TOWARDS ARBITRARY PULSE SHAPES IN THE TERAHERTZ DOMAIN*

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Abstract

The TU Dortmund University operates the 1.5-GeV electron storage ring DELTA as a synchrotron light source in user operation and for accererator physics research. At a dedicated beamline, experiments with (sub-)THz radiation are carried out. Here, an interaction of short laser pulses with electron bunches is used to modulate the electron energy which causes the formation of a dip in the longitudinal electron density, giving rise to the coherent emission of radiation between 75 GHz and 6 THz. The standard mode of operation is the generation of broadband radiation. However, more sophisticated energy modulation schemes were implemented using a liquid-crystal phase modulator. Here, a modulation of the spectral phase of the laser is used to control the spectral shape of the THz pulses. The resulting THz spectra have a relative bandwidth of about 2%. Measurement results from the different THz generation schemes are presented.

INTRODUCTION

DELTA is a 1.5-GeV electron storage ring operated by the TU Dortmund University. Ultrashort VUV [1, 2] and THz pulses are routinely generated at the dedicated short-pulse facility [3, 4]. Here, an interaction between a short pulse from a Ti:sapphire laser system and an electron bunch in the storage ring is used to modulate the electron energy inside the electromagnetic undulator U250. The periodic energy modulation imprinted by the laser, transforms into a density modulation in the subsequent magnets. The laser system is operated at a repetition rate of 1 kHz and offers pulse energies of up to 8 mJ. For the energy modulation, either the direct 800-nm laser radiation or frequency-doubled 400-nm laser pulses are used. For the application of the coherent harmonic generation (CHG) scheme, where radiation in the UV and VUV regime is generated, the U250 is operated in an optical-klystron-like configuration consisting of three independent sections, modulator (7 periods), chicane (3 periods) and radiator (7 periods).

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. Hence, the U250 is used as a single, 19-period undulator. 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.

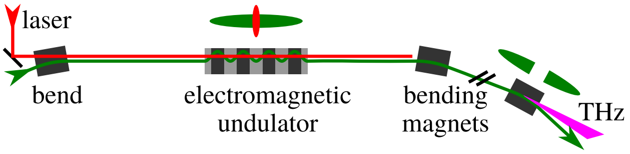

Figure 1: Setup for the coherent emission of laser-induced THz radiation (see text for details).

Table 1: Parameters of the Electron Storage Ring DELTA

beam energy	1.5 GeV
circumference	115.2 m
revolution time	384 ns
multibunch current	130 mA (max.)
single-bunch current	20 mA (max.)
bunch length	100 ps (FWHM)
horizontal beam emittance	18 nm rad
relative energy spread	7×10^{-4}
momentum compaction factor	5×10^{-3}

LASER-INDUCED THz RADIATION AT STORAGE RINGS

The short-pulse facility at DELTA is routinely operated for the generation of broadband THz radiation. In recent years, steps towards better control of the spectro-temporal pulse properties were made. A periodic intensity modulation of laser pulses with a duration of up to 20 ps, can be used to narrow the spectral width.

Broadband THz Radiation

Figure 2 shows two spectra of coherently emitted THz radiation. Here, a laser pulse with a duration of 40 fs is used. The energy modulation is either carried out with 800-nm laser pulses (blue curve) or 400-nm laser pulses (red curve). The spectra were measured using a Fourier-transform spectrometer [5]. The pulse energy of 800-nm radiation is 3.5 mJ while it is only 2.4 mJ at 400 nm. The lower pulse energy translates into a spectral shift towards higher frequencies.

Narrowband THz Radiation

To achieve narrowband spectra, a periodic intensity modulation of the laser pulses is used. This is realized by dispersing the laser beam at a grating and focussing each wavelength with a cylindrical lens to a reflective, computer controlled spatial light modulator (SLM). As shown in Fig. 3, a frequency-selective phase shift is applied at the position

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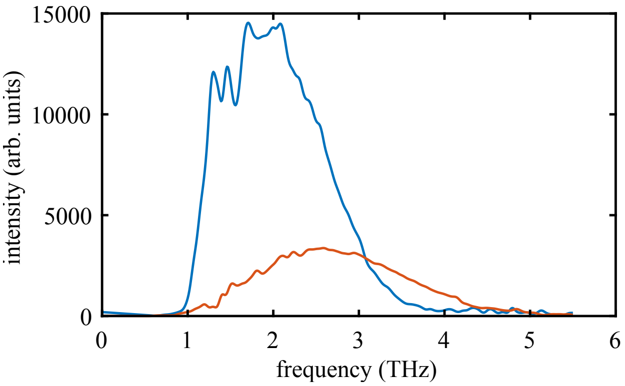

Figure 2: THz spectra induced by a laser-electron interaction between a 100 ps long electron bunch and 40 fs long laser pulses with a wavelength of 800 nm (blue curve) or 400 nm (red curve).

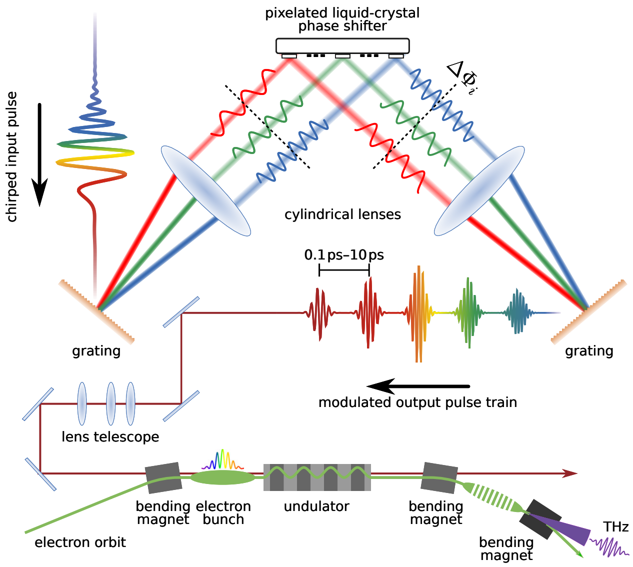

Figure 3: Temporal shaping of a laser pulse is possible by optically mapping the beam onto the Fourier plane and introducing a frequency-selective phase shift. The angles and distances are not to scale.

of the phase modulator in the so-called Fourier plane. The SLM contains a 2D phase-shifter matrix of 1920 × 1080 pixels. Here, columnwise the same shift is programmed and the spatially dispersed beam is recombined by another cylindrical lens and a grating. The horizontal position $x(\omega)$ of the pixels reflecting laser radiation with a frequency ω reads [6]

$$x(\omega) - x_0 = f \cdot \tan\left[\arcsin\left(\frac{2\pi c}{\omega g} - \sin\theta_i\right) - \arcsin\left(\frac{2\pi c}{\omega_0 g} - \sin\theta_i\right)\right], \qquad (1)$$

with the central position x_0 of the modulator, the focal length f of the lenses, the central frequency ω_0, the angle of incidence θ_i at the first grating and the grating constant (line distance) g. In addition to the theoretical description, a spectral calibration measurement was carried out. Equation (1) gives a relation between the transverse coordinate in the Fourier plane and the laser frequency, allowing to manipulate the spectral phase in the spatial domain.

Temporal Laser Pulse Shaping

The spectral phase $\phi(\omega)$ of a laser pulse is described as a Taylor series in ω with the central frequency ω_0 as

$$\phi(\omega) = D_0 + D_1 \cdot (\omega - \omega_0) + D_2 \cdot (\omega - \omega_0)^2 + D_3 \cdot (\omega - \omega_0)^3 + \dots \qquad (2)$$

The second order D_2 defines the pulse length and D_3 is the third-order dispersion. To generate narrowband THz pulses, the third-order dispersion needs to be suppressed [7]. The grating compressor from the laser system introduces a significant D_3 [8] which is corrected by the SLM by adding the inverse of the third-order term

$$\phi_{\mathrm{SLM,corr}}(\omega) = -D_3 \cdot (\omega - \omega_0)^3. \qquad (3)$$

Applying an additional phase modulation

$$\phi_{\mathrm{SLM,mod}}(\omega) \propto \cos\left[\Delta T \cdot (\omega - \omega_0)\right], \qquad (4)$$

leads to the occurence of a laser pulse train with a temporal pulse spacing of ΔT. The pulse spacing is monitored with an intensity autocorrelator measuring the intensity modulation of the laser pulse. With a periodic modulation, the laser pulse is used to interact with the electrons to generate narrowband THz pulses. Figure 4 shows a series of narrowband spectra under variation of the modulation frequency from 1.5 THz to 6 THz. The spectral width is varied between 80 GHz (top) and 200 GHz (bottom) by changing the amplitude of the phase modulation.

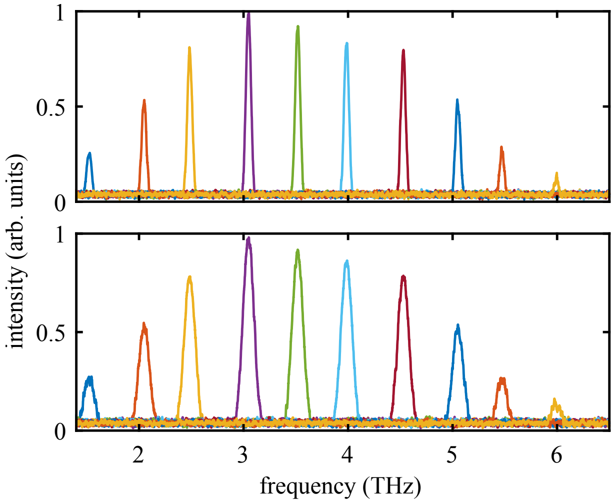

Figure 4: Narrowband THz spectra from a laser-electron interaction with intensity modulation induced by a spatial light modulator. The bandwidth was either set to 80 GHz (top) or 200 GHz (bottom) by changing the phase-shifting pattern.

COMPLEX SPECTRAL SHAPES

Further attemps to shape THz spectra include the generation of rectangular and trapezoidal spectra. The resulting spectra are shown in Fig. 5. Here, multiple terms to form the spectral phase are summed up and applied to the phase modulator. However, as the total phase shift gets larger, sub-harmonics of the original modulation frequency arise in the spectra. Here, these are cancelled out by applying another modulation according to Eq. (4) with a cosine modulation of half the original frequency shifted by π. This leads to destructive interference of the sub-harmonics and clean spectra.

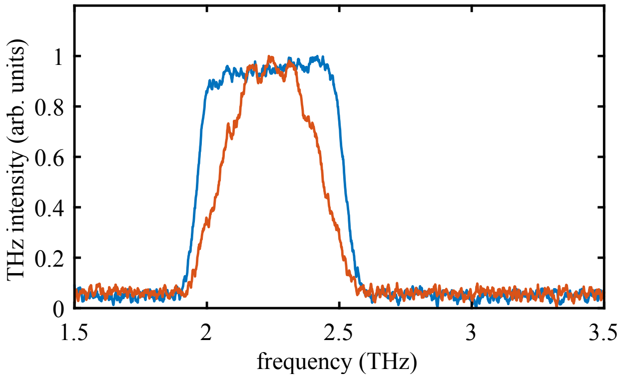

Figure 5: Attempts to generate a rectangular spectrum (blue) and a trapezoidal spectrum (red).

CONCLUSION AND OUTLOOK

In recent years, several attempts to shape THz pulses were implemented at DELTA. So far, the intensity modulation of laser pulses by an SLM in the Fourier plane offers the largest flexibility regarding the resulting spectra. Narrowband as well as more complex spectra were generated by a fully remote-controlled optical setup. As a next step, the phase modulator shall be used to create chirped THz pulses which can be compressed by a dispersive material or another kind of THz pulse compressor.

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