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Precise Frequency Measurement of Continuous-Wave Terahertz Radiation Based on THz Comb

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Abstract

We demonstrated a frequency measurement of CW-THz wave referring to THz frequency comb. Effectiveness of the proposed method is demonstrated by measurement of sub-THz test sources. The achieved precision of frequency measurement was $2.0*10^{-11}$.

I. Introduction

Optical frequency comb generated by a mode-locked femtosecond laser has emerged as a new mode for optical frequency metrology [1]. Since the frequency comb structure can be used as a precise ruler in the frequency domain, such combs have received a lot of interest as a metrological tool in the ultraviolet through the mid-infrared region. Recently, the concept of a frequency comb has been extended to the THz region using a stabilized fs mode-locked laser in combination with a photoconductive antenna (PCA) [2]. When the optical comb is incident to a PCA for THz detection, THz comb of photocarrier (PC-THz comb) is induced in the PCA. Since the PC-THz comb possesses attractive features for THz frequency metrology, including excellent accuracy and stability, broadband selectivity, ultra-narrow linewidth, and exact multiplication, the PCA having the PC-THz comb can be used as a THz detector having a precise ruler of THz frequency. In this paper, we demonstrate determination of the absolute frequency of a sub-THz CW test source based on THz comb, namely THz spectrum analyzer [3, 4].

II. Principles

Our THz spectrum analyzer is based on a heterodyne technique based on photoconductive mixing, as shown in Fig. 1(a). Compared with the electrical heterodyne method, a key difference here is that the PCA is used as a heterodyne receiver for a measured CW-THz wave, enabling the operation at room temperature without the need for cryogenic cooling. Another difference is the use of a PC-THz comb as a local oscillator with multiple frequencies covering from the sub-THz to the THz region.

Figure 1(b) shows the corresponding spectral behavior in THz and radio frequency (RF) region for the proposed method. First, the PC-THz comb is induced in the PCA by irradiating the optical comb onto the antenna gap. When a measured CW-THz wave is incident to the PCA under this condition, photoconductive heterodyned mixing process between the measured wave and the comb modes results in generation of multiple beat signals between them in the RF region. Since a beat signal at the lowest frequency (freq. = f_b), namely f_b beat signal, is generated by mixing of the measured wave with the m-th comb mode (freq. = mf) nearest in frequency to the measured wave, the f_x value is given as

$$f_x = mf + f_b. \qquad (1)$$

Therefore, if m, f, and f_b are known, the absolute frequency of the measured wave can be determined. The f and f_b can be measured by an RF frequency counter and spectrum analyzer, respectively. In order to determine the m value, the mode-locked frequency is change from f to $f+\delta f$ by adjustment of the laser cavity length. This results in change of the beat frequency by $f_b+\delta f_b$. Since the δf_b is equal to $m\delta f$, the m value is determined by the following equation.

$$m = \delta f_b \,/\, \delta f_b \qquad (2)$$

In this way, the absolute frequency of the CW-THz wave can be determined by measuring the f, f_b, δf, and δf_b.

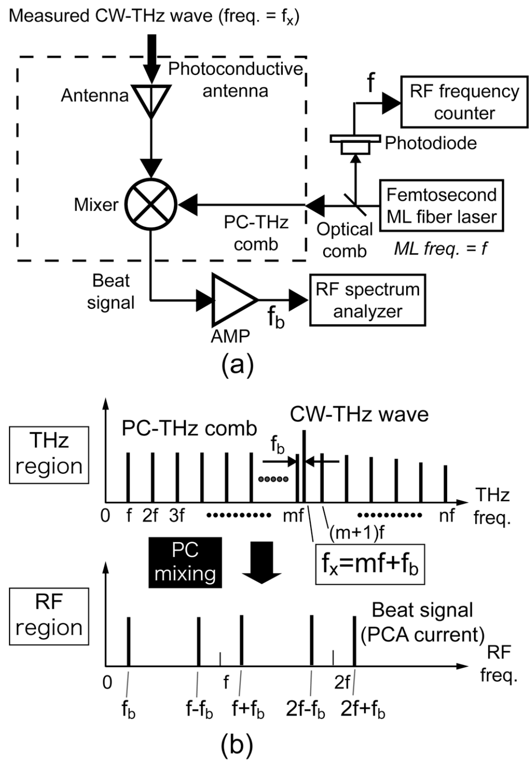

Fig. 1. (a) Principle and (b) spectral behavior of THz spectrum analyzer.

III. RESULTS

First, we measured the spectral shape of CW-THz wave (tuning range = 75-110 GHz, output power = 2.5 mW, linewidth < 0.6 Hz) radiated from an active frequency multiplier chain (multiplication factor = 6) combined with a frequency synthesizer (tuning range = 12.5-18.33 GHz) and a rubidium (Rb) frequency standard (accuracy = 5×10^{-11} and stability = 2×10^{-11} at 1s). Frequency spacing of the PC-THz comb is beforehand stabilized by phase-locking the mode-locked frequency of the fiber laser to the Rb frequency standard. Figure 2(a) shows the spectrum of the f_b beat signal (RBW = 1Hz and sweep time = 2.3 s) when the output frequency of the CW source is set at 80 GHz. The linewidth of the beat signal was only 1.8 Hz, indicating the narrow linewidth of THz comb mode.

Second, we measured 140-GHz CW-THz wave generated by photomixing of two near-infrared CW laser phase-locked to dual optical comb, respectively [5]. Figure 2(b) shows the spectrum of the f_b beat signal. The linewidth of the CW-THz radiation was 631 kHz when a Gaussian function was fitted to the spectral shape. Since the linewidth of the comb mode is much narrower than that of the beat signal, the spectrum reflects the spectral characteristics of this CW-THz source.

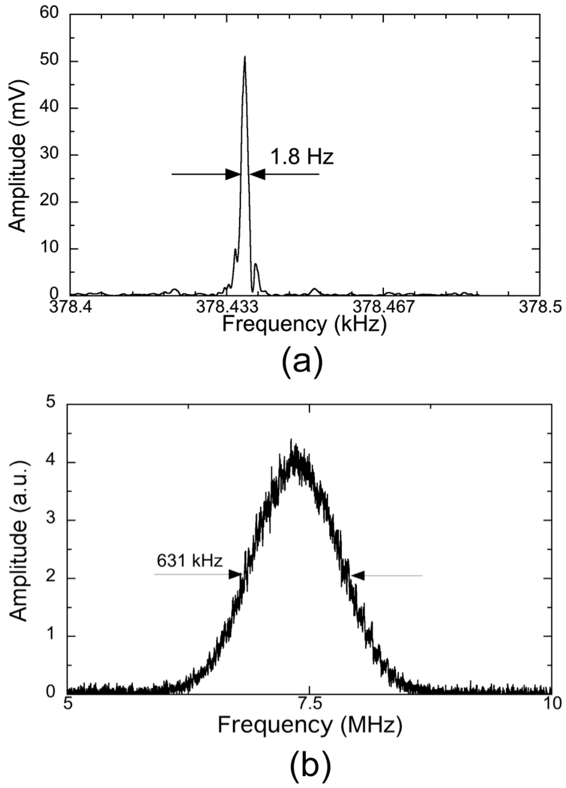

Fig. 2. Spectrum of f_b beat signal. (a) 99-GHz active frequency multiplier chain and (b) 140-GHz photomixing source.

Finally, we determined the *m* value of the active frequency multiplier chain based on the above procedure. To this end, the mode-locked frequency is changed by 25 Hz (= δf). This results in deviation of -35.6 kHz (= δf_b) in the beat frequency as shown in Fig. 3. By substituting the δf and δf_b values for Eq. 2, the *m* value was determined to be 1,426. Therefore, the absolute frequency of the test source was determined to be 80,033,760,458 Hz from Eq. 1. Error of the measured frequency and the output frequency of the test source is 2 Hz, corresponding to a precision of $2*10^{-11}$.

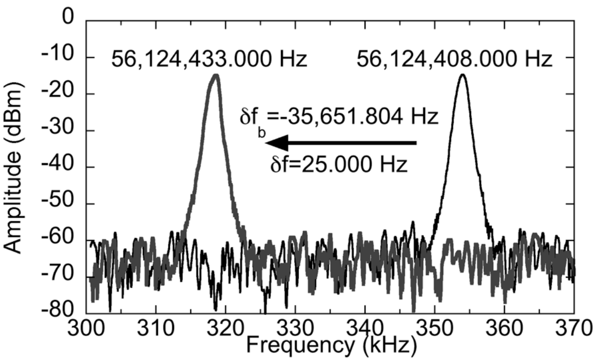

Fig. 3. Change of beat frequency (δf_b) by shift of ML frequency (δf).

IV. CONCLUSIONS

We have developed a THz spectrum analyzer that can be used to measure the absolute frequency and spectral shape of CW-THz wave. The proposed method has the potential to become a powerful tool for THz frequency metrology.

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