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Time-domain terahertz spectroscopy based on asynchronous optical sampling with femtosecond semiconductor disk laser

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A terahertz time-domain spectroscopy (THz-TDS) system using an optically pumped semiconductor disk laser and high-speed asynchronous optical sampling is reported. The combination of these techniques holds considerable promise towards a compact and low-cost implementation of THz-TDS. The spectrometer offers a 333 ps time delay window scanned at 10 kHz and delivers more than 1.2 THz spectral coverage at a data acquisition time of one minute. As a proof-of-principle experiment, a 0.8 THz resonance of a frequency-selective surface structure was measured.

Introduction: Terahertz time-domain spectroscopy (THz-TDS) is a well established technique to determine material properties in the range between 100 GHz and 10 THz with applications in pharmaceutical product inspection [1], label-free readout of DNA sensors [2], gas spectroscopy and sensing [3]. Current systems are based on modelocked bulk or fibre lasers which are relatively expensive and voluminous and may pose a considerable barrier preventing the introduction of THz-TDS into emerging applications outside of scientific laboratories. Modelocked semiconductor disk lasers (SDLs, sometimes called vertical external cavity surface emitting lasers or VECSELs) are promising candidates for an all-semiconductor alternative source of femtosecond pulses with compact dimensions and low cost [4, 5]. Such lasers have recently been used in a conventional THz-TDS setup with a mechanical delay stage for time-delay scanning [6]. In addition to the size and cost advantages of femtosecond SDLs, their typically high repetition rates ($f_{SDL} \geq 1$ GHz) are attractive for high-speed asynchronous optical sampling (ASOPS). High-speed ASOPS is a recently developed technique permitting rapid THz-TDS measurements without a mechanical delay stage [7]. A THz-TDS system using high-speed ASOPS has been demonstrated at 2 kHz scan rate with 7 THz spectral coverage and with a signal-to-noise ratio (SNR) of better than 40 dB in 1 s of data acquisition time [8]. Two modelocked Ti:sapphire (Ti:Sa) lasers were employed, one as a pump laser to generate pulsed THz radiation in a photoconductive emitter [9], the other to probe the THz radiation after interaction with a sample in the spectrometer. In a standard high-speed ASOPS system the two lasers have repetition rates $f_{R1} \simeq f_{R2} \simeq f_R = 1$ GHz and an actively stabilised repetition rate offset $\Delta f_R = f_{R1} - f_{R2}$ of a few kilohertz [7]. The repetition rate offset causes the time delay between pairs of pump and probe pulses to be ramped between zero and $1/f_R$ at the scan frequency $f_{scan} = \Delta f_R$. The time-delay increment from pulse pair to pulse pair is given by $\Delta f_R/f_R^2$ and represents the theoretical lowest time resolution limit. In this Letter, we report a high-speed ASOPS THz-TDS system employing a modelocked SDL, which replaces one Ti:Sa laser and serves as the probe laser. Our experiment is a first step combining the new technologies in an effort towards a high-speed, highly compact and cost-efficient THz-TDS tool.

Experimental setup: Fig. 1 shows the setup of our THz time-domain spectrometer. The Ti:Sa laser is Kerr-lens modelocked and emits 40 fs pulses at a repetition rate of $f_{Ti:Sa} \simeq 1$ GHz, has a centre wavelength of 825 nm and maximum average output power of 900 mW [7]. The diode-pumped SDL is similar to the lasers presented in [4, 5]. The 50 mm-long 'V'-shaped cavity contains an output coupler (0.75% transmission), an InGaAs/AlGaAs chip as the gain medium, and a semiconductor saturable absorber mirror as the passive modelocker [10]. In the SDL, 370 fs pulses are generated at a repetition rate of $f_{SDL} \simeq 3$ GHz with a centre wavelength of 1048 nm and an average output power of 12 mW. To stabilise the repetition rate offset, a small part of both lasers ($\simeq$ 3 mW) is split off and focused on high bandwidth photodiodes (PD1 and PD2) to detect the laser repetition rates (see Fig. 1). While the SDL is free-running, the Ti:Sa repetition rate is feedback loop controlled by a piezo-driven mirror. The repetition rate offset lock is performed using the third harmonic of the Ti:Sa repetition rate and the first harmonic of the SDL. The offset locking electronics have been described in [7]. The repetition rate offset is chosen to be $\Delta f_R = f_{Ti:Sa} - f_{SDL}/3 = 10$ kHz, which is also the scan rate. The time-delay increment is given by $\Delta f_R/f_{Ti:Sa}^2 = 10$ fs. THz radiation pulses with about 300 fs duration are generated at 1 GHz repetition rate by illuminating a large-area THz emitter [9] with approximately 600 mW of average pump power from the Ti:Sa laser. The THz radiation is collected and focused by two pairs of parabolic mirrors (M1 to M4) onto a (110) ZnTe electro-optic detection crystal. The probe pulse train from the SDL (9 mW average power) is used to sample the THz transient via the Pockels effect in the ZnTe crystal and is detected using a photoreceiver (PD3) with 125 MHz bandwidth. The photoreceiver output is digitised using a 100 MS/s, 14-bit digitiser board (A/D) that is triggered by a 10 kHz TTL level signal from the laser stabilisation electronics [7]. The data acquisition of a single THz trace requires $1/\Delta f_R \simeq 100$ μs. Several thousands of single traces are averaged to increase SNR. The 3 GHz repetition rate of the probe laser limits the usable time-delay window to $1/f_{SDL} \simeq 333$ ps. Only one out of three consecutive pulses from the probe laser contributes to the signal, while contributions from the other two pulses are negligible as long as the THz transient has essentially decayed within the first 333 ps, which is the case in our experiment. As a test, we determine a known transmission resonance of a frequency-selective surface (FSS) structure [11, 12], which is inserted in the focused region of the THz beam.

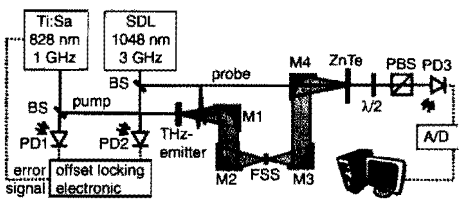

Fig. 1 *THz time-domain spectrometer setup including repetition rate offset stabilisation for high-speed ASOPS*

Solid lines correspond to optical paths, dashed lines to electronic connections BS: optical beam splitter; PD1, PD2, PD3: amplified photodiodes; M1 to M4: parabolic mirrors; FSS: frequency-selective surface structure; PBS: polarising beam splitter; A/D: analogue-to-digital converter

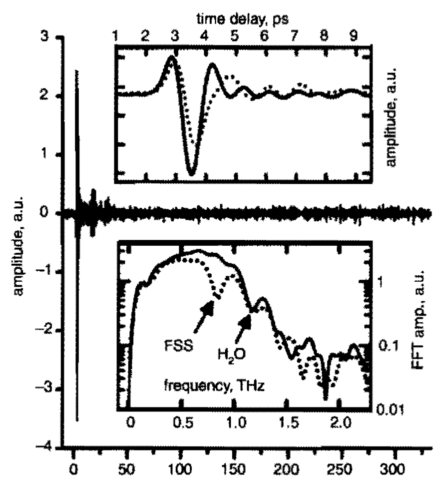

Fig. 2 *Detected THz time-domain transient*

Upper inset: Zoom into first 10 ps of THz transients without (solid line)/with (dotted line) FSS structure
Lower inset: Fast Fourier transforms of THz transients shown in upper inset

Experimental data: In Fig. 2, the detected THz pulse transient without the FSS structure in the setup is shown up to 330 ps time delay. The data acquisition time was one minute. The upper inset of Fig. 2 shows the zoom into the first 10 ps of two THz transients. One transient was recorded without, the other with, transmission through the FSS structure in the focused region of the THz setup (see Fig. 2, solid line/dotted line). The observed THz pulse duration is approximately 600–700 fs in both cases. Comparing the transients, the FSS influence can be observed as amplitude attenuation and phase shift. The lower inset of Fig. 2 shows the corresponding fast Fourier transforms (FFTs) of the transients. In the dotted FFT curve an absorption line at 0.8 THz can be observed, which is in agreement with the previously measured resonance of the FSS structure. In both FFT curves a water absorption line at

1.2 THz is resolved and demonstrates that the usable spectral coverage extends to somewhat above this value. The THz emitter supports a spectral coverage of $\simeq$ 7 THz. Present limitations are the pulse duration of the SDL (370 fs here; sub-200 fs pulses were demonstrated in [4]) as well as its timing jitter resulting from a mechanical design very sensitive to acoustic perturbations. The SNR is currently at 56, mainly due to the low available probe power for electro-optic detection. Efforts to increase the output power of the SDL using a tapered diode amplifier are under way [4] which will also enable use of modelocked SDLs for both pumping and probing. Longer averaging times, which can increase SNR, are currently prevented by a slow, thermally caused drift of the SDL repetition rate. A repetition rate of $\simeq$ 3 GHz also for the pump laser will improve SNR, too; at present we use only every third probe pulse.

Conclusion: We present a THz-TDS system based on high-speed ASOPS using a femtosecond semiconductor disk laser and a modelocked Ti:sapphire laser as probe and pump laser, respectively. The system has a scan rate of 10 kHz and offers more than 1.2 THz spectral coverage at a SNR of 56. Significantly improved performance can be expected by straightforward mechanical optimisation of the SDL. Increasing the output power of femtosecond SDLs, e.g. by a tapered diode amplifier, will enable their use for both pumping and probing. We conclude that a rapid scanning, compact and low-cost THz-TDS system is feasible if modelocked SDL technology is combined with high-speed ASOPS. This may lead the way to higher-volume applications of THz-TDS outside of scientific laboratories.

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