

A pulsed THz Imaging System with a line focus and a balanced 1-D detection scheme with two industrial CCD line-scan cameras

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Abstract: We present a pulsed THz Imaging System with a line focus intended to speed up measurements. A balanced 1-D detection scheme working with two industrial line-scan cameras is used. The instrument is implemented without the need for an amplified laser system, increasing the industrial applicability. The instrumental characteristics are determined.

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1. Introduction

For real-world applications, terahertz (THz) imaging and THz time-domain spectroscopy (TDS) systems still lack the speed that is necessary to cover large sample areas in almost real time. Speed is mainly limited by the need for mechanical delay stages as well as by single-pixel emitters and sensors resulting in a long process of scanning the sample. In order to improve measurement speed, various approaches are currently pursued ranging from faster delay lines over coupled laser systems and CW systems for certain applications to multi-pixel sensors and emitters - in particular unbalanced 2-D methods based on electro-optical sampling (EOS) working with a charge-coupled device (CCD) camera [1,2]. Also systems using CMOS cameras have been demonstrated [3]. Furthermore balanced methods using only one CMOS camera and an arrayed polarizer were shown by Kitahara et al. [4]. They state that the system noise was highly affected by unstable environmental conditions such as air temperature which likely prevents it from being used in industrial applications.

In this paper, we report on focusing a whole THz line rather than a spot on the sample, and detecting the complete line in one step. By using a balanced measurement technique, we improve the signal-to-noise ratio (SNR) and thus the measurement speed. We were able to base our work on earlier experiences we made from a system with a detection scheme based on EOS and only one 2-D CCD camera [5–7]. In contrast to the work presented by Yasui et al. [8], we do not use an amplified laser system in order to keep the system usable in an industrial environment.

2. Setup and Components

We use a transmission THz TDS setup (see Fig. 1). The emitter, a $50\mu\text{m}$ bowtie antenna, is pumped with optical pulses of 80mW average power from a Ti:sapphire laser with a center wavelength of 780nm, a pulse-duration of less than 100fs, and a repetition rate of 80MHz. The modulation of the excited photocurrent is electrically controlled and the chopping signal is processed in a computer that also triggers the detector.

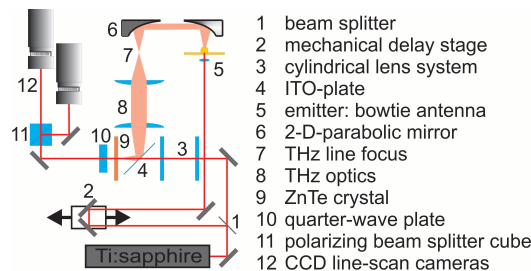


Fig. 1. Setup.

The THz line focus is achieved with a custom-made aluminum mirror which is shaped in such a manner that only one dimension of the THz beam is focused while the other remains unchanged [see Fig. 2(a)]. This goal is achieved by having a reflective surface that features a parabolic curvature in 2 dimensions and not a paraboloid curvature in 3 dimensions as most customary mirrors do. This is why we call it a "2-D parabolic mirror". The parabolic curvature

is approximated with 120 linear segments. The assembly accuracy with about $10\mu\text{m}$ is well below wavelength. The transformation characteristics were simulated with ZEMAX[®] [see Fig. 2(b)].

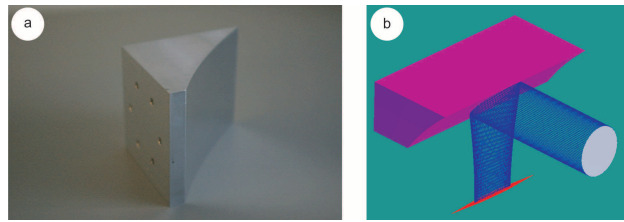


Fig. 2. (a) 2-D Parabolic Mirror, (b) ZEMAX[®]-Simulation.

The THz detector consists of a modified EOS setup [9]: The zinc telluride (ZnTe) crystal is illuminated by a linearly expanded laser beam and the THz line focus is imaged on the ZnTe crystal, overlapping the optical beam by the use of an indium tin oxide (ITO) plate. The ZnTe crystal is then imaged through a quarter-wave plate onto the CCD lines of two coupled industrial line-scan cameras *A* and *B* by means of a polarizing beam splitter cube.

3. Spatially Resolved, Balanced Detection

The EOS measurement technique is based on modulating the birefringence of the ZnTe crystal via an applied electric field which modulates the polarization ellipticity of the optical probe beam passing through the crystal. The amplitude and phase of the electric field is then detected by polarization analysing the ellipticity modulation of the optical beam after the ZnTe crystal by means of a polarizing beam splitter cube [10]. The radiant flux in any of the two different polarization directions is recorded with a CCD line-scan camera (see Fig. 3) for all positions along the focal line with the 2048 pixels of each CCD sensor line simultaneously.

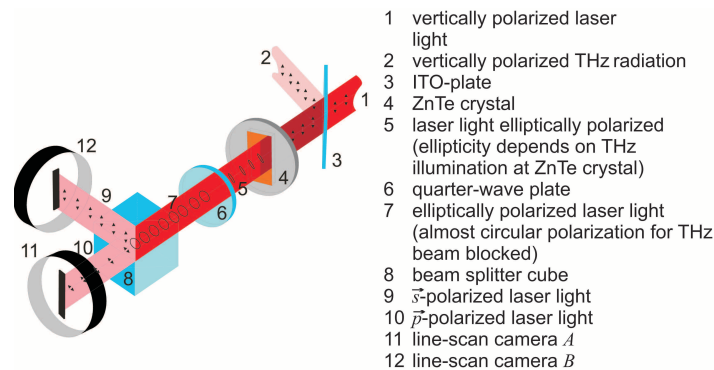


Fig. 3. Detection Scheme.

By applying a pixel-wise difference algorithm to the two line signals, one achieves a balanced detection of the THz electric field. To further improve SNR, the signal is also chopped in time as proposed by Jiang et al. [11].

A single square-wave signal generator forms a clock to the experiment. Each camera is triggered by that square-wave generator and writes its recorded lines into a data record called “frame” until such a frame consists of 500 lines and can be sent as a matrix

$$F_{n,m}^x \quad x \in \{A, B\}; n = 1, \dots, 500; m = 1, \dots, 2048 \quad (1)$$

to the corresponding frame grabber card of the camera computer. The upper limit of 500 lines was chosen in order to guarantee error-free data transfer which depends on the processing speed of the computer. Since the bias voltage of the emitter antenna is triggered by the same square-wave signal generator via a frequency divider with a fixed factor of 2, all even line-numbers of the frame cover one state of the antenna, e.g. emitting THz, while all odd line-numbers constitute the other state of the antenna, i.e. not emitting THz. For each camera, a new frame $F_{n,m}^x$ with its elements $f_{k,m}^x$ respectively $f_{l,m}^x$ defined as follows

$$F_{n,m}^x = \begin{cases} f_{k,m}^x = (F_{i,m}^x + F_{i+1,m}^x)/2 \\ f_{l,m}^x = (F_{i,m}^x - F_{i+1,m}^x)/2 \end{cases} \quad (2)$$

$$x \in \{A, B\}; k = 1, \dots, 250; l = 251, \dots, 500; m = 1, \dots, 2048; i = 1, 3, 5, \dots, 499$$

is calculated. The first 250 lines of the frame $F_{n,m}^x$ form a two-line average and are only used for alignment purposes. The divisor with a value of 2 is needed to make sure, that the values remain within the digital limits given by the type of data variables used in the program. The last 250 lines compose the lock-in method of the so-called “electrical chopping technique”. We further enhance the detected THz signal by making use of a balanced detection scheme, that is to subtract frame $F_{n,m}^A$ of camera *A* from frame $F_{n,m}^B$ of camera *B*

$$F_{n,m}'' = (F_{n,m}^B - F_{n,m}^A)/2 \quad n = 1, \dots, 500; m = 1, \dots, 2048. \quad (3)$$

Lines 251 to 500 of each frame $F_{n,m}''$ are averaged into a “result line” which is displayed as a graph on the screen and can be saved to disk as a “.tif”-image file. Again, the divisor with a value of 2 keeps the values within the digital limits of the data variables.

4. Signal Processing and Measurement

A THz TDS measurement is realized by moving the delay in such a manner that the THz waveform is sampled by the shorter optical laser pulses. TDS measurements thus result in a series of “.tif”-image files each slide of which contains a result line, i.e. the spatially resolved measured THz electric field averaged for a particular short period of delay time (see Fig. 4).

By putting all slides together, one not only retrieves the waveform for each sensor pixel but can also make a “tomographic” film that allows to “fly” through the sample [12,13]. By moving the object perpendicular to the vertically aligned THz line focus and the beam direction, one can also image samples.

The display rate achievable on the computer screen depends on the THz system’s clock frequency and the level of averaging and is limited by the maximum camera repetition frequency.

5. System Characterization

A “T-shaped” polytetrafluoroethylene (PTFE) sample was used for characterizing the system and checking the alignment (see Fig. 5). The bar is 27 mm wide (*b*), 2 mm high (*a*) and 1 mm thick (*r*, calculated as the difference of *e* and *d*) on top of the supporting block. The supporting block behind the bar is 4 mm thick (*c*).

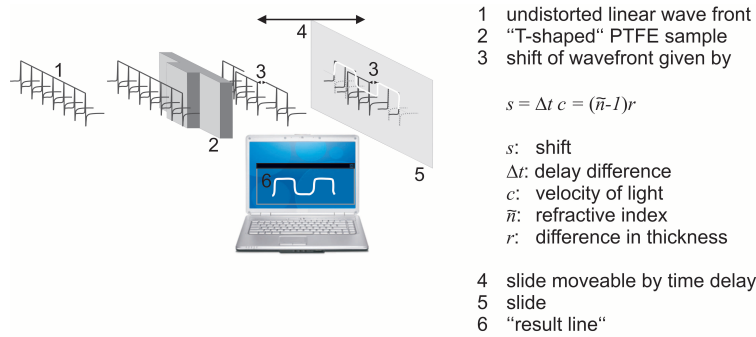


Fig. 4. TDS measurement. For display simplification, the picture is rotated by 90°.

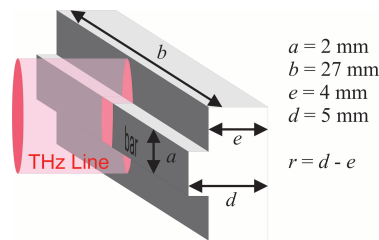


Fig. 5. "T-shaped" PTFE Sample.

A spatially resolved TDS measurement of the "T-shaped" PTFE sample clearly shows the retarded wave front where the central part of the line focus propagates through the bar [see Fig. 6(a)].

The difference in delay time between the main wave front and the retarded middle part of the wave front is $\Delta t = 1.44 \text{ ps}$. This corresponds perfectly to a calculated shift of $\Delta t = \frac{(\bar{n}-1)r}{c} = 1.43 \text{ ps}$ with $\bar{n} = 1.43$, $r = 1 \text{ mm}$ and $c = 3 \cdot 10^8 \text{ ms}^{-1}$. The height of the retarded part of the wave front measures 2.14 mm and thus matches the true dimension of 2 mm precisely. The height of the complete THz line focus measures 11.4 mm compared to an earlier measurement, where, without sample, by applying appropriate apertures, the THz focus was estimated to being 10 mm high and 2.5 mm wide. These results are close to the absolute limits of the setup given by the components, particularly the quarter-wave plate with a clear aperture of 12.7 mm.

A "tomographic" film, showing what can be seen on the computer display while "flying through" the "T-shaped" PTFE sample is also provided together with this article.

The maximum amplitude SNR achieved with this instrument is 30 amounting to 30 dB. This value was measured by dividing the maximum value of a time-domain waveform [see Fig. 6(c)] by the root mean square deviation of the values derived from the same waveform up to 5 ps before the pulse maximum.

The spectrum of this measurement shows that the bandwidth of the system reaches 2.5 THz [see Fig. 6(b) and Fig. 6(d)] with the sample surrounded by air with reduced water vapor content. Small blue areas representing low spectral amplitude [marked with white ellipses in Fig. 6(b)] are due to scattering and diffraction effects which result in destructive interference. Additional oscillations can be seen in the spectral plot. They result from the Fourier transformation of the echo pulses at around 50 ps. Some water vapor absorption lines can still be seen, reveal-

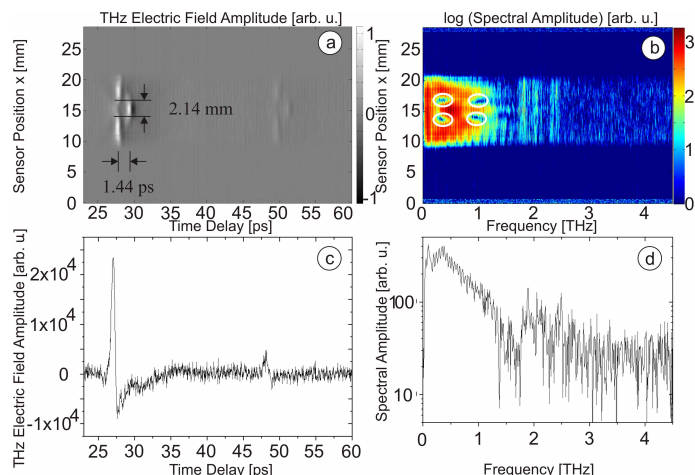


Fig. 6. (a) Spatially resolved THz Electric Field Amplitude in Time Domain (Media 1). (b) Spatially resolved THz Spectral Amplitude. (c) Example for a measured THz waveform at position $x = 18.9$ mm. (d) Fourier transformation of the waveform plotted in (c). One can see that the bandwidth goes up to 2.5 THz. However, due to the imperfect purging, water absorption lines around 1.4 THz and 1.6 THz and between 2.2 THz and 2.3 THz are seen.

ing that the sample environment was not perfectly purged with dry air. Especially the stronger resonances around 1.4 THz and 1.6 THz and between 2.2 THz and 2.3 THz are seen.

To verify the capabilities of the system for fast measurements, the camera was operated at 3.3 kHz resulting in an acquisition time of 150 ms per frame; 12 frames are averaged into one block. The delay stage, changing the path length of the single-folded probe beam, was moved in such a way that 93 ps of delay time were measured in 14 min. The measurement time for the illuminated area of 28.5 mm^2 is comparable to the time a conventional scanning system would need to scan the same area with a comparably high spatial and spectral resolution. The SNR determined in these measurements dropped slightly to 25.

The measurement speed is limited by the maximum speed of the delay line and can be increased by more than a factor of 100 assuming modifications to the camera control software but would cause a further drop in SNR which is currently not acceptable. The SNR may be increased by using stronger emitters, for example a larger bowtie antenna operated with higher optical power and supply voltage.

6. Conclusion

A THz imaging system with a line focus was realized without the need of an amplified laser system. A balanced 1-D detection scheme with two industrial CCD line-scan cameras has been demonstrated. Furthermore, sophisticated software permits not only signal balancing but also a lock-in procedure to be applied to the data of each camera. The geometry of the line focus was measured to be 11.4 mm in height and 2.5 mm in width. The resolution in space and in delay time of the setup was verified with a “T-shaped” PTFE sample. The 2 mm structure was perfectly resolved and the measured delay time was in agreement with predictions. A maximum SNR of 30 has been achieved so far.

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