A SIMPLE SPECTRAL CALIBRATION TECHNIQUE FOR TERAHERTZ FREE ELECTRON LASER RADIATION

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Abstract

Upconversion of terahertz FEL radiation to the optical spectral region allows the use of highly efficient optical detection techniques (such as photo-diodes, spectrometers, array detectors) for sensitive characterization of the THz radiation. For online monitoring of the FEL radiation, a small fraction of the radiation is upconverted to the near-infrared region using a ZnTe crystal and a narrow bandwidth continuous wave (cw) laser operating at 780 nm. The ZnTe crystal does not need any angle tuning, and allows the efficient conversion of all wavelengths longer than 100 micrometer. Because the upconversion laser is cw, the FEL radiation is automatically temporally synchronized. Furthermore, the narrow bandwidth of the continuous wave laser ensures that the spectral properties of the upconverted light can be directly related to the FEL radiation. In this contribution we demonstrate the upconversion technique for the spectral characterization of THz pulses of FELIX (100-220 micrometer radiation). In the near future, the upconversion spectrometer will be used as online wavelength spectrometer for FLARE, the THz FEL under construction at the Radboud University in Nijmegen which will operate in the 100-1500 micrometer spectral range.

INTRODUCTION

Real-time, online monitoring of the frequency spectrum of the FEL pulses is an essential diagnostic tool for reliable FEL operation. For the terahertz spectral range, such a real-time diagnostic tool is not straightforward, as spectrometers with multichannel detectors are not readily available. Upconversion of terahertz radiation to the optical spectral region allows the use of highly efficient optical components and detectors.

Upconversion can be achieve by sum en difference frequency mixing of the THz light and near infrared (or visible) light in a non-linear crystal. Sidebands are generated at frequencies $\nu_0 \pm \nu_{THz}$, with ν_0 the frequency of the optical laser. If this laser is a continuous wave (cw) laser, temporal overlap between the FEL pulses and the continuous wave laser light is automatically achieved. At the Santa Barbara mm wave FEL, this upconversion technique has been used to determine the wavelength of the FEL radiation [1].

For FLARE, the THz FEL which is under construction at the Radboud University in Nijmegen [2, 3], we have increased and quantified the sensitivity and spectral resolution of this technique [4]. Since FLARE is still under construction, measurements have been performed at the longest wavelengths of the FELIX free electron laser (100-220 μm) [5]. In this contribution, we report on our latest results.

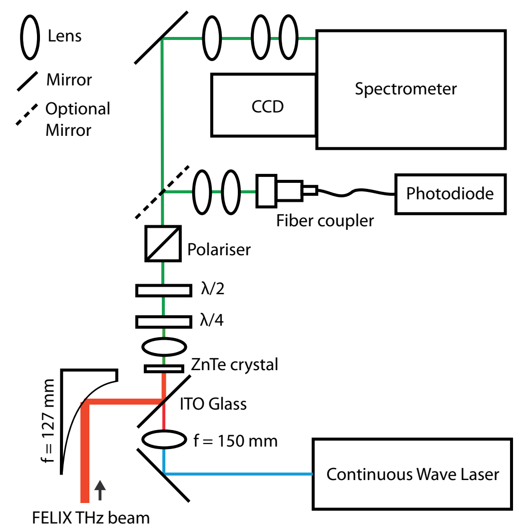

Figure 1: (color) Upconversion spectrometer for spectral measurements of THz FEL radiation.

EXPERIMENTAL SETUP

Figure 1 shows a scheme of the upconversion spectrometer. The continuous wave laser is a single-mode Ti:Sapphire laser providing 200 mW of output at a wavelength of 780 nm with a linewidth of approximately 1 MHz. The cw beam is focussed on a ZnTe crystal, together with the FELIX THz beam. An ITO coated plate acts as a beam combiner. The polarization of the laser and the FEL are parallel [6]. As the polarization of the sidebands is perpendicular to the polarization of the 780 nm laser, the intensity of the carrier can easily be suppressed by several orders of magnitude using polarizing optics [4]. A fast optical detector, like a photodiode, can be used to measure the temporal structure of the upconverted light (both sidebands). Alternatively, the light is directed towards a grating spectrometer equipped with a gated image-intensified CCD camera, for spectral measurements.

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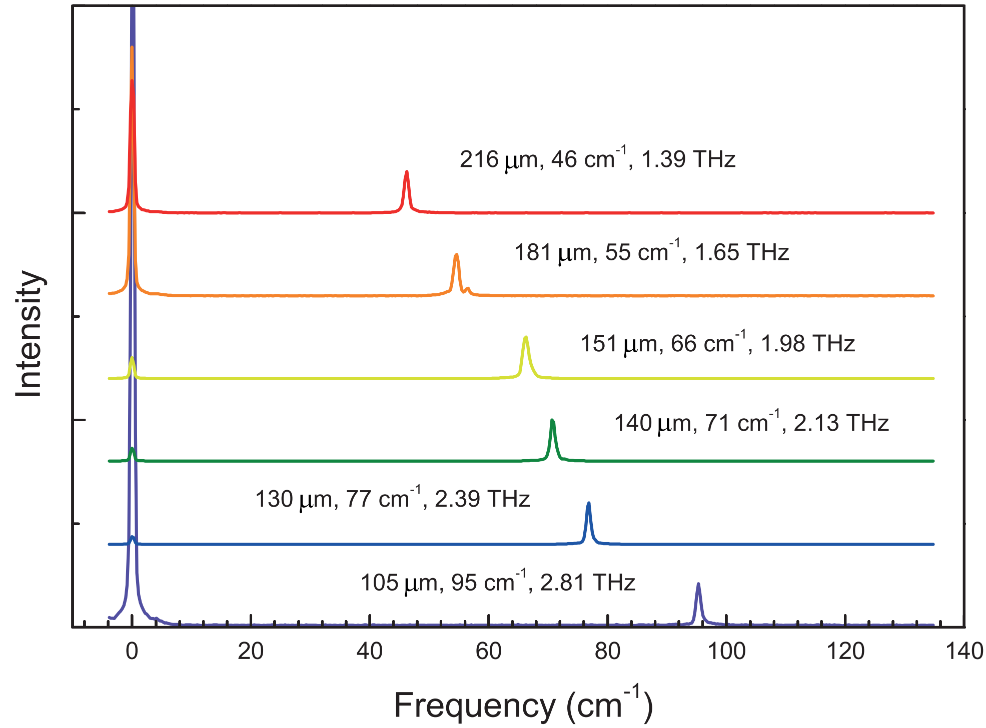

Figure 2: (color) Single-shot spectral measurement for several FEL wavelengths. The frequency of the continuous wave 780 nm laser has been set to zero, such that the THz frequency can be directly read.

SPECTRAL MEASUREMENTS

Directing the light to the spectrometer / CCD camera combination allows single-shot spectral measurements. Figure 2 shows spectra for six different FELIX wavelengths. The individual spectra are normalized to the maximum of the sideband signal (the peak on the right). The frequency of the 780 nm laser is 12829 cm^{-1}, and only one sideband can be detected with this setting of the grating spectrometer (the other sideband does not exit the spectrometer). For each spectrum the frequency of the THz FEL pulse is given by the frequency difference of the two peaks. Note that these spectra have been recorded without any change to the ZnTe crystal orientation of spectrometer setting, thus demonstrating the simplicity and flexibility of the detection scheme.

With ZnTe as non-linear crystal, THz radiation with frequencies up to 3 THz (i.e. wavelengths longer than 100 μm) can be efficiently upconverted [7, 6]. This limitation arises from a transverse-optical lattice oscillation in ZnTe at a frequency of 5.3 THz [7] In fact, the choice of the non-linear crystal for upconversion is exactly the same as the choice for electro-optic detection (the same χ^2 effect), and information on crystal properties and limitation can be found in the literature (see for example, references [8, 9] and references therein).

The spectra of Figure 2 have been recorded with a micropulse energy of 1 μJ (measured in front of the ZnTe crystal) and with the near infrared laser at a power of only 20 mW. With an attenuation of 38 dB (factor of 6310) in the THz beam, resulting in a micropulse energy of 160 pJ at 151 μm wavelength, and with 20 mW of the Ti:Sapphire laser, the generated difference frequency band could at maximum detector gain still be detected at a single-shot

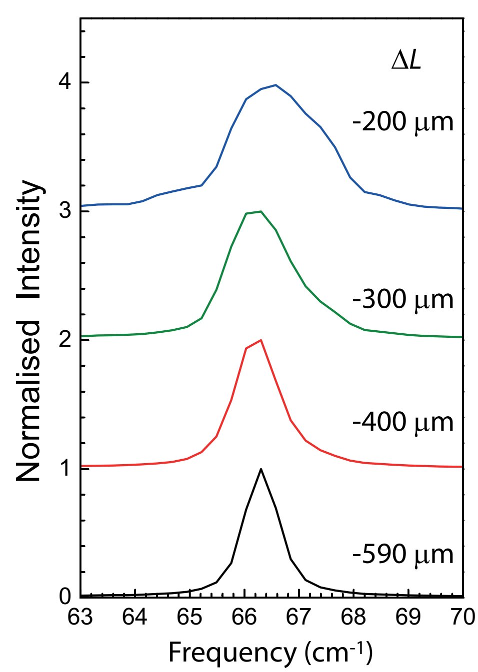

Figure 3: (color) Single-shot spectral measurement for several detunings (ΔL) of the FEL cavity.

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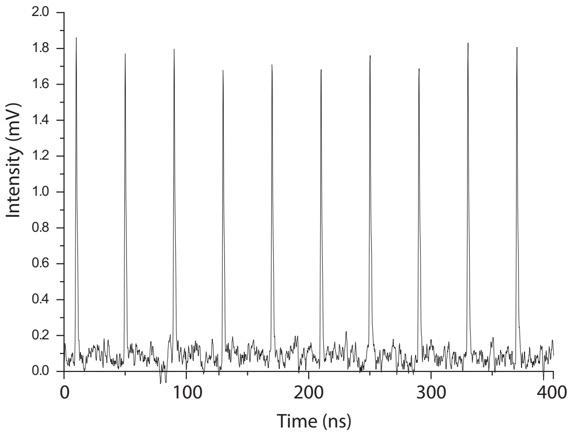

Figure 4: Temporal structure of part of the FELIX macropulse. The micropulse repetition rate is 25 MHz.

basis with a S/N exceeding 5.

The spectral bandwidth of the FELIX pulses can be varied by changing the length of the optical cavity of the FEL [10], which changes the synchronism between the optical pulses circulating the cavity and the injected electron bunches. Figure 3 shows the spectra of the FEL pulse for four different cavity detunings. The resolution of the upconversion spectrometer is not enough to fully resolve the most narrow FEL pulse. Currently, the resolution is about 0.2 cm^{-1} due to the dispersion of the grating spectrometer and CCD pixel size to almost equal extent. Note that the contribution due to the finite bandwidth of the continuous wave upconversion laser, about 10^{-5} cm^{-1}, is completely negligible.

TEMPORAL MEASUREMENTS

The upconversion scheme can also be used to visualize the temporal structure of the THz FEL pulse. The light transmitted by the polarizing optics is now coupled into a fiber, which is connected to a fast photodiode. The photodiode signal is recorded with a 500 MHz oscilloscope, and is shown in Figure 4. The FEL wavelength was 150 μm (2 THz). The FELIX micropulse repetition frequency was 25 MHz, which therefore gives a sideband pulse every 40 ns. The temporal resolution of the photodiode and oscilloscope is not enough to resolve the actual micropulses which have a duration of approximately 30 ps.

UPGRADE OF THE UPCONVERSION SPECTROMETER

The upconversion spectrometer presented here is directly suitable for FLARE. The full wavelength range of FLARE, 100-1500 μm (0.2-3 THz) can be upconverted as can be seen in Figure 2. The long wavelengths can be detected as well, as has been demonstrated by Jamison et al. [6] where the spectrum of the Coulomb field of sub-picosecond electron bunches (covering the spectral range from 0-2 THz) could be measured with the upconversion technique.

FLARE will combine a short-pulse pump-probe mode (1% resolution) with a high resolution spectroscopic mode (spectral resolution $10^{-5} - 10^{-6}$). For the pump-probe mode the resolution of the upconversion spectrometer, 0.2 cm^{-1}, is not sufficient for long wavelengths. Work is in progress to replace the optical grating spectrometer / CCD camera system by similar system with higher resolution, that is, more resolving power for the spectrometer, and more pixels for the camera. For the high spectroscopic mode, we plan to extend the upconversion spectrometer with a wavemeter.

In order to simplify the experimental geometry, the single mode continuous wave Ti:Sapphire laser will be replaced by a more robust (and much cheaper) diode-laser system. This will ensure reliable daily operation of the FLARE spectrometer.

CONCLUSION

We have demonstrated the measurement of the spectrum of single THz FEL pulses by upconverting it to optical frequencies. This method allows the use of rather simple lasers and directly provides the spectrum of the THz pulse in real-time and in a single-shot.

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