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Terahertz diagnostic systems based on frequency combs without moving parts

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***Abstract*—We exploit information and communications technologies to build a radio frequency-driven frequency comb spanning several hundred gigahertz. We investigated electro-optic modulators, which can serve as building blocks in frequency combs, terahertz generation and terahertz detection systems. These devices have high potential for applications in robust laser-based diagnostics at electron accelerators. We have reduced the pulse length generated by a frequency-comb without moving parts by more than one order of magnitude to less than 150 fs, fitting a Lorentzian-type autocorrelation function.**

I. INTRODUCTION

TERAHERTZ techniques [1] are an ideal toolset to study the dynamics of ultra-short electron bunches in accelerators [2]. The electron bunch lengths correspond to timescales of a few fs to ps. These bunches exhibit electron densities with microstructures corresponding to sub-ps THz-field transients, emit THz photons and coherent synchrotron radiation.

Electron bunch diagnostics employs THz time-domain spectrometers and single-shot electro-optic sampling systems. These systems typically use mode-locked lasers with fixed cavity lengths. Hence, synchronizing these lasers to electron accelerator-based light and other laser sources requires moving parts such as piezo-drivers and motors to change the overall laser cavity length.

Here, we present progress on exploring radio frequency (RF)-driven frequency combs based on telecommunication technology in terahertz and electro-optic detection schemes.

The particle accelerators' master clock operates, for example, at 500 MHz (IEEE UHF) or 3 GHz (IEEE S band). This RF master clock naturally synchronizes the RF-driven frequency comb and accelerator systems as a common reference frequency.

Thus, this scheme gives access to a wide range of purely electronic modulation schemes benefiting from synergies with telecommunication methods.

II. RESULTS

Figure 1 shows a scheme of the experimental setup. All optical connections and components use polarization-maintaining fibers (PMF) and fiber connectors with angled physical contact (FC/APC) up to the non-linear fiber (NLF). Our design of the frequency comb uses PMF throughout.

In previous experiments [2], we have shown that a 250-GHz wide frequency comb, corresponding to an optical bandwidth of more than 2 nm, can generate a pulse train with a repetition rate of 10 GHz and pulse lengths variable in the range of (3.3 ± 0.6) ps for Lorentzian-type autocorrelation functions.

In the experimental setup, described in reference [2], we have added a 2 km long, non-linear fiber (NLF; Sumitomo Electric Industries, Japan), which flattens and decreases dispersion. Additional amplification with a second erbium-doped fiber amplifier (EDFA; model FA-30; Pritel, Inc., USA) with a saturated output power of up to +30 dBm (1 W) increases the bandwidth further (Fig. 1).

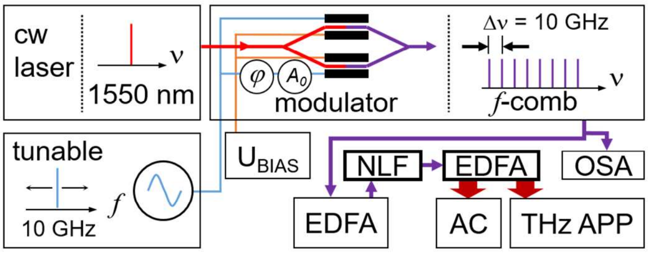

Fig. 1. Scheme for frequency combs (*f*-combs) using a continuous-wave (cw), narrow-band (<100 Hz), telecommunication-wavelength laser, tunable radio frequency (RF) source, and modulator in a Mach-Zehnder interferometer. The interferometer is biased with a voltage U_{BIAS}. A phase-shifter φ and attenuator A_0 compensate differences in the modulator arms due to fabrication tolerances. For characterization, an optical spectrum analyzer (OSA) and autocorrelator (AC), after an erbium-doped fiber amplifier (EDFA), are used. In addition to [2], using a non-linear fiber (NLF) and further amplification (EDFA) compresses the individual pulses of the 10-GHz pulse train to the sub-ps timescale for synchronized terahertz (THz) generation and electro-optic applications (APP).

The setup shown in Figure 1 was used to compress the pulses from the *f*-comb and to enable systematic studies. Figure 2 shows sub-ps pulses for partially optimized parameters. A pulse duration of less than 150 fs was obtained.

This value approaches the regime of current fiber-based mode-locked lasers. Thus, their replacement by such frequency combs without moving parts becomes feasible.

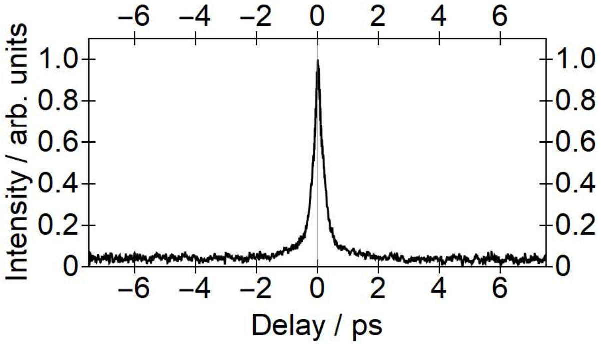

Fig. 2. Measured autocorrelation function (ACF) of 241 fs for partially optimized settings, which leads, by fitting of a Lorentzian-type function, to a pulse duration of less than 150 fs. The output power of the cw laser at 193.40 THz (1550.12 nm) was set to 16 mW (+12 dBm). The radio frequency was set to 10 GHz at +17 dBm (~51 mW). The bias voltage U_{BIAS} was set to 2.39 V and the first EDFA following the *f*-comb was set at 1 A and 26 °C. The second EDFA was set at 0.87 A to not overload the autocorrelator (AC, see Fig. 1).

Figure 1 shows that several parameters can be varied including the output power of the cw laser, the cw laser frequency, the output power of the radio frequency (RF) and the

RF itself, the voltage to bias the modulator, phase-shift and attenuation between the two interferometer arms in the modulator, and the operation values of both EDFAs. In addition, the dispersion function of the currently rigid non-linear fiber can be altered, for example also by an electronically controlled waveshaper.

Figure 3 illustrates, as an example, the dependence of the autocorrelation function on the output power of the cw laser and the bias voltage of the modulator. Small changes in the bias voltage of only 1% significantly alters the dependencies. At a bias voltage of 2.39 V, the pulse length varies by more than a factor of four. For an *f*-comb with a flat spectrum, meaning all central teeth of the comb have a similar power, and decreasing in power outer modes, a lower cw laser power will reduced the outer modes, so that they vanish into the noise floor (cf. Fig. 2 in Ref. [2]). This leads to a narrowing of the frequency comb and longer pulse lengths.

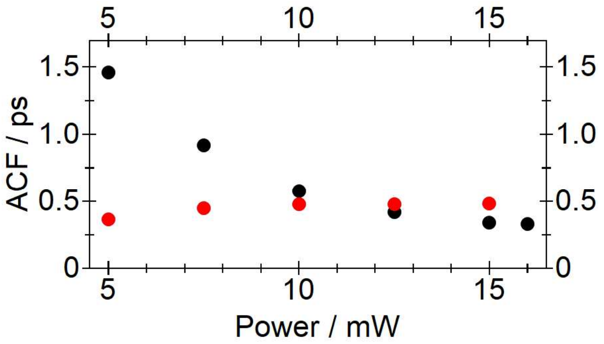

Fig. 3. Extracted ACF value for the measured autocorrelation function (see also Fig. 2) as a function of the output power of the cw laser at 193.40 THz (1550.12 nm). The radio frequency was set to 10 GHz at +17 dBm (~51 mW). The bias voltage U_{BIAS} was set to 2.39 V (black points) and 2.42 V (red points).

However, the overall behavior is more complex. At a bias voltage of 2.42 V, the pulse length is shortest at the lowest cw laser power and increases for higher cw laser power, but the pulse length only varies by 11%.

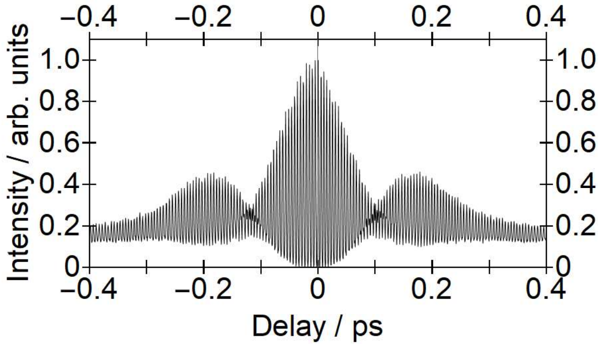

Fig. 4. Measured autocorrelation function (ACF) for a different setting showing an interferometric autocorrelation for the comb spectrum centered at 1550 nm (ν ≈ 193 THz) and coherence with 1/ν ≈ 5.2 fs.

Figure 4 shows an autocorrelation function at a higher resolution. Due to coherence, the carrier frequency of the cw laser at 1550.12 nm (193.40 THz) is visible. The appearance of satellites at delays around 150 fs to 200 fs corresponds to the non-trivial spectral shape of the frequency comb.

III. SUMMARY AND OUTLOOK

We report on RF-driven frequency combs providing sub-ps pulses with less than 150 fs duration at a pulse repetition rate of 10 GHz. The pulse length approaches the regime of current fiber-based mode-locked lasers using piezo-drivers and motors to change the overall laser cavity length. Thus, their replacement by such RF-driven frequency combs without moving parts becomes feasible.

The repetition rate is widely tunable and directly controlled by the RF source with high precision. This source is equipped with a pulse modulator to generate, for example, tailored RF pulse-trains, to explore various types of frequency combs and modulation schemes.

The free parameters can be optimized for different goals and are well suited for methods such as machine learning [3]. Using THz emitters [4], high-repetition rate pulse-trains in the THz range can be generated. The detection of such pulse trains is feasible with single-shot spectrometers capable of recording different spectral channels simultaneously at high-repetition rates [5] in the GHz range. Systematic studies are under way to include further compression, coding and decoding schemes, terahertz generation and terahertz detection [6].

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