An ultra-high-resolution technique for detection of terahertz pulses

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***Abstract*— We present a novel technique for the detection terahertz pulses generated by femtosecond lasers. It features a Hz-level resolution and does not require a mechanical delay stage or a second femtosecond laser. It works by opto-electronically downconverting the individual frequency components composing the terahertz pulse. Unlike other techniques, it does not require an external spectrum analyzer or a lock-in amplifier for its implementation, although it can also be implemented using them. We believe this technique is a valuable tool to study the ultimate frequency stability of terahertz pulsed systems and the phase noise of the femtosecond lasers that drives them.**

I. Introduction

Two main techniques exist for the detection of terahertz pulses. The first one utilizes a delayed copy of the femtosecond pulse used for terahertz generation to probe the generated pulse in a photoconductive detector. To resolve its temporal structure, the time delay between terahertz and probing pulse is varied using a mechanical delay stage. The current in the photoconductive detector, which is proportional to the amplitude of both pulses and to their relative phase difference, is recorded for each delay step. This results in a time trace that reconstructs the field of the probed pulse. Its spectrum is then obtained by means of a discrete Fourier transform (DFT). Thus, the frequency resolution is dependent on the number of acquired points and on the sampling frequency, ensuing unpractically long measurement times for resolutions below 1 GHz. The second one, known as ASOPS, utilizes an additional femtosecond laser with a slightly different repetition rate to probe the emitted terahertz pulse. The slight difference in repetition rates effectively results in a temporal delay between the pulses, allowing to get rid of the mechanical delay stage [1]. To a certain extent, this removes the trade-off between acquisition time and frequency resolution, since the terahertz pulse can be sampled within the time that it takes for the pulses to temporally overlap again, determined by the inverse of the repetition rate difference. Nevertheless, it becomes challenging to keep the two lasers fully phase-locked for the time that it takes to average out enough traces to reduce the noise floor to an acceptable level. Still, resolutions as good as 82.6 MHz have been achieved with this technique [1].

These two techniques probe the terahertz pulse in the time domain, rendering all the spectral information at once but with limited resolution. However, none of them allows to fully characterize the true phase noise and the frequency stability of the terahertz pulse, since the probing pulse always remains phase locked to the terahertz pulse. The technique presented here, coined Frequency Selective Optoelectronic Downconversion (FreSOD) [2], probes the emitted terahertz pulse directly in the frequency domain using an ultra-stable terahertz local oscillator (LO) that is not phase-locked to the terahertz pulse. This allows to achieve much higher frequency resolution and permits the characterization of the true frequency stability and phase noise of the terahertz pulse.

II. Architecture

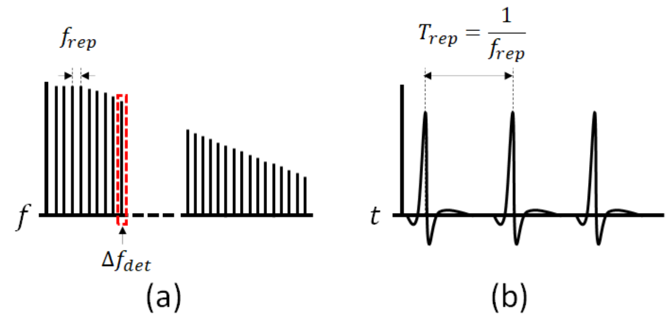

Fig. 1. Representation of a terahertz pulse: (a) in frequency and (b) in time domain. The discrete spectral structure is a consequence of its periodic nature.

The central idea of the architecture is to look at the terahertz pulse in the frequency domain, where it is just a collection of equally spaced terahertz frequency components, with a spacing given by the repetition rate f_{rep} [2], as shown in Fig. 1.

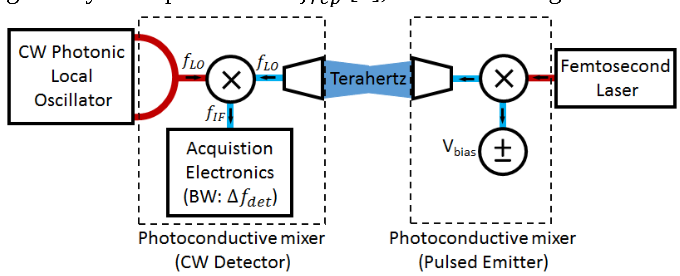

Fig. 2. Schematic diagram of FreSOD architecture.

FreSOD utilizes a continuous-wave (CW) photoconductive mixer driven by an ultra-low-noise CW photonic LO to heterodyne the terahertz pulse, as depicted in Fig. 2. In principle, all the frequency components are heterodyned by the mixer, however, the finite detection bandwidth Δf_{det} of the post-detection electronics connected to it acts as a filter. Since Δf_{det} usually ranges between a few hundred of kHz and few MHz, only the terahertz component that is closest to the LO frequency can be detected. This requires a photonic LO with a high spectral purity and accuracy, but such requirements can easily be provided by an electro-optically (EO) generated photonic LO [3]. The key is to generate mutually coherent optical sidebands by modulating the output of a CW laser with an electro-optical phase modulator (EOM) driven by a CW RF signal generator with a frequency f_{RF}. After the generation of multiple optical sidebands, as given by the Jacobi-Anger expansion, two of them are selected by using tunable optical filters and subsequently combined into a single optical output. The output optical signal is focused onto the active area of the CW photoconductive mixer, resulting in the excitation of carriers at the rate given by the frequency difference between

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the two sidebands. Since the two sidebands are mutually coherent, they exhibit a frequency difference which is an exact multiple of the RF frequency nf_{RF}. Thus, the frequency of the excited carriers is as pure and as accurate as the frequency of the RF signal generator. The excited carriers then get accelerated to a velocity proportional to the field strength of the incoming terahertz signal, producing all the mixing products between the frequency components of the incoming terahertz pulse and the EO excited carriers acting as LO. Since the mixing product of interest is the one lying within Δf_{det}, it can be easily detected with non-expensive acquisition electronics.

III. RESULTS

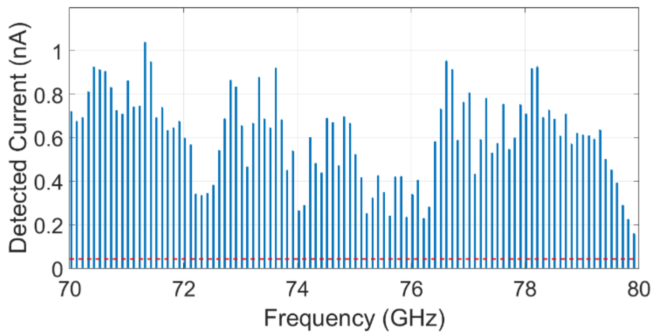

Fig. 3. Amplitude of the terahertz frequency components within the 70-80 GHz range as displayed by a lock-in amplifier. Dashed line indicates detection limit.

A terahertz pulse emitted by an ErAs:In(Al)GaAs photomixer driven by a passively-locked 1550-nm Menlo femtosecond laser with a duration of 100 fs and a nominal repetition rate of 100 MHz was used to demonstrate the detection capabilities of FreSOD. For downconversion, we employed an ErAs:InGaAs photoconductive mixer with a log-periodic antenna driven by an EO-generated CW photonic LO. A transimpedance amplifier (TIA) connected after the mixer was used as post-detection electronics. Here, we show three possible implementations using different acquisition electronics: a lock-in amplifier, an electronic spectrum analyzer (ESA) and an acquisition card.

Fig. 3 shows the amplitude of the detected frequency components within the 70-80 GHz range as measured by a lock-in amplifier connected directly to the TIA used after the mixer. The reference oscillator of the lock-in amplifier was set to match the intermediate frequency (IF) of the mixing product of interest while the CW photonic LO was swept to downconvert all components between 70 and 80 GHz [2]. This measurement clearly exhibits the discrete spectral structure of the terahertz pulse and shows that FreSOD can even be used for spectroscopic measurements [2].

Fig. 4 shows a comparison between the spectra of the 750th and the 3400th component of the terahertz pulse as measured by an ESA connected directly to TIA used after the mixer. As it is evident, there is a linewidth increase for the 3400th component. This is expected, since the higher the frequency component in the terahertz pulse, the more the separation between the optical components of the femtosecond laser generating it, and the less coherence between them. Indeed, it is possible to measure the degree of coherence between the different components of the femtosecond laser in this manner, allowing a full characterization of the phase noise of the terahertz pulse and of the laser generating it [2]. Note the Hz-level accuracy in the frequency of each component, indicating a repetition rate slightly smaller than 100 MHz.

Fig. 5 shows a spectrogram of the 721st component captured with an acquisition card connected to an anti-aliasing filter used after the TIA [4]. The acquisition card digitizes the time domain signal containing the mixing product of interest, and a DFT renders its spectrum. The observed drift is due to the passive nature of the stabilization employed in the femtosecond laser, as confirmed by further measurements [4]. This measurement underscores the capability of FreSOD as a tool to characterize the ultimate frequency stability limits of pulsed terahertz systems without the phase noise influence of an additional ESA, lock-in amplifier, or any other external reference oscillator. Therefore, the measured frequency resolution solely depends on the spectral purity of the RF generator used for the photonic LO generation (assuming the timing jitter of a low-speed acquisition electronics is negligible). This makes FreSOD a true optoelectronic spectrum analyzer for terahertz pulses.

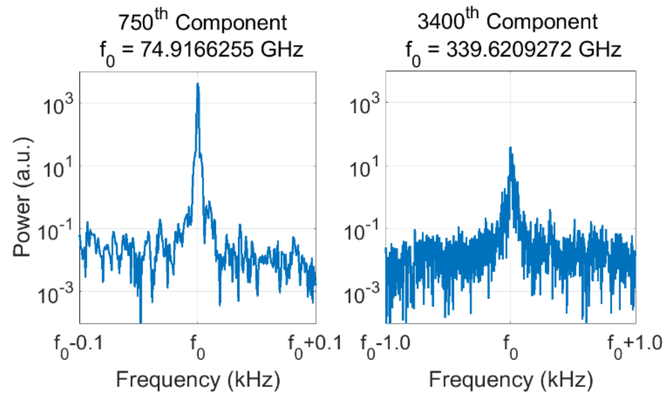

Fig. 4. Comparison between the 750th and the 3400th terahertz components as displayed by an ESA. Resolution bandwidths: 0.817 Hz and 1.63 Hz, respectively [2].

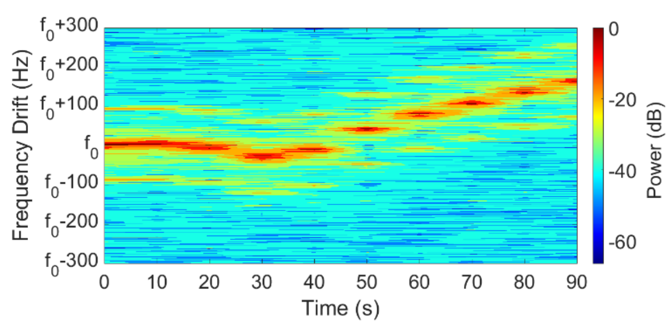

Fig. 5. Spectrogram of the 721st component as captured by an acquisition card connected to a computer. Resolution bandwidth: 1 Hz [4].

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