Real-time monitoring of continuous-wave terahertz radiation using a fiber-based, terahertz-comb-referenced spectrum analyzer

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Abstract: We propose a fiber-based, terahertz-comb-referenced spectrum analyzer which has the advantages of being a portable, alignment-free, robust, and flexible apparatus suitable for practical use. To this end, we constructed a 1550-nm mode-locked Er-doped fiber laser whose mode-locked frequency was stabilized precisely by referring to a rubidium frequency standard, and used it to generate a highly stable terahertz (THz) frequency comb in a photoconductive antenna or an electro-optic crystal. By standardizing the THz comb, we determined the frequency accuracy of an active-frequency-multiplier-chain (AFMC) source to be 2.4×10^{-11}. Furthermore, the potential of the THz spectrum analyzer was effectively demonstrated by real-time monitoring of the spectral behavior of the AFMC source and a photomixing source of two free-running CW lasers at adjacent wavelengths.

OCIS codes: (120.3930) Metrological instrumentation; (120.6200) Spectrometers and spectroscopic instrumentation; (300.6320) Spectroscopy, high-resolution; (300.6495) Spectroscopy, terahertz.

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1. Introduction

A spectrum analyzer is a fundamental frequency measurement instrument widely used for radio-frequency wave, microwave, and millimeter wave. However, it has been difficult to use in the terahertz (THz) region, lying at the boundary between the infrared and millimeter-wave bands. Recently, new types of spectrum analyzers using a mode-locked Ti:Sapphire laser have been proposed and developed which can measure the absolute frequency and spectral shape of continuous-wave (CW) THz radiation without the need for cooling. One such device is a THz-comb-referenced spectrum analyzer [1] using a frequency comb of photocarriers (PC-THz comb) generated in a photoconductive antenna (PCA) [2]. By precisely stabilizing a laser mode-locked frequency and hence the PC-THz comb by referring to a rubidium (Rb) frequency standard, the absolute frequency of CW-THz radiation in the sub-THz and THz regions could be measured to a precision of 10^{-11}. A second type of spectrum analyzer is based on a non-synchronized electro-optic sampling technique using a free-running Ti:Sapphire laser, and has been applied to frequency measurements of a CW CO_2 laser at 28 THz [3].

From the standpoint of practical use, such as spectral analysis of various CW-THz sources, portable, alignment-free, robust, flexible, and inexpensive devices are ideal. However, the use of the Ti:Sapphire laser in those spectrum analyzers is an obstacle to achieving their characteristics. One promising alternative laser source for THz spectrum analysis is a mode-locked erbium-doped (Er-doped) fiber laser with a center wavelength of 1550 nm, which has the advantages of being compact, stable, and relatively inexpensive. Also, use of the Er-doped fiber laser enable us to benefit by generation of stable THz comb because it does not employ a free-space cavity but a fiber cavity tolerant of surrounding disturbances. Furthermore, direct coupling between the laser output and the PCA using an optical fiber, namely fiber-coupled PCA, eliminates free-space propagation of the laser light with many mirrors and lenses and enables the measurement head to be placed at any position [4]. Such fiber-based THz spectrum analyzers are likely to become portable, alignment-free, robust, and flexible measurement tools. However, highly stabilized fiber lasers to meet the requirement of the THz-comb-referenced spectrum analyzer are still lacking.

In this paper, we first construct the mode-locked Er-doped fiber laser whose mode-locked frequency is stabilized precisely by referring to the Rb frequency standard, and use it to generate the THz comb in a PCA or an electro-optic crystal. By standardizing the THz comb, we achieved a fiber-based, THz-comb-referenced spectrum analyzer. To evaluate a potential of the fiber-coupled PCA, we compare signal-to-noise ratio among four kinds of photoconductive detections and free-space electro-optic sampling detection. After evaluation of the basic performance of the frequency measurement and comparison with the previous Ti:Sapphire-laser-based spectrum analyzer, we perform real-time monitoring of CW-THz radiation generated by an active frequency multiplier chain [5] and by photomixing of two free-running CW lasers with a uni-traveling-carrier photodiodes (UTC-PD) [6].

2. Experimental setup

2.1 THz-comb-referenced spectrum analyzer

Figure 1 shows a schematic diagram of the experimental setup. The THz-comb-referenced spectrum analyzer was composed of a mode-locked-frequency-stabilized, Er-doped fiber

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laser, a THz detection unit, and RF frequency instruments. The principles of operation have been given in detail elsewhere [1]. The output of the fiber laser was delivered to a THz detection unit by an optical fiber. The CW-THz radiation from a test source propagated in free space through a pair of THz lens (Pax Co., Tsurupica), and was then incident on the THz detection unit. Photoconductive, or electro-optical, heterodyne mixing between the CW-THz radiation and the THz comb in the detection unit generates beat signals in the RF region. The beat signal with the lowest frequency (freq. = f_b), referred to as f_b beat signal, is measured with an RF spectrum analyzer (Agilent E4402B with a frequency range of 100 Hz to 3 GHz) and an RF frequency counter (Agilent 53132A 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 (PD), and its mode-locked frequency (freq. = f) is measured using the RF frequency counter. The RF spectrum analyzer and RF frequency counter are synchronized to a Rb frequency standard (Rb frequency standard 1; Stanford Research Systems FS725 with frequency = 10 MHz). When accuracy is defined as the degree of closeness of a measured quantity to its true value, the frequency accuracy of the Rb frequency standard 1 is $\pm 5 \times 10^{-11}$ at shipment in specifications. Aging of the frequency standard is less than 5×10^{-11} per month.

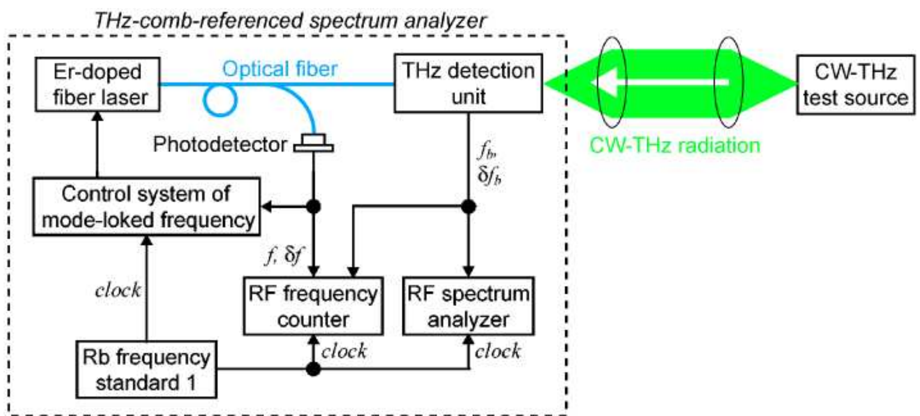

Fig. 1. Experimental setup.

2.2 Mode-locked-frequency-stabilized, Er-doped fiber laser

We constructed a self-starting, stretched-pulse mode-locked Er-doped fiber laser oscillator and amplifier [7] for use as a laser source to generate the PC-THz comb. The laser oscillator was a ring resonator that employed nonlinear polarization rotation as a passively mode-locking mechanism. To quickly fine-control the mode-locked frequency by adjustment of the cavity length, a portion of the fiber cavity was rolled on a drum-type piezoelectric actuator. Furthermore, slow, coarse control of the mode-locked frequency could be achieved by varying the temperature of the fiber cavity with a Peltier heater. The 20th harmonic component of the mode-locked frequency was filtered, amplified, and used to stabilize the mode-locked frequency using a proportional and integral (PI) control system referred to the Rb frequency standard 1.

Figure 2 shows the instability of the mode-locked frequency in the free-running condition (black plots) and the stabilized condition (red plots). Here, frequency instability is the degree to which further frequency measurements show the same results. It is clear from a comparison between them that the mode-locked frequency is highly stabilized by the laser control system. For comparison, frequency instability of the Rb frequency standard is also shown in Fig. 2 (see green plots). The frequency instability with the stabilized control is almost equal to that of the Rb frequency standard. One reason why the frequency instability of the stabilized mode-locked frequency somewhat exceeds that of the referenced Rb frequency standard is likely due to difference of the experimental conditions between them. Another reason is

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systematic errors caused by the frequency counter and/or frequency synthesizer used in the present setup, due for example to insufficient frequency calibration of the instruments. The excellent stability achieved with the laser control enabled us to generate a stable and accurate PC-THz comb, and perform frequency measurements with high precision.

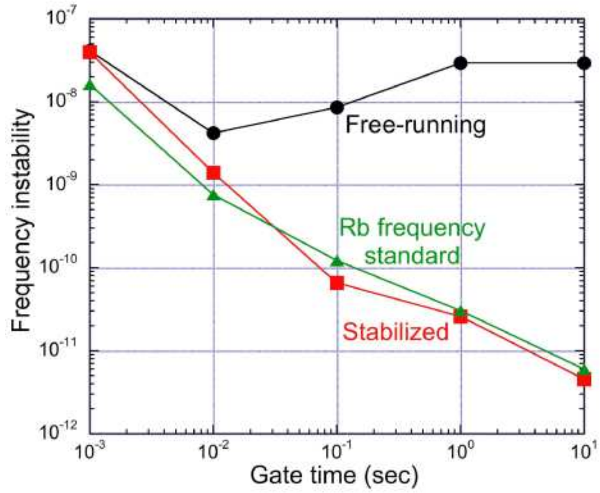

Fig. 2. Frequency instability of mode-locked frequency with and without the laser control (red and black plots), and the Rb frequency standard (green plots).

The output light from the laser oscillator was amplified by a home-built Er-doped fiber amplifier, and the resulting laser output had a center wavelength of 1550 nm, an average power of 90 mW, a pulse duration of 40 fs, and a mode-locked frequency of 56,122,206 Hz.

2.3 THz detection unit

We used the four types of THz detection units shown in Fig. 3 and compared their signal-to-noise ratio. The first unit is a bowtie-shaped, low-temperature-grown GaAs PCA (LT-GaAs-PCA; bowtie length = 1 mm, maximum input power = 10 mW for 800-nm light) equipped with a hemispherical silicon lens. In this unit, the laser light is converted by second-harmonic-generation (SHG) to half its original wavelength using a nonlinear optical crystal (β-BaB_2O_4, thickness = 8 mm), as shown in Fig. 3(a). The resulting SHG light (center wavelength = 775 nm, average power = 6 mW) is focused using a lens onto an antenna gap in the PCA. This results in the generation of a PC-THz comb in the PCA. The output current signal from the PCA is amplified by a high-gain current preamplifier (AMP; bandwidth = 1 MHz and sensitivity = 4×10^6 V/A). On the other hand, use of the PCA without the need for wavelength conversion is attractive for achieving direct coupling between the laser output and the PCA using an optical fiber. The above LT-GaAs-PCA has a little sensitivity even for 1550-nm laser light whose energy does not exceed the optical band gap of GaAs (1.43 eV at room temperature, corresponding wavelength of 867 nm) [8]. Recently, a low-temperature-grown InGaAs/InAlAs PCA (LT-InGaAs/InAlAs-PCA) has been further developed for detecting laser light around 1550 nm [4]. Therefore, we used bowtie-shaped LT-GaAs-PCA (bowtie length = 1 mm, maximum input power = unknown for 1550-nm light) and LT-InGaAs/InAlAs-PCA (bowtie length = 3 mm, maximum input power = 30 mW for 1550-nm light), directly triggered by the 20 mW and 30 mW fundamental lights from the fiber laser, as the second and third THz detection units [see Figs. 3(b) and (c)]. The fourth unit is based on the free-space electro-optic sampling (FSEOS) method because the FSEOS enables electro-optically heterodyne beat-down based on the THz comb [9]. Therefore, a 1 mm-thick (110) ZnTe crystal was used in this unit [see Fig. 3(d)]. The SHG light (center wavelength = 775 nm, average power = 8 mW) was detected with an auto-balanced photodetector (bandwidth = 125 kHz) after passing through the polarizer (PL), a quarter waveplate ($\lambda/4$), ZnTe crystal,

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and a Rochon prism (RP). Difference of the SHG power between setups of Figs. 3(a) and (d) is due to the condition of the fiber laser, such as pulse pedestal or polarization purity, which changes the conversion efficiency to the SHG light.

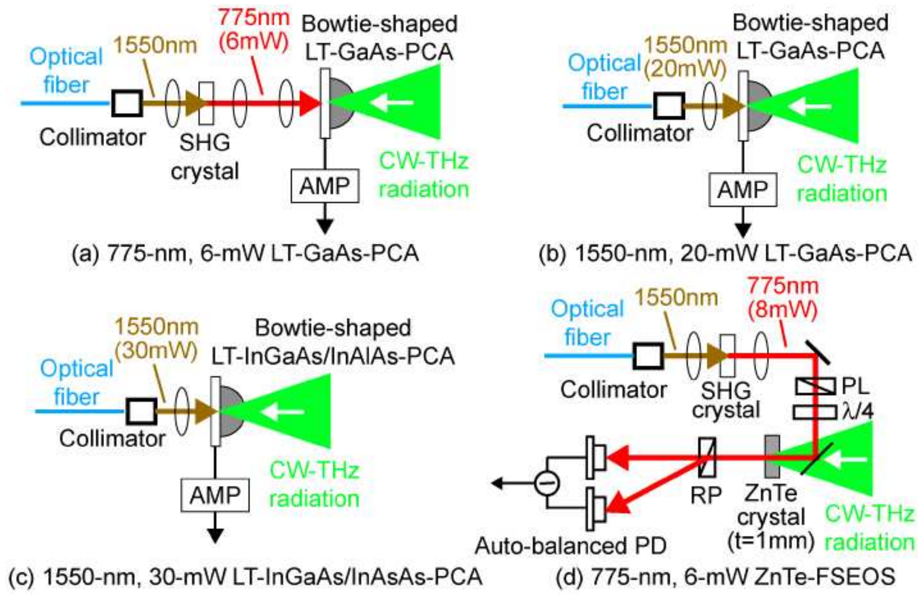

Fig. 3. THz detection unit. (a) bowtie-shaped LT-GaAs-PCA triggered by 775-nm, 6-mW light, (b) bowtie-shaped LT-GaAs-PCA triggered by 1550-nm, 20-mW light, (c) bowtie-shaped LT-InGaAs/InAlAs-PCA triggered by 1550-nm, 30-mW light, and (d) FSEOS of 1mm-thick ZnTe crystal probed by 775-nm, 6-mW light. AMP: high-gain current preamplifier; PL: polarizer; λ/4: quarter waveplate; RP: Rochon prism.

2.4 CW-THz test source

Two kinds of CW sources emitting in the low-frequency THz region were used as test sources in this experiment. The first was an active frequency multiplier chain (Millitech AMC-10-R0000 with multiplication factor = 6, tuning range = 75–110 GHz), referred to as an AFMC source, as shown in Fig. 4(a). The AFMC source multiplies output frequency of a frequency synthesizer (Agilent E8257D with frequency = 12.5–18.33 GHz, and linewidth < 0.1 Hz) by six, and then radiates the resulting electromagnetic wave in free space via a horn antenna. Since this AFMC source is synchronized to another Rb frequency standard (Rb frequency standard 2; Stanford Research Systems FS725 with frequency = 10 MHz, accuracy at shipment = $\pm 5 \times 10^{-11}$ and aging $< 5 \times 10^{-11}$ per month in specifications), it acts as an accurate, stable, tunable test source. The second test source was produced by photomixing of two CW near-infrared lasers at adjacent wavelengths (CWL1 and CWL2) with a UTC-PD [6], as shown in Fig. 4(b), which can be used for broadband wireless communications and spectroscopic sensing. The two CW lasers were external cavity wavelength-tunable laser diodes with an emission wavelength of 1550 nm (Koshin Kogaku Co., LS-601A-15S1, spectral linewidth ≤ 100 kHz) and operated in free-running mode (frequency fluctuation < 100 MHz/hour). 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 photomixed by a F-band UTC-PD (available frequency = 90-140 GHz) equipped with a horn antenna. The polarization of CWL1 could be made to significantly overlap with that of CWL2 by adjusting a half waveplate (λ/2) and a quarter waveplate (λ/4). The output power was set to be 100 µW at a frequency of 120 GHz.

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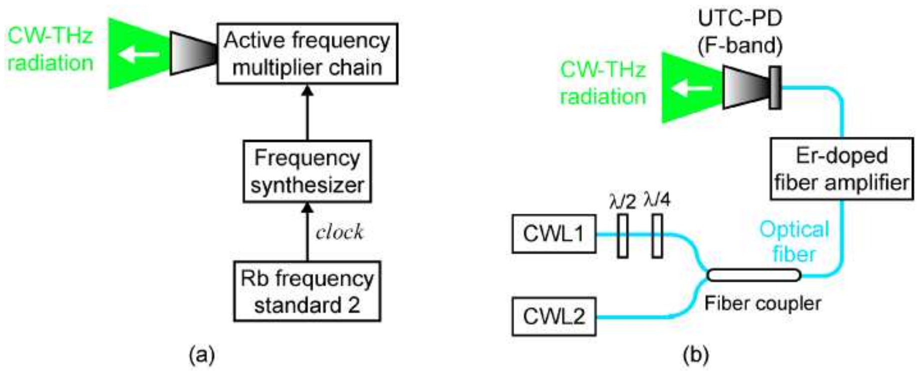

Fig. 4. Test source for CW-THz radiation. (a) Active frequency multiplier chain (output power = 5.4 mW at 80 GHz and tuning range = 75–110 GHz) driven by a frequency synthesizer and (b) photomixing source (output power = 100 μW and output frequency = 120 GHz) of two free-running near-infrared lasers (CWL1 and CWL2) with a F-band uni-traveling-carrier photodiodes (UTC-PD).

3. Results

We evaluated the basic performance of the fiber-based, THz-comb-referenced spectrum analyzer using the AFMC source as a test source because it is synchronized to the Rb frequency standard and hence is highly accurate and stable. The output frequency of the AFMC source was set to be 80 GHz. We first compared the signal-to-noise ratio (SNR) of the f_b beat signals obtained by four THz detection units: LT-GaAs-PCA triggered by a 775-nm, 6-mW light [(a) 775-nm, 6-mW LT-GaAs-PCA], LT-GaAs-PCA triggered by a 1550-nm, 20-mW light [(b) 1550-nm, 20-mW LT-GaAs-PCA], LT-InGaAs/InAlAs-PCA triggered by a 1550-nm, 30-mW light [(c) 1550-nm, 30-mW LT-InGaAs/InAlAs-PCA], and FSEOS of a 1 mm ZnTe crystal probed by a 775-nm, 8-mW light [(d) 775-nm, 8-mW ZnTe-FSEOS]. Figure 5 shows a comparison of the logarithmic-scale spectra of the f_b beat signal for the four units, measured by the RF spectrum analyzer with a sweep rate of 43.5 kHz/s and a resolution bandwidth (RBW) of 1 kHz. The highest SNR of 57 dB was achieved with the (a) 775-nm, 6-mW LT-GaAs-PCA. The (b) 1550-nm, 20-mW LT-GaAs-PCA and the (c) 1550-nm, 30-mW LT-InGaAs/InAlAs-PCA, capable of direct coupling with the fiber laser output via the optical fiber, yielded a SNR of 31 dB and 40 dB, respectively. Conversely, the lowest SNR of 29 dB was obtained for the (d) 775-nm, 8-mW ZnTe-FSEOS. Since the output power of the AFMC source was 5.4 mW (= + 7.3 dBm) at 80 GHz, the detection limit for THz power is estimated to be 11 nW for the (a) 775-nm, 6-mW LT-GaAs-PCA, 4300 nW for the (b) 1550-nm, 20-mW LT-GaAs-PCA, 540 nW for the (c) 1550-nm, 30-mW LT-InGaAs/InAlAs-PCA, and 6800 nW for the (d) 775-nm, 8-mW ZnTe-FSEOS. However, this comparison was performed under different probe power conditions. Differences in probe power can be corrected by assuming that signals measured in the PCA and FSEOS are proportional to the power of the probe beam. Normalized to the result for the (a) 775-nm, 6-mW LT-GaAs-PCA, the corrected detection sensitivities are 0.077% for the (b) 1550-nm, 20-mW LT-GaAs-PCA, 0.41% for the (c) 1550-nm, 30-mW LT-InGaAs/InAlAs-PCA, and 0.12% for the (d) 775-nm, 8-mW ZnTe-FSEOS. Thus, from the viewpoint of high SNR, the (a) 775-nm, 6-mW LT-GaAs-PCA is the best choice at this stage although it requires the wavelength conversion optics, which are slight obstacles to direct PCA coupling. Conversely, to benefit by the direct coupling capability while keeping moderate SNR, the (c) 1550-nm, 30-mW LT-InGaAs/InAlAs-PCA is an attractive THz detection unit. In subsequent experiments, we used the (c) 1550-nm, 30-mW LT-InGaAs/InAlAs-PCA for the high-power AFMC source and the (a) 775-nm, 6-mW LT-GaAs-PCA for the lower-power photomixing source as the THz detection unit.

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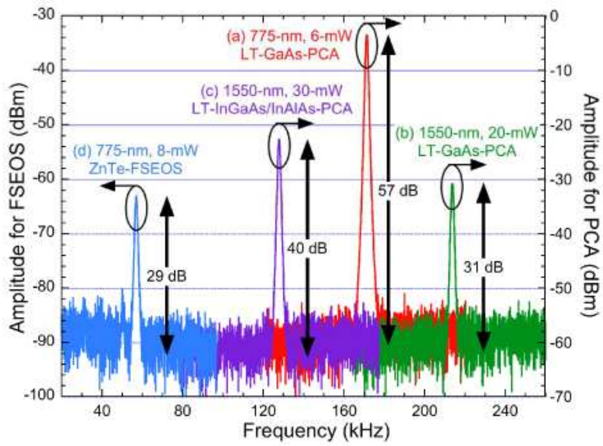

Fig. 5. Comparison of signal-to-noise ratio of the f_b beat signal obtained by four THz detection units (RBW = 1 kHz and sweep rate = 43.5 kHz/s). A test source is the AFMC source with output power of 5.4 mW at frequency of 80 GHz.

We next evaluated the spectral linewidth of the f_b beat signal when the output frequency of the AFMC source is set to be 100 GHz. Figure 6(a) shows a linear-scale spectrum of this signal, measured by the RF spectrum analyzer with a sweep rate of 43.5 Hz/s and an RBW of 1 Hz. The resulting linewidth of the beat signal was 1.8 Hz. However, since this linewidth may be limited by the RBW of the RF spectrum analyzer (minimum RBW = 1 Hz), we next evaluated the linewidth in detail by measuring the frequency fluctuation of the f_b beat signal with the RF frequency counter. Figure 6(b) show the fluctuation of the beat frequency, represented by the standard deviation, with respect to various gate times. Such narrow linewidth of the beat signal enables us to perform the frequency measurement with high precision.

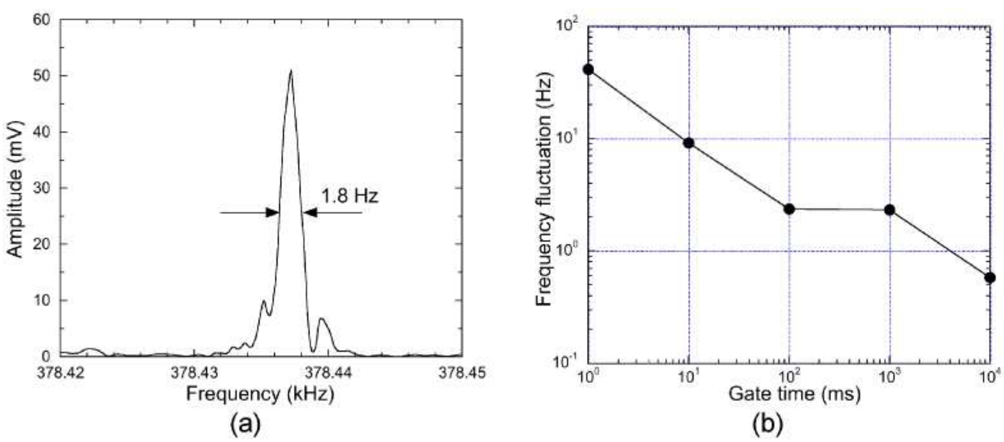

Fig. 6. (a) Spectra of the f_b beat signal of the AFMC source measured by the RF spectrum analyzer (RBW = 1 Hz and sweep rate = 43.5 Hz/s). (b) Frequency fluctuation of the f_b beat signal measured by the RF frequency counter.

In the THz-comb-referenced spectrum analyzer measurement, the absolute frequency of the measured CW-THz radiation ($= f_{THz}$) is given as follows

$$f_{THz} = mf \pm f_b. \tag{1}$$

where m is order of the comb mode nearest in frequency to the CW-THz radiation, f is mode-locked frequency of the fiber laser, and f_b is the lowest frequency of beat signals [1]. The f

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and f_b values were measured to be 56,122,206.03 Hz and 356,156 Hz with the RF frequency counter, respectively. To determine the value of m and the sign of f_b, the frequency f was changed by δf (= 25 Hz) using the laser control system. This resulted in a change of the beat frequency by δf_b (= 44,549 Hz). Since $|\delta f_b|$ is equal to $|m\delta f\,|$, m is determined as

$$m = \frac{|\delta f_b|}{|\delta f|} = \frac{|44,549|}{|25|} = 1,781.96 \approx 1,782. \quad (2)$$

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

$$\begin{aligned} f_{THz} &= mf - f_b \\ &= 1,782 * 56,122,206.03 - 356,156 \\ &= 100,009,414,989.46\, Hz. \end{aligned} \quad (3)$$

Since the actual set frequency of the AFMC test source was 100,009,414,988.9 Hz, the error between the set and measured frequencies was only 0.56 Hz. When the frequency accuracy of the test source is defined as the ratio of the error to the f_{THz}, the corresponding accuracy was 8.7×10^{-10}. To evaluate the frequency accuracy of the AFMC source in available frequency range, we determined the absolute frequency of the source while tuning its output frequency from 75 to 110 GHz at 5-GHz intervals. The resulting accuracy for eight different measurement frequencies was shown as black plots in Fig. 7. A mean accuracy of 2.4×10^{-11} was obtained for this source. Here, let us consider the reason why frequency accuracy of the THz spectrum analyzer exceeds that of the Rb frequency standard. Although frequency accuracy of 5×10^{-11} for the Rb frequency standard is the value at shipment, aging of the frequency standard deviates its output frequency slowly from the shipment value. If the frequency drift caused by the aging makes the output frequency apart from a true value of 10 MHz, the actual frequency accuracy becomes worse than the shipment value. Conversely, if it goes close to the true value, the actual accuracy becomes better. We consider that the two Rb frequency standards used in this experiment come under the latter case. Therefore, the frequency accuracy of the THz spectrum analyzer exceeds that of the Rb frequency standard at shipment.

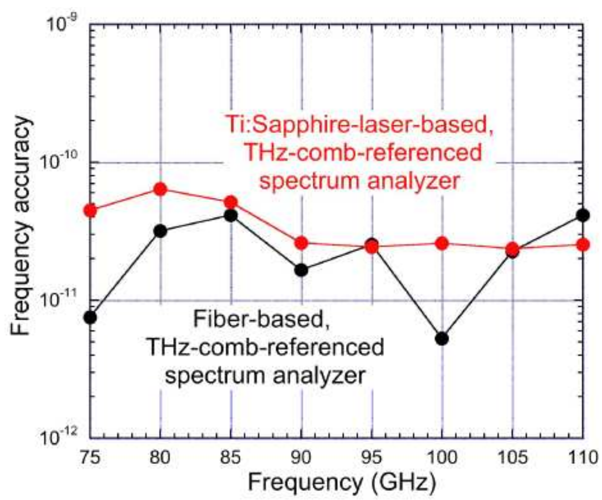

Fig. 7. Frequency accuracy of the AFMC source measured with the fiber-based, THz-comb-referenced spectrum analyzer (black plots) and the Ti:Sapphire-laser-based one (red plots).

For comparison, we indicated the frequency accuracy of the same test source measured with the previous spectrum analyzer using a Ti:Sapphire laser [1] as red plots in Fig. 7. A comparison between them reveals a little improved frequency accuracy in the case of the

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present spectrum analyzer. We consider that this improvement is due to stable THz comb generated by the fiber laser robust to surrounding disturbances. We next compare the present spectrum analyzers with the previous one in terms of simplicity and convenience. The previous spectrum analyzer has often required precise alignments of the laser cavity and optical components to maintain the laser for best condition and optimize the PCA, respectively. Conversely, the fiber laser used in the present spectrum analyzer has needed a few adjustments of the laser cavity although it has been working in continuous operation more than several months. Such the continuous operation of the fiber laser also enables us to benefit by stable long-term stability. Furthermore, rigid Poynting vector of the laser beam saves us a lot of labor to adjust the optical components. Most importantly, use of fiber-coupled PCA achieves easy handling of the measurement head and robustness to the surrounding disturbances. Therefore, the present fiber-based spectrum analyzer surpasses the previous one in frequency accuracy, simplicity of operation, robustness, and long-term stability.

Finally, real-time monitoring of the frequency spectrum for two kinds of test sources was carried out by measuring the f_b beat signal with the RF spectrum analyzer. Since the output frequency of the AFMC source is highly accurate and stable, we evaluated the effectiveness of the stabilized control of the PC-THz comb by observing the f_b beat signal with the laser control turned off and on. Figures 8(a) and (b) illustrate five consecutive spectra of the beat signal without and with the laser stabilization measured at 6-sec intervals, respectively (sweep rate = 16.5 kHz/s, and RBW = 100 Hz). Also, temporal changes of the beat spectra without and with the laser stabilization are shown as movies in Media 1 and 2 (full span = 10 kHz, sweep time = 605 ms, and RBW = 100 Hz). The beat frequency is tightly pinned to a certain value under laser stabilization, whereas it fluctuates over a range of several kHz without the stabilization. This difference reflects that of the mode-locked frequency instability shown in Fig. 2. Therefore, stabilization of the mode-locked frequency is indispensable for precise determination of the absolute frequency of the CW-THz radiation.

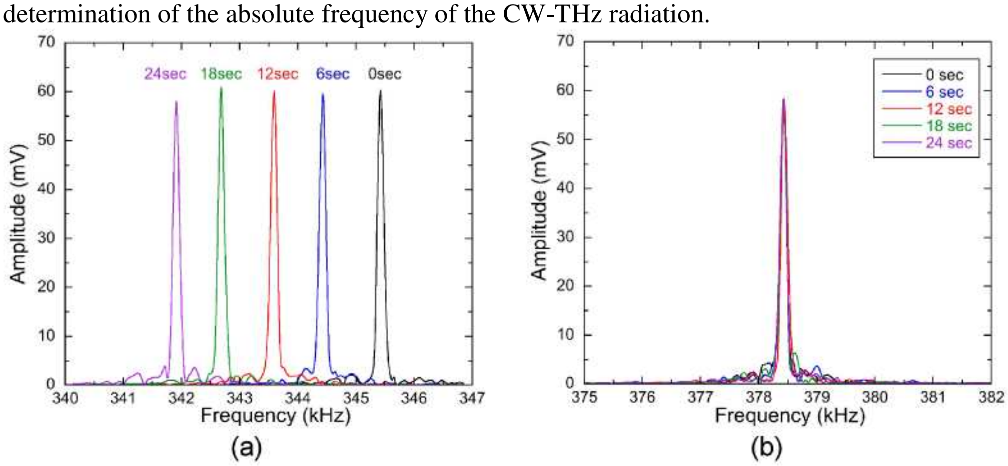

Fig. 8. Spectra of the f_b beat signal of the AFMC source (a) without (Media 1) and (b) with the laser stabilization (Media 2). Five consecutive spectra of the beat signal were measured at 6-sec intervals. RBW = 100 Hz and sweep rate = 16.5 kHz/s.

We next used the THz spectrum analyzer for real-time monitoring of the photomixing source. The resulting image and movie of the beat spectrum are shown in Fig. 9 (sweep rate = 75 MHz/s, and RBW = 1 kHz) and Media 3 (full span = 1.5 MHz, sweep time = 19.3 ms, and RBW = 10 kHz), respectively. In contrast to the stable AFMC source, the beat frequency of the photomixing source exhibits large fluctuations within a spectral window of 1.5 MHz. This is because the two CW lasers used for the photomixing are operated in free-running mode without any frequency control. Work is in progress to suppress the frequency fluctuation of the CW-THz radiation by precisely controlling the optical frequencies of the two CW lasers [10].

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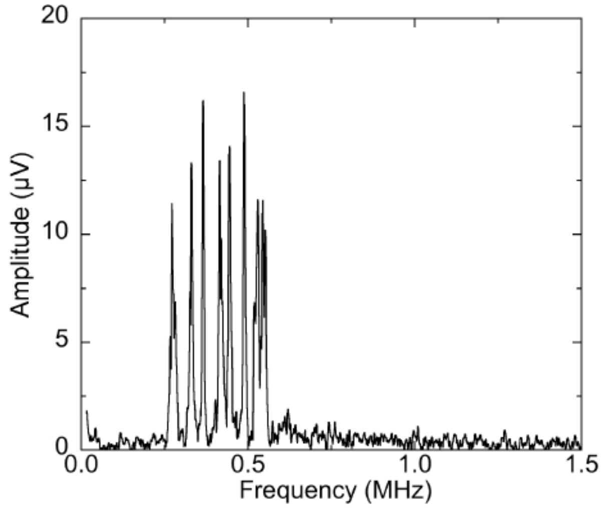

Fig. 9. Spectrum of the f_b beat signal of the photomixing source (Media 3). RBW = 1 kHz and sweep rate = 75 MHz/s.

4. Conclusion

We have developed a fiber-based, THz-comb–referenced spectrum analyzer using a mode-locked Er-doped fiber laser to achieve a portable, alignment-free, robust, and flexible apparatus suitable for practical use. The lowest detection limit of 11 nW for THz power was achieved when using the (a) 775-nm, 6-mW LT-GaAs-PCA as a THz detection unit. Furthermore, a fiber-coupled, (c) 1550-nm, 30-mW LT-InGaAs/InAlAs-PCA can be used for measurement of CW-THz sources with a power of the order of µW. Conversely, the (d) 775-nm, 8-mW ZnTe-FSEOS is less attractive than the PCA because of its low SNR and difficulty of the direct coupling due to complicated optical systems for wavelength conversion and auto-balanced detection. We determined the absolute frequency of the AFMC source in frequency range from 75 to 110 GHz and obtained the mean frequency accuracy of 2.4×10^{-11}. Finally, we demonstrated real-time monitoring of the spectral behavior of the AFMC source and the photomixing source comprising two free-running CW lasers. These sources exhibited contrasting behavior in the frequency domain, in that the former was highly stable whereas the latter exhibited large fluctuations. Although the frequencies of the test sources were in the low-frequency THz region due to the limitation of our available CW-THz sources, it is natural to believe that the THz spectrum analyzer can be extended to the higher frequency THz region in the same manner as the THz spectrum analyzer based on non-synchronized electro-optic sampling [3]. This is because the spectral bandwidth of the THz spectrum analyzer is limited mainly by spectral sensitivity of the PCA or FSEOS. For example, the spectral characteristics of the LT-GaAs-PCA as a THz detector have been investigated using THz time-domain spectroscopy, for which a bandwidth of 170 THz was achieved [11]. Therefore, the THz-comb-referenced spectrum analyzer can cover the entire THz spectral region. Real-time monitoring with such a THz spectrum analyzer is a powerful technique for detailed characterization of the spectral behavior of various CW-THz sources. Furthermore, it paves the way for establishment of frequency metrology in THz region.

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