Fourier-Transform Terahertz Spectroscopy Using Terahertz Frequency Comb

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Abstract: We demonstrate high-resolution Fourier-transform terahertz spectroscopy using two terahertz frequency combs with stabilized different repetition frequencies without a mechanical time delay tool.

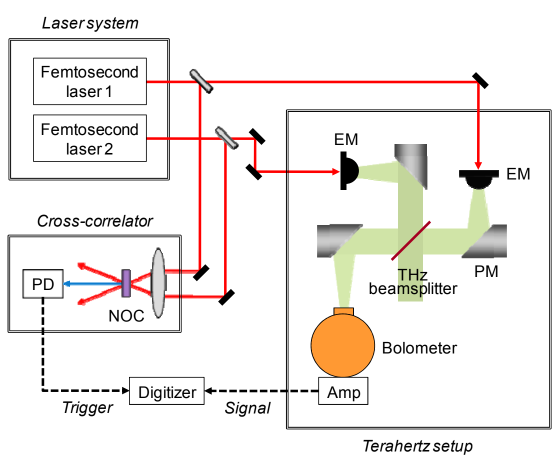
OCIS codes: (300.6300) Spectroscopy, Fourier transforms; (300.6495) Spectroscopy, terahertz

1. Introduction

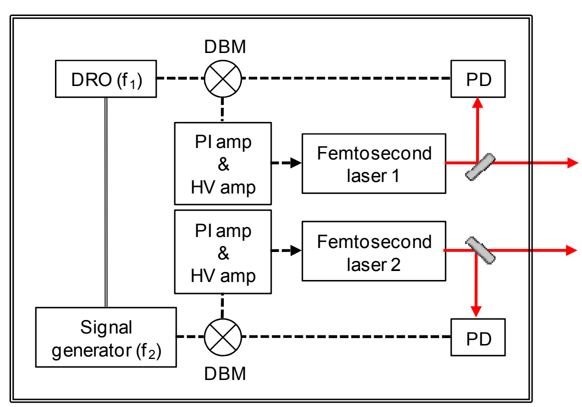
Conventional Fourier-transform (FT) spectroscopy is widely used for characterization of materials especially in the infrared (IR) range. One source and an interferometer are used to measure an interferogram in the FT spectroscopy, where one arm of the interferometer has a moving mirror to scan a time delay. Also, frequency-comb FT spectroscopy has been demonstrated in the IR range, in which two IR pulsed sources with non-stabilized different repetition frequencies are used so that a time delay is scanned without a mechanical time delay stage [1,2]. In this paper, we demonstrate high-resolution FT terahertz (FT-THz) spectroscopy using two terahertz (THz) frequency combs with stabilized different repetition frequencies.

2. Experimental methods

We developed an experimental setup for high-resolution FT-THz spectroscopy using THz frequency comb. Fig. 1(a) shows a schematic diagram of our experimental configuration. We employ a laser system comprising two femtosecond lasers and two phase-locked loops for stabilization of repetition frequencies of femtosecond lasers, as depicted in detail in Fig. 1(b). The repetition frequencies are actively stabilized by locking the tenth harmonics of the repetition frequencies to reference signals from a dielectric resonance oscillator (1 GHz) and a signal generator (1 GHz - 1 kHz), respectively. Using the optical cross-correlation method, it is confirmed that a relative timing jitter between optical pulses from the two femtosecond lasers is lower than 280 fs over the entire time delay window. Two THz frequency combs are generated at repetition frequencies of 100 MHz and 100 MHz – 100 Hz from two photoconductive antennas irradiated by optical pulses from the laser system. The THz frequency combs are combined by a THz beamsplitter that is a 2 μm thick nitrocellulose film with a metallic coating providing ~25 %



(a)



(b)

Fig. 1. Schematic diagrams of our experimental configuration (a) and laser system (b). NOC: nonlinear optical crystal, PD: amplified photodetector, EM: THz emitter (photoconductive antenna here), PM: off-axis parabolic mirror, Amp: amplifier, PI amp: proportional-integral amplifier, HV amp: high-voltage amplifier, DBM: double balanced mixer, and DRO: dielectric resonance oscillator.

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reflection and ~25 % transmission over a very wide bandwidth. The combined THz frequency comb is detected by a cryogenic bolometer followed by an amplifier with a bandwidth of 1 MHz. A low-pass filter placed in front of the bolometer blocks electromagnetic waves at more than 3 THz. The time delay between the THz frequency combs is scanned at the difference frequency of 100 Hz, and a time delay window of 10 ns can be obtained corresponding to the pulse-to-pulse time interval. A digitizer acquires a time-domain data i.e. an interferogram from the detected signal when triggered by an optical sum-frequency signal that is generated at the difference frequency by a cross-correlator. Repetitive interferogram scans can be averaged to reduce noises on an interferogram.

3. Results

Fig. 2(a) shows a typical interferogram measured from FT-THz spectroscopy using THz frequency comb. 10,000 interferogram scans were averaged during 200 seconds to enhance a signal-to-noise ratio (SNR). The interferogram was measured on the real time window of 10 ms equivalent to the inverse of the difference frequency of 100 Hz, as shown on the upper horizontal axis. The real time can be converted into the time delay using the conversion factor ($\Delta f/f = 10^{-6}$), which results in the time delay window of 10 ns as shown on the lower horizontal axis. The interferogram has an almost symmetric shape around the zero time delay as it should. The THz spectrum is obtained by carrying out fast Fourier transform of the interferogram, as displayed in Fig. 2(b). The spectrum has a frequency step of 100 MHz, the inverse of 10 ns, and a bandwidth close to 2 THz. Since the measurement was performed at a humidity of 35 %, water vapor absorption lines are shown as narrow notches on the spectrum. The SNR increases with the measurement time i.e. the number of averaged scans, and the dependence of the SNR on the measurement time is close to the shot noise limit.

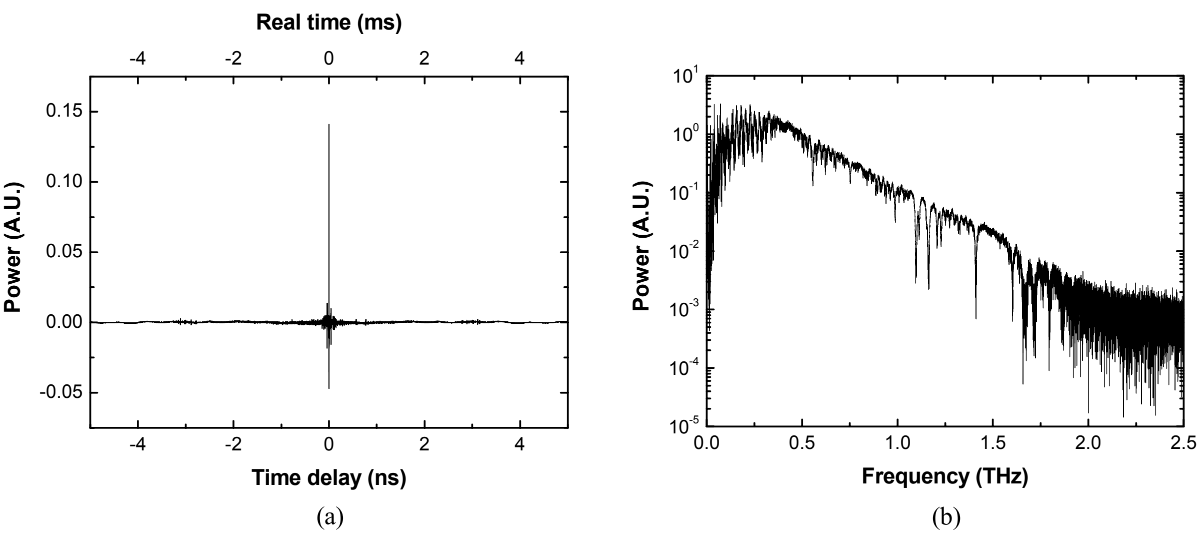

Fig. 2. (a) Typical interferogram measured from the FT-THz spectroscopy using THz frequency comb. (b) THz spectrum obtained by Fourier transform of the interferogram in (a).

4. Summary

Without a mechanical delay method, two THz frequency combs with different repetition frequencies have been used as sources in FT-THz spectroscopy to get a time delay window as long as 10 ns, which is the maximum value achievable with a repetition frequency of 100 MHz. A THz spectrum with a spectral resolution of 100 MHz can be obtained by Fourier transform of an interferogram. In addition to high-resolution spectroscopy, this spectrometer is potentially applicable to transient spectroscopy of non-repetitive phenomena through repetition of a rapid single scan.

5. References

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