Measurement of < 20 fs bunch length using coherent transition radiation

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By monitoring coherent transition radiation (CTR) with a Michelson interferometer, bunch length measurement was investigated. Less-than-20-fs electron bunches were generated by a photocathode-based linear accelerator (linac) and a magnetic bunch compressor. From the femtosecond electron bunch of 2.1 pC and 32 MeV, CTR was measured using a Michelson interferometer that had two detectors with different spectral ranges, which enhanced the detection spectral range of CTR (ranging from 3 to 50 THz) and enabled us to determine the bunch length of the electron bunch. A model based on the interferometer's frequency sensitivity was proposed and introduced to analyze the measured interferograms. The measured interferograms and the frequency spectra were explained using the model.

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I. INTRODUCTION

Ultrashort electron bunches with durations of picoseconds to femtoseconds [1–13] are widely used in accelerator physics applications, such as free-electron lasers [14–16] and laser-Compton x rays [17]. A short electron bunch is the key element in time-resolved studies of ultrafast reactions and phenomena, including ultrafast electron diffraction (UED) [18,19] and pulse radiolysis [20–23]. The time resolution of UED and pulse radiolysis depends on the electron bunch length. In UED, an electron bunch is used as a probe source, and ultrafast phenomena are monitored using electron diffraction patterns. Pulse radiolysis is also an important technique that involves an electron bunch and is a useful and powerful tool for observing ultrafast radiation-induced phenomena and analyzing the kinetics of these mechanisms. The application fields of this technique are expanding to include chemistry, physics, and biology, and much effort has been devoted to improving the time resolution. Recently, a time resolution of ~ 240 fs was achieved in pulse radiolysis with electron bunches of ~ 100 fs from a photocathode-based linear accelerator (linac) with femtosecond laser pulses used as the probe light [21]. Even in convolution-based analyses, the time resolution of these time-resolved measurements depends on the electron bunch length [21]. Therefore, the generation of ultrashort electron bunches is important for improving the time resolution of these techniques. To characterize these ultrashort bunches, it is necessary to improve the

techniques for bunch length measurements. Pulse radiolysis with higher time resolution would provide a more comprehensive understanding of ultrafast phenomena, for both monitoring and controlling radiation-induced phenomena. Using a femtosecond-streak camera, some of the authors measured an electron bunch length of 100 fs with 170 pC by measuring the Cherenkov light from the electron bunches [7]. Short electron bunches are also useful for generating electromagnetic (EM) waves in the terahertz range. The coherent radiation from electron bunches in the terahertz spectral range has been studied for applications such as beam diagnoses [4,5,11,12], pump sources in time-resolved x-ray absorption spectroscopy [9,13], probe sources in terahertz imaging and spectroscopy [11], and beam acceleration [9]. An electron bunch emits intense radiation at a wavelength longer than the bunch length when crossing a boundary between different media, and this radiation is called coherent transition radiation (CTR) [1–5,10,12,13]. The spectrum of CTR depends on the bunch form factor [2], which is expressed using the square modulus of the Fourier transform (FT) of an electron bunch distribution in the time domain. In the 1990s, CTR spectra obtained from ~ 800 fs electron bunches were analyzed using grating-type spectrometers [2]. Longitudinal profile measurements were performed on picosecond or subpicosecond electron bunches, and time-domain approaches were achieved using a filtered model [4] or Kramers-Kronig relations [3,5]. Recently, measurement of the root mean square (rms) Coulomb field was demonstrated by an electro-optic (EO) monitor on a 60-fs electron bunch [6,8]. Interferometers were also used for full width at half maximum (FWHM) measurements on ~ 50 fs electron bunches [1,10,13].

In the present study, to improve the time resolution of the pulse radiolysis technique, bunch length measurement was

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investigated by monitoring CTR using a Michelson interferometer. The ultrashort electron bunches were generated by a photocathode-based linac with a magnetic bunch compressor. Bunch length measurement is also important for characterizing electron bunches. Enabling analysis of broadband terahertz waves up to 50 THz, the technique using a Michelson interferometer with two detectors could be a useful and effective method for characterizing a wide range of bunch lengths and may be an applicable technique for ultrashort bunch lengths (as short as 10 fs or less).

II. EXPERIMENTAL SETUP

A. Generation of femtosecond electron bunches using a photocathode-based linac

The schematic diagram of the laser photocathode radio-frequency (rf) electron gun linac at the Institute of Scientific and Industrial Research in Osaka University is shown in Fig. 1 [7,11,21,22,24–26]. The linac is composed of a 1.6-cell S-band (2.856 GHz) rf electron gun with a copper cathode, a 2-m-long S-band acceleration tube, and a magnetic bunch compressor [7]. In the present study, rf from a klystron was fed to both the rf gun and the accelerating tube, which was equipped with phase shifters. The klystron was operated at a pulse width of 4 μ s and a repetition rate of 10 Hz. The photocathode was irradiated by a 266-nm femtosecond laser pulse from the third harmonic of a Ti:sapphire femtosecond laser with a regenerative amplifier (Tsunami with Spitfire, Spectra-Physics) [26]. The incident angle on the photocathode was $\sim 2^\circ$ with respect to the electron beam axis. To obtain low-transverse-emittance electron bunches, an iris with a 2.5-mm diameter and a quartz lens with a 5-m focal length were placed between the injection port of the gun and the laser output port of the laser (in air), and the laser energy was reduced to 6 ± 0.2 μ J/pulse. The distance between the

lens and the cathode was 1.7 m. By measuring the spot size at the equivalent distance of the cathode, the spot size of the UV pulse was determined to have a full width at half maximum of 0.6 ± 0.02 mm. In the present experiments, the charges of the electron bunches were suppressed to the picocoulomb order to reduce bunch length growth resulting from the space charge effect. To generate electron bunches with low transverse and longitudinal emittances, the laser injection phase was set to 15° [26], although the bunch charge was maximized near the rf crest, which was $\sim 80^\circ$. The obtained beam energy at the gun exit was ~ 4 MeV. The electron bunches were accelerated up to 32 MeV by the booster linac with an energy-phase correlation optimal for compression. According to a previous study investigating the phase-scan technique using this linac, the rms bunch length of the electron bunches generated by the femtosecond laser was estimated to be ~ 280 fs at the gun exit for a bunch charge of 4 pC; compression by the magnetic bunch compressor was not applied [26]. The femtosecond electron bunch was compressed by rotating the phase-space distribution in the magnetic bunch compressor, which was composed of a pair of 45° bending magnets (B1 and B2), two pairs of quadrupole magnets (Q3, Q4, Q5, and Q6), and a pair of sextupole magnets (S1 and S2). The sextupole magnets in the compressor served to compensate for the second-order effect, which would cause bunch length growth because of the nonlinear transformation of the energy-phase correlation [7,24,25]. The charge of the electron bunch was estimated using an integrating current transformer. The electron bunch was compressed by the compressor, and the bunch length measurements were conducted on the compressed bunch using the Michelson interferometer [11].

B. Bunch length measurement system

Our measurement scheme follows the time-domain approaches applied by Kung *et al.* [1] and Murokh *et al.* [4]. In the present study, the Michelson interferometer was used to measure interferograms produced by autocorrelation of CTR generated by the electron bunches [1,4,5,10,13]. Some studies have reported electron bunch measurement with this technique using detectors comprised of liquid-helium-cooled bolometers [1,2,5,9,11], pyroelectric detectors [10,12,13], and Golay cells [4]. In this study, both development and calibration of a broadband interferometer for analysis of ultrashort electron bunches were proposed to expand the applicative spectral range to the higher frequencies of a terahertz EM wave; this expansion is crucial for bunch length measurements of ultrashort electron bunches. The spectrum of coherent radiation is related to the bunch form factor, and it is known that a shorter electron bunch emits EM waves with higher frequency components [2,4]. Therefore, detection of a wider range of EM waves is necessary for analyzing the bunch length of ultrashort electron bunches. To satisfy

FIG. 1. Schematic diagram of a laser photocathode rf electron gun linac. Q1-6: quadrupole magnet; B1, 2: bending magnet; S1, 2: sextupole magnet. The rf electron gun was a 1.6-cell electron gun, and a solenoid magnet was equipped immediately after the gun exit. The linac tube was composed of 54 cells. The magnetic bunch compressor was composed of a pair of bending magnets, two pairs of quadrupole magnets, and a pair of sextupole magnets.

these requirements, a mercury cadmium telluride (MCT) photoconductive detector (which, compared with bolometers, is sensitive to higher frequencies of EM waves) was selected for the present experiment. In addition, a model for analyzing the obtained interferogram was proposed. Details of the model will be discussed in the next section.

The schematic for the electron bunch length measurement system using the Michelson interferometer is shown in Fig. 2. To avoid absorption of terahertz waves by normal air (especially moisture), all optics (except for the detectors) were placed in a vacuum chamber. Figures 2(a) and 2(b) show switchable optics for measuring an infrared light source (IRS) (which is used as a standard light source to calibrate and optimize the alignment of optics) and for measuring CTR generated by electron bunches, respectively. Initially, the interferometer was calibrated and optimized using an IRS (IRS-001C, IR System) with a filament of ~ 3 mm. The light from the IRS was modulated to 1 kHz by an optical chopper (MC2000 with MC1F10, Thorlabs), and the intensity and position of a tunable mirror were simultaneously acquired using a digital lock-in detection technique for precisely optimizing the interferometer. After measuring the IRS, the signal from the detector was amplified using a built-in preamplifier from the bolometer (gain: 200), and the amplified signal was then fed to a lock-in amplifier (LI5640, NF) locked by a reference signal from the optical chopper. No frequency filter was used for the lock-in amplifier. The filament temperature of the IRS was set to ~ 1173 K. The surface of the filament was coated with a blackbody spray (JSC-3, Japan Sensor) to generate blackbody radiation according to Planck's law. The terahertz wave from the IRS was

FIG. 2. Measurement system using a Michelson interferometer for (a) an infrared light source and (b) CTR from electron bunches. IRS: an infrared light source; C: an optical chopper (1 kHz modulation); M: a plane mirror; OAP: an off-axis parabolic mirror used for collimation and focusing on the detectors; BS: a beam splitter; MCT: a MCT photoconductive detector; B: a bolometer; beam port: a port made of titanium foil. Except for the detectors, all optics were set up in a vacuum chamber. The components surrounded with dashed lines [(a) and (b)] were designed to be switchable. M5 was placed on a delay stage for sweeping the mirror. The signal was acquired using a digital lock-in amplifier for the IRS measurement and an oscilloscope for CTR measurement.

collimated and was then split in two by a beam splitter (BS) made of a $380 \mu\text{m}$ -thick high-resistivity silicon (HRSi) wafer. One of the terahertz waves was reflected by a fixed mirror (M4), while the other was reflected by a position-tunable mirror (M5) on a delay stage (SGSP26-50 with SHOT-302MS, Sigmakoki). Finally, the two terahertz waves were superimposed, and the autocorrelated terahertz wave was fed to the detector. The detector was a liquid-helium-cooled silicon bolometer (general-purpose 4.2-K system, Infrared Laboratories) with a conventional far-IR cut-on filter (600 cm^{-1}) [27] or a liquid-nitrogen-cooled MCT photoconductive detector (P5274-01, Hamamatsu photonics). The focal length of both off-axis parabolic mirrors (OAP1 and OAP2) was 191 mm. The window materials of the inlet port of the bolometer and the MCT detector were high-density polyethylene and KRS-5 (thallium bromoiodide), respectively. The signal was acquired by sweeping the tunable mirror (M5). Therefore, the interferogram was obtained as a function of the tunable mirror's position, which can be converted to time delay. The frequency spectrum was obtained using the FT of the interferogram. After optimizing the optics with the IRS, the IRS part was switched to the optics for electron bunch measurement. The target material generating CTR was an aluminum mirror (M1). The electron bunch was introduced to the mirror at 45° after passing through titanium foil (with a $20 \mu\text{m}$ thickness), which separated the high-vacuum beam line from the measurement system, which was operated at a lower vacuum in the chamber. Based on the bolometer's measurement of CTR, the signal from the detector was amplified by the bolometer's built-in preamplifier (gain: 1000), and the amplified signal was then acquired using an oscilloscope (TDS3054B, Tektronix), which was triggered by a signal synchronized to the frequency-divided rf. In the case of the MCT detector, a preamplifier (model 5307, NF, gain: 500) was used. Interferograms were obtained by sweeping the tunable mirror (M5).

C. Theoretical description for analysis of the measured interferograms

The bunch length can be obtained by analyzing the interferogram of CTR. Frequency components of coherent radiation, such as CTR, are known to have a relationship with the bunch form factor, which is described by the square modulus of the FT of the bunch distribution. Bunch form factor F_b is expressed as a function of angular frequency ω , as follows [2,4]:

$$F_b(\omega) = \left| \int_{-\infty}^{+\infty} \rho(t) e^{-i\omega t} dt \right|^2, \quad (1)$$

where $\rho(t)$ denotes the longitudinal charge distribution as a function of time t . When $\rho(t)$ has an ideal Gaussian distribution with rms bunch length σ , the longitudinal charge distribution will be written as follows:

$$\rho(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-t^2/2\sigma^2}. \quad (2)$$

An analytical form of the bunch form factor can be expressed as follows:

$$F_b(\omega) = e^{-\sigma^2\omega^2}. \quad (3)$$

If an experiment is conducted with an ideal measurement system that has ideal frequency sensitivity at any frequency, the interferogram could have a Gaussian distribution. However, experimentally obtained interferograms cannot have the Gaussian distribution because real experimental setups typically contain limitations and nonflat sensitivity in the spectral range of the detection system (which may include whole optics and effects of a high-pass filter resulting from diffraction limits, such as physical apertures) [1,4,12]. Therefore, the bunch length measurement system's sensitivity and the effects of the filter should be considered when analyzing an interferogram based on the time-domain approach. Murokh *et al.* introduced effects from both the high-pass filter and the bunch length into an analytical form for interferogram $i(\tau)$, as follows [4]:

$$i(\tau) \propto e^{-\tau^2/4\sigma^2} - \frac{2\sigma}{\sqrt{\sigma^2 + \xi^2}} e^{-\tau^2/4(\sigma^2 + \xi^2)} + \frac{\sigma}{\sqrt{\sigma^2 + 2\xi^2}} e^{-\tau^2/4(\sigma^2 + 2\xi^2)}, \quad (4)$$

where τ and ξ denote the time delay and the reciprocal of the cutoff frequency, respectively, of the high-pass filter. By fitting the interferograms using Eq. (4), the rms bunch length is obtained. However, to explain the experimental data, it is necessary to include the effect of the detection system's frequency dependence, and the experimental data were not always well fitted with Eq. (4), as shown in Sec. III C. Therefore, an analytical method based on the frequency dependence of the detection system's sensitivity was proposed and introduced for the present experiments. To clarify the frequency dependence of the detection system's sensitivity, the blackbody radiation was measured by the same system used to measure the electron bunch length. According to Planck's law, the blackbody radiation at temperature T is given by the following:

$$B(\omega) = \frac{\hbar\omega^3}{4\pi^3 c^2} \frac{1}{e^{\hbar\omega/k_B T} - 1}, \quad (5)$$

where $B(\omega)$, $\hbar$, c , and k_B denote the spectral radiance, the reduced Planck constant, the speed of light, and the Boltzmann constant, respectively. The experimentally obtained spectrum of the blackbody radiation would differ from the spectrum expressed by Eq. (5) because of the effects of physical apertures, absorption and reflectance on beam splitters, and detector characteristics. Here, the

system's frequency sensitivity $S(\omega)$ will be introduced as a function of ω , as follows:

$$S(\omega) = \frac{I_{\text{IRS}}(\omega)}{B(\omega)}, \quad (6)$$

where $I_{\text{IRS}}(\omega)$ is an experimentally obtained frequency spectrum acquired by measuring an IRS. Therefore, $S(\omega)$ is obtained as numerical values, which are characteristic of the applied measurement system. Assuming the frequency spectrum of CTR can be expressed as a product of the bunch form factor and the frequency sensitivity, frequency spectrum $K(\omega)$ and interferogram $k(\tau)$ are expressed as follows:

$$K(\omega) = F_b(\omega)S(\omega) = e^{-\sigma^2\omega^2}S(\omega), \quad (7)$$

$$k(\tau) \propto \int K(\omega) e^{i\omega\tau} d\omega = \int e^{-\sigma^2\omega^2} S(\omega) e^{i\omega\tau} d\omega. \quad (8)$$

In Eq. (8), the interferogram will be obtained from the inverse FT, according to Eq. (7). Both the frequency spectrum and the interferogram will be obtained as numerical values.

In this paper, the electron bunch analysis based on Eq. (4) will be called the filtered model, and the model proposed above will be called the sensitivity model. Interferograms were acquired for CTR generated by ultra-short electron bunches and were analyzed using those two models. Equations were derived under the assumption of a longitudinal charge distribution for a bunch with a Gaussian shape. It is also important to account for the symmetry of the bunch distribution. The measurement of the asymmetric electron bunch distribution was conducted based on interferometers using Kramers-Kronig relations [3,5,13]. Using EO sampling, the time domain measurement was also reported [6,8], and this measurement is a better method for directly measuring the asymmetry of an electron bunch. Because combinations of several techniques, such as EO sampling and photoconductive antennas [28–32] with interferometry, could be good candidates for analyzing bunch length with respect to the symmetry of the electron bunches, it is preferable to examine the effects of bunch shapes. However, consideration of asymmetry exceeds the scope of this article, and the assumption of a symmetric bunch was adopted.

III. RESULTS AND DISCUSSION

A. Characterization of the measurement system using the IRS

All optical alignments shown in Fig. 2(a) were optimized using the IRS as a light source. The criteria were the output signal intensities at the centerburst position. The signals from the high-frequency components were more sensitive to the alignment than the signals from the low-frequency

components. The signal intensity at each frequency was determined by the product of the emitted light intensity from the IRS and the sensitivity of a detector at the corresponding frequency. Experimentally, the signal intensity at the centerburst position gave reliable information for achieving the correct alignment for the present frequency region. The larger signal at the centerburst position resulted in better spectral spread. The interferograms and the frequency spectra of the IRS measured by both the bolometer and the MCT detector are shown in Fig. 3. As is clearly depicted in Fig. 3(a), the interferogram obtained from the MCT detector had a sharper centerburst signal than the signal obtained using the bolometer. This difference results because, compared with the bolometer, the MCT detector has broader sensitivity toward the high-frequency region. The frequency spectrum obtained from the FT of the interferograms acquired by the MCT detector had broadband sensitivity of 11 to 50 THz and no signal in the low-frequency region (up to 11 THz) because of insufficient sensitivity, as shown in Fig. 3(b). Conversely, the frequency spectrum obtained from the interferogram taken by the bolometer had narrow sensitivity of 3 to 15 THz because of the limited sensitivity of the bolometer. For simplicity, comparison of the detection frequency region was made at 10% of each detector's maximum intensity. The lower and upper cutoff frequencies of the MCT detector originated from the band-gap energy and transmittance, respectively, of the HRSi beam splitter. The

two cutoff frequencies of the bolometer resulted from the diffraction limit and the transmittance, respectively, of the polyethylene window. The dip observed around 20 THz is explained by lattice absorption in silicon. The IRS spectrum attained maximum intensity around 70 THz, as calculated by Eq. (5), but the experimentally obtainable signal could not be reproduced, even if the MCT detector (which had broadband sensitivity) was used in the experiment. Therefore, the sensitivity model will be required for properly evaluating the obtained spectra. Before the bunch length measurement, the IRS part was replaced with the mirror, as shown in Fig. 2(b).

B. Bunch length measurement using the bolometer

Before measuring the interferograms, the signal from the bolometer was maximized by tuning the magnetic bunch compressor to achieve maximum bunch compression. According to the bunch form factor [Eq. (3)], the spectrum of CTR generated by an electron bunch will be extended toward higher frequencies. Because a CTR spectrum monotonically decreases with respect to frequency, the signal intensity measured by the bolometer will increase when the CTR spectrum broadens under identical bunch charge conditions. The dependence of the bunch length on the accelerating phase was measured using the bolometer, as shown in Fig. 4. The 15° accelerating phase in the gun and the 2.1-pC bunch charge were the fixed conditions for

FIG. 3. (a) Interferograms and (b) frequency spectra obtained from measurements of the infrared light source by the bolometer (square) and the MCT detector (circle) with factors and offsets. The spectral radiance of Planck's law at 1173 K (dashed line) was also plotted against frequency alongside experimental values. The spectral radiance was used for calculating the frequency sensitivity given by Eq. (5).

the measurements. Under these conditions, the dependence of the bunch length on the accelerating phase was examined to optimize the linac phase for generating ultrashort electron pulses. The rms bunch length was estimated by the least-squares fittings of the interferogram based on analysis using the filtered model and the sensitivity model. From the filtered model, the rms bunch lengths were determined to be 106, 76, and 21 fs at phases of 90°, 100°, and 105°, respectively. From the sensitivity model, the rms bunch lengths were determined to be 87, 63, and 26 fs at phases of 90°, 100°, and 105°, respectively. In the region with frequencies between 0 and 2 THz and frequencies higher than 20 THz, the bolometer obtained no reasonable signal. The measured interferograms were well expressed by both of the filtered model and the sensitivity model. There was almost no difference between the derived bunch lengths from the two models. In the present case, both the shape of the high-pass filter used in the filter function and the response of the bolometer were quite similar. Therefore, analysis using both models produced similar results. The effective frequency spectrum of the filtered model is considered to be the product of the corresponding elements of the filter function and the bunch form factor with respect to the frequency. It is expected that differences between the filtered model and the sensitivity model would appear when the spectrum predicted by the bunch form factor extended toward frequencies where the bolometer has limited sensitivity. The CTR spectrum from bunches with a length of several tens of femtoseconds might have some emission in the range of 15 to 20 THz, where the bolometer has limited sensitivity; however, the contributions of the signal from those frequencies to the total signal appeared too small to change the fitting parameters. Therefore, the qualities of the fitting based on the filtered model were similar to the qualities obtained using the sensitivity model, as shown in Fig. 4. In Fig. 5, the rms bunch lengths were plotted against the accelerating phases in the linac. An accelerating phase in a linac changes the energy modulation of an electron bunch. In order to compress the electron bunch in the magnetic bunch compressor, adequate energy modulation of the electron bunch is required because of a momentum compaction factor. For example, the factor R_{56} was -63 mm [24,25] for this compressor. As clearly shown in Fig. 5, the minimum bunch length was obtained at the phase of 105°. In a previous study, to achieve maximum compression of the electron bunch, which was generated by picosecond laser pulse irradiation ($\lambda = 262$ nm), the optimal acceleration phase in the linac was 94°, and the bunches were compressed to a rms of ~ 400 fs at a 1-nC bunch charge [7]. The difference between the optimal accelerating phases in the previous study and the present case is assumed to result from differing conditions, such as the bunch length, the energy per pulse of the UV source laser for cathode irradiation, the laser injection phase, the charge density in beam transportation, and the tuning of the

bunch compressor. Analyzed using the two models, the trends in bunch length as a function of the linac phase agreed with each other. Based on the shapes and the bunch length estimated by fitting the interferograms, the optimal acceleration phase in the linac was determined to be 105° for the present conditions.

C. Benchmark of the MCT detector

The interferograms of CTR measured using the MCT detector and the obtained frequency spectra are shown in Fig. 6. The fitting curves from both the filter model and the sensitivity model are also depicted in the figure. The accelerating phase for the gun, the bunch charge, and the linac phase were 15°, 2.1 pC, and 105°, respectively. The magnetic bunch compressor was tuned before measuring the interferogram, and this sequence was identical to the procedure for the bolometer. The interferograms were fitted using Eq. (8) for the analysis based on the sensitivity model or using Eq. (4) for the analysis based on the filtered model, as shown in Fig. 6(b). The rms bunch length was estimated to be 8.9 fs based on the sensitivity model and 14 fs based on the filtered model. Because the MCT detector has no sensitivity at frequencies higher than

FIG. 4. Interferograms of CTR for 90° (diamond), 100° (square), and 105° (circle) accelerating phases in the linac measured with the bolometer. The interferograms were analyzed with the filtered model (dotted line) and the sensitivity model (solid line). The rms bunch lengths were determined to be 106, 76, and 21 fs at linac phases of 90°, 100°, and 105°, respectively, using the filtered model, while the corresponding values were 87, 63, and 26 fs using the sensitivity model. The interferograms were plotted with offsets and normalizing factors. Factors of 4, 2, and 1 were used at phases of 90°, 100°, and 105°, respectively.

100 THz, a frequency sensitivity under 100 THz was used for the analysis. In the measured interferogram, the oscillation beside the centerburst can be explained by the effect of the band-gap energy, which cut off the sensitivity at low frequencies, and was not caused by the diffraction limit. The fitted curve based on the sensitivity model could express the entire interferogram (including the oscillations), whereas the fitted curve based on the filtered model could not explain the experimental interferogram (except around the centerburst). This result was expected because the function for the filtered model [Eq. (4)] cannot express these oscillations. Even if the interferogram's fitting quality better resembled the fitting acquired using the sensitivity model, the experimental value and the fitting curve at the frequency region higher than ~ 30 THz were in poor agreement. This finding results because the high-cycle signals on the interferogram correspond to the high-frequency components on the frequency spectrum. Furthermore, when the FT was conducted on the experimentally obtained interferogram (including experimental errors/noises related to the sampling interval), these noises would appear in the high-frequency region of the frequency spectrum. In the present case, $S(\omega)$ was precisely determined, and almost no error originated from $S(\omega)$ when the interferogram was fitted with Eq. (7). Even under this condition, the calibration would not affect the experimental errors/noises. As shown in Fig. 6(a), the intensity of the signal spiked near 10 THz, where the cutoff frequency (resulting from the band-gap energy of the MCT, as predicted based on the sensitivity limitation of the MCT detector) is located. The frequency spectrum calculated using the sensitivity model agreed well with the experimental data, including the dip resulting from lattice absorption of the beam splitter, whereas the filtered model could not reproduce the experimental data. The bunch lengths obtained from analysis using the sensitivity model for the interferogram measured with the MCT detector and for the interferogram measured with the bolometer were in

FIG. 5. Root-mean-square bunch length as a function of the accelerating phase in the linac measured with the bolometer. The interferograms were analyzed using the filtered model (cross) and the sensitivity model (circle).

FIG. 6. (a) CTR frequency spectra of the experimental values (circles) and fitting curves from the filtered model (dashed line) and the sensitivity model (solid line). (b) Interferograms for each data set. Root-mean-square bunch lengths were determined to be 14 and 8.9 fs based on the least-squares fitting from the filtered model and the sensitivity model, respectively. All data was measured by the MCT detector.

poor agreement, even when the measurement conditions were identical (although the detector differed). The interferogram measured with the MCT detector resulted in a bunch length of 8.9 fs, while the interferogram measured with the bolometer resulted in a bunch length of 26 fs. Because the quality of analysis appeared fairly similar for both interferograms, the difference can be explained by the bolometer's lack of sensitivity at the high-frequency region, which meant that the bolometer was not suitable for measuring bunches of several tens of femtoseconds. Especially in the case of the MCT detector, the sensitivity model is worthwhile for evaluating bunch length in the frequency spectrum or the time domain. The analysis of the interferogram obtained by the sensitivity model indicated that <20 fs electron bunches were generated. Although assuming both the bunch form factor and a symmetric electron bunch with a Gaussian distribution was required, a <20 fs electron bunch with 2.1 pC was successfully measured using the Michelson interferometer with the MCT detector. It was also suggested that, when the bunch length became shorter than 20 fs, it was difficult to obtain realistic bunch lengths using the bolometer because of the

limited sensitivity of the bolometer in the high-frequency region.

IV. CONCLUSION

Measurement of the bunch length using CTR was investigated based on a Michelson interferometer with a bolometer and a MCT detector. Electron bunches of <20 fs were generated using a photocathode rf gun linac with a magnetic bunch compressor. The photocathode rf gun was driven by femtosecond UV pulses, and the generated electron bunches were compressed by the compressor. According to the interferometer's measurement of the IRS, the sensitivity of the bolometer and the MCT detector ranged from 3 to 15 THz and 11 to 50 THz, respectively. Generated by an electron bunch of 2.1 pC and 32 MeV, CTR was measured using the interferometer with the bolometer and the MCT detector. To analyze the interferogram, two methods were tested. A bunch length of 8.9 fs was obtained based on the model using the sensitivity of the measurement system, while a bunch length of 14 fs was obtained using the filtered model. Generation of <20 fs electron bunches was successfully achieved. In addition, the analytical method of the interferogram was improved by accounting for the effects of the diffraction limit, the bunch length, and the detection system's sensitivity. The sensitivity model was applied to the analysis of the interferogram, and the experimentally obtained interferogram was well expressed based on this treatment. Using broadband optics to measure shorter electron bunches, expansion of interferometers' available frequency region is currently under development.

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- [1] P. Kung, H.-C. Lihn, H. Wiedemann, and D. Bocek, *Phys. Rev. Lett.* **73**, 967 (1994).
 - [2] T. Takahashi, T. Kanai, Y. Shibata, K. Ishi, M. Ikezawa, T. Nakazato, M. Oyamada, S. Urasawa, T. Yamakawa, K. Takami, T. Matsuyama, K. Kobayashi, and Y. Fujita, *Phys. Rev. E* **50**, 4041 (1994).
 - [3] R. Lai and A. J. Sievers, *Phys. Rev. E* **50**, R3342 (1994).
 - [4] A. Murokh, J. B. Rosenzweig, M. Hogan, H. Suk, G. Travish, and U. Happek, *Nucl. Instrum. Methods Phys. Res., Sect. A* **410**, 452 (1998).
 - [5] T. Watanabe, M. Uesaka, J. Sugahara, T. Ueda, K. Yoshii, Y. Shibata, F. Sakai, S. Kondo, M. Kando, H. Kotaki, and K. Nakajima, *Nucl. Instrum. Methods Phys. Res., Sect. A* **437**, 1 (1999).
 - [6] I. Wilke, A. M. MacLeod, W. A. Gillespie, G. Berden, G. M. H. Knippels, and A. F. G. van der Meer, *Phys. Rev. Lett.* **88**, 124801 (2002).
 - [7] J. Yang, T. Kondoh, K. Kan, T. Kozawa, Y. Yoshida, and S. Tagawa, *Nucl. Instrum. Methods Phys. Res., Sect. A* **556**, 52 (2006).
 - [8] G. Berden, W. A. Gillespie, S. P. Jamison, E.-A. Knabbe, A. M. MacLeod, A. F. G. van der Meer, P. J. Phillips, H. Schlarb, B. Schmidt, P. Schmüser, and B. Steffen, *Phys. Rev. Lett.* **99**, 164801 (2007).
 - [9] A. M. Cook, R. Tikhoplav, S. Y. Tochitsky, G. Travish, O. B. Williams, and J. B. Rosenzweig, *Phys. Rev. Lett.* **103**, 095003 (2009).
 - [10] D. Daranciang, J. Goodfellow, M. Fuchs, H. Wen, S. Ghimire, D. A. Reis, H. Loos, A. S. Fisher, and A. M. Lindenberg, *Appl. Phys. Lett.* **99**, 141117 (2011).
 - [11] K. Kan, J. Yang, A. Ogata, T. Kondoh, K. Norizawa, and Y. Yoshida, *Appl. Phys. Lett.* **99**, 231503 (2011).
 - [12] S. Wesch, B. Schmidt, C. Behrens, H. Delsim-Hashemi, and P. Schmüser, *Nucl. Instrum. Methods Phys. Res., Sect. A* **665**, 40 (2011).
 - [13] Z. Wu, A. S. Fisher, J. Goodfellow, M. Fuchs, D. Daranciang, M. Hogan, H. Loos, and A. Lindenberg, *Rev. Sci. Instrum.* **84**, 022701 (2013).
 - [14] A. F. G. van der Meer, *Nucl. Instrum. Methods Phys. Res., Sect. A* **528**, 8 (2004).
 - [15] H. Wabnitz, A. R. B. de Castro, P. Gürtler, T. Laarmann, W. Laasch, J. Schulz, and T. Möller, *Phys. Rev. Lett.* **94**, 023001 (2005).
 - [16] T. Shintake *et al.* (49 Collaboration), *Phys. Rev. ST Accel. Beams* **12**, 070701 (2009).
 - [17] J. Yang, M. Washio, A. Endo, and T. Hori, *Nucl. Instrum. Methods Phys. Res., Sect. A* **428**, 556 (1999).
 - [18] P. Musumeci, J. T. Moody, and C. M. Scoby, *Ultramicroscopy* **108**, 1450 (2008).
 - [19] J. Yang, K. Kan, T. Kondoh, Y. Yoshida, K. Tanimura, and J. Urakawa, *Nucl. Instrum. Methods Phys. Res., Sect. A* **637**, S24 (2011).
 - [20] C. D. Jonah, *Rev. Sci. Instrum.* **46**, 62 (1975).
 - [21] J. Yang, T. Kondoh, K. Kan, and Y. Yoshida, *Nucl. Instrum. Methods Phys. Res., Sect. A* **629**, 6 (2011).
 - [22] K. Kan, T. Kondoh, J. Yang, A. Ogata, K. Norizawa, and Y. Yoshida, *Rev. Sci. Instrum.* **83**, 073302 (2012).
 - [23] T. Kondoh, J. Yang, K. Norizawa, K. Kan, T. Kozawa, A. Ogata, S. Tagawa, and Y. Yoshida, *Radiat. Phys. Chem.* **84**, 30 (2013).
 - [24] K. Kan, J. Yang, T. Kondoh, K. Norizawa, and Y. Yoshida, *Nucl. Instrum. Methods Phys. Res., Sect. A* **597**, 126 (2008).
 - [25] K. Kan, J. Yang, T. Kondoh, K. Norizawa, A. Ogata, T. Kozawa, and Y. Yoshida, *Nucl. Instrum. Methods Phys. Res., Sect. A* **622**, 35 (2010).
 - [26] K. Kan, J. Yang, T. Kondoh, and Y. Yoshida, *Nucl. Instrum. Methods Phys. Res., Sect. A* **659**, 44 (2011).
 - [27] The cut-on filter was equipped in front of the detector. The filter originally came with the bolometer and was made of thin polyethylene with a diamond scatter layer.
 - [28] D. H. Auston, *Appl. Phys. Lett.* **26**, 101 (1975).

-
- [29] T.-I. Jeon, J. Zhang, and D. Grischkowsky, *Appl. Phys. Lett.* **86**, 161904 (2005).
- [30] S. Winnerl, B. Zimmermann, F. Peter, H. Schneider, and M. Helm, *Opt. Express* **17**, 1571 (2009).
- [31] S. Winnerl, R. Hubrich, M. Mittendorff, H. Schneider, and M. Helm, *New J. Phys.* **14**, 103049 (2012).
- [32] K. Kan, J. Yang, A. Ogata, S. Sakakihara, T. Kondoh, K. Norizawa, I. Nozawa, T. Toigawa, Y. Yoshida, H. Kitahara, K. Takano, M. Hangyo, R. Kuroda, and H. Toyokawa, *Appl. Phys. Lett.* **102**, 221118 (2013).