Real-Time Absolute Frequency Measurement of CW-THz Radiation Based on a Free-Running THz Comb

Takashi Ogura[1], Kenta Hayashi[1], Kosuke Nagai[1], Yoshiaki Nakajima[2,3], Hajime Inaba[2,4], Kaoru Minoshima[2,3], and Takeshi Yasui[1,2]

[1]Tokushima University, 2-1, Minami-Josanjima-cho, Tokushima, Tokushima 770-8506, Japan
[2]ERATO Intelligent Optical Synthesizer Project, JST, 1-5-1, Chofugaoka, Chofu, Tokyo 182-8585, Japan
[3]The University of Electro-Communications, 1-5-1, Chofugaoka, Chofu, Tokyo 182-8585, Japan
[4]National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan

Abstract

Absolute frequency of continuous-wave terahertz radiation was determined at an acuracy of 10^{-11} in real time by modulating a frequency spacing of photocarrier terahertz comb induced by a free-running femtosecond laser.

I. Introduction

Frequency measurement is the most basic measurement technology in the light and electric waves, but in THz region (wavelength = 30 ~ 3000 μm, frequency = 0.1 ~ 10 THz) which has not been explored for a long time, it has been difficult to measure frequencies in THz region with high accuracy in a room temperature environment. Therefore, we have been researching THz-comb-referenced spectrum analyzer which enables high precision frequency measurement at room temperature environment by following the procedures described as below: First, generate photocarrier terahertz frequency comb (PC-THz comb) in photoconductive antenna (PCA). Second, mix CW-THz wave and the generated PC-THz comb. Finally, beat down the resultant signal to the RF region by photoconductive mixing [1, 2]. However, in these previous researches, it is necessary to measure beat frequencies before and after shifting comb interval (= repetition frequency) in order to determine the comb mode number that is nearest to the CW-THz wave. This temporally serial, two-step measurement has been an obstacle to the real-time measurement. Recently, the absolute frequency of fluctuating CW-THz wave has been determined by measuring two beat frequencies simultaneously using two PC-THz combs with different comb intervals [3]. However, the use of dual stabilized femtosecond lasers may hinder its wide use. In this paper, we report here that we realized high-speed absolute frequency measurement using a single, free-running, frequency-modulated PC-THz comb.

II. Principle

THz-comb-referenced spectrum analyzer is based on a heterodyne technique based on photoconductive mixing [1, 2]. Figure 1(a) shows the spectral behavior of PC-THz comb mode (freq. interval = f_{rep}) and CW-THz radiation (freq. = f_{THz}) in this method. When f_{rep} is modulated sinusoidally (maximum f_{rep} value = f_{rep_max}, minimum f_{rep} value = f_{rep_min}), f_{beat} is also modulated in synchronization with the modulated f_{rep} (maximum f_{beat} value = f_{beat_max}, minimum f_{beat} value = f_{beat_min}) as shown Fig. 1(b). If fluctuation of f_{THz} is much slower than modulation frequency of f_{rep}, the mode order m of PC-THz comb nearest in frequency to f_{THz} can be determined using the following equation.

$$m = (f_{beat\_\max} - f_{beat\_\min}) / (f_{rep\_\max} - f_{rep\_\min}). \qquad (1)$$

Finally, f_{THz} is calculated as follow

$$f_{THz} = mf_{rep} - f_{beat} \quad \langle \text{in-phase between } f_{rep} \text{ and } f_{beat} \rangle \qquad (2)$$
$$f_{THz} = mf_{rep} + f_{beat} \quad \langle \text{out-of-phase between } f_{rep} \text{ and } f_{beat} \rangle$$

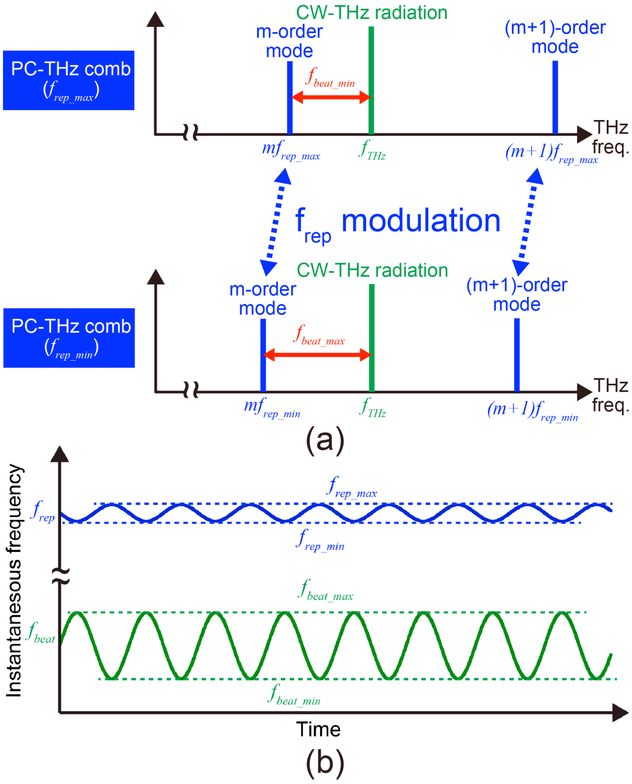

Fig. 1. Principle of operation.

III. Experimental Setup

Figure 2 shows an experimental setup of the proposed method. A femtosecond fiber laser (center wavelength = 1550 nm, pulse duration = 50 fs) was operated in free-running condition around a repetition frequency of 100 MHz. Then f_{rep} is modulated sinusoidally at frequency of

100 Hz by changing the fiber cavity length with PZT. When a CW-THz radiation is incident onto a photoconductive antenna (PCA) for THz detection together with a f_{rep}-modulated laser beam, a beat signal between PC-THz comb mode and CW-THz radiation is generated from PCA as a current signal. The current beat signal was amplified by a current preamplifier. Temporal waveforms of the beat signal and the laser pulse signal are acquired at a sampling rate of 100 MHz by a fast digitizer. Instantaneous frequency values of them (f_{beat} and f_{rep}) were obtained using a Hilbert transform [4].

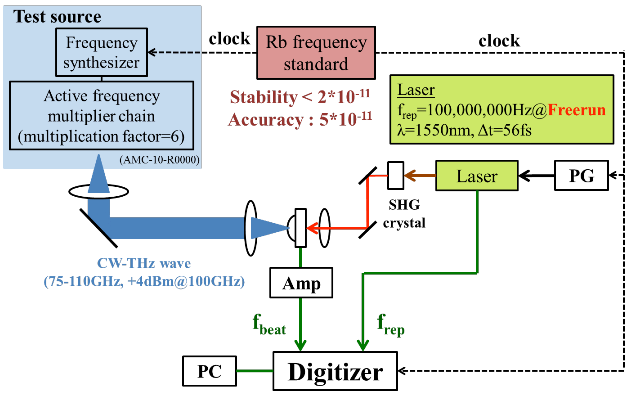

Fig. 2. Experimental setup

IV. Results

Figure 3(a) and 3(b) respectively show the temporal change of f_{rep} and f_{beat} when we used an active frequency multiplier chain (frequency range = 75~120 GHz, linewidth < 0.6 Hz, f_{THz} = 100.001,004 GHz) as a test source. From f_{beat_max} = 998 kHz, f_{beat_min} = 995 kHz, f_{rep_max} = 100.000,009 MHz, and f_{rep_min} = 100.000,006 MHz in Fig. 3(a), m was determined to be 1000. Finally, we confirmed that f_{THz} was fluctuated around 100.001,004 GHz as shown in Fig. 3(c). The determined f_{THz} coincided with the configured f_{THz} with accuracy of 10^{-11}.

V. Conclusions

We measured the absolute frequency of the CW-THz radiation with accuracy of 10^{-11} in real time using a single, free-running, f_{rep}-modulated femtosecond laser. Although f_{rep} is actively modulated in this paper, the similar experiment will be performed using the natural walking of f_{rep} in the free-running laser.

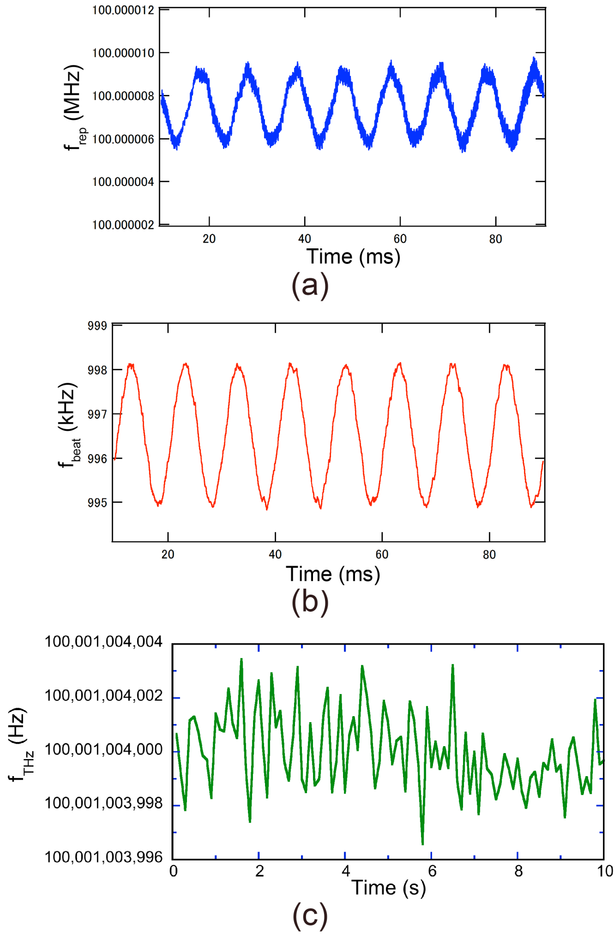

Fig. 3. Temporal change of (a) f_{rep}, (b) f_{beat}, and (c) f_{THz}.

References

[1] S. Yokoyama, R. Nakamura, M. Nose, T. Araki, and T. Yasui, "Terahertz spectrum analyzer based on a terahertz frequency comb," *Opt. Express*, vol. 16, pp. 13052-13061, Aug. 2008.

[2] T. Yasui, R. Nakamura, K. Kawamoto, A. Ihara, Y. Fujimoto, S. Yokoyama, H. Inaba, K. Minoshima, T. Nagatsuma, and T. Araki, "Real-time monitoring of continuous-wave terahertz radiation using a fiber-based, terahertz-comb-referenced spectrum analyzer," *Opt. Express*, vol. 17, pp. 17034-17043, Sep. 2009.

[3] K. Hayashi, H. Inaba, K. Minoshima, and T. Yasui, "Real-time absolute frequency measurement of CW-THz wave based on dual THz combs," in *CLEO:Science and Innovations 2014*, Technical Digest (CD) (Optical Society of America, 2014), paper Stu1F.4.

[4] H. Füser, R. Judaschke, and M. Bieler, "High-precision frequency measurements in the spectral region using an unstabilized femtosecond laser," *Appl. Phys. Lett.*, vol. 99, art. 121111, Sep.2011.