STUDY ON A TIME-DOMAIN SPECTROSCOPY SYSTEM FOR COHERENT TERAHERTZ PULSE SPECTRUM MEASUREMENT FROM 5 MeV ELECTRON BEAM

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Abstract

Terahertz wave, expected to apply spectral analysis and imaging, has recently developed both source and detector components. For the terahertz source, the coherent radiation from electron linac is expected to be the high power terahertz source. At Waseda University, we have been studying high quality electron beam generation using Cs-Te photocathode RF-Gun and its application. We tried to generate terahertz wave by the coherent radiation and to measure its spectrum by a time-domain spectroscopy (TDS) technique. Adopting this technique, ultra-short laser pulse is needed as probe light. A terahertz waveform appears by delaying the timing of probe pulse. A spectrum of terahertz wave is also led by the waveform, by using the Fourier transform. We succeeded in constructing the probe laser system operating at 119 MHz repetition rate. The pulse duration was compressed down to 190 fs (FWHM) by using pulse compressor. We also succeeded in measuring a terahertz radiation from a photoconductive antenna. In this conference, we will report the outline of our terahertz TDS system, recent progress of our laser system, and terahertz wave generation and detection, with the future prospects.

INTRODUCTION

Terahertz wave falls in between infrared and microwave in the electromagnetic spectrum. Terahertz wave is expected to apply spectral analysis and imaging and it has recently developed both source and detector components. For the terahertz source, the coherent radiation from electron linac is expected to be the high power terahertz source. At Waseda University, The Cs-Te photocathode RF-gun has been developed, and the coherent terahertz pulse generation via Cherenkov radiation has been studied as an application of high quality electron beam. We tried to generate terahertz wave by the coherent radiation and to measure its spectrum by the time-domain spectroscopy (TDS) technique. By adopting this technique, we can obtain the terahertz pulse form and its spectrum by using the Fourier transform. Also, the TDS technique requires probe light with good stability and ultra-short pulse duration. We have developed an Yb fiber laser as a reliable and cost-effective ultra-fast probe light source.

THZ GENERATION AND TIME-DOMAIN SPECTROSCOPY

By using a tilted electron beam, we generated a coherent Cherenkov light. We call this technique PMCCR (Phase Matching Coherent Cherenkov Radiation). Figure 1 shows the schematic view of PMCCR. Radiation angle of Cherenkov light θ_c is expressed by the following:

$$\cos\theta_c = \frac{1}{n\beta}. \quad (1)$$

Where n is the refractive index of the medium and β is the Lorentz factor. When an electron beam passing the medium is tilted to be perpendicular to the radiation angle, the velocity of the radiation direction component of the beam ($\beta c \times \cos\theta_c$) is equal to the velocity of Cherenkov light (c/n). Cherenkov light emitted from all electron beam overlap each other when the beam size is much smaller than the wavelength of radiation [1].

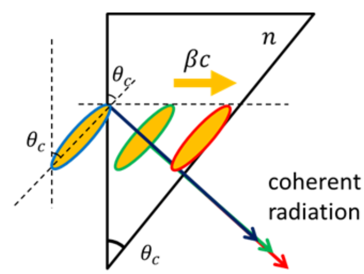

Figure 1: The schematic view of PMCCR.

In order to evaluate the spectrum of THz pulse by PMCCR, we use the TDS technique by using the EO (Electro-Optic) crystal. Figure 2 shows the schematic view of the TDS technique. When measuring the terahertz wave, the EO crystal is illuminated by terahertz wave and probe laser pulse at the same time. Refractive index of the EO crystal is modified by terahertz wave illumination and polarization of the probe light is modulated by the refractive index modification. Polarization modulation of the probe light is detected as an amplitude modulation by a pair of photodiodes. A terahertz waveform can be obtained by delaying the timing of probe pulse illumination. A spectrum of terahertz wave is also led by the waveform by the Fourier transform.

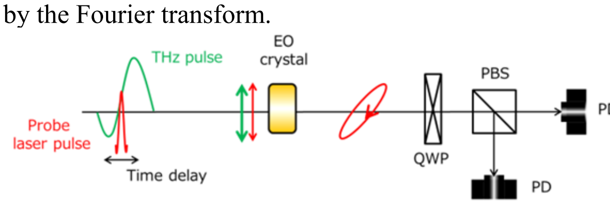

Figure 2: The schematic view of the TDS technique.

Before evaluating the spectrum of THz pulse of PMCCR, we measured a terahertz radiation from a photoconductive antenna (PCA). It confirms that our laser system can be used for the TDS measurement. When measur-

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ing the terahertz wave, PCA is illuminated by terahertz wave and probe pulse at the same time. A terahertz waveform can be obtained by delaying the timing of probe pulse illumination.

EXPERIMENT SET UP

We have developed a fiber laser oscillator for a probe light of the TDS technique. We use an Yb-doped fiber as a gain medium. In order to obtain a mode-locked laser pulse, we applied non-linear polarization rotation (NLPR) method. When the linearly polarized light passes through the Yb-doped fiber, it changes into elliptically polarized light by the NLPR of the optical Kerr effect. The rotation degree is dependent on the light intensity. By adjusting a polarization, only the high intensity light can be passed through. Combining with the polarizer, it can work as a saturable absorber, thus we can get a mode-locked laser pulse. Figure 3 shows the setup of our mode-locked Yb-doped fiber laser system. The Yb-doped fiber in the oscillator is pumped by a 975nm laser diode (LD) and emitted light at a wavelength of 1030nm. The bandpass filter, which filters both in the time and frequency, is used to mode-lock the laser pulse in the cavity by keeping the pulse short in the oscillator. The piezo actuator is attached to a reflection mirror to control the repetition frequency. Also, reflection mirror is mounted on a micrometer stage to adjust the cavity length roughly. For the polarization adjustor, two quarter-wave plates (QWP), a half-wave plate (HWP) and a polarizing beam splitter (PBS) are used. After the oscillator, fiber amplifier and pulse compressor are introduced. After the amplifier, the laser power was 250 mW. Then, the laser pulse was compressed to femtosecond order by compensating the chirp. The diffraction grating and the prism pair are used as a compressor.

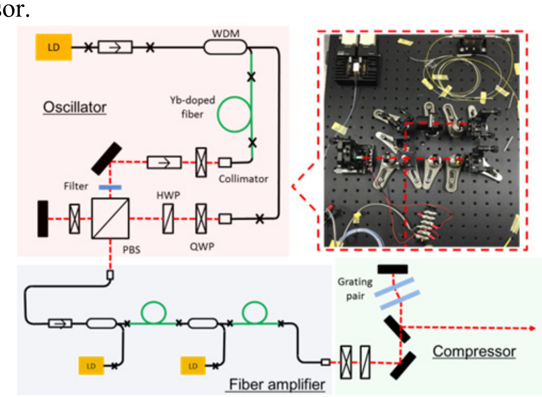

Figure 3: Setup of mode-locked Yb-doped fiber laser system.

Figure 4 shows the beam line layout of THz pulse generation. Solenoid magnet is used for compensating the emittance of the electron beam generated by the RF-Gun. Q-doublet is used for focusing the electron beam. The beam is tilted by RF deflector and directed to the target by the steering magnet. We use a triangular prism made from TOPAS polymer as a target because it is almost transparency and its refractive index is almost constant (n~1.52) in the terahertz frequency range. [2] Cherenkov radiation angle from Eq.(1) is approximately 48.9 °.One of corners of triangular prism is cut by 48.9° and the electron beam is tilted to the same angle by RF deflector.

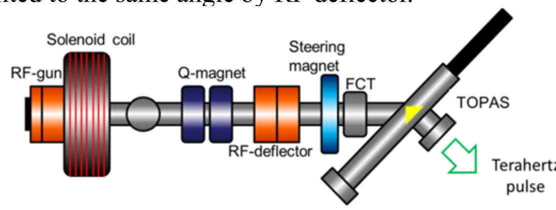

Figure 4: beam line layout.

Figure 5 shows setup of terahertz light detection part. The polarization of both the terahertz light and probe light are set to be horizontal for optimal electro-optic phase modulation. Terahertz light collimated by an off-axis parabolic mirror (OAP) pass through beam splitter. This beam splitter is made from nitrocellulose thin film. It can be passed through terahertz light. Tsurupica lens is used in order to increase terahertz electric field per unit area at the EO crystal. The EO crystal is <110> oriented ZnTe crystal. It is placed at the focal point of the terahertz light found out by knife edge method. Probe light is reflected by the beam splitter at 40 % of reflectance and directed to the EO crystal. After passing the EO crystal, probe light is optically biased with a fixed retardation π/2 by a QWP, analyzed by a PBS, and measured by a pair of photodiodes. [3]

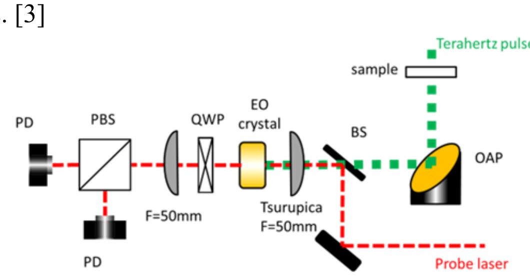

Figure 5: Setup of terahertz light detection.

RESULT AND DISCUSSION

THz Pulse Generation

Terahertz pulse generated coherent radiation is measured by Quasi-Optical schottky Diode detector (QOD) with 1THz band pass filter. Figure 6 shows plot of terahertz pulse intensity at 1 THz as a function of bunch charge. Terahertz pulse is coherent because the intensity is proportional to the square of the charge.

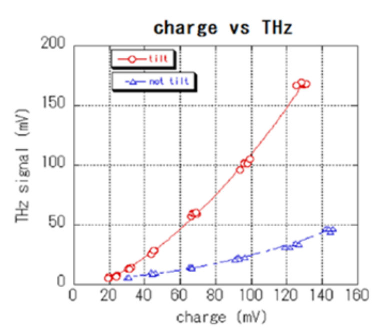

Figure 6: Plot of THz intensity at 1 THz as a function of bunch charge.

Yb Fiber Laser System

Figure 7 shows mode-locked pulses from Yb-doped fiber laser observed by photo-detector. Table 1 shows parameter of the laser pulse of the oscillator. Pulse duration was measured by the autocorrelator. Table 2 shows parameter of the laser pulse of the compressor. The laser pulse was compressed to femtosecond order, from 4.43ps to 190 fs with 167.3 mW of power.

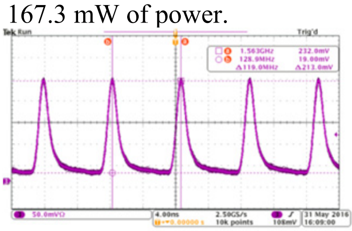

Figure 7: Mode-locked pulses from Yb-doped fiber laser.

Table 1: Parameters of the Laser Pulse of the Oscillator

Parameters	Value
Pulse repetition rate	119 MHz
Average power	87.4 mW
Center wavelength (FWHM)	1032.5 nm
Spectral width (FWHM)	12.8 nm
Pulse duration (FWHM)	1.37 ps

Table 2: Parameters of the Laser Pulse of the Compressor

Parameters	Value
Average power	167.3 mW
Pulse duration (FWHM)	190 fs

THz Pulse Detection (PCA)

Figure 8 (a) shows terahertz waveform. We selected a polymethyl methacrylate (PMMA) plate with 30 mm thick as sample. By using the Fourier transform, we also achieve a spectrum of terahertz wave, Figure 8 (b). This clearly shows THz wave absorption by the PMMA plate. Finally, we derived the refractive index of PMMA from the spectrum data. The refractive index derived was agreed with which reported before [4]. This successful results using PCA, we confirmed that our laser system can usable for the THz pulse detection of PMCCR.

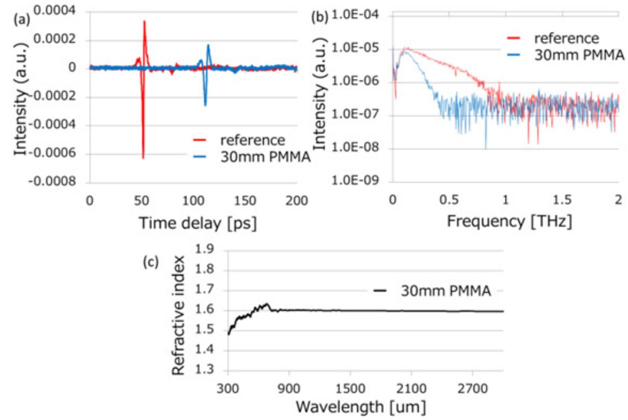

Figure 8: (a) Measured THz waveform by time-domain spectroscopy technique. (b) Obtained spectrum by using the Fourier transform. (c) The refractive index of PMMA measured by the TDS technique.

THz Pulse Detection (PMCCR)

Figure 9 (a) shows terahertz waveform. We selected a ZnTe crystal with 1mm thick. By using the Fourier transform, we also achieve a spectrum of terahertz wave, Figure 9 (b). This terahertz pulse includes up to 2 THz frequency. [1] However, we couldn't observe high frequency component because the sensitivity of the crystal is a maximum of 0.8 THz at Yb probe light.

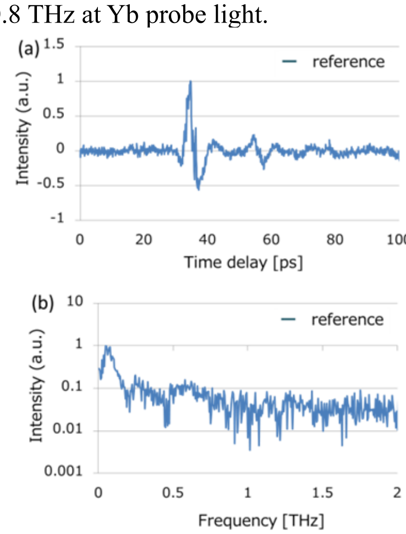

Figure 9: (a) Measured THz waveform by time-domain spectroscopy technique. (b) Obtained spectrum by using the Fourier transform.

CONCLUSIONS

We have developed a mode-locked Yb fiber laser for the TDS technique. The laser parameters of 119 MHz repetition rate, 167.3 mW average power, 190 fs (FWHM) pulse duration were achieved. We succeeded in observing THz waveform, its spectrum, and the refractive index of PMMA by the TDS technique. In near future, we will improve the sensitivity for the terahertz pulse detection, which can be realized by using the second harmonics pulses of Er probe instead of Yb probe.

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