

Extraction of Beat Signal between Dual THz Combs Using Dual THz Spectrum Analyzers

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Abstract—It is crucial in asynchronous-optical-sampling THz time-domain spectroscopy or dual THz comb spectroscopy to suppress the timing jitter of the mode-locked frequency between two femtosecond lasers or frequency fluctuation of a beat signal between two THz combs because the fluctuation of them distorts the linearity of frequency scale in the spectrum. In this paper, dual THz spectrum analyzers were effectively used to extract a beat signal between dual THz combs around 0.1 THz. The resulting beat signal has a linewidth below 1 Hz and a signal-to-noise ratio of 20 dB. Furthermore, the extracted beat signal was used to suppress the remained timing jitter effectively.

I. INTRODUCTION

USE of two stabilized femtosecond lasers with slightly mismatched mode-locked frequencies (f_{rep1} , f_{rep2}) for generation and detection of THz radiation enables an asynchronous-optical-sampling THz time-domain spectroscopy (ASOPS-THz-TDS) [1-3] or dual THz comb spectroscopy [4, 5]. Attractive features in these methods include high resolution and accuracy in the broadband THz spectroscopy. However, in reality, frequency fluctuation of a beat signal Δf_{rep} ($= f_{rep2} - f_{rep1}$) between those two THz combs, corresponding to timing jitter of the mode-locked frequency between two femtosecond lasers, limits the spectral accuracy and resolution because a frequency scale of the spectrum is downscaled to RF region based on a ratio of f_{rep1} to Δf_{rep} . Even though the f_{rep1} and f_{rep2} can be well stabilized by direct control of them, Δf_{rep} is still fluctuated due to its indirect control via direct control of f_{rep1} and f_{rep2} . If fluctuation of Δf_{rep} can be extracted precisely, the remaining fluctuation of the beat signal will be well suppressed by direct control of Δf_{rep} . To this end, a higher harmonic component of Δf_{rep} should be extracted because the Δf_{rep} is too low frequency to use for precise laser control. In this paper, we extracted a 1071-th harmonic component of Δf_{rep} , or a beat signal between two THz combs around 0.1 THz. Furthermore, the extracted beat signal was used to suppress the timing jitter of the mode-locked frequency between two femtosecond lasers.

II. METHOD

We extracted a beat signal between dual THz combs using dual THz spectrum analyzers as shown in Fig. 1(a). THz spectrum analyzer is based on a heterodyne technique based on photoconductive mixing [6, 7]. Compared with the electrical heterodyne technique, a key difference here is the use of a photocarrier THz (PC-THz) comb, whose frequency covers from the sub-THz to the THz region, as a local oscillator with multiple frequencies. When two stabilized femtosecond fiber laser lights (center wavelength = 1550 nm, pulse duration = 50 fs, $f_{rep1} = 100,000,000$ Hz, $f_{rep2} = 100,000,010$ Hz) are incident

onto two independent photoconductive antennae (PCA1 and PCA2), two PC-THz combs with different frequency intervals of f_{rep1} and f_{rep2} are induced in PCA1 and PCA2 as shown in Fig. 1(b). Then, when CW-THz wave ($f_{THz} = 107.1$ GHz) is incident onto both PCA1 and PCA 2, two beat signals with f_{beat1} ($= f_{THz} - mf_{rep1}$) and f_{beat2} ($= f_{THz} - mf_{rep2}$) are generated as PCA current signals, where m is the order of comb mode nearest in frequency to f_{THz} . Finally, we obtained the beat signal between two PC-THz comb ($mf_{rep2} - mf_{rep1} = m\Delta f_{rep}$) by electrically mixing these two beat signals and low-pass filtering after amplification.

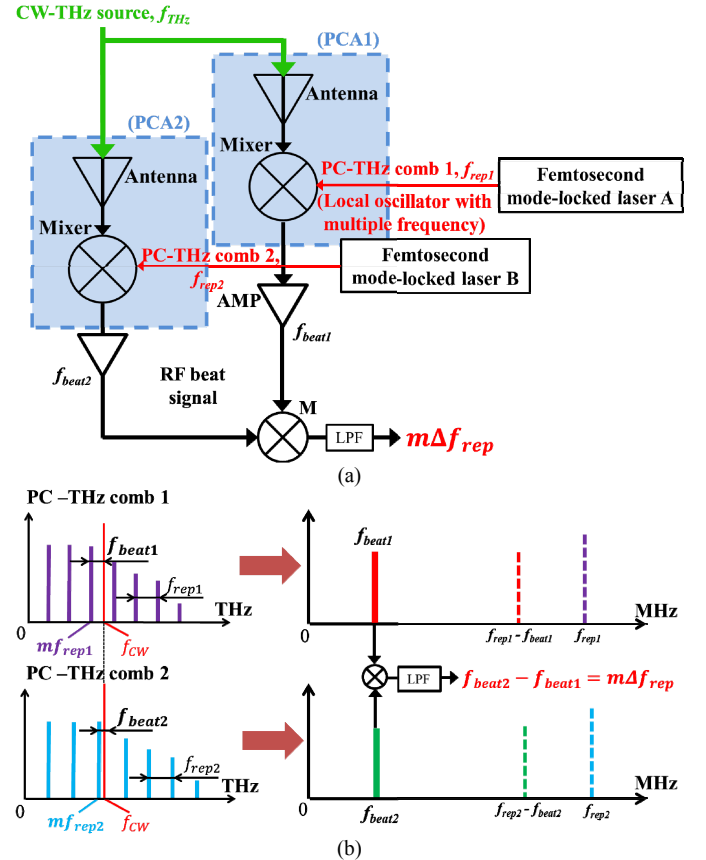


Fig. 1. (a) Experimental setup and (b) spectral behavior of dual THz spectrum analyzers.

III. RESULTS

Figure 2 shows an RF spectrum of a beat signal between dual PC-THz combs around 0.1 THz. The signal-to-noise ratio of the beat signal was achieved to 20 dB, which is sufficient to use as a control signal for laser stabilization. On the other hand, the extracted beat signal has a linewidth below 1 Hz which is limited by RBW of 1 Hz in RF spectrum analyzer. The narrow-linewidth beat signal sensitively reflects the timing

jitter between dual PC-THz combs.

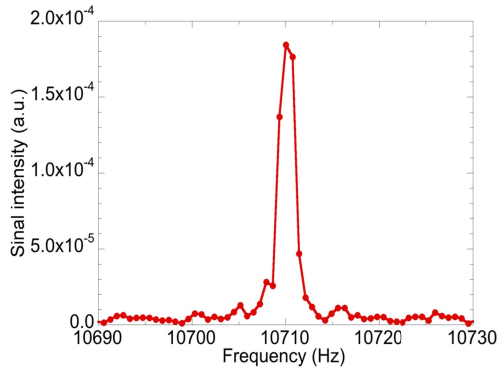


Fig. 2. RF spectrum of a beat signal between dual PC-THz combs around 0.1 THz (RBW = 1 Hz).

Figure 3 shows a frequency fluctuation of the beat signal with respect to gate time. The frequency fluctuation for free-running, dual femtosecond lasers is shown as a black line, indicating a little increase of the frequency fluctuation with respect to the gate time. For reference, the frequency fluctuation for direct control of f_{rep1} and f_{rep2} is shown as blue plots. Comparison between them indicated that the direct control of f_{rep1} and f_{rep2} reduce the fluctuation of the beat frequency. To further reduce the timing jitter, the beat signal was used to control f_{rep2} so that $m\Delta f_{rep}$ is constant while f_{rep1} is fixed at a certain value. The resulting frequency fluctuation was indicated as red plots. Such direct control of f_{rep1} and $m\Delta f_{rep}$ suppressed the timing jitter effectively and contribute to improve the spectral resolution and accuracy in the ASOPS-THz-TDS and dual THz comb spectroscopy.

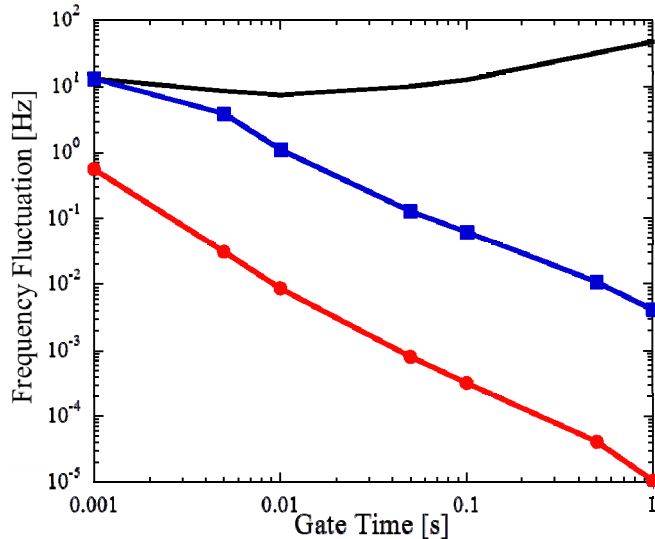


Fig. 3. Frequency fluctuation of beat signal with respect to gate time for free-running dual femtosecond lasers, direct control of f_{rep1} and f_{rep2} , and control of f_{rep1} and $m\Delta f_{rep}$.

IV. SUMMARY

Use of dual THz spectrum analyzers enables us to extract a beat signal between dual PC-THz combs around 0.1 THz. The extracted beat signal will be used not only to suppress the remained timing jitter effectively but also to combine an adaptive sampling method using two free-running lasers [8] with dual THz comb spectroscopy.

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