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A TUNABLE NARROWBAND SOURCE IN THE SUB-THz AND THz RANGE AT DELTA*

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Abstract

At DELTA, a 1.5-GeV electron storage ring operated as a synchrotron light source by the TU Dortmund University, an interaction of ultrashort laser pulses with electron bunches is used to generate broadband as well as tunable narrowband radiation in the frequency range between 75 GHz and 5.6 THz. The performance of the source was studied using two different Fourier-transform spectrometers. It was demonstrated that the source can be used for the characterization and comparison of Schottky-diode based detectors, e.g., an on-chip spectrometer enabling single-shot applications.

INTRODUCTION

The 1.5-GeV electron storage ring DELTA is operated as a synchrotron light source by the TU Dortmund University. In 2011, the short-pulse source using the coherent harmonic generation (CHG) principle was implemented [1, 2]. At this source, ultrashort VUV and THz pulses are generated by an interaction between a 40-fs Ti:sapphire laser pulse and a short slice of a single electron bunch. The interaction inside the electromagnetic undulator U250 leads to a modulation of the electron energy. The laser system is operated at a repetition rate of 1 kHz, offering a pulse energy of up to 8 mJ. For the generation of CHG radiation, the undulator is operated in an optical-klystron-like configuration with three sections, modulator (7 periods), chicane (3 periods) and radiator (7 periods). Further information on the generation of CHG radiation in the VUV regime is given in [3]. Using the whole undulator as modulator leads to a stronger energy modulation which is especially beneficial for THz radiation generation. This energy modulation is converted into an electron density dip on the picosecond scale in the subsequent magnet lattice and gives rise to the coherent emission of THz radiation at a bending magnet equipped with a beamline dedicated to (sub-)THz experiments [4, 5]. Details are given in Fig. 1 and Table 1.

LASER-INDUCED THz DOUBLE PULSES

The spectral composition of the THz radiation is defined by the longitudinal electron density. Hence, a manipulation of the spectrum can be achieved by changing the temporal evolution of the laser pulses. One method is to use an interferometer (see Fig. 2) to create two laser pulses with a delay of tens of micrometers. With such a displacement, the two interaction regions merge due to longitudinal dispersion and the resulting dip in the longitudinal electron density effectively broadens depending on the displacement. The effect of delays between 20 μm and 80 μm is shown in Fig. 3, where a shift of the whole spectrum from a central frequency of 3.8 THz to 2.2 THz can be observed. For larger delays, the spectral behavior of the THz radiation changes as soon as two distinctly separated THz pulses are generated. In this case, the radiation spectrum shows the interference of the two pulses in the THz frequency domain. Hence, a sinusoidal modulation of the spectrum is visible with a modulation frequency depending on the pulse separation. Measurements with delays of 1.2 mm and 2.4 mm delay are shown in Fig. 4.

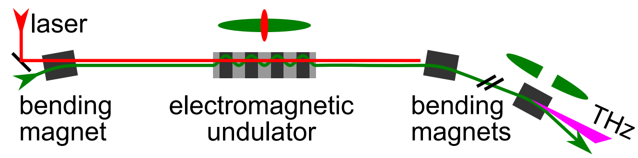

Figure 1: Sketch of the setup used to produce THz radiation (see text for details).

Table 1: Parameters of the Electron Storage Ring DELTA

beam energy	1.5 GeV
circumference	115.2 m
revolution time	384 ns
multi-bunch current	130 mA (max.)
single-bunch current	20 mA (max.)
bunch length	100 ps (FWHM)
horizontal beam emittance	15 nm rad
relative energy spread	7×10^{-4}
momentum compaction factor	5×10^{-3}

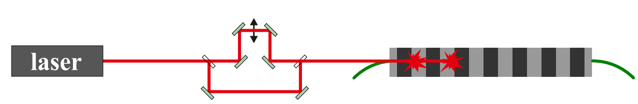

Figure 2: The spectral shape of the resulting THz radiation can be influenced using an interaction of two laser pulses delayed with respect to each other.

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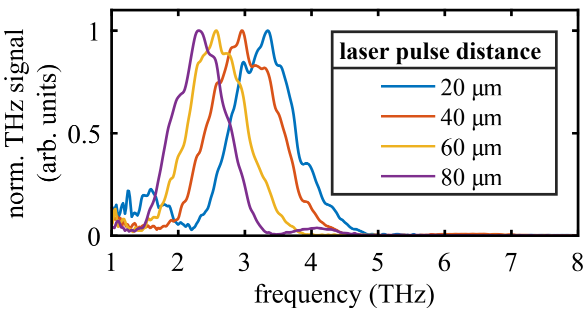

Figure 3: THz spectra influenced by a twofold laser interaction with a delay between 20 µm and 80 µm (see text for details).

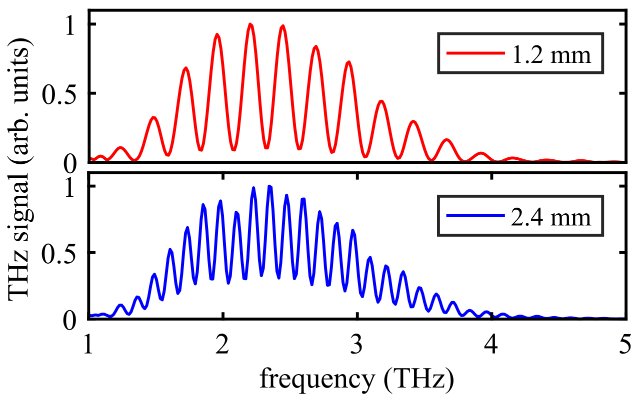

Figure 4: Two widely separated energy-modulated regions (red: 1.2 mm, blue: 2.4 mm delay) lead to the generation of two THz pulses. The temporal interference is observed in the spectrum which was measured using a Fourier-transform spectrometer with a Mylar beamsplitter.

GENERATION OF TUNABLE, NARROWBAND THZ PULSES

Compared to broadband radiation, a tunable narrowband source opens further experimental opportunities. In 2014, first experiments dedicated to the generation of tunable narrowband THz pulses were conducted at DELTA, using a setup from PhLAM (Lille, France) to realize the chirped-pulse beating (CPB) scheme [6–10]. The CPB method uses partially compressed, chirped pulses from the laser amplifier, which are sent through a Michelson-like interferometer. The relative delay introduced by the interferometer leads to a beating when recombining the pulses and hence a sinusoidal intensity modulation occurs. Recently, a permanent setup at DELTA following the same approach was developed and commissioned.

Using two different Fourier-transform spectrometers, it was shown experimentally that at DELTA the CPB method allows to generate radiation between 75 GHz and 5.5 THz [11–13]. The relative bandwidth equals about 10 %. A theoretical discussion can be found in [7]. The shape of the radiation spectrum depends on the laser modulation, as well as the storage ring parameters r_{51}, r_{52} and r_{56}.

Laser Diagnostics

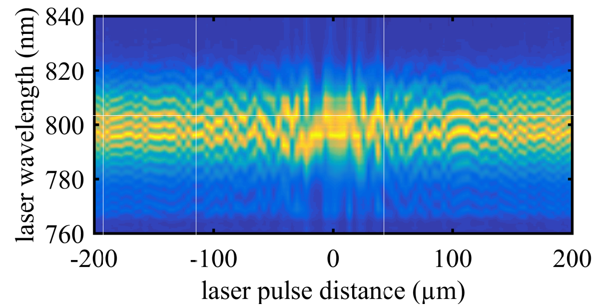

Figure 5: The interference spectrum of two laser pulses is used to determine the zero-delay position.

Besides adjusting laser pulse length and chirp, the generation of narrowband THz radiation requires to precise knowledge of the zero-delay position of the interferometer. The interferometer used for these experiments offers two outputs, one of which is used to monitor the laser spectrum. As long as the pulses do not overlap, the spectrum is modulated due to interference between them. The modulation frequency is lower for shorter delays. The laser spectrum as a function of the delay is shown in Fig. 5. To allow for a prediction of the central THz output frequency, a calibration of the longitudinal pulse-intensity modulation is needed. A self-built intensity autocorrelator was used to measure the temporal laser intensity profile as function of the delay and a coefficient of 5.5 GHz/µm was determined. An example of a measured longitudinal laser profile is given in Fig. 6 and the calibration curve is plotted in Fig. 7. To allow for a fast and precise control of the narrowband radiation frequency, the laser interferometer is equipped with a feedback-controlled piezo actuator enabling the user to change the desired THz frequency within seconds.

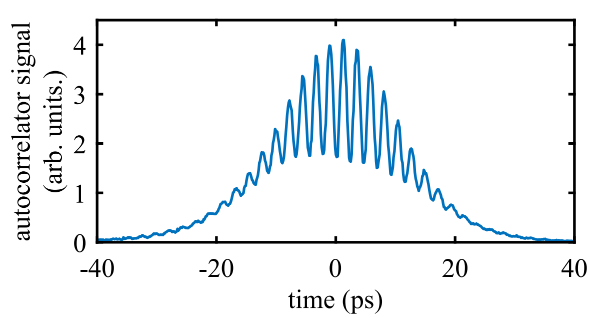

Figure 6: Intensity autocorrelation of a modulated laser pulse.

Towards a Spectral Calibration of THz Detectors

The spectral calibration of THz detectors is still difficult because tunable sources are rare especially if pulsed sources are needed. The CPB-based THz generation provides an ideal tool to benchmark the spectral bandwidth of detectors by continuously sweeping the frequency while capturing

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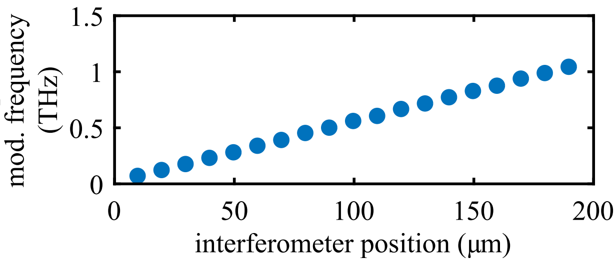

Figure 7: The modulation frequency of the laser pulse intensity depends linearly on the interferometer delay.

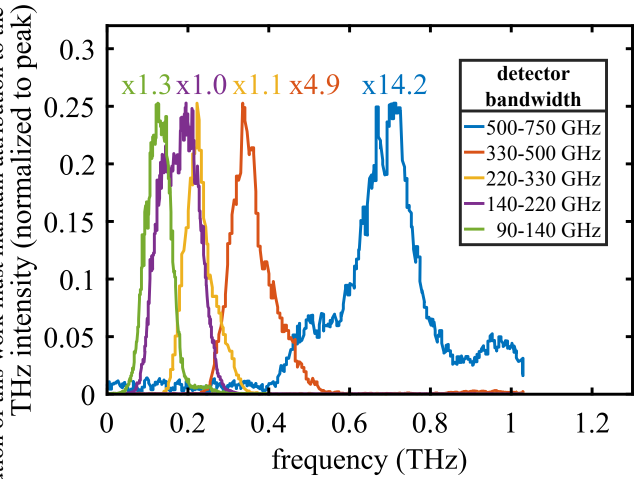

Figure 8: Signals from five narrowband Schottky-barrier detectors irradiated by narrowband sub-THz radiation during a frequency sweep between 0 and 1 THz. The normalization factors are listed above the curves.

the detector response. Figure 8 shows the peak-normalized signals of five different narrowband Schottky detectors [14]. The normalization factors are listed above the curves. The detector bandwidths range from 90 GHz to 750 GHz with a division into five different bands. The responses of the detectors acquired using narrowband THz radiation match the data given by the manufacturer (see plot legend), but are still a convolution of the generated spectrum which changes in intensity depending on the frequency and the spectral sensitivity of each detector. Improvements of the laser setup, particularly, the pulse compressor, are foreseen to reduce the bandwidth of the output spectra even further.

Spectral Tuning to the Detector Sensitivity

THz radiation at DELTA also serves as a tool for finding and optimizing the temporal and spatial overlap of laser and electrons which is mandatory for the generation of CHG radiation. Usually, the laser-induced THz signals are produced during the single-bunch operation of the storage ring, where the bunch charge equals about 2 nC and the charge in multi-bunch mode of up to 0.4 nC is insufficient to generate detectable THz radiation. Using the CPB setup, it was recently possible to precisely tune the THz radiation frequency to the sensitive region of a Schottky-barrier detector (SBD) [15] and detect THz signals even with low bunch charge. In Fig. 9, the timing of the laser-electron interaction is swept through 45 radio frequency (RF) buckets filled with a maximum charge of 0.4 nC. A comparison with a measurement from the standard fill pattern monitor is also shown. Here, the spectral matching is a chance to generate sub-THz radiation during standard user operation, which was impossible with broadband emission.

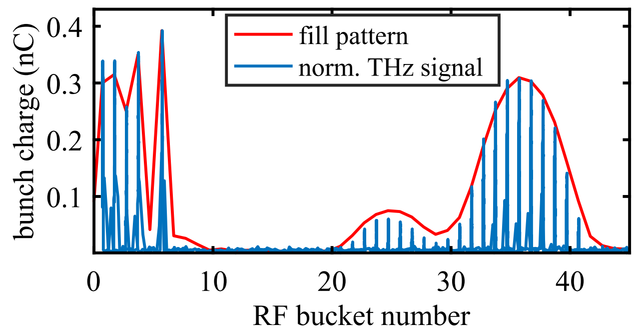

Figure 9: Measurements of the multi-bunch fill pattern of DELTA with a conventional RF-based method (red) and a successive temporal shift of the laser-electron interaction through the RF buckets (blue).

OUTLOOK

The detection of pulses being tens of picoseconds long is technically challenging. Recently, the fast data acquisition system *KAPTURE* [16] developed by KIT (Karlsruhe, Germany) has been permanently installed at DELTA. It enables ultrahigh bandwidth measurements at MHz trigger rates synchronized to the storage ring RF. It will also be used to test a single-shot spectrometer developed by TU Dresden and to carry out turn-by-turn measurements. This millimeter-scale on-chip THz spectrometer is based on eight Schottky diode detectors with narrowband THz antennas acting as filters [17]. Being manufactured in a standard GaAs process, simultaneous detection of multiple THz frequencies on one chip is possible. To further improve the understanding of the laser-electron interaction in general, measurements of the longitudinal electron density using an electro-optical method [18] are currently under preparation.

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