High-Speed Broadband Frequency Sweep of Continuous-Wave Terahertz Radiation

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***Abstract*—We present a new technical implementation of a high-speed broadband frequency sweep of continuous-wave terahertz (THz) radiation. THz frequency sweeping with a kHz sweep rate and a THz sweep range is implemented using THz photomixing in which an optical beat source consists of a wavelength-swept laser and a distributed feedback laser diode. During the frequency sweep, frequency-domain THz interferograms are measured using the coherent homodyne detection employing signal averaging for noise reduction, which can give time-of-flight information via fast Fourier transform. Multiple reflections in a Si wafer and the thickness of the wafer are measured to demonstrate the potential of this method for fast THz tomography and thickness measurement.**

I. INTRODUCTION

FREQUENCY sweeping is required to measure frequency-domain terahertz (THz) signals in THz spectroscopy, tomography, and radar imaging using continuous-wave (CW) radiation. While the frequency modulated CW THz method employing electronic components can have a high modulation rate of several kHz, the frequency modulation range is usually less than 100 GHz. The THz photomixing method can have a wide frequency sweep range of more than 1 THz but commonly requires a relatively long frequency sweep time due to slow laser frequency tuning.

In this paper, we present an experimental implementation of unprecedented THz frequency sweeping with a kHz sweep rate and a THz sweep range using THz photomixing where an optical beat source is comprised of a wavelength-swept laser (WSL) and a distributed feedback laser diode (DFB-LD). During the frequency sweep, frequency-domain THz interferograms are measured using the coherent homodyne detection method that specifically employs signal averaging instead of lock-in detection for noise reduction. The potential of this method for fast thickness measurement and THz tomography is demonstrated via measurement of a Si wafer.

II. EXPERIMENTAL SETUP

Figure 1(a) shows a schematic diagram of our experimental setup. To achieve the high-speed broadband THz frequency sweep, we use a beat-frequency-swept optical beat source with a kHz sweep rate in THz photomixing. The optical beat source consists of a DFB-LD and a WSL based on a semiconductor optical amplifier and a fiber Fabry-Perot tunable filter, of which the output power spectra are displayed in Fig. 1(b). The DFB-LD is operated at a fixed wavelength of 1545 nm, and the output wavelength of the WSL is swept from 1544 to 1558 nm at a kHz sweep rate. The optical setup is constructed for the coherent homodyne detection. Frequency-domain THz signals are measured in the frequency range up to 1.5 THz, where the large part of the output wavelength range of the WSL is used as indicated by the colored region in Fig. 1(b).

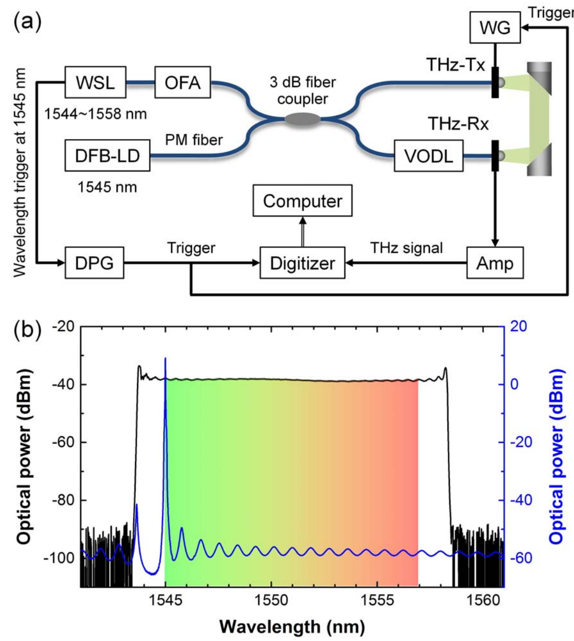

Fig. 1. (a) Schematic diagram of our experimental setup. PM fiber: polarization-maintaining fiber, OFA: PM optical fiber amplifier, THz-Tx: THz CW transmitter, WG: waveform generator, VODL: variable optical delay line, THz-Rx: THz CW receiver, DPG: digital delay/pulse generator, Amp: current preamplifier. (b) Output power spectra of the DFB-LD and the WSL.

When a THz CW transmitter biased by a waveform generator is irradiated by the optical beat source, CW THz radiation is emitted from the transmitter and is guided into a THz CW receiver by two off-axis parabolic mirrors. A photocurrent is generated from the receiver that is biased by the electric field of the CW THz radiation and irradiated by the optical beat source. The photocurrent is amplified using a current preamplifier with a bandwidth of 220 kHz and a gain of 1×10^7 V/A. A digital delay/pulse generator triggered by a wavelength trigger signal at 1545 nm produces a TTL signal at the same frequency as the sweep rate. Frequency-domain data traces are consecutively acquired at the sweep rate from the preamplifier by a digitizer with a sampling rate of 3 MS/s triggered by the TTL signal. At the same time, the TTL signal triggers the waveform generator to provide the transmitter with a bias voltage modulated at half the sweep rate. The signal-to-noise ratio of the THz data can be enhanced by subtracting noise traces acquired with the bias off from THz data traces carrying noise acquired with the bias on and averaging the resultant THz data traces. Using a Fabry-Perot interferometer, we measured the time variation of the optical frequency of the WSL and thus that of the THz frequency. THz data traces can be obtained with respect to the THz frequency by converting the time to the THz frequency using the time variation of the THz frequency.

III. Experimental Results

The time delay between the two paths leading to the receiver from the coupler can be varied by the variable optical delay line. Figure 2 shows frequency-domain THz data measured at different time delays, which were obtained by averaging 5,000 traces acquired in 10 s with the sweep rate set to 1 kHz. The THz data result from optoelectronic interference between the electric field of CW THz radiation and photocarriers in the receiver. The period of the interference pattern in the THz interferograms is equal to the reciprocal of the time delay. In other words, the fast Fourier transform (FFT) of the frequency-domain THz interferograms results in peaks in the time-delay domain. The full width at half maximum (FWHM) of the peaks is about 1.37 ps, resulting from the wide frequency range. The FFT results of such frequency-domain THz interferograms can be used as axial-scan data in reflection-mode THz tomography utilizing time-of-flight information. In that case, the axial resolution would be approximately 0.21 mm, corresponding to the FWHM.

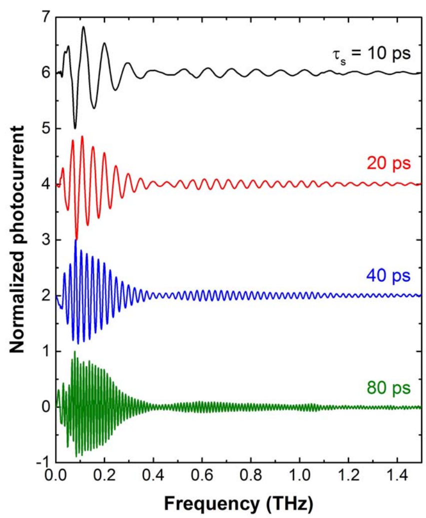

Fig. 2. Normalized frequency-domain THz interferograms measured at different time delays with a sweep rate of 1 kHz. They are vertically shifted for clarity.

The THz interferograms in Fig. 2 were normalized using their respective maximum absolute values. Actually, the maximum absolute value and the maximum FFT amplitude of a THz interferogram decrease with the increasing time delay, as shown by the blue dots in Fig. 3. This is due to two factors: the coherence time of the WSL and the detection bandwidth determined by the preamplifier. In Fig. 3, the black dots indicate the maximum FFT amplitudes of WSL interferograms measured at different time delays with a sweep rate of 1 kHz using the Mach-Zehnder interferometer illustrated in the inset. The coherence time of the WSL is estimated as 49 ps when the maximum FFT amplitude falls to 50%. The optical beat source and the THz wave have the same coherence time as the WSL since the DFB-LD has relatively quite a long coherence time. Thus, the maximum FFT amplitude of the THz interferogram should decrease with the increasing time delay in the same way as that of the WSL interferogram.

However, the maximum FFT amplitude of the THz interferogram decreases more rapidly with the increasing time delay than that of the WSL interferogram, as shown in Fig. 3. Since the detection frequency is linearly proportional to the time delay, the time delay can be linearly converted into the detection frequency in Fig. 3. The difference between the maximum FFT amplitudes of the THz and WSL interferograms is ascribed to the gain spectrum of the preamplifier because the gain of the preamplifier decreases with the increasing detection frequency.

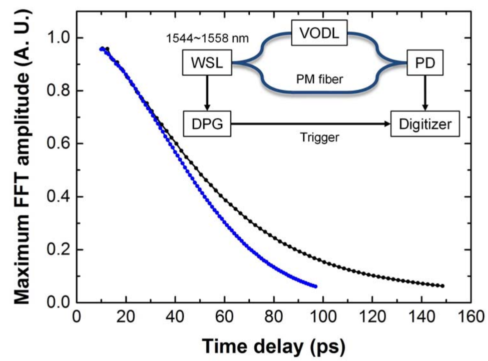

Fig. 3. Maximum FFT amplitudes of THz (blue dots) and WSL (black dots) interferograms measured at different time delays with a sweep rate of 1 kHz. WSL interferograms were measured using the Mach-Zehnder interferometer illustrated in the inset. PD: photodetector.

We demonstrate the potential of this method for fast thickness measurement and THz tomography. Figure 4 displays the normalized FFT amplitudes of THz interferograms measured with and without an undoped Si wafer in the THz path. The thickness of the Si wafer is given by

$$d = \frac{c}{2}\left(\Delta\tau_2 - 2\Delta\tau_1\right) \tag{1}$$

where $\Delta\tau_1$ is the time delay difference between the main peaks in the reference and sample data, $\Delta\tau_2$ is the time delay difference between the peaks due to multiple reflections in the sample data, and c is the speed of light in vacuum. The thickness of the Si wafer is estimated as 0.512 mm, which deviates by 0.4 % from the thickness value of 0.510 mm mechanically measured with an accuracy of 0.5 µm.

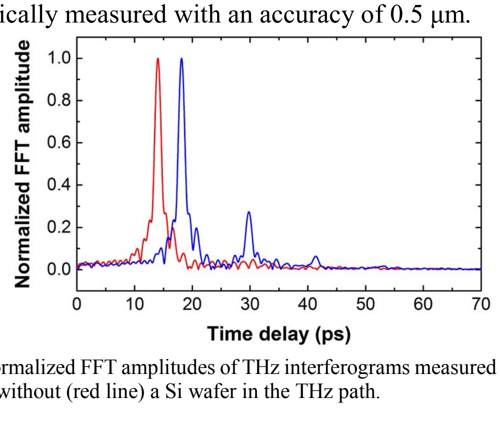

Fig. 4. Normalized FFT amplitudes of THz interferograms measured with (blue line) and without (red line) a Si wafer in the THz path.

IV. Summary

We have presented a method for THz frequency sweeping with a kHz sweep rate and a THz sweep range. Frequency-domain THz interferograms could be rapidly measured using the coherent homodyne detection employing signal averaging. Potential applications of this method include high-speed THz tomography and fast thickness measurement.