Continuously tunable, phase-locked, continuous-wave terahertz generator based on photomixing of two continuous-wave lasers locked to two independent optical combs

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A continuously tunable, phase-locked, single-frequency, continuous-wave (cw) terahertz generator has been demonstrated around 120 GHz, corresponding to the spectral bandwidth of the F-band unitraveling-carrier photodiode (UTC-PD) used as a photomixer in this study. This cw-terahertz generator is based on 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 continuous tuning range of the presented method was three orders of magnitude around 0.1 THz and two orders around 1 THz broader than that of a previous photomixing method in which two cw lasers are phase locked to a single optical comb, and fully covered the available spectral bandwidth of the F-band UTC-PD. The spectral behavior of the tight locking and continuous tuning of 120 GHz cw-terahertz radiation was confirmed in real time by use of a terahertz-comb-referenced spectrum analyzer. This cw-terahertz generator shows promise as a terahertz clock and synthesizer for terahertz frequency metrology. © *2010 American Institute of Physics*. [doi:10.1063/1.3305324]

I. INTRODUCTION

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

Recently, terahertz spectrum analyzers based on a photocarrier terahertz frequency comb[2–4] and a nonsynchronized electro-optic sampling technique[5] have been proposed and effectively applied to measure the absolute frequency and spectral shape of continuous-wave terahertz (cw-terahertz) radiation. On the other hand, accurate, stable, and tunable cw-terahertz sources are still lacking. Frequency-stabilized cw-terahertz sources have been achieved by active control of a terahertz quantum cascade laser (terahertz-QCL);[6,7] however, it is difficult to tune the frequency in a broad range due to the restricted tunable range of the terahertz-QCL, typically a few hundreds gigahertz depending on its band structure.[8] One promising alternative method for widely tunable cw-terahertz sources is photomixing of two cw near-infrared lasers of adjacent wavelengths with a photomixer, such as a unitraveling-carrier photodiode (UTC-PD)[9] or a photoconductive antenna (PCA).[10] With this method, however, it is difficult to obtain accurate, stable cw-terahertz radiation because the conventional photomixing techniques are based on

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free-running cw lasers without frequency control.[3] If the optical frequencies of the cw lasers for photomixing could be well stabilized in the optical region, photomixing techniques would enable accurate, stable, and tunable cw-terahertz generation.

One attractive frequency reference for simultaneous control of two cw lasers is an optical frequency comb.[11] A stable millimeter-wave synthesizer has been realized by photomixing two cw lasers locked to an optical comb generator based on an electro-optic modulator.[12] Following it, accurate, stable, phase-locked cw-terahertz radiation 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 broadband optical comb based on a mode-locked Ti:sapphire laser.[13] 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 a single optical comb, when scanning the frequency interval of the comb, the optical frequencies of the two cw lasers change simultaneously, like bellows of an accordion. This common-mode behavior cancels most of the optical frequency change in the two cw lasers. As a result, the continuous tuning range of the cw-terahertz radiation is much smaller than that of the optical frequency in the cw lasers. If the optical frequency of one cw laser is made accurately tunable while that of the other cw laser is fixed at a certain value, the continuous tuning range of the cw-terahertz radiation would be greatly enhanced, equaling that of the optical frequency in the tunable cw laser.

In the study described in this paper, we demonstrated continuous tuning of phase-locked cw-terahertz radiation based on photomixing of an accurately tunable cw laser and a tightly fixed cw laser in the optical frequency region. The two cw lasers were, respectively, phase locked to two independent optical combs, based on mode-locked Er-doped fiber lasers,[14] to increase the range of continuous tuning of the cw-terahertz radiation while maintaining high-frequency accuracy and stability. To evaluate the potential of the proposed method for application to a terahertz clock and synthesizer, tight locking and continuous tuning of the cw-terahertz radiation were observed in real time with a fiber-based, terahertz-comb-referenced spectrum analyzer.[3] The currently demonstrated tuning range was over 16 MHz, which is limited by the electrical bandwidth of the terahertz spectrum analyzer used for the measurement. In the current cw-terahertz generation system, however, there are no obstacles to achieving continuous tuning of 110 GHz without losing phase locking to the comb, thus fully covering the available spectral bandwidth of the F-band UTC-PD photomixer used in this study.

II. PRINCIPLE OF OPERATION

Let us compare the continuous tuning range of photomixing-based cw-terahertz radiation between the previous method[13] and our proposed method. We consider the previous method shown in Fig. 1(a). Two cw lasers (CWL1

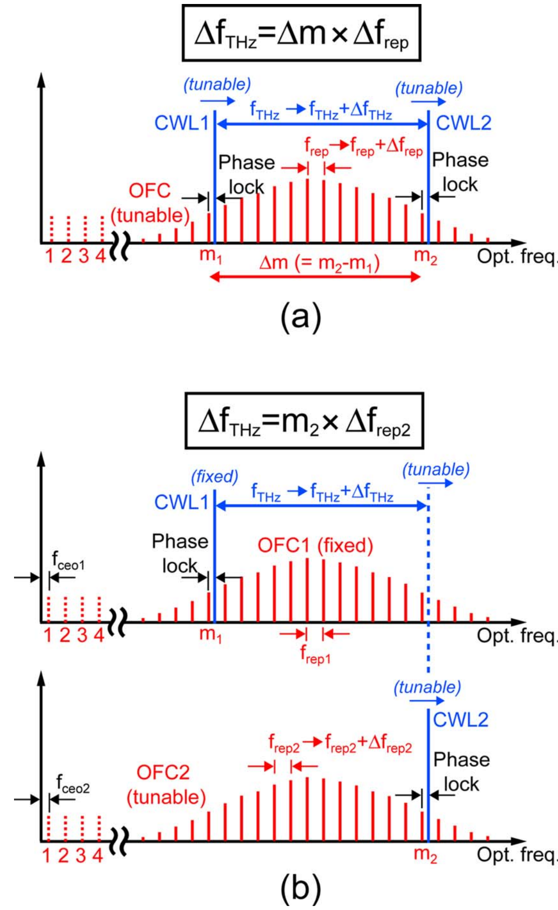

FIG. 1. (Color online) Continuous tuning of the phase-locked cw-terahertz radiation based on photomixing of (a) two cw lasers (CWL1 and CWL2) referenced to a single optical comb (OFC) and (b) two cw lasers (CWL1 and CWL2) referenced to two independent optical combs (OFC1 and OFC2).

and CWL2) are respectively phase locked to two different modes (m_1 and m_2) of a single optical frequency comb (OFC) (frequency interval of comb modes=f_{rep}) and are then optically heterodyned by a photomixer to generate cw-terahertz radiation. The frequency of the cw-terahertz radiation (f_{THz}) is determined by the optical frequency separation of the two cw lasers. Therefore, it is possible to generate f_{THz} discretely in increments of f_{rep} within the spectral bandwidth of the photomixer by selection of the targeted modes m_1 and m_2. Furthermore, f_{THz} can be tuned continuously by scanning f_{rep} while locking the two cw lasers to the comb. In this case, the range of continuous tuning (Δf_{THz}) is determined by the product of the scanning range of f_{rep} (Δf_{rep}) and the number of comb lines between the two cw lasers ($\Delta m = m_2 - m_1$). For example, $\Delta m = 20,000$ when $f_{THz} = 1$ THz and $f_{rep} = 50$ MHz, and $\Delta m = 2000$ when $f_{THz} = 0.1$ THz and $f_{rep} = 50$ MHz. Therefore, when $\Delta f_{rep} = 500$ kHz, which is 1% of f_{rep}, $\Delta f_{THz} = 10$ and 1 GHz, for $f_{THz} = 1$ and 0.1 THz, respectively.

In our method, consider that the two cw lasers (CWL1 and CWL2) are respectively locked to two independent optical combs (OFC1 and OFC2), as shown in Fig. 1(b). We assume that the carrier-envelope offset frequencies (f_{ceo1} and f_{ceo2}) of the two combs are fixed by respective laser control. If the repetition frequency of OFC2 (=f_{rep2}) is tunable (tun-

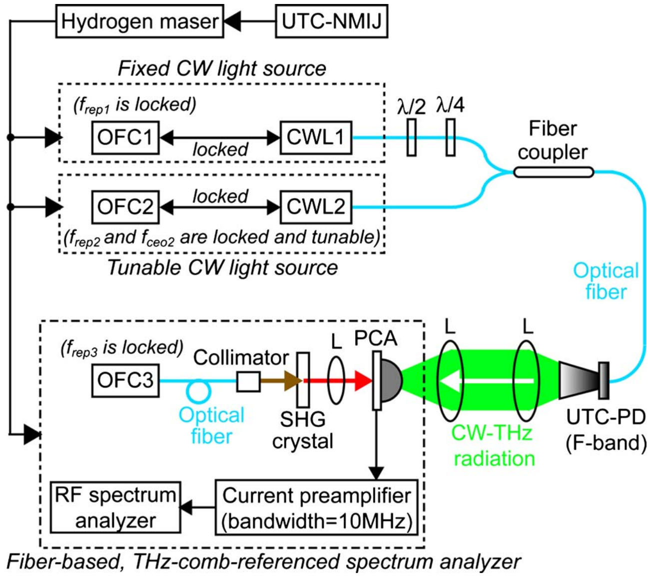

FIG. 2. (Color online) Experimental setup. OFC1, OFC2, and OFC3: optical frequency combs; CWL1 and CWL2: cw near-infrared lasers; $\lambda/2$: half-wave plate; $\lambda/4$: quarter-wave plate; UTC-PD: unitraveling-carrier photodiode for photomixing; L: lenses; PCA: photoconductive antenna; SHG crystal: second-harmonic-generation crystal; UTC-NMIJ: coordinated universal time operated by the National Metrology Institute of Japan.

able range $=\Delta f_{\mathrm{rep2}}$), whereas that of OFC1 ($=f_{\mathrm{rep1}}$) is fixed, the tuning range of the cw-terahertz radiation (Δf_{THz}) is determined by the product of Δf_{rep2} and the comb mode (m_2) to which the cw laser used for tuning (CWL2) is locked. The value of m_2 reaches 3 880 000 when the optical frequency of the CWL2 is 194 THz (corresponding wavelength =1550 nm) and f_{rep2} is 50 MHz, which is two orders of magnitude higher than the value of Δm for photomixing with $f_{\mathrm{THz}}=1$ THz. Furthermore, when f_{THz} is set to 0.12 THz, as demonstrated in the following experiments, the value of m_2 is three orders of magnitude higher than the value of Δm. In this method, with $\Delta f_{\mathrm{rep}}=500$ kHz, the frequency tuning range of the terahertz radiation, Δf_{THz}, could reach 2 THz. Therefore, our method enables a large increase in the continuously tuning range, Δf_{THz}, of the cw-terahertz radiation compared with the previous method.

III. EXPERIMENTAL SETUP

The experimental setup of the proposed method is shown in Fig. 2. 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 Corp., Q8326). CWL1 and CWL2 were respectively phase locked to two independent optical combs of mode-locked 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). Details of the phase-locking process are given elsewhere.[15] 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-terahertz generator as discussed later, it was not stabilized in the presented system due to financial limitation. However, principal objective of this study is to confirm the principle and usefulness of the continuously tunable cw-terahertz generator based on two independent optical combs. We consider that its principle and usefulness 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 m_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). On the other hand, 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.[15] If we use a cw laser having broader tunability 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 CWL2 by adjusting a half-wave plate ($\lambda/2$) and a quarter-wave plate ($\lambda/4$). 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-terahertz radiation with an average power of 250 μW at a frequency of 120 GHz. This power is almost equal to that of the traditional system based on photomixing of two free-running cw lasers with the UTC-PD.

To evaluate the spectral characteristics of the proposed cw-terahertz generator, we used a fiber-based, terahertz-comb-referenced spectrum analyzer (spectral range =0.075–1.5 THz, frequency accuracy $=2.4\times10^{-11}$, spectral resolution=2.3 Hz at a gate time of 1 s, detection limit of terahertz power=11 nW).[2,3] The free-space-propagating cw-terahertz radiation passing through a pair of terahertz lenses (Pax Co., Tsurupica) was made incident on a bow-tie-shaped, low-temperature-grown GaAs PCA in the terahertz spectrum analyzer. The PCA was triggered by 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 photocarrier terahertz comb without frequency offset.[4] The spectrum analyzer was based on a frequency beat measurement between the cw-terahertz radiation and the photocarrier terahertz comb. 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

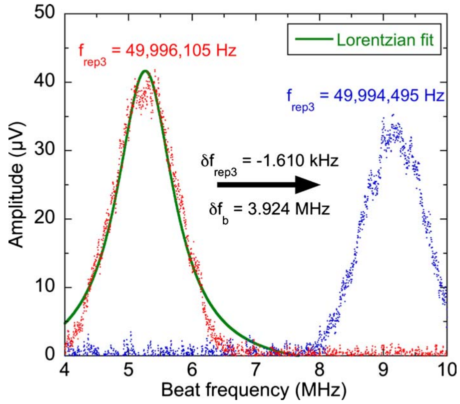

FIG. 3. (Color online) Spectra of f_b beat signal when f_{rep3} is set at 49 996 105 Hz (red plots) and 49 994 495 Hz (blue plots) (sweep time = 189 ms, RBW = 10 kHz, number of integrated signals = 100). The fitting result for the red plots is shown as a green curve for comparison.

measured with a rf spectrum analyzer. Details of the terahertz-comb-referenced spectrum analyzer are given elsewhere.[2,3] The absolute frequency and spectral shape of the cw-terahertz radiation were measured by the terahertz-comb-referenced spectrum analyzer referenced to the frequency standard.

IV. RESULTS

A. Terahertz clock

To evaluate the potential performance of the presented system as a terahertz clock, we generated frequency-locked cw-terahertz radiation by photomixing two fixed light sources. Here, the combination of CWL2 and OFC2 in Fig. 2 was also used as the second light source. The red plots in Fig. 3 illustrates the linear-scale spectrum of a beat signal at the lowest frequency f_b, namely, the f_b beat signal, measured by the rf spectrum analyzer [sweep time = 189 ms, resolution bandwidth (RBW) = 10 kHz, number of integrated signals = 100]. The linewidth of the cw-terahertz radiation was 1.093 ± 0.008 MHz when a Lorentzian function was fitted to the spectral shape by regression analysis based on Levenberg–Marquardt algorithm. The fitting result is shown as a green curve in Fig. 3 for comparison. The reason why we use the Lorentzian fit is that spectrum of the cw laser usually indicates the Lorentzian shape although the terahertz spectrum looks like the Gaussian shape. We consider that the Gaussian-like spectral shape is caused by fast fluctuations of optical frequency in the two cw lasers. 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-terahertz radiation.

In the frequency measurement with the terahertz-comb-referenced spectrum analyzer, the absolute frequency of the cw-terahertz radiation (=f_{THz}) is given by

$$f_{THz} = nf_{rep3} \pm f_b, \tag{1}$$

where n is the order of the terahertz comb mode nearest in frequency to the cw-terahertz radiation, f_{rep3} is the frequency interval of OFC3, and f_b is the lowest beat frequency.[2] A portion of the output light from OFC3 was detected with a photodetector (not shown in Fig. 2), and f_{rep3} was measured to be 49 996 105 Hz with a rf frequency counter. The value of f_b was calculated to be 5.264 MHz by fitting the red plots in Fig. 3 to a Lorentzian function, in which uncertainty of ±2 kHz was achieved using the regression analysis based on Levenberg–Marquardt algorithm. To determine n 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 blue plots in Fig. 3. Since $|\delta f_b|$ is equal to $|n\delta f_{rep3}|$, n is determined from

$$n = \frac{|\delta f_b|}{|\delta f_{rep3}|} = \frac{|3.924 \times 10^6|}{|-1.610 \times 10^3|} = 2.437 \times 10^3, \tag{2}$$

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

$$f_{THz} = nf_{rep3} + f_b = 2.437 \times 10^3 \times 4.999\,610\,5 \times 10^7 + 5.264 \times 10^6 = 121.845\,772 \text{ GHz}. \tag{3}$$

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 terahertz spectrum analyzer measurement and the optical wavemeter measurement. Since the optical frequency resolution of the wavemeter (=10 MHz) was much smaller than this discrepancy, the error caused by the wavemeter measurement is likely to be negligible. Since the terahertz spectrum analyzer had the same frequency accuracy as that of the reference frequency standard, we considered the two major components for the uncertainty of the cw-terahertz generator induced in the terahertz 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 n value based on Eq. (2). Therefore, the uncertainty in the peak analysis would lead to an uncertainty of 100 MHz, or 0.083%, in the f_{THz} value obtained based on Eq. (3). 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 shown in Fig. 3, using the terahertz 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 Eqs. (2) and

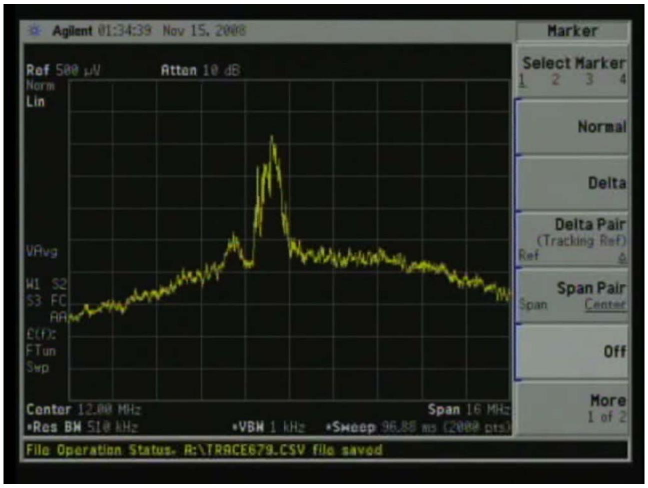

FIG. 4. Real-time monitoring of the phase-locked cw-terahertz radiation when locking its output frequency at 121.845 772 GHz (full span=4 MHz, sweep time=97 ms, and RBW=510 kHz) (enhanced online). [URL: http://dx.doi.org/10.1063/1.3305324.1]

(3). 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 terahertz spectrum analyzer measurement and the optical wavemeter measurement was within the estimated uncertainty of the cw-terahertz generator. If f_{ceo1} were further stabilized in the same manner as f_{ceo2}, the relative standard uncertainty in the terahertz spectrum analyzer measurement would be substantially decreased. Further improvement is expected if the linewidth of the cw-terahertz radiation can be narrowed by fast feedback control of the cw lasers.

Real-time monitoring of the frequency-locked cw-terahertz radiation was demonstrated and is shown as a movie in Fig. 4 (full span=4 MHz, sweep time=97 ms, and RBW=510 kHz). The raised background floor was due to the noise characteristics of the current preamplifier used in the terahertz spectrum analyzer whereas the small peak beside the cw-terahertz radiation resulted from electromagnetic noise propagating in free space. Although signal-to-noise ratio of the terahertz spectrum is a little poor due to insufficient gain of the current preamplifier, it is important to note that the terahertz-comb-referenced spectrum analyzer captures the spectrum of the cw-terahertz radiation in real time without the need for cryogenic cooling of detector or mixer. As a result, spectral behavior of the cw-terahertz radiation can be investigated in detail. For example, the center frequency of the cw-terahertz radiation was tightly fixed at a certain value although its spectral shape was a little fluctuated by instability of optical frequency in the two light sources for photomixing. We previously measured the frequency spectrum of the cw-terahertz radiation generated by photomixing of two free-running cw lasers and confirmed that its spectrum largely fluctuated due to instability of the optical frequencies in the two free-running cw lasers.[3] Comparison with the present results clearly shows the superiority of the proposed method even though f_{ceo1} was not stabilized. If f_{ceo1} was further stabilized, this cw-terahertz generator could be used as an F-band terahertz clock with accuracy and stability equal to those of the reference frequency standard used.

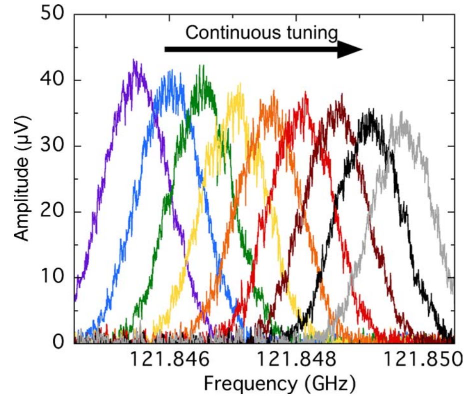

FIG. 5. (Color online) Continuous tuning of the phase-locked cw-terahertz radiation around 121.85 GHz by scanning f_{rep2} at 0.14-Hz intervals (sweep time=189 ms, RBW=10 kHz, number of integrated signals=100).

B. Terahertz synthesizer

The current cw-terahertz 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 COMB2.[15] We show here the result of continuous tuning of the cw-terahertz radiation around 121.85 GHz by scanning f_{rep2} at 0.14 Hz intervals. The resulting consecutive spectra of the cw-terahertz radiation are shown in Fig. 5 (sweep time=189 ms, RBW =10 kHz, number of integrated signals=100), in which the horizontal coordinate is scaled by the terahertz spectrum analyzer. The reason why the amplitude of the terahertz spectrum decreases as the frequency increases is frequency dependence of the gain in the current preamplifier rather than that of the output power from the UTC-PD. We fitted their spectral shapes to Lorentzian functions and determined the center frequencies of the cw-terahertz radiation (f_{THz}) in nine consecutive spectra. The relationship between the change of f_{rep2} (Δf_{rep2}) and that of f_{THz} (Δf_{THz}) is shown in Fig. 6. A linear relationship was found in the form $\Delta f_{THz}=m_2\Delta f_{rep2}$, where m_2=3 757 241, with a regression coefficient of 0.999 92. Although Δf_{rep2} was changed by only 1.12 Hz in

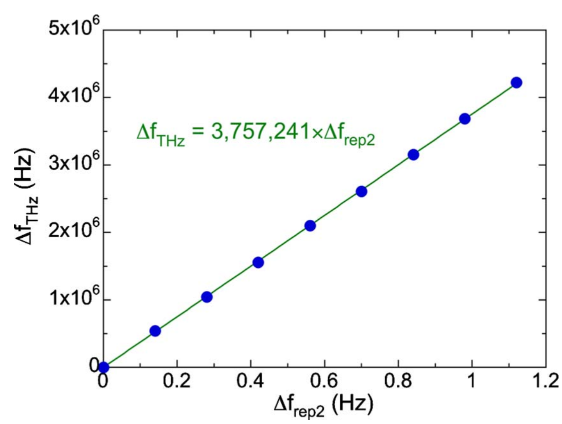

FIG. 6. (Color online) Relationship between change of f_{rep2} (Δf_{rep2}) and that of f_{THz} (Δf_{THz}).

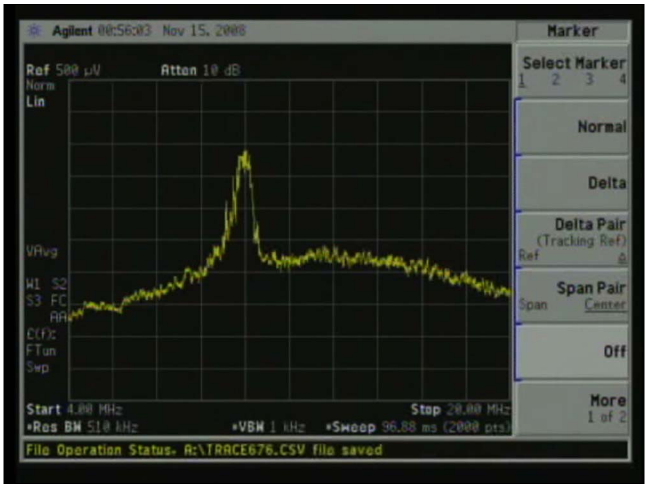

FIG. 7. (Color online) Real-time monitoring of the phase-locked cw-terahertz radiation while tuning its output frequency continuously around 121.85 GHz (full span=16 MHz, sweep time=97 ms, and RBW =510 kHz) (enhanced online). [URL: http://dx.doi.org/10.1063/1.3305324.2]

Fig. 6, the slope m_2 is maintained in full range of Δf_{rep2} (=450 kHz). This results in continuous tuning of 110 GHz. It is important to note that the slope m_2 of the present method was three orders of magnitude larger than the slope Δm of the previous method[13] when f_{THz} was set to around 0.12 THz. This resulted in a large expansion of the continuous tuning range of the cw-terahertz radiation. From the optical wavemeter measurement, we also determined m_2 to be 3 803 061. Although there is a discrepancy of 45 820, or 1.2%, in these m_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. 5 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. 5, it leads to an error in m_2 of 238 679, or 6.3%. Therefore, the discrepancy between the two m_2 values is within the uncertainty of the cw-terahertz generator. This can be further improved if the range of the frequency scanning is increased, together with stabilizing f_{ceo1}.

Finally, we demonstrated real-time monitoring of the cw-terahertz radiation while tuning its output frequency continuously around 121.85 GHz. The resulting movie is shown in Fig. 7 (full span=16 MHz, sweep time=97 ms, and RBW=510 kHz). Smooth tuning of the cw-terahertz radiation was achieved over 16 MHz in this demonstration, although the signal power became smaller at higher frequencies due to the frequency response of the current preamplifier used in the terahertz spectrum analyzer. It should be emphasized that the tuning range of this demonstration is not limited by the proposed cw-terahertz 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.[15] This tuning range can cover the frequency bandwidth of the F-band UTC-PD photomixer, ranging from 90 to 140 GHz. Furthermore, if we use a broadband photomixer, such as PCA,[10] and a CWL2 having the continuous tunability over a few terahertz, it will be possible to extend tuning range of this cw-terahertz generator to 1.7 THz.

V. CONCLUSION

Continuously tunable, phase-locked, 120 GHz cw radiation was demonstrated by photomixing of two stabilized cw lasers referenced to two independent fiber combs. The spectral behavior of the tight locking and continuous tuning of the cw-terahertz radiation was evaluated in detail with a terahertz-comb-referenced spectrum analyzer. The evaluation clearly indicated the high potential of the proposed method for application to a terahertz clock and synthesizer. Although continuous tuning of the cw-terahertz radiation is limited within the F-band due to the available spectral bandwidth of the UTC-PD photomixer (=90–140 GHz) in this study, it should be possible to achieve it in the frequency region over 1 THz by using a high-frequency photomixer, such as a PCA,[10] in place of the UTC-PD. The combination of the developed cw-terahertz generator with the terahertz-comb-referenced spectrum analyzer will pave the way for establishment of frequency metrology in the terahertz region. Furthermore, it is expected to find applications in carrier wave generation for broadband wireless communications, in local oscillators for heterodyne receivers, and in high-resolution spectroscopy.

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[1]M. Tonouchi, Nat. Photonics **1**, 97 (2007).
[2]S. Yokoyama, R. Nakamura, M. Nose, T. Araki, and T. Yasui, Opt. Express **16**, 13052 (2008).
[3]T. Yasui, R. Nakamura, K. Kawamoto, A. Ihara, Y. Fujimoto, S. Yokoyama, H. Inaba, K. Minoshima, T. Nagatsuma, and T. Araki, Opt. Express **17**, 17034 (2009).
[4]T. Yasui, Y. Kabetani, E. Saneyoshi, S. Yokoyama, and T. Araki, Appl. Phys. Lett. **88**, 241104 (2006).
[5]P. Gaal, M. B. Raschke, K. Reimann, and M. Woerner, Nat. Photonics **1**, 577 (2007).
[6]A. L. Betz, R. T. Boreiko, B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, Opt. Lett. **30**, 1837 (2005).
[7]A. A. Danylov, T. M. Goyette, J. Waldman, M. J. Coulombe, A. J. Gatesman, R. H. Giles, W. D. Goodhue, X. Qian, and W. E. Nixon, Opt. Express **17**, 7525 (2009).
[8]S. P. Khanna, M. Salih, P. Dean, A. G. Davies, and E. H. Linfield, Appl. Phys. Lett. **95**, 181101 (2009).
[9]T. Nagatsuma, H. Ito, and T. Ishibashi, Laser Photonics Rev. **3**, 123 (2009).
[10]S. Matsuura, M. Tani, and K. Sakai, Appl. Phys. Lett. **70**, 559 (1997).
[11]Th. Udem, R. Holzwarth, and T. W. Hänsch, Nature (London) **416**, 233 (2002).
[12]M. Musha, A. Ueda, M. Horikoshi, K. Nakagawa, M. Ishiguro, K. Ueda, and H. Ito, Opt. Commun. **240**, 201 (2004).

[13]Q. Quraishi, M. Griebel, T. Kleine-Ostmann, and R. Bratschitsch, Opt. Lett. **30**, 3231 (2005).
[14]H. Inaba, Y. Daimon, F.-L. Hong, A. Onae, K. Minoshima, T. R. Schibli, H. Matsumoto, M. Hirano, T. Okuno, M. Onishi, and M. Nakazawa, Opt. Express **14**, 5223 (2006).
[15]H. Takahashi, Y. Nakajima, H. Inaba, and K. Minoshima, Conference on Lasers and Electro-Optics (CLEO) 2009, Technical Digest (CD), Optical Society of America, 2009 (unpublished), Paper No. CTuK4.