Experimental Observation of Ultra-intense Laser-Driven Target Normal Sheath Radiation in the Terahertz Region

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Ultra-intense radiation in the terahertz (THz) regime with energy up to 36 mJ per laser shot, corresponding to ~5% laser-THz conversion efficiency, is experimentally observed from the rear side of the laser-irradiated solid target using a 20 TW fs laser system. The radiation emitted in a conical angle around 45 degree shows radial polarization and lasts for a duration about tens of ps. The waveform, angular distribution, and polarization of the THz radiation observed experimentally are in good agreement with that the radiation characteristics originated from deceleration of high-energy relativistic electrons passing through the sheath electric field behind the target. Two-dimensional particle-in-cell simulation is used to further clarify this emission mechanism.

1. Introduction

Terahertz (THz) radiation has continuously attracted significant interest over the last two decades because of its wide range of potential applications. We present an observation of THz generated by the target normal sheath radiation (TSNR) mechanism. THz emission of 36 mJ pulse energy from the rear side of the target is observed. The measured temporal waveform, angular distribution, as well as polarization indicate that this THz radiation originates from the energetic electron deceleration in the charge-separation field behind the target, which is known for ion acceleration through target normal sheath acceleration (TNSA) [1]. The experimental results are further clarified by particle-in-cell (PIC) simulation and analytical modeling.

2. Experiment and Simulation

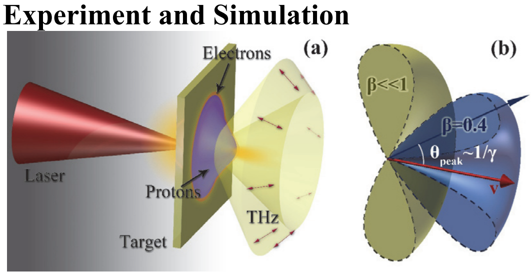

Fig. 1. (a) Schematic of the THz radiation formation process. (b) Radiation pattern for an electron accelerated in its direction of motion.

TSNR mechanism for generating strong THz radiation is illuminated in Fig. 1. Relativistic electrons accelerated in laser-solid interaction propagate through the target and establish at its rear a strong charge-separation field or sheath electric field of order ~TV/m. The very energetic electrons at the sheath front are decelerated by the intense electrostatic force and thereby emit radiation. The TNSR polarization state, which depends on the directions of the observer and the electron motion, can be assumed to have a radial distribution (red arrows in Fig. 1(a)). The angular power distribution has then a typical relativistic dipole pattern, as shown in Fig. 1(b).

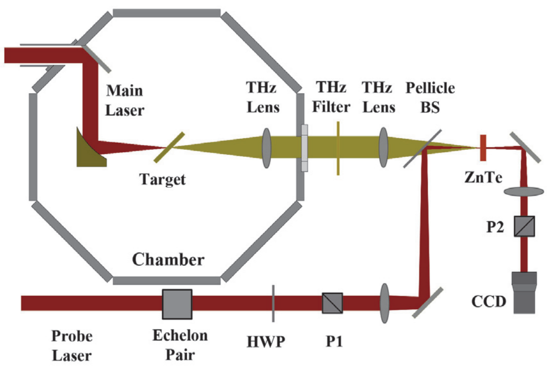

Fig. 2. Experimental setup.

The TNSR mechanism is experimentally investigated using the P3 laser facility at Osaka University. The experimental setup is shown in Fig. 2. The 20 TW laser pulses are focused on a

10 μm-thick copper foil with a peak intensity of 3×10^{19} W/cm^2. The THz radiation from the target's rear side is collected to a single-shot THz time-domain spectroscopy (TDS) system to obtain the temporal wave profile, with time steps of ~94.3 fs and a total time window of ~37.7 ps,

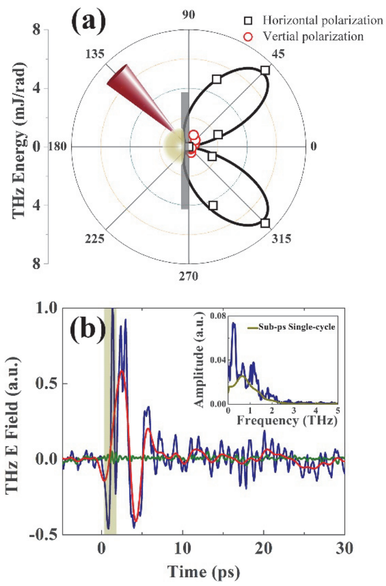

Fig. 3. (a) Angular distribution of the THz energy in the horizontal plane. (b) Evolution of the THz radiation.

A calibrated Golay cell coupled to a polyethylene THz polarizer is used to measure the THz energy and the polarization distribution. The results, as shown in Fig. 3(a), confirm that the THz radiation emitted from the target's rear surface has a radially symmetric cone structure with radial polarization, which agrees well with the theoretical predictions as shown in Fig. 1(a). The single pulse THz energy measured at 45° is ~0.35 mJ with a collection solid angle of 0.0485 sr, corresponding to 7.2 mJ/sr. The total, or integrated, energy emitted into this 2π solid angle is then ~36 mJ, with a laser-to-THz radiation conversion efficiency of ~5%.

Figure 3(b) shows the THz temporal profile obtained by the TDS system. In addition to the sub-ps single-cycle oscillation, (as shown in the yellow shade area), the THz output of TSNR shows an envelope by the red solid curve in Fig. 3(b), with a width ~10 ps, together with high-frequency oscillations that last for more than 30 ps. The long period of this radiation is consistent with the typical sheath evolution lifetime [2], which implies that the observed THz radiation originates from the TNSA electron motion in the sheath.

To further clarify the TSNR model for THz radiation, two-dimensional (2D) PIC simulations are carried out using the PDLPICC2D code. As shown in Fig. 4, the results show the existence of a charge separation field E_z, which indicates that the electrons are keep escaping and being pulled back to the plasma sheath after few picoseconds. This can be responsible for the few-ps low frequency envelope (red solid curve in Fig. 3(b)). Since most of the electrons are confined around the sheath plasma and the typical lifetime of the sheath is few ps time scale, a considerable proportion of the sheath energy can be radiated in the THz range, which explain the high conversion efficiency observed.

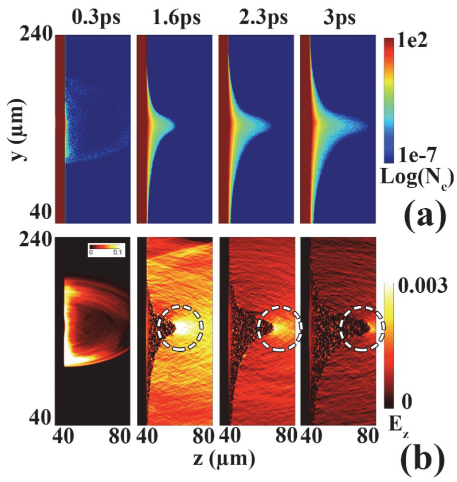

Fig. 4. 2D PIC simulation results. (a) Evolution of the sheath electron distribution. (b) Evolution of the charge separation field Ez.

3. Summary

Extremely intense coherent THz radiation with pulse energy of ~36 mJ and laser-to-THz radiation conversion efficiency of 5% produced by tabletop laser-solid target interaction is experimentally observed. The measured THz wave profile, radial polarization, and dipole-like radiation pattern indicate that the radiation originates from sheath electron deceleration during the TNSA process, which are supported by 2D PIC simulation and theoretical analysis.

Acknowledgments

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