ELECTRON ACCELERATION WITH A ULTRAFAST GUN DRIVEN BY SINGLE-CYCLE TERAHERTZ PULSES

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Abstract

We present results on an improved THz-driven electron gun using transversely-incident single-cycle THz pulses using a horn-coupler. Intrinsic synchronization between the electrons and the driving field was achieved by using a single laser system to create electrons by UV photoemission and to create THz radiation by difference frequency generation in a tilted-pulse front geometry. Details of the optical setups for the UV and THz pulses will be described as well as preliminary results showing evidence of electron acceleration.

INTRODUCTION

Strong-field terahertz (THz) pulses have many applications, such as time-resolved nonlinear spectroscopy, THz imaging and electron acceleration. Optical rectification (OR) via the tilted pulse front (TPF) technique in lithium niobate (LN) was employed to generate intense THz pulses, in which the pulse front of the IR pump is tilted by a certain angle to realize broadband phase matching inside the crystal. Compact particle accelerators driven by such intense THz pulses are very promising to become alternatives of the conventional DC gun and RF gun accelerators. Researches on electron acceleration by THz pulses appear rapidly in recent years. E. Nanni *et al.* observed a maximum electron energy gain of 7 keV by a compact THz-driven linear accelerator [1], Huang *et al.* demonstrated ~1 keV electron acceleration by a parallel-plate ultrafast gun [2], and more recently, Li *et al.* demonstrated accelerated electrons exceeding 5 keV from metallic nano-tips [3].

In this paper, a 2D horn-structure ultrafast electron gun was implemented inside a vacuum chamber for electron acceleration by THz pulses that were generated by the TPF method from a Yb:KYW amplifier. Electron signal was measured by a channeltron electron multiplier (CEM) and multi peaks induced by the enhanced electric field inside the ultrafast gun were observed by scanning the time delay between THz and ultraviolet (UV) pulses. Preliminary result shows that the accelerated electron energy is around several keV, and electron charge is around several fC.

EXPEIRIMENT SETUP

As shown in Fig. 1, the whole system includes a Yb: KYW laser amplifier, a THz generation setup, an optical parametric amplification (OPA) system, UV pulse generation, timing delay system between THz and UV pulses, horn-structure electron gun, and electron detection system (channeltron, electrometer, and oscilloscope, *etc.*). Inset of the Fig. 1 shows the designed structure of the electron gun. THz pulses were injected into the horn coupler, and UV pulses were injected through a slit to the surface of the gun to generate electrons. Electrons were accelerated by the synchronized THz pulses, and measured by the detection system.

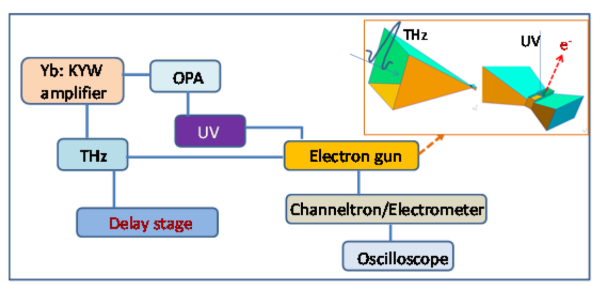

Fig.1: Schematic of the whole system of the electron acceleration in an ultrafast gun by THz pulses.

THz pulses were generated from our home-made 1030-nm, 1-kHz, 650-fs, 4-mJ Yb:KYW amplifier via the TFP technique with a 1500 lines/mm grating. A small portion of the IR pump (~220 μJ) was utilized to build up an OPA system, which was composed of a white-light generation setup by a 6-mm YAG crystal, two amplification stages, and two prism-based compressors (one for pre-compensation of chirp, and another for compression of

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final output pulse), as shown in Fig. 2. As a result, 760-nm, 10-μJ, ~80-100 fs pulses were generated. UV pulses at 253 nm, ~ 50 nJ and ~ 50 fs were generated via third harmonic generation by shooting these IR pulses into two phase-matched BBO crystals.

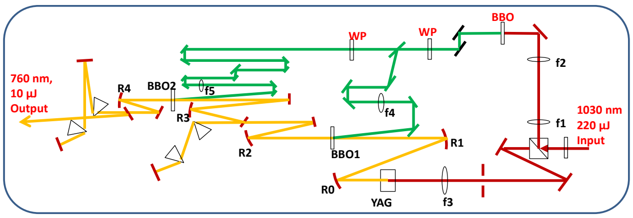

Figure 2: Schematic of the OPA generation system.

To increased the UV pulse energy, a second UV beam line was also established by the method of fourth hamonics generation of fundamental pulses. The beam size was reduced by two lenses, and two BBOs were placed inside the vacuum chamber to generated UV pulses, as shown in Fig. 3. As a result, ~ 200 nJ, ~300 fs UV pulses can be generated. During the experiment of the electron acceleration by THz pulses, these two UV beams can be switched easiliy.

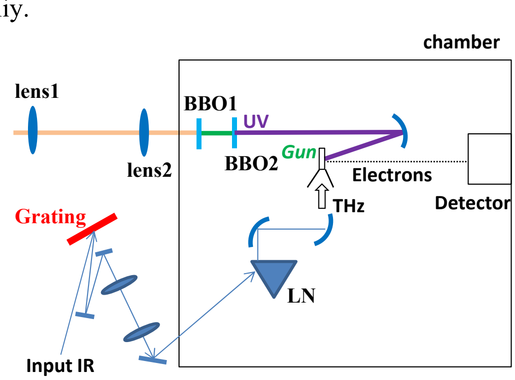

Figure 3: Schematic of THz generation and electron acceleration system.

EXPEIRIMENTAL RESULTS

THz pulses were generated by the TPF method. One of the key point is to realize phase matching in LN. The magnification factor of a two-lens imaging system to relay the IR beam to the crystal was designed to be 0.5, and the angle of incidence on the grating was 56.2 degrees. At IR pump energy of 3.75 mJ, measured THz energy was around 8 μJ at room temperature, and measured IR beam at the crystal has a beam diameter of 3.5 mm at $1/e^2$ to avoid optical damage on the crystal. THz pulses were transmitted by a plane mirror and two parabolic mirrors with a de-magnification factor of 0.5 and a transmission loss of 50%, and then they were collected by the horn coupler to accelerate electrons.

Electro-optic sampling (EOS) measurement were performed at two cases (room temperature of 293 K, and cryogenic temperature of 97 K) to characterize the THz temporal waveform. Figure 4(a) shows a single cycle THz

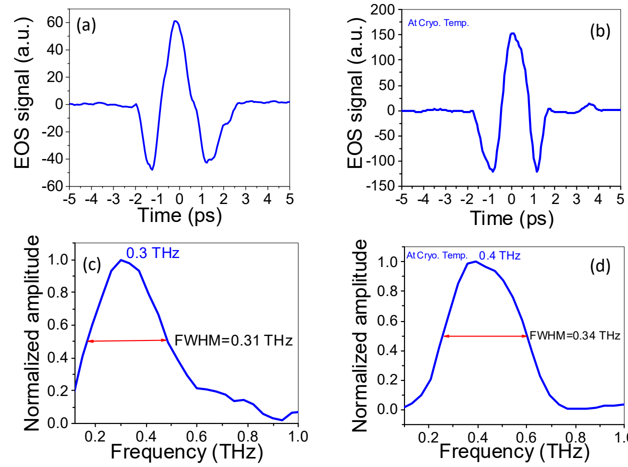

Figure 4: EOS traces and spectra at two cases: room temperature and cyro. Temperature. (a) EOS signal for the THz pulses at room temperature; (b) EOS signal for the THz pulses at cyro. Tempearature; (c) Normalizd amplitude of THz pulses in the frequency domain at room temperature. (d) Normalized amplitude of THz pulses in the frequency domain at cyro. tempearature.

pulse with duration of ~2.5 ps at room temperature. The related THz spectrum was shown in Fig. 4(c). THz spectrum was centered at 0.3 THz, and the bandwidth was around 0.31 THz. Furthermore, when we cooled down the LN crystal to cryo. temperature, as shown in Fig. 4(b) and (d), the EOS trace shows a shorter pulse duration of ~1.8 ps, and THz spectrum was centered at 0.4 THz with a bandwidth of 0.34 THz. The output THz energy at cyro. temperature was enhanced by a factor of around 1.5 after we optimized the THz pulse generation setup.

THz beam at the focus point after two parabolic mirrors was measured by a THz camera (Ophire Photonics, Pyrocam IV). A typical THz image was shown in Fig. 5 (b), the beam diameter at $1/e^2$ was 1.57 mm at horizontal direction (Fig. 5(a)) and 1.68 mm at vertical direction (Fig. 5(c)), respectively.

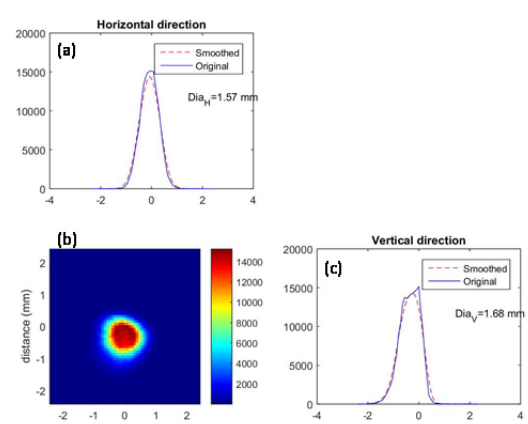

Figure 5: THz beam diameters at horizontal (a) and vertical (c) directions are 1.57 and 1.68 mm respectively. The

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THz image observed by the THz camera was shown in (b).

The ultrafast gun has a 2D horn structure (named *horn gun*), and it was designed to realize the focusing of the THz beam on both vertical and horizontal planes [4], as shown in the inset of Fig. 1(a). UV pulses were injected into the horn gun as a photocathode laser, and electrons were produced on the surface of the gun (the material is copper) because of photoemission. Then the electrons were accelerated by the synchronized THz pulses, left the slit of the gun, and detected by the channeltron. Front-end of the channeltron was connected to the ground and rear-end was connected to a positive 2000 volts DC voltage. Then based on the secondary electron emission effect, electrons could be amplified with a gain of $\sim 10^7$. As shown in Fig. 6, we could see voltage change with THz OFF and with THz ON. Electrons acceleration from the horn gun can be verified by switch ON and OFF the THz pulses. This voltage signal measured by the oscilloscope is related to the accelerated electrons signals, and the value of the peak voltage is proportional to the electron bunch current and charge.

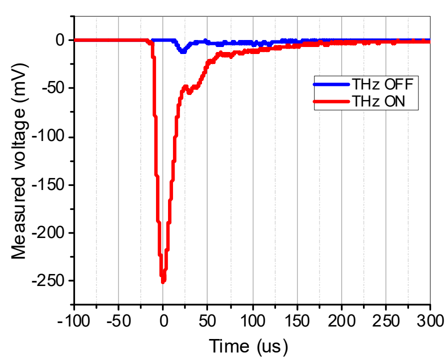

Figure 6: Measured voltage induced by accelerated electrons with THz OFF and ON.

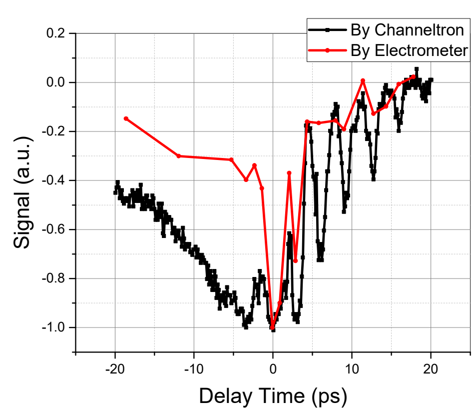

Figure 7: Electron signals measured by channeltron and by electrometer versus delay time between THz and UV pulses. Several peaks were observed during the scanning.

Relative timing of the THz and UV pulses could be changed by moving a motorized delay stage. The electron signal measured by channeltron is varied by scanning the time delay between the THz and UV pulses, as shown in Fig. 7. Here the time when the electron signal reached to the maximum was set to be zero. Several peaks were observed during the scanning, which can be related to electron acceleration process by the enhanced electric field of the THz pulses inside the ultrafast horn gun. An exponential decay behavior was also observed, which may because of the thermally-assisted THz field emission [2]. When the front-end of the channeltron was connected with the electrometer (Keithley 6514) and the DC bias voltage was turn off, the absolute charge can be measured. Here the channeltron can be considered as a Faraday cup. The measured current at zero point was ~4 pA, which corresponds to ~4 fC of electron charge. Timing scanning was also done by the electrometer, as shown in Fig. 7, with a quite similar behavior compared with the case by channeltron.

Further electron characterization will be continued with the electron image measurement by multi-channel plate (MCP), a retarding field analyzer (RFA), a magnetic lens, and a PCB steer. Primary result shows that the accelerated electron energy is around several keV.

SUMMARY

In summary, we have demonstrated a horn-structure ultrafast gun experimentally. Electrons induced by the UV pulses can be accelerated by the intense THz pulses. EOS traces of THz pulses at room and cyro. temperatures are measured. Electron dynamics related to the enhanced electric field inside the gun by changing the time delay was investigated, and around several keV electron acceleration by single-cycle terahertz pulses was observed.

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