



Terahertz asynchronous optical sampling spectroscopy with lock-in detection

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Abstract: We demonstrate a terahertz asynchronous optical sampling (THz-ASOPS) spectrometer incorporating a lock-in amplifier. The experimental setup employs a high-voltage pulse generator to drive a photoconductive antenna emitter, generating precisely modulated terahertz pulses that are subsequently detected by a photoconductive antenna detector. The detection system features a two-stage amplification process: initial signal amplification through a low-noise current preamplifier, followed by processing with a digital lock-in amplifier. Experimental characterization demonstrates significant performance enhancements, with a 3-fold improvement in the time-domain peak signal-to-noise ratio and a 5 dB increase in the spectral dynamic range. These results substantiate the effectiveness of the lock-in detection approach in enhancing THz-ASOPS spectroscopic performance.

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1. Introduction

Terahertz time-domain spectroscopy (THz-TDS) has emerged as a robust and versatile technique with extensive applications across various scientific domains [1–4]. The conventional THz-TDS configuration employs a mechanical delay line to establish an optical path difference between the pump and probe femtosecond laser pulses, facilitating equivalent-time sampling of terahertz electric field waveforms. Subsequent Fourier transformation of these time-domain signals yields the corresponding terahertz spectral information [5]. Nevertheless, this mechanical delay line-based sampling approach presents inherent limitations, including constrained detection speed, compromised system stability, limited positioning accuracy, and restricted frequency resolution [6–9].

To overcome these limitations, the asynchronous optical sampling technique utilizing dual terahertz combs (THz-ASOPS) has emerged as an innovative solution. The foundation of this approach was established in 2006 when Yasui et al. [10] pioneered a terahertz dual-comb spectroscopy system, demonstrating the functional equivalence between THz-ASOPS and conventional THz-TDS. The THz-ASOPS system incorporates two key components: a phase-locked loop [11] and a frequency synthesizer, which maintain precise control over the repetition rates of the pump and probe femtosecond lasers with a fixed frequency offset typically below 10 kHz [12–14]. This configuration facilitates rapid equivalent-time sampling through the generation of a periodic, linearly increasing phase delay between the laser pulses, enabling scanning speeds on the millisecond timescale [15]. Furthermore, the technique achieves enhanced frequency resolution through extended sampling time windows and enables continuous acquisition of multiple terahertz pulses.

In recent years, THz-ASOPS technology has made significant progress. Baker et al. [16] developed a self-triggered THz-ASOPS system based on a bidirectional mode-locked fiber laser, which achieves a dynamic range of more than 70 dB in the 0.1-2 THz band without any mechanical delay line or stabilization electronics, greatly simplifying the system structure. Mosley et al. [17] achieved a breakthrough implementation in terahertz chip waveguides incorporating integrated photoconductive switches, attaining a scanning rate of 100 Hz and 88 dB dynamic range. Nakagawa et al. [18] developed an innovative software-based jitter correction algorithm for free-running lasers that suppresses residual jitter to <0.1 ps while preserving sub-GHz spectral resolution. Furthermore, Okano et al. [19] significantly enhanced system stability through a dual optical frequency comb architecture, achieving a frequency stability of 8.0×10^{-17} . These technical advancements contribute to substantial improvements in THz-ASOPS performance.

Although the THz-ASOPS spectroscopy significantly increase the sampling speed and frequency resolution, there are no reported investigations on the integration of lock-in detection to suppress noise and to further optimize the system performance. This study presents a systematic investigation of lock-in amplification effects on THz-ASOPS spectroscopic performance. Our experimental configuration incorporates a high-power pulse generator coupled with a lock-in amplifier, enabling comprehensive signal processing through high-frequency modulation, amplification, and demodulation. Comparative analysis reveals substantial performance improvements, with the lock-in detection scheme achieving a 3-fold enhancement in the time-domain terahertz electric field pulse's peak signal-to-noise ratio (SNR) and a 5 dB improvement in the spectral dynamic range (DR) compared to conventional detection methods. These findings establish a new paradigm for terahertz spectroscopy, facilitating advanced research and applications requiring high-speed acquisition, superior frequency resolution, and extended dynamic range capabilities.

2. Principles and experimental setup

The electromagnetic radiation generated by a low-temperature GaAs (LT-GaAs) photoconductive antenna (PCA) under DC voltage bias, when excited by a femtosecond laser operating at repetition frequency f_{r1} , can be mathematically expressed as follows,

$$E(t) = \sum_n A_n \cos(2\pi n f_{r1} t), \quad (1)$$

where n is a positive integer, f_{r1} is the repetition frequency of the pump femtosecond laser, and A_n is the amplitude of the electric field with frequency $n f_{r1}$. When the repetition frequency of the pump femtosecond laser is stabilized using a phase-locked loop (PLL), the terahertz PCA emitter can be treated as a terahertz electromagnetic (EM) comb [20]. For a zero-bias PCA, when it is irradiated by a femtosecond laser with a stabilized repetition frequency of f_{r2} , the photo-generated electron concentration n_e can be expressed as,

$$n_e(t) = \sum_m B_m \cos(2\pi m f_{r2} t), \quad (2)$$

where m is a positive integer, B_m is the expansion coefficient at the frequency of $m f_{r2}$. In this case the zero-bias PCA can be referred to as a photo-generated carrier (PC) comb [20]. Since the mobility of holes is much lower than that of electrons in LT-GaAs, the contribution of holes is neglected below. When the terahertz wave emitted from the PCA EM comb illuminates on the PCA PC comb, the resulting photocurrent can be described by the following equation,

$$i_{ph}(t) = T_n \mu E(t) n_e(t) = \mu \sum_n T_n A_n \cos(2\pi n f_{r1} t) \sum_m B_m \cos(2\pi m f_{r2} t), \quad (3)$$

where T_n is the transfer function of the THz-ASOPS spectrometer, μ is the electron mobility. Equation (3) contains a series of low-frequency components,

$$i_{ph}(t) = \sum_{n=1}^M T_n \mu A_n B_n \cos(2\pi n \Delta f t), \quad (4)$$

where $\Delta f = f_{r1} - f_{r2}$, in which $f_{r1} > f_{r2}$ is assumed.

If the highest frequency comb tooth number of the EM comb is N and the condition $N\Delta f = N(f_{r1} - f_{r2}) < f_{r1}/2$ is satisfied, Eqn. (4) demonstrates that the EM comb under measurement is down-converted to a photocurrent spectrum in the radio-frequency (RF) range without aliasing. The terahertz EM comb spectrum can be recovered by multiplying the frequencies of the RF spectrum with a down-conversion compression factor [21,22] of $f_{r1}/\Delta f$.

Figure 1(a) schematically illustrates the operational principle of THz-ASOPS spectroscopy [23]. The system employs a pump femtosecond laser beam with repetition frequency f_{r1} , which is focused onto the feed gap of a DC-biased (40 V) PCA emitter to generate electron-hole pairs. The resulting sub-picosecond transient photocurrent pulses driven by the DC electric field, produce terahertz pulse radiation (indicated in red) at repetition frequency f_{r1} . Simultaneously, a probe femtosecond laser beam with repetition frequency $f_{r2} = f_{r1} - \Delta f$ (indicated in blue) illuminates the PCA detector to create electron-hole pairs. As described by Eqn. (4), the photo-excited carriers in the PCA detector are driven by the incident terahertz electric field pulse train, resulting in a down-converted photocurrent pulse train at repetition frequency Δf . The above physical process represents the ASOPS of terahertz electric field pulses. The corresponding sampling time interval $\Delta\tau$ is given by [24],

$$\Delta\tau = \frac{1}{f_{r1} - \Delta f} - \frac{1}{f_{r1}} = \frac{\Delta f}{f_{r1}(f_{r1} - \Delta f)} \approx \frac{\Delta f}{f_{r1}^2}. \quad (5)$$

And the laboratory acquisition time t for a complete terahertz pulse is,

$$t = \frac{1}{f_{r1} - \Delta f} \times \frac{f_{r1}}{\Delta f} \approx \frac{1}{\Delta f}. \quad (6)$$

The total sampling time window $\tau = 1/f_{r1}$. The relationship between the laboratory time t and the sampling time τ is expressed as,

$$t = \tau \times \frac{f_{r1}}{\Delta f}. \quad (7)$$

Upon complete sampling of the terahertz pulse, the time-domain signal can be Fourier transformed to obtain the corresponding terahertz spectrum.

In conventional THz-TDS systems, signal modulation through mechanical chopping combined with lock-in amplification represents a standard approach for $1/f$ noise suppression. This methodology effectively reduces both low-frequency ($1/f$) and high-frequency noise components while significantly enhancing the SNR. The noise reduction mechanism primarily involves five key processes: (1) spectral shifting through signal modulation, (2) band-pass filtering of the modulated signal, (3) frequency-selective AC amplification, (4) phase-sensitive detection [25], and (5) low-pass filtering during demodulation. These combined processes enable the effective noise suppression.

Figure 1(b) illustrates the principle of lock-in detection. the first-order modulation signal radiated from the PCA emitter driven by a square-wave voltage pulse train with the minimum voltage of 0 V can be represented as,

$$E_m(t) = E(t) \left(\frac{1}{2} + \frac{2}{\pi} \cos(2\pi f_m t) \right), \quad (8)$$

where $E_m(t)$ is the modulated terahertz pulse and f_m is the modulation frequency. The higher frequency components are severely reduced due to the bandwidth of the system. From Eqns. (1), (2), (4) and (8), the final modulated photocurrent $i_{phm}(t)$ at the output of the PCA detector can be

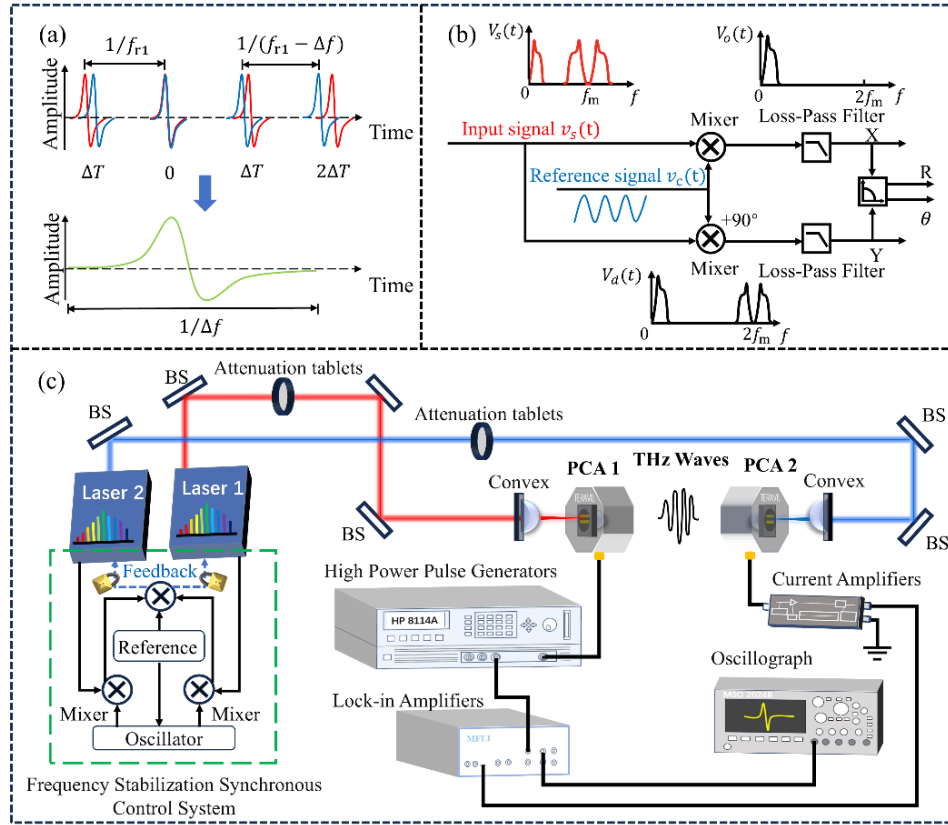


Fig. 1. Schematic diagram of the THz-ASOPS with lock-in detection spectroscopy system. (a) Schematic of THz-ASOPS principle, (b) schematic of lock-in detection process, and (c) experimental setup diagram of the THz-ASOPS with lock-in detection spectrometer.

expressed as,

$$i_{phm}(t) = \sum_{n=1}^M T_n \mu A_n B_n \left\{ 0.5 \cos(2\pi n \Delta f t) + \frac{1}{\pi} \cos[2\pi(f_m \pm n \Delta f)t] \right\}. \quad (9)$$

The photocurrent signal undergoes a comprehensive processing chain consisting of sequential stages: low-noise current amplification, band-pass filtering, AC amplification, phase-sensitive detection (through multiplication with a reference signal), and low-pass filtering. This signal processing cascade ultimately reconstructs the original terahertz electric field pulse waveform. The lock-in detection scheme demonstrates effective noise suppression capabilities, particularly for $1/f$ noise and out-of-band noise components, while preserving the essential spectral characteristics of the terahertz signal.

Figure 1(c) presents the system architecture of the THz-ASOPS spectrometer integrated with lock-in detection. The system consists of two primary components: the optical subsystem and the electrical subsystem. The optical subsystem is consisted of two femtosecond lasers (Menlo Systems, C-Fiber 780, with an output wavelength of 780 nm, each possessing an average power exceeding 100 mW and pulse widths of less than 100 fs) and the repetition frequency stabilization and synchronization module (Menlo Systems, ASOPS, EM100) for the two femtosecond lasers. The electrical system comprises a PCA emitter (Teravil, ETM-8), a preamplifier (FEMTO, DHPCA-100 I/V), a high-power pulse generator (Agilent 8114A, 100 V/2 A), a lock-in amplifier

(Zurich Instruments, HF2LI 50 MHz), and an oscilloscope (KEYSIGHT, DSAZ504A, 1 G sample/s).

As illustrated in Fig. 1(c), the system configuration employs two synchronized femtosecond lasers: a pump laser (red pathway) operating at a repetition rate $f_{r1}=100$ MHz and a probe laser (blue pathway) operating at $f_{r2} = f_{r1} - \Delta f$. Both laser beams are precisely focused onto their respective PCA elements. To prevent potential damage from excessive optical power, adjustable optical attenuators are incorporated in both beam paths to maintain optimal power levels for PCA operation. The PCA emitter is driven by a high-power pulse generator delivering square-wave voltage pulses with the 20 V amplitude and the minimum voltage of 0 V, 1 μ s width (1.0 MHz), and 50% duty cycle. Limited by the circuit bandwidth, the PCA emitter cannot be well modulated when the frequency of square-wave voltage pulse is larger than 1.0 MHz. The resulting photocurrent from the PCA detector undergoes amplification through a preamplifier (gain: 10^6 V/A) before being processed by the lock-in amplifier for signal demodulation and amplification. The processed time-domain terahertz electric field signal is subsequently acquired by the oscilloscope, with spectral information obtained through Fourier transformation of the time-domain data.

The compression factor $f_{r1}/\Delta f$ affects the frequency conversion factor (from low to high frequency), the down-conversion signal bandwidth, and the terahertz pulse acquisition rate [26]. In our experimental setup, the modulation frequency f_m is set to 1 MHz, while the repetition frequency difference Δf between the two femtosecond lasers is fixed at 5 Hz. In this case, if the terahertz bandwidth is 2.0 THz, the down-conversion signal bandwidth is 100 kHz, which is much smaller than the modulation frequency. The spectral data acquisition time is inversely proportional to Δf , and for $\Delta f = 5$ Hz, an acquisition time of 0.2 s is needed to acquire a 10-ns-long temporal data set, which is fast enough for conventional spectral measurements. The frequency resolution is another key parameter, which is determined by the repetition frequency f_{r1} of the pump femtosecond laser. The frequency resolution of 100 MHz (f_{r1}) is much higher than the traditional terahertz time-domain spectroscopy (~ 5 GHz) [27].

3. Experimental results and analysis

Experiments were conducted to evaluate the performance enhancement of the THz-ASOPS with lock-in detection spectrometer. All measurements were performed under controlled environmental conditions, maintaining an ambient temperature of 25 °C and a relative humidity of 37%. To ensure high accuracy and consistency in signal acquisition, each data point was averaged over 64 repetitions.

3.1. Modulation terahertz electric-field pulse

To quantitatively assess the modulation scheme's performance, we systematically acquired and analyzed time-domain terahertz electric field pulse data under modulated conditions. Figure 2 presents a comparative analysis of normalized terahertz field pulses generated by the PCA transmitter under two distinct driving configurations: (1) high-power pulse generator operation (20 V, 1 MHz, 50% duty cycle) and (2) DC voltage source operation (40 V). Through careful optimization of system parameters, equivalent photovoltaic conversion efficiency was maintained for both configurations, ensuring valid comparative analysis. The DC voltage-driven configuration serves as the reference measurement for performance evaluation.

Figure 2(a) presents the modulated, reference, and demodulated time-domain signals, while Figs. 2(b) and 2(c) provide detailed and zoomed-in views of two time intervals in Fig. 2(a). Figure 2(a) demonstrates that the profiles of the normalized time-domain modulated and demodulated signals are superposition with the DC-driven signal, and the carrier frequency equals the set modulation frequency, which indicates that the terahertz PCA emitter can be modulated at 1 MHz and no distortion is introduced. The details in Figs. 2(b) and 2(c) clearly

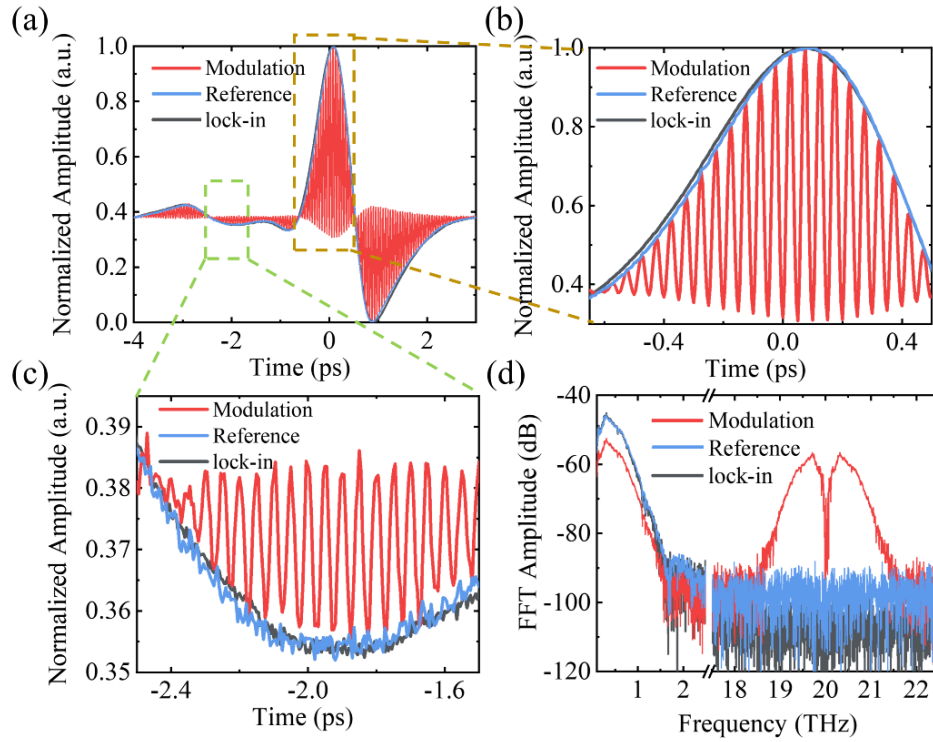


Fig. 2. Modulated, demodulated, and reference signals. (a) Normalized time-domain terahertz electric field pulses driven by the high-power pulse generator and the DC voltage source, respectively. (b) and (c) display the zoomed-in views of the main peak and the details in the -2.5 ~ -1.5 ps range, respectively. (d) Terahertz spectra by Fourier-transforming the modulated, demodulated, and reference time-domain data, respectively.

demonstrate that the amplitude of the modulated signal aligns well with the reference signal. In addition, as shown in Fig. 2(c), the high frequency noise on the demodulated curve is effectively suppressed [28]. Figure 2(d) displays the three terahertz spectra by Fourier-transforming the corresponding time-domain data shown in Fig. 2(a), respectively. The effective bandwidth of the terahertz spectrum is 1.5 THz, with two sidebands appearing near the modulation frequency (1 MHz), corresponding to approximately 20 THz ($1 \text{ MHz} \times f_{t1} / \Delta f$) in the terahertz spectrum. The characteristics of the modulated terahertz spectrum are consistent with those of the reference terahertz spectrum, although the amplitude of the modulated signal is attenuated compared to the reference one, as predicted by Eqn. (9).

3.2. Results of lock-in detection

Figure 3 presents a comparative analysis of measurement results obtained from the THz-ASOPS spectrometer with lock-in detection and reference data. Figure 3(a) demonstrates the time-domain terahertz electric field pulses acquired using both measurement techniques, recorded over a time window of $\tau = 1/f_{t1} = 10 \text{ ns}$. The main peaks and other minor features are essentially identical for the two terahertz electric field pulses, except for a deviation in the DC component in the reference data. Figures 3(b) and (c) provide the zoomed-in details of the main peaks and the minor features of the time-domain data where the DC component is removed, which indicates that the modulation of terahertz signal and the lock-in detection do not introduce distortions [29]. Figure 3(d) depicts the background noises for the lock-in and reference data, from which

the noise amplitudes 1.2×10^{-3} and 6.3×10^{-4} are obtained, respectively. In comparison with the reference terahertz pulse, the lock-in one shows a substantial increase in the peak value and a significant reduction in the background noise level. This results in a three-fold enhancement (600/200) for the lock-in detection scheme.

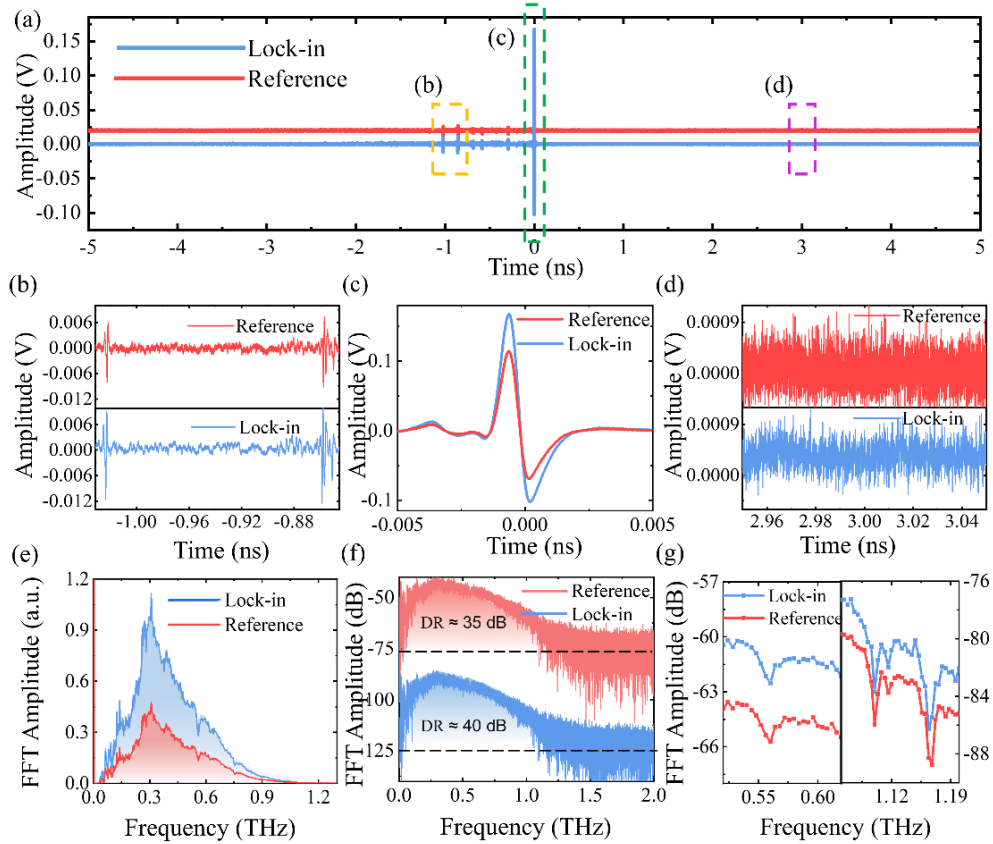


Fig. 3. Comparison of lock-in and reference data for THz-ASOPS with lock-in detection system. (a) Time-domain demodulated and the reference electric field pulses over one full temporal cycle (10 ns). (b), (c) and (d) show the zoomed-in details of the noise and signal marked in (a), respectively. (e) and (f) Fourier transformed spectra in linear and logarithmic scales of spectral amplitude. There is a vertical 50 dB down shift of the lock-in spectrum for clarity. (g) The zoomed-in water vapor absorption lines located at 0.556, 1.097, and 1.163 THz obtained from the corresponding spectra shown in (f).

Figures 3(e) and 3(f) present the Fourier-transformed spectra in linear and logarithmic scales for the y axis, revealing that the spectral range for the both cases spans from 0.1 THz to 1.2 THz. The lock-in spectral intensity exhibits a significant enhancement. Furthermore, the peak DR of the lock-in spectrum is approximately 40 dB, representing an improvement of about 5 dB compared to that (35 dB) of the reference one. To verify the accuracy of the measured spectra, water vapor absorption lines at 0.557 THz, 1.097 THz, and 1.163 THz were chosen within the measured spectra. As shown in Fig. 3(g), due to the long sampling time window (10 ns, a nominal 100 MHz frequency resolution), these absorption peaks are clearly identified. The positions of the water vapor absorption peaks in both measurements are precisely aligned without any deviation, confirming the accuracy, consistency, and reliability of the measured spectra.

3.3. Influence of other parameters

To validate the measurement consistency and accuracy of the THz-ASOPS spectrometer with lock-in detection, Fig. 4(a) presents a comparative analysis of two consecutive 10-ns time-domain acquisitions. The results demonstrate excellent temporal agreement across the entire sampling window. Figure 4(b) provides a zoomed-in view of the satellite peaks from Fig. 4(a), further showing the consistency of the terahertz time-domain data from the two measurements.

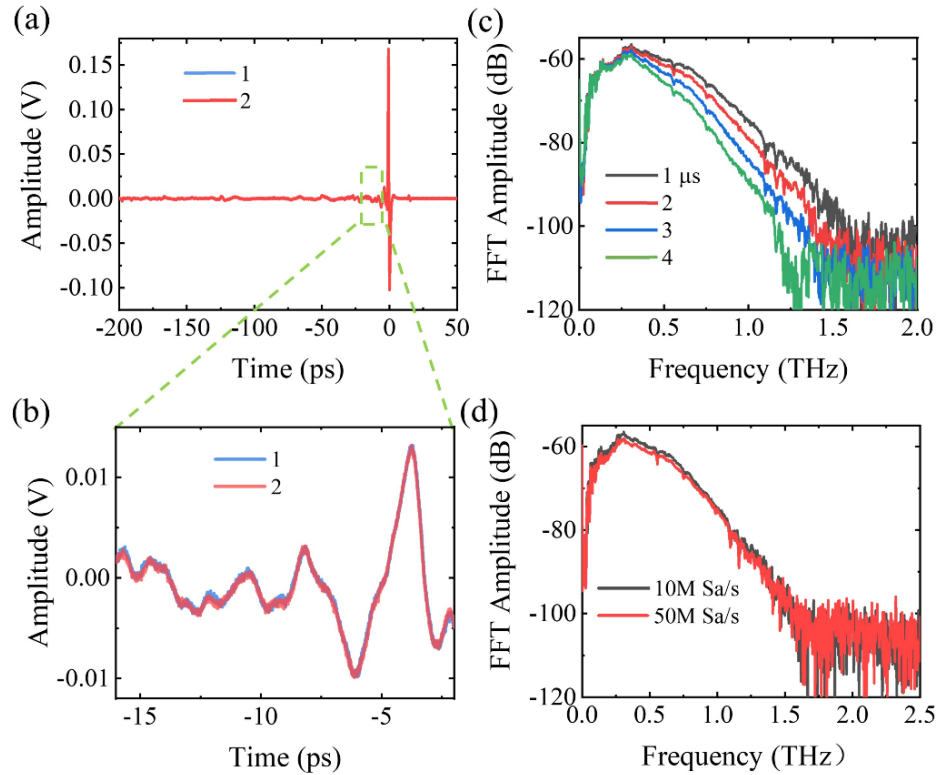


Fig. 4. Stability of the THz-ASOPS with lock-in detection and effects of integration time and sampling rate. (a) Two consecutive measurements of the time-domain terahertz pulse, (b) zoomed-in satellite features of terahertz time-domain data in (a), (c) terahertz spectra for different integration times, and (d) terahertz spectra for different sampling rates.

The system performance is critically influenced by signal processing parameters, particularly the integration time in the lock-in detection scheme [30]. A major factor affecting the SNR is the low-pass filtering during demodulation, where the integration time determines the filter's bandwidth. Shorter integration times increase the low-pass filter (LPF) cutoff frequency, potentially admitting additional high-frequency noise, while excessively long integration times reduce the cutoff frequency, potentially attenuating essential high-frequency spectral components. To systematically evaluate this trade-off, we examined integration times of 1, 2, 3, and 4 μ s, with results presented in Fig. 4(c). The terahertz spectra exhibit a consistent trend, with the reduction of the high-frequency components progressively as the integration time increases. This observation indicates that the high-frequency portion of the signal is partially attenuated by the LPF, while the high-frequency background noise is also reduced. Consequently, the selection of an appropriate integration time is a critical factor influencing the bandwidth of the THz-ASOPS with lock-in detection system.

Furthermore, the sampling rate were rigorously evaluated in accordance with the Nyquist-Shannon sampling theorem. To ensure faithful signal reconstruction without aliasing distortion, the sampling frequency must exceed twice the signal's highest frequency component. We conducted comparative experiments using sampling rates of 10 MSa/s and 50 MSa/s, with results shown in Fig. 4(d). The two sampling rates yield virtually identical results, confirming that the selected sampling rates satisfy the Nyquist criterion through oversampling, thereby maintaining measurement accuracy and preventing spectral aliasing.

4. Conclusion

This study presents a systematic exploration of THz-ASOPS spectroscopy integrated with lock-in detection. The system employs a high-power pulse generator to drive the PCA emitter, enabling successful terahertz wave modulation at 1 MHz. The modulated terahertz signal is received by a PCA detector, with the resulting photocurrent undergoing pre-amplification before processing through a digital lock-in amplifier. The implemented lock-in detection scheme yields significant performance improvements, including a 3-fold enhancement in SNR and a 5 dB improvement in DR compared to the conventional detection approach. This advanced THz-ASOPS spectroscopy system with integrated lock-in detection establishes a robust platform for various practical applications, particularly in high-precision spectral analysis [31,32], absolute distance measurement [33], and three-dimensional imaging requiring exceptional precision and stability [34].

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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