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Field Intensity Detection of Individual Terahertz Pulses at 80 MHz Repetition Rate

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Abstract We present a new approach to detect the intensity of individual terahertz pulses at repetition rates as high as 80 MHz. Our setup comprises a femtosecond fiber laser, an InGaAs-based terahertz emitter, a zero-bias Schottky detector, and a high-speed data acquisition unit. The detected pulses consist of two lobes with half-widths of 1–2 ns, which is much shorter than the inverse repetition rate of the laser. The system lends itself for high-speed terahertz transmission measurements, e.g., to study wetting dynamics in real time.

Keywords Ultra-high-speed terahertz transmission measurements · InGaAs photoconductive switch · Zero-bias Schottky diode · Time-domain terahertz · Wetting dynamics

1 Introduction

Since the invention of photoconductive switches in 1984 [1], time-domain terahertz (TD-THz) instrumentation has undergone a remarkable performance boost. Applications for TD-THz systems range from fundamental studies of nanostructures and metamaterials to non-destructive testing of plastic composites and paint layers, from security screening of parcels and envelopes to water-level monitoring in plants, and from semiconductor inspection to the identification of hazardous chemicals [2, 3]. As of today, a plethora of TD-THz platforms is commercially available, the one common principle being a pump-probe approach: On the transmitter side, a terahertz emitter "translates" a short laser pulse into terahertz radiation, which—on the receiver side—is sampled with a time-shifted copy of the laser pulse. This concept usually includes a time delay, which is either realized with a mechanical stage or by synchronizing the pulse trains of two lasers. Whilst mechanical delays achieve measurement rates of 10–500 Hz (i.e., pulse traces per second) [4, 5], systems based on synchronized

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repetition rates reach into kilohertz regimes [6–8]. Yet, in both cases, the velocity of the time delay remains the bottleneck in terms of attainable data rates.

As early as 1998, Jiang and Zhang demonstrated the time-resolved detection of individual terahertz pulses by employing probe pulses with a linear frequency chirp [9, 10]. However, since their setup utilized a CCD camera with a minimum exposure time of 10 ms, the repetition rate of the femtosecond laser had to be reduced to 50 Hz, i.e., to a speed akin to that of mechanical translation stages. In addition, their experiment still featured an adjustable delay in order to synchronize the arrival of terahertz and readout pulses on the electro-optic detector.

On the other hand, there exists a demand for TD-THz instruments that operate at significantly higher measurement speeds. One field of research that calls for much faster acquisition speeds is the study of protein dynamics in water [11]. Biomolecules solved in water unfold within milli- or microseconds and, consequently, the terahertz absorption properties of the protein-liquid mixture change on the same time scale. In an industrial setting, truly “ultrafast” means are required to monitor the properties of rapidly moving samples with high spatial resolution, e.g., to scan folded boxes for lacking components, or to control material parameters in papermaking [12]. Yet, another scenario is the assessment of drought stress in plants [13]. In all of these applications, TD-THz techniques have proven their potential, but today’s systems are simply not fast enough for widespread industrial use.

In this letter, we present a novel, compact and cost-efficient system which assesses the intensity of individual terahertz pulses without any a delay stage or “pulse-picking” means. By using a high-bandwidth Schottky diode as terahertz receiver, we sacrifice any spectral information contained in the incident terahertz pulse, yet the terahertz intensity itself is recorded at an unprecedented rate. Owing to sufficiently strong terahertz emitters, our setup requires neither lock-in detection nor signal averaging and, consequently, field intensity measurements of individual terahertz pulses become feasible. In other words, the measurement speed is only limited by the repetition rate of the utilized femtosecond laser, which, in our experiment, amounts to 80 MHz. The new concept thus lends itself to the observation of dynamic processes with a temporal resolution as short as a few nanoseconds.

2 Experimental Setup

Figure 1 shows a schematic representation of the measurement setup. The system comprises four core components, namely (i) a compact fiber-based femtosecond laser, (ii) a high-power photoconductive terahertz emitter, (iii) an ultrafast terahertz detector with gigahertz bandwidth, and (iv) a fast data acquisition unit.

The laser (FemtoFErb 1560, Toptica Photonics) emits short pulses with a halfwidth of approx. 80 fs, a repetition rate of 80 MHz, an output power of ~100 mW, and a center

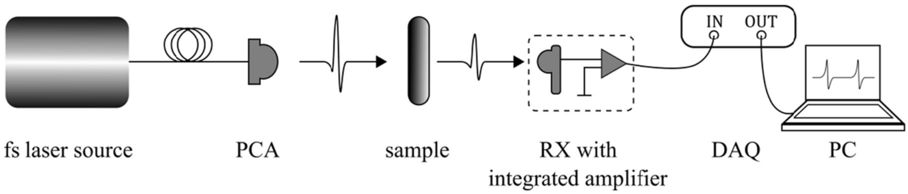

Fig. 1 Schematic of the measurement setup. *PCA* photoconductive antenna, *RX* broadband receiver, *DAQ* data acquisition unit, *PC* external computer for data processing

wavelength of 1560 nm. The pulses are delivered via a single-mode, polarization-maintaining fiber of approx. 5 m length. To provide an optimum pulse shape at the location of the terahertz emitter, the system includes dispersion-compensating fibers which are spliced into the fiber-optic beam path. The fiber assembly also serves to attenuate the laser output to an incident power of ~20 mW on the photoconductive antenna.

The terahertz emitter (model THz-P-TX, Fraunhofer Heinrich-Hertz Institute, Berlin) combines a high-mobility InAlAs/InGaAs multilayer heterostructure [14, 15] with a strip-line antenna geometry, using a 100-μm mesa-structured photoconductive gap region [16]. The module is packaged into a compact housing of 25 mm diameter, where a single-mode, polarization-maintaining fiber pigtail guarantees stable optical excitation.

The photoconductive emitter converts the optical pulse train into terahertz radiation with an average power of approx. 25 μW [16]. The spectral width spans 6 THz, with the highest power being emitted at frequencies around 450 GHz. The time interval between two consecutive pulses is given by the inverse repetition rate of the laser (1/80 MHz=12.5 ns).

The receiver unit (model 3DL 12C LS2500, ACST GmbH) features a zero-bias Schottky diode with a usable frequency range of 50 GHz—1.2 THz [17, 18]. The bandwidth of the Schottky receiver thus matches the peak power of the incident terahertz pulse. A fast amplifier with 4 GHz bandwidth converts the output of the Schottky diode to voltage signals, which are recorded and processed by a high-speed data acquisition unit (WaveRunner 44Xi-A, LeCroy) at a sampling rate of 5 GS/s. Even though the receiver unit acts as low-pass filter, broadening the emitted terahertz pulse in time, it is still sufficiently fast to resolve individual terahertz pulses, i.e., the total measurement rate exceeds 80 MHz.

Owing to both the high terahertz power generated by the photoconductive switch and the high sensitivity of the Schottky receiver, our setup requires neither a delay stage nor any lock-in, signal averaging or pulse-picking means. This simplifies the detection electronics significantly and enables data rates unmatched by any other TD-THz technique. Indeed, compared to traditional TD-THz platforms, the acquisition speed of our instrument is four to seven orders of magnitude faster.

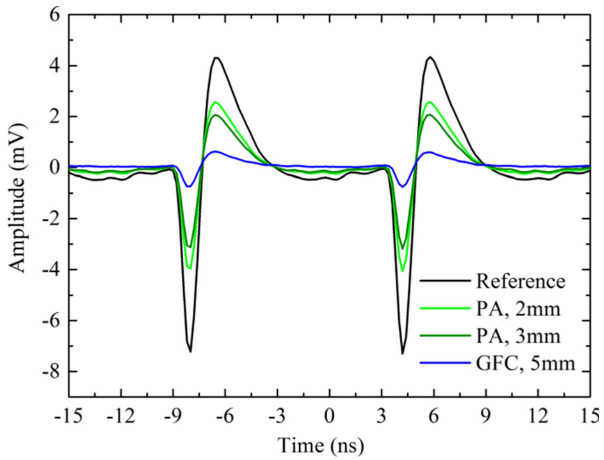

Fig. 2 Terahertz field intensities measured at 80 MHz pulse rate. Shown is a reference trace and pulses transmitted through three different samples (*PA* polyamide, *GFC* glass fiber composite)

3 Results and Discussion

Figure 2 presents signal traces of individual terahertz pulses, acquired at a repetition rate of 80 MHz. The curves depict an air reference (black) and three sample measurements (colored) recorded in transmission geometry. We used plastic-plate samples made of polyamide (PA, 2 and 3 mm thickness) and a glass fiber composite (GFC, 5 mm thickness). The shape of the pulses resembles the amplitude trace of photoconductive receivers; however, since the Schottky detector measures the terahertz power and not the electric field of the incident pulse, the bi-polar shape is clearly an artifact, attributed to electric ringing in the integrated RF amplifier [19]. The halfwidth of the negative and positive lobes amounts to 0.98 and 2.12 ns, respectively, a result of low-pass filtering of the original terahertz pulse (width ~650 fs) in the receiver electronics. The value of relevance is the peak level of the pulses, which mirrors the transmission properties of the samples, i.e., the intensity varies depending on absorption and reflection losses in the material under test. The three samples depicted in Figs. 2—2 mm PA, 3 mm PA, and GFC—attenuate the peak intensity by 43 %, 55 %, and 88 %, respectively. We note that our setup is able to quantify these transmission properties on a time scale of only 10 ns. These findings demonstrate the suitability of our instrument for quality control of plastic products with sub-microsecond temporal resolution.

In a second proof-of-principle experiment, we monitored the wetting dynamics of three different samples moistened with water: We successively placed a sheet of tissue paper, a piece of lump sugar, and a sponge in the terahertz beam path and wetted the edge of each sample with a pipette. Within a few hundred milliseconds, the water droplet spread across each sample, and the transmitted terahertz intensity decreased accordingly, as shown in Fig. 3.

Since a time resolution on the sub-millisecond level fully suffices to resolve the absorption dynamics of our case study, we chose to average 1000 consecutive terahertz pulses; in other words, we slowed the system down to data rates of ~10 μs, which is still orders of magnitude faster than conventional TD-THz instruments. Figure 3 shows the peak intensity of the terahertz pulses, i.e., the sum of positive and negative lobes, versus time. The black, blue, and red lines represent the water absorption dynamics for the tissue paper, sugar, and sponge,

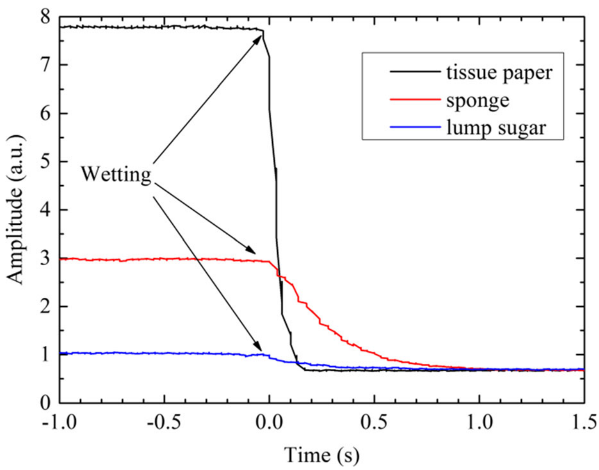

Fig. 3 Absorption dynamics of three different samples wetted with water. *Blue* lump sugar, *red* sponge, *black* tissue paper

respectively. We obtain absorption time constants (90 %/10 % values) of 606 ms for the sponge, 570 ms for the piece of sugar, and 137 ms for the tissue paper.

4 Conclusion and Outlook

We have presented a TD-THz measurement system capable of resolving individual terahertz pulses at 80 MHz repetition rate. The assembly unites a compact femtosecond fiber laser, a powerful InGaAs-based photoconductive switch and a high-bandwidth Schottky-diode receiver. The acquisition speed achieved with this combination was only limited by the repetition rate of our laser.

Since our concept eliminates the need for any mechanical or electronic delay stages, it can be realized in a very robust and cost-efficient design. Due to the high terahertz power and the sensitivity of the Schottky detector, data acquisition is accomplished even without any signal averaging or lock-in schemes.

Whilst the spectral content of the terahertz pulse is lost due to low-pass-filtering in the detection circuit, the system assesses terahertz field intensity values at an unprecedented rate. This enables transmission measurements on nanosecond time scales, not only in research labs but, owing to the high mechanical stability of the components, even in harsh industrial environments. We envisage that the technique will open new perspectives both for the observation of biological processes, such as protein dynamics, and for non-destructive testing applications on rapidly moving samples, such as conveyor belts or paper machines. Thus, the system may pave the way towards a broader acceptance of TD-THz technologies in the industry—thanks to a significant advantage in terms of speed: In contrast to state-of-the-art TD-THz systems, our setup is 10,000 to 10,000,000 times faster.

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