Low-noise terahertz material parameter extraction using a spinning wheel

Jegathisvaran Balakrishnan, Bernd M. Fischer, and Derek Abbott
Centre for Biomedical Engineering (CBME) and School of Electrical & Electronic Engineering,
The University of Adelaide 5005, Australia

***Abstract*— We demonstrate measurement of material optical parameters, in the THz regime, by mounting the sample under test on a spinning wheel. The proposed measurement technique is implemented using double-modulated terahertz differential time-domain spectroscopy (double-modulated THz-DTDS). Spinning sample addresses fundamental limitations imposed by linear sample dithering. The concept of spinning the sample allows rapid switching between the reference and sample signals with a single mechanical delay scan. We validate this technique by measuring the dielectric properties of thick polymer material.**

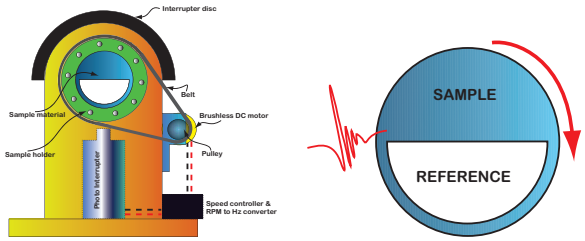
I. Introduction

In a typical conventional THz-TDS setup, a complete scan consists of a reference (air) scan and a sample (material) scan. In order to obtain a high SNR, each scan requires a separate delay stage scan with a measurement time of several minutes depending on the time constant set by the lock-in amplifier. A number of significant studies have motivated the need for a fast and reliable THz measurement technique, including: fast scanning of terahertz signal using oscillating and rotary optical delay lines [1, 2], real-time terahertz scanner for moving objects, and a rapid-phase modulation for high speed terahertz imaging and spectroscopy [3].

In this paper, we demonstrate an experimental results of a spinning wheel technique implemented using a double-modulated differential terahertz time-domain spectroscopy (double-modulated THz-DTDS) experimental setup [4, 6, 7]. The spinning wheel technique enables a rapid succession of measurements between the reference and sample signals with a single delay stage scan. This technique allows an improvement in the reference and sample measurements time by at least a factor of two as compared to the conventional THz-TDS measurement technique. Furthermore, we demonstrate a proof-of-principle showing that noise decreases as a function of the spinning wheel modulation frequency. The spinning wheel technique is experimentally verified using polyvinyl chloride (PVC) polymer material. A standardized thickness of 3 mm is used for all samples herein and this is a trade-off between maximising bandwidth and maximising THz interaction depth in the samples.

II. Spinning wheel

The spinning wheel is a mechanism proposed to address the mechanical instability in the dithering technique (Fig. 1). The spinning wheel consists of five main parts: sample holder, sample material, photointerrupter and interrupter disc, rpm to Hz converter circuit and brushless DC motor set which consists of pulley, timing belt, high speed three-phase DC motor, and speed controller.



(a) Prototype of spinning wheel (b) Front view of sample material

Fig. 1. **Prototype of spinning wheel for double-modulated DTDS polymer measurements.** Fig. 1a shows a prototype of the spinning wheel with mounted test sample. The spinning wheel is located in the focal plane with a modulation frequency ranging from 66 Hz to 310 Hz. As THz beam transmits through the rotating sample, a rapid succesion of measurements between the reference and sample can be achieved. In Fig. 1b, the front view of the test sample is shown. The test sample is designed to be half reference (air) and half sample (polymer). Adapted from [6].

The sample holder is built using a robust stainless steel wheel supported by a low friction ball bearings. The wheel is driven by a high speed brushless DC motor with a built-in governor mode. A custom-built pulley, a timing belt and a speed controller are attached to the motor. The sample is designed with half reference (air) and half sample (polymer) as shown in Fig. 1b. This design allows a rapid succession of measurements between reference and sample as the wheel spins. A photointerrupter electronic circuit and a photointerrupter disc, which are used to convert the wheel's spinning speed (rpm) into frequency (Hz) are attached to the spinning wheel.

III. Signal extraction method

Figure 2 shows a lock-in amplifier (LIA) setup configuration for signal extraction. In this setup, an additional external mixer based on MC1495P multiplier chip is added as compared to previously presented setup configuration [5]. This setup configuration is implemented in an existing THz-TDS system without any further modification. As the rotating spinning wheel with mounted test sample is placed in the THz beam path, double-modulated signal is produced. This signal is amplified using a pre-amp and fed into the lock-in amplifier configuration for mean and amplitude signals extraction (Fig. 2). With the mean and amplitude signals, the reference and sample signals can be extracted based on the formulas given in [4, 6, 7]. In Fig. 3, a simulated time-domain output signal

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of a mixer at nth step of the delay stage is illustrated. Here, the double-modulated signal is demodulated with the chopper reference signal without any filtering process. Based on this figure, one can clearly identify the reference signal, $E_{\mathrm{ref}}(t)$, sample signal, $E_{\mathrm{sam}}(t)$, mean signal, $E_{\mathrm{mean}}(t)$, and amplitude signal, $E_{\mathrm{amplitude}}(t)$.

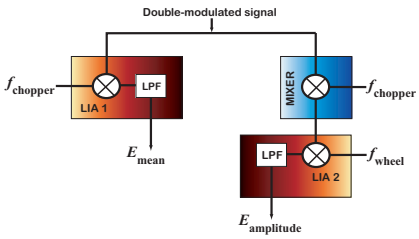


Fig. 2. **A simultaneous dual-waveform acquisition (mean and amplitude) using two lock-in amplifiers and a mixer.**

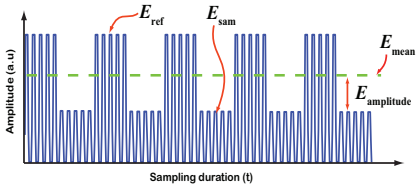
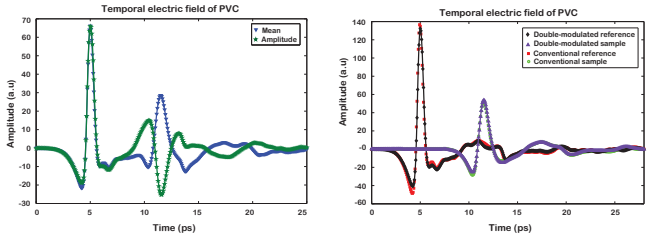


Fig. 3. **Time-domain simulated output signal of a mixer at nth step of the delay stage.**

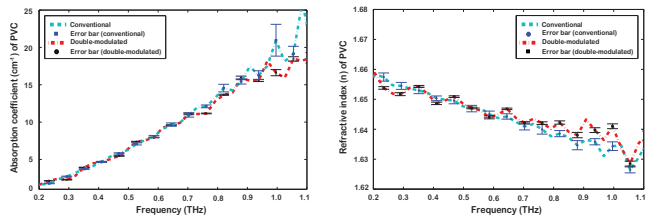
IV. Results and Discussion

In this section, we validate the spinning wheel technique using a polymer material PVC as a sample under test. At every nth step of the delay stage, reference and sample signals are measured in a rapid succession. This produces mean and amplitude waveforms simultaneously at the output channel of LIA1 and LIA2 (Fig. 4a). Therefore, with the mean and amplitude signals, the reference and sample temporal waveforms can be obtained (Fig. 4b). Here, the reference and sample waveforms from the double-modulated technique are compared with the reference and sample waveforms obtained from conventional THz-TDS technique. Based on our observation, a close match is obtained. These results are then used to calculate the terahertz transmission properties (i.e., absorption coefficient and refractive index) of the sample test. Figure 5 shows the terahertz transmission properties of PVC measured using the double-modulated spinning wheel which then compared with the terahertz transmission properties of PVC obtained from conventional THz-TDS measurement technique. Here, the results shows an excellent match. Furthermore, these results agree well with the literature [8]. We have also demonstrated the noise performance of the spinning wheel technique by optimising the frequency of operation of the spinning wheel. Figure 6 reveals that the noise detected in the THz system can reduced by increasing the modulation frequency of the spinning wheel.



(a) (b)

Fig. 4. **Mean and amplitude waveforms of PVC.** Figure 4a shows the mean and amplitude waveforms of PVC obtained through the double-modulated DTDS technique and Fig. 4b shows the double-modulated and conventional reference and sample waveforms of PVC.



(a) (b)

Fig. 5. **Absorption coefficient and refractive index of PVC.** This figure depicts the double-modulated and conventional absorption coefficient and refractive index of PVC, indicating a close match. The error bars indicate uncertainties in the conventional technique and double-modulated spinning wheel technique.

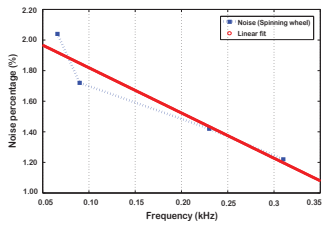


Fig. 6. **Noise performance of the THz system detected using a spinning wheel technique as a function of modulation frequency.**

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