High-performance fiber-laser-based terahertz spectrometer

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Received August 19, 2010; revised October 12, 2010; accepted October 14, 2010;
posted October 18, 2010 (Doc. ID 133685); published November 9, 2010

We have developed a rapid scanning terahertz (THz) spectrometer based on a synchronized two-fiber-laser system. When the system is set to the asynchronous optical sampling mode, THz spectra extending to 3 THz can be acquired within 1 μs at a signal-to-noise ratio of the electric field of better than 20. Signal averaging results in a dynamic range of more than 60 dB, and frequency components of more than 4 THz can be detected. When the lasers are set to the same repetition rate, electronically controlled optical sampling at a rate of 2.5 kHz is demonstrated, making the system versatile for different spectroscopic applications. Finally, we compare the THz emission spectra of a photoconductive switch that is pumped at 780 nm and a nonlinear DAST crystal excited at 1550 nm. We find that the spectral range of the spectrometer is significantly enhanced at higher frequencies, while the dynamic range remains constant.

OCIS codes: 120.6200, 160.4890, 300.6495.

The use of mode-locked femtosecond lasers in combination with nonlinear crystals and photoconductive switches, together with field-resolved detection via electro-optic sampling or photoconductive antennas, has led to many applications in the field of terahertz (THz) spectroscopy [1]. Generally common for most systems is the use of a weak probe pulse, split off from the original laser beam and then mechanically delayed in time to sample the electric field of the THz pulses. This mechanical delay is usually realized by a motorized translation stage where the THz waveform is acquired step by step. An alternative to this approach is the use of fast-scanning devices. Loudspeaker membranes typically achieve scan rates of 10–30 Hz, while specialized wheels can achieve scan rates exceeding 200 Hz [2]. Only recently was it shown that, by employing two synchronized lasers with a constant offset in their repetition rate, these limitations can be overcome. With the technique called asynchronous optical sampling (ASOPS) [3] it was demonstrated that scan rates of up to 10 kHz are possible [4].

However, since in ASOPS the entire time (typically 10 ns) between neighboring pulses is scanned, most of the scanning time is wasted since the time range of interest in THz spectroscopy is normally less than 100 ps. To improve this ratio, one can go to higher repetition rates or use the technique of electronically controlled optical sampling (ECOPS) [5], where the adjustable delay between the two lasers is realized by varying the phase of the synchronization signal (for instance, from a master clock) for one of the lasers. In this case, only the delay range of interest can be selected without acquisition of unneeded data points.

The use of high-precision ASOPS for THz spectroscopy was first demonstrated using two synchronized Ti:sapphire (Ti:Sa) lasers with repetition rates of around 82 MHz [6] and was significantly improved with lasers operating at a repetition rate of 1 GHz [4]. There, the lasers had large average powers of about 1 W and were used to generate THz pulses with state-of-the-art photoconductive antennas [7] (PCAs) as emitters. Recently, a higher timing precision of 40 fs and a correspondingly higher detection bandwidth [8] were achieved. For frequencies up to 6 THz, ASOPS systems represent very promising instruments for high-speed and high-resolution data acquisition without the worries of mechanical delays, zero path differences, or beam pointing issues.

To improve the systems' ease of use, it would be of great advantage if the nonstandard Ti:Sa lasers could be replaced by much cheaper fiber lasers. They would also enable true turnkey operation and short warm-up times, with no need for realignment. In fact, development of femtosecond fiber-laser technology has progressed significantly in recent years, and average optical powers and pulse lengths have become comparable to Ti:Sa oscillator systems. Together with their superior stability—both in

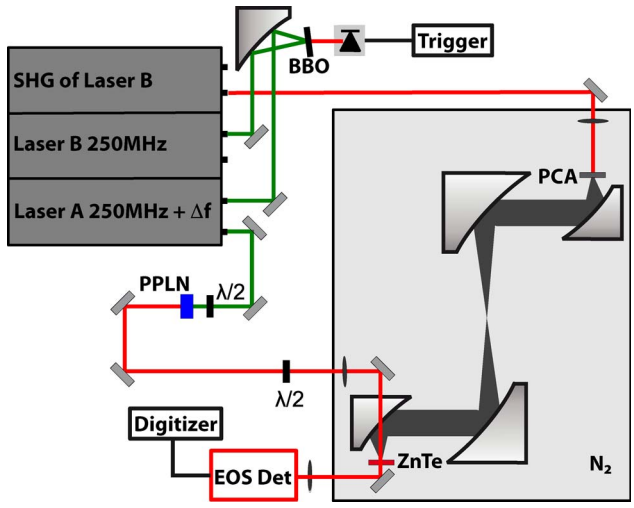

Fig. 1. (Color online) Layout of the THz spectrometer. The two synchronized 1550 nm fiber lasers B and A serve for THz generation and detection, respectively. When a PCA is used for THz generation, the frequency-doubled output of laser B is used for excitation. The secondary output ports of the lasers are focused onto a 1-mm-thick β-BaB_2O_4 crystal to generate a cross-correlation signal, providing the trigger for data acquisition. Laser A is frequency doubled in a periodically poled $LiNbO_3$ (PPLN) crystal to generate the 780 nm sampling pulses.

power and in timing—these lasers bring all prerequisites to enable high-performance and precision THz spectroscopy together with the ASOPS technique. The principle of such a system was recently demonstrated [9], but the system's spectral bandwidth, scan rate, and dynamic range are below what was previously reported for a Ti:Sa-laser-based instrument.

In this Letter we report the development of a fiber-based ASOPS system for THz spectroscopy with scan rates of 2.5 kHz, acquisition times of only 1 μs, and a bandwidth of more than 4 THz when signal averaging is applied. We also demonstrate system operation in the ECOPS mode and compare today's most efficient THz emitter at 780 nm (an interdigitated PCA) with a DAST crystal excited at 1550 nm. We show that, with our system, these THz generation processes are equally efficient and extend the central frequency of the THz pulses to 2.4 THz.

The laser system we use consists of two amplified Er-doped fiber lasers (TWIN M-Fiber A, Menlo Systems) emitting 80 fs pulses centered at 1550 nm at a repetition rate f_{REP} of 250 MHz and an average power of 440 mW (see Fig. 1). The repetition rates of both lasers are frequency stabilized and a frequency synthesizer can add an adjustable (1 Hz – 10 kHz) frequency offset Δf to Laser A. The timing jitter for the lasers rises from 1 fs at 10 kHz to 100 fs rms at 1 Hz, which is smaller than or of the order of the individual pulse duration, resulting in high time resolution. In ASOPS mode, the entire time between adjacent pulses ($1/f_{\mathrm{REP}} = 4$ ns) is scanned during the inverse of the offset frequency. For fast data acquisition, Δf is set to 2.5 kHz, which results in a time step of 100 fs, matching well the individual pulse widths and the timing jitter. It is important to note that this ideal time resolution is achieved only when data acquisition (photodetector and digitizer) has a bandwidth of at least 100 MHz [4]. Otherwise, the measured waveforms will be distorted.

For THz generation with oscillator systems, GaAs-based PCAs excited above the bandgap (1.42 eV = 873 nm) result in high peak amplitudes and spectral bandwidth [7]. To be able to use these emitters, the output of Laser B can be sent to a second harmonic stage, where 70 fs pulses centered around 780 nm are generated at an average power of 150 mW. For THz generation, these pulses are focused (spot size ≈ 300 μm) on a large-area interdigitated PCA [7], here with a gap spacing of 1.5 μm. A 20-μs-long voltage pulse of 6 V, triggered by the ASOPS electronics at Δf, is applied. The THz radiation is collected and refocused with four off-axis parabolic mirrors (see Fig. 1), with an additional focus after the second mirror for small samples. The entire path of the THz pulses can be purged with dry nitrogen. To take advantage of the large electro-optic constant and long coherence length of $\langle 110 \rangle$ ZnTe at 800 nm [10], we frequency double Laser A with a periodically poled $LiNbO_3$ crystal. We used a 500-μm-thick $\langle 110 \rangle$ ZnTe crystal for electro-optic sampling. A 500-μm-thick $\langle 110 \rangle$ GaAs was tested at a wavelength of 1550 nm and gave identical waveforms but with reduced signal strength [11]. The probe pulse is analyzed in the standard configuration with a $\lambda/4$ plate and a polarizing beam splitter, whose output is sent to a balanced photoreceiver with high bandwidth (Thorlabs PDB110A-AC). The signal is sent through a passive 100 MHz bandpass filter before being analyzed with a digitizer (GaGe Compuscope 14200), where signal processing is performed. The data acquisition is precisely triggered using the cross-correlation signal that is generated from two secondary outputs of the lasers, as shown in Fig. 1.

The spectra of the purged setup in this configuration are shown in Fig. 2. In the inset we plot the waveform of a single scan with 250 laser pulses, acquired within 1 μs. The signal-to-noise ratio of the peak electric field is larger than 20, and the dynamic range in the spectrum is about 20 dB. Also shown in the main graph are spectra with 1000 and one million averages, corresponding to acquisition times of 0.4 and 400 s. The noise floor drops from 2×10^{-1} at 1 μs to about 2×10^{-4} at 400 s, showing a dynamic range of more than 60 dB at 1 THz. Because of the high stability of our lasers, this value can be exceeded when longer averaging times are used. The inset demonstrates that this instrument is capable of taking full time-domain scans within 1 μs, i.e., it can function as a THz camera with a bandwidth of 1 MHz and demonstrates the potential to probe transmission changes in combination with microsecond-long THz pulses from the UCSB Free Electron Lasers or with ultrahigh pulsed magnetic fields when synchronized to the lasers' master clock.

The laser system can also operate in the ECOPS mode, where the repetition rates of both lasers are set to the same frequency. To obtain a THz waveform under this condition, one must introduce either a mechanical delay or a precisely controlled phase shift in one of the lasers with respect to the master clock. By varying this phase shift, again, the entire inverse of the lasers' repetition rate can be scanned. However, much more important is the ability to select the time-delay window of interest, usually a few tens of picoseconds. In our laser system, this phase shift is realized by offsetting the working point of the synchronization with an ac or dc voltage. The induced time-delay scales linearly with the voltage and therefore enables electronically controlled optical sampling. The absolute scaling of the time axis is done by matching

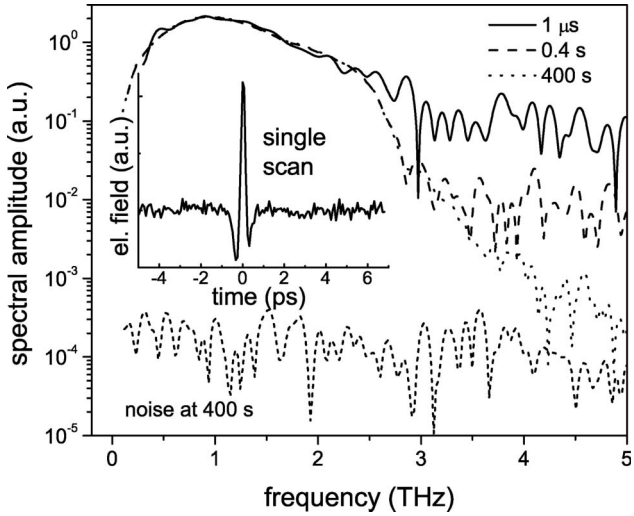

Fig. 2. Amplitude spectra of the purged setup for different averaging times and the noise spectrum for 400 s. The inset shows a single scan, taken within 1 μs.

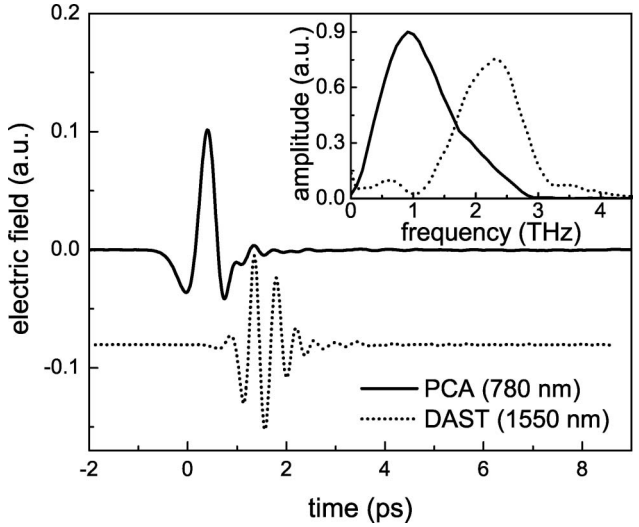

Fig. 3. THz waveforms acquired in ECOPS mode with 1000 averages (400 ms acquisition time). The solid curves in the graph are taken from a photoconductive emitter excited with 780 nm pulses. The dashed curves were taken when 1550 nm pulses generated THz in a DAST crystal.

the observed waveforms with those acquired in ASOPS mode. In this work, we apply a triangular voltage signal at a rate of 2.5 kHz to the phase of Laser A and scan a time window of just 20 ps. Consequently, the acquisition of a 20 ps waveform now takes hundreds of microseconds, about a thousand times longer than when using ASOPS at the same scanning rate. Naturally, this much slower scanning results in a much better signal-to-noise ratio for a single scan, and high dynamic ranges can now be achieved with less averages and shorter acquisition times. As an example, the THz waveform for 1000 averages (400 ms acquisition time) is shown in Fig. 3, together with its spectrum (solid curves). The extracted dynamic range at 1 THz is 50 dB, compared to 40 dB when ASOPS is used at equal acquisition time. Therefore, whenever a high bandwidth of 1 MHz is not needed and spectral resolution of a 20 ps scan is sufficient, ECOPS provides a high-performance mode for THz spectroscopy in our system.

We also investigated the use of high-quality 4-dimethylamino-N-methyl-4-stilbazolium tosylate (DAST) crystals, which have recently attracted much attention as efficient THz emitters for lasers running at 1550 nm [12]. Particularly interesting is the extremely high nonlinearity and long coherence lengths when excited at 1550 nm along the crystals' c axis. We replaced the 780 nm driven PCA with a 690-μm-thick DAST crystal that was excited at 1550 nm with the full power of Laser A. The 780 nm pulses from Laser B were then used for electro-optic sampling. The results are shown as the dashed curves in Fig. 3, where the system was running in ECOPS mode under the same conditions as for the PCA (1000 averages, dry N_2 purged). It was checked that the optical power on the balanced photodiodes was the same for both measurements, demonstrating that, when a DAST crystal is used at the full power of 440 mW, the resulting electric field strength and optical power is essentially equal to that when the laser is frequency doubled and a PCA is used. Additionally, the central frequency is now located at 2.4 THz, along with phonon-related absorption around 1 THz and a cutoff above 3 THz due to phase matching. It is clearly seen that, on an absolute scale, using a DAST emitter in a fiber-laser-based system can actually enhance higher frequencies significantly and that both emitter concepts are complementary.

In summary, it is demonstrated that THz spectrometers based on fiber lasers can achieve a performance comparable to state-of-the-art systems based on Ti:Sa lasers, with the benefit of increased stability, true turnkey operation, and robustness, and extended spectral bandwidth with the use of a DAST crystal.

Financial support by the W. M. Keck Foundation and the National Science Foundation (NSF) under grants DMR 0703925 and 1006603 is thankfully acknowledged, and D. S. thanks the Alexander-von-Humboldt Foundation for financial support. The authors thank Manfred Helm for lending the DAST crystal.

References

1. M. Tonouchi, Nat. Photon. **1**, 97 (2007).
2. F. Ellrich, D. Molter, T. Weinland, M. Theuer, J. Jonuscheit, and R. Beigang, in *IEEE Proceedings of the 33rd International Conference on Infrared, Millimeter, and Terahertz Waves* (IEEE, 2008).
3. P. A. Elzinga, F. E. Lytle, Y. Jian, G. B. King, and N. M. Laurendeau, Appl. Opt. **26**, 4303 (1987).
4. A. Bartels, R. Cerna, C. Kistner, A. Thoma, F. Hudert, C. Janke, and T. Dekorsy, Rev. Sci. Instrum. **78**, 035107 (2007).
5. F. Tauser, C. Rausch, J. H. Posthumus, and F. Lison, Proc. SPIE **6881**, 68810O (2008).
6. T. Yasui, E. Saneyoshi, and T. Araki, Appl. Phys. Lett. **87**, 061101 (2005).
7. A. Dreyhaupt, S. Winnerl, M. Helm, and T. Dekorsy, Opt. Lett. **31**, 1546 (2006).
8. G. Klatt, R. Gebs, C. Janke, T. Dekorsy, and A. Bartels, Opt. Express **17**, 22847 (2009).
9. T. Yasui, M. Nose, A. Ihara, K. Kawamoto, S. Yokoyama, H. Inaba, K. Minoshima, and T. Araki, Opt. Lett. **35**, 1689 (2010).
10. B. Pradarutti, G. Matthäus, S. Riehemann, G. Notni, S. Nolte, and A. Tünnermann, Opt. Commun. **281**, 5031 (2008).
11. M. Nagaia, K. Tanaka, H. Ohtake, T. Bessho, T. Sugiura, T. Hirosumi, and M. Yoshida, Appl. Phys. Lett. **85**, 3974 (2004).
12. A. Schneider, M. Stillhart, and P. Günter, Opt. Express **14**, 5376 (2006).