Direct Time Axis Reconstruction for THz-TDS Systems With ultra-high Repetition Rates

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***Abstract*— Exploiting the high repetition rate of a monolithically integrated, fiber-coupled and mode-locked laser diode, we were able to accurately reconstruct the time axis of a compact terahertz time-domain spectroscopy (THz-TDS) system without an interferometer or a delay-line encoder. We achieved acquisition rates of 0.5 traces per second using a continuous driving mode of the optical delay unit (ODU) while maintaining a precise time.**

I. Introduction

The uncertainties from delay-lines in THz-TDS systems have been a focus in recent research activities. Recent publications have shown that these have a severe impact on the retrieved THz spectra [1], [2]. A method to overcome these errors is e.g. the application of an interferometer [3]. However, the addition of an interferometer increases cost and complexity of the system. Our presented method can be adapted for any ODU without the need of an interferometer or an encoder as long as a mode-locked laser diode (MLLD) is used [4], [5]. By exploiting the high repetition rate of mode-locked laser diodes, the spacing between pulses can be used to calculate an accurate time axis.

II. Setup

The laser used for the measurements is an extremely stable passively mode-locked two-section quantum dot laser with an RF linewidth around 30 kHz [6] in a conventional THz-TDS setup. The optical output of the laser is split by a 50/50 coupler with one signal delayed by a fiber-coupled ODU (ODL-650, Oz-Optics), before fed to the THz antennas. The emitter is realized as a biased antenna-integrated photodiode, whereas the detector consists of an unbiased photoconductive antenna. A coarse reconstruction of the time axis can be done by considering the specified ODU speed of 30 mm/s and the sample rate of the employed analog-to-digital converter.

To validate the reconstruction method, an interferometer was added to the setup enabling precise measurement of the time axis. For this purpose, a single-frequency laser with a wavelength of 1550 nm and a polarization orthogonally to the MLLD's polarization was combined with the MMLD by a polarization beam splitter (PBS). A second PBS was used to split the light after passing through the ODU. The MMLD's radiation was used for the THz generation and detection, while the signal from the single-frequency laser was used to monitor the position of the ODU during measurement. For both versions of the setup a lock-in-amplifier (MFLI, Zurich Instruments) was used for data acquisition.

III. Results

As a first step, the sampled data is truncated to cut out data sampled during the acceleration of the ODU. Having a well-known and stable repetition rate of 50.17 GHz, the temporal spacing between the measured pulses must be 19.93 ps. Using this information and the characteristic features of the measured pulse as shown in Fig. 1(a), a time axis can be derived without any additional information. Fig. 1(b) shows the resulting deviation of the derived axis from the originally measured axis. The deviation is dominated by a linearly increasing error which indicates that the specified ODU speed is inaccurate. The inset of Fig. 1(b) shows the deviation after the subtraction of the linear error which is related to non-constant movement of the ODU. The sampled data is then fitted to the new derived time axis. The resulting frequency domain is shown in Fig. 2. Comparing the 20th frequency component, the deviation from the expected maximum at 1.0034 THz is reduced by 20 GHz to the expected value.

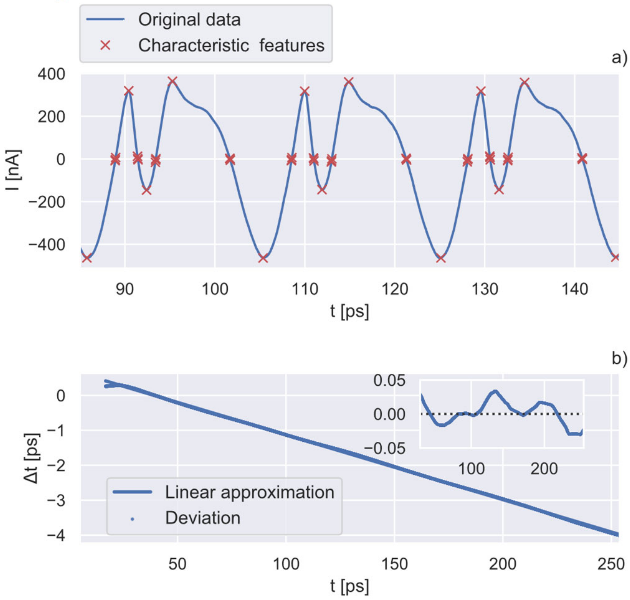

Fig. 1 (a) Original data with marked characteristic features. (b) Resulting deviation between calculated time-axis and reconstructed time-axis.

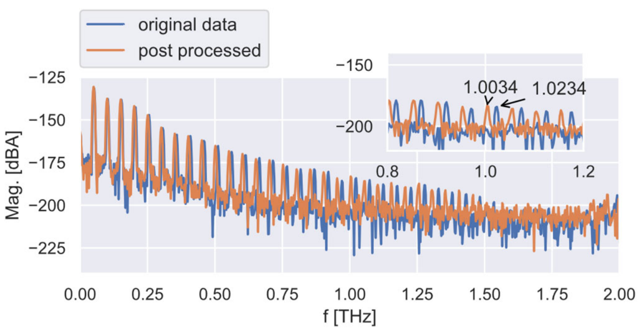

Fig. 2 Frequency domain representation of the data shown in Fig. 1. The 20th maximum is marked with its position on the frequency axis.

To validate the results, the measurements were repeated with the interferometer. This allows us the exact estimation of the ODU position during its movement and a comparison to the reconstructed time axis. However, to resolve the data of the interferometer, a minimum time resolution of 5.17 fs was needed. Therefore, the sample rate had to be adjusted resulting in an overall time resolution of 0.91 fs. Besides, the added parts in the receiver arm of the THz-TDS system led to a decrease in optical power as well as additional dispersion within the added fibre. Altogether leading to a worse signal-to-noise ratio (SNR) and lower bandwidth when compared to the previous measurement results.

The maxima of the interferometer data are used to calculate the time axis. Afterwards, the time axis is linearized and applied to the THz data by a cubic spline interpolation. The deviation of the time axis as shown in Fig. 3 is similar to the previously found deviation (cf. Fig. 1 (b)). Due to the much higher resolution, the interferometer measurements de-linearized deviations differ when comparing both insets of Fig. 1 (b) and Fig. 3. The higher resolution enables the corrections of higher frequency modulations within the time axis deviation which are mentioned by A. Rehn et. al. in [1]. The resulting frequency spectrum shown in Fig. 4 lacks in dynamic range as well as in bandwidth due to the previously mentioned changes to the setup. Therefore the 10th maximum is marked within the inset instead of the 20th as done in Fig. 2. The 10th maximum of the interferometer monitored data is off by 2.8 GHz which lies within the frequency resolution of 4.8 GHz. In comparison, the 10th maximum of the data where the time axis is calculated by estimating a linear movement of the delay line is off by 6 GHz which is not within the frequency resolution. Here it is to mention that the accruing error is increasing with rising frequency and therefore the importance of a correctly acquired time axis is increasing for higher frequencies.

In summary, the results from both the measured time axis as well as the reconstructed time axis show similar behavior when comparing to a linear approximated time axis. The deviations of linear approximations are direct results of non-linear movements which are partly systematic and partly stochastic. Both causing disturbances within measurements and thereby distorting results. This shows the importance of a suitable method of measuring or calculating the delay line position in such systems.

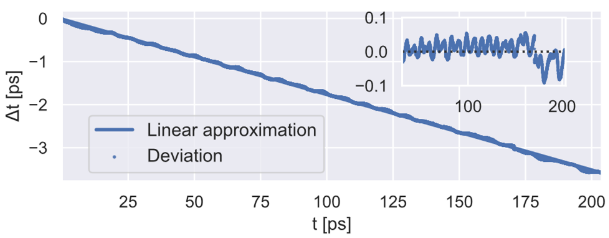

Fig. 3 Resulting deviation between calculated time-axis and reconstructed time-axis.

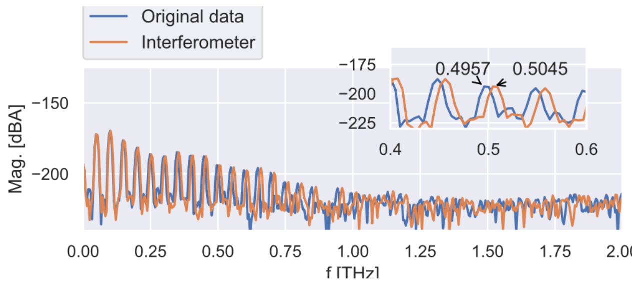

Fig. 4 Frequency domain representation of the data monitored with the interferometer. The 10th maximum is marked with its position on the frequency axis.

IV. Conclusion

In this paper, we presented an effortless method for the reconstruction of a precise time axis in mechanical ODU aided THz measurements based on the ultra-high repetition rate of a MLLD. While an interferometer aided ODU offers the possibility of high-precision and high-resolution time axis acquisition, it requires additional equipment which increases the size and the price of the measurement system. We demonstrate that the novel method enables a precise reconstruction of the time axis. However, systemic deviations from the linear movement of the ODU with a high frequency still require an interferometer as we have shown. For the future, we are planning to counter this challenge by compensating for the arising errors in the frequency domain by a post-processing step. In summary, our approach has the potential to make high precision ODUs superfluous and thus enabling low-cost system concepts without compromising the data quality.

References

[1] A. Rehn, D. Jahn, J. C. Balzer, and M. Koch, “Periodic sampling errors in terahertz time-domain measurements,” *Opt. Express*, vol. 25, no. 6, p. 6712, 2017.

[2] D. Jahn, S. Lippert, M. Bisi, L. Oberto, J. C. Balzer, and M. Koch, “On the Influence of Delay Line Uncertainty in THz Time-Domain Spectroscopy,” *J. Infrared, Millimeter, Terahertz Waves*, vol. 37, no. 6, pp. 605–613, 2016.

[3] D. Molter, M. Trierweiler, F. Ellrich, J. Jonuscheit, and G. Von Freymann, “Interferometry-aided terahertz time-domain spectroscopy,” *Opt. Express*, vol. 25, no. 7, p. 7547, Apr. 2017.

[4] K. Merghem, S. F. Busch, F. Lelarge, M. Koch, A. Ramdane, and J. C. Balzer, “Terahertz Time-Domain Spectroscopy System Driven by a Monolithic Semiconductor Laser,” *J. Infrared, Millimeter, Terahertz Waves*, vol. 38, no. 8, pp. 958–962, Aug. 2017.

[5] K.-H. Tybussek, K. Kolpatzeck, F. Faridi, S. Preu, and J. C. Balzer, “Terahertz Time-Domain Spectroscopy Based on Commercially Available 1550 nm Fabry–Perot Laser Diode and ErAs:In(Al)GaAs Photoconductors,” *Appl. Sci.*, vol. 9, no. 13, p. 2704, Jul. 2019.

[6] M. Zander *et al.*, “High performance BH InAs/InP QD and InGaAsP/InP QW mode-locked lasers as comb and pulse sources,” in *Optical Fiber Communication Conference (OFC) 2020*, 2020, p. T3C.4.