GENERATION OF SELF-AMPLIFIED SPONTANEOUS EMISSION AND ITS HIGHER HARMONICS IN THE FAR-INFRARED REGION

R. Kato†, R. A. V. Kumar, T. Igo, M. Kuwahara, T. Konishi, M. Fujimoto, Y. Nakamura, S. Isaka, S. Mitani, S. Okuda, S. Suemine and G. Isoyama,
Institute of Scientific and Industrial Research, Osaka University
8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

Abstract

We are conducting experiments to generate self-amplified spontaneous emission (SASE) in the far-infrared region and to measure its characteristics, including peak power, dependency on the K-value, and the spectral width, using a single bunch electron beam accelerated with the L-band linac at ISIR, Osaka University. The measured characteristics are in good agreement with the one-dimensional model of SASE. We have also observed the second and the third harmonic peaks of SASE originating from the nonlinear harmonic generation.

1 INTRODUCTION

Self-amplified spontaneous emission (SASE) using a high gain single pass free electron laser (FEL) is expected to be one of promising approaches to realize X-ray lasers [1,2]. In this scheme, a seed of light is spontaneous undulator radiation emitted by the electron bunch at the entrance of the undulator, and it is amplified by interacting with the electron bunch to the saturation power level. When SASE at the fundamental wavelength grows up exponentially, higher harmonics also begin developing exponentially with the gain length equal to that of the fundamental radiation divided by n, where n is the harmonic order [3,4,5]. This process is called the nonlinear harmonic generation of SASE. The third harmonic power is expected to reach one percent of the fundamental power in the proposed X-ray SASE-FELs. Since the fundamental power at a few Angstrom will be higher than 10 GW, the higher harmonics will have considerable power. On the other hand, in order to realize SASE-FEL in the X-ray region, a high energy electron beam of some tens of GeV with extremely low emittance and a peak current higher than 1 kA, and a long undulator over 100 m are required. The shorter the wavelength becomes, the more severe these requirements become. Therefore, the higher harmonics generation has attracted much attention as a method to produce higher energy photons.

We are conducting experimental study on SASE in the wavelength region from far infrared to submillimeter using the L-band linac at the Institute of Scientific and Industrial Research (ISIR), Osaka University [6]. We will report recent experimental results including the higher harmonic generation of SASE.

†kato@sanken.osaka-u.ac.jp

2 LINAC AND FEL SYSTEM

The L-band linac at ISIR consists of an electron gun, a sub-harmonic buncher (SHB) system, a prebuncher, a buncher and a main accelerating tube. The gun is a thermionic gun with a cathode area of 3 cm^2 (EIMAC, YU-156), from which the electron beam with a peak current up to 18 A and a duration of 5 ns is injected into the SHB system for SASE experiments. The SHB system to produce an intense single-bunch beam is composed of two 1/12 and one 1/6 subharmonic cavities of the accelerating frequency 1.3 GHz. Due to the velocity modulation with the SHB system, the electron beam is compressed to 500 ps at the entrance of the prebuncher. The prebuncher and the buncher are travelling wave tubes with the same frequency of the main accelerating tube. The electron beam is bunched into 20 – 30 ps by the prebuncher and the buncher, and accelerated to 11 - 32 MeV with the main accelerating tube.

Table 1: Parameters of the electron beam and the wiggler

Electron beam	
Accelerating frequency	1.3 GHz
Energy	11-14 MeV
Energy spread	2-4 % (FWHM)
Charge/bunch	< 20 nC
Bunch length	20-30 ps
Peak current	< 1 kA
Normalized emittance	150-200 π mm mrad
Repetition	60 Hz
Mode	Single bunch
Wiggler	
Total length	1.92 m
Magnetic period	60 mm
No. of periods	32
Magnet gap	120-30 mm
Peak field	0.37 T
K-value	0.01-1.47

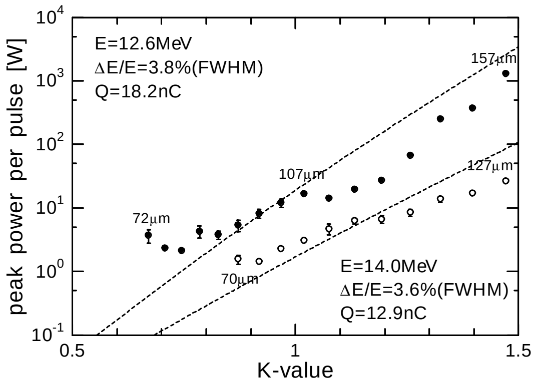

Figure 1: Peak power of SASE measured as a function of K-value of the wiggler. The solid and the open circles denote the measured data points for the beam energy of 12.6 and 14.0 MeV, respectively. The dashed lines were theoretical values predicted by one-dimensional model. See text for details.

The electron beam is transported via an achromatic beam transport line to the 32 period planar wiggler with the period length of 60 mm. The K-value of the wiggler can be varied from 0.01 to 1.47 by changing the magnet gap. The main characteristics of the electron beam and the wiggler are listed in Table 1.

Light emitted by the electron beam traversing the wiggler was reflected with a downstream mirror and led to a far-infrared monochromator in the measurement room via an evacuated optical transport line. The high vacuum in the beam transport line and the low vacuum in the optical transport line are separated by a 0.2 mm thick, 20 mm in diameter synthetic diamond window. The monochromator is a cross Czerny-Turner type with a plane reflective grating. The grating is grooved with 7.9 lines / mm (Thermo RGL) and its blaze wavelength is 112.5 μm. The monochromator can be used in the wavelength region from 50 to 200 μm. The spectral resolution of the monochromator is almost constant over the range and approximately 1.5 μm for a slit width of 6 mm. The monochromatized light was detected with a Ge:Ga photoconductive detector cooled with liquid-helium.

The total sensitivity of this measurement system, including the sensitivity of the detector, the efficiency of the monochromator, and the transport efficiency of the optical transport line and transmittance of the windows, was calibrated over the wavelength range using a blackbody radiator of a temperature 1273 K. The radiator was placed at a position optically equivalent to the first focal point. In order to exclude the stray light in the monochromator, a 50 μm or 100 μm short-wavelength cut filter was inserted between the monochromator and the detector.

3 EXPERIMENTAL RESULTS AND DISCCUSIONS

3.1 Peak power of SASE

In this experiment, we used a plane mirror instead of the plane reflective grating in the monochromator. Fig. 1 shows the peak power of emitted light as a function of the K-value of the wiggler. The filled circles show the measured peak power for the beam of E=12.6 MeV, the energy spread ΔE/E=3.8 % (FWHM) and charge Q=18.2 nC. The open circles show the peak power for E=14.0 MeV, ΔE/E=3.6 % and Q=12.9 nC. The data points and the error bars show average values and standard deviations, respectively, of five highest intensities in thirty successive optical pulses. In the upper case (12.6 MeV) of Fig. 1, the K-value was varied from 0.67 to 1.47 and accordingly the wavelength changed from 72 to 157 μm. The optical power was estimated from the signal intensity using the detector sensitivity calibrated with the blackbody radiation, transmittance of the vacuum windows, and the pulse length assumed as $\Delta t \approx \Delta\omega^{-1}$, where $\Delta\omega$ is the spectral width of SASE. The one-dimensional (1D) theory predicts the spectral width of SASE in the exponential growth region as

$$\frac{\sigma_\lambda}{\lambda} \cong 0.91\sqrt{\frac{\rho}{N}} \qquad (1)$$

where ρ is the FEL parameter, N the period number of the wiggler. The dashed lines show the optical power predicted by the 1D theory. In these calculations, the start-up power for SASE was calculated using $P_{in} = 3(4\pi)^{1/2}\rho^2 P_b / N_\lambda (\ln(N_\lambda/\rho))^{1/2}$, where N_λ is the number of electrons in a wavelength and P_b the electron beam power. The functional dependence of the measured optical power on the K-value is in good agreement with the SASE theory.

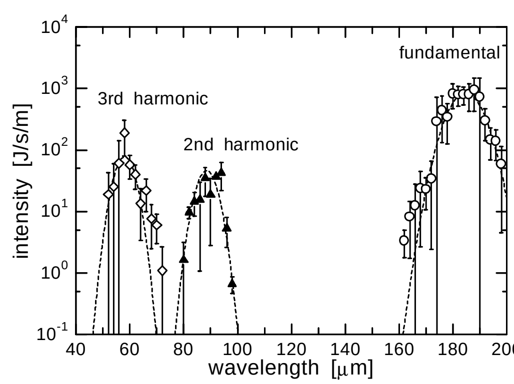

Figure 2: Absolute wavelength spectra of fundamental and higher harmonics of SASE. The open circles, the filled triangles, and the open diamonds denote the fundamental, the second harmonic, and the third harmonic peaks, respectively. The dashed lines show Gaussian distributions fitted to the peaks. See text for details.

3.2 Spectrum of SASE

We have measured the wavelength spectrum of SASE for E = 11.3 MeV, ΔE/E = 3.6 % and Q = 9.2 nC. The K-value is 1.47 at the wiggler gap 30 mm. Fig. 2 shows wavelength spectrum of SASE in the wavelength region from 50 to 200 μm measured in these experimental conditions. The intensities were divided by the sensitivity of the measurement system calibrated by the blackbody radiation and thus absolute values were derived in units of J/s/m, which stand for power in unit wavelength. Three peaks appear around 60, 90 and 180 μm in the spectrum.

The highest peak around 180 μm has been identified as the fundamental SASE since the wavelength agrees with the calculated value using the electron energy and the K-value. Since the other peaks disappeared when a 100 μm short-wavelength cut filter was inserted between the monochromator and the detector, we confirmed they were not stray light. Because the peaks are observed only when the fundamental peak is strong, and because they do not appear by themselves, the peaks around 90 and 60 μm have been assigned as the second and the third harmonic radiation, respectively, generated by the nonlinear harmonic generation of SASE.

Using each peak area and the pulse duration of the signal from the detector, 200 ns, the energy of an optical pulse is derived to be 2.75 nJ for the fundamental peak, 73 pJ for the second harmonic, and 182 pJ for the third harmonic. The energy ratio of the second harmonic to the fundamental is 2.7 % and that of the third harmonic is 6.6 %. These energy ratios are much larger than those predicted for the X-FEL projects.

3.3 Spectral width and the gain length

Spectral widths of these peak were derived by the least square fit of the Gaussian distribution function to the measured values denoted by the dashed lines in Fig. 2; the fractional widths are 2.9 % for the fundamental peak (the standard deviation), 3.6 % for the second harmonic peak, and 5.3 % for the third harmonic peak. The spectral width of the fundamental radiation in the exponential gain region is given by the 1D theory as Eq. (1). In the present experimental conditions, the spectral width is calculated to be 2.6 %, which agrees well with the measured value, 2.9 %.

It is predicted by theory that the gain length of the n-th harmonic is equal to that of the fundamental radiation divided by n. Let the gain length of the fundamental, the second harmonic, and the third harmonic radiation be $L_G^{(1)}$, $L_G^{(2)}$, and $L_G^{(3)}$, respectively, the following relation holds.

$$\frac{1}{L_G^{(1)}}:\frac{1}{L_G^{(2)}}:\frac{1}{L_G^{(3)}}=1:2:3 \qquad (2)$$

For the fundamental radiation, the gain length L_G is in proportion to the cooperation length L_C divided by the wavelength λ. Assuming this relation holds for the higher harmonics, the gain length can be related to the fractional spectral width, σ_λ/λ as

$$\frac{1}{L_G}\propto\frac{\lambda}{L_C}\propto\frac{\lambda}{\Delta t}\approx\lambda\cdot\Delta\omega=\Delta\lambda\cdot\omega=2\pi c\frac{\Delta\lambda}{\lambda}\propto\frac{\sigma_\lambda}{\lambda}, \quad (3)$$

where we assume that the Fourier transform relation holds between the spectral width $\Delta\omega$ and the pulse duration Δt as $\Delta\omega\Delta t\approx 1$. Substituting the measured spectral widths, we obtain the ratios

$$\frac{1}{L_G^{(1)}}:\frac{1}{L_G^{(2)}}:\frac{1}{L_G^{(3)}}=2.9:3.6:5.3(\%)=1:1.24:1.83 \quad (4)$$

which should be compared with the theoretical prediction given in Eq. (2). Although the measured spectral width of the fundamental radiation agrees well with the 1D theory, the spectral width ratios of the second and the third harmonic to the fundamental radiation are smaller than the theoretical predictions, 1:2:3, which suggests that gain lengths of the second and the third harmonic are longer than the prediction. It should be noted that the ratio between the spectral widths of the second and the third harmonic 3.6 : 5.3 (%) = 1 : 1.47 is close to the theoretical value, 2 : 3 = 1 : 1.5.

The optical pulse duration of the fundamental radiation is evaluated from the spectral width to be 1.5 ps using the Fourier transform relation. The peak power of the fundamental radiation is estimated, using the energy in an optical pulse and the pulse duration, to be 1.9 kW, which also agrees well with the 1D theory, 2.6 kW. Since the saturation power is estimated to be 135 MW using the 1D theory, the present experimental conditions are far away from realizing power saturation of SASE. We have, nevertheless, observed the second and the third harmonics of SASE with the large energy ratios to the fundamental, which indicates that bunching of the electron beam develops considerably, because the FEL parameter is large.

6 REFERENCES

[1] The LCLS Design Study Group, SLAC-R-521 (April 1998).
[2] R. Brinkmann, et al., DESY Report 1997-048.
[3] R. Bonifacio, L. De Salvo, and P. Pierini, Nucl. Instr. and Meth. **A293** (1990) 627.
[4] H. P. Freund, S. G. Biedron, and S. V. Milton, IEEE Quantum Electron. **QE-36** (2000) 275.
[5] Z. Huang and K. J. Kim, Phys. Rev. E **62** (2000) 7295.
[6] R. Kato, et. al., Nucl. Instr. and Meth. **A445** (2000) 164.