method, using a single optical comb.

regression coefficient of 0.999 92. Although Δf_{rep2} was changed by only 1.12 Hz in Fig. 14, the tuning rate n_2 is maintained in full range of Δf_{rep2} (=450 kHz). In this case, Δf_{THz} reaches 1.7 THz. For comparison, we also indicated a theoretical relationship between Δf_{rep} and Δf_{THz} ($\Delta f_{\mathrm{THz}} = \Delta n \Delta f_{\mathrm{rep}}$) in the previous method, using a single optical comb (frequency interval of comb modes = f_{rep} = 51.150 MHz) by the blue color when f_{THz} was set to around 121.85 GHz. The resulting Δn was 2382. It is important to note that the tuning rate n_2 of the present method was three orders of magnitude larger than the tuning rate Δn of the previous method. This resulted in a large expansion of the continuous tuning range of the CW-THz wave.

From the optical wavemeter measurement, we also determined n_2 to be 3 803 061. Although there is a discrepancy of 45 820, or 1.2%, in these n_2 values, we attributed the main cause of this discrepancy to the fluctuation of f_{ceo1}, as discussed in the previous section. The acquisition time for all spectra in Fig. 13 was about 25 min. The frequency drift of the measured f_b beat signal indicated that f_{ceo1} changed by 250 kHz in 25 min. Since this deviation of f_{ceo1} shifts Δf_{THz} by 250 kHz between the beginning and end of the experiment of Fig. 13, it leads to an error in n_2 of 238 679, or 6.3%. Therefore, the discrepancy between the two n_2 values is within the uncertainty of the CW-THz generator. This can be further improved if the range of the frequency scanning is increased, together with stabilizing f_{ceo1}. Smooth tuning of the CW-THz wave over 16 MHz was achieved elsewhere [19], although the signal power became smaller at higher frequencies due to the frequency response of the current preamplifier used in the THz spectrum analyzer. It should be emphasized that the tuning range of this demonstration is not limited by the proposed CW-THz generator but by the electrical bandwidth of the current preamplifier. Therefore, we believe that it should be possible to extend the tuning range to 110 GHz in the current system because we have already demonstrated continuous tuning of 110 GHz in the optical domain, using the same setup [27]. Although the THz-QCL [13] and the AFMC source (see Fig. 7) have greater or similar tuning range at the sub-THz and THz regions, the proposed CW-THz generator has the potential to exceed them in wide tunability. If we use a broad-band photomixer, such as PCA [15], and extend tuning range of CWL2 over a few THz, it will be possible to extend tuning range of this CW-THz generator to 1.7 THz at arbitrary center frequencies.

V. Conclusion

We reviewed two techniques of THz frequency metrology based on the frequency comb. Most important point in this review is that the coherent link of frequency established by the frequency comb enables to realize the THz frequency metrology traceable to time of the SI base units. The THz-comb-referenced spectrum analyzer achieved the absolute frequency measurement of the CW test sources at the precision of 10^{-11}, which is limited by the performance of the Rb atomic clock used. We also confirmed that spectral bandwidth of this THz spectrum analyzer was extended over 1 THz. Next, continuously tunable, single-frequency CW-THz generator was demonstrated around 120 GHz by photomixing of two stabilized CW lasers referenced to two independent optical combs. The continuous tuning rate n_2 in the presented method was enhanced by three orders of magnitude larger than that Δn of the previous method, using the single comb. There was a discrepancy of the absolute frequency of the CW-THz generator between the THz spectrum analyzer measurement and the optical wavemeter measurement due to the free-running f_{ceo1}. However, if the f_{ceo1} is further stabilized, it should be emphasized that the absolute THz frequency can be determined at the precision of the frequency standard used, such as the hydrogen maser or Rb atomic clock, by measuring f_{ceo1} (fixed), f_{ceo2} (fixed), f_{rep1} (fixed), f_{rep2} (tunable), n_1 (fixed), n_2 (fixed), and beat frequency (fixed) between CWL1 (CWL2) and OFC1 (OFC2). This is the big advantage over other tunable CW-THz sources [28]. Therefore, this CW-THz generator has the high potential for application to a THz clock and synthesizer. On the other hand, from the standpoint of practical use, these fiber-based techniques have the advantage of being a portable, alignment-free, robust, and flexible apparatus. The combination of the CW-THz generator with the THz-comb-referenced spectrum analyzer will pave the way for establishment of frequency metrology in the THz region.

ACKNOWLEDGMENT

The authors would like to thank R. Nakamura, A. Ihara, M. Nose, K. Kawamoto, and Y. Fujimoto of the Graduate School of Engineering Science, Osaka University, and H. Takahashi and Y. Iwamoto of the Faculty of Science and Technology, Tokyo University of Science for their experimental support for the part of the work. T. Yasui is grateful to Drs. I. Hosako and N. Sekine from the National Institute of Information and Communications Technology for fruitful discussions.

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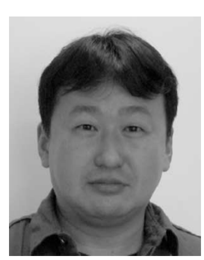

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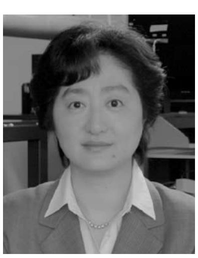

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