# Precise Frequency Measurement of Sub-THz Test Source Referring to as Terahertz Frequency Comb

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***Abstract*—We proposed a new method of THz frequency measurement referring to as THz frequency comb. Effectiveness of the proposed method is demonstrated by measurement of a 100-GHz test source. The achieved precision and signal-to-noise ratio of frequency measurement were $2.85\times10^{-11}$ and 46.2 dB, respectively.**

## I. Introduction

Optical frequency comb generated by a mode-locked Ti:S 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 visible through the 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, namely 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 100-GHz CW test source .

## II. Principle

Our THz spectrum analyzer is based on a heterodyne technique as shown in Figure 1 Compared with the electrical heterodyne method, a key difference here is that the PCA is used as both a heterodyne receiver for a measured CW-THz wave and a demodulator converting the optical comb into the PC-THz comb. Use of the PCA provides high, broadband spectral sensitivity in the THz region without the need for 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.

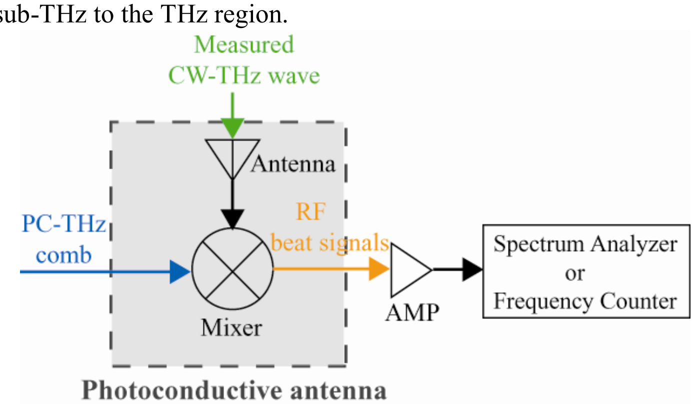


Fig. 1 Setup of THz THz spectrum analyzer.

Figure 2 shows the corresponding spectral behavior in optical, 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 having the PC-THz comb, photoconductive heterodyned mixing process between the measured wave and the comb modes results in generation of many beat signals between them in the RF region. Since a beat signal at the lowest frequency (freq. = fb) is generated by mixing of the measured wave with the m-th comb mode (freq. = mf) nearest in frequency to the measured wave, the fx value is given as

$$f_x = mf + f_b. \tag{1}$$

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 ($f_b+\delta f_b$). Since the $\delta f_b$ is equal to m$\delta f$, the $m$ value is determined by the following equation.

$$m = \delta f_b \,/\, \delta f \tag{2}$$

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

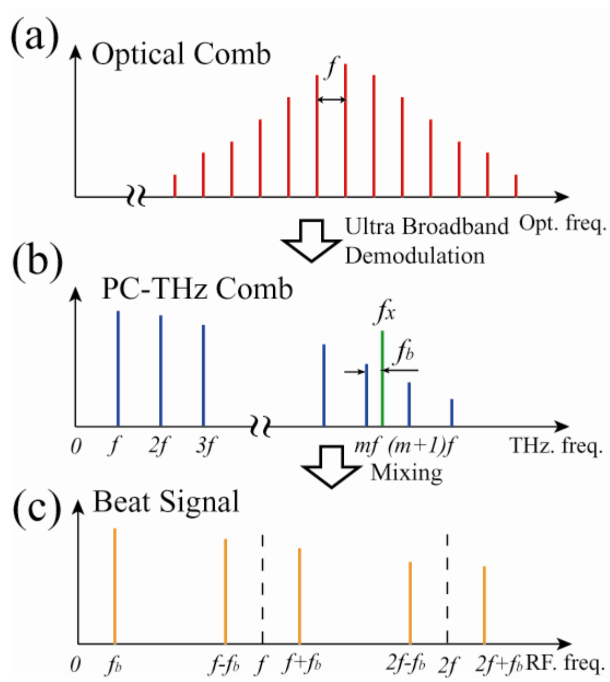


Fig. 2 Principle of THz frequency measurement.

## III. RESULTS

To test the THz spectrum analyzer, we here used a CW sub-THz test source (tuning range = 75-110 GHz, output power = 2.5 mW, linewidth < 0.6 Hz) composed of an active frequency multiplier chain (multiplication factor = 6), a frequency synthesizer (tuning range = 12.5-18.33 GHz), and a rubidium (Rb) frequency standard (accuracy = $5\times10^{-11}$ and stability = $2\times10^{-11}$ at 1s). Frequency spacing of the PC-THz comb is beforehand stabilized by a precise control system of the laser mode-locked frequency based on the Rb frequency standard. Figure 3(a) and (b) illustrate the linear-scale and logarithmic-scale spectra of the beat signal at the lowest frequency when the output frequency of the CW source and the mode-locked frequency are set at 99,007,200,000 Hz and 81,823,757 Hz, respectively (RBW = 1Hz and Sweep time = 2.3 s). The linewidth of the beat signal was 1.35 Hz from Figure 3(a) while the signal-to-noise ratio was 46.2 dB from Figure 3(b).

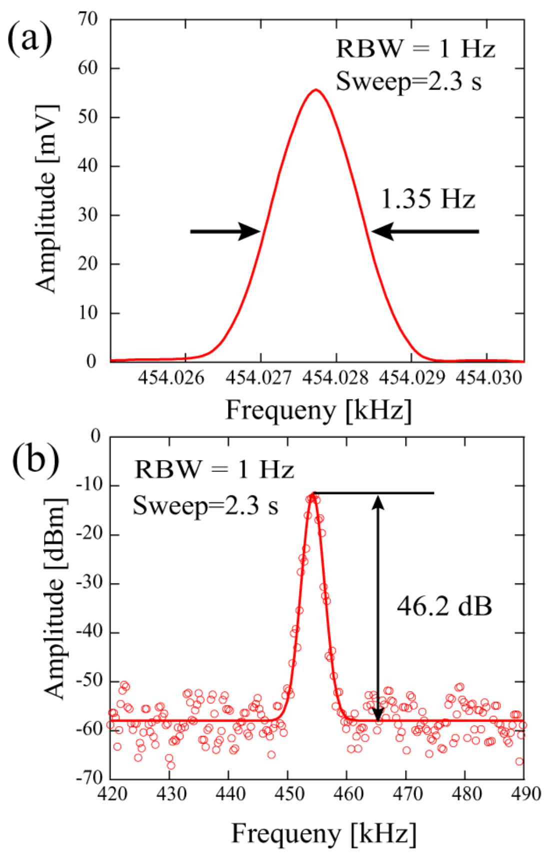


Fig. 3 (a) Linear-scale spectrum of the beat signal at the lowest frequency. (b) Log-scale spectrum.

Next, we determined the $m$ value based on the above procedure. To this end, the mode-locked frequency is changed by 100 Hz (= $\delta f$). This results in deviation of 121 kHz (= $\delta f_b$) in the beat frequency as shown in Figure 4 (sweep time = 773 ms, RBW = 1 kHz). By substituting the $\delta f$ and $\delta f_b$ values for Eq. 2, the $m$ value was determined to be 1,210. Therefore, the absolute frequency of the test source was determined to be 99,007,119,998 Hz from Eq. 1. Error of the measured frequency and the output frequency of the test source is 2 Hz. Furthermore, we determined the absolute frequency of the test source while tuning the output frequency from 75 to 110 GHz at 5 GHz intervals. Results at each frequency are summarized in Table 1.When the measurement precision of the THz spectrum analyzer is defined as a ratio of the error to the setting frequency, average precision of this demonstration was $2.85\times10^{-11}$.

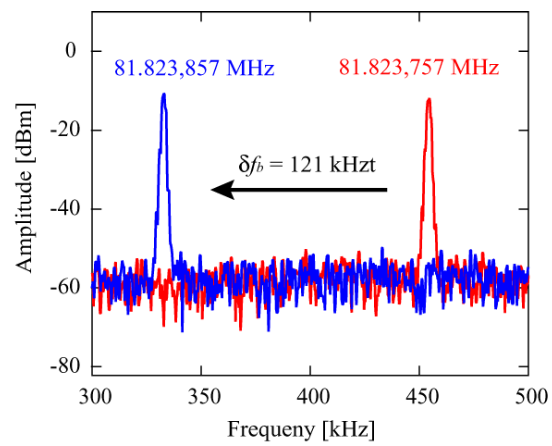


Fig. 4 Spectrum of beat signals at 81.823,857 and 81.823,757 MHz.

Table 1 Absolute frequency measurement of tuned test source

| Setting frequency [GHz] | Measured frequency [GHz] | Error [Hz] | Precision |
|---|---|---|---|
| 75.033,334,800 | 75.033,334,796,637 | 3.363 | $4.482\times10^{-11}$ |
| 80.024,623,200 | 80.024,623,199,487 | 0.513 | $6.411\times10^{-11}$ |
| 85,015,851,600 | 85.015,851,595,634 | 4.366 | $5.136\times10^{-11}$ |
| 90.007,140,000 | 90.007,139,997,658 | 2.342 | $2.602\times10^{-11}$ |
| 94.998,446,400 | 94.998,446,397,685 | 2.315 | $2.437\times10^{-11}$ |
| 99.989,728,800 | 99.989,728,797,413 | 2.587 | $2.587\times10^{-11}$ |
| 104.981,061,354 | 104.981,061,351,511 | 2.489 | $2.371\times10^{-11}$ |
| 109.972,299,617 | 109.972,299,614,217 | 2.783 | $2.531\times10^{-11}$ |
| | Average | 2.595 | $2.848\times10^{-11}$ |

## IV. CONCLUSION

We proposed the THz spectrum analyzer based on the PC-THz comb and demonstrated determination of the absolute frequency of the sub-THz test source. The achieved precision and signal-to-noise ratio of frequency measurement were $2.85\times10^{-11}$ and 50 dB, respectively.

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[2] T. Yasui *et al.*, Appl. Phys. Lett. **88**, 241104 (2006).