中国计量科学研究院
National Institute of Metrology

Automatic and accurate characterization of femtosecond optical pulses

Yuqiang Deng[1], Qing Sun[1], Shiying Cao[1], Jing Yu[1], Ching-yue Wang[2], and Zhigang Zhang[3]

[1] *Optics Division, National Institute of Metrology, China;*
[2] *Tianjin University;* [3] *Peking University*

E-mail: yqdeng@nim.ac.cn

Sep. 21, 2011

NEWRAD 2011, SBR_OR_002

中国计量科学研究院
National Institute of Metrology

——*Ultrashort optical pulses and terahertz waves measurements*

Yuqiang Deng[1], Qing Sun[1], Shiying Cao[1], Jing Yu[1], Ching-yue Wang[2], and Zhigang Zhang[3]

[1] Optics Division, National Institute of Metrology, China;
[2] Tianjin University; [3] Peking University

E-mail: yqdeng@nim.ac.cn

Sep. 21, 2011

Overview

I. Characterization of ultrashort optical pulses

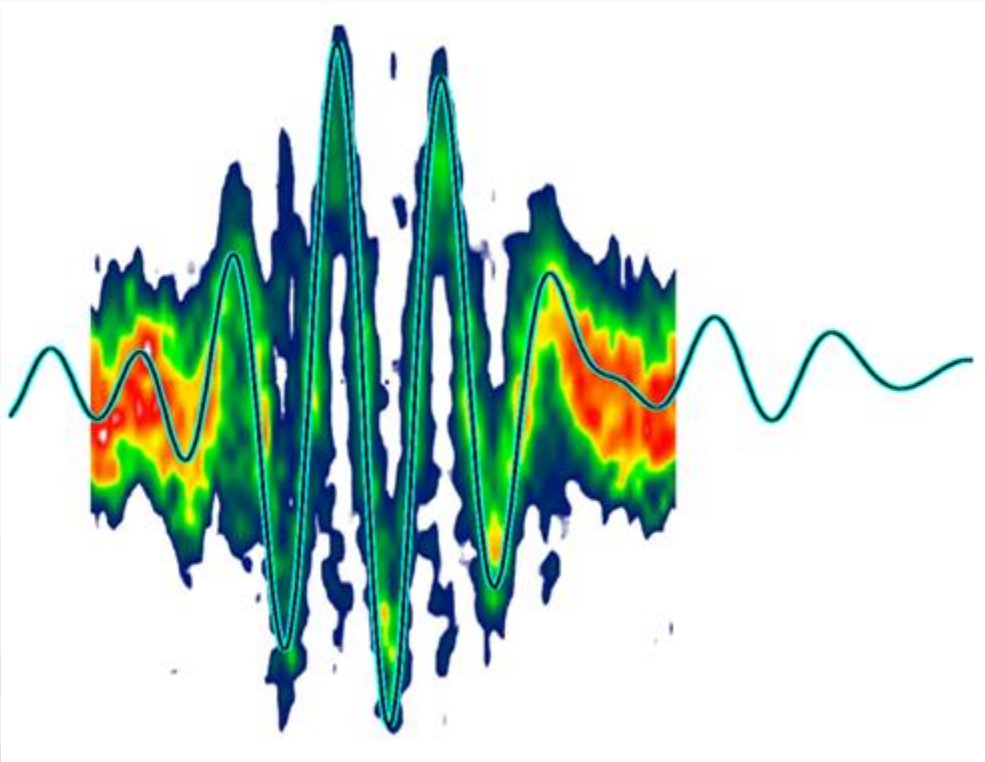
II. Measurement of chromatic dispersion of optical elements

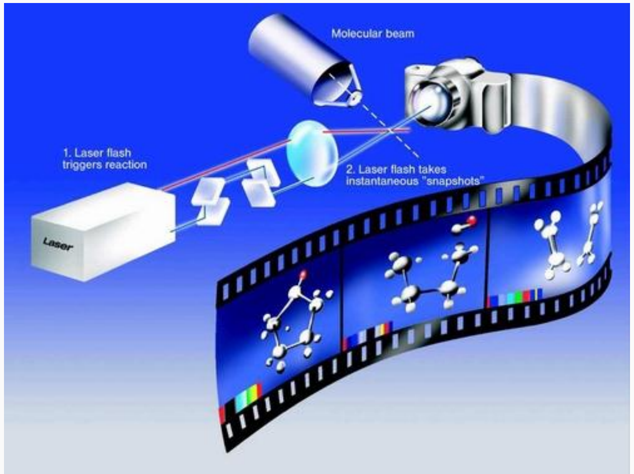
III. Terahertz spectra measurement and analysis

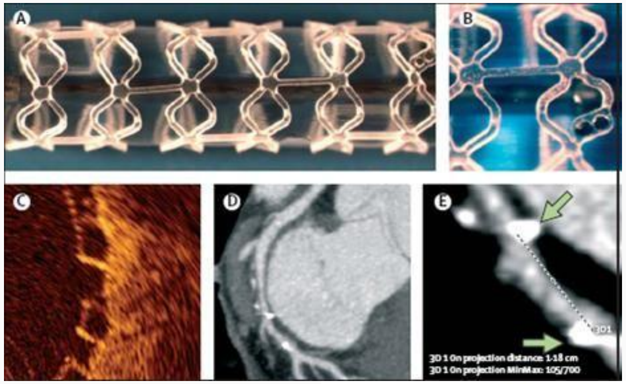
IV. Summarization

I. Characterization of ultrashort optical pulses

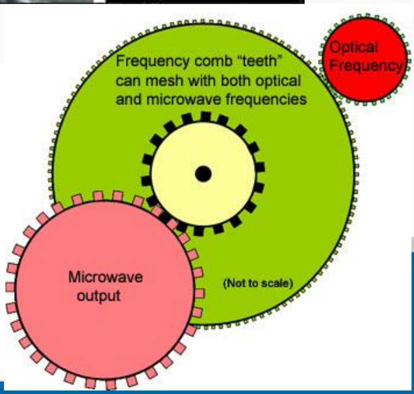
$1\ \text{fs} = 1 \times 10^{-15}\ \text{s}$







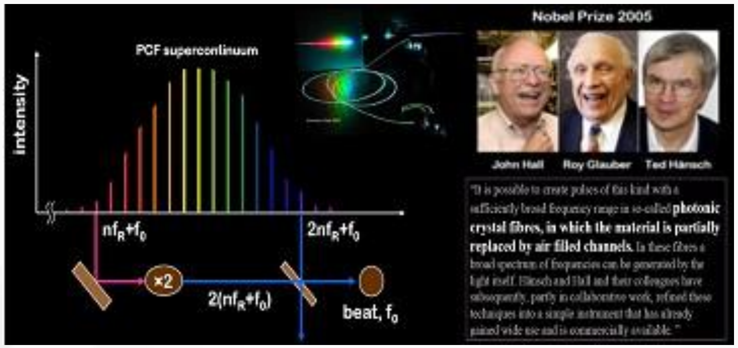
Electric field of an ultrashort optical pulses



Spectrum of an ultrashort optical pulses

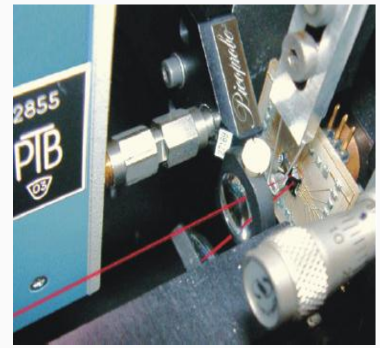
I. Characterization of ultrashort optical pulses

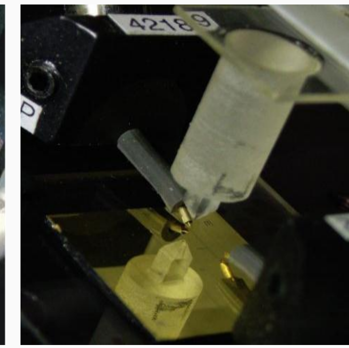
Applications of ultrashort optical pulses in recent activities of NMIs.



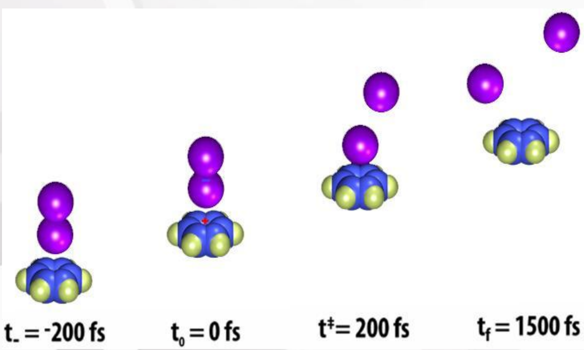
Time and frequency metrology

Length metrology

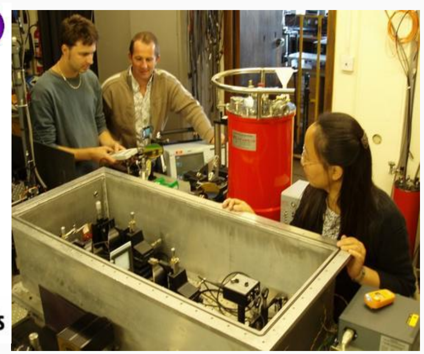




Ultrafast electric pulses metrology



Ultrafast chemistry metrology



Terahertz frequency metrology

Terahertz power metrology

Terahertz imaging metrology

中国计量科学研究院
National Institute of Metrology

I. Characterization of ultrashort optical pulses

Why ultrashort optical pulses measurements?

—An important and widely used parameter

—Effects in optics experiments of ultrafast information and high field physics

—Weights in uncertainty budget of ultrafast E-pulses characterization, ultrafast chemistry metrology and terahertz metrology

—IEC 60825-1 Safety of laser products –Part 1: Equipment classification and requirements: "***pulse duration information shall be provided***" (L. 13, P. 65)

I. Characterization of ultrashort optical pulses

- The Dilemma

**In order to measure
an event in time,
you need a *shorter* one.**

To study this event, you need a strobe light pulse that's shorter

Photograph taken by Harold Edgerton, MIT

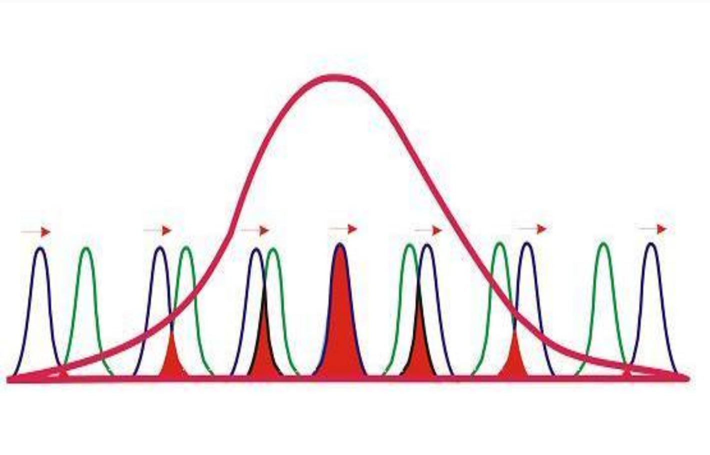
**But then, to measure the strobe light pulse,
you need a detector whose response time is even shorter.**

And so on…

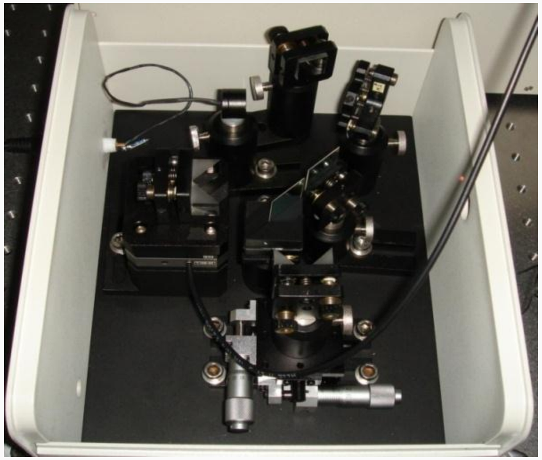
So, now, how do you measure the *shortest* event?

I. Characterization of ultrashort optical pulses

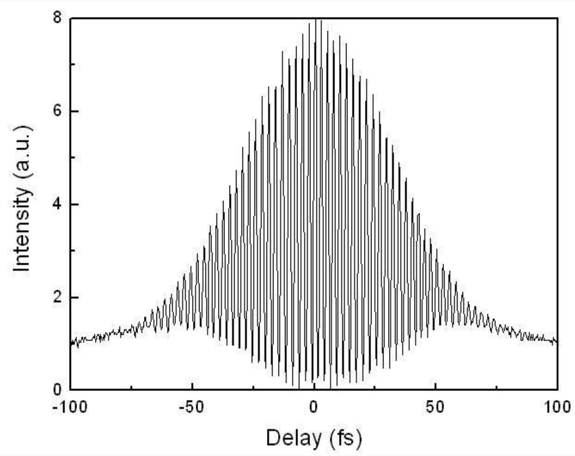
Pulse Measurement in the Time Domain: *Autocorrelator*



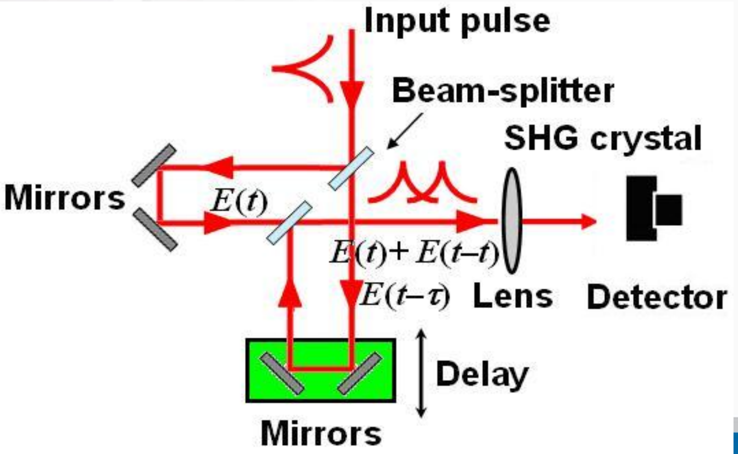
Schematic of autocorrelation



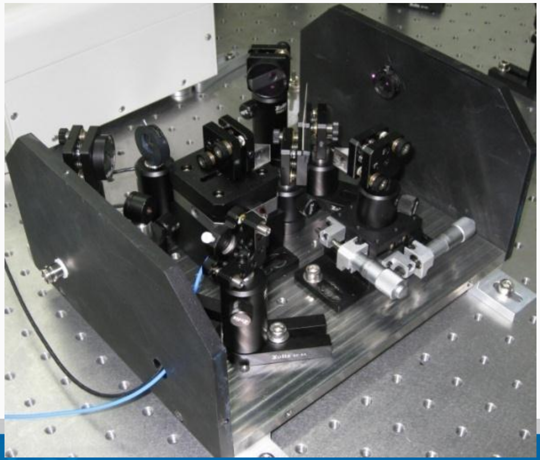
Experimental setup



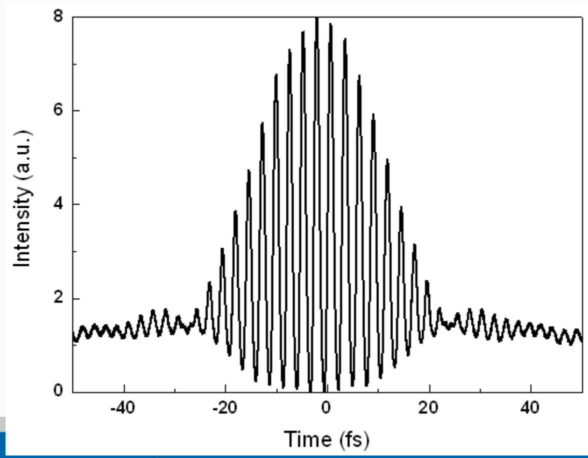
AC of a 27 fs pulse



Schematic of autocorrelation



Experimental setup



AC of a 18 fs pulse

I. Characterization of ultrashort optical pulses

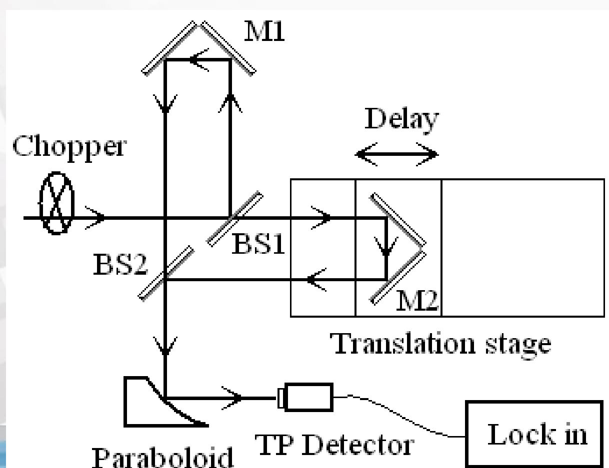
A versatile SHG autocorrelator:

—Broad bandwidth (*fit for both Ti:sapphire laser and fiber laser*)

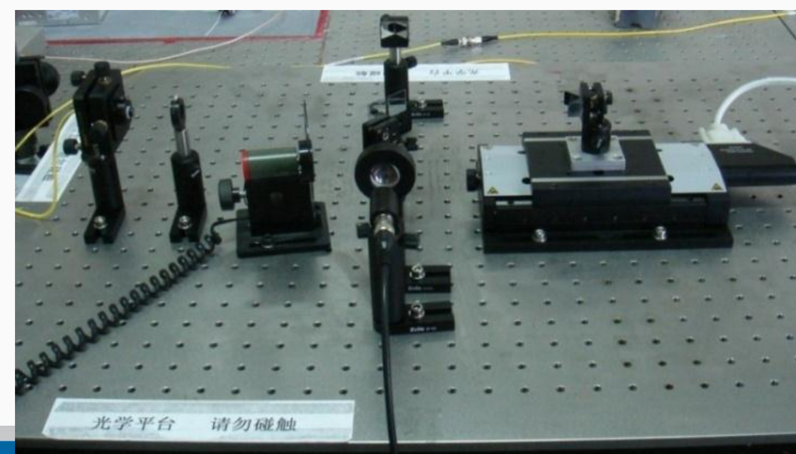
—Large scanning range (*measurement form sub-10 fs to 100 ps*)

—Inerferometric autocorrelation and intensity autocorrelation (*convenient switch between accurate measurement and fast measurement*)

—Self-calibration



Schematic of the versatile autocorrelator



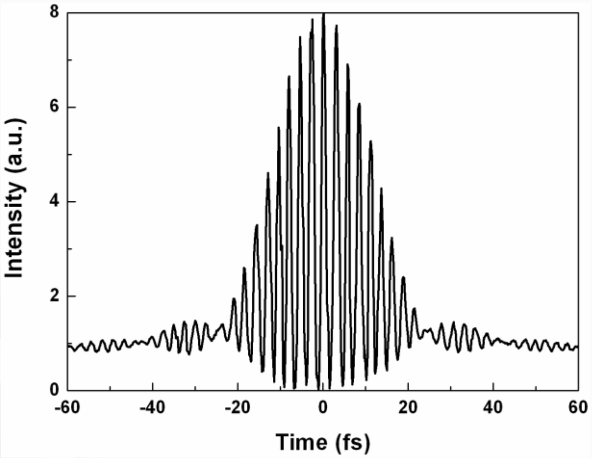
Experimental setup

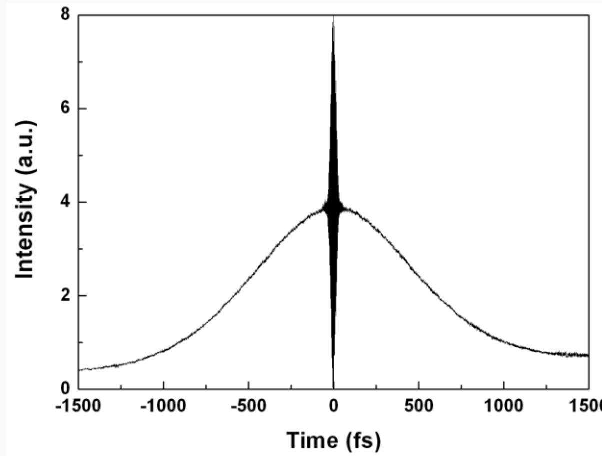
中国计量科学研究院
National Institute of Metrology

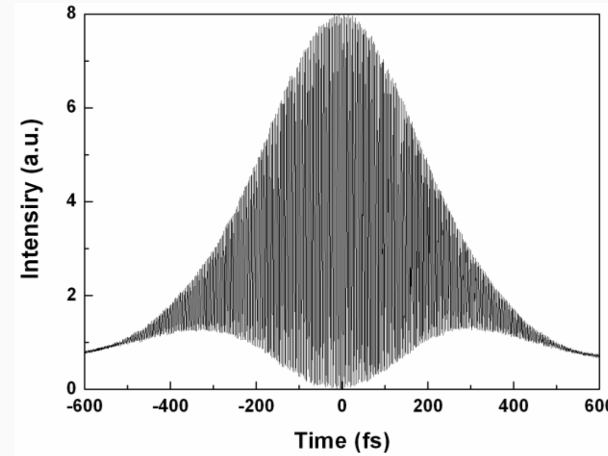
I. Characterization of ultrashort optical pulses

- Our experimental results

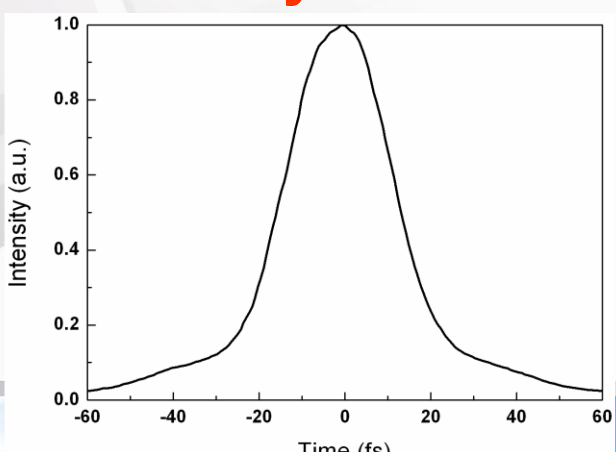
Inerferomatric autocorrelation

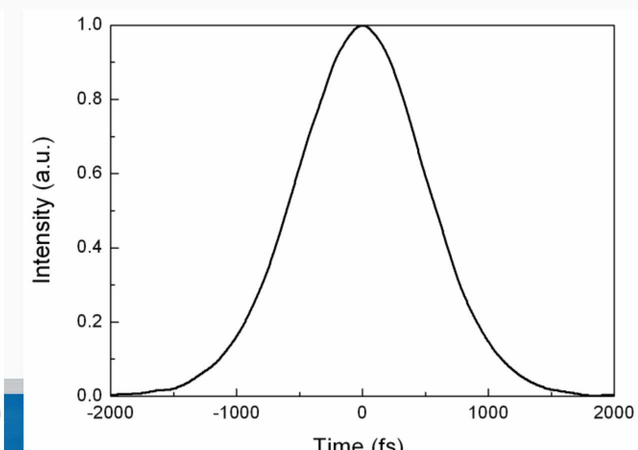


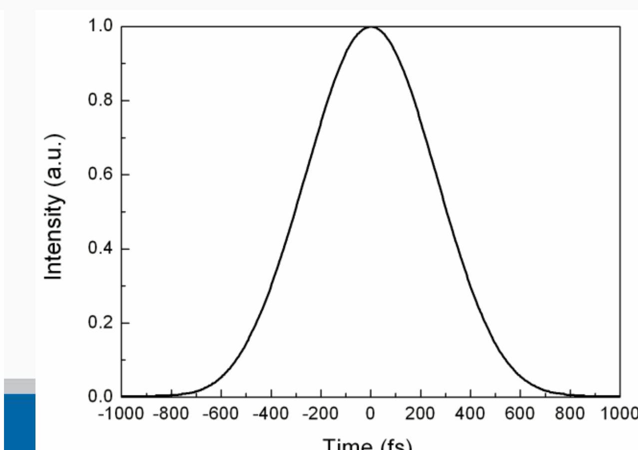




Inensity autocorrelation



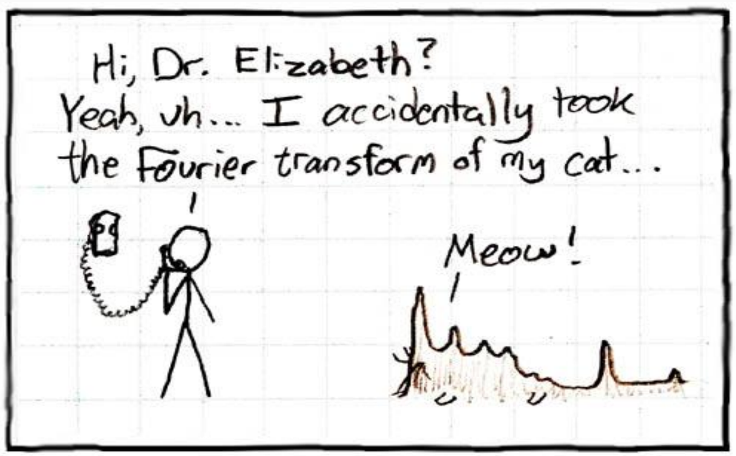


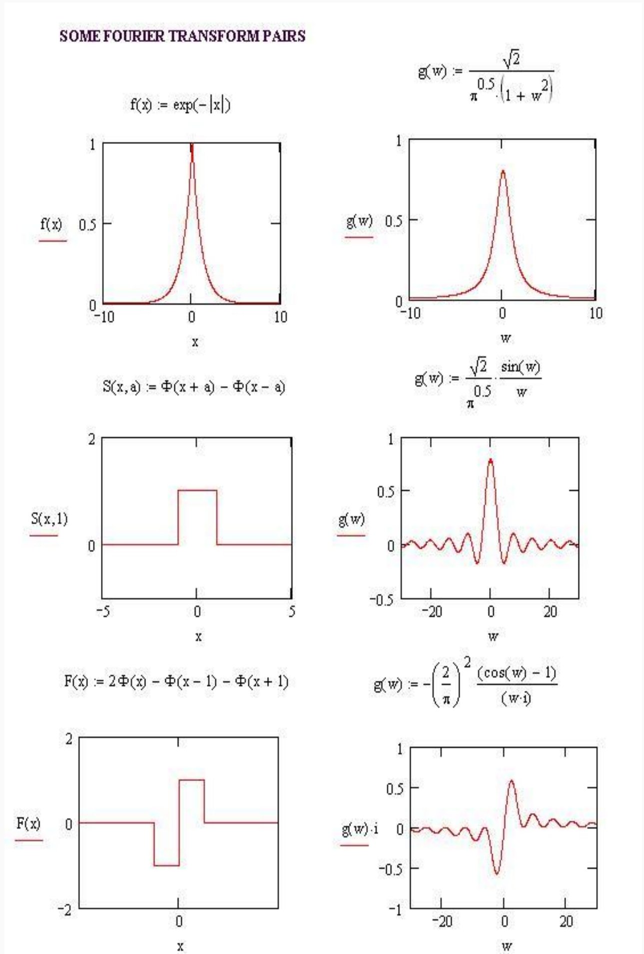


Ti:sapphire laser **Strong chirped pulse** **Fiber laser**

I. Characterization of ultrashort optical pulses

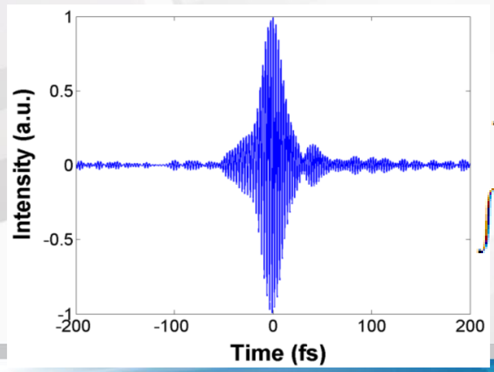
- Fourier transform and inverse Fourier transform





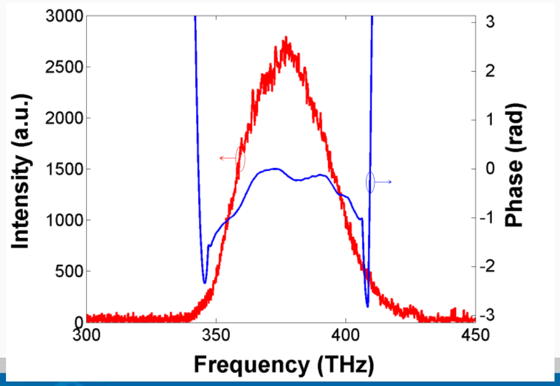
$S(\omega)$ → Spectrometer

$\varphi(\omega)$ →How?



$\int F(t)e^{2\pi i\omega t}dt$

$\int F(\omega)e^{-2\pi i\omega t}d\omega$



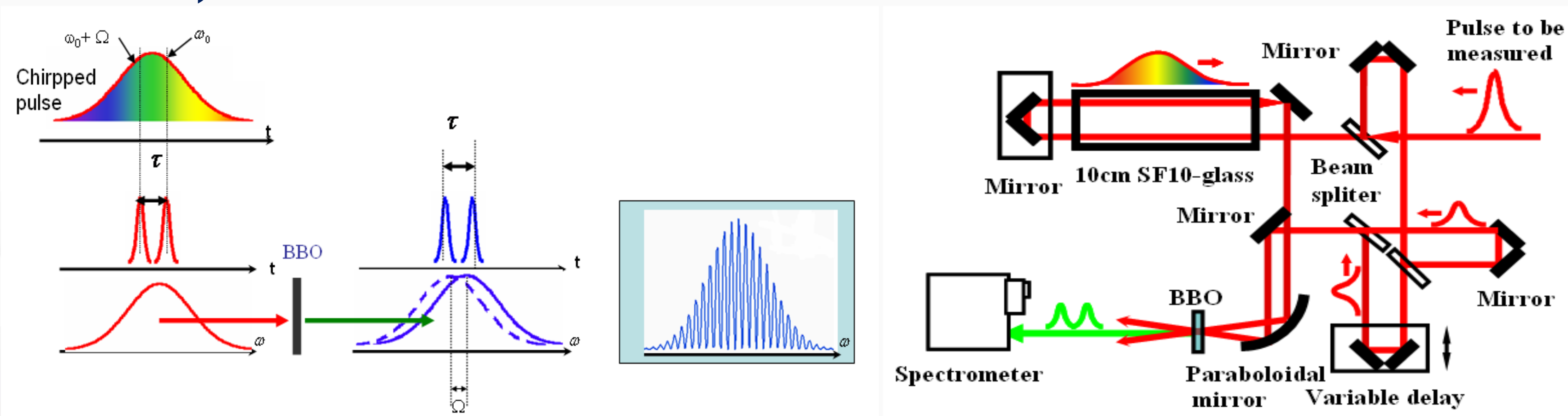
$P(t)e^{2\pi i\omega t+\varphi(t)}$

$S(\omega)e^{2\pi i\omega t+\varphi(\omega)}$

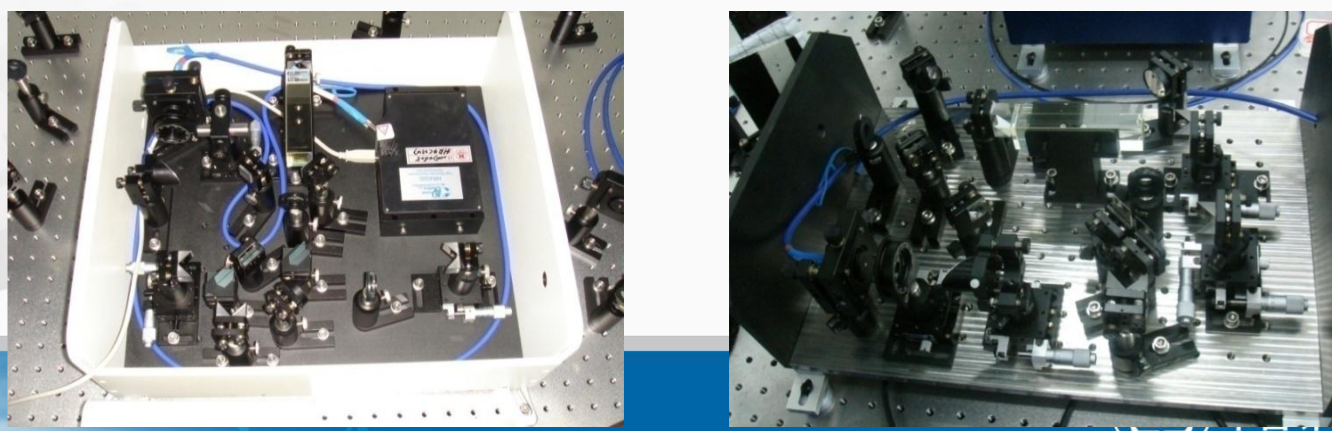
I. Characterization of ultrashort optical pulses

Pulse Measurement in the Frequency Domain:

Spectral Phase Interferometry for Direct-Electric field Reconstruction (SPIDER)

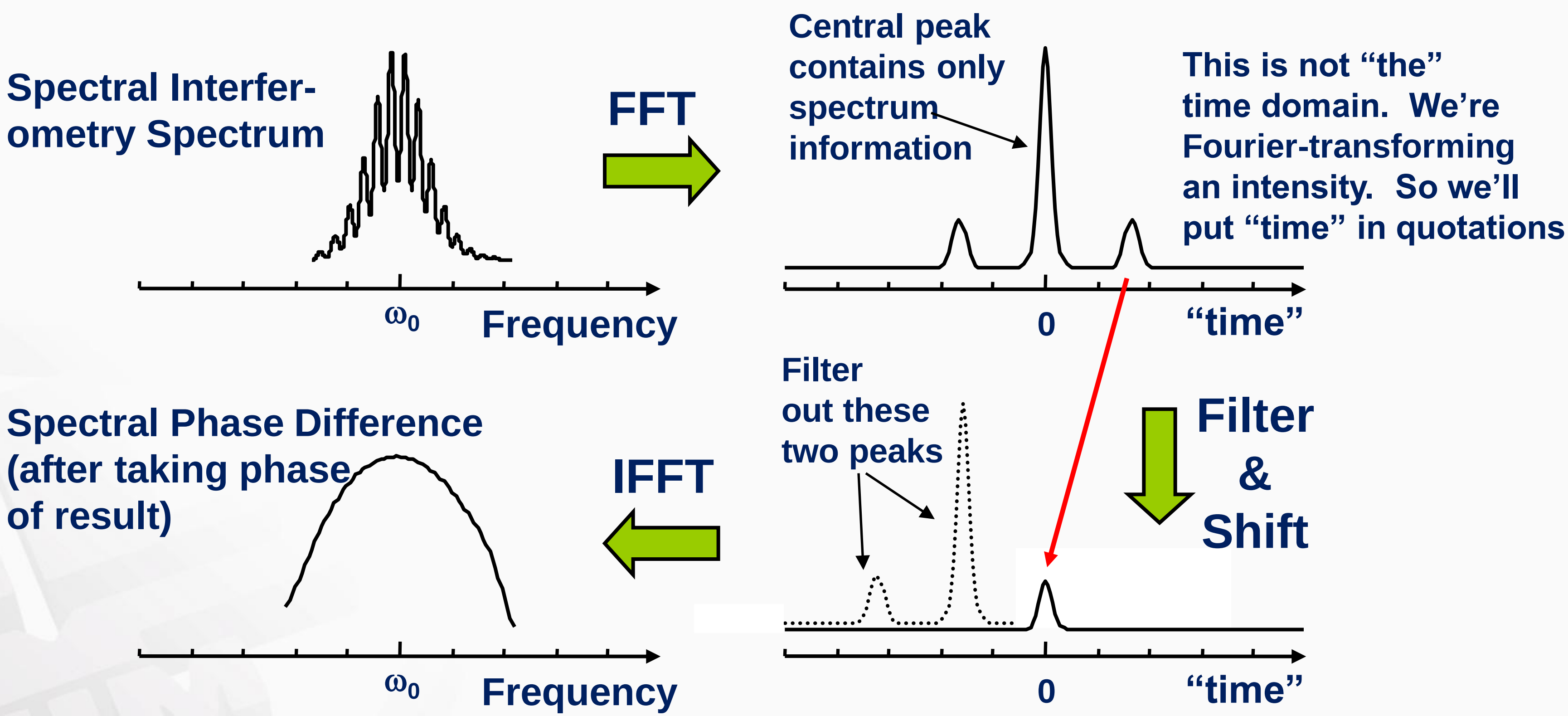


Schematic of SPIDER



Experimental setup of SPIDER

I. Characterization of ultrashort optical pulses

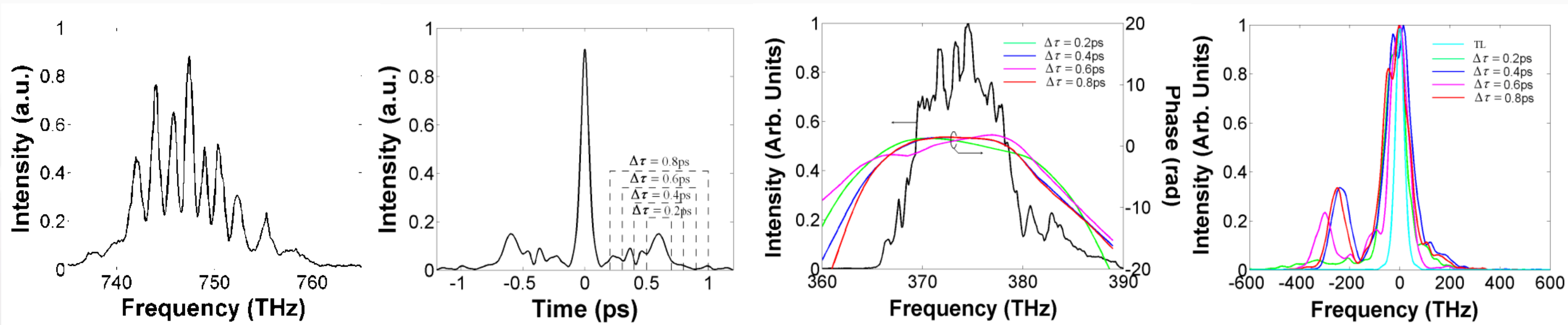


Subtracting off the spectral phase of the reference pulse yields the unknown-pulse spectral phase.

Interferogram Analysis, D. W. Robinson and G. T. Reid, Eds., Institute of Physics Publishing, Bristol (1993) pp. 141-193

I. Characterization of ultrashort optical pulses

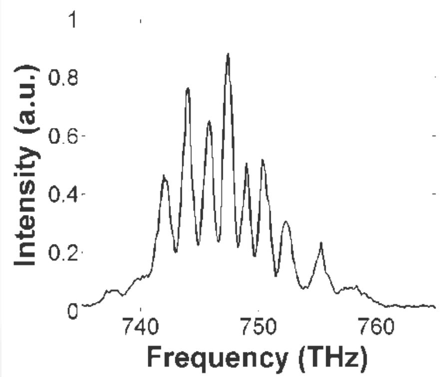
With traditional Fourier-transform, uncertainty of phase retrieval is arisen: Different filters produce different phase.



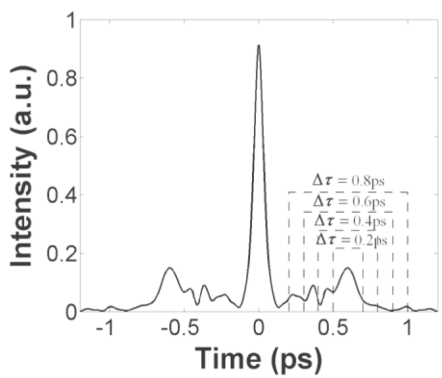
Spectral interferogram **FT and filters** **Retrieved spectral phases** **Reconstructed pulses**

I. Characterization of ultrashort optical pulses

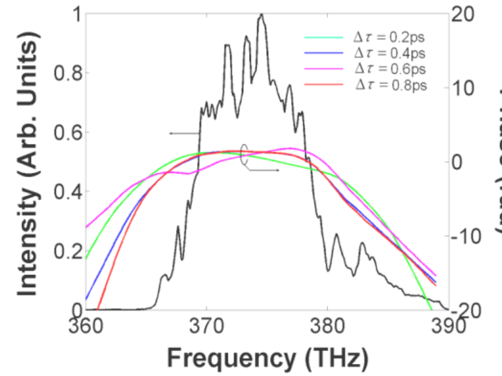
With traditional Fourier-transform, uncertainty of phase retrieval is arisen: Different filters produce different phase.



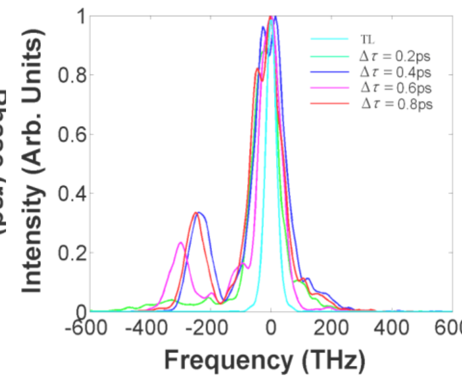
Spectral interferogram



FT and filters

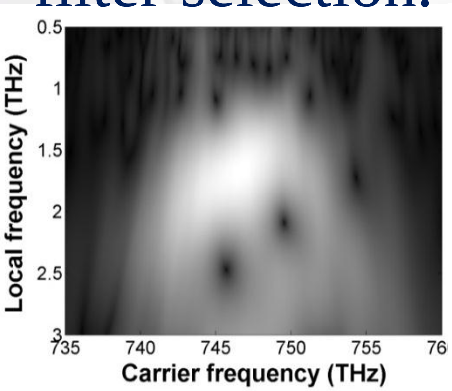


Retrieved spectral phases

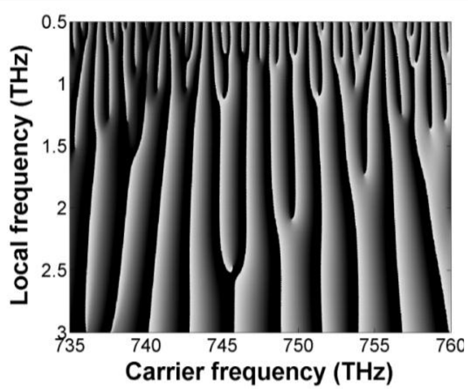


Reconstructed pulses

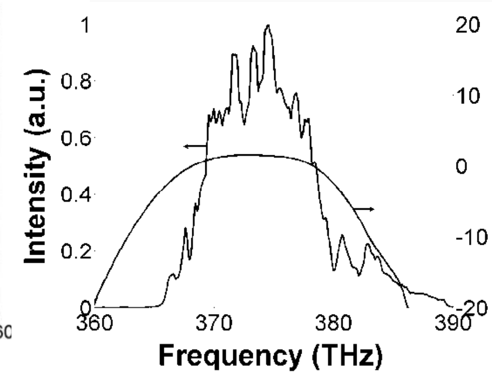
Wavelet-transform can retrieve a certain phase because there are no filter selection.



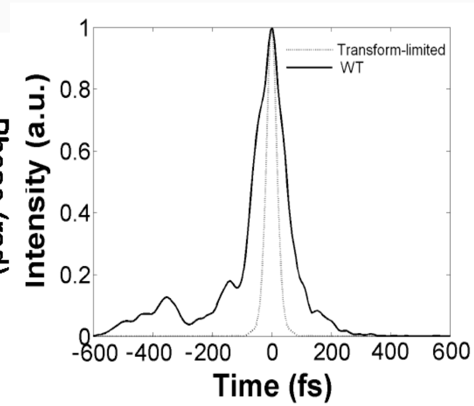
Magnitude of WT



Phase of WT



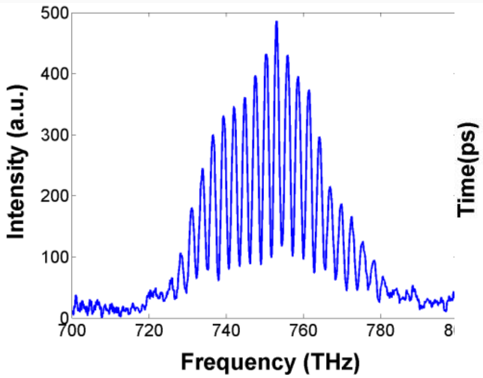
Retrieved spectral phase



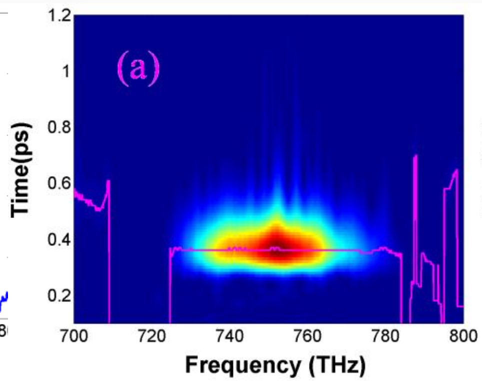
Reconstructed pulse

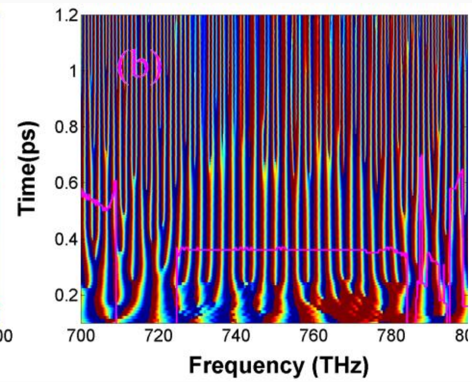
I. Characterization of ultrashort optical pulses

The simulated aucorrelation produced from the reconstructed pulse with retrieved phase agrees well with the measured one.

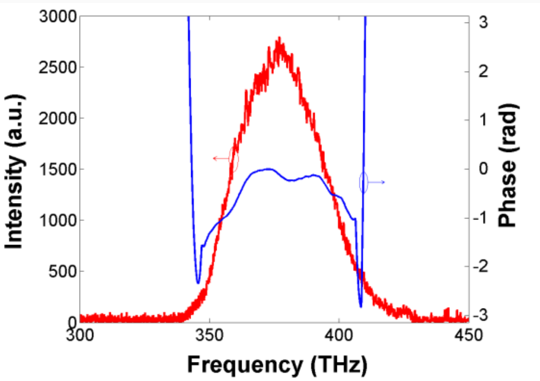


Measured spectral interferogram

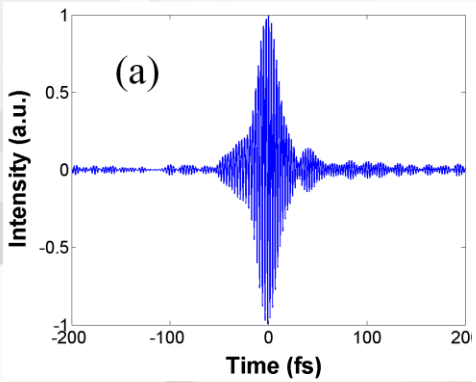




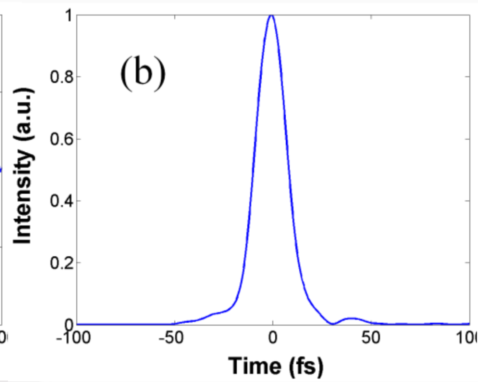
Results of wavelet-transform



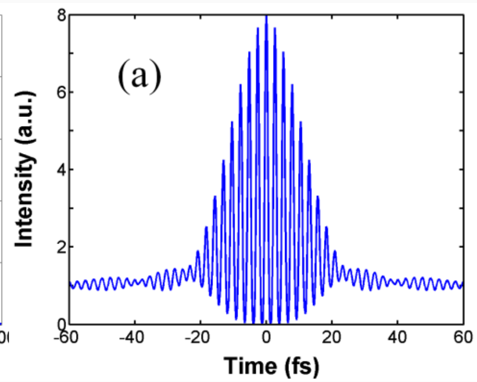
Spectrum and retrieved phase



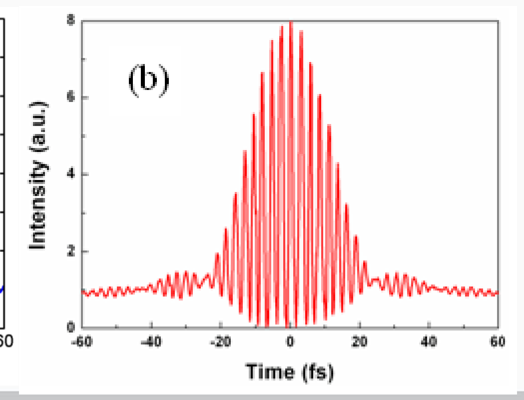
Reconstructed E-field



Reconstructed waveform



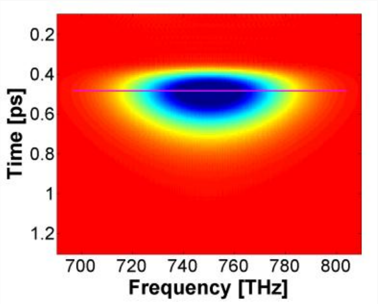
Simulated autocorrelation



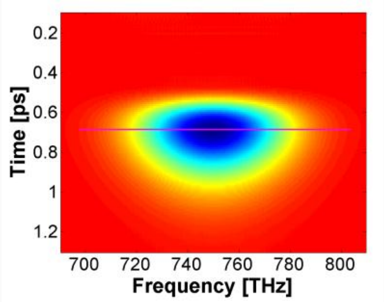
Measured autocorrelation

I. Characterization of ultrashort optical pulses

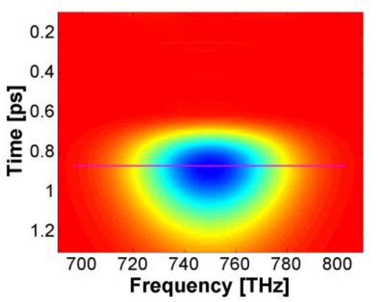
Some typical SPIDER trace



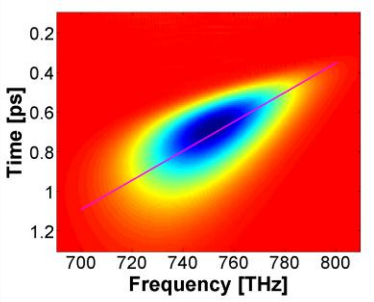
Negative quadratic phase



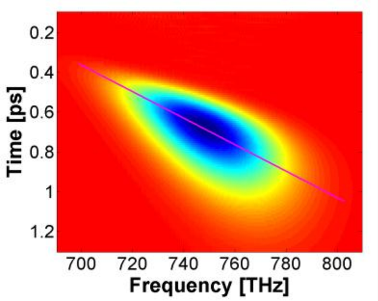
Zero phase



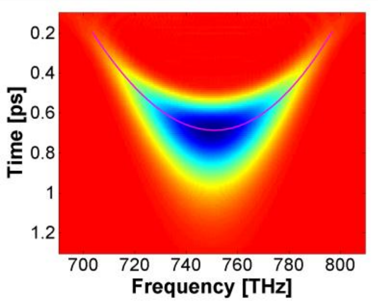
Positive quadratic phase



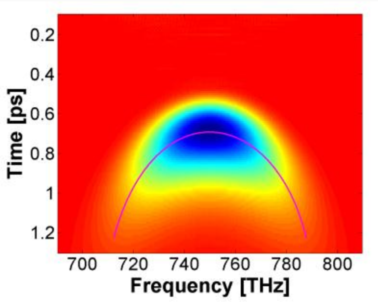
Negative cubic phase



Positive cubic phase



Negative quartic phase



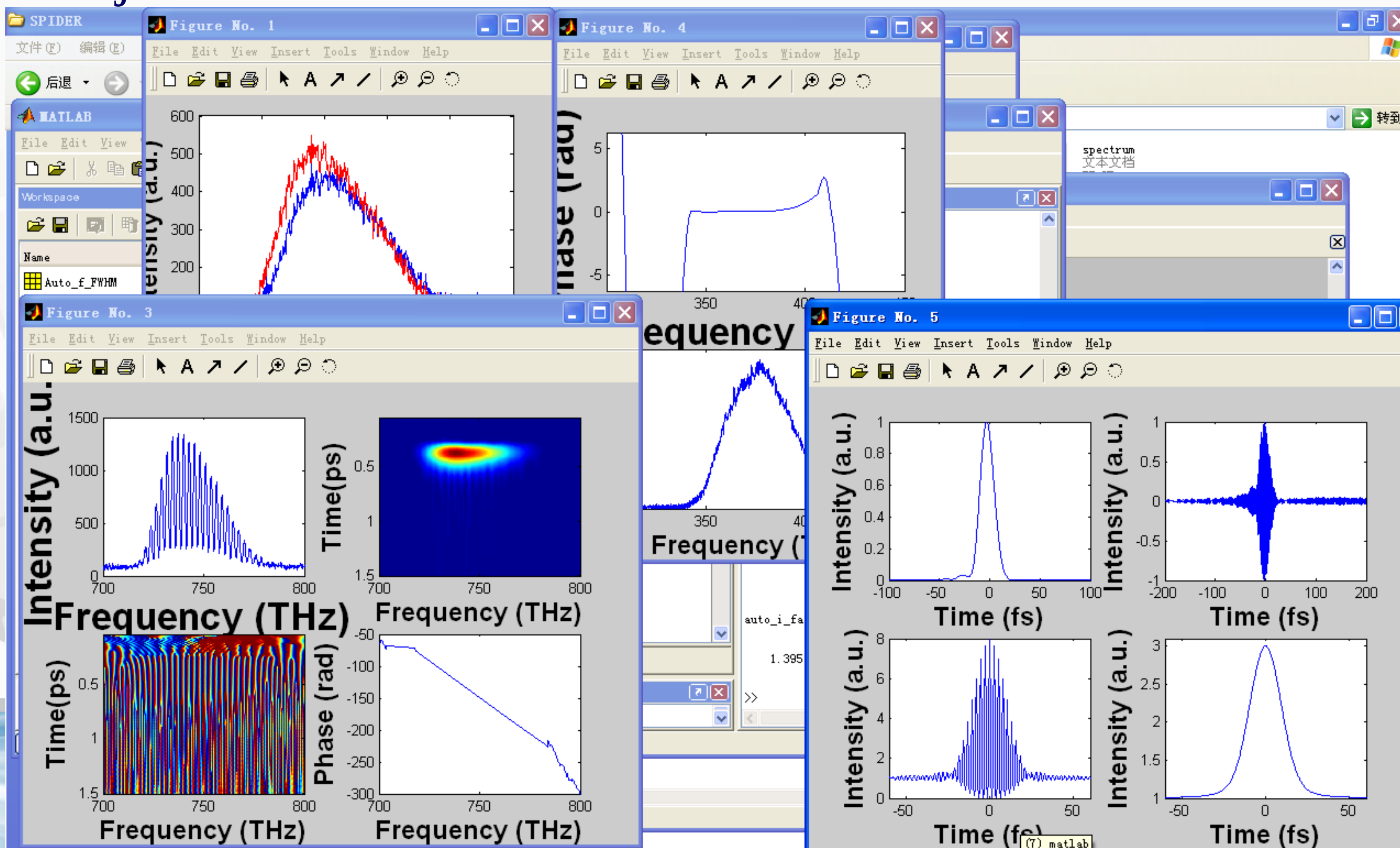
Positive quartic phase

I. Characterization of ultrashort optical pulses

Software for femtosecond optical pulses reconstruction:

—All the parameters were calculated automatically.

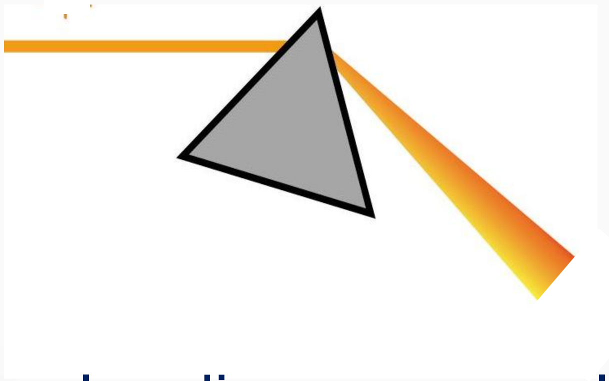
—Accuracy is improved, because manual parameter selection and filter adjustment is removed.



II. Chromatic dispersion measurement of optical elements

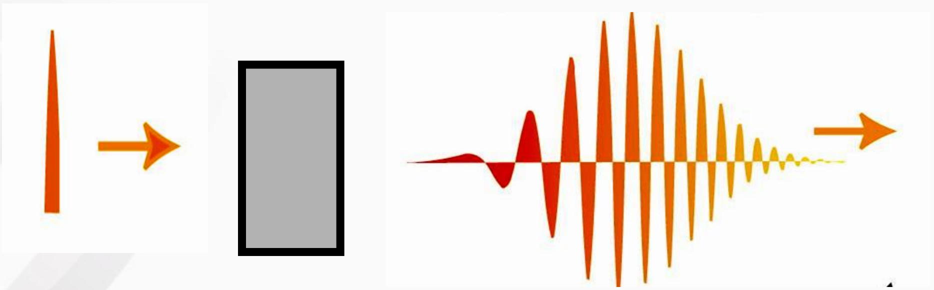
The dependence of the refractive index on wavelength has two effects on a pulse, one in space and the other in time.

Dispersion disperses a pulse in space (angle):



"Angular dispersion"
$dn/d\lambda$

Dispersion also disperses a pulse in time:



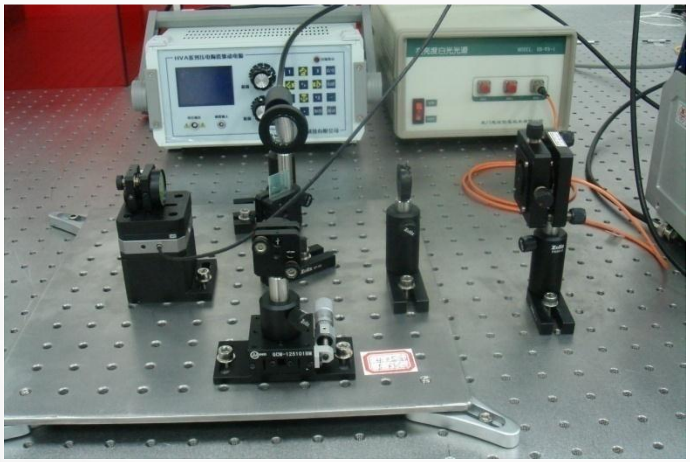
"Chirp"
$d^2n/d\lambda^2$

Both of these effects play major roles in ultrafast optics.

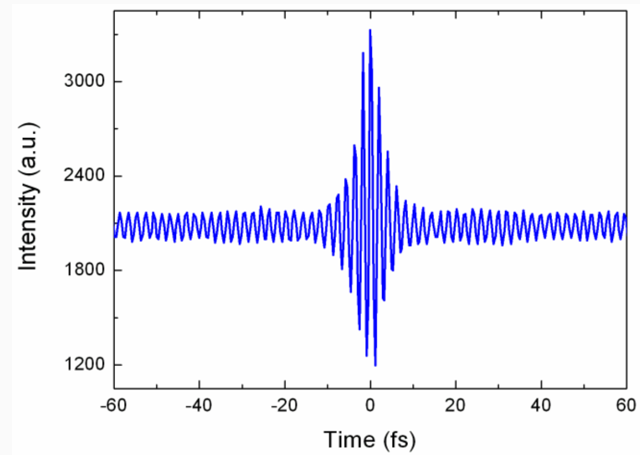
II. Chromatic dispersion measurement of optical elements

Chromatic dispersion measurement

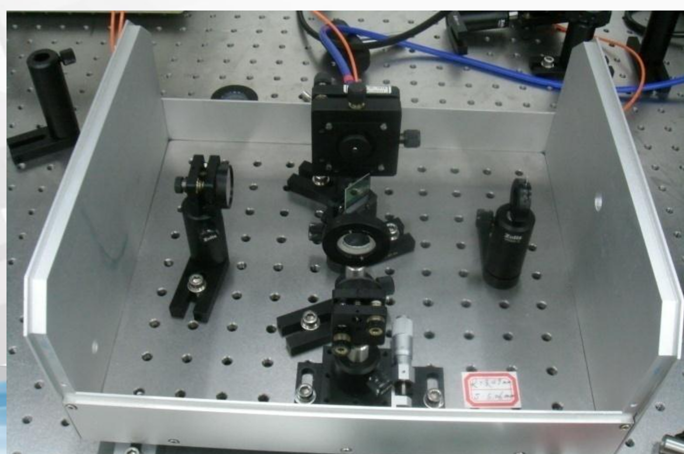
--White light interferometry (WLI)



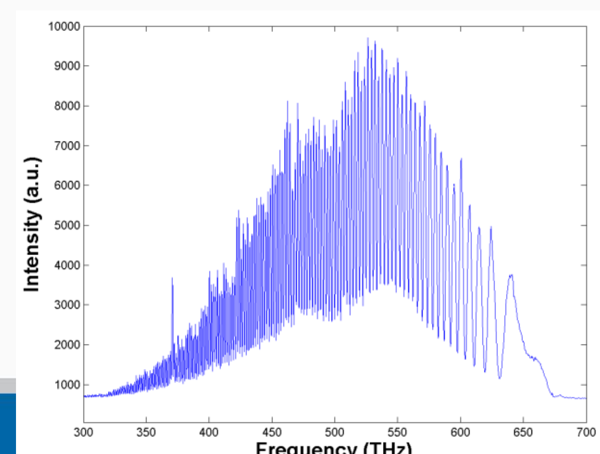
Time domain WLI



Time domain interferogram



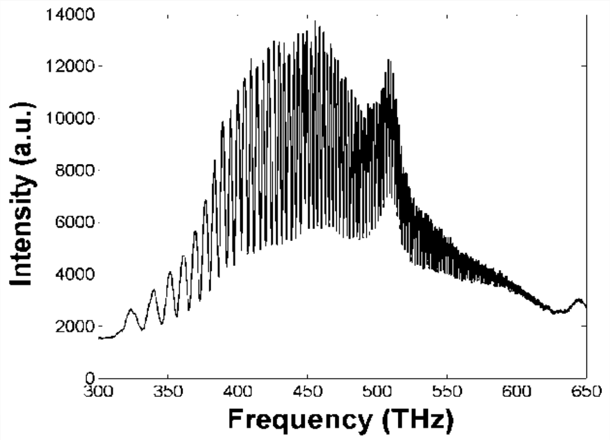
Frequency domain WLI



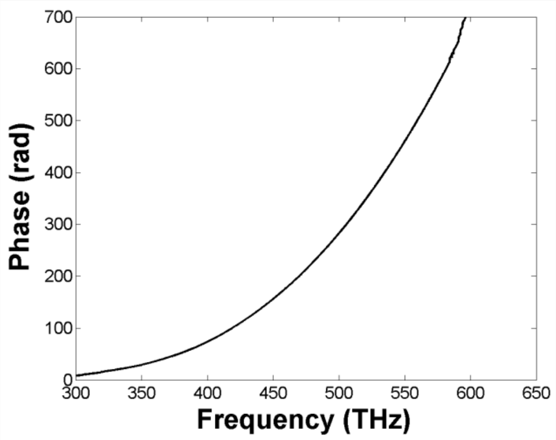
Frequency domain interferogram

II. Chromatic dispersion measurement of optical elements

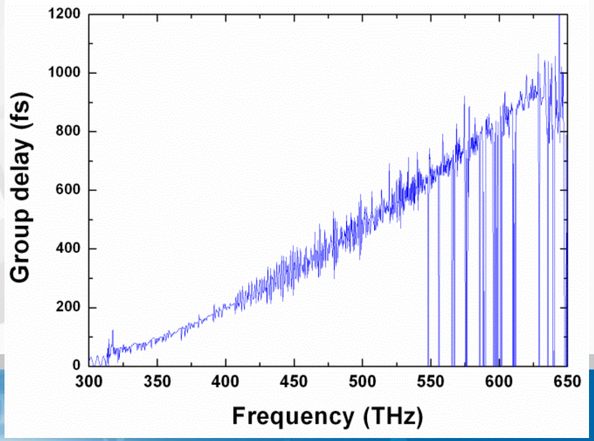
Traditional CD extraction retrieve spectral phase first, and get GD and GDD from one and two times of phase differentiations.



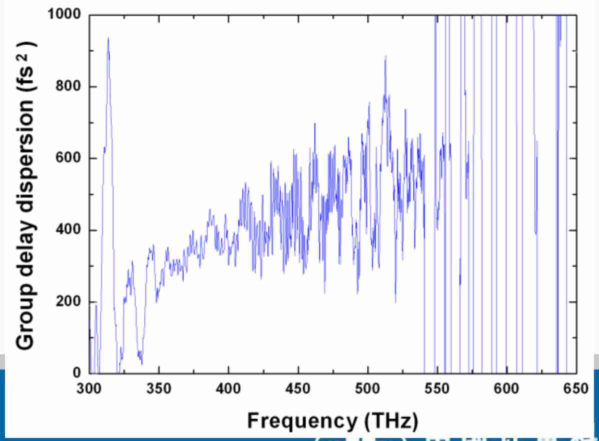
Spectral interferogram of Fused silica



Extracted spectral phase



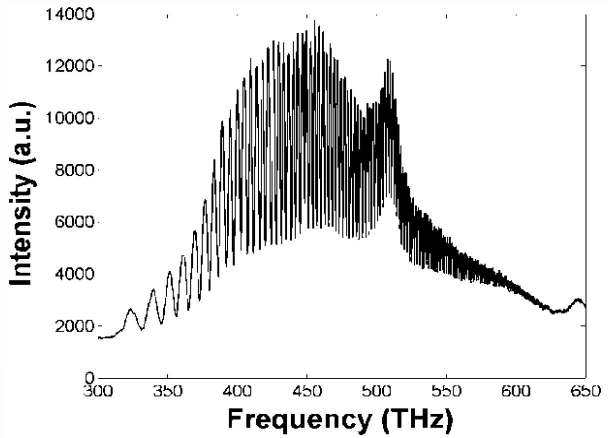
Measured GD of Fused silica



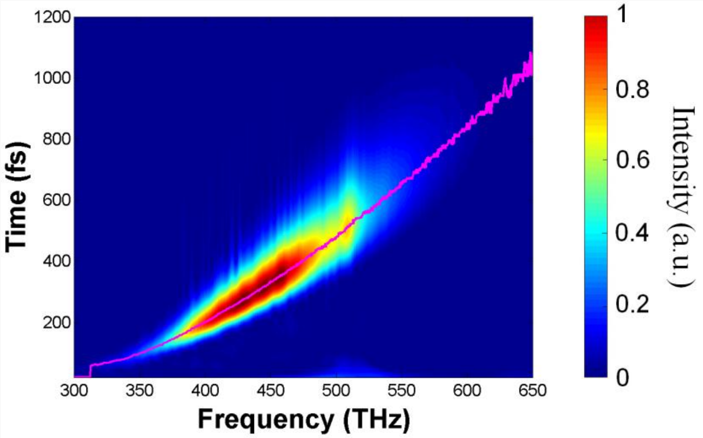
Measured GDD of Fused silica

II. Chromatic dispersion measurement of optical elements

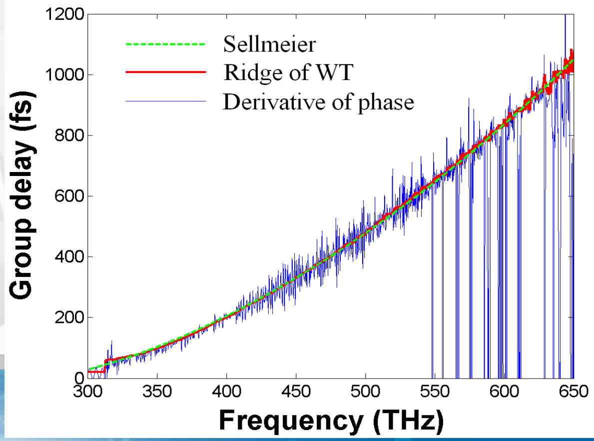
Direct read GD greatly reduced the noise produced from phase derivative.



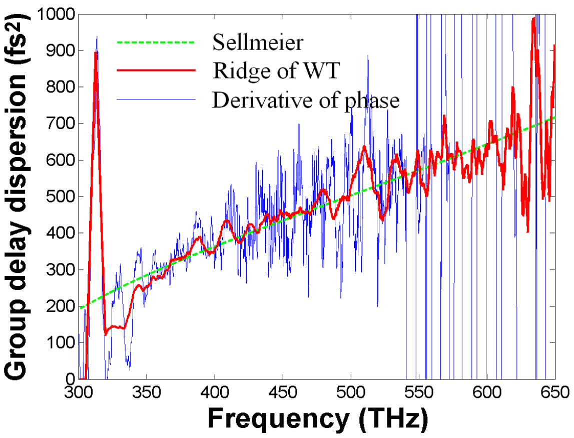
Spectral interferogram of Fused silica



WT of the spectral interferogram



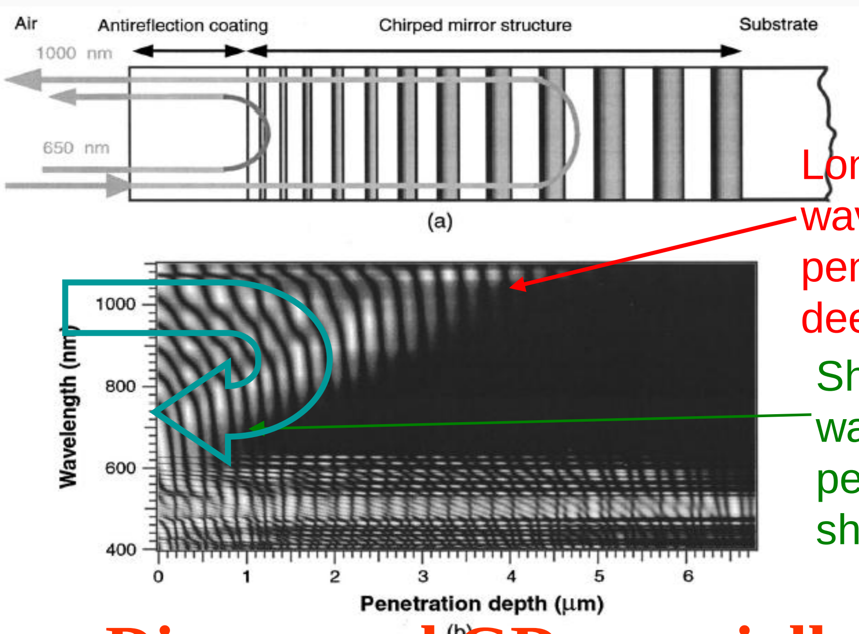
Measured GD of Fused silica



Measured GDD of Fused silica

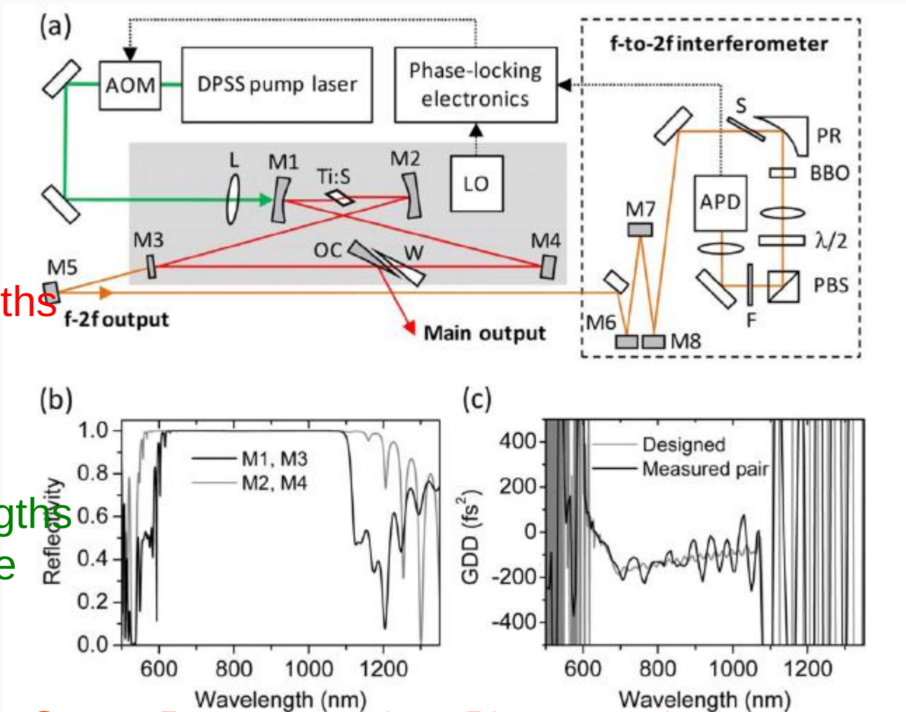
II. Chromatic dispersion measurement of optical elements

Chirped mirror coatings offer an alternative to prisms and gratings for dispersion compensation.



Long wavelengths penetrate deep

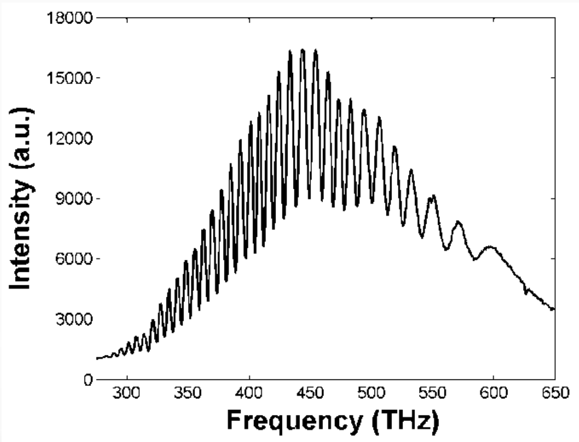
Short wavelengths penetrate shallow



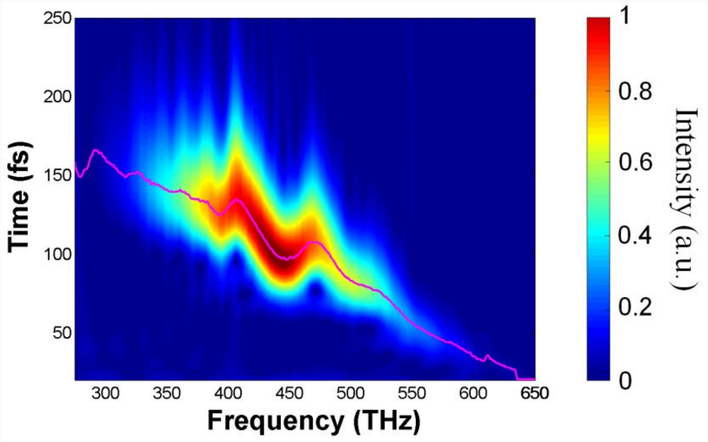
Direct read GD especially suit for chromatic dispersion extraction of chirped mirror or fiber, because curve fitting is not available in these circumstance.

II. Chromatic dispersion measurement of optical elements

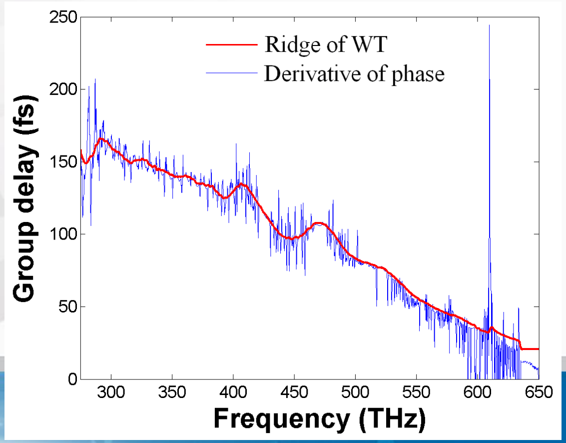
Direct read GD for chromatic dispersion extraction of chirped mirror.



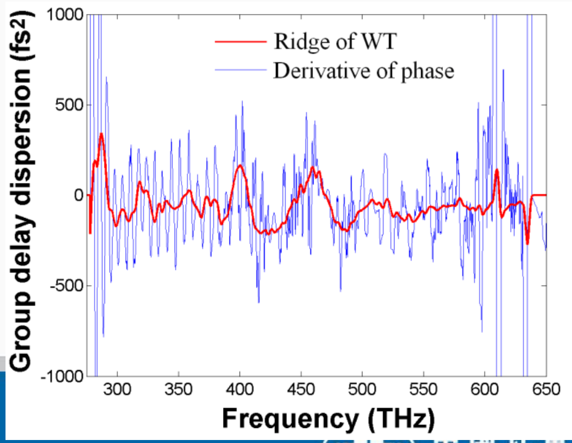
Spectral interferogram of Chirped mirror



WT of the spectral interferogram



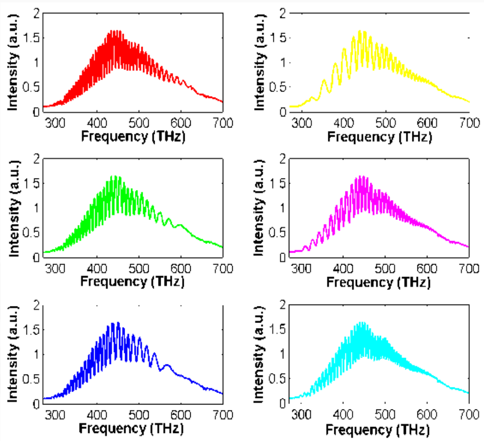
Measured GD of Chirped mirror



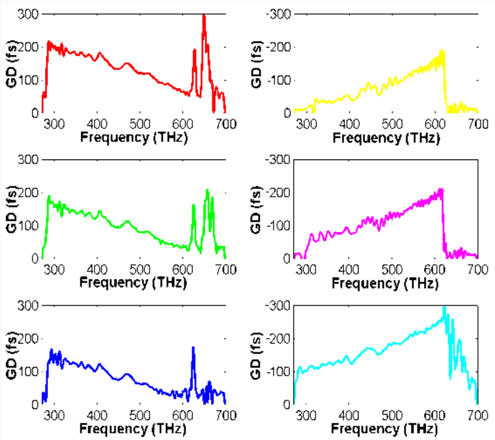
Measured GDD of Chirped mirror

II. Chromatic dispersion measurement of optical elements

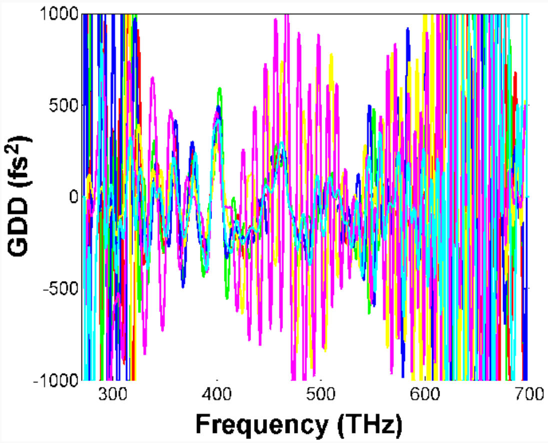
Chromatic dispersion extracted from different optical delays can agree well with direct read GD.



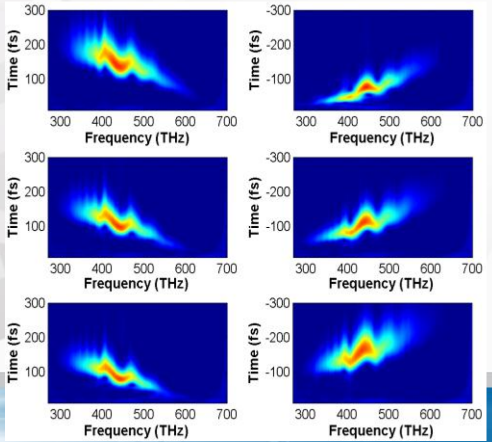
SI with different delays



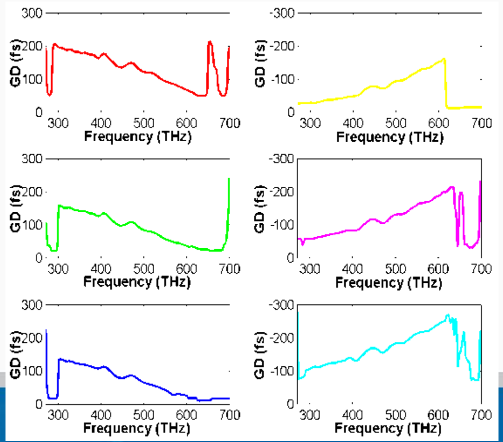
GD with phase derivative



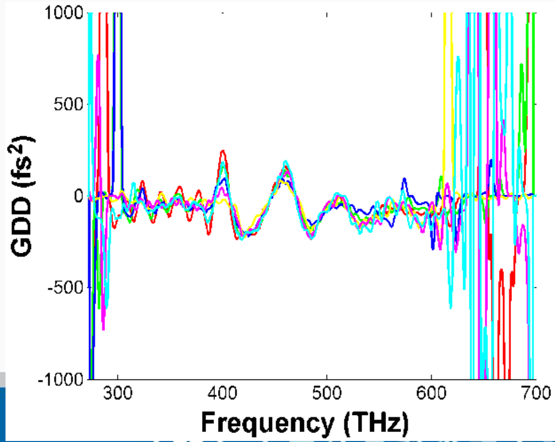
GDD with phase derivative



Time-frequency distribution of SI



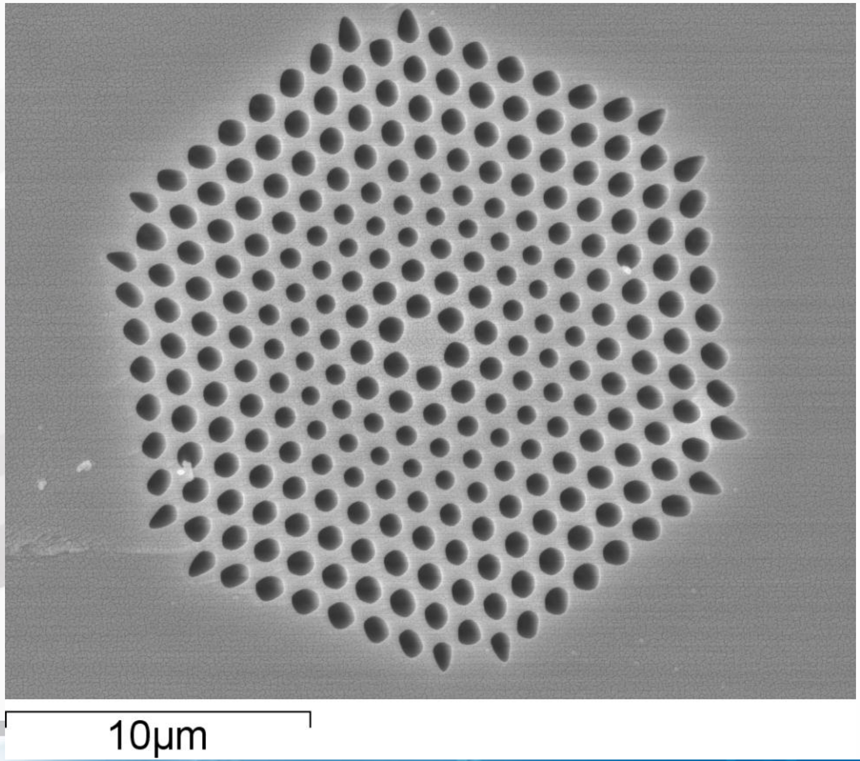
Direct read GD



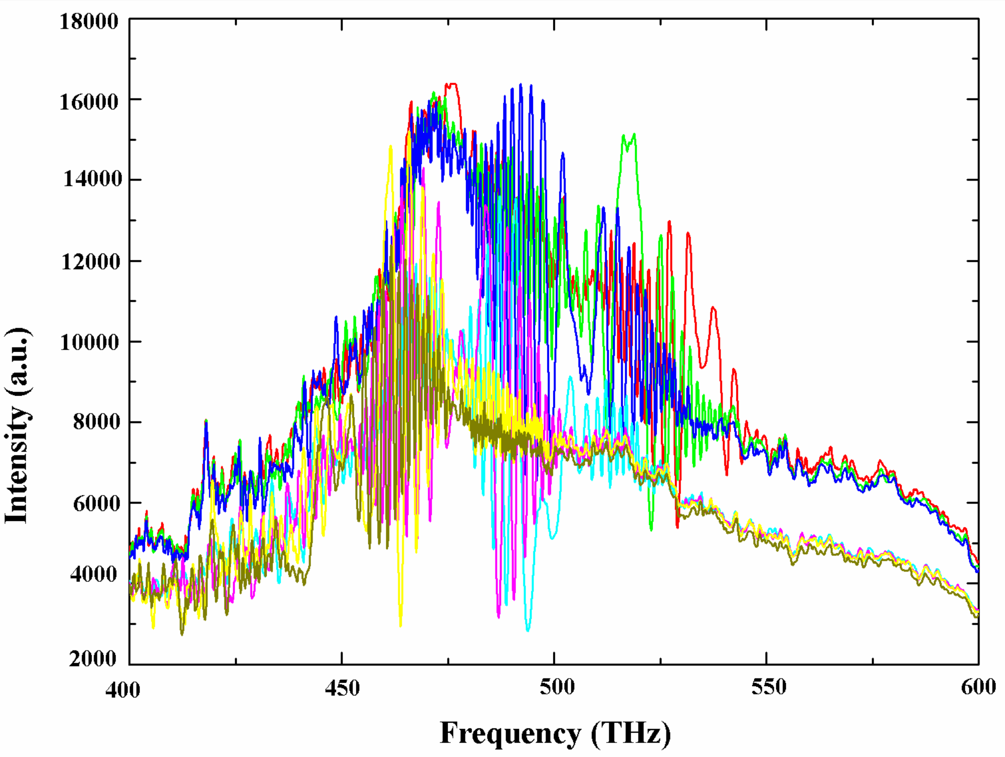
Direct read GDD

II. Chromatic dispersion measurement of optical elements

Chromatic dispersion of photonic crystal fiber (also name micro-structure fiber) is very large and complex, which can be extracted from muti-sectional measurement of spectral interferograms and connected the directly read GD.



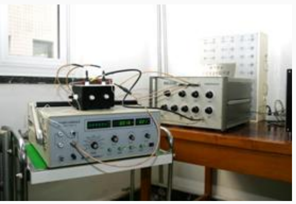
Section view of PCF



Measured SIs

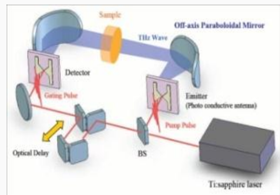
III. Terahertz generation and measurement

Terahertz (THz): Frequency: 0.1～10 THz;
Wavelength: 3mm～10μm

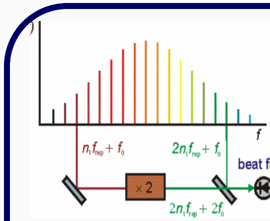


Electricity metrology

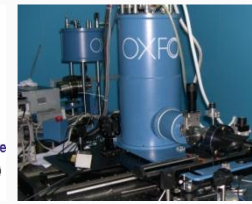
Wireless and microwave metrology



Terahertz metrology



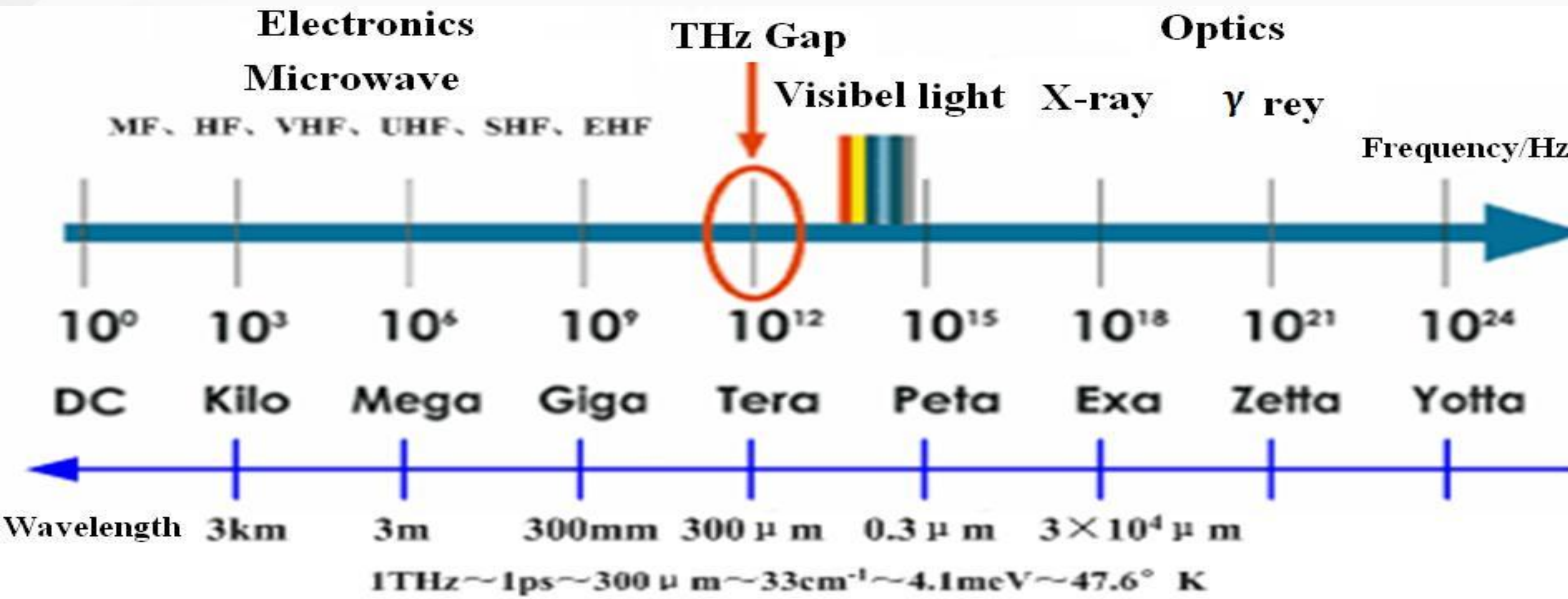
Time and frequency metrology



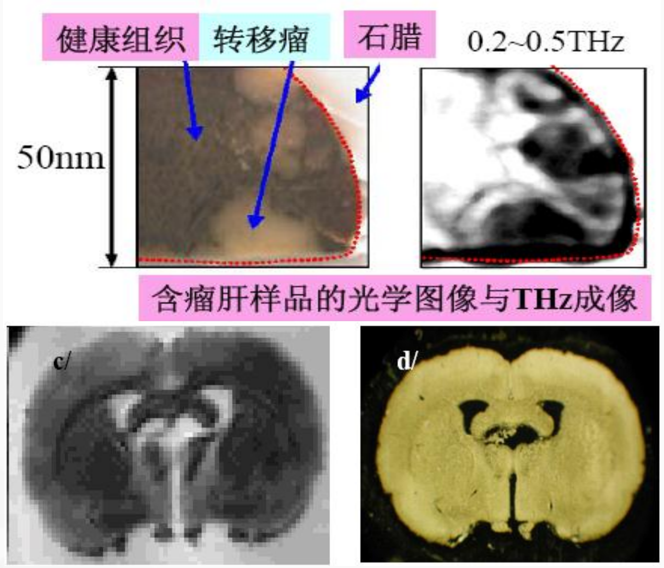
Optical radiation metrology

Length metrology

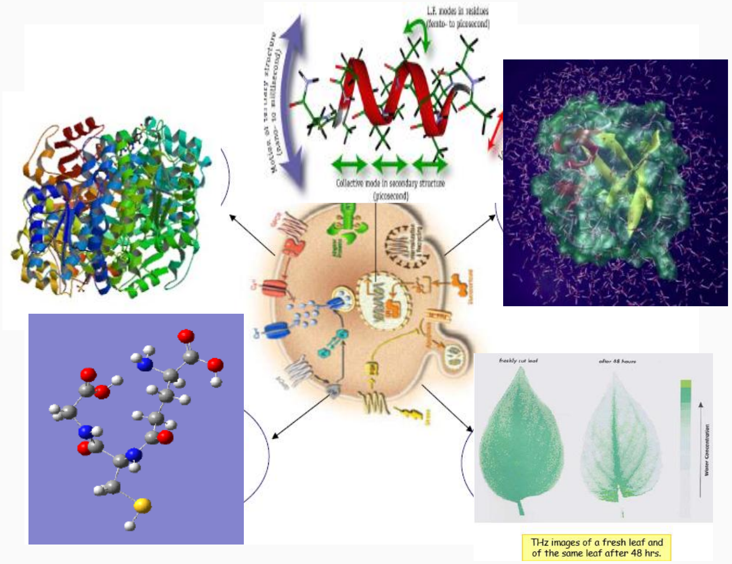
X-ray metrology



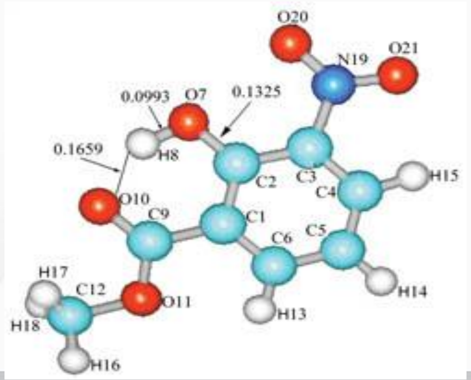
III. Terahertz generation and measurement



Medical imaging



DNA and life science research

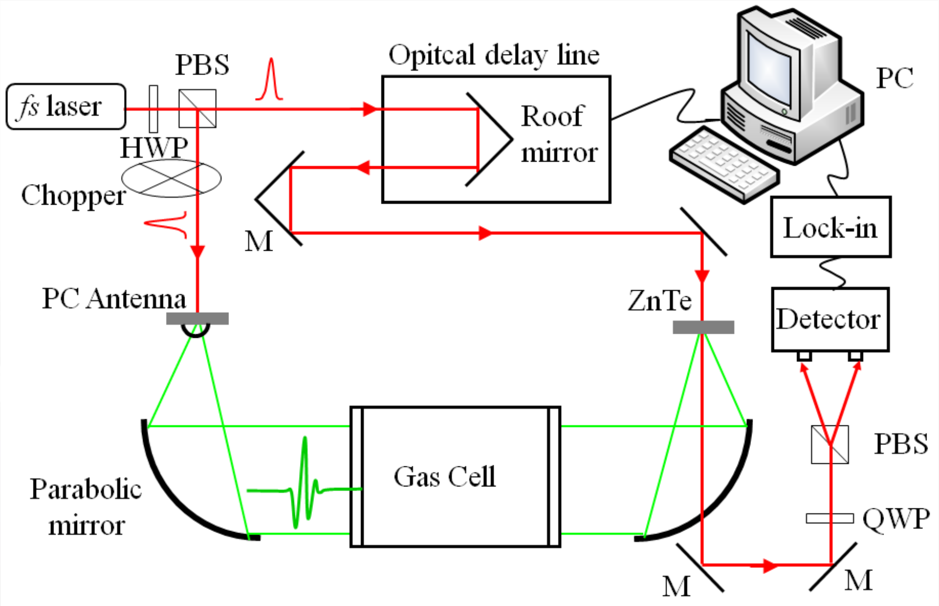


Medicine component analysis

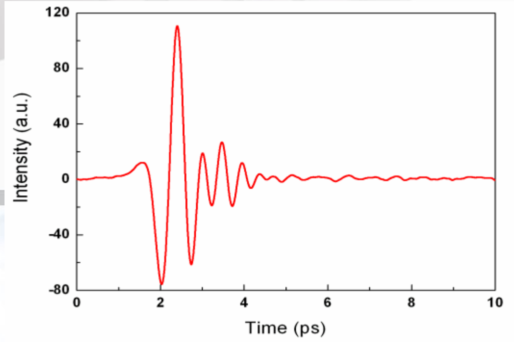
Security check

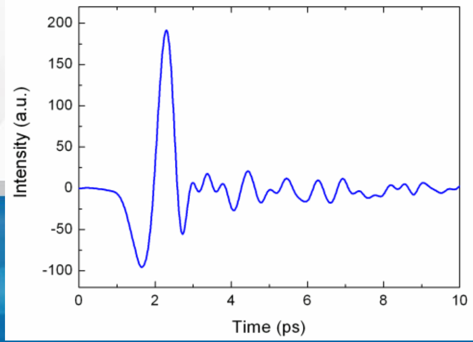
III. Terahertz generation and measurement

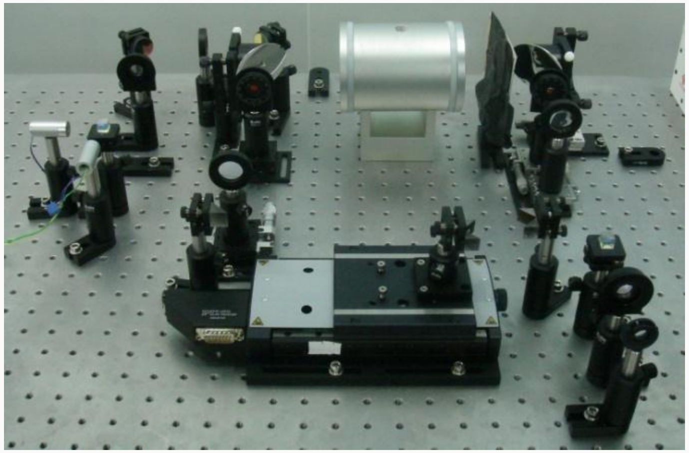
Home-made terahertz time-domain spectrometer



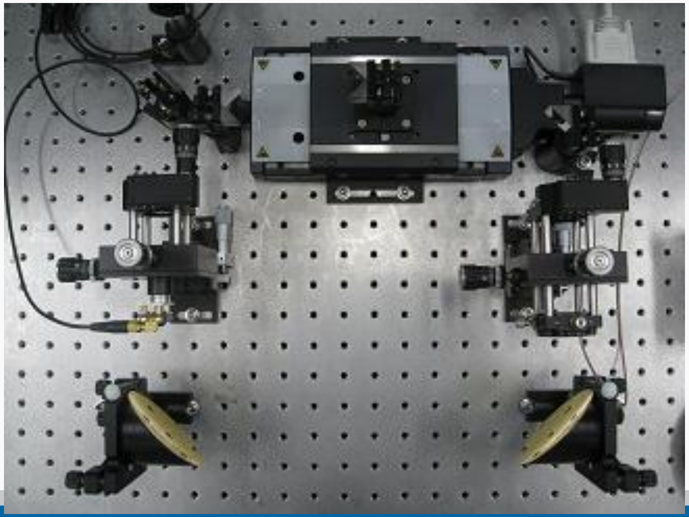
Schematic of THz TDS







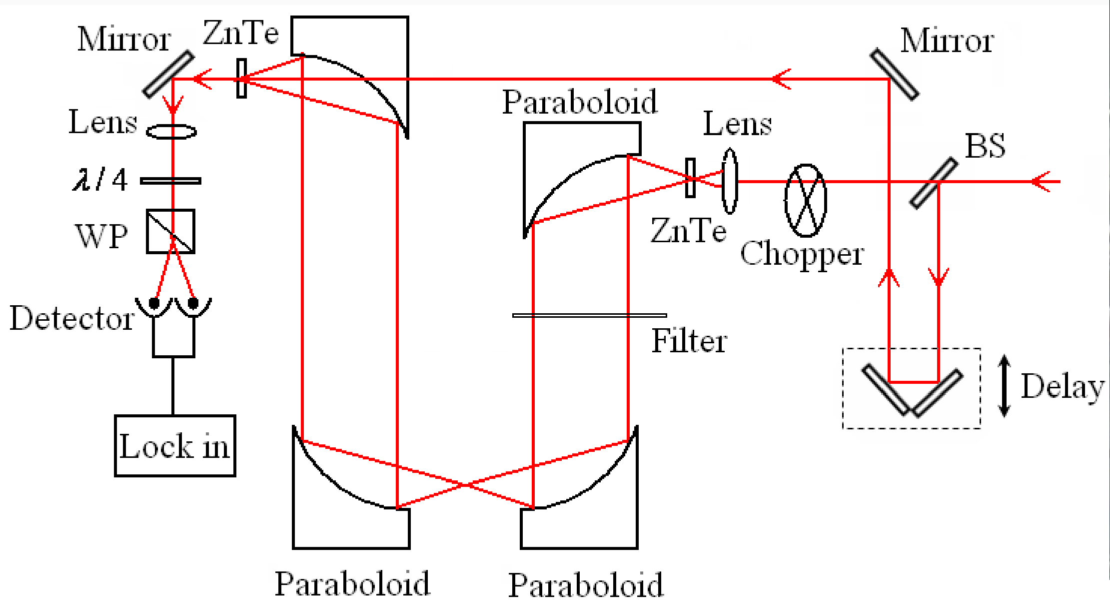
Terahertz generation and detection with zinc telluride crystral

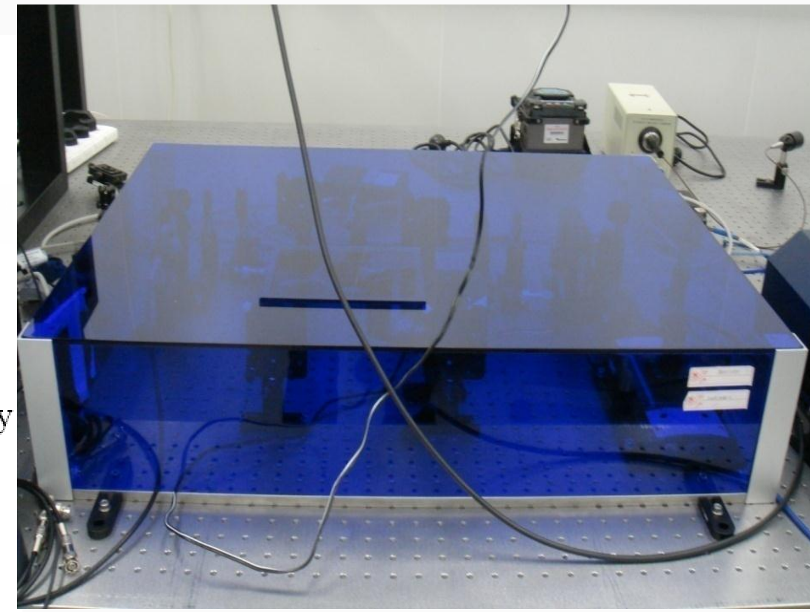


Terahertz generation and detection with photoconductive antenna

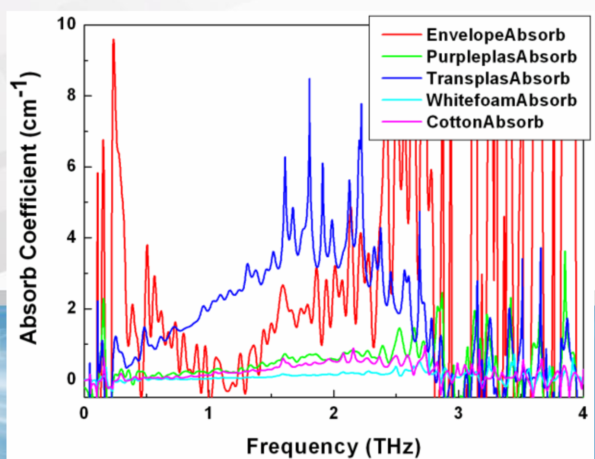
III. Terahertz generation and measurement

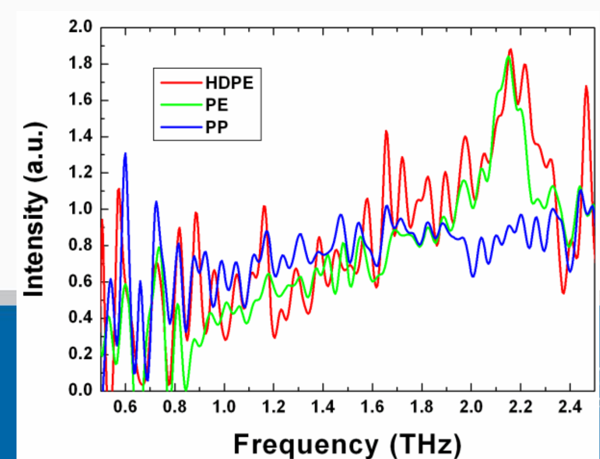
A 8-*f* terahertz time-domain spectroscopy system





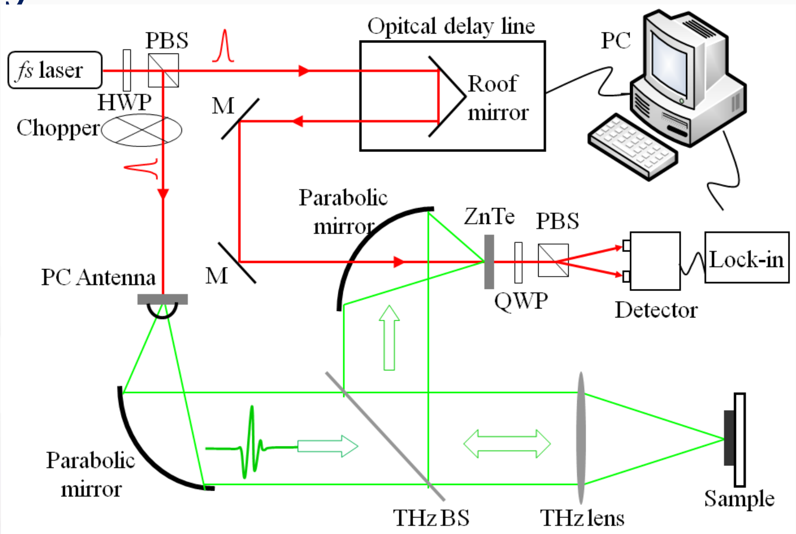
Home-made 8-*f* THz time-domain spectrometer

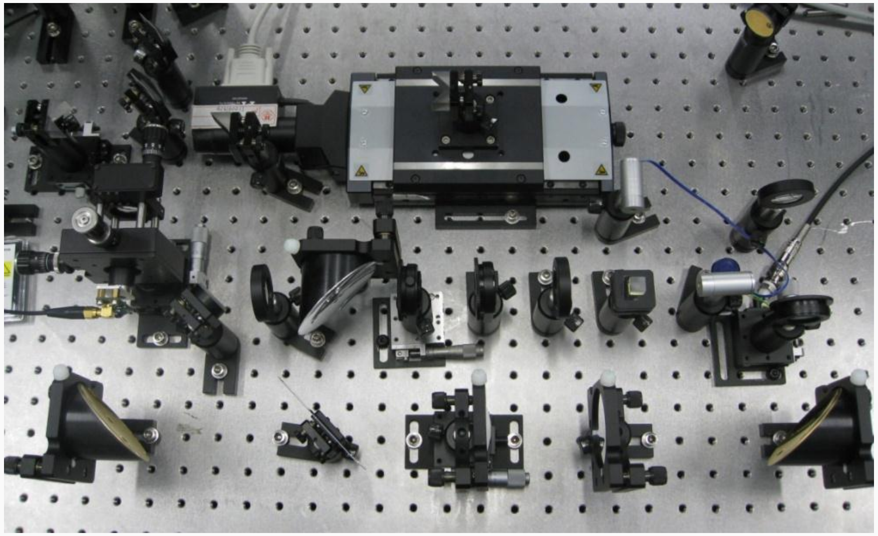


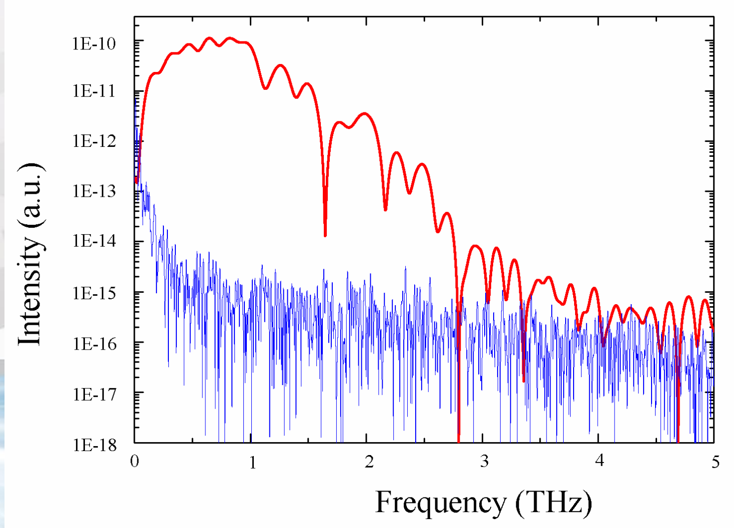


III. Terahertz generation and measurement

A reflection-type terahertz time-domain spectroscopy system







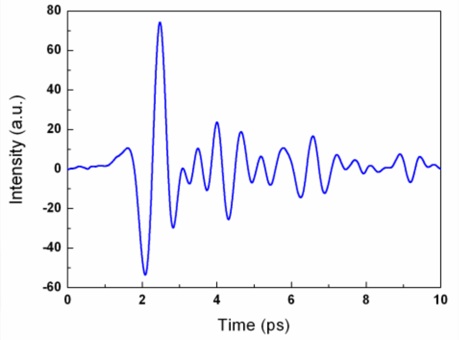
Home-made reflection-type THz time-domain spectrometer

Spectra of signal and noise

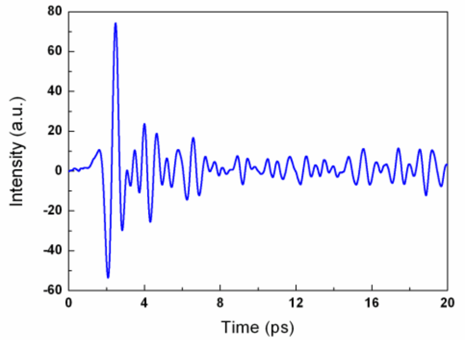
III. Terahertz generation and measurement

Joint time-frequency analysis of THz spectra

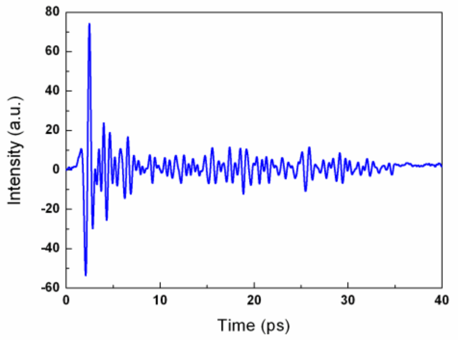
THz waveforms in ambient atmosphere



THz in 10 ps length

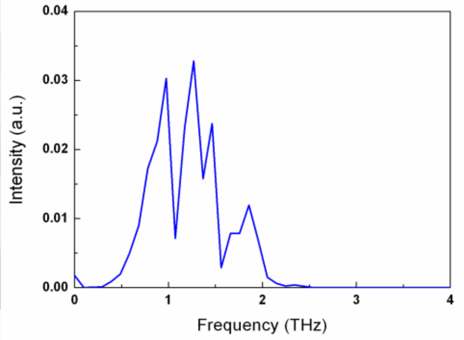


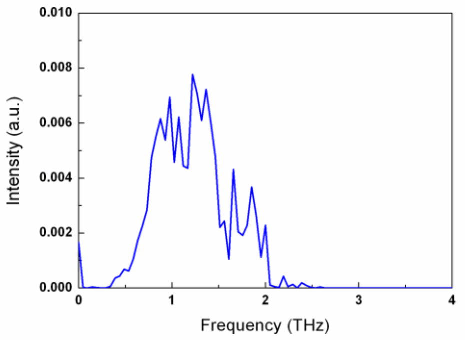
THz in 20 ps length

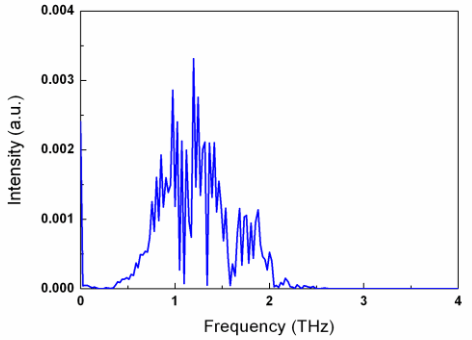


THz in 10 ps length

Fourier transform of THz spectra



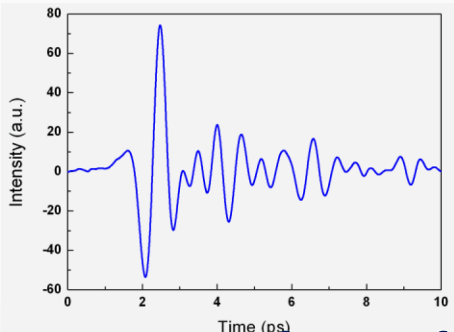


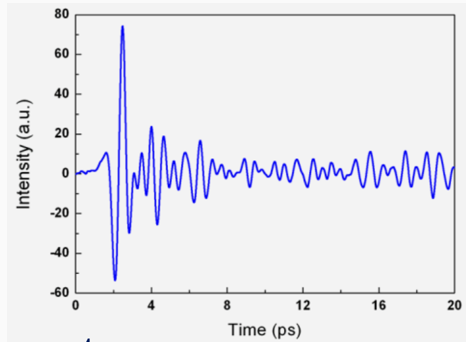


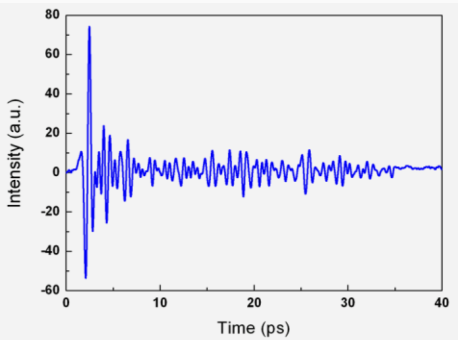
III. Terahertz generation and measurement

Joint time-frequency analysis of THz spectra

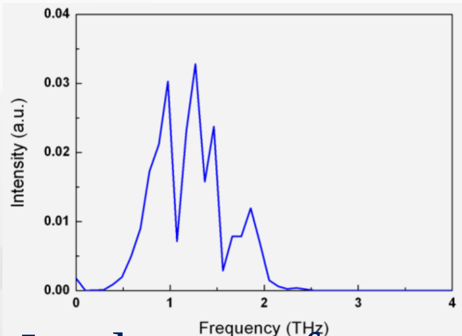
THz waveforms in ambient atmosphere

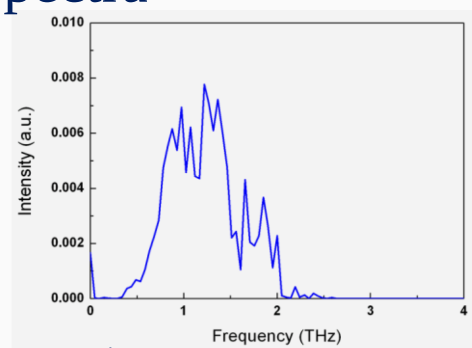


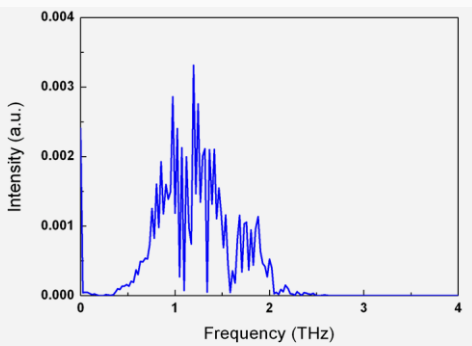




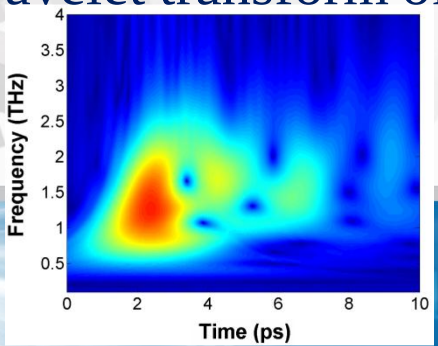
Fourier transform of THz spectra

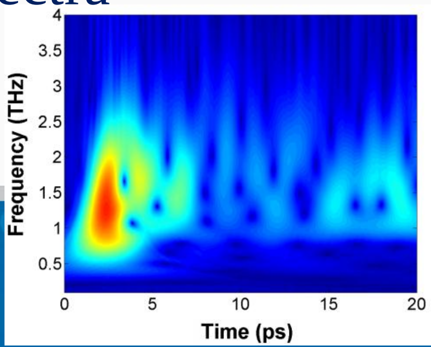


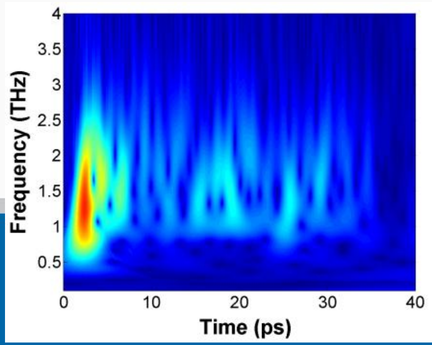




Wavelet transform of THz spectra







IV. Summarization

- We have home-made a set of instrument for ultrashort optical pulses and terahertz radiation measurement:

—Autocorrelator

—SPIDER

—White light interferometer

—Transmission-type THz-TDS

—Reflection-type THz-TDS

- We have introduced some new techniques for ultrashort optical pulses phase retrieval and terahertz spectrum analysis, the accuracy of measurements was improved:

—WT for spectral phase retrieval

—GD direct read from time-frequency ridge

—Joint time and frequency analysis of terahertz wave

Selected publications

1. **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," ***Optics Letters* 33**, 2855-2857 (2008).
2. **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," ***Optics Express* 13**, 2120-2126 (2005).
3. **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," ***Optics Express* 17**, 6038-6043 (2009).
4. **Y. Deng**, C. Wang, L. Chai, and Z. Zhang, "Determination of Gabor wavelet shaping factor for accurate phase retrieval with wavelet-transform," ***Applied Physics B* 81**, 1107-1111 (2005).
5. **Y. Deng**, W. Yang, and Z. Zhang, "Shape selection of wavelets for accurate chromatic dispersion measurement of white-light spectral," ***Applied Physics B* 98**, 347-351 (2010).
6. **Y. Deng**, Z. Wu, S. Cao, L. Chai, C. Wang, and Z. Zhang, "Spectral phase extraction from spectral interferogram for structured spectrum of femtosecond optical pulses," ***Optics Communications* 268**, 1-6 (2006).
7. **Y. Deng**, S. Cao, J. Yu, T. Xu, Q. Fan, C. Wang, and Z. Zhang, "Wavelet-transform analysis for carrier-envelope phase extraction of amplified ultrashort optical pulses," ***Optics and Lasers in Engineering* 47**(12), 1362-1365 (2009).
8. **Y. Deng**, Z. Wu, S. Cao, L. Chai, C. Wang, and Z. Zhang, "Characterization of femtosecond optical pulses with wavelet-transform of spectrum shearing interferogram," ***Ultrafast Optics V*** (Springer-Verlag, 2007).
9. **Y. Deng**, Q. Xing, L. Lang, S. Li, L. Chai, C. Wang, and Z. Zhang, "Water vapor absorption spectroscopy in terahertz range using wavelet-transform analysis," ***Ultrafast Optics V*** (Springer-Verlag, 2007).

Thank you very much for your attention!

yqdeng@nim.ac.cn

中国计量科学研究院
National Institute of Metrology