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PULSE SHAPING METHODS FOR LASER-INDUCED GENERATION OF THz RADIATION AT THE DELTA STORAGE RING*

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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, a dedicated beamline is used for experiments with (sub-)THz radiation. Here, an interaction of short laser pulses with electron bunches to give rise to coherently emitted broadband as well as tunable narrowband radiation from 75 GHz to 5.6 THz. For the narrowband operation of the source, a laser pulse with periodic intensity modulation is used. An interferometric approach, the chirped-pulse beating technique, is routinely employed for this purpose. Recently, pulse shaping techniques using spatial light modulators are investigated to gain more flexible control of the laser pulse shape and the spectrotemporal properties of the resulting THz pulses.

INTRODUCTION

The TU Dortmund University operates the 1.5-GeV electron storage ring DELTA as a synchrotron light source. At the dedicated short-pulse facility [1,2], ultrashort VUV [3,4] and THz pulses are generated based on an interaction between a 40-fs Ti:sapphire laser pulse and a short slice of a single electron bunch inside the electromagnetic undulator U250. The interaction causes a periodic modulation of the electron energy which transforms to a density modulation. The laser system, which is operated at a repetition rate of 1 kHz, offers pulse energies of up to 8 mJ. Depending on the respective experiment, the U250 is operated in different modes. For the generation of CHG radiation in the UV and VUV regime, it is operated in an optical-klystron-like configuration consisting of three independent sections, modulator (7 periods), chicane (3 periods) and radiator (7 periods).

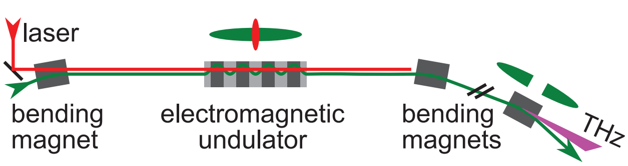

Figure 1: Setup for the coherent emission of laser-induced THz radiation (see text for details).

For the coherent emission of laser-induced THz radiation, only a modulator and a bending magnet as a radiative device after a dispersive section are needed. A sketch of the facility is depicted in Fig. 1. THz radiation is emitted coherently because energy-dependent path lengths transform the laser-induced energy modulation into a (sub-)millimeter dip in the longitudinal electron density. Parameters of the storage ring are given in Table 1.

Table 1: Parameters of the Electron Storage Ring DELTA

beam energy	1.5 GeV
circumference	115.2 m
revolution time	384 ns
multibunch 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}

LASER-INDUCED THz RADIATION AT STORAGE RINGS

Since 2011, broadband radiation is generated at the DELTA THz beamline. Studies to further shape the emission spectrum started in 2014 with the implementation of the chirped-pulse beating approach [5–7]. Here, a strechted and intensity-modulated pulse is used to narrow the emission spectrum. The modulation generated by a Michelson interferometer and the relative delay between the interferometer arms leads to a beating at (sub-)THz frequencies of the recombined laser beams. The energy modulation follows the periodicity of the modulation and hence the THz spectrum narrows.

Gain Curve and Accessible Frequency Range

A theoretical description of the spectrum of laser-induced THz radiation was given by Evain et al. [8]. The total emission spectrum $P(\omega)$ of an electron bunch of N_e electrons with a single-electron power spectrum $P_e(\omega)$ is given by

$$P(\omega) = P_e(\omega) N_e \left(1 + (N_e - 1) g^2(\omega)\right). \qquad (1)$$

In the case of a longitudinal density modulation, the form factor g^2, which is the squared Fourier transform of the longitudinal electron density ρ, is expressed as a function of the laser modulation frequency f, the matrix elements [9] of linear beam optics r_{51}, r_{52} and r_{56}, the horizontal rms bunch size σ_x and divergence and $\sigma_{x'}$ and the relative rms energy

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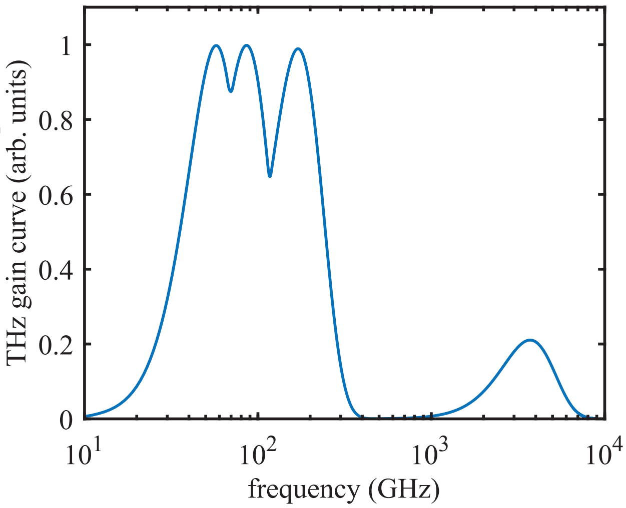

Figure 2: Calculated accessible frequency range of laser-induced THz radiation over four revolutions given by the gain curve $g^2(f)$ (see Eq. 2).

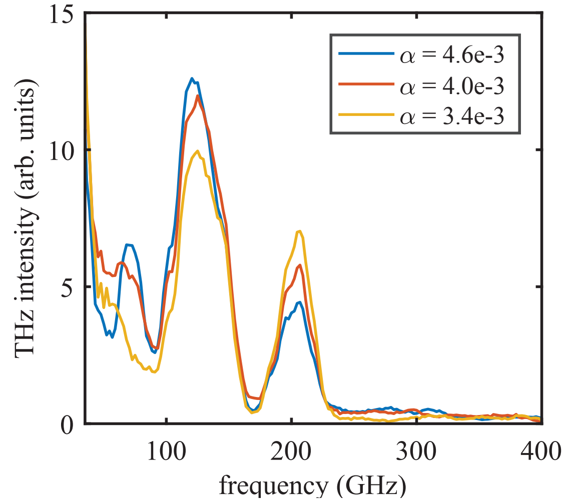

Figure 3: THz spectra measured for slightly different values of the momentum compaction factor α. The standard operation mode is shown in blue.

spread σ_E/E:

$$\begin{aligned} g^2(f) &= \left| \int \rho(t) e^{i\omega t} \mathrm{d}t \right|^2 \\ &\propto \left(r_{56} \frac{\sigma_E}{E} \frac{2\pi f}{c} \right)^4 \\ &\quad \cdot \exp\left[-\left(\frac{2\pi f}{c}\right) \left(r_{51}^2 \sigma_x^2 + r_{52}^2 \sigma_{x'}^2 + r_{56}^2 \frac{\sigma_E^2}{E^2} \right) \right]. \end{aligned} \tag{2}$$

The matrix elements r_{5j} are evaluated for all magnetic devices between the laser-electron interaction and the radiating bending magnet. Since the energy modulation persists for several revolutions, multi-turn effects are taken into account. To determine the spectral range which is accessible by laser-induced radiation at DELTA, the calculated coherent emission integrated over four revolutions is shown in Fig. 2. According to Fig. 2, the THz radiation spectrum should be interrupted in the range between about 400 GHz to 900 GHz. In experiments [10] at DELTA, THz radiation was generated in a tunable range from 75 GHz to 5.6 THz with a significant drop of THz intensity between 400 GHz and 600 GHz. Equation 3 implies, that the dispersive properties of the storage ring change the shape of the gain curve $g(f)$. Figure 3 shows experimental results of THz spectra acquired under variation of the momentum compaction factor α from the nominal value $\alpha \approx 4.6 \times 10^{-3}$ down to $\alpha \approx 3.4 \times 10^{-3}$. Here, an intensity shift from lower to higher frequencies is observable. Since the lowered momentum compaction factor α implies a lower value of r_{56}, the observation is in accordance with Eq. 3.

LASER PULSE SHAPING

Spatial Light Modulation

The electro-optical properties of liquid-crystal materials are widely used in optical applications such as liquid-crystal displays. The birefringence of these materials is used to either influence the phase or amplitude of incident light depending on an external control voltage. Recently, two-dimensional liquid-crystal-on-silicon (LCOS) arrays optimized for phase manipulation of laser pulses have become commercially available. These devices being either reflective or transmissive are called spatial light modulators (SLM). Here, the liquid-crystal layer is backcoated with a broadband highly-reflective layer. The device allows to introduce a programmable spatial phase shift. In the following experiments, a Holoeye PLUTO-2 [11] LCOS phase modulator was used for beam manipulation. This model offers a resolution of 1920×1080 pixels covering an active area of $15.35 \times 8.64\,\mathrm{mm}^2$. With laser radiation of 800 nm wavelength, the maximum phase shift is 4.8π. The spatial modulation allows to implement the function of basic optical elements like apertures or (Fresnel) lenses but also more sophisticated optical devices in software.

Temporal Laser Pulse Shaping

The temporal shape of Fourier-limited laser pulses can be changed by a spatial modulation in the Fourier plane of an optical setup [12] as is shown in Fig. 4. Here, a frequency-selective phase shift is applied along the laser spectrum by using an optical grating as a dispersive element. Following the grating, a cylindrical lens removes the beam divergence. At the SLM, a position-dependent phase shift is applied. In the idealized case of a flat spectral phase of the incoming beam, the modulation pattern follows a sinusoidal shape. A second grating transforms from the optical Fourier plane back to the time domain, with a periodic modulation of the pulse intensity.

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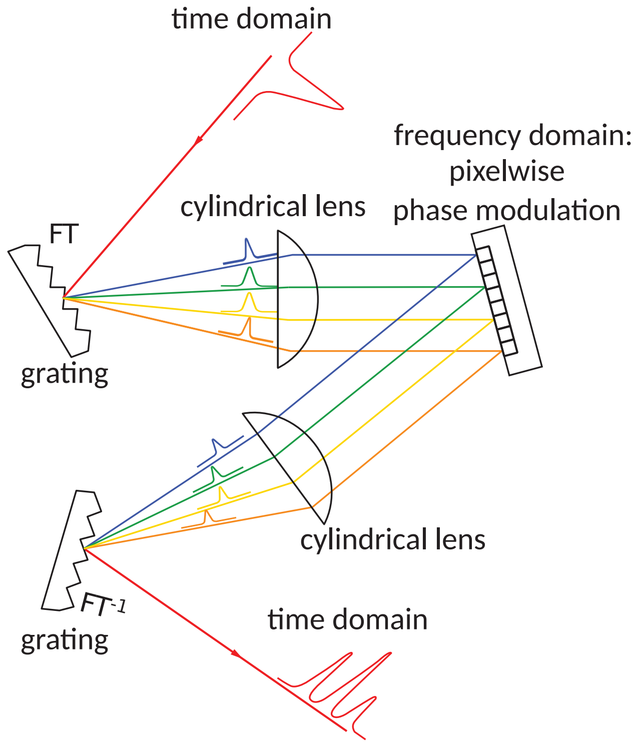

Figure 4: Temporal shaping of a laser pulse is possible by optically mapping the beam onto the Fourier plane and introducing a frequency-selective phase shift. The angles and distances are not to scale.

TOWARDS ARBITRARY PULSE SHAPES IN THE THz DOMAIN

By shaping laser pulses using spatial phase modulation, a more flexible control of the laser pulse shape and the spectrotemporal pulse properties is achieved. Moreover, imperfections of optics or the laser system itself are adressable.

First Results

Recently an optical setup according to Fig. 4 was used for the laser-electron interaction at the DELTA short-pulse facility. By applying sinusoidal phase patterns of different periodicity, a narrowband THz spectrum could be shifted between 100 GHz and 250 GHz in a demonstration experiment. The amount of experimental data presented here results from limited experimental time. It is expected that a much broader frequency range can accessed using this method.

CONCLUSION AND OUTLOOK

Two methods to generate tunable, narrowband THz radiation were applied at DELTA. While the interferometric approach has proven to work over a broad frequency range, promising measurements using an SLM were carried out. It is expected that both pulse shaping techniques cover the same frequency range but that the SLM approach will allow for more sophisticated and more exotic pulse shapes like multiple pulses of same height or arbitrary pulses with controllable steepness.

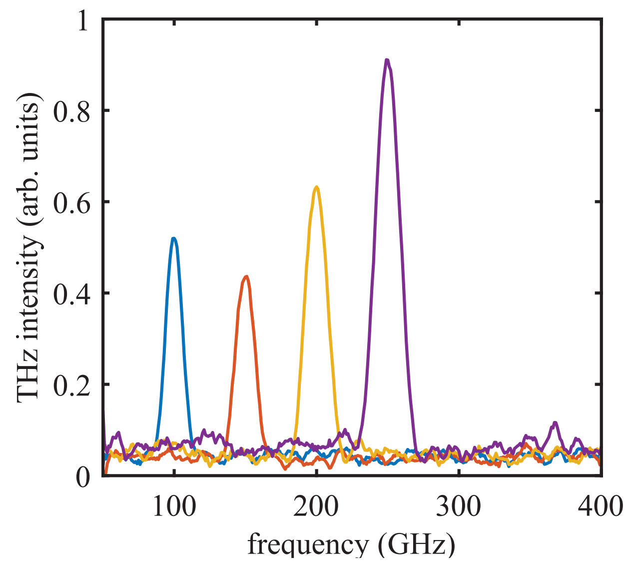

Figure 5: Narrowband sub-THz spectra acquired using a spatial light modulator.

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