CHARACTERIZATION OF THE THz RADIATION-BASED BUNCH LENGTH MEASUREMENT SYSTEM FOR THE NSRRC PHOTOINJECTOR

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Abstract

A part of high brightness photo-injector (HBI) project at NSRRC is intending to adopt Coherent Transition Radiation (CTR) and Coherent Undulator Radiation (CUR) to generate THz radiation with an ultrashort electron bunch. Such high intensity THz sources allow the THz spectrum to be conducted easily with a THz interferometer and a Golay cell detector. Furthermore, the radiation spectrum carries information of the electron distribution which allows ultrashort electron bunch length measurements. For verifying correct measuring procedure during the CTR and CUR experiments, a conventional THz radiation generated by optical rectification from a ZnTe crystal has been performed. The produced THz pulse was sent into a Michelson interferometer which is designed for the autocorrelation of the intense, sub-mm and mm-wavelength, spatially-coherent radiation pulses. The THz spectrum can be further obtained from the interferogram by the Fourier transform process. In such way, the THz spectrum can be investigated if the result is satisfactory and can be applied on the THz CTR and CUR experiments for the next step.

INTRODUCTION

THz radiation is referred to as electromagnetic waves of frequencies from 0.3 to 30 THz. This band has many applications such as condensate physics, astronomy, telemetry and medical image. A good THz radiation source shall have the property of wide bandwidth and high power as well as excellent tunability and stability. The free-electron laser has the above properties as a good radiation source. However, such radiation source needs quite high cost in construction and maintenance.

Generation of CTR and CUR in the THz region using the S-band photo-injector linac system at NSRRC is under construction. The layout of the system is shown in Fig. 1. Using velocity bunching, an electron bunch in the linac can be accelerated and compressed simultaneously. Start-to-end simulation of space charge dynamics shows that a 100 pC electron bunch with effective bunch length of ~ 90 fs can be generated in the system.

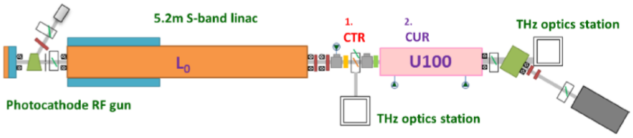

Figure 1: Layout of the photo-injector system for generation of coherent THz radiations at NSRRC.

Narrow-band tunable fully coherent THz radiation can be produced from a U100 planar undulator when it is driven by such ultrashort electron bunch. The THz pulse energy can be expected as high as ~ 3 μJ [1].

THz GENERATION AND DETECTION

There are several technologies to generate THz radiation such as photoconductive antenna (PCA) [2], optical rectification (OR) [3], differential frequency generation (DFG) [4], and gases or air plasma [5].

Before the CTR and CUR experiments, the OR method is adopted to produce the THz sources for the preliminary test. OR is a second-order nonlinear optical process in which, following the application of an intense laser field, a quasi dc polarization is induced in an electro-optic crystal due to difference frequency generation. This effect was first observed in 1962 by M, Bass et al., by using Ruby lasers in a KDP crystal [6].

THz generation occurs via optical rectification in a <110> ZnTe crystal. Optical rectification is a difference frequency mixing and occurs in media with large second order susceptibility, $\chi^{(2)}$. Optical rectification is actually analogous to frequency doubling. That is, a polarization is induced in the crystal that is the difference of the individual frequencies instead of their sum. This is due to the well-known trigonometric relation:

$$cos(\mathrm{A}) * cos(\mathrm{B}) = [\cos(A+B)+\cos(a-B)]/2 \tag{1}$$

Thus, light of a given frequency passing through a nonlinear medium will generate the same amount of both sum and difference frequencies, corresponding to second harmonic and dc [7].

Mathematically, the polarization P can be expanded into a power series of the electric field E*opt,*

$$\vec{\mathrm{P}}(\mathrm{t}) = \chi^{(1)}(t)\vec{E}_{opt}(t) + \chi^{(2)}(t)\vec{E}_{opt}(t)^2 + \chi^{(3)}(t)\vec{E}_{opt}(t)^3 + \cdots \tag{2}$$

where$\chi^{(n)}$ is the nth order nonlinear susceptibility tensor. This is the result of noncentrosymmetric nature of the nonlinear crystal, which induces optical rectification. If the incident light is a plane wave, then it can be expressed as,

$$\vec{E}_{opt}(t) = \int_0^\infty \vec{E}_{opt}(\omega)\exp(-i\omega t)\,\mathrm{d}\omega + \mathrm{cc}. \tag{3}$$

By substituting Eq. (3) into Eq. (2), the polarization for the optical rectification can be rewritten as,

$$\begin{aligned}\vec{P}_{\mathrm{OR}}^{(2)}(\mathrm{t}) &= 2\chi^{(2)}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\vec{E}_{opt}(\omega_1)\vec{E}_{\mathrm{opt}}^{*}(\omega_2)\exp[-i(\omega_1 \pm \omega_2)t]\,\mathrm{d}\omega_1\mathrm{d}\omega_2 \\ &= 2\chi^{(2)}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\vec{E}_{opt}(\omega+\Omega)\vec{E}_{\mathrm{opt}}^{*}(\omega)\exp[-i\Omega t]\,\mathrm{d}\omega\mathrm{d}\Omega\end{aligned} \tag{4}$$

In the far field, the radiated electric field $\vec{E}_{THz}(t)$ is proportional to the second order derivative of the induced polarization with respect to time.

$$\vec{E}_{THz}(t) \propto \frac{\partial^2}{\partial \mathrm{t}^2}\vec{P}_{\mathrm{OR}}^{(2)}(\mathrm{t}) \tag{5}$$

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For efficient transfer of energy from optical to THz radiation, the phase matching condition, which is given by the following equation, should be satisfied:

$$k(\omega+\Omega)-k(\omega)=k_{THz}(\Omega) \tag{6}$$

Here, k is the wave vector, ω is the angular frequency of the pump beam, and Ω is one particular frequency of the radiated THz wave packet [8].

EXPERIMENTAL SETUP

In this testing experiment the NSRRC ultrafast laser system is used to generate the THz radiation by optical rectification from a ZnTe crystal. The laser system is a Ti:sapphire laser system based on the chirped-pulse amplification technique. It delivers 800-nm central wavelength, 3.5-mJ IR laser pulse with energy stability <0.3% RMS, 100-fs pulse duration and 1-kHz repetition rate. Following the high brightness injector project the whole laser system was moved to the NSRRC linac test laboratory and installed in a temperature-humidity controlled clean room in 2015. As shown in Fig. 2, an energy tuner, consisting of a half-wave plate and a thin film polarizer, is installed in the optical path to modify the laser power. A 15-mm square, 1-mm thick, <110> ZnTe crystal is used as the THz emitter. The laser pulse is focused to a beam size of 5-mm diameter at the ZnTe crystal position by a convex lens with 30-cm focal length. Two 90 degree, gold-coated off-axis parabolic mirrors (OAP) with 3-inch diameter and 15-cm focal length are used for measuring the THz power. The emitted THz pulse is collected and collimated by the first OAP. Two pieces of Teflon with 10-mm thickness are used to block the residual 800-nm laser pulse. The collimated THz pulse is further focused by the second OAP and redirect the THz pulse onto a Golay cell detector (Microtech Instruments) to measure the THz power. A chopper positioned in front of the PE window of the Golay cell detector allowed modulation of the THz beam. The THz power can be retrieved from the detected signal and the responsivity of the detector. Once the second OAP is removed, the THz pulse can be transported into the bunch length interferometer system (BLIS) to resolve the THz spectrum, as shown in Fig. 3. The BLIS, made by RadiaBeam technologies [9], is a compact THz interferometer designed for the autocorrelation of the intense, sub-mm and mm-wavelength, spatially-coherent radiation pulses. By systematically measuring the signal at the detector for different values of τ, one can obtain the autocorrelation function of the input pulse:

$$S(\tau)\propto\int I(t)I(t+\tau)dt \tag{7}$$

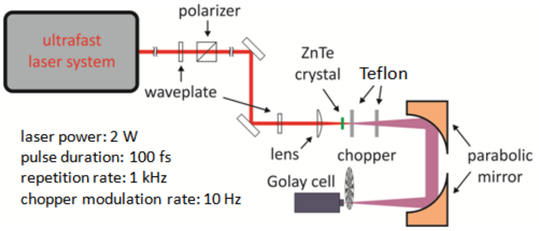


Figure 2: Setup of THz generation.

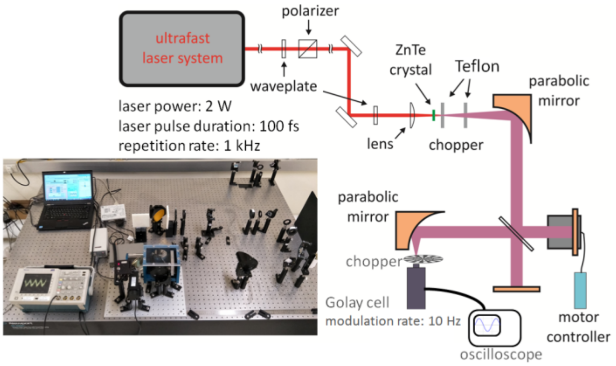
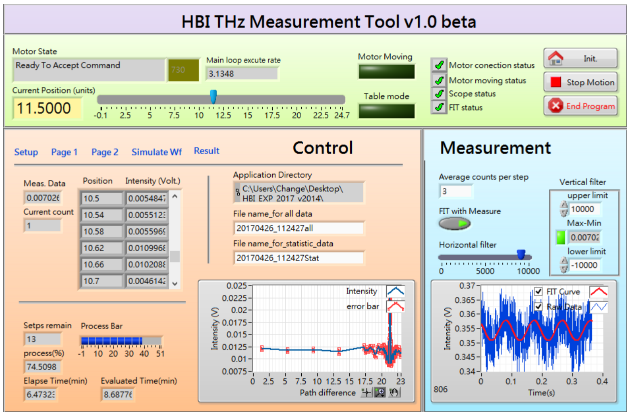


Figure 3: Setup of the BLIS.

Complete software for automatic measurement by LabVIEW is constructed for integrating the movement of the translation stage within the interferometer, control of oscilloscope, data acquisition, statistic, filter, storage of data and fitting sine wave. The automation of time and human power consuming works of the thousands of data measurement can be done by just pressing one button to save much time. The user interface of the software and the work flow diagram are shown in Fig.4 and Fig. 5, respectively.

During the usage of the software, users can execute coarse or equal step adjustment of movement. After finding the peak value, fine measurement would be proceeded according to the found peak as the center and encircling it by various moving radius tables for the measurement. Three ranges are defined for different sampling resolution, such as r1 for highest density measurement, r1- r2 for looser sampling and r2-r3 for roughest acquisition. Such sampling procedure can save much time and keep the precision of the measurement.

Data fitting is a very common task when analyzing measured data. This involves finding a formula that most appropriately describes the relationship between one or more independent variables to a dependent variable. In this program, the data fitting can be done by selecting on-line or off-line function which uses WE-Fit toolkit for LabVIEW [10] to achieve fast and precise fitting works.


HBI THz Measurement Tool v1.0 beta

Motor State: Ready To Accept Command 730
Main loop excute rate: 3.1348
Current Position (units): 11.5000

☑ Motor conection status
☑ Motor moving status
☑ Scope status
☑ FIT status

Control

Meas. Data: 0.00702€
Current count: 1

Position	Intensity (Volt.)
10.5	0.0054847
10.54	0.0055123
10.58	0.0055969
10.62	0.0109968
10.66	0.0102088
10.7	0.0046142

Application Directory: C:\Users\Change\Desktop\HBI EXP 2017 v2014\
File name_for all data: 20170426_112427all
File name_for_statistic_data: 20170426_112427Stat

Setps remain: 13
Process Bar
process(%): 74.5098
Elapse Time(min): 6.47323
Evaluated Time(min): 8.68776

Measurement

Average counts per step: 3
FIT with Measure
Horizontal filter
Vertical filter
upper limit: 10000
Max-Min: 0.00702
lower limit: -10000

Figure 4: Integration measurement software.

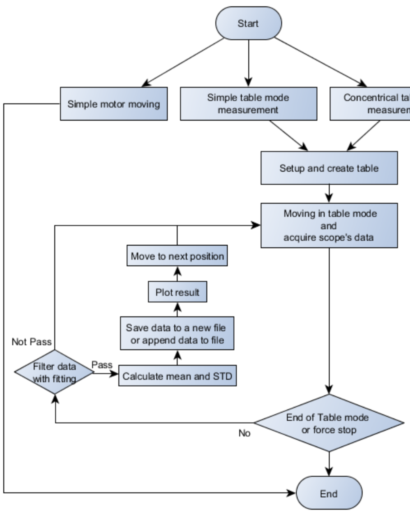


Figure 5: Flow chart of the software operation.

EXPERIMENTAL RESULTS AND CONCLUSION

The measured THz signal is about 42 mV. Figure 6 shows the raw data (blue line) obtained from the Golay cell detector and the fitting sine curve (red line). According to the response of the Golay cell with 10 Hz modulation rate, the THz output is about 12.4 µW, corresponding to a conversion efficiency of 6.2×10^{-6}. The result of Michelson interferometer is shown in Fig.7 and the full width at half maximum (FWHM) is about 150 µm. The THz radiation generated from the ZnTe crystal is detected by using the Michelson interferometer and custom designed software which is used for simplifying and automation of the measurement procedure. After the construction of CTR and CUR in the near future, these measurement tools can be directly applied to the ultrashort bunch length measurement.

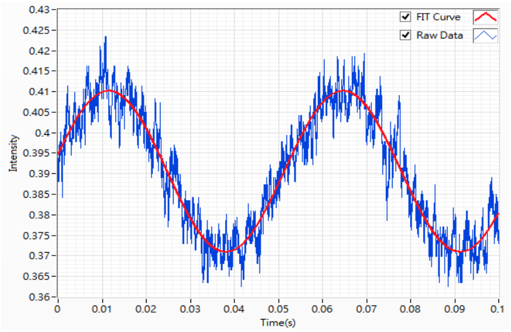


Figure 6: the measured THz signal (blue line) and the fitting sine curve (red line) from the Golay cell detector.

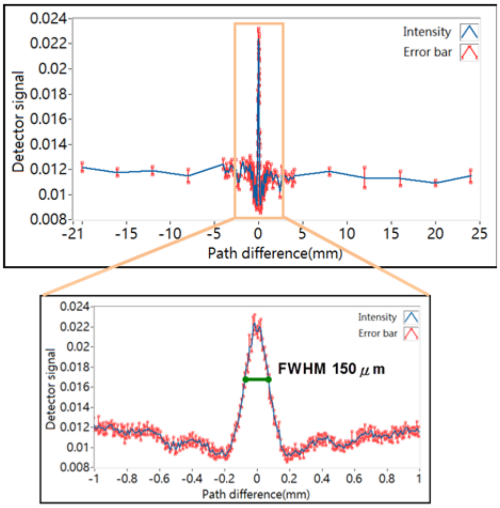


Figure 7: Interferogram obtained from the BLIS.

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