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Development of high power THz-TDS system based on S-band compact electron linac

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ABSTRACT

The high power terahertz (THz)-time domain spectroscopy (TDS) system has been designed based on S-band compact electron linac at Advanced Industrial Science and Technology (AIST). The THz pulse is expected to have the peak power of about 25 kW with frequency range 0.1–2 THz using the 40 MeV electron beam which has about 1 nC bunch charge with 300 fs bunch length (rms). The aptitude discussion of the EO sampling method with ZnTe crystal was accomplished to apply to our THz-TDS system. The preliminary experiment of the absorption measurements of P-PPV on the Si wafer has been successfully demonstrated using the 0.1 THz coherent synchrotron radiation (CSR) pulse and W-band rf detector. It is confirmed that the intense of the THz pulse is enough to perform the THz-TDS analysis of the sample on the Si wafer. In near future, the investigation of the un-researched materials will be started in the frequency range 0.1–2 THz with our high power THz-TDS system.

1. Introduction

The terahertz (THz) radiation is a useful tool for progressing on biomedical and material studies (Mittleman et al., 1996). Especially, THz-time domain spectroscopy (THz-TDS) has recently emerged as a powerful probe of charge transport in materials, owing to the fact that it provides a probe of the complex conductivity in a wide frequency range with sub-picosecond time resolution (Kawayama et al., 2002). However, even if the conventional laser-driven THz source has a high repetition rate about 100 MHz, its power is quite low about 1 mW which corresponds to pulse energy of about 10^{-17} J/pulse (10 aJ/pulse) with pulse length of about 1 ps. Typical peak power of THz pulse is about 10 mW, so that the investigation of the sample that has large absorption in the THz region is not practical. The high peak power THz source is required instead of the laser-based THz source. Especially, it is difficult to investigate liquid materials using the low power THz-TDS because water is opaque to THz. Consequently, the high power THz-TDS is necessary to measure the complex refractive index of the un-researched electronic materials such as conductive polymers in liquid state and to investigate the spectral fingerprints of the biological samples and so on. While optical rectification has long provided an accessible means to generate terahertz pulses (Chang et al., 2006; Reimann et al., 2003), their energies have been well under 100 nJ. The free electron laser sources have been able to generate high power terahertz pulses that have at least 1 μJ of energy (Knippels et al., 1999). The generation of terahertz pulses with 1.5 μJ of single-cycle terahertz pulses using about 50 mJ/pulse Ti:sapphire laser (Blanchard et al., 2007), but the total system is quite large. The generation of single-cycle terahertz pulses via four-wave mixing of the fundamental and the second harmonic of 25 fs pulses from a Ti:sapphire amplifier in air plasma were recently reported (Bartel et al., 2005). Until recently, such high power THz source is not applied to the TDS.

On the other hand, coherent synchrotron radiation (CSR)-based THz source, which has high peak power of kW-order has been designed for the high power THz-TDS system using the S-band compact electron linac at National Institute of Advanced Industrial Science and Technology (AIST) in Japan. The CSR THz pulse can be generated in a wavelength between 150 μm and 3 mm (0.1–2 THz) using ultra short electron bunch with a bunch length of 300 fs (rms) and energy of 40 MeV.

2. Feasibility study

2.1. System design of THz-TDS based on S-band compact linac

In our concept design for the high power THz-TDS, total system should be compact and installed in a room of middle size about

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10 m × 10 m including all components. The 40 MeV compact S-band linac has a electron injector, an achromatic arc section for the bunch compressor, a 90° bending magnet and laser systems. The electron injector consists of a laser photocathode rf gun which has the BNL-type S-band 1.6 cell cavity with Cs_2Te photocathode load-lock system and a solenoid magnet for the emittance compensation. It can generate the low-emittance electron beam with more than 1 nC. The electron beam can be accelerated up to about 40 MeV using S-band linac and the rf source of a 20 MW klystron. The electron beam is compressed down to 300 fs using the magnetic bunch compressor. The CSR of THz region is generated from the ultra short and high charge electron bunch at the 90° bending magnet located after *Q*-triplet downstream from the bunch compressor. The THz CSR pulse is extracted from the *z*-cut quartz window for the THz-TDS. Fig. 1 shows a top view of the THz-TDS system based on S-band compact electron linac.

2.2. Theoretical and experimental THz CSR generation

Synchrotron radiation less than critical frequency ω_c is coherently emitted from a ultra short electron bunch (σ_z). Its frequency is expressed by

$$\omega_c = \pi c/\sigma_z. \tag{1}$$

The total photons (I_{tot}) with both of incoherent and coherent radiation are derived from equations

$$I_{tot} = I_{inc}(1 + (N - 1)f(\omega)) \tag{2}$$

and

$$f(\omega) = e^{-(\omega\sigma_z)^2/2}. \tag{3}$$

Here, I_{inc} is the photons of incoherent radiation, *N* is the number of electrons in the bunch and $f(\omega)$ is the Fourier transform of the longitudinal electron density for Gaussian bunches with bunch length σ_z (Blum et al., 1991). In Fig. 2, the enhancement factor as a function of frequency, I_{tot}/I_{inc}, was calculated by changing the electron bunch length from 100 to 500 fs with 1 nC and 40 MeV against the in CSR yield of about 0.1 THz which is normalized to 1.

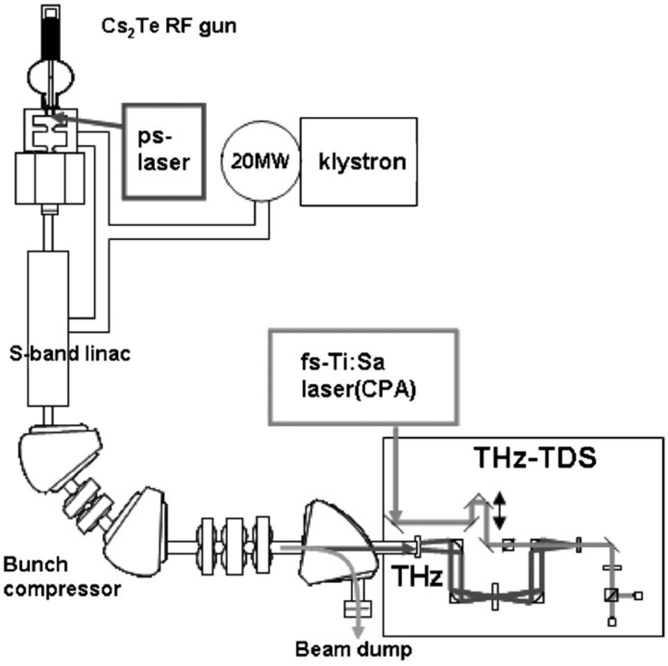

Fig. 1. THz-TDS system based on S-band linac.

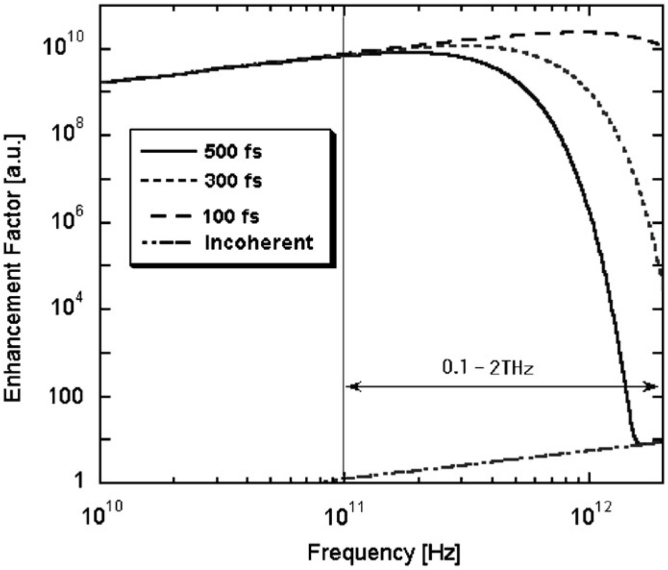

Fig. 2. Enhancement factor of CSR as a function of frequency by changing electron rms bunch length (500, 300, 100 fs, incoherent radiation).

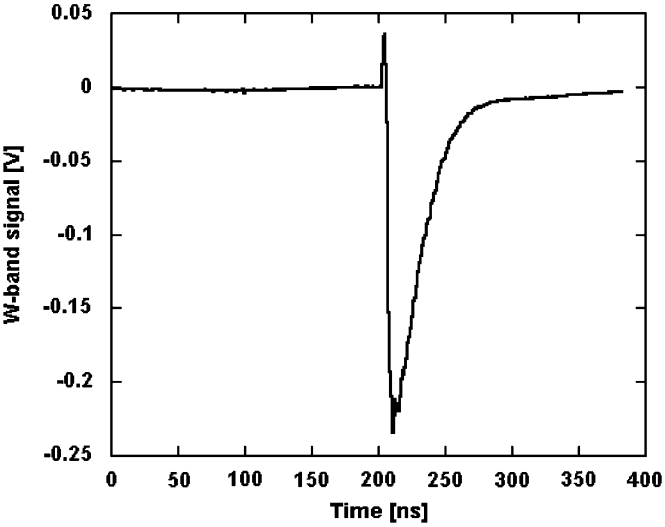

Fig. 3. Detected signal of W-band detector.

In Fig. 3, about 0.1 THz CSR radiation generated from 40 MeV ($\gamma = 78$) electron bunch with less than 500 fs and 1 nC was estimated to be about 2.5 pJ/mm^2/pulse at 60 cm down stream from a radiation point by a W-band rf detector (WiseWave FAS-10SF-01) which has a sensitive area of 1 mm × 2 mm, the sensitive range 0.075–0.11 THz and its signal of 500 mV corresponds to 1 mW. As a result of Fig. 2, the total energy of extracted THz CSR with a range 0.1–2 THz was estimated to be about 5 nJ/pulse within area of about 200 mm^2 at 60 cm because the synchrotron radiation has divergence of $1/\gamma$. In case of 300 fs electron bunch, we can obtain the total energy of about 65 nJ with range 0.1–2 THz and its peak power is estimated about 25 kW.

2.3. THz-TDS system with EO sampling method

In our design of the THz-TDS system (Fig. 4), generated THz pulse is extracted from the *z*-cut quartz window and focused to a sample using off-axis parabolic mirrors. Transmitted THz pulse is