Direct Detection of THz Pulse Position and Amplitude

H. Pühringer, M. Pfleger and S. Katletz
Research Center for Non Destructive Testing GmbH, Altenberger Str. 69, 4040 Linz, Austria
Email: stefan.katletz@recendt.at

***Abstract*—We present a novel measurement method to continuously measure the temporal position and amplitude of a terahertz (THz) pulse in a typical time-domain setup. Currently we have achieved a sampling time of $50\,\mathrm{Hz}$ and a resolution of less than $10\,\mu\mathrm{m}$. The method is therefore very well suited for online measurements in production processes to monitor the thickness and inhomogeneities in the composition of non-conducting materials.**

I. Introduction and Background

It is sometimes convenient, for certain applications, to directly measure the pulse position and amplitude of a typical time-domain THz setup. This information can be used to detect changes in the thickness, distance of a surface or interface, or inhomogneities in the composition of the tested material. The big advantage of the presented method is its high measurement speed, and the complexity of data post-processing being drastically reduced. It could therefore be used for an online measurement system to monitor, e.g., the thicknesses of sheets of paper or polymer foils. As a drawback, this technique is restricted to measure only the properties of a single pulse.

The application of THz waves to measure the thickness of paints was already shown in reflection [1], for paper thickness and water content [2], for polymer and additive content at the end of an extruder [3], and for thickness measurement of polyethylene (PE) using a CW system [4]. The determination of the thickness of tablet coatings was obtained at 100 measurements per minute with a minimum thickness of $40\,\mu\mathrm{m}$ [5]. In contrast the presented method achieves a better thickness resolution, while the speed is currently only restricted by the data acquisition and feedback control.

A. Detection Scheme

We use a standard THz time-domain (TD) setup as described in [6]. However, instead of modulating the photoconductive emitter antenna (PCA) with a alternating voltage at $\sim 5\,\mathrm{kHz}$, we apply a constant DC voltage and instead modulate the delay time with a fast oscillating mirror mounted on a moving coil actuator at its eigenfrequency of ~ 300 Hz. The resulting signal at the detector PCA is then analyzed with a lock-in amplifier at the 1$^{\mathrm{st}}$ and 2$^{\mathrm{nd}}$ harmonic of the modulation frequency. After optimizing the modulation amplitude to roughly the pulse width, the first signal will become proportional to the pulse amplitude. The second signal has a very characteristic signature which can be used to control the overall time delay. That means, the temporal displacement of the THz pulse, either caused by a change of the optical pathlength in the THz beam, or a movement of the reflecting interface, can be compensated by readjusting the time delay of the femtosecond probe pulse. The feedback control was implemented on a real-time PXI system from National Instruments, which steers the position of the mechanical delay stage from Physik Instrumente. The schematic drawing of the toal data acquisition system is shown in Fig. 1. The real-time OS and the user interface run in fact on a single personal computer, which is divided into two virtual machines. The lock-in amplifier also generates the reference signal for driving the moving coil actuator.

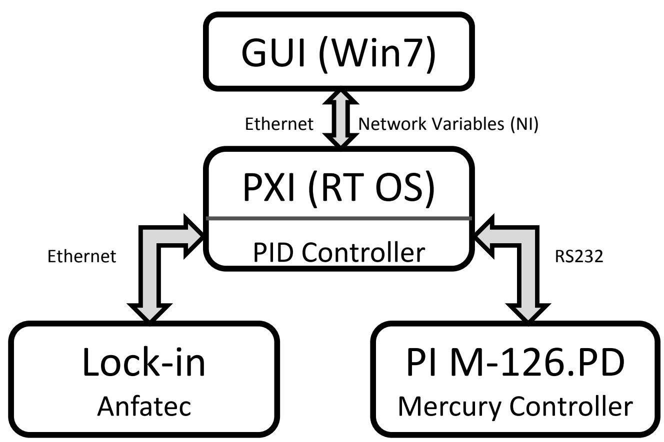

Fig. 1. Schematic drawing of the real-time system that was used for the measurements.

II. Results

The THz pulse measured with a lock-in amplifier and by modulation of the emitter voltage is shown in Fig. 2 (solid line with square symbols, x-axis is the position of the mechanical delay line). If the delay time is modulated (and the emitter voltage is held constant), the signal at twice the oscillation frequency resembles the THz pulse (solid line). At the pulse position the signal can be approximated well by a straight line (solid line with circles). The sensitivity of the signal (slope of the linear regression) is about $75\,\mathrm{V/mm}$, and the noise level (RMS) is roughly 0.3 V (indicated by the error bars in Fig. 2). Therefore, the resolution is currently limited to $\Delta d =$

$\frac{\text{RMS}}{\text{sensitiviy}} \frac{2\Delta x}{n-1} \approx 16\mu m$ (for a typical dielectric material with refractive index $n = 1.5$ [7]).

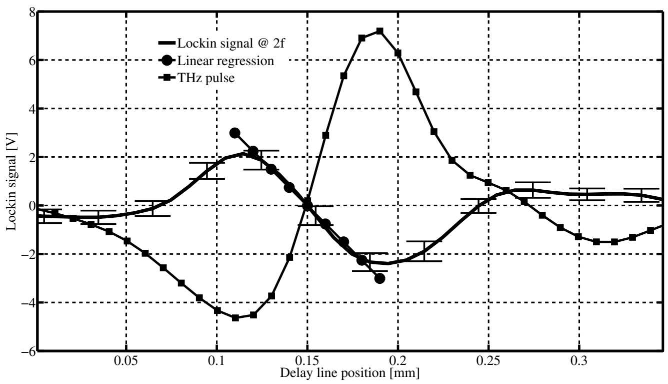

Fig. 2. THz pulse and demodulated measurement signal at twice the modulation frequency as a function of the offset position of the mechanical delay time.

The signal at twice the modulation frequency was subsequently used for controlling the mechanical delay line and to monitor the pulse position, which changes if sheets of paper are inserted into the beam path of the THz pulse. In Fig. 3 we show the position of the delay line during subsequent additions and removals of paper (single or two layers). From the refractive index of paper of about $n = 1.5$ [8] and $d = \frac{2\Delta x}{n-1}$, the thickness of the inserted material can be calculated and agrees well with the nominal thickness of $110\ \mu\text{m}$ and $220\ \mu\text{m}$, respectively. As can be seen, the feedback control is stable for sudden and large changes in the thickness.

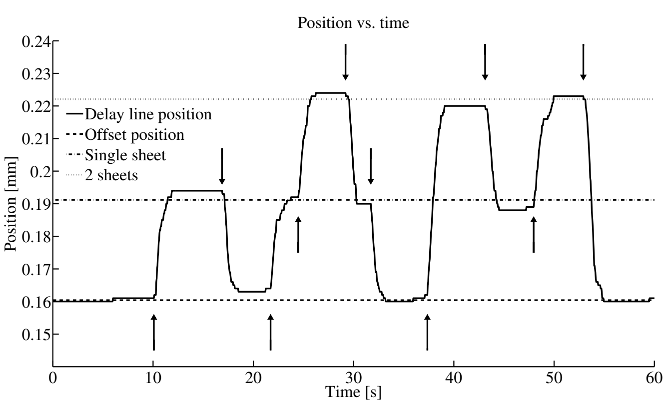

Fig. 3. Time trace of the detected number of sheets of paper (thickness roughly $100\ \mu\text{m}$. The arrows indicate the points where either a single or two sheets are inserted into the THz beam path, the dashed horizontal line represents the reference position.

III. Conclusion

We have presented a novel THz TD setup to directly detect the pulse amplitude and position. The method is very accurate and fast and therefore has a potential for on-line measurement applications. It has also been used to measure the thickness of various layers of polymer foils [9], where also the pulse amplitude was recorded. This would also allow monitoring changes in the polymeric material during the extrusion process, e.g., due to additives which cause additional attenuation.

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