Broadband Free Electron Laser by the Use of Prebunched Electron Beam

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(Received 30 December 1996)

Using prebunched electrons of 35 MeV from a linear accelerator, we have constructed a new type of free electron laser (FEL) which has a quasicontinuous spectrum in the millimeter wave region. The FEL consists of an open resonator and a bending magnet. Wave packets of coherent radiation from electron bunches are stored in the resonator to stimulate the radiation from the following bunches. The accumulated radiation is composed of overtones of the radio frequency of the accelerator and is quasicontinuously distributed over a wide region. By tuning the resonator, either all overtones or a part of them are amplified. [S0031-9007(97)02867-6]

PACS numbers: 41.60.Cr

The spectroscopic research requires a light source which covers a wide spectral region. The free electron laser (FEL) is one of such sources [1]. In the millimeter and submillimeter wave regions, the FEL is developed as an intense and tunable monochromatic source by many researchers using an undulator [2–6]. The frequency of the output radiation is tuned by changing the energy of electrons or by changing the magnetic field of the undulator. In most cases, however, the tunable range of radiation is limited. The intense radiation of the FEL is due to the coherent radiation from the bunch of electrons [7].

Also, from the bunch of electrons in an accelerator, coherent radiation is emitted in the spectral region where the wavelength is longer than the size of the bunch [8,9]. Recently, observations of coherent synchrotron and coherent transition radiation in the millimeter wave region were made by short-bunched electrons from linear accelerators [10–14].

The coherent radiation from an electron bunch has a continuous spectrum, and its energy spectrum $W(\lambda)$ is expressed as [11,14–16]

$$\begin{aligned} W(\lambda) &= N^2 w(\lambda) f(\lambda) \\ &= N^2 w(\lambda) \left| \int S(\mathbf{x}) e^{i\mathbf{k}\cdot\mathbf{x}} d\mathbf{x} \right|^2, \end{aligned} \tag{1}$$

where $w(\lambda)$ is the radiation energy emitted from one electron, and N is the number of electrons in the bunch: The bunch form factor $f(\lambda)$ for the radiation with wave vector $\mathbf{k}$ is the Fourier transform of the density distribution function $S(\mathbf{x})$ of the electrons in the bunch. Since N is a large number, the intensity of coherent radiation is enormously enhanced in comparison with the ordinary incoherent radiation, $Nw(\lambda)$.

From the linear accelerator, the bunches of electrons are successively ejected at the interval of the radio frequency (RF) of acceleration. It has been shown experimentally that all wave packets generated from the successive bunches have the same form, and they interfere coherently with each other [17]. Consequently, the radiation has a quasicontinuous spectrum composed of a series of line spectra whose frequencies are higher harmonics of the RF of the accelerator.

In this Letter we report on a broadband FEL by coherent synchrotron radiation in the millimeter wave region from the bunched electrons of the linear accelerator. With an open cavity which is resonant with the RF, the wave packet of the coherent radiation was superposed on the subsequent bunches to stimulate emission of the radiation. Recently, a similar trial has been reported for transition radiation [18]. In the present experiment, amplification of the radiation of the quasicontinuous spectrum has been observed over a wide range in the millimeter wave region.

The experimental setup is schematically shown in Fig. 1. An electron beam of the energy 35 MeV generated by the L-band linear accelerator of the Research Reactor Institute, Kyoto University, was guided to an open resonator with the two mirrors M1 and M2 which are shown in the inset of Fig. 1. A magnetic field of 80 G was applied to the electron beam with the bending magnet BM. The beam crossed the mirror M1 with the incident angle $\alpha = 1/\gamma$, where γ is the Lorentz factor, and passed along a circular orbit in the magnetic field and left the resonator with the angle α from the optical axis of the resonator [19]. The orbital radius of the beam was 14.6 m and the critical wavelength of synchrotron radiation was 190 μm.

The mirror M1 of the resonator was a plane mirror of aluminum foil 15 μm thick and 95 mm in diameter,

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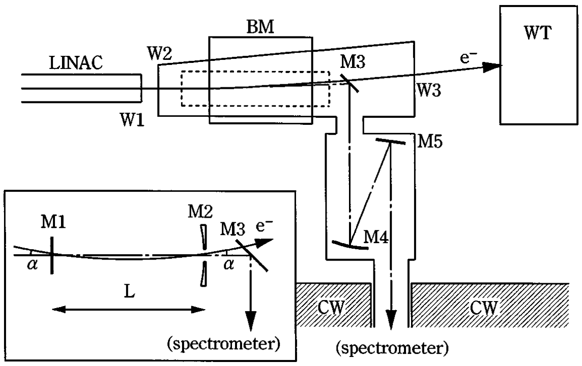

FIG. 1. Schematic layout of the experiment. BM: bending magnet; W1, W2: titanium windows; W3: aluminum windows; M3, M5: plane mirrors; M4: spherical mirror; WT: water tank (beam catcher); CW: concrete wall. The inset shows the open cavity composed of the mirror M1 of Al foil and the mirror M2 of a fused quartz whose central part of 20 mm in diameter is transparent. The trajectory of the electron beam is shown by the thin solid curve.

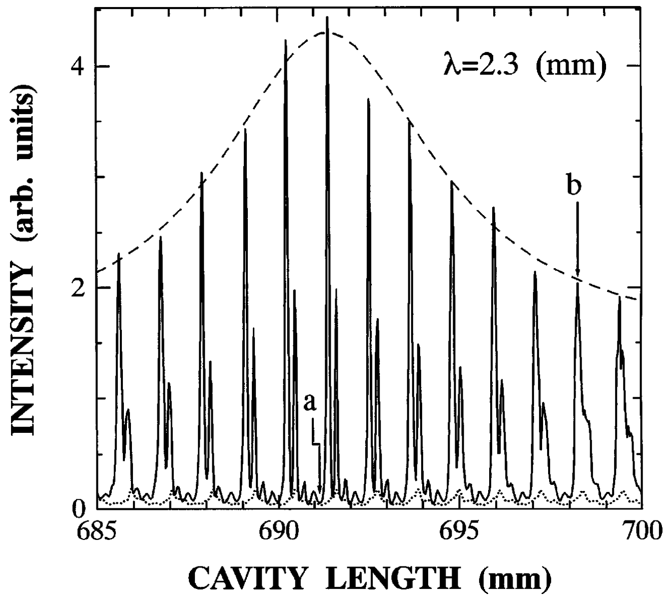

FIG. 2. Detuning curve of the intensity with the cavity length observed at $\lambda = 2.30$ mm. The dotted curve shows the result obtained on the condition that the mirror M2 is tilted by 2° from the optimum direction. The dashed curve is the calculated envelope of the peaks with $Q = 30$.

while M2 was a concave mirror of aluminum coated fused quartz 128 mm in diameter, and its focal length was 1200 mm. The central part (20 mm in diameter) of the mirror M2 was not coated, and the radiation generated in the resonator was extracted through the transparent part. The distance between the mirrors M1 and M2 was variable around 691 mm.

The conditions of the electron beam were as follows: The RF was 1300.8 MHz, and the energy and the energy spread were 35 MeV and 7%. The duration of a pulse was 1.9 μs, and the repetition of the pulse was 13 Hz. The average beam current was 6 μA. Hence the one pulse was composed of about 2500 bunches, and the average number of electrons in the bunch was 1.1×10^9. The distance between the successive bunches was 230.47 mm. The transverse cross section of the beam was circular and its diameter, or the full width at half maximum (FWHM) of the transverse distribution of electrons, was 8 mm at the position of the mirror M1. The beam emittance was 80 mm mrad. It has been confirmed that this beam emits coherent synchrotron radiation in the millimeter wave region [12].

The radiation from the open resonator was reflected by the plane mirror M3 of an aluminum coated fused quartz to a far-infrared spectrometer of the grating type, and the radiation was detected by a liquid-helium-cooled Si bolometer.

The solid curve in Fig. 2 shows the variation of the intensity with the cavity length L of the resonator measured at the wavelength λ of 2.30 mm, the 100th harmonic of the RF. The curve shows a periodic structure with the period of $\lambda/2$. Each structure has a main peak and a few subpeaks. The main peak was confirmed to be related to synchrotron radiation, and the secondary peak is related to transition radiation, as described below. The main peaks show the maximum at the resonant position of the cavity length, where L is considered to be three times the RF wavelength, 691.4 mm.

When the mirror M2 was tilted by 2° from the optimum condition to make the resonator ineffective, stimulation of emission disappeared. The dotted curve in Fig. 2 shows the variation of the intensity thus obtained. Compared with the intensity of the tilted resonator, the intensity at the maximum peak was enhanced by a factor of about 90.

These results show that the wave packets of coherent synchrotron radiation generated from bunches circulate around the resonator, and stimulate emission from the subsequent bunch.

Such a cyclic process stabilizes after a characteristic time of the resonator $QL/\pi c$, where Q is the quality factor of the resonator. At the stabilized stage, the energy stored in the resonator by a pulse composed of N_b bunches may be expressed as [20]

$$W_{\mathrm{pulse}} = N_b \lambda_b \sum_m W'(\lambda_m) g(\lambda_m, Q, L)/m^2, \qquad (2)$$

$$g(\lambda, Q, L) = [1 - 2\cos(4\pi L/\lambda)\exp(-2\pi/Q) + \exp(-4\pi/Q)]^{-1}, \qquad (3)$$

where λ_b is the distance between the successive bunches, 230.47 mm, and $W'(\lambda)$ is the intensity of stimulated radiation from a single bunch. The intensity $W'(\lambda)$ is proportional to $W(\lambda)$ of Eq. (1), if the effect of the change of spectrum due to the optical modes in the resonator is negligible. The radiation emitted from the successive bunches results in the harmonics of the RF of the accelerator, and the wavelength of the mth harmonic

λ_m is λ_b/m. The harmonic is resonant with the cavity when the following condition is satisfied:

$$\lambda_m = \lambda_b/m = 2L/n\,, \tag{4}$$

where m and n are integers.

The observed envelope of the main peaks and of the linewidth of the maximum peak at $L = 691.4$ mm in Fig. 2 are explained well by Eq. (2) with the quality factor Q of 30. The dashed curve in Fig. 2 shows the calculated envelope.

At the maximum peak of the resonant position in Fig. 2, the length L is $3\lambda_b$. Therefore, the whole overtones of the RF with $m = 1, 2, 3, \ldots,$ satisfy the resonant condition of Eq. (4) with $n = 6m$. The spectrum observed at this whole resonance of the entire overtones is shown by the solid curve in the upper part of Fig. 3: It has been observed as a continuous spectrum, since the resolving power of the spectrometer ($\lambda/\Delta\lambda$) is 40 at $\lambda = 2$ mm and is too low to resolve each component of the overtones.

We observed spectra by changing the cavity length from the whole resonance to the length $L = 690.8$ mm (marked by an arrow a in Fig. 2) and to $L = 698.3$ mm (arrow b). At $L = 690.8$ mm, the intensity in Fig. 2 shows a minimum.

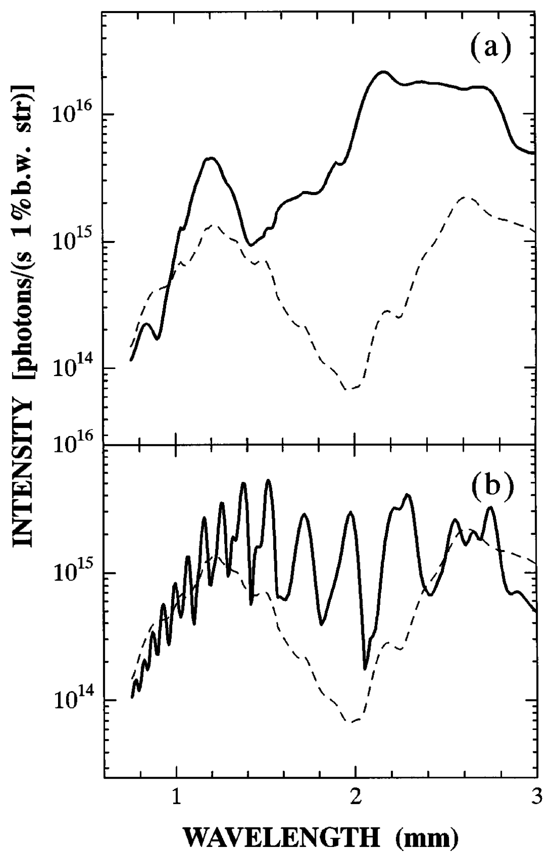

FIG. 3. (a) Spectrum observed at the whole resonance, i.e., the on-resonance condition (solid curve) for the whole harmonics. The dashed curve shows the spectrum at an off-resonance condition shown by the arrow a in Fig. 2. (b) Spectrum observed at a selectively resonant condition for particular harmonics with the cavity length shown by the arrow b in Fig. 2. The dashed curve shows the same off-resonance spectrum as in the upper figure (a).

The observed spectrum for $L = 690.8$ mm is shown by the dashed curve in Fig. 3(a). In this case, the overtones of the RF satisfies the resonance condition only at $\lambda = 0.7$ mm, which is outside the observation. The spectral intensity of the solid curve of the whole resonance is higher by about an order of magnitude than the dashed curve in the wavelength region $\lambda > 1.8$ mm.

For the cavity length of 698.3 mm, where the intensity in Fig. 2 has a local maximum, the observed spectrum is shown by the solid curve in Fig. 3(b). The spectrum has a periodic structure and particular overtones are selectively amplified. For the cavity length of 698.3 mm, the resonance should occur selectively when the overtones of the RF tune to the resonant cavity satisfying the condition of Eq. (4), $230.47/m = 2L/n$, with two integers m and n. The peaks in Fig. 3(b) are seen, for example, at wavelengths 2.78 mm ($m = 83$, $n = 503$), 2.30 mm (100, 606), 1.97 mm (117, 709), and 1.73 mm (133, 806), as expected.

The main peak in Fig. 2 was confirmed to be due to synchrotron radiation from the following observations: Firstly, the main peak at the cavity length $L = 691.4$ mm was polarized in the orbital plane of the beam and the degree of polarization defined by $(I_\parallel - I_\perp)/(I_\parallel + I_\perp)$ was 0.25, where $I_\parallel$ and $I_\perp$ are horizontally and vertically polarized components of the radiation. Secondly, the intensity of the maximum peak was observed to decrease with the decrease of the magnetic field. The closed circles in Fig. 4 show the variation of the peak intensity at $\lambda = 2.3$ mm.

According to the theory of undulator radiation, the output energy of the undulator is proportional to $K^2/(1 + K^2)$, where K is the undulator parameter defined by

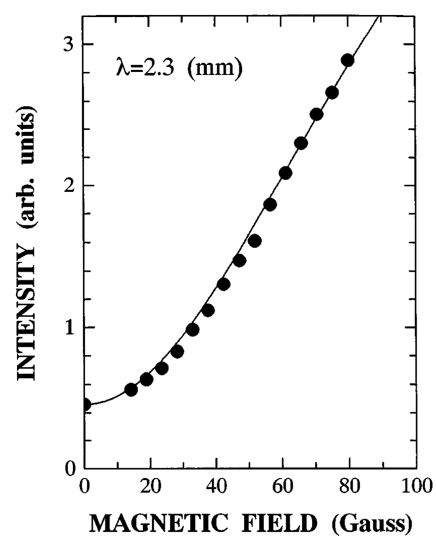

FIG. 4. Dependence of the intensity of the main peak on the magnetic field. Closed circles show the experimental result and the solid curve is the calculated intensity of a half-period undulator radiation in an arbitrary unit.

$K = eBd/2\pi m_e c^2$, B and d being the magnetic field and the periodic length of the undulator, respectively [19]. In the present case, the period is one-half, and d is taken as twice the length of the bending magnet, $d = 100$ cm. The dependence of the value of the function $K^2/(1 + K^2)$ on the magnetic field is shown in Fig. 4 in arbitrary units by the solid curve. This curve is shifted upward by the amount of the residual intensity which was observed without the magnetic field. The experimental dependence of the intensity on the magnetic field is in good agreement with the theory.

The intensity of the secondary peak in Fig. 2 depended little on the magnetic field, and the degree of polarization of the secondary peak was nearly zero. Hence we consider that the secondary peak, as well as the residual intensity of the main peak without the magnetic field, is related to transition radiation emitted from the electrons passing through the mirrors of the resonator. A study on the process of the stimulation of the transition radiation is under way in connection with the optical modes in the resonator.

The shape of the spectrum shown by the solid curve in Fig. 3(a) has a rough resemblance to that of coherent synchrotron radiation expressed by Eq. (1) and observed previously [12]. However, it has some structure such as broad peaks at $\lambda = 1.2$ and 2.2 mm, and these are to be studied further also in connection with the optical modes in the resonator.

The total output power of the radiation integrated over the observed region was evaluated to be 52 μW. Hence the radiation energy was 4 μJ per pulse which was composed of 2500 bunches. The spot size of the radiation stored in the cavity was estimated to be 66 mm in diameter at $\lambda = 2.3$ mm at the position of the mirror M2. Therefore the energy of the radiation in the cavity was estimated to be about 45 μJ per pulse from the size of the output window. The radiation power will be increased by an order of magnitude or more, if we improve the experimental conditions such as operational conditions of the beam and the parameters of the resonator.

In conclusion, it has been shown that effective amplification of coherent synchrotron radiation from the short-bunched electrons occurs. The radiation of the prebunched FEL has the quasicontinuous spectrum. Furthermore, when the cavity length is varied, we can select other spectra of radiation as shown in Fig. 3. The principle of the operation is applicable to any wavelength region, and the prebunched FEL will be a useful light source because of its broad spectrum.

We thank T. Tsutaya of RISM, K. Takami and the staff of RRIKU for their technical support and assistance during the experiment.

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