MICROFABRICATION OF RELATIVISTIC ELECTRON BEAM BY LASER AND ITS APPLICATION TO THz COHERENT SYNCHROTRON RADIATION*

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Abstract

It is well known that broadband coherent synchrotron radiation (CSR) is emitted by an electron bunch whose length is shorter than radiation wavelength. However, even a long electron bunch can emit CSR when it has micro-density structure whose characteristic length is equal to the radiation wavelength. Recently, we have demonstrated that, by injecting amplitude modulated laser pulses into an electron storage ring, quasi-monochromatic and tunable terahertz (THz) CSR could be produced. In this method, periodic micro-density structure of THz scale was created on the electron bunch, as the result of the laser-electron interaction. The bunch emitted quasi-monochromatic THz radiation in a uniform dipole filed, not in an undulator. This new technology provides a way to imprint periodic wave patterns inside the electron bunch phase space. In adding to the light source applications, this would be a new tool to investigate electron beam dynamics.

INTRODUCTION

A terahertz (THz) light is used as a powerful tool for researches in physics, chemistry, biology, materials science and medicine. There is undeveloped frequency region of the electromagnetic spectrum from 0.3 to 20 THz (10–600 cm^{-1}). Recently, the coherent synchrotron radiation (CSR) emitted from relativistic electrons is expected as a new THz source filled this region.

For future accelerators, such as linac-based free electron lasers, energy recovery linacs, and linear colliders, it is predicted that the CSR wake potential causes bunch lengthening and emittance growth [1]. To investigate these phenomena systematically, the experimental study of the emitted CSR is essential.

The first observation of THz CSR from relativistic electrons was reported by the group of Tohoku University [2]. They accelerated short electron bunches to the energy of 180 MeV and applied a uniform dipole field to them. As the results, the broadband CSR was observed in the wavelength of 4.5–25 cm^{-1} and the intensity was five orders of magnitude compared with that of incoherent SR.

Even a long electron bunch can emit CSR when it has micro-density structure whose length is equal to radiation wavelength. The laser slicing technique is a method of producing a micro-density structure on an electron bunch in the longitudinal direction. In this technique, a part of electrons in the bunch is knocked out by a short laser pulses. Then a dip structure is shaped on the bunch along the longitudinal direction. The generation of THz CSR by this technique have been reported [3, 4], including our own [5], during the past two years.

Recently, we have demonstrated that tunable and quasi-monochromatic THz CSR could be produced by using amplitude modulated laser pulses instead of short laser pulses [6]. In this experiment, the periodic micro-density structure of THz scale was created on the electron bunch. The bunch emitted quasi-monochromatic THz radiation in a uniform dipole filed, not in an undulator. In this paper, we report details of the generation of tunable and quasi-monochromatic THz CSR by using amplitude modulated laser pulses at the UVSOR-II storage ring.

PRINCIPLE OF CSR GENERATION

The radiation power $P(k)$ emitted by an electron bunch is written as a function of the wave number k as follows [7],

$$P(k) = N\,p(k) + N(N-1)F(k)\,p(k), \quad (1)$$

where N and $p(k)$ are the number of electrons and the radiation power from each single electron. A form factor $F(k)$ of an electron bunch is related to the longitudinal electron density $Q(z)$ via Fourier transform and defined as

$$F(k) \equiv \left| \int dz\, Q(z) \exp\left(-ikz\right) \right|^2. \quad (2)$$

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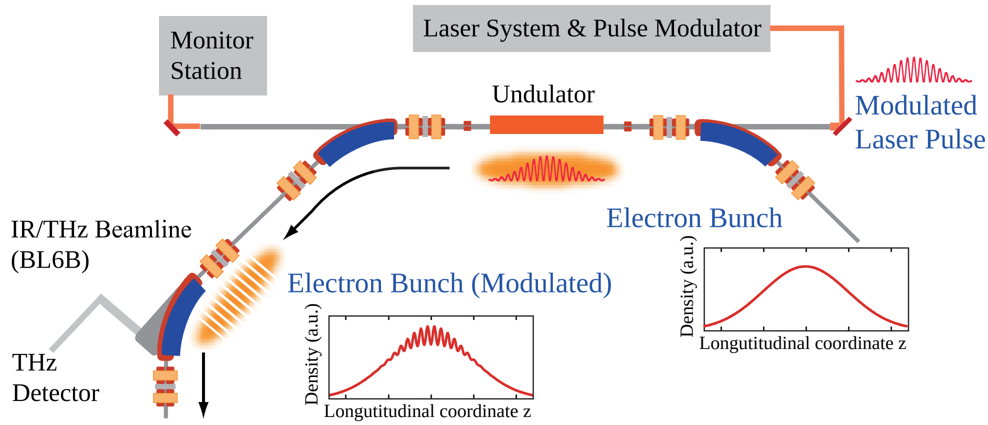

Figure 1: Schematic view of experimental setup and the calculated density on the modulated electron bunch.

Table 1: Main parameters of the UVSOR-II storage ring for the THz CSR experiments.

Electron energy (MeV)	600
Circumference (m)	53.2
Natural emittance (nm rad)	17.4
Natural energy spread	3.4×10^{-4}
RF frequency (MHz)	90.1
Natural bunch length (ps)	$\sim$80 (rms)
Bending radius (m)	2.2
Momentum compaction factor	0.028
Momentum acceptance (%)	1

The first term in Eq. 1 corresponds to the normal (incoherent) synchrotron radiation and second term to the CSR. When the electron bunch length is very short or the bunch has a single narrow dip structure, the $F(k)$ has a finite value for the wavelength longer than the bunch length of the dip length. In the case, the emitted CSR spectrum becomes broadband. On the other hand, in the ideal case that the electron bunch has the periodic density structure, the value of $F(k)$ becomes zero everywhere except at the wave number corresponding to the periodic length. As the result, the emitted CSR spectrum becomes monochromatic.

EXPERIMENTAL SETUP

The schematic view of the experimental setup is shown in Fig. 1. At first the modulated laser pulse is injected to the undulator section of the ring. If a resonant condition is satisfied such that the laser wavelength is equal to the wavelength of the undulator radiation of the first harmonic, the injected laser and electrons exchange their energy. After this interaction, an energy modulation is created on the electron bunch. As a second step, the energy modulation is converted to a density modulation as the electron bunch pass through the following bending magnet. Then THz CSR is emitted and it's spectrum is measured at the IR/THz beamline installed at the second bending magnet.

The UVSOR-II storage ring was operated at the energy of 600 MeV since it was easy to achieve the resonant condition. The experiment was carried out at beam currents of 0–40 mA in the single-bunch mode to avoid the spontaneous bursts of THz CSR [8]. The main parameters of the UVSOR-II storage ring during the experiment are summarized in Table 1.

The laser pulses were produced by a commercial Ti:sapphire laser system (Coherent Mira 900-F and Legend F-HE). To produce amplitude modulated laser pulses, a technique called 'chirped pulse beating' was used [9]. This system consisted of a stretcher based on a grating pair and a Michelson interferometer, and enabled us to obtain a sinusoidal modulation with a widely scalable pulse duration and modulation period. The pulse duration could be varied from a few ps to 100 ps and the modulation period was chosen in the range of 1–2 ps.

The THz CSR was analyzed at the IR/THz beamline (BL6B) using an in-vacuum Martin-Puplett Fourier transform far-infrared spectrometer and was detected by an InSb bolometer (QMS, QFI/2) [10], which enabled the recording of spectra in the 2–55 cm^{-1} range with a resolution of 0.5 cm^{-1}. The pulse processing was made using a gated integrator (SRS250) to reduce background from normal synchrotron radiation. The gated integrator was triggered by the 1 kHz oscillator of the Ti:sapphire laser and width was chosen around 1 μs, which corresponds to the response time of the InSb bolometer.

RESULTS AND DISCUSSIONS

First experiment was carried out using the pulse duration of 2 ps and then the pulse duration was increased to 60 ps. This increased the number of modulation periods, and enabled to reduce drastically the spectrum width of the emitted radiation from $\sim$4 cm^{-1} to $\sim$1 cm^{-1}. Typical THz CSR spectra are shown in Fig. 2. The data were taken at a 60-ps-long pulse and two positions of the Michelson interferometer corresponding to the modulation frequencies of laser pulse of 16 cm^{-1} and 24 cm^{-1} respectively. Com-

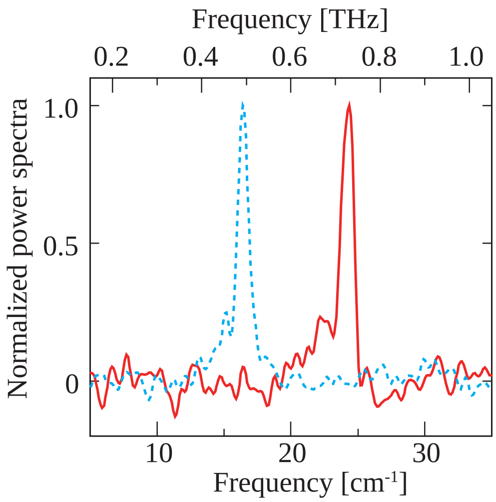

Figure 2: Typical narrowband THz CSR spectra. Each data was taken at a 60-ps-long pulse and the different conditions of the laser modulation period. The resolution of the spectrometer is 0.5 cm^{-1}.

pared with the conventional CSR obtained by the laser slicing technique, it is obvious that the band width of the spectra was much narrower.

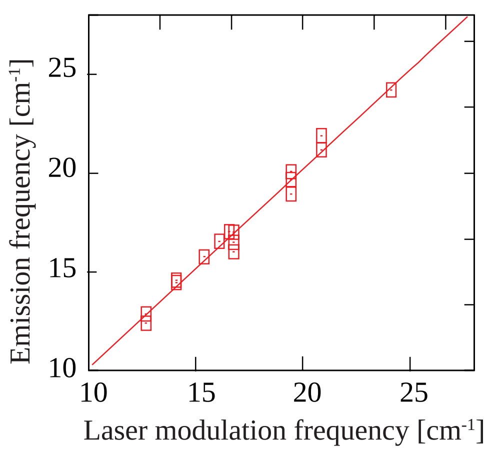

Figure 3: Peak frequency of THz CSR as a function of laser modulation frequency (obtained with pulses of 2 ps and 60 ps). The solid line is the 45° line.

Another important feature of this technique, the emission frequency of THz CSR is tuned just by adjusting the Michelson interferometer position and shown as a function of laser modulation frequency in Fig. 3. The data points indicated by open squares corresponds to experimental results, which was obtained with the pulse duration of 2 ps and 60 ps, and the solid line is the 45° line. This figure shows that the emission frequency was exactly same as the modulation frequency.

CONCLUSIONS

Microfabrication of relativistic electron beam by using amplitude modulated laser pulses was successfully demonstrated at the UVSOR-II storage ring. This method provides a way to imprint periodic wave patterns inside the electron bunch phase space. As the result, quasi-monochromatic and tunable THz CSR was emitted in a uniform dipole field. The peak frequency was tuned just by adjusting the laser system.

The experiment reported here were destined to feasibility studies and not optimized for high power generation. Thus, for the light source applications, further studies are required for the optimization of THz emission (power, band width and so on) and the identification of technical and fundamental limits.

In addition to the light source applications, this method has the possibilities of fundamental researches in electron beam dynamics. The experimental studies of spatiotemporal instabilities are important to operate accelerators. Despite the existence of some theories predicted the occurrence of instabilities, experiments of these theories are difficult because phase space evolutions are usually not observable directly in real time, and also because methods for selectively perturbing short wavenumbers were lacking up to now. However these experiments would be realized by imprinting periodic wave patterns inside the electron bunch and monitoring the emitted THz radiation.

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