High Precision Measurement of Terahertz Frequency Based on Frequency Comb

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A terahertz frequency comb is built by using a commercial femtosecond fiber laser and a fiber-coupled terahertz photoconductive antenna. The absolute frequency of terahertz test source is measured with a measurement uncertainty of 3.2×10^{-11}. A method for terahertz frequency measurement by using unstabilized femtosecond laser is also introduced. Compare to the method by using stabilized femtosecond laser, the system is greatly simplified.

INTRODUCTION

Optical frequency comb is an ultra-precision measuring tool, which has revolutionized the field of optical frequency measurement. Terahertz (THz) electromagnetic wave, lying at the boundary between microwave and the infrared, has emerged as a new method for spectroscopy, imaging, communication and other applications. As frequency is one of the most important physical quantities of EM waves, high precision measurement of THz frequency is also required. The development of a new optical frequency comb to achieve THz frequency measurement has also become a hot topic in recent years [1-3].

In this paper, we demonstrate high precision THz frequency measurement based on frequency comb, by using an stabilized or an unstabilized femtosecond laser, respectively.

PRINCIPLES

A femtosecond laser contains a series of frequency combs with the frequency of $f_{n\_opt} = n\cdot f_r + f_0$, where f_r represents the laser pulse repetition frequency and f_0 represents the carrier envelope phase shift. The photoconductive antenna generates broad band THz radiation excided by the femtosecond laser. f_0 is offset during the difference-frequency processes. Thus, the THz frequency comb can be expressed as $f_{m\_THz} = m\cdot f_r$.

As shown in Figure 1, the frequency of the measured THz source can be expressed as $f_{THz} = m\cdot f_r \pm f_b$, where f_b represents the beat frequency of the measured THz source and THz frequency comb. In the equation, both f_r and f_b can be directly measured by using a frequency counter. The only unknown value is m, which must be obtained to determine the frequency of the measured THz source.

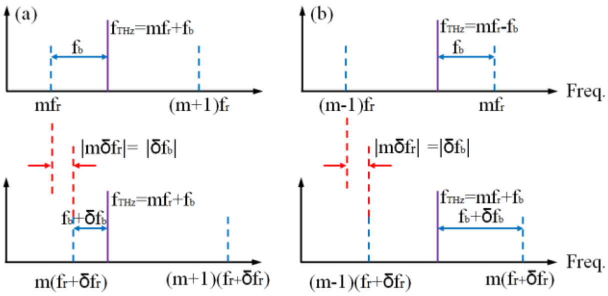

Figure 1. Principle of THz frequency measurement

If interval of the THz frequency comb varies from f_r to $f_r + \delta f_r$, the beat frequency signal will change from f_b to $f_b + \delta f_b$, and $|\delta f_b| = |m\cdot\delta f_r|$. Thus, the following relationship can be obtained:

$$m = \mathrm{int}\left(\left|\frac{\delta f_b}{\delta f_r}\right|\right) \tag{1}$$

The frequency of the measured THz source can be expressed as:

$$f_{THz} = \begin{cases} m\cdot f_r + f_b, \delta f_b/\delta f_r < 0 \\ m\cdot f_r - f_b, \delta f_b/\delta f_r > 0 \end{cases} \tag{2}$$

MEASUREMENT USING STABILIZED LASER

The femtosecond laser used was manufactured by Toptica Photonics AG, with the output central wavelength of 1550 nm, the pulse width of 80 fs. The repetition frequency was stabilized using feedback control system. The laser was divided into two beams by a fiber coupler, one beam connected to the fiber-coupled THz photoconductive antenna to generate a THz frequency comb. The other laser beam was detected by a high-speed photodiode, which inputted the pulse signal into the frequency counter to measure repetition frequency. After the output signal from the frequency synthesizer was multiplied six times by the frequency multiplication module, a THz signal with the frequency range of 75–110 GHz was generated.

The THz signal was irradiated on the surface of the photoconductive antenna, focused by silicon lens and then interacted with the THz frequency comb. The beat frequency signal obtained was amplified and inputted into the spectrum analyzer for measurement. Both frequency counters and the frequency synthesizer in the measurement system referred to the rubidium frequency standard.

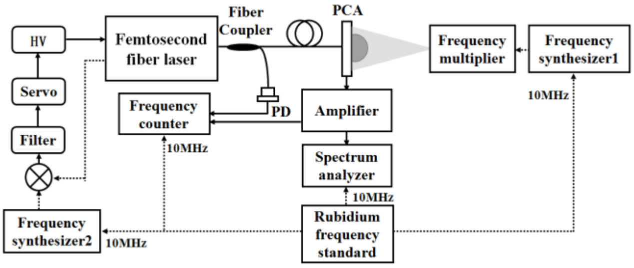

Figure 2. Experimental setup of THz frequency measurement system using stabilized laser

Figure 3 shows the beat signal measured by the spectrum analyzer before and after the repetition frequency change. The absolute frequency of THz test source is obtained according to Equation (2) with a measurement uncertainty of 3.2×10^{-11}.

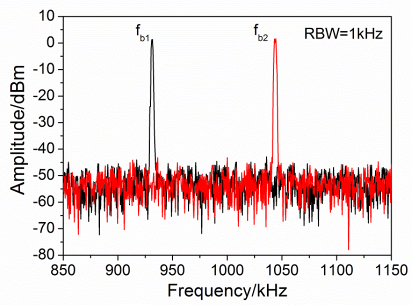

Figure 3. Spectra of f_b with different f_r

MEASUREMENT USING UNSTABILIZED LASER

To simplify the measurement system, we propose a new method. Instead of carrying out complicated stabilization control over repetition frequency of the laser, it was only needed to simultaneously acquire repetition and beat frequencies using two frequency counters as shown in Figure 4.

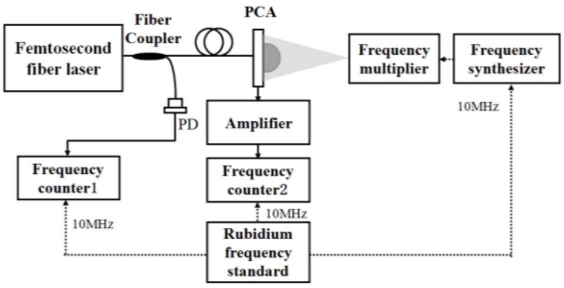

Figure 4. Experimental setup of THz frequency measurement system using unstabilized laser

According to the principle of measurement, the variation of repetition frequency f_r will result in corresponding change in the beat frequency f_b. Figure 5 present the results of measurement of f_r and f_b in a continuous 40-minute period.

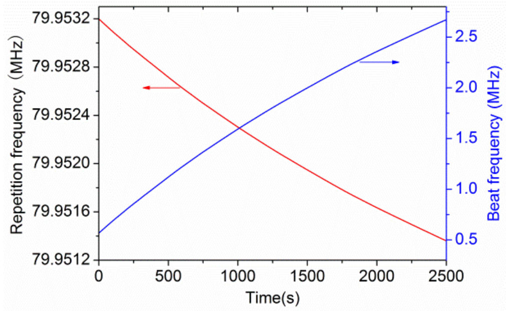

Figure 5. Continuous measurement of f_r and f_b

The value of *m* was calculated as follows:

$$m=\mathrm{int}\left(\frac{1}{N-M}\sum_{n=1}^{N-M}\left|\frac{f_b(n+M)-f_b(n)}{f_r(n+M)-f_r(n)}\right|\right) \qquad (3)$$

Where, N stands for the total number of data and M stands for the selected data interval. The frequency of the measured THz source was calculated as follows:

$$f_{THz}=\frac{1}{N}\sum_{n=1}^{N} m\cdot f_r(n)\pm f_b(n) \qquad (4)$$

Compare to the method by using stabilized femtosecond laser, although the measurement precision dropped from the order of 10^{-11} to the order of 10^{-10}, the measurement system was greatly simplified.

CONCLUSIONS

A THz frequency comb is built by using a commercial femtosecond fiber laser and a fiber-coupled THz photoconductive antenna. The absolute frequency of THz test source is measured with a measurement uncertainty of 3.2×10^{-11}. A method for THz frequency measurement by using an unstabilized femtosecond laser is also introduced.

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