High-Resolution Terahertz Time-Domain Spectroscopy Using a Wavelet Power Spectrum Estimation Technique

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Abstract: It is shown that a wavelet power spectrum estimation technique can be applied to high-resolution terahertz time-domain spectroscopy using asynchronous optical sampling to effectively remove noises without sacrificing spectral features on a spectrum.

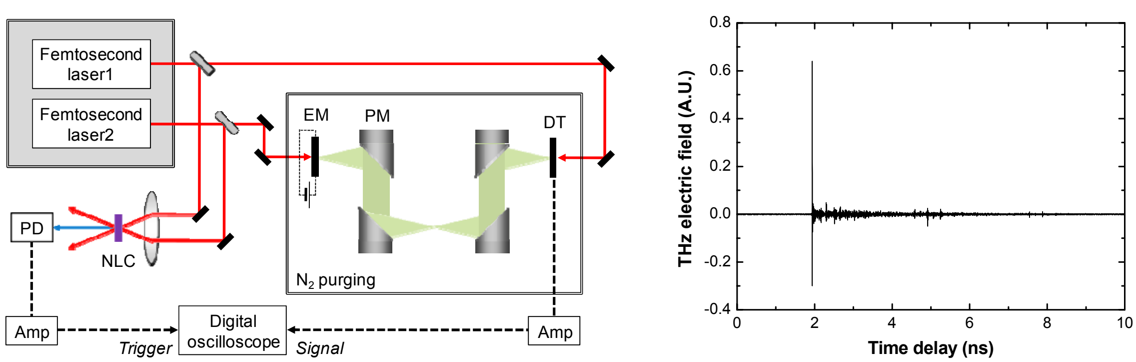
OCIS codes: (300.6495) Spectroscopy, terahertz; (100.7410) Wavelets

1. Introduction

Recently, high-resolution terahertz time-domain spectroscopy (THz-TDS) has been demonstrated using asynchronous optical sampling (AOS) [1,2]. There can be a long-lasting tail signal following a main THz pulse in time-domain signals measured from the AOS THz-TDS, which is measured only on short time windows in the conventional THz-TDS. The tail signal may be due to elements for THz generation and detection or multi-reflection of the THz wave on optical components. Since the tail signal causes additional noises on the spectrum, signal processing techniques need to be used to remove the noises on the spectrum. In this paper, we present that the quality of the high-resolution spectrum can be enhanced by using a wavelet power spectrum estimation technique.

2. AOS THz-TDS

We established a system for AOS THz-TDS as shown in Fig. 1(a), where a dual-laser system is employed for THz pulse generation and detection, comprising two femtosecond lasers and two phase-locked loops for repetition frequency stabilization. Two photoconductive antennas are used as a THz emitter and detector. THz pulses generated from the THz emitter using the femtosecond laser 2 have a repetition frequency of 100 MHz, and are sampled in the THz detector by optical sampling pulses from the femtosecond laser 1 with a repetition frequency of 100 MHz - 20 Hz. Without a mechanical time delay tool, a temporal sampling position is scanned at the difference frequency of 20Hz and a 10 ns long time window can be obtained. A digital oscilloscope acquires time-domain data when triggered by an optical sum-frequency signal that is generated by a cross-correlator.



(a) (b)

Fig. 1. (a) Our experimental configuration for AOS THz-TDS. (b) A typical time-domain waveform with a time window of 10 ns measured from the AOS THz-TDS.

In Fig. 1(b), a typical time-domain signal with a time window of 10 ns is shown to have a long-lasting tail signal. Also, the spectrum obtained by fast Fourier transform of the time-domain waveform and a transmittance spectrum of water vapor are displayed by the black lines in Fig. 2(a) and 2(b), respectively. It is shown that the

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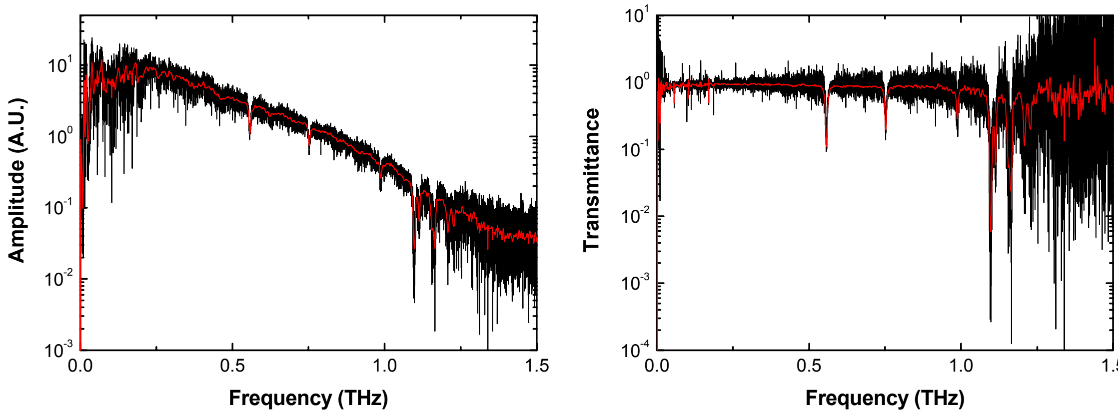
high-resolution spectra with a frequency resolution of 100 MHz have additional noises due to the tail signal as well as background noises, which deteriorate the signal-to-noise ratio.



(a) (b)

Fig. 2. (a) The Spectrum (black line) obtained by FFT of the time-domain waveform in Fig. 1(b) and that (red line) after processed using the wavelet spectrum estimation technique. (b) A measured transmittance spectrum of water vapor (black line) and that (red line) after the signal processing.

3. Wavelet power spectrum estimation technique

Estimation of the power spectrum of the THz-TDS data can be viewed as a nonparametric statistical estimation problem of a stationary random process. Note that the power spectrum S(f) of the THz-TDS signal x(t) and its periodogram I(f) are given by

$$S(f) = \sum_{n=-\infty}^{\infty} r(n) e^{-i2\pi nf}, \quad I(f) = \left| \sum_{n=0}^{2N-1} x(n) e^{-i2\pi nf} \right|^2, \tag{1}$$

where r(n) denotes the autocorrelation function of x(n). For this type of problem, a nonparametric approach based on a wavelet spectrum estimation technique can be very powerful [3]. More specifically, Moulin [3] showed that the power spectrum is related to the periodogram in the following manner

$$\ln I\left(\frac{k}{2N}\right) - \gamma = \ln S\left(\frac{k}{2N}\right) + \varepsilon(k), \quad k = 0,1,\ldots,N-1 \tag{2}$$

for some constant γ. Here, ε(k) is independent and identically distributed with zero mean non-Gaussian noise. We now apply orthogonal wavelet transform to the $\ln I\left(\frac{k}{2N}\right)$ to decompose the periodogram into different scale wavelet coefficients. Then, the resulting individual wavelet coefficient is compared with a fixed threshold value and truncated toward zero when its magnitude is smaller than the threshold value. The final spectrum is reconstructed by applying inverse wavelet transform to the processed wavelet coefficients. Fig. 2 clearly demonstrates that the wavelet power spectrum estimation technique can effectively remove noises with making no change in the water vapor absorption lines. Even though the approach appears very simple, the wavelet power spectrum estimation enjoys optimality by capturing statistically significant components of power spectrum density. Compared to the conventional low-pass filtering approach, the wavelet power spectrum estimation technique can effectively remove the noise without affecting narrow spectral features. Therefore, the wavelet power spectrum estimation technique is ideally suitable for AOS THz-TDS that has a high spectral resolution to capture narrow spectral features.

4. References

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