Terahertz Time-resolved Spectroscopy with Wavelet-transform

Yuqiang Deng, and Qing Sun
Optics Division, National Institute of Metrology
Beijing 100013, China

Feng Liu, Changlei Wang, and Qirong Xing
School of Precision Instruments and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China

***Abstract*—We introduce a new technique for the joint time-frequency analysis of terahertz time-domain spectroscopy based on wavelet-transform technique. With this technique, the frequency components in the different parts of the pulse are clearly exhibited in different time locations. This technique avoids interference spectrum even when the echo terahertz pulse emerges. By varying the shape of the analysis wavelet, high time resolution and high frequency resolution are easily obtained.**

Keywords-component; Ultrafast optics, spectroscopy, time domain analysis, wavelet transforms

I. INTRODUCTION

Recent advancements in the fields of ultrashort pulsed lasers, non-linear optics and crystal growth techniques have enabled the emergence of practical sources of bright, coherent, broadband terahertz (THz) pulses and allowed room temperature detection [1]. Coherent detection methods make it possible to record not just intensity but time-resolved amplitude of the electric field [2]. The THz time domain spectroscopy (THz-TDS) [3] uses the coherent detection of the broadband pulses to analyze the THz spectral response of chemicals and materials sensitively in this range. It has been used to characterize gases, liquids, and biology specimens.

The conventional THz-TDS is based on Fourier-transform (FT) technique [4]; the entire temporal THz pulses are transformed into frequency domain for spectral analysis. With FT technique, the frequency resolution is relevant to the temporal length of the waveform; therefore, to improve the frequency resolution, the scanning length of temporal THz waveform needs to be extended. However, the noise in the extended length would be introduced into the analyzed spectra and thus yields inconsistent spectra from measured THz with different scanning lengths. When the scanning length is extended, the echo THz pulse reflected between the two surfaces of the electro-optic (EO) crystal is recorded. The echo pulses would arouse interference spectrum with the original one in the frequency domain.

We have applied the wavelet-transform (WT) technique in spectral phase retrieval of femtosecond optical pulses [5] and direct group delay extraction from white-light spectral interferogram [6, 7]. Also the WT has been used in noise removal, data compressing, signal classification, and imaging in THz signal processing [8-10]. In this paper, we introduce WT to the joint time-frequency analysis of THz pulses. This technique could remove the noise and avoid the interference spectrum generated from traditional FT technique.

II. TERAHERTZ SPECTRAL ANALYSIS WITH FOURIER-TRANSFORM

We have measured the THz pulses from our home-made THz-TDS system. A 1 mm Zinc Telluride is used as the EO crystal, and the measured terahertz electric fields in dry air and in air conditions are shown in Fig. 1(a) and 1(b), respectively.

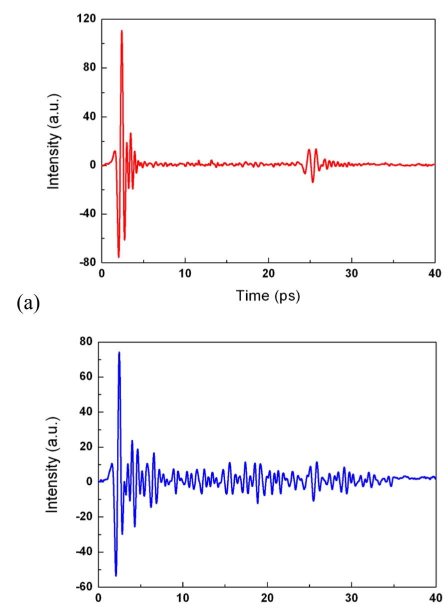

Fig. 1. Measured THz waveforms in dry air (a) and in air (b).

With FT technique, there are interference spectra in frequency domain (see the green curves in Fig. 2.). It is because there are two pulses in time domain: one is the original pulse, and the other is the echo one. Their spectra have different phases; therefore, interference occurs in frequency domain.

To avoid the interference spectra, we intercept the THz transient in 10 ps and 20 ps lengths so that the echo pulse is excluded. However, we obtained inconsistent spectra from

978-1-4244-6516-3/10/$26.00 ©2010 IEEE

different lengths of THz pulses (see Fig. 2.).

Fourier analysis transforms entire temporal waveform into frequency domain, and the frequency resolution is related to the temporal length of the waveform. If the transformed waveform is short, the frequency resolution is very low and some frequency component is lost; if the transformed waveform is very long, the echo pulse is included and interference spectrum is formed. In some circumstances, such as in Fig. 1(b), the optimal length of the waveform is difficult to determine.

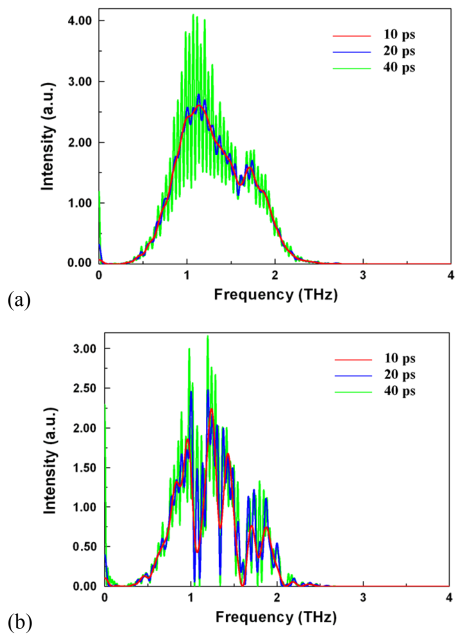

Fig. 2. The FT of THz in dry air (a) and in air (b).

III. TERAHERTZ SPECTRAL ANALYSIS WITH WAVELET-TRANSFORM

A wavelet is localized in both time and frequency domain. Signals with sharp changes or a pulsed shape are better analyzed with a wavelet than with a smooth sinusoid [8]. The WT performs a "local Fourier analysis" by analyzing and representing signals in terms of shifted and dilated versions of time-localized and oscillating functions. Since THz pulses are localized in both time and frequency domain, they are naturally suited to signal processing methods based on wavelets [10].

We use Gabor wavelet as the analysis wavelet, and the WT of THz in Fig. 1 are shown in Fig. 3. Figure 3 shows with WT technique, the frequency components in different time location can be clearly distinguished. Also, the spectrum has no interference even when the echo pulse is recorded because of the excellent location of wavelet in both time domain and frequency domain.

With WT technique, the dispersion is clearly exhibited. The refractive index in THz frequency range can also be measured from the delay of each frequency components in the time-frequency distribution analyzed with WT technique.

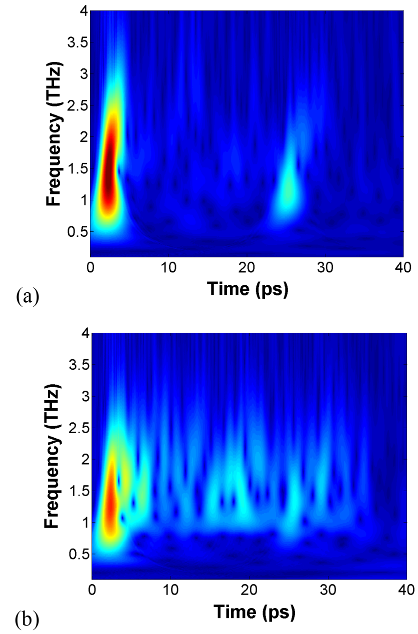

Fig. 3. The WT of THz in dry air and in air. (a) 40 *ps* THz in dry air, (b) 40 *ps* THz in air.

IV. IMPROVEMENT OF FREQUENCY RESOLUTION

We have examined the shaping factor (SF) of Gabor wavelet for the phase retrieval of femtosecond optical pulses [11] and the group delay extraction of ultrashort laser elements [12]. We demonstrated that time resolution and frequency resolution can be determined by the SF [11, 12]. In the analysis of time domain signal, small SF has high time resolution and large SF has high frequency resolution; therefore, we can easily improve time resolution and frequency resolution by varying SF.

In the foregoing analysis (Fig. 3), the SF is Gs=5.3, it has a relative high time resolution and high frequency resolution simultaneously. We then enlarge SF to improve the frequency resolution. We choose Gs=53.4; the time-frequency distributions of THz (Fig. 1) are shown in Fig. 4.

From Fig. 4, the frequency components of the THz are clearly shown. Figure 4 demonstrated that SF allows a convenient switching between time and frequency domains. We can easily improve frequency resolution by enlarging SF.

A larger SF means more oscillations under the envelope, and thus the time resolution is averaged. It gives a large uncertainty in time, but a small uncertainty in frequency domain. The WT analyzed with large SF is very similar to FT. The comparisons of WT with large SF and FT are also shown in Fig. 4.

In Fig. 4, the peaks and valleys of the time-frequency distributions with WT technique projected to the frequency

axis agree excellently with those obtained with FT technique. The wavelet analysis with large SF averaged the time distributions in the spectral range; therefore it is analogous to FT. In other words, FT is a special kind of WT, whose SF is infinite large.

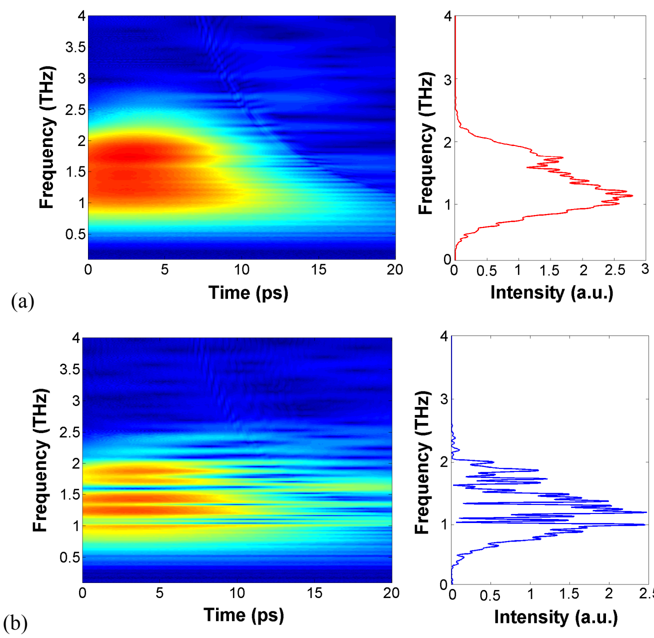

Fig. 4. Comparisons of the time-frequency analysis by WT (*Gs*=53.4) with the spectral analysis by FT. (a) THz in dry air, left: WT, right: FT, (b) THz in air, left: WT, right: FT.

The absorption coefficient of water vapor analyzed with WT in large SF case and those obtained with FT are shown in Fig. 5 together. From Fig. 5, we can see that the water vapor absorption lines analyzed with the two techniques can agree excellently. The results can also agree well with those reported by other literatures [13, 14].

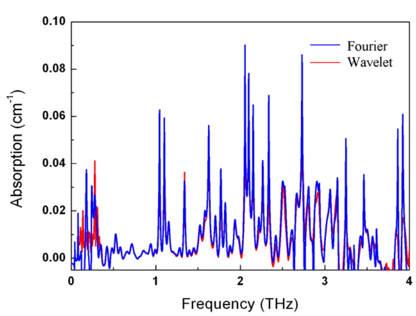

Fig.5. Comparison of the absorption lines analyzed by WT with those obtained by FT.

V. Conclusion

We have introduced a novel technique, WT, into the spectral analysis of THz-TDS. This technique displays the joint time and frequency information on a two-dimensional plane, on which time-resolved spectroscopy and dispersion are clearly exhibited. With this technique, the inconstant spectra is avoided, and there is no interference spectrum even when the echo pulse is recorded. The WT technique allows the switching between time and frequency domains, and it is very convenient to enhance the time resolution and frequency resolution by varying the SF. This technique is an extension of conventional THz-TDS; it is useful in characterizing gases, liquids, and solids, and other applications of terahertz radiations.

References

[1] D. H. Auston and M. C. Nuss, "Electrooptic generation and detection of femtosecond electrical transients," *IEEE J. Quantum Electron.* vol. 24, pp. 184-197, 1988.

[2] A. J. Fitzgerald, E. Berry, N. N. Zinovev, G. C. Walker, M. A. Smith and J. M. Chamberlain, "An introduction to medical imaging with coherent terahertz frequency radiation," *Phys. Med. Biol.* vol. 47, pp. R67-R84, 2002.

[3] P. R. Smith, D. H. Auston and M. C. Nuss, "Subpicosecond photoconducting dipole antennas," *IEEE J. Quantum Electron.* vol. 24, pp. 255-260, 1988.

[4] P. R. Griffiths, "Photometric precision in infrared spectra measured by Fourier transform spectroscopy," *Appl. Spectrosc.* vol. 29, pp. 11-14, 1975.

[5] Y. Deng, Z. Wu, L. Chai, C. Wang, K. Yamane, R. Morita, M. Yamashita, and Z. Zhang, "Wavelet-transform analysis of spectral shearing interferometry for phase reconstruction of femtosecond optical pulses," *Opt. Express* vol. 13, pp. 2120-2126, 2005.

[6] Y. Deng, W. Yang, C. Zhou, X. Wang, J. Tao, W. Kong, and Z. Zhang, "Direct measurement of group delay with joint time-frequency analysis of white light spectral interferogram," *Opt. Lett.* vol. 33, pp. 2855-2857, 2008.

[7] Y. Deng, W. Yang, C. Zhou, X. Wang, J. Tao, W. Kong, and Z. Zhang, "Wavelet-transform analysis for group delay extraction of white light spectral interferograms," *Opt. Express* vol. 17, pp. 6038-6043, 2009.

[8] C. C. Te, B. Ferguson and D. Abbott, "Investigation of biomaterial classification using T-rays," *Proc. SPIE* vol. 4937, pp. 294-306, 2002.

[9] R. K. H. Galvão, S. Hadjiloucas, J. W. Bowen, C. J. Coelho, "Optimal discrimination and classification of THz spectra in the wavelet domain," *Opt. Express* vol. 11, pp. 1462-1473, 2003.

[10] D. M. Mittleman, R. H. Jacobsen, R. Neelamani, R. G. Baraniuk and M. C. Nuss, "Gas sensing using terahertz time-domain spectroscopy," *Appl. Phys. B* vol. 67, pp. 379-390, 1998.

[11] Y. Deng, C. Wang, L. Chai, and Z. Zhang, "Determination of Gabor wavelet shaping factor for accurate phase retrieval with wavelet-transform," *Appl. Phys. B* vol. 81, pp. 1107-1111, 2005.

[12] Y. Deng, W. Yang, and Z. Zhang, "Shape selection of wavelets for accurate chromatic dispersion measurement of white-light spectral," *Appl. Phys. B* vol. 98, pp. 347-351, 2010.

[13] R. J. Foltynowicz and R. E. Allman, "Terahertz time-domain spectroscopy of atmospheric water vapor from 0.4 to 2.7 THz " (Sandia report, SAND2005-5709, 2005). http://www.prod.sandia.gov/cgi-bin/techlib/access-control.pl/2005/055709.pdf.

[14] G. Klatt, R. Gebs, C. Janke, T. Dekorsy, and A. Bartels, "Rapid-scanning terahertz precision spectrometer with more than 6 THz spectral coverage," Opt. Express vol. 17, pp. 22847-22854, 2009.