DEVELOPMENT OF AN EO SAMPLING METHOD FOR THz PULSE DETECTION

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Abstract

We have been studying an S-band Cs-Te photo-cathode rf gun at Waseda University. The high quality electron beam produced by the rf gun is used to generate a high-power coherent terahertz pulse via Cherenkov radiation. This terahertz pulse can be applied to imaging and material analysis. As a preliminary step towards material analysis, we conducted experiments on terahertz time domain spectroscopy by EO sampling method to reveal major parameters of the terahertz pulse such as the pulse form and the spectrum. EO sampling method has high frequency response and suitable for high peak power terahertz pulses. In terahertz time domain spectroscopy, the duration of the probe light needs to be much faster than that of the terahertz pulse. Therefore, we developed a mode locked Yb fiber laser based on nonlinear polarization rotation as a reliable and cost-effective ultra-fast probe light source. The laser generates 3.59 ps chirped pulses which are compressed to 209 fs with a grating pair. In this conference, we will report the performance of the Yb fiber laser and results of EO sampling experiments.

INTRODUCTION

The photo-cathode rf gun has been developed at Waseda University, and a high-power coherent terahertz pulse generation via Cherenkov radiation has been studied as an application of electron beam. To reveal major parameters of the generated terahertz pulse, we conducted experiments on terahertz time domain spectroscopy by EO (Electro-Optic) sampling method. In terahertz time domain spectroscopy, we can obtain the pulse form. And its Fourier transform gives the spectrum. Temporal resolution of the pulse form is determined mainly by the pulse duration of probe light. Probe light is required to be pulsed light with good stability. On these backgrounds, we have started to study Yb fiber laser based on nonlinear polarization rotation as a reliable and cost-effective ultra-fast probe light source.

PHASE MATCHED COHERENT CHERENKOV RADIATION(PMCCR)

We generate a coherent Cherenkov light using a beam tilted by an rf deflector, we call this technique PMCCR. Figure 1 shows the principle of PMCCR. Radiation angle of Cherenkov radiation θ_c is expressed as follows by the refractive index n of the medium and the Lorentz factor β.

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

When electron beam tilted to be perpendicular to the radiation angle θ_c pass the medium, the radiation direction component of the velocity of the bunch ($\beta c \times \cos\theta_c$) is equal to phase velocity of Cherenkov light (c/n). Therefore Cherenkov light emitted from all electrons in the bunch overlap each other with same phase when the beam size is much smaller than the wavelength of light [TUPOW047].

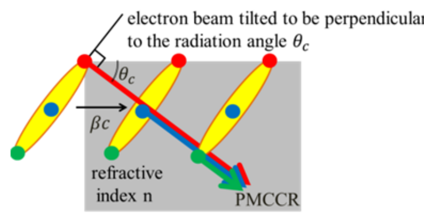

Figure 1: The principle of PMCCR.

EO SAMPLING METHOD

The EO detection of the terahertz pulse is based on the linear EO effect. When terahertz pulse and probe laser pass the EO crystal at the same time, the electric terahertz field modifies the refractive index only for the electric field direction of the EO crystal and then polarization of the probe light is modified. Polarization modulation of the probe light is detected as an amplitude modulation by a pair of the photodiodes.

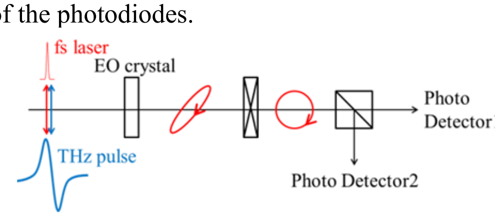

Figure 2: the principle of EO sampling method.

Yb DOPED FIBER

We have developed a fiber laser oscillator for a probe light of EO sampling method. We use an Yb-doped fiber as a gain medium.

The energy level of Yb^{3+} has a simple structure compared with Er^{3+}, Nd^{3+}, and it is possible to ignore the excited-state absorption, therefore excitation efficiency of Yb^{3+} is higher than the others. In addition, since the fluorescence lifetime is relatively long (~1ms), it has high storage capacity of energy. It is possible to add

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highly-concentrated Yb^{3+} ions to the fiber due to low concentration quenching. It enables the gain medium length to be shortened for high repetition operation. Quantum defect is as low as 10%, a high average power can be achieved. It has ability to emit the light of very wide range from 975nm to 1200nm. As stated above, the Yb-doped fiber has a lot of advantages as a probe light of EO sampling method [1].

FIBER LASER SYSTEM

Nonlinear polarization rotation (NPR) is a kind of passive mode-locking method. Figure 3 shows a mechanism of NPR mode-locking. It can be considered as a saturable absorber utilizing the nonlinearity of the glass. When the linearly polarized light passes through the fiber, it is changed to elliptically polarized light because the refractive index of the glass is not isotropic. Elliptically polarized light is rotated by the optical Kerr effect, the rotation degree is in proportion to the light intensity and fiber length. The high intensity light such as the center of the pulse is transmitted through, and the low intensity light is not passed through by adjusting a polarization. By that means, we can obtain a mode-locked laser pulse. In this experiment, the polarization controller composed of two quarter-wave plates, a half-wave plate and polarizing beam splitter (PBS) was used.

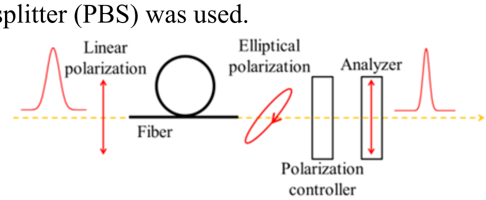

Figure 3: The principle of NPR.

Our Yb fiber laser generates a linearly chirped pulse. It can be compressed to femtosecond order by compensating a chirp. In this experiment, the compressor is composed of the diffraction grating and the prism pair. To achieve enough power of compressed pulse, we have an amplifier before the compressor.

EXPERIMENTAL SETUP

We have developed a stable mode-locked Yb fiber laser based on NPR. Figure 4 shows a mode-locked Yb-doped fiber laser setup. The Yb-doped fiber is pumped by a 975nm laser diode. Simiralitons have parabolic temporal profiles with linear chirp, and their temporal as well as spectral widths grow exponentially [2]. In order to stabilize the pulse in the cavity, we used the bandpass filter, which filters both in the time and frequency domains due to the large chirp present. Also, we attached a piezo actuator to a reflection mirror and adjusted the cavity length by placing the reflection mirror on a micrometer stage so that it is possible to control the repetition frequency.

After the oscillator, we introduced fiber amplifier and pulse compressor. Figure 5 shows the layout of fiber amplifier and compressor setup. Yb fiber amplifier amplified the pulsed laser up to 250mW. We used not only a pair of transmission gratings but a pair of prisms for pulse compression because the chirp of the pulse thought not to be perfectly linear.

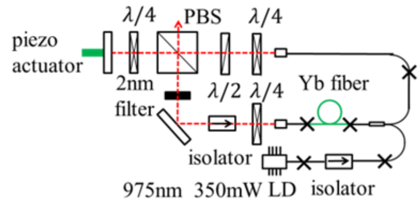

Figure 4: A mode locked Yb fiber laser setup.

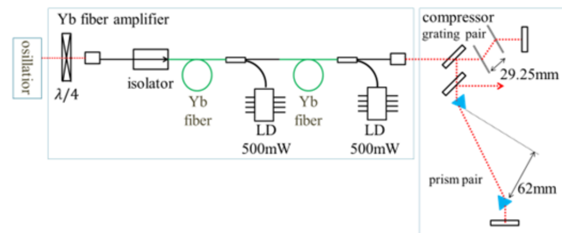

Figure 5: Yb fiber amplifier and pulse compressor setup.

Figure 6 shows the beam line layout of THz pulse generation. The emittance of the electron beam generated by the rf gun is compensated by solenoid magnet. And then the electron beam is focused by Q-doublet, tilted by rf deflector and directed to the target by steering magnet. We use triangular prism made from TOPAS polymer as a target because it is almost transparency and its refractive index is almost constant (n~1.52) for the terahertz range [4]. Therefore, coherent radiation can be achieved in a wide terahertz range. Cherenkov radiation angle from Eq. (1) is approximately 48.9 °. One of corners of triangular prism is 48.9°and electron beam is tilted to the same angle by rf deflector.

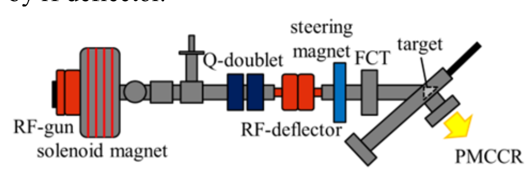

Figure 6: Beam line layout.

Figure 7 shows scheme of the setup for EO sampling method. 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. The polarization of both the probe light and terahertz light are set to be horizontal for optimal electro-optic phase modulation. The probe light is optically biased with a fixed retardation π/2 by a quarter-wave plate, analyzed by polarizing beam splitter, and measured by a balanced photodetector [3].

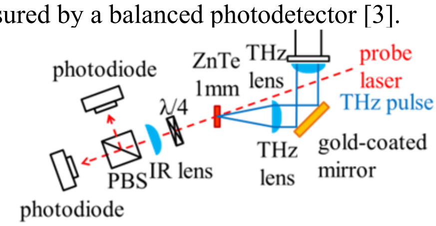

Figure 7: Scheme of the setup for EO sampling.

RESULT AND DISCUSSION

THz Pulse Generation

THz pulse is measured by Quasi-Optical schottky Diode detector (QOD) with 0.5THz band pass filter. Figure 8 shows plot of THz intensity at 0.5 THz as a function of bunch charge. THz pulse is coherent because The THz intensity is proportional to the square of the charge.

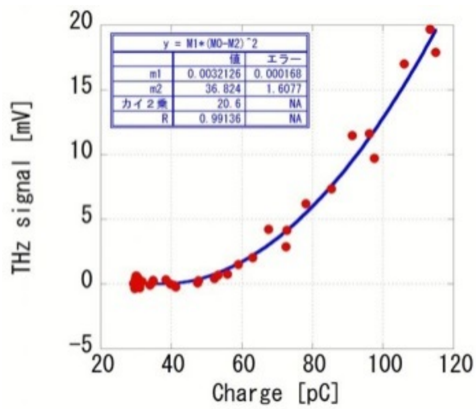

Figure 8: Plot of THz intensity at 0.5 THz as a function of bunch charge.

Yb Fiber Laser

Figure 9 shows mode-locked pulses from Yb-doped fiber laser observed by photo-detector and the oscilloscope. Pulse repetition rate obtained was 119MHz, average power was 87.3mW and pulse duration measured by the autocorrelator was 1.33ps (FWHM) and resulting pulse energy and peak power per pulse were 0.734nJ and 0.552kW, respectively. The center wavelength was 1033.2nm, the spectral width was 14.6nm (FWHM).

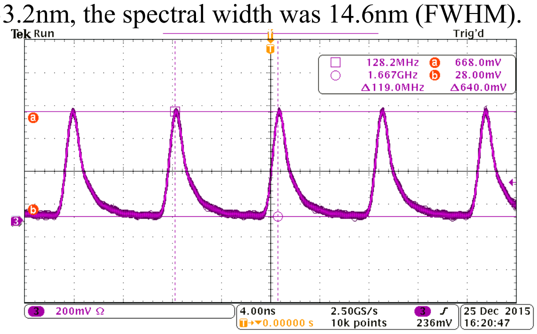

Figure 9: Mode-locked pulses from Yb-doped fiber laser.

Yb Fiber Amplifer and Compressor

We obtained the high output power (253mW) and the change of spectrum by nonlinear optical effect was not observed in fiber amplifier. The center wavelength was 1033.6nm, the spectral width was 14.4nm (FWHM). Pulse duration measured by the autocorrelator was 3.59ps (FWHM). Figure10 shows the pulse form after the pulse compressor measured by the autocorrelator. We succeeded to compress pulse duration down to 209 fs and average power was reduced from 253mW to 170.3mW by loss of the compressor.

THz Pulse Detection Test

In this time, THz pulse could not be observed by EO sampling method. The reason is considered that an alignment was not perfect and the probe light and the THz pulse did not spatially and/or temporally overlap each other in the EO crystal.

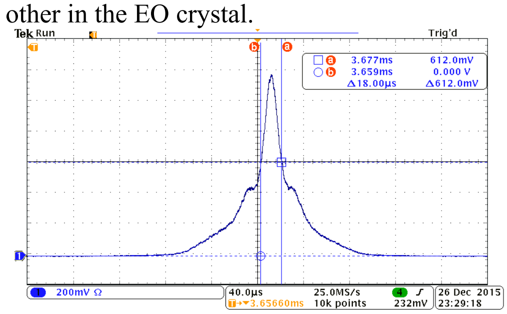

Figure 10: The pulse duration after compressor measured by autocorrelator.

CONCLUSIONS

We have developed a mode-locked Yb fiber laser based on non-linear polarization rotation as a femtosecond probe light for EO sampling method. We obtained pulse repetition rate of 119MHz, average power of 170.3mW, pulse duration of 209fs (FWHM). We could not detect THz pulse by EO sampling method while THz pulse is detected by QOD. By the QOD detection, we confirmed a coherent THz radiation using our rf electron gun system.

In near future, we will try further experiments of THz pulse detection by EO sampling. We will change our setup to make probe light and THz pulse to propagate collinear into crystal by using pellicle beam splitter, because oblique incident of the probe light into crystal is considered to be main problem of the optical path alignment.

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