Observation of Coherent Effect in Undulator Radiation

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The coherent effect in spontaneous emission has been observed in a low-energy, low-gain, waveguide-mode free-electron laser. The intensity of the radiation was more than 10^3 times stronger than that of the incoherent radiation. This enhancement is due to coherent radiation emitted by the electron beam which is randomly modulated by micropulses whose typical pulse width ($\sim$35 ps) is comparable to the radiation wavelength. The measured power tends towards a quadratic dependence on the electron-beam current.

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Relativistic electrons passing through a magnetic undulator are subject to transverse acceleration, which results in emission of spontaneous radiation. The amount and spectrum of this radiation is a crucial factor in the start-up process of the free-electron-laser (FEL) oscillator. This radiation has been used as a light source in many fields and also as a diagnostic tool for the electron beam.

After the radiation emitted by a wiggling particle was first discussed analytically [1], theoretical [2–12] and experimental [13–15] investigation of this radiation was carried out by several authors. Nodvick and Saxon [16] predicted coherent synchrotron radiation from an electron beam with a bunch length comparable to the radiation wavelength. Recently the coherent effect in synchrotron radiation from a bending magnet [17] and in Cherenkov radiation [18] has been observed in a wavelength region comparable to the longitudinal electron bunch length. Even though the coherent effect in the undulator is expected [1,3], there has been no report of an observation of coherent undulator radiation. It is very difficult to generate a short electron beam whose bunch length is comparable to the wavelength of radiation in the visible or ir region. We have developed a laser-irradiated photocathode for a millimeter-wavelength-range FEL; hence our system is adequate to carry out experiments on coherent undulator radiation.

In this paper, we report on the observation of the coherent effect in spontaneous emission. Intense radiation power, which was more than 10^3 times stronger than the power of incoherent radiation, was observed. This enhancement is caused by the coherent radiation of electron-beam micropulses (pulse width $\sim$35 ps), which have a slightly longer pulse duration than the emitted radiation wavelength. The measured radiation power tends towards a quadratic dependence on the electron-beam current. It was confirmed experimentally that the enhancement of the radiation power was caused by the electron-beam micropulses.

The radiation power emitted by electrons passing through the undulator can be obtained by using Nodvick and Saxon's analytical consideration [16]. The total power P_t radiated by N electrons is

$$P_t = P\left|\sum_j e^{-i\varphi_j}\right|^2 \sim NP + N^2 Pf\,, \tag{1}$$

where φ_j is the phase of the radiation emitted by the jth electron. The first term gives the incoherent power and the second term represents the coherent radiation. If we assume sinusoidal motion of the electrons in an undulator, the radiation phase difference emitted by two electrons is $(k-k_w)z$ relative to the observer, where k and k_w are the wave numbers of the radiation and the undulator magnetic field, respectively, and z is the distance between electrons. The form factor f can be expressed as

$$f = \left(\int \cos(k'z) S(z)\, dz\right)^2 \tag{2}$$

and

$$k' = k - k_w\,,$$

where $S(z)dz$ is the probability that a given electron is found in the interval between z and $z+dz$. If the contribution of the individual electrons are random in phase as a result of the statistical longitudinal distribution of the electron beam over a length much larger than the wavelength of the radiation, the second term of Eq. (1) can be neglected and the total power is N times the power radiated by the individual electron. When the wavelength of the radiation is comparable to the pulse width of the electron beam, enhancement of the radiation power is expected due to the coherent effect. If the electrons are distributed according to a Gaussian law, then

$$S(z) = (\sqrt{2}/a\sqrt{\pi}) \exp(-2z^2/a^2) \tag{3}$$

and

$$f(a) = \exp[-(k'a/2)^2] \tag{4}$$

for a fixed wavelength of the radiation, where a is the half width at e^{-2} of the electron-beam peak value. In the case of a Gaussian distribution, the FWHM is ap-

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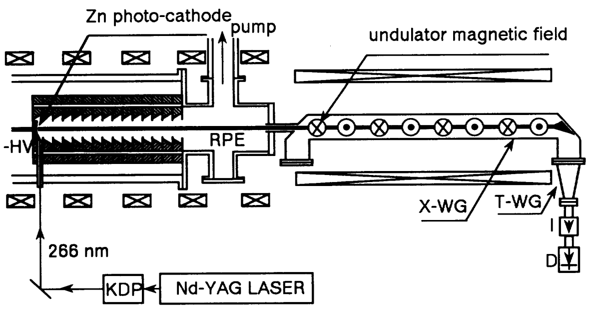

FIG. 1. Schematic diagram of spontaneous emission experimental setup (RPE denotes relativistic photoelectron beam, D denotes 1N26C microwave diode, I denotes isolator, X-WG denotes X-band waveguide, and T-WG denotes tapered waveguide).

proximately 1.18 times α for the same pulse.

Figure 1 shows the experimental setup. The relativistic photoelectron beam (RPE, 610 keV, FWHM 8 ns) is generated by electrostatically accelerating the photoelectrons produced by the fourth harmonic (266 nm, 15 mJ, 8 ns) of a Q-switched Nd-doped yttrium aluminum garnet (Nd-YAlG) laser pulse incident on a Zn cathode. The maximum current and the beam diameter of the RPE in the waveguide are 1.5 A and 0.5 cm, respectively.

The current of the RPE could be controlled precisely by changing the power of the fourth harmonic of a Q-switched Nd-YAlG laser. Optical attenuators for UV light were used to control the RPE current by keeping the temporal pulse shape of the irradiation laser beam unchanged. A typical wave form of the fourth harmonic of a Q-switched Nd-YAlG laser is shown in Fig. 2(a). It was measured using a streak camera; in this condition, the temporal resolution is 12 ps, and the typical micropulse FWHM was measured to be approximately 30 ps. Most of the pulses are separated by more than 500 ps. Since the fast rise time of the current pulse is determined entirely by the laser pulse input at the laser-irradiated photocathode [19–21], it is expected that the temporal pulse shape of the RPE is the same as that of a randomly modulated laser pulse. The temporal wave form of the electron beam was measured using Cherenkov radiation emitted in quartz fiber from the electron beam. We have observed micropulses in the electron beam. A typical wave form of the electron-beam micropulse is shown in Fig. 2(b). The pulse width of the micropulses is broadened; this is due to the dispersion of the multimode quartz fiber and the wide spectrum of the Cherenkov radiation. By considering the pulse spreading effect due to the dispersion of the fiber, the typical FWHM of the micropulse shown in Fig. 2(b) is calculated to be approximately 35 ps. This result is in good agreement with the typical pulse width of micropulses in the irradiation laser pulse.

The current-driven undulator magnetic field has a pitch of 5 cm, and the number of undulator periods is 2.5 in the adiabatic region and 17 in the interaction region. The radiation generated by the RPE is guided by 120-cm-long X-band waveguide (X-WG, 2.29×1.02 cm^2) and is introduced into a Ka-band waveguide (Ka-WG, 0.71×0.355 cm^2) through a tapered waveguide (T-WG).

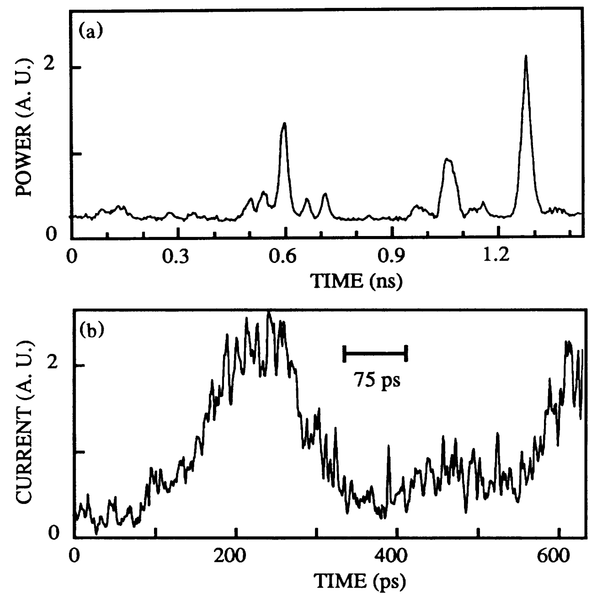

FIG. 2. (a) Typical wave form of the fourth harmonic of a Q-switched Nd-YAlG laser, which was measured using a streak camera using 12-ps temporal resolution. (b) Typical wave form of the electron-beam micropulse. The marker of 75 ps represents the value of the pulse width broadened by the dispersion of the Cherenkov radiation and multimode quartz fiber.

A calibrated microwave diode, type 1N26C, was used to monitor the wave form of the undulator radiation and measure the radiation power. The microwave diode was

TABLE I. Experimental parameters.

Electron beam	Energy	0.61 MeV
	Current (max.)	1.5 A
	Beam diameter	5 mm
	Pulse width	8 ns (macropulse)
		30–100 ps (micropulse)
Undulator	Type	Planar, electromagnet
	Pitch length	5 cm
	Number of periods	2.5 (adiabatic region)
		17 (interaction region)
	Magnetic flux strength	0.5 kG
Guiding coil	Magnetic flux strength	2.1 kG
Radiation	Wavelength	7.4 mm

calibrated using a reference power of 0.1–30 mW, which was obtained by a calibrated variable attenuator and Gunn oscillator. The experimental conditions are listed in Table I.

Figure 3 shows the measured power of the spontaneous emission as a function of the electron-beam current (dots). The dashed line is the theoretically calculated power of the incoherent radiation for an 8-ns RPE current. The number of the electrons is 3×10^{10} for a 0.5-A RPE current. Each measured value of radiation power is an average of ten shots and the error bar represents the standard deviation of measured power. The measured power of the radiation is more than 10^3 times stronger compared to the theoretically calculated power of the incoherent radiation. While the calculated power shows a linear dependence on the electron-beam current, the measured power tends towards a quadratic dependence on the electron-beam current.

To explain the large discrepancy between the measured and the theoretically calculated power of the incoherent radiation, the effect of the coherent radiation due to the electron-beam micropulses is introduced. The solid line in Fig. 3 is the fitted line of the measured radiation power based on the assumption that the measured power is coherent radiation. The enhancement ratio between the coherent radiation power P_c of the fitted line and the theoretically calculated power of incoherent radiation, P_{in}, is

$$P_c/P_{\text{in}} = n_p \times N_c^2 f(\alpha)/N_{\text{in}}\,, \qquad (5)$$

where n_p is the number of micropulses which contribute to the coherent radiation power, N_c is the number of electrons in a typical micropulse, and N_{in} is the number of electrons in the total electron beam. The number of electrons in a micropulse is estimated to be approximately 5×10^8 for a 0.5-A RPE current. Judging from peaks contained in the wave form of the undulator radiation, the radiation power is on the average due to the contribution of 8 micropulses. The enhancement ratio between the coherent radiation power of the fitted line and the theoretically calculated power of the incoherent radiation is 7.7×10^3 for a 0.5-A RPE current. From Eqs. (4) and (5), the pulse width of the electron-beam micropulse corresponding to the fitted line is calculated to be 33 ps. For simplicity, the wave form of the electron-beam micropulse is assumed to have a Gaussian distribution. This value of 33 ps pulse width calculated from the fitted line based on the assumption of coherent radiation is in good agreement with the measured value of the pulse width. From the above results, it is considered that the enhanced radiation power is caused by the coherent effect of the undulator radiation due to the electron-beam micropulses having approximately 35 ps pulse width.

The coherent radiation is affected by the separation distance between micropulses. If we consider the slippage effect which is caused by the velocity difference between

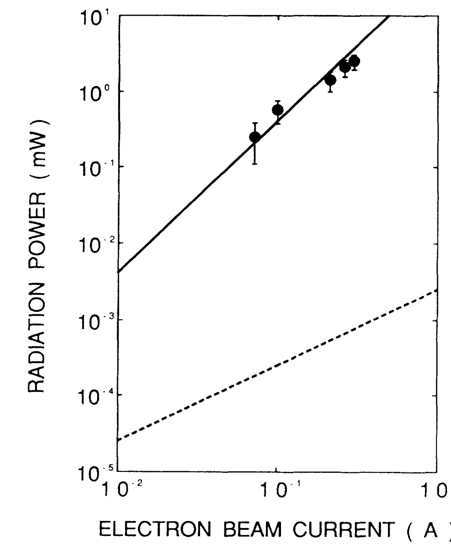

FIG. 3. The measured power (dots) of the spontaneous emission as a function of the electron-beam current. The dashed and solid lines represent the theoretically calculated power of incoherent and coherent radiation, respectively. The coherent radiation power is theoretically calculated for radiation with a wavelength of 7.4 mm and an electron-beam pulse width of 33 ps. The number of electrons in a micropulse is estimated to be 5×10^8 for a 0.5-A RPE current.

the radiation and electrons in an undulator, each electron of the RPE emits radiation of pulse width 500 ps, which is given by a slippage distance of

$$L = (v_r - v_e^*)\Delta t\,, \qquad (6)$$

where v_r is the group velocity of radiation, v_e^* is the longitudinal velocity of electron, and Δt ($=n\lambda_w/v_e^*$, where n and λ_w are the number and wavelength of the undulator periods, respectively) is the time in the laboratory frame during which the electron emits. Micropulses of the RPE emit radiation of pulse width 500–600 ps. Since the separation of micropulses is more than 500 ps, individual micropulses emit radiation independently.

To confirm that the enhancement of the radiation power is caused by the coherent effect due to the electron-beam micropulses, an electron beam having no micropulses was used. The electron beam having no micropulses could be produced by making use of the space-charge limitation of the electron-beam current density in the acceleration tube, when the irradiated laser power is more than 1 MW. The radiation power radiated by the electron beam having no micropulses was approximately at the noise level. This was in contrast to the result for the radiation power radiated from the electron beam having micropulses, which had a high level of radiation power. In this comparison, the current of the electron beam having no micropulses was higher than the peak current of the micropulses. From the above results, we can conclude that the enhanced radiation power is caused by the coherent effect due to micropulses of the electron beam.

In summary, we have observed intense spontaneous emission in a low-energy, low-gain, waveguide-mode FEL. The measured power of the radiation was more than 10^3 times stronger than the theoretical power of the incoherent radiation. The measured power shows quadratic behavior with respect to the electron-beam current. The coherent effect caused by the micropulses of 33 ps is introduced as a possible mechanism of this phenomena, and it agrees well with experimental results. It was confirmed experimentally that the enhancement of the radiation power was caused by the electron-beam micropulses. High-intensity spontaneous emission in the low-energy, low-gain FEL introduces the possibility for another strong and tunable light source in the millimeter-wavelength range.

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