

# Smith-Purcell effect using femtosecond electron beam

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## Abstract

In this paper, Smith-Purcell effect, which utilizes metallic grating and electron bunch, was investigated for a new device of terahertz (THz)-wave generation. Electron bunches and metallic gratings realized monochromatic or multimode THz-wave generation at a frequency of  $<0.7$  THz.

## フェムト秒電子ビームを用いたスミス・パーセル効果の研究

### 1. Introduction

Ultrashort, e. g. femtosecond [1] or picosecond, electron bunches are used in accelerator physics applications such as free electron lasers (FELs), laser-Compton X-ray, and pulse radiolysis [2]. On the other hand, electron bunches with short bunch lengths are also useful for electro-magnetic (EM) radiation production in terahertz (THz) range because the inverse of 1 ps bunch length corresponding to the frequency of 1 THz. A shorter electron bunch can emit EM radiation of higher frequency according to the bunch form factor, which is described by the Fourier coefficients of the bunch distribution [3]. Furthermore, the radiation intensity at lower frequency than the inverse of the bunch length is proportional to the electron number, e. g.  $\approx 10^9$  at 1 nC. As the result, an intense THz-wave can be generated by such electron bunches. In the studies on EM radiation emitted from electrons, Cherenkov radiation (CR) has been studied since the 1930s [4] and radiation yield dependence on wavelength and angular distribution was reported. In the 1990s, the bunch form factor [3] and angular distribution of coherent transient radiation (CTR) from electron bunches were measured experimentally. Recently, not only monochromatic THz-wave [5] but also multimode one [6,7] of  $<0.4$  THz were generated by coherent Cherenkov radiation (CCR). Another THz-wave generation method, which utilized a periodic electron bunch distribution, generated narrow-band THz-wave up to  $\approx 0.86$  THz for a bunch length diagnostic [8]. Alike THz-wave generated by a laser, that generated by an accelerator would be useful to a probe light, which monitors conductivity due to quasi-free electrons, or imaging for medical and security use.

In this study, Smith-Purcell effect [9], which utilizes metallic grating and electron bunch, was investigated for a new device of THz-wave generation. Electron bunches with  $\approx 0.2$  ps bunch length from a photocathode RF gun

linac was used for the Smith-Purcell radiation (SPR).

### 2. Experimental arrangement

The photocathode RF gun linac and SPR measurement system are shown in Fig. 1. The details of the linac are discussed in references [10,11,12]. Figure 1(a) shows the linac system. The electron bunch was generated by a 1.6-cell S-band (2856 MHz) RF gun with a copper cathode and a Nd:YLF picosecond laser. The pulse width of the UV pulse from the laser was measured to be 5 ps in FWHM as a Gaussian distribution. The UV light was projected onto the cathode surface at an incident angle of approximately  $2^\circ$  along the electron beam direction. The beam energy at the gun exit was 4.2 MeV. The picosecond electron bunch produced by the RF gun was accelerated up to  $\sim 32$  MeV by a 2 m long S-band travelling-wave linac with an optimal energy-phase correlation for the bunch compression, in which the head electrons of the bunch have more energy than the bunch tail. Finally, the energy-phase-correlated electron bunch is compressed into femtosecond by rotating the phase space distribution in the magnetic bunch compressor, which is constructed with two  $45^\circ$ -bending magnets (B1 and B2), four quadrupole magnets (Q3, Q4, Q5, and Q6), and two sextupole magnets (S1 and S2). The femtosecond electron bunch was obtained by adjusting the energy modulation in the linac, e. g., compressed bunch length of  $\sim 0.2$  ps in rms measured by a streak camera at a bunch charge of  $\sim 40$  pC and a linac phase of  $97.5^\circ$ .

In the experiment, the bunch charge was fixed to 210 pC. The femtosecond electron bunch was used in SPR measurement, which utilized metallic gratings as shown in Fig 1(b). The grating was made of aluminum and fabricated by a numerical control machining. The period length of the grating was 2 mm. The grating had rectangular structures and dips, of which depths was 1 mm. The total lengths of the grating were 300 mm in order to investigate the dependence of THz-wave on a radiation angle easily. THz-wave produced by SPR was analyzed

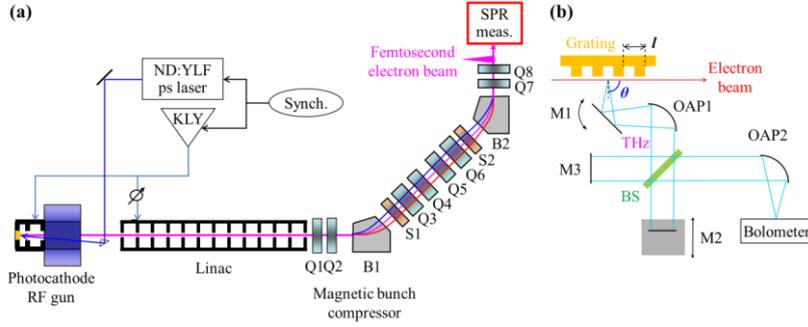


Figure 1: (a) Photocathode RF gun linac. Q denotes a quadrupole magnet; B, a bending magnet; S, a sextupole magnet. (b) SPR measurement system. OAP denotes an off-axis parabolic mirror; M, a plane mirror; BS, a beam splitter.

by a Michelson interferometer. Electron beam generates image charge in a grating, resulting in dipole radiation at a radiation angle. A plain mirror (M1), which rotated along the vertical axis, was set 50 mm away from the approximate center of the grating for directing THz-wave at a radiation angle. When the mirror (M1) rotated, THz-wave at a radiation angle of  $\theta$  was selected for the next off-axis parabolic mirror (OAP1) with a focal length of 191 mm. The THz-wave produced by SPR was separated by a beam splitter (BS) made of 0.15 mm-thick n-type Si. One of the THz-wave was reflected by a moving mirror (M2). Finally, the separated THz-waves joined together at a 4.2K silicon bolometer (Infrared Laboratories Inc.). The frequency spectra of SPR were analyzed by the fast Fourier transform (FFT) of an interferogram with 128 points and 0.5 ps time step, in which the bolometer output as a function of the moving mirror position was recorded. Interferogram was obtained by an oscilloscope using 20 sweeps of the peak-to-peak output from the bolometer. The measured THz-wave at various radiation angles are not radiated from the same point because of the rotated mirror (M1).

### 3. Results and discussion

#### 3.1 Theoretical description for frequency and radiation angle

The frequency of  $n$ -th mode of SPR,  $f_n$ , radiated at a radiation angle,  $\theta$ , can be expressed as [9]

$$f_n = cn/l(1/\beta - \cos \theta) \quad (1)$$

where  $c$  denotes the light speed;  $l$ , the period length of the grating;  $\beta$ , the beam speed as shown in Fig. 1(b). According to Eq. (1), the frequency of SPR,  $f_n$ , decreases with increasing the radiation angle,  $\theta$ , at the same order,  $n$ , and the period length,  $l$ . The frequency of SPR varies in inverse proportion to the period length,  $l$ . When the angle of the mirror (M1) varies with the amount of  $\Delta\theta$ , the radiation angle of selected SPR varies with the amount of  $2\Delta\theta$  because of a reflection.

#### 3.2 Interferogram and frequency spectrum

Figure 2 shows the dependence of SPR on radiation angle. Figure 2(a) shows the interferograms for three different radiation angles using the 2 mm-period grating. A periodic oscillation was observed because of frequency components. In this case, the bolometer output, which corresponded to the detected intensity of THz-wave, was maximized at a radiation angle of  $54^\circ$ . Figure 2(b) shows the frequency spectra for three different radiation angles. All the spectra had discrete components according to Eq. (1). Some frequencies of the discrete components agreed to the theoretical calculation. However a spike at a lower frequency of the fundamental mode was observed at a radiation angle of  $54^\circ$  because of scattering of THz-wave in the experiment. At a radiation angle of  $54^\circ$ , frequency spikes up to 2nf order are slightly observed. Intensities of spikes could not be expected by considering spectral response according to the order at a radiation angle of  $110^\circ$ .

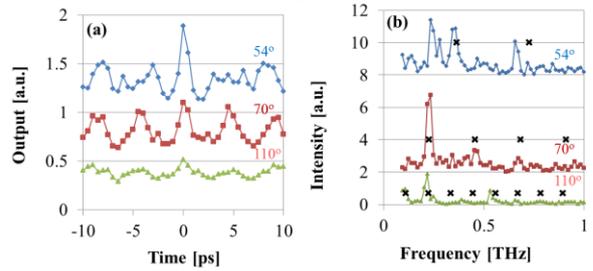


Figure 2: (a) Interferograms for 54, 70, 110° radiation angles with only offsets adjusted for comparison. (b) Frequency spectra for 54, 70, 110° radiation angles with only offsets adjusted. The theoretical frequencies (cross) using Eq. (1) were shown.

#### 3.3 Frequency spectra and radiation angles

Figure 3 shows the dependence of SPR on radiation angle. In the experiment, multimode THz-wave was observed with changing the radiation angle, e. g., the 1st and 2nd modes at a radiation angle of  $54^\circ$ , the 2nd mode

at  $110^\circ$ . In this case, the bolometer output, which corresponded to the averaged value of the interferogram, was maximized at a radiation angle of  $54^\circ$ , although the output should be considered based on scattering of THz-wave, detection efficiency, and spectral response of the interferometer.

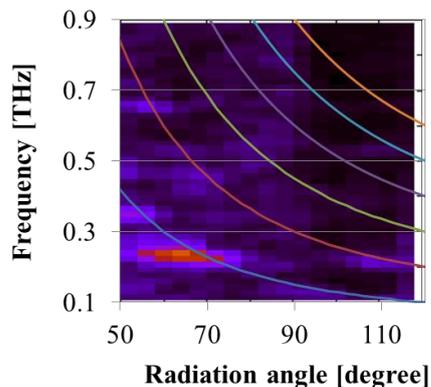


Figure 3: Dependence of frequency spectra of SPR on radiation angle. The color map denotes experimental data. The theoretical frequencies (lines) using Eq. (1) were shown from the 1st (bottom) to 5th (top) modes.

#### 4. Conclusions

Smith-Purcell effect, which utilizes metallic grating and electron bunch, was investigated for a new device of terahertz (THz)-wave generation. Electron bunches and metallic gratings realized monochromatic or THz-wave generation at a frequency of  $<0.7$  THz using a grating with a period length of 2 mm. The bolometer output, which corresponded to the detected intensity of THz-wave, was maximized at a radiation angle of  $54^\circ$ .

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