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Photoconductive antenna as local oscillator in terahertz frequency measurement: heterodyne efficiency and bias effect

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Abstract
In a photoconductive antenna (PCA), femtosecond-laser-excited carriers will form a broadband terahertz photon-carrier (PC) comb, and the terahertz PC comb can be used as a multi-frequency local oscillator to carry out heterodyne detection of continuous terahertz sources with high frequency accuracy. In this paper, the heterodyne efficiency and the bias effects of a PCA terahertz PC comb are investigated. The results show that the pair beat signals (with the beat frequencies lower than the repetition frequency of femtosecond laser) of a continuous terahertz source and the two adjacent comb teeth do not decrease with the increase of beat frequency. Applying a bias voltage to the PCA can effectively enhance the terahertz emission efficiency. However, such a bias voltage has no positive effects on the heterodyne detection responsivity because the heterodyne detection is intrinsically based on the terahertz rectification effect that is proportional to the photo-excited electrons. In addition, by using a reference terahertz source with high frequency stability, it is possible to measure the fluctuation and the drift of the repetition frequency of femtosecond lasers with higher accuracy. The results are helpful for improving the performance of terahertz frequency measurement system based on PCA PC combs.

Keywords Femtosecond laser · Photoconductive antenna · Terahertz frequency comb · Heterodyne detection

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1 Introduction

In recent years, with the improvements of terahertz sources and detectors, there has been a great development in terahertz science and technology, especially in terahertz spectroscopic and imaging applications (Jepsen et al. 2011). The frequency of a terahertz wave is one of the most fundamental parameters. The accurate measurement of terahertz frequency and the establishment of terahertz frequency measurement standard are the basis of many terahertz applications (Yasui et al. 2001, 2010, 2015; Plusquellic and Diddams 2016), for example, terahertz radar imaging, terahertz communication, and terahertz precision spectroscopic techniques (Yasui 2010; Jamshidifar and Bolivar 2017). In comparison with microwave band, the frequency of terahertz wave cannot be directly measured with traditional electrical equipments, such as spectrum analyzers and oscilloscopes, due to the bandwidth limitation. Meanwhile, in terahertz regime, because of the limitations of low output power of sources, low sensitivity of detectors, and poor performance of nonlinear crystals, the optical frequency measurement methods cannot be directly applied to terahertz frequency measurements (Wang et al. 2010).

In a femtosecond (fs)-laser-pumped photoconductive antenna (PCA), there is a traceable broadband frequency photon-carrier (PC) comb covering the most part of terahertz band (Barbieri et al. 2010, 2011; Füser and Bieler 2014). Such a terahertz PC comb can be utilized as a local oscillator to down-convert the frequency of a terahertz continuous-wave (CW) source to radio frequency through a heterodyne detection process, and the terahertz frequency can be measured indirectly by a spectrum analyzer or a frequency counter. This provides an efficient, inexpensive, traceable, and highly accurate solution for measuring terahertz frequency.

Due to the importance of terahertz frequency measurement, many investigations on this subject have been reported in recent years. Yokoyama et al. (2008) used a PCA PC comb to measure the frequency of a terahertz CW source. The ratio of $\Delta f/f$ (relative frequency variation, RFV) reaches to 2.8×10^{-11}, where Δf is the frequency uncertainty. Füser et al. (2011) proposed a reference detection channel to correct the repetition frequency variation of an unlocked fs laser. By using the Hilbert transformation, the real-time repetition frequency of the fs laser was obtained, and the RFV of $(9\pm3)\times10^{-14}$ was reached. Sun et al. (2016a, b) have also completed the construction of terahertz frequency measurement system, and the measured values of RFV are 1×10^{-10} and 3.3×10^{-13} by using unlocked and locked terahertz PC combs, respectively.

Except for the application in terahertz frequency measurement, the terahertz PCA frequency combs have also been used to construct precision terahertz time-domain and frequency-domain spectroscopic systems (Yasui et al. 2015; Hsieh et al. 2014; Coddington et al. 2016). The PCA frequency combs play key roles on the above applications because of their wide frequency coverage and high sensitivity. However, some of the characteristics of the terahertz PC combs, such as the dependence of heterodyne detection sensitivity on beat frequency and the effects of bias on the detection process, are still unexplored. In this paper, by using a vector network analyzer with high power stability and high frequency stability, the following characteristics of a terahertz PC comb pumped by an unlocked fs laser are investigated systemically. (1) The beat frequency efficiency between the terahertz CW source and the two nearest adjacent terahertz frequency comb teeth does not monotonically decrease with the increase of frequency difference. Therefore, instead of measuring the beat signal in the 0–$f_r/2$ frequency region with f_r the repetition of fs laser, it is preferable to measure the mirror beat signal located in frequency range of $f_r/2$–f_r due to the much

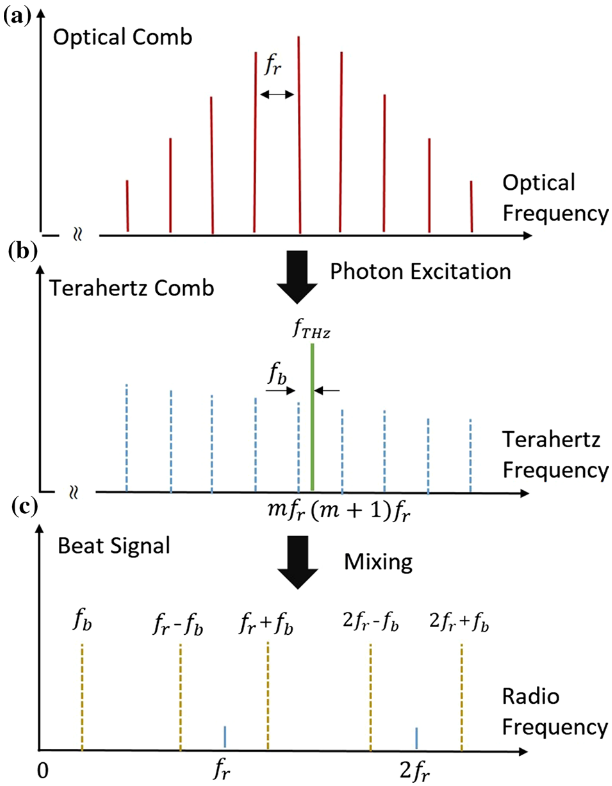

Fig. 1 Principle of terahertz frequency measurement based on terahertz PC comb. **a** Optical frequency, **b** terahertz frequency, and **c** radio frequency

smaller flicker noise. (2) Applying a bias voltage to the PCA has no positive effects on the heterodyne detection responsivity, which is very different from traditional heterodyne detection schemes. We show that the frequency mixing in a PCA is based on the terahertz-field-induced current rectification, which is proportional to the density of photon-excited electrons, but is not related to transient photon current. (3) By using a reference terahertz source with high frequency stability, it is possible to measure the fluctuation and the drift of the repetition frequency of a free-running fs laser with higher accuracy, which provides a new way to realize high precision repetition frequency locking of fs lasers and the synchronization of two fs lasers. These results are helpful for improving the performance of terahertz frequency measurement systems based on terahertz frequency combs. The PCA frequency combs provide a traceable frequency transfer channel between the terahertz and optical bands.

2 Principle and setup

Figure 1 shows the principle of terahertz frequency measurement based on PC comb. The pulse train emitted from the fs laser is a series of equally-spaced frequency comb teeth in the frequency domain (Yasui et al. 2010), and the frequency interval is exactly its repetition frequency f_r (Fig. 1a). In the PCA, a broadband terahertz PC comb is formed under the excitation of the fs laser (Fig. 1b). When a terahertz CW wave (f_{THz}) impinges on the

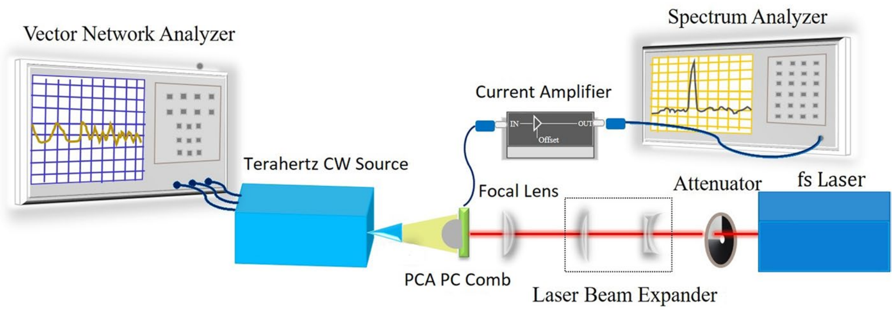

Fig. 2 Schematic of the terahertz frequency measurement setup

PCA, there is a group of beat signals between the terahertz CW wave and the PC comb via a terahertz-field-induced rectification process. The beat signal positioned in the radio frequency region of 0–$f_r/2$ (Fig. 1c), originates from the mixing of the terahertz CW wave and the *m*-th tooth of the PC comb closest to the CW frequency. The terahertz frequency can be expressed as,

$$f_{\mathrm{THz}} = mf_{\mathrm{r}} \pm f_{\mathrm{b}}, \quad (1)$$

where *m* is an integer.

Figure 2 shows the schematic of the experimental setup. The main parameters of the fiber fs laser (C-Fiber 780, Menlo System Inc.) are as follows. The output central wavelength is 780 nm, the pulse width (full width at half magnitude, FWHM) is less than 100 fs, and the pulse repetition frequency is 100 MHz. The PCA (dipole type with a gap of 5 μm) excited by the fs laser will produce a terahertz PC comb. The rectification effect that originates from the interaction between the input terahertz CW wave and the PC comb, will produce alternate current signal with multi beat radio frequency components. An attenuator is used to keep the incident light intensity under the damage threshold of PCA. A current amplifier (DHPCA-100, Femto Inc.), with the maximum bandwidth of 200 MHz and the gain from 10^2 to 10^8 V/A, is applied to amplify the photon current and convert it to a voltage output. A spectrum analyzer (N9322C, Keysight Inc.), with the bandwidth of 9 kHz–7 GHz, is used to display the radio signal in frequency domain. The terahertz CW source, continuously tuned from 0.14 to 0.22 THz, is produced by a vector network analyzer (N5242A, Keysight Inc.), with the bandwidth of 10 MHz–26.5 GHz, equipped with an external frequency extended module (WR10, Virginia Diodes Inc.). The maximum output power of terahertz CW wave is 10 dBm, and the evaluated value of RFV is about 4.0×10^{-10} (Keysight data sheet)[1].

[1] https://www.keysight.comN5242-90007.pdf. The relative frequency variations are ± 0.1 ppm/year and 0.1 ppm with temperature range from − 10 to 70 °C. The temperature variation is about 0.3 °C during the measurements, and the evaluated frequency variation is about 4.0×10^{-10}. The frequency variation with time is much smaller than that with temperature, which is ignored in our experiments.

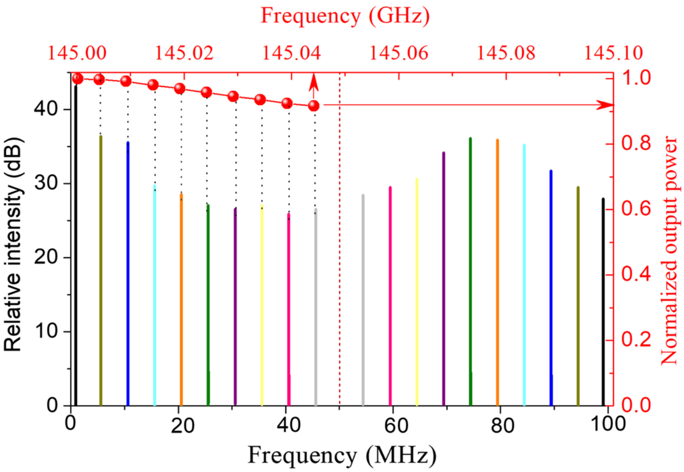

Fig. 3 Relative intensities of beat signals with different beat frequencies and the normalized output power of the terahertz CW source at about 145 GHz (left-bottom frame) and normalized output power of the CW terahertz source (right-top frame)

3 Results and discussion

3.1 Dependence of heterodyne efficiency on beat frequency

The frequency of the terahertz CW wave under test is between two neighboring teeth of the terahertz PC comb. The frequencies of the two lowest beat signals are f_b and $f_r - f_b$. By tuning the output frequency of the terahertz CW source within a very small range, the lowest pair frequencies of the beat signals are distributed in the RF region of 0–100 MHz. The intensities of 10 beat signals near 145 GHz are shown in Fig. 3. For $f_b < 50$ MHz, the intensities of the beat signals decrease with increasing beat frequency. However, when the frequencies of beat signals are in the region of 50–80 MHz, the intensities of these beat signals show an inverse trend. For the 7 pairs of beat signals in 15–85 MHz, for each pair of beat signals corresponding to the same terahertz CW wave, the amplitude of the beat signal located at higher frequency is larger than that of the mirror one. For the other 3 pairs of beat signals, the trend is inverse. As shown in Fig. 3, the power of the terahertz CW source only decreases slightly with the increase of frequency, which cannot be responsible for the above behavior of beat signals. The gain of the current amplifier is checked by using a signal generator (SMB 100A, Rohde and Schwarz Inc.), and the result shows that the gain is nearly constant in 0–100 MHz bandwidth. The experimental data indicate that with increasing the beat frequency f_b when $f_b < f_r$, the heterodyne detection responsivity is not reduced monotonically, which is different from the reported results (Yang et al. 2017). In 0.14–0.22 THz region, the dependence of heterodyne efficiency on beat frequency presents a similar behavior. The heterodyne responsivity maybe determined by many factors, such as the spectral distribution of output power of the fs laser, microscopic dynamic generation and recombination processes of carriers in the PCA, and beat frequency.

The above results are useful to increase the signal-to-noise ratio. In the low frequency band, due to the influence of flicker noise, the system background noise is higher. If the heterodyne detection responsivity is not decreased monotonically with the increase of beat

Table 1 Intensities of the first tooth and the two lowest beat signals of the terahertz PC comb with static bias

Frequency	f_r		f_b		$f_r - f_b$	
Bias (V)	0	15	0	15	0	15
Intensity (dBm)	−73.0	−58.1	−78.7	−79.3	−84.8	−84.2

frequency, the beat signals can be measured in the frequency range of $f_r/2$–f_r, where the effect of flicker noise can be ignored.

3.2 Influence of bias voltage on signal-to-noise ratio of beat signal

The effect of bias on the heterodyne detection responsivity is measured. Table 1 shows the intensities of the first tooth (f_r) and the two lowest beat signals with 0 and 15 V bias voltages applied on the PCA, respectively. The experimental data clearly show that the static bias does not improve the heterodyne detection sensitivity, but the intensity of the first tooth is greatly enhanced when the external bias is applied. The changes of the above signal intensities show similar behaviors with different bias voltages below threshold (30 V) of the PCA.

The different bias-dependent behaviors of the signals at f_b ($f_r - f_b$) and f_r show that different mechanisms. The signals at f_b and $f_r - f_b$ originate from the terahertz-field-induced rectification. We give a theoretical description explanation on this process in Fourier domain. The terahertz-field-induced current in an fs laser pumped PCA is expressed as (Lee 2009),

$$\mathrm{j}(t) = e\mu n_{pc}(t) E_{THz}(t) \tag{2}$$

where e is electron charge, μ is the electron mobility, n_{pc} is the photon-excited electron concentration, and E_{THz} is terahertz electric field. When a terahertz CW wave is incident into an fs-laser-pumped PCA, the rectification current can be written as,

$$\mathrm{j}(t) = e\mu \left[\sum_{n-1}^{N} C_n \cos\left(2n\pi f_b t\right) \right] E_{THz} \cos\left(2\pi f_{THz} t\right) \tag{3}$$

where N is the maximum order of comb teeth in the fs laser and f_{THz} is terahertz frequency. If we assume that M is the order of the comb tooth closest to the terahertz frequency, the heterodyne current can be described by the following equation,

$$\begin{aligned} \mathrm{j}(t) &= e\mu C_M \cos\left(2n\pi f_b t\right) E_{THz} \cos\left(2\pi f_{THz} t\right) \\ &= \frac{1}{2} e\mu C_M \left\{ \cos\left[\left(Mf_b - f_{THz}\right)t\right] + \cos\left[\left(Mf_b + f_{THz}\right)t\right] \right\}. \end{aligned} \tag{4}$$

The value of the frequency component Mf_b–f_{THz} is in the frequency range of 0–$f_r/2$, which is the observed beat signal. From Eq. (4), the intensity of the beat signal is not a function of external bias, and our experimental data agree with the above theoretical prediction. The beat signals at f_b and $f_r - f_b$ are not from the mixing of two terahertz fields, which is very different from the traditional heterodyne detection process. Further, on the contrary, the static electric field introduces a heterodyne-independent background current, which will reduce the signal-to-noise ratio of the heterodyne detection signal. In the bias PCA pumped by an fs laser, two terahertz frequency combs, a PC comb and an electromagnetic (EM) comb are produced at the same time. The intensity of the EM comb is

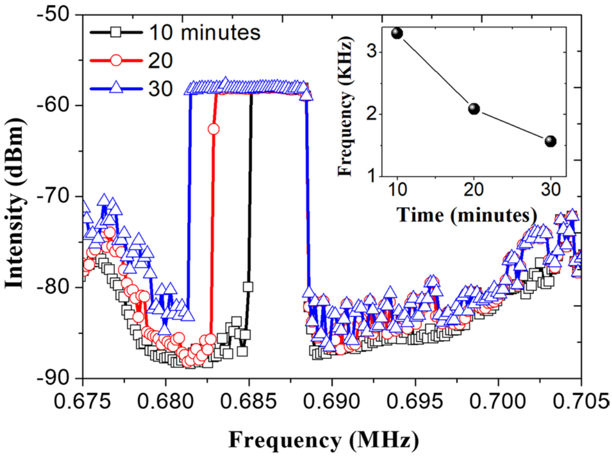

Fig. 4 The beat signal frequency shift during a continuous 30-min period with the spectrum analyzer working in max-hold mode

proportional to the bias voltage applied to the PCA. The signal at f_r (and mf_r, $m=2, 3, 4\ldots$) is from the self-mixing between the PC comb and the EM comb based on the same heterodyne detection process. Therefore, the signal at f_r increases with bias voltage (Lee 2009).

3.3 Frequency stability measurement based on PC comb

The time-dependent drift and fluctuation of repetition frequency of an fs laser are fundamental parameters. According to Eq. (1), if the variation of repetition frequency is Δf_r, the beat signal $f_b=f_{THz}\pm mf_r$, will change $m\Delta f_r$, which indicates that the frequency variation is amplified by m times. In this case, the frequency error introduced by spectrum analyzers or frequency counters is reduced by m times. Figure 4 shows the beat signals recorded by the spectrum analyzer working in max-hold mode at time intervals of 10 min, after the laser running 30 min. The results clearly show that the variation of repetition frequency is dominated by frequency drift during the early stage of the fs laser switched on, and such frequency drift gradually decreases with time. In Fig. 4, the terahertz frequency f_{THz} is set to 180.002 GHz, and from Eq. (1), $m=1800$ is derived. The measured repetition frequency drifts during the three continued 10-min time intervals are 3304, 2087, and 1568 Hz, respectively. Thus the real values of repetition frequency drifts are 1.84, 1.16, and 0.87 Hz, respectively. In the above calculation, the frequency variation of the terahertz CW source Δf_{THz} must be considered. In the condition of $\Delta f_{THz}\ll\Delta f_r$, the above technical scheme will give more precision results.

Previous investigations have shown that the intrinsic linewidth of terahertz quantum cascade lasers (QCLs) is very narrow (Sirtori et al. 2013; Jirauschek and Tzenov 2017; Li et al. 2015; Wan et al. 2017; Rosch et al. 2015). If a molecular-absorption-line stabilized terahertz QCL is applied as the reference source, the typical value of m will reach to 2.5×10^4 ($f_{THz}=2.5$ THz). Therefore, it is possible to greatly increase the measurement precision of the repetition frequency stability of fs lasers, and provide a new technique for high precision repetition frequency locking. Nagano et al. (2013) have demonstrated a similar technical scheme to realize a terahertz-to-microwave synthesizer with high frequency precision and low phase noise. Moreover, the PCA frequency PC combs can also be utilized to lock the frequency of terahertz sources with frequency precision tracing to that of stabilized fs lasers.

4 Conclusion

In summary, the characteristics of terahertz PC comb produced by an unlocked fs laser-excited PCA are studied. We find that the heterodyne efficiency between the terahertz CW source and the two adjacent terahertz comb teeth does not decrease with the increase of beat frequency. From the basic detection principle, we explain why applying a bias voltage to the PCA can effectively increase the emission efficiency of the photocurrent and the intensity of terahertz radiation, but cannot improve the heterodyne detection responsivity. Based on terahertz PC combs, it is possible to achieve high precision repetition frequency locking of fs lasers and the synchronization of two fs lasers. A traceable frequency transfer channel can be established between the terahertz and the optical bands by using PCA PC combs.

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