BUNCH LENGTH MEASUREMENT USING COHERENT CHERENKOV RADIATION

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Abstract

In this paper, generation of quasi-monochromatic terahertz (THz) using multimode Coherent Cherenkov Radiation (CCR) on the order of 0.1 THz was investigated. CCR was generated by a hollow dielectric tube covered by a metal and an electron bunch from a photocathode radio-frequency (RF) gun linac. The intensity and frequency of CCR were measured directly by a Michelson interferometer and a bolometer. The frequency spectra measured by the interferometer indicated sharp peaks close to frequencies of 0.09 THz and 0.14 THz, which corresponded to TM_{03} and TM_{04} modes, respectively, according to theoretical calculation for a tube with inner and outer radii of 5 mm and 7 mm. The maximum gain of TM_{03} mode due to the tube length was obtained as 1.5 dB/cm. The other higher modes, e. g. 0.36 THz (TM_{09}) and 0.40 THz (TM_{010}), were also observed from a 150 mm long tube at a bunch charge of 15 pC, which decreased space charge effect and the bunch length. Finally, a new method for bunch diagnostic based on multimode CCR was proposed.

INTRODUCTION

Femtosecond electron bunches on the order of 100 fs or less [1] can be used in accelerator physics applications such as free electron lasers (FELs) [2,3] and laser-compton X-ray [4,5]. Such electron bunches are also key elements in the study of ultrafast reactions and phenomena in time-resolved pump-probe experiments involving the application of techniques such as ultrafast electron diffraction (UED) [6,7] and pulse radiolysis [8,9]. The time resolutions in UED and pulse radiolysis depend on the electron bunch length. In UED, an electron bunch is used as a probe source and ultrafast phenomena, such as laser-induced phase transients, are monitored using electron diffraction patterns. Pulse radiolysis also involves the use of an electron bunch and a laser; this technique is a powerful tool that can be used for the observation of ultrafast radiation-induced phenomena involving the mechanical motions of electrons and atomic nuclei in reaction mechanisms that are studied in physics, chemistry, and biology.

At Osaka University, a photocathode-based linear accelerator (linac) and a magnetic bunch compressor were constructed for femtosecond pulse radiolysis based on a femtosecond electron bunch. A picosecond electron bunch with a transverse emittance of approximately 3 mm-mrad was generated using a photocathode radio frequency (RF) gun by projecting a Nd:YLF picosecond laser onto a copper cathode [10,11,12]. The electron bunch was accelerated up to 32 MeV by the booster linear accelerator with an optimal energy-phase correlation in the bunch (the acceleration of the bunch head was greater than that of the bunch tail) for compression of the bunch. Finally, the electron bunch was successfully compressed into femtoseconds, e.g., 98 fs in root-mean-square (rms) at 0.2 nC [10]. A femtosecond electron bunch has been used in pulse radiolysis in order to study the kinetics of solvated electrons with time resolution of femtoseconds [8,9].

In this paper, generation of quasi-monochromatic THz using multimode CCR was investigated. In the experiment, multimode CCR was generated by a hollow dielectric tube covered by a metal and the electron bunch from the photocathode RF gun linac. The intensity and frequency of CCR were measured by a Michelson interferometer and a bolometer. Finally, a bunch length diagnostic using multimode CCR was proposed.

EXPRIMENTAL ARRANGEMENT

The diagram of multimode CCR and measurement system are shown in Fig. 1. 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 [10]. The pulse width of the UV light 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^{o} 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 27 MeV by a 2 m long S-band travelling-wave linac with a minimum energy spread. In the experiment, the picosecond electron bunch at the linac exit was used for multimode CCR generation. When the picosecond electron bunch moves on the axis of a hollow dielectric tube covered by a metal, partially periodic electric field, i. e. quasi-monochromatic THz, is induced as shown in Fig. 1. This slow-wave structure of the hollow dielectric tube supports modes with phase velocity equal to the beam velocity, which contain fundamental and higher modes. The inner and outer radii of the tube, made of fused silica, were 5 mm and 7 mm, respectively, resulting in the tube wall thickness of 2 mm. The hollow tube was covered by a copper conductive tape for a metal boundary condition, which reflects and stores EM radiation in the tube. In order to measure the intensity and frequency of CCR, a Michelson interferometer was set 25 mm downstream of the tube in the air. The CCR

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generated in the tube was reflected by an off-axis parabolic mirror (OAP1) with a focal length of 25 mm. The parallel THz light was separated by a beam splitter (BS) and one of the THz light was reflected by a moving mirror (M2). The mirror diameters except an off-axis parabolic mirror (OAP2) were <30 mm. The two THz light joined together at a 4.2K silicon bolometer. The intensity and frequency of CCR were analyzed by the fast Fourier transform (FFT) of an interferogram, which is a dependence of the bolometer output on the moving mirror (M2) position.

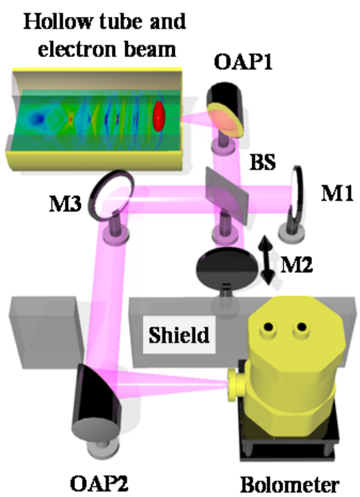

Figure 1: Diagram of multimode CCR and measurement system. OAP denotes an off-axis parabolic mirror; M, a plane mirror; BS, a beam splitter.

RESULTS AND DISCUSSIONS

Analytical Frequency of TM Mode

The frequency of multimode CCR depends on the hollow dielectric tube conditions. Assuming azimuthally symmetric Transverse Magnetic (TM) mode along the tube axis is induced, frequency of TM_{0n} mode can be expressed as [13,14]

$$\frac{s}{k\varepsilon}\frac{I_1(ka)}{I_0(ka)} = \frac{\psi_0}{\psi_1}, \qquad (1)$$

where k and s denote the radial wave numbers in the vacuum and dielectric regions; a, the inner radius of the tube; Ψ_0 and Ψ_1 [13], functions composed of the inner and outer radii and Bessel functions of the first and second kinds. If Eq. (1) is satisfied, phase velocity is equal to the beam velocity. The theoretical frequencies of TM_{0n} modes were calculated for the tube with the relative permittivity of 3.8 and the inner and outer radii of 5 mm and 7mm.

Dependence on Tube Length

In the multimode CCR experiment, the dependence of the intensity on the tube length was investigated as shown in Fig 2. An interferogram with data points of 128 and a time step of 1 ps was measured for the FFT calculation. The laser injection phase onto the cathode was fixed to 10^{o} relative to the zero-crossing of the RF, which maximized the bolometer output. The bunch charge was 100 pC at a laser energy of 120 μJ and an injection phase of 10^{o}. The bolometer output depends on both the bunch charge and bunch length at the tube. The bunch charge increases due to Schottky effect at a high injection phase, however, the bunch length increases due to space charge force overwhelming RF compression effect. The opposite occurs at a low injection phase. According to Kim's model [15], bunch compression due to RF slope would be caused at an injection phase of $<70^{o}$ with a maximum RF field of 90 MV/m in the gun. As the result, the bolometer output was maximized by the balance between the bunch charge and the bunch length. Figure 2(a) shows the interferograms for three different tube lengths. The periodic oscillation from a 150 mm long tube decayed more slowly than that from a 50 mm long tube because the tube length decided the energy of CCR stored in the tube. Figure 2(b) shows the frequency spectra for three different tube lengths. All the spectra indicated sharp peaks at frequencies of 0.09 THz and 0.14 THz, which corresponded to TM_{03} and TM_{04} modes, respectively, according to Eq. (1). Thus, multimode CCR on the order of 0.1 THz was first demonstrated and the peaks could be explained by the theoretical frequency. The absence of the lower modes, e. g. TM_{01} or TM_{02}, would be caused by the frequency characteristics of the bolometer and the beam splitter, the mirror diameters and the loss in the fused silica. Figure 2(c) shows the intensities for TM_{03} and TM_{04} modes as a function of the tube length. The intensity increased nonlinearly at a tube length of >100 mm. The maximum gain of TM_{03} mode due to the tube length was obtained as 1.5 dB/cm at a tube length of 125 mm. A saturation was observed at a tube length of ≈150 mm. The nonlinear increase intensity would be caused by the EM field propagating through the electron bunch [16]. The saturation would be caused by the balance between the EM radiation production due to beam energy loss and the dielectric loss in the fused silica.

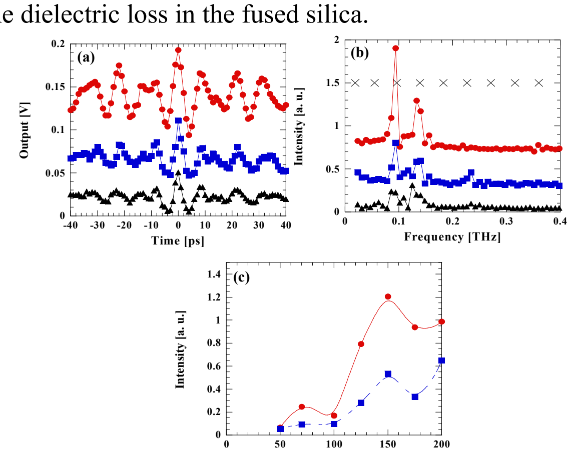

Figure 2: (a) Interferograms for 150, 100 and 50 mm tube lengths with offsets and factors adjusted for comparison. (b) Frequency spectra for 150, 100 and 50 mm tube lengths with offsets and factors adjusted. The theoretical

frequencies of TM_{0n} modes (cross) according to Eq. (1) were shown. (c) Intensities for TM_{03} and TM_{04} modes as a function of the tube length.

Dependence on Bunch Charge

The bunch charge decides not only the bolometer output but also the bunch length due to initial space charge effect at the cathode surface. Figure 4(a) shows the interferograms near the centerburst position for three different bunch charges. The tube length and laser injection phase were fixed to 150 mm and 10^{o}, respectively. The 150 mm long tube enabled a measurement at a bunch charge of <10 pC. The interferograms at bunch charges of 15 and 8 pC were sharpened compared with that at a bunch charge of 150 pC. The information regarding the overall intensity of the spectrum is represented by only a few measurements near the centerburst position because of the separated THz traveling the same path length. It is obvious that a higher mode CCR is included at bunch charges of ≤15 pC, although the intensity decreases. Figure 4(b) shows the frequency spectra for three different bunch charges. The other higher modes, e. g. 0.36 THz (TM_{09}) and 0.40 THz (TM_{010}), were observed successfully at a bunch charge of ≤15 pC. Figure 4(c) shows the intensities for TM_{03}, TM_{04} and TM_{09} modes as a function of the bunch charge. The intensity of TM_{03} mode increased nonlinearly at a high bunch charge. The intensity of TM_{04} mode also increased, however, the increasing rate did not agree to that of TM_{03} mode. The intensity of TM_{09} mode was maximized at a bunch charge of 8 pC. Thus, the increasing rate of each mode due to the bunch charge was not a constant. It is expected that the CCR intensity at a different mode reveals the bunch form factor, which changes drastically in THz region.

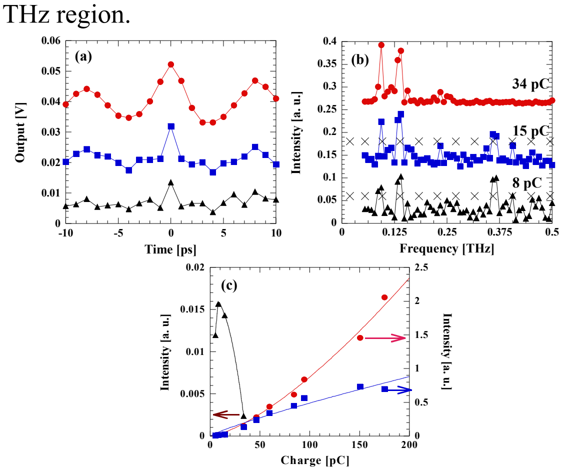

Figure 3: Interferograms near the centerburst position for 34, 15 and 8 pC bunch charges with offsets and factors adjusted for comparison. (b) Frequency spectra for 34, 15 and 8 pC bunch charges with offsets and factors adjusted for comparison. The theoretical frequencies of TM_{0n} modes (cross) were shown. (c) Intensities for TM_{03}, TM_{04} and TM_{09} modes as a function of the bunch charge.

CONCLUSIONS

In conclusion, generation of quasi-monochromatic THz using multimode CCR on the order of 0.1 THz was demonstrated experimentally and the peaks in the frequency spectra could be explained by the theoretical frequency. The CCR intensity at a different mode would reveal the bunch form factor, which changes drastically in THz region. The comprehension of the bunch form factor would be applied to a bunch length measurement. The demonstration of multimode CCR indicates the potential of this method as generation of designed flexible quasi-monochromatic THz, bunch diagnostic. In the future, more intense CCR will be generated by a femtosecond electron bunch, which is compressed by a magnetic bunch compressor using an achromatic arc. The other applications of multimode CCR are expected for a probe light in pulse radiolysis, which can monitor a transient structure of a molecule ionized by electron beam irradiation, and a non-invasive imaging.

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