

# GENERATION OF TWO TERAHERTZ RADIATION PULSES WITH CONTINUOUSLY TUNABLE FREQUENCY AND TIME DELAY\*

Wenxing Wang, Haoran Zhang, Shimin Jiang, Zhigang He<sup>†</sup>  
National Synchrotron Radiation Laboratory,  
University of Science and Technology of China, Hefei, China

## Abstract

We propose to generate two narrow band terahertz pulses radiated from two temporally modulated relativistic electron beams, which are generated in a photo-injector. The temporal profile of the drive laser is modulated by means of the paired chirped pulses beating technique, leading to the generation of two pre-bunched electron beams. Coherent transient radiation (CTR) is considered as the mechanism for terahertz radiation generation. The frequencies of the two terahertz pulses can be independently tuned by adjusting the paired beating frequencies, and the interval between the two terahertz pulses can be adjusted by the optical delay line.

## INTRODUCTION

Terahertz (0.1–1.0 THz) electromagnetic wave has important application value in material science, biomedicine, imaging and other aspects due to its unique penetrating ability, spectral resolution and low photon energy. As for terahertz time-domain spectroscopy (THz-TDS), the THz binary lens tomography is used to image the objects at various positions along the beam propagation path onto the same image plane [1, 2]. Thus, the novel terahertz light source with high intensity and good frequency tunability has become very attractive work.

The terahertz light source based on accelerator is attractive for its advantage of high peak power. A compact terahertz source based on linac can be realized through the super-radiation of pre-bunched electron beams. The energy emitted from pre-bunched electron can be expressed by [3]

$$W(\omega) = W_0(\omega) [N_e + N_e(N_e - 1) f(\omega)] \quad (1)$$

where  $W_0(\omega)$  is the energy emitted from single electron,  $N_e$  is the number of electrons,  $\omega$  is the frequency of the emitted radiation, and  $f(\omega)$  is the bunch form factor, which is defined as the Fourier transform of the electron longitudinal distribution

$$f(\omega) = \frac{1}{N_e(N_e - 1)} \sum_{j,k=1(j \neq k)}^{N_e} e^{i\omega(z_j - z_k)/c} \quad (2)$$

where  $z_j$  is the longitudinal position of the  $j$ th electron relative to the reference electron in a bunch. The shorter the electron beam length is and the more uniform the longitudinal interval is, the higher the bunch form factor will be.

\* Work supported by National Natural Science Foundation of China under contracts No. 11775216 and No. 51627901

<sup>†</sup> Email: hezhg@ustc.edu.cn

As can be seen from the Equation (1), the bunch form factor  $f(\omega)$  defines the radiation spectrum. Therefore, when the longitudinal structure of the electron micro-bunches has the characteristic of terahertz repeat frequency, the coherent transition radiation emitted will feature on the corresponding frequency, thus leading to high-intensity terahertz radiation source.

The generation of pre-bunched electron beams with picosecond or sub-picosecond micro structure has been widely studied. Using a laser pulse train with terahertz repetition frequency, which can be realized by laser polarization beam splitting and stacking [4], spectral shaping and chirped pulse frequency beating [5], to excite a photocathode electron gun is proved feasible for producing a pre-bunched electron beam with a clustered frequency in the terahertz range.

In this paper, a temporary pulse-shaping scheme featured on the paired chirped pulses beating technique is proposed to obtain two trains of cathode-driven laser pulses beating at terahertz frequencies, leading to the generation of two electron beams with the similar temporal structure, and a compact two-pulse terahertz source based on linear accelerator is proposed. The schematic diagram of the device is shown in Figure 1. Coherent transition radiation (CTR) is considered as the mechanism for terahertz radiation generation. The frequencies of the CTR can be tuned within terahertz band corresponding to the laser beating frequencies, and the time interval between the two radiation pulse can be adjusted within several pico-seconds.

## SIMULATION AND RESULT

We use the chirped pulse beating method to produce the ultrashort laser pulse trains. Figure 1 shows the optical path of chirped pulses beating at double frequencies. The incident femto-second laser pulse is extended in the time domain through the parallel diffraction gratings, and the broadened laser pulse is divided into two sub-pulses after passing through a beam splitter with a light intensity ratio of 50:50. The double sets of Michelson interferometers induce the superposition of each chirped pulse with respective time-shift replica, leading to the output pulses [6]:

$$\begin{aligned} I_{1,2}(t) &= |E(t + \tau_{1,2}/2) + E(t - \tau_{1,2}/2)|^2 \\ &= I^+(t) + I^-(t) \\ &\quad + 2\sqrt{I^+(t)I^-(t)} * \cos(4\mu\tau_{1,2}t + \omega_0\tau_{1,2}) \end{aligned} \quad (3)$$

where  $\tau_{1,2}$  are the separate time-shift with the subscript representing the double beating parts,  $1/2\mu$  is the negative group velocity dispersion introduced by grating pair, and

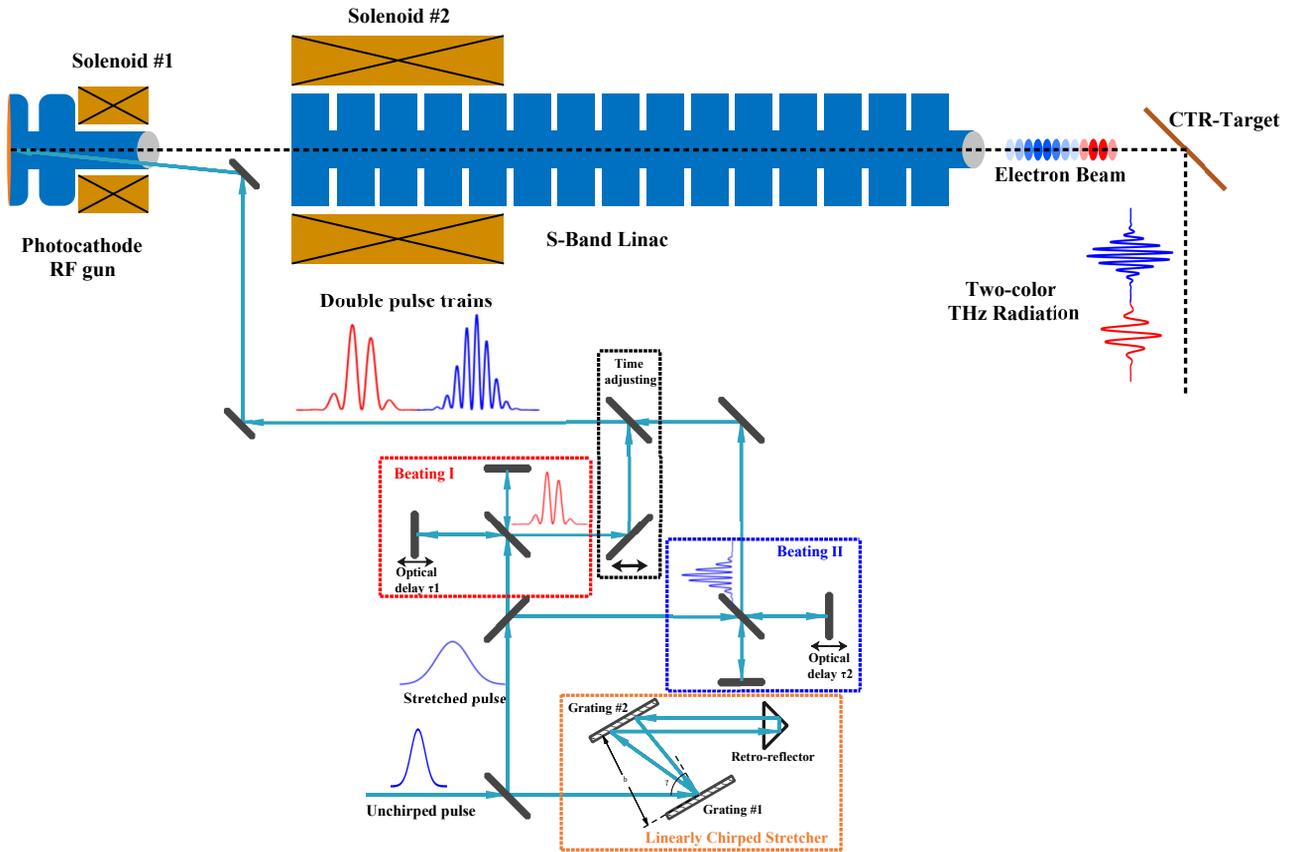


Figure 1: A schematic diagram of a tunable two-color terahertz radiation generator and a design of a beat frequency laser optical path.

$\omega_0$  is the frequency of the unchirped pulse. The last term in the Equation (3) contains the quasi-sinusoidal optical modulation at the beating frequency  $f_0$ , which is given by [6]

$$f_0(\tau, \mu) = \frac{\mu\tau}{2\pi} \quad (4)$$

Under the same group velocity dispersion  $1/2\mu$ , the beating frequency of each splitted chirped pulse can be independently adjusted by tuning the beating time delay  $\tau_{1,2}$  of each group of Michelson interferometers. The chirped light split-time adjustment component in the optical path is composed of a plane mirror and a beam-combination mirror. By adjusting the position of the two optical mirrors, the center interval of two laser pulse trains has a temporary delay  $\tau$ .

In the simulation calculation, the initial laser pulse was selected as a triple frequency titanium sapphire amplifier laser source, with the central wavelength of 266 nm and pulse width (FWHM) of 75 fs. Considering the conversion efficiency of the chirped beating optical path and the chosen cathode material (copper), the generation of tens of pico-coulomb electron beams requires the laser energy to be within a few microjoules. The initial 266 nm laser pulse was broadened through parallel grating pairs, and the broadened pulse width (FWHM) is 5.88 ps. With the three sets of beating time delay  $\tau_1, \tau_2$  and beam splitting temporal delay  $\tau$ , which are listed in the Table 1, the calculated temporal

profile of the double beating frequency laser trains are shown in Figure 2 (a). The paired beat frequencies of each set of double laser pulse trains is listed: 0.977 THz and 2.051 THz, 1.465 THz and 2.539 THz, 3.027 THz and 4.004 THz.

Table 1: Three Sets of Time Delays in the Optical Progress of Double Chirped Pulses Beating Laser Trains

Beating time delays		Beam splitting delay
$\tau_1$	$\tau_2$	$\tau$
0.2 ps	0.4 ps	5.5 ps
0.3 ps	0.5 ps	4.5 ps
0.6 ps	0.8 ps	4.0 ps

A 1.6-cell photo-cathode microwave gun and a 3m SLAC type traveling wave accelerator (TWA) are considered as the electron beam acceleration structure. The parameters are listed in Table2. The TWA entrance is located 0.8 meters downstream of the RF gun exit. Since the photoelectron emission from the photo-cathode is prompt with respect to the drive laser, the temporal distribution of the electron beam is consistent with that of the laser pulse trains.

We use ASTRA [7] code to simulate the electron beam. The effect of space charge force has been considered. In the simulation, the electron beam with the same micro-pulse structure as the beat-frequency laser contains two kinds of

Table 2: Electron Acceleration Structure Parameters

Parameters	Symbol	Value
RF frequency	$f_{rf}$	2856 MHz
Gun field	$E_{gun}$	120 MV/m
Solenoid #1	$B_1$	0.14 T
TWA field	$E_{TWA}$	20 MV/m
Solenoid #2	$B_2$	0.01 T
Total charge	$Q$	10 pC

electron beam micro-pulses with different cluster frequencies in the length of nearly 20 ps, and the total charge of the electron beam is 10 pC. The transverse size of the double beating frequency electron trains at the TWA exit are shown in Figure 2 (b).

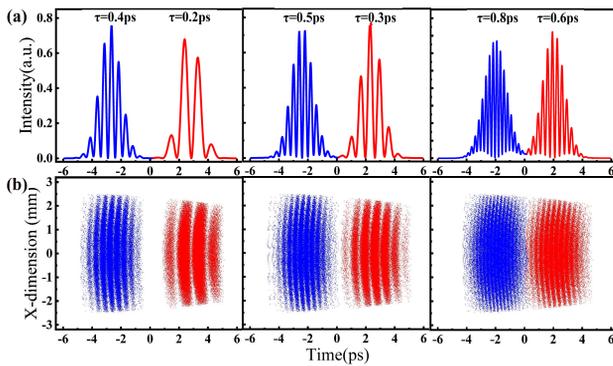


Figure 2: Laser pulse train distribution and electron beam transverse distribution.

A metal target is placed downstream for transit radiation at 1m away from the end of the electron beam acceleration structure. The electron beam will generate the corresponding two terahertz electromagnetic radiation pulses in the form of transit radiation.  $U_1$  is the transition radiation energy emitted from a single electron and expressed by the Ginzburg-Frank formula

$$U_1 \approx \frac{e^2}{2\pi^2 \epsilon_0 c} (\ln \gamma + \ln 2 - 0.5) \quad (5)$$

Due to the quasi-sinusoidal structure of the electron beams, the transition radiation generated by the electron beam with the metal target will be coherently enhanced at the bunching frequencies of the electron beams. When the electron beams cluster in terahertz band, the coherent transition radiation is terahertz radiation. Figure 3 shows the calculated spectrum of the transition radiation wave using the formula 1. The calculated radiation spectrum is well focused at the bunching frequencies of the double electron beams, which is in accord with the bunch form factor defined by the Equation (2), and the bandwidth of the radiation is within 0.5 THz.

## SUMMARY

The double-frequency chirped pulse beating technology provides the paired laser pulse trains at paired repeat frequencies within terahertz band. With the adjustability of the

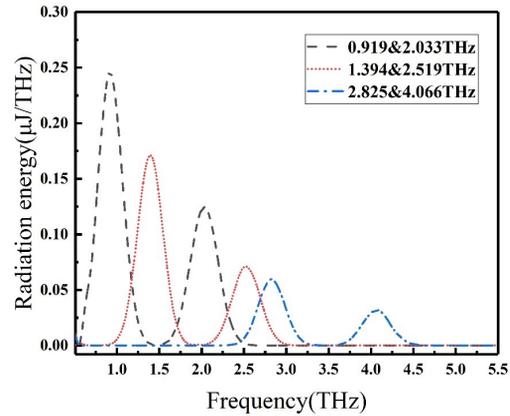


Figure 3: CTR spectrum.

repeating frequencies of each chirped pulse train, the photocathode is able to generate double electron beams bunching at separate and tunable bunching frequencies. The CTR spectrum calculated based on the accelerated pre-bunching electron beams shows the possibility for tunable two-color terahertz waves generation.

## REFERENCES

- [1] S. Wang and X. Zhang, "Pulsed terahertz tomography," *Journal of Physics D: Applied Physics*, vol. 37, no. 4, R1–R36, 2004.
- [2] S. Wang and X.-C. Zhang, "Terahertz wave tomographic imaging with a fresnel lens," *Chinese Optics Letters*, vol. 1, no. 1, pp. 53–55, 2003.
- [3] C. J. Hirschmugl, M. Sagurton, and G. P. Williams, "Multiparticle coherence calculations for synchrotron-radiation emission," *Phys. Rev. A*, vol. 44, pp. 1316–1320, 2 Jul. 1991. doi: 10.1103/PhysRevA.44.1316.
- [4] Z. He, Y. Xu, W. Li, and Q. Jia, "Generation of quasiequally spaced ultrashort microbunches in a photocathode rf gun," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 775, pp. 77–83, 2015.
- [5] Y. Shen, X. Yang, G. Carr, Y. Hidaka, J. B. Murphy, and X. Wang, "Tunable few-cycle and multicycle coherent terahertz radiation from relativistic electrons," *Physical Review Letters*, vol. 107, no. 20, p. 204 801, 2011.
- [6] A. S. Weling and D. H. Auston, "Novel sources and detectors for coherent tunable narrow-band terahertz radiation in free space," *Journal of the Optical Society of America B: Optical Physics*, vol. 13, no. 12, pp. 2783–2792, 1996.
- [7] K. Floettmann, *Astra user manual*. [http://www.desy.de/~mpyflo/Astra\\_documentation/](http://www.desy.de/~mpyflo/Astra_documentation/)