Terahertz TDS signal de-noising using wavelet shrinkage

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The field of terahertz (THz) science and technology has achieved significant progress over the last decades. Research interest focuses on THz spectroscopy and imaging. The signal-to-noise ratio (SNR) of the THz system is of great importance in the application of THz spectroscopy and imaging. In this letter, the wavelet de-noising technology is used to improve SNR and increase the speed of the THz time-domain spectroscopy system by reducing the repeating times.

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Terahertz (THz) radiation lies between the infrared and millimeter regions of the electromagnetic spectrum. The THz region is typically defined as the frequency range of 0.1–10 THz, or wavelength of 30–300 μm[1,2]. It has diverse applications, such as in security and material science[3−5]. However, standard THz time-domain spectroscopy (THz-TDS) systems currently suffer from limitations in terms of speed, accuracy, and resolution. There are several sources of noise in THz-TDS systems, such as laser noise and emitter noise[6,7]. In this letter, wavelet de-noising technology is used to reduce the noise and increase the speed of the THz-TDS system by reducing the repeating times.

Wavelet analysis has been widely used in signal processing and imaging. It has also been used in signal de-noising field successfully. There are three kinds of wavelet de-noising methods, including wavelet shrinkage, projection means, and correlation method. In this letter, wavelet shrinkage is used. Wavelet shrinkage is a signal de-noising technique, which is based on the idea of the threshold of the wavelet coefficients. The coefficients with small absolute values are considered to encode most of the noise. On the other hand, the main information is included in the coefficients that have large absolute values. If those with small absolute values can be eliminated, the signal can have less noise.

The main steps of the de-noising technique by wavelet shrinkage can be described as follows[7]:

1. Wavelet transformation: It transforms signal S into approximate coefficients and detail coefficients by convolving S with low-pass filter LD and high-pass filter HD. Figure 1 shows the schematic decomposition of discrete wavelet transform at level 2. After this process, detail coefficients cD_1 and cD_2 and approximate coefficients cA_2 are obtained. For the level N, we have to decompose the approximate coefficients cA_2 until the approximate coefficients cA_N are obtained.
2. Threshold process: Threshold values are calculated and operated for each coefficient.
3. Inverse wavelet transform: After this process, the signal with less noise is achieved.

Two THz-TDS systems were used in the experiment, namely, a TPI 3000 system (TeraView Ltd., Cambridge, UK) and a home-made system. The effects of wavelet family, decomposition level, and threshold selection in wavelet de-noising technique were also investigated. The experimental procedures are detailed below.

1. White noise with Gaussian shape was added to the THz signal measured, so that the SNR of the THz signal reached 3 dB.
2. Both soft and hard thresholds were used in the wavelet shrinkage process.
3. The SNR was calculated by comparing the

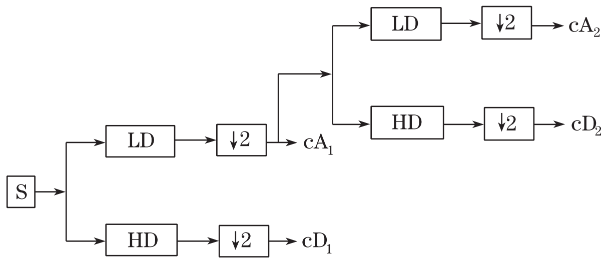

Fig. 1. The schematic decomposition of discrete wavelet transform at level 2.

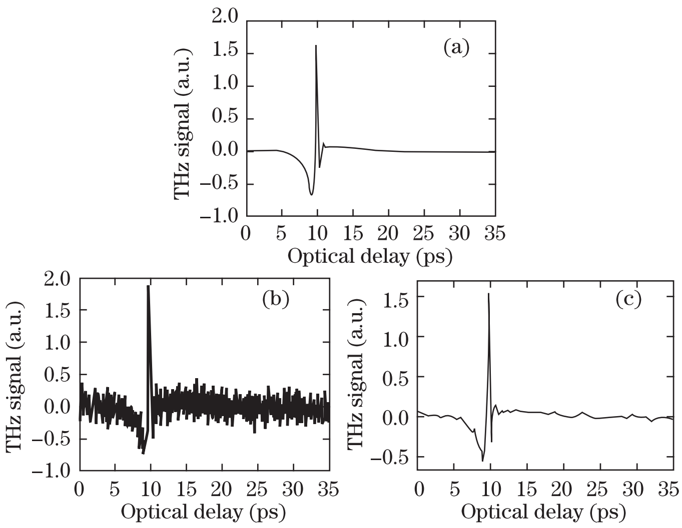

Fig. 2. THz signal by wavelet de-noising: (a) original signal, (b) noising signal with the SNR in 3 dB, and (c) de-noising signal.

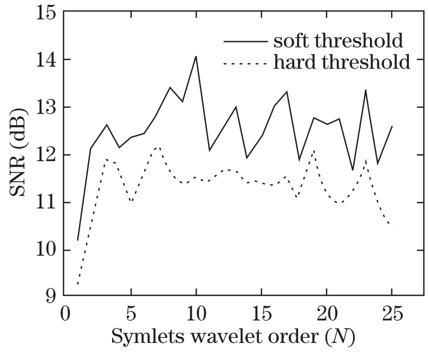

Fig. 3. The SNR improvement along with the Symlets wavelet order *N*.

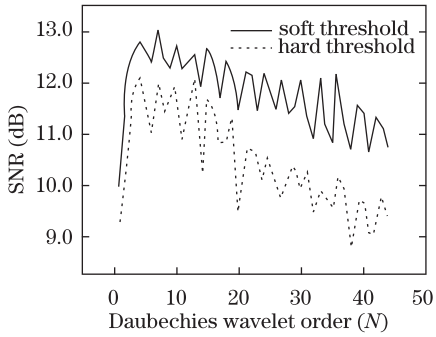

Fig. 4. The SNR improvement along with the Daubechies wavelet order *N*.

de-noising signal to the origin signal.

In the experiment, the original signal was obtained experimentally from a TPI 3000 system. Daubechies, Biorthogonal, Symlets, and Coiflets wavelet families were chosen, and the order of each wavelet was changed so as to obtain an ideal SNR. The influence of decomposition level of each wavelet shrinkage process was also studied. The THz signal processed by wavelet de-noising is shown in Fig. 2.

In the experiment, the Symlets wavelet family performed better than others. By using the Symlets wavelet family, the maximum SNR improvement increased to 14 dB (the SNR improvement is shown in Fig. 3). For each wavelet family, an ideal order is achieved and it is 10 for the Symlets family. It is clear that soft threshold performed better than hard threshold in wavelet de-noising (Fig. 3 and 4) . The SNR is also influenced by the

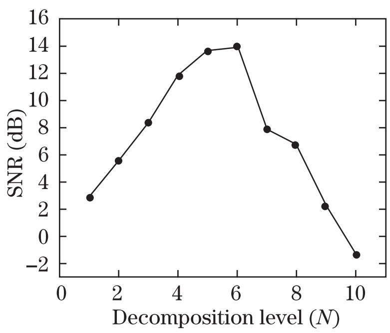

Fig. 5. The SNR improvement along with the sym10 wavelet at decomposition level *N*.

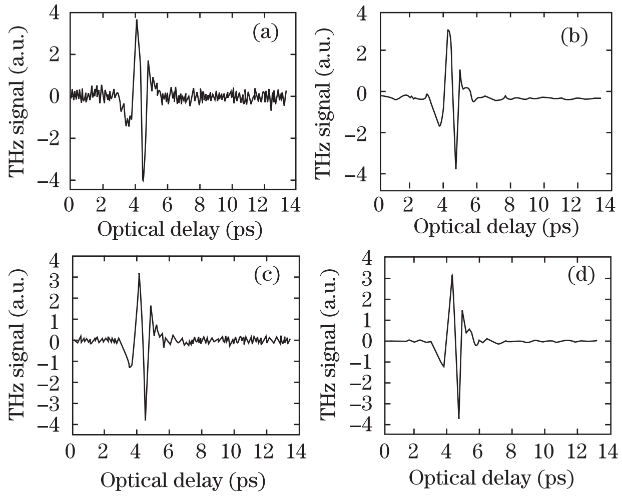

Fig. 6. (a) The original signal, (b) the signal after de-noising using sym10 wavelet and the decomposition level six, (c) the signal after ten times average of the original signal, and (d) the signal after five times average of the de-noising signals.

decomposition level in wavelet transformation.Figure 5 shows the SNR improvement by de-noising with the sym10 wavelet on decomposition level changing.

Figure 6(a) shows one of the THz signals measured by our home-made THz-TDS system, which contains great amounts of noise. It is clear that the signal after 5 times the average of the de-noising signals is better than the original signal after the 10 times average shown in Fig. 6(c) and (d). This means that wavelet de-noising technique can be used to increase the speed of the THz-TDS system by reducing the repeating times.

In conclusions, we have demonstrated wavelet de-noising technique, which can be used to increase the speed of the THz system by reducing the repeating times. However, future works must study the other applications of wavelet de-noising technique.

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