200 ns pulse high-voltage supply for terahertz field emission

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We present a method of generating 200 ns high-voltage (up to 40 kV) pulses operating at repetition rates of up to 100 kHz, which may be synchronized with laser pulses. These supplies are simple to make and were developed for ultrafast terahertz pulse generation from GaAs photoconductive antennas using a high-repetition-rate regeneratively amplified laser. We also show an improvement in signal-to-noise ratio over a continuous dc bias field and application of the supply to terahertz pulse generation. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2724769]

I. INTRODUCTION

Pulsed sources of electromagnetic radiation in the terahertz frequency range have ever-increasing applications such as imaging, spectroscopy, charge transfer studies, and other fundamental research.[1,2] In order to produce high energy or high average power terahertz pulses, the use of large area photoconductive antennas has always been preferred. In such photoconductive antennas, a femtosecond laser pulse generates carriers in the conduction band, which are accelerated by an external bias field resulting in a current surge. This current surge will then produce electromagnetic radiation, which—in the far field—is proportional to the time derivative of the current.[3] Even at and above the laser saturation fluence (about 50 $\mu J/cm^2$ in semi-insulating (SI) GaAs) the emitted terahertz radiation scales linearly with the applied dc bias voltage.[4] High-voltage sources therefore allow higher efficiency and higher power terahertz generation. Laser-synchronized pulsed supplies have been used in the past for biasing photoconductive antennas based on GaAs and on other semiconductors and for aligning solutions of dipolar molecules.[5] However, the upper limit of the bias field can be limited by arcing and corona discharge or by emitter heating. The breakdown voltage of GaAs is higher than that of air and so any arcing will result in degradation of the emitter and introduction of electrical noise leading to the emitter failing. These effects can be minimized by applying voltage pulses of as short a duration as possible, since we know that field breakdown in air is dependent on electric-field duration.[6]

We have previously discussed the advantages of different types of field biasing.[7] Here we describe the design and practical advantages of a high-voltage (40 kV) 200 ns pulse generator with high average power that can be synchronized at repetition rates of up to 100 kHz suitable for applications with high-repetition-rate (up to 200 kHz) regeneratively amplified lasers.

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II. PRINCIPLES AND CONSTRUCTION

The transformer-based design shown in Figs. 1 and 2 was chosen because, although transformers are not capable of generating the shortest pulses, they provide good reliability, allow the use of relatively low-voltage semiconductors, and allow series connection of the outputs to achieve higher voltages.

The output transformers T2/T3 are driven in parallel by the high current 1000 V metal-oxide semiconductor field-effect transistor (MOSFET) FET1 (APT10025JVR). In the absence of a trigger, the capacitors C3/C4 charge through the transformer primary to the voltage of the external dc supply. When a trigger is received, FET1 turns on and C3/C4 discharges rapidly through the primaries, generating a voltage transient (Fig. 3, inset). This configuration is used rather than the more common "flyback converter"[8] because the turn-on time of FET1 is typically 22 ns compared to a turn-off time of 97 ns. The high-power MOSFET (necessary for high repetition rates) has a high intrinsic gate-source capacitance of 15 nF and the remainder of the circuit is optimized to deliver the high current necessary to charge this within this short turn-on time. The gate is driven by MOSFET FET2 which is connected in a low-inductance loop around reservoir capacitor C1 (40 nF ceramic) and the drain of FET1. The gate voltage of FET1 is limited to 10 V by the varistor Var-1 and R2 (15 Ω, noninductive). The trigger input from the laser drives T1 via FET3 (BUZ31L), and the protection components, R5 (1 kΩ), and Var-4. The output of T1A is rectified to provide a 12 V supply at C2 (1 μF) for FET2. This reduces the current demand on the high-voltage dc supply which maintains the 12 V supply via R3 when no trigger is received. T1B generates the high current drive for FET2 (limited at 15 V by Var-2) and, in conjunction with T1A, isolates the laser electronics from the high-voltage output transients. The turn-off time of the complete switch is determined by R4. Here, a value of 100 Ω enables a switched repetition rate of 100 kHz to be achieved.

The output transformers T2 and T3 are symmetrically connected to earth to reduce the peak voltage from the ground plane. This effectively doubles the total voltage be-

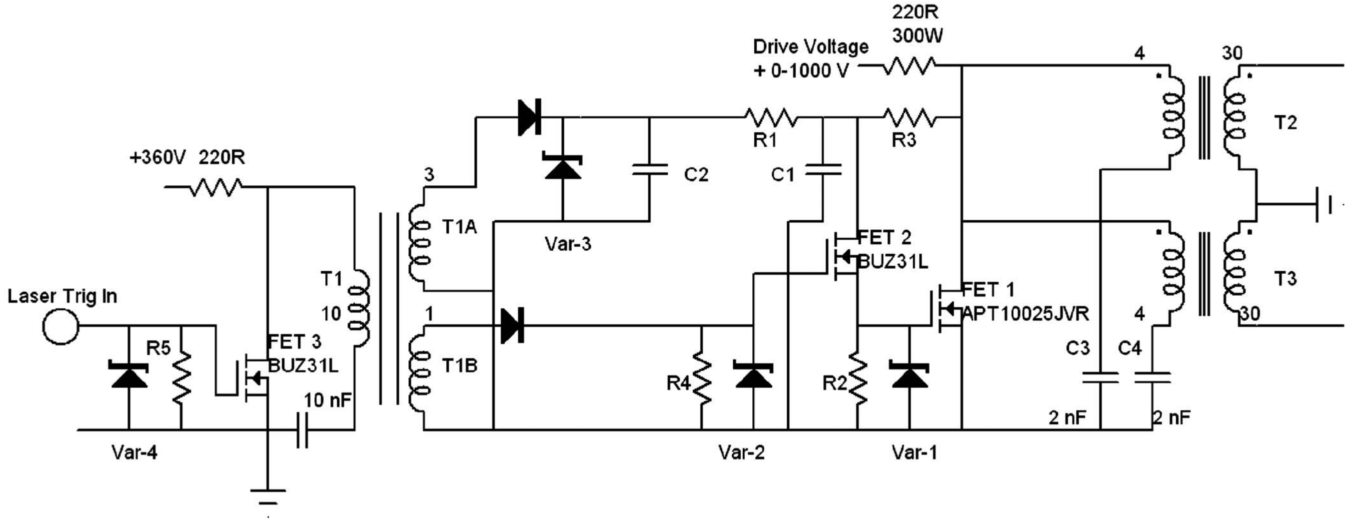

FIG. 1. Circuit diagram of the dc pulsed power supply.

fore transformer breakdown occurs and reduces rf interference. The design of the output transformers is the major factor in the output pulse shape. These were hand wound on 3F3 ferrite U-cores with a turn ratio of 4:30 using 28 SWG ($0.375\ mm^2$) insulated wire. These relatively large cores allowed the high-voltage insulated wire to be used, increasing the breakdown voltage and reducing the interwinding capacitance. In addition, each layer was covered with polyvinyl chloride (PVC) electrical tape. Otherwise, the transformers were conventional with the secondary wound on top of the primary and the high-voltage secondary tap on the outermost layer. The turn ratio of 4:30 was found to give the best compromise between voltage gain and pulse duration.

Using a homebuilt 1 kV dc power supply and operating at 100 kHz, the pulsed supply is capable of producing a total peak voltage of 20 kV for a drive voltage of 733 V at 0.4 A (this current is linear in repetition rate and peak-voltage). At a lower repetition rate (1 kHz), 40 kV is achievable. Figure 3 shows the output from the positive side of the supply measured by a Tektronix P6015A probe. The primary pulse has a duration of approximately 200 ns and is followed by a short period of ringing. This ringing, which arises from the intrinsic capacitance and inductance of the transformer, can be quite sustained. The pulse shown in Fig. 3 is the result of damping the transformer to minimize this. This can be achieved by adding resistance to the primary but here it is done very effectively by driving the transformer into saturation. The capacitors C3/C4 control the current in the primaries and are adjusted by trial and error to give the best compromise between the output voltage, ringing, and the inevitable increase in supply current with increased damping. Experiments were carried out with the high-voltage supply for terahertz pulse generation from a photoconductive antenna. The antenna consisted of a $3\ cm^2$ SI-GaAs ⟨100⟩-cut wafer, which had electrodes formed from silver paint separated by 5 mm and was connected to the power supply by screened BNC cables. Figure 2 shows an image of the actual supply, which is placed in an earthed metal box to further reduce any interference effects. A 200 kHz regeneratively amplified Ti: sapphire laser system produced 3 μJ pulses centered at 800 nm with a pulse duration of 100 fs. The pump beam (98% of the power, collimated to a 6 mm beam diameter) was sent through a variable delay stage before be-

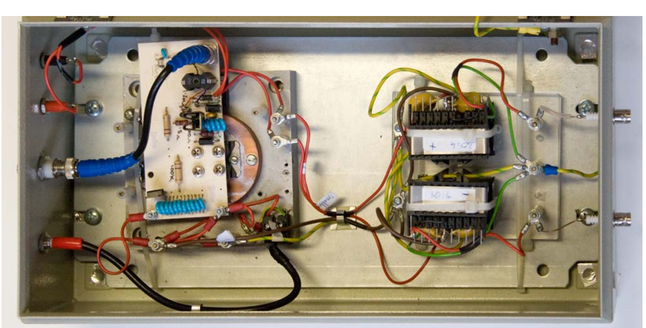

FIG. 2. (Color online) Image of the dc pulsed power supply. At the bottom left are the HV power supply and trigger connections. In the center is the FET switch on a copper heat sink while on the right are the transformers with BNC connectors out for each transformer with a common symmetrically connected earth.

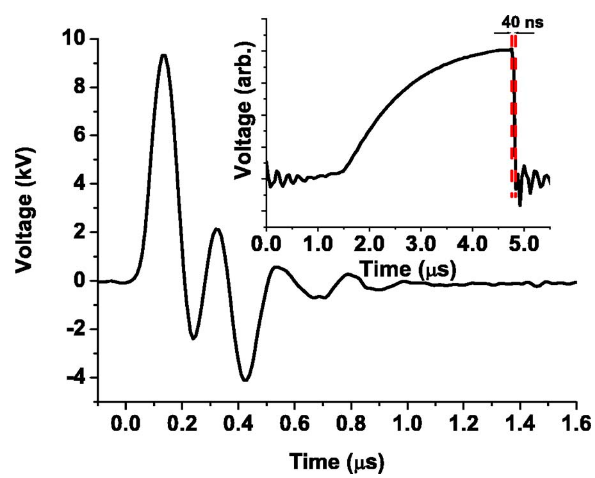

FIG. 3. (Color online) Output voltage pulse measured (from the positive output transformer) at 100 kHz and (inset) the 40 ns switching time of FET1.

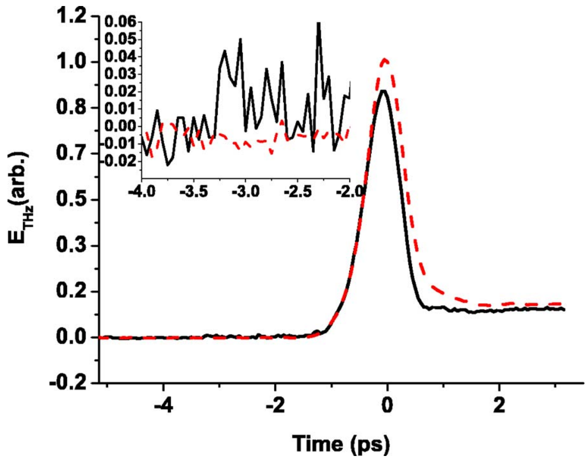

FIG. 4. (Color online) Terahertz pulse from the GaAs wafer with an applied electric field of 500 V for both the dc supply (solid) and the pulsed supply (dashed) and (inset) the base line from −4 to −2 ps showing the improved signal-to-noise ratio.

ing directed onto the antenna, symmetrically filling the area between the electrodes.[9] The emitted terahertz radiation was detected at a distance of 5 cm by electro-optic sampling[10] using a 0.5-mm-thick ⟨110⟩-cut ZnTe crystal in a reflection geometry as described previously.[2,11] It was confirmed experimentally that the 5 cm distance between the generator and detector provides a far-field signal.[5] Balanced detection is used, where the diodes are connected to a Stanford SR810 lock-in amplifier. No additional interference effects were encountered in the detection. The reflection geometry is experimentally convenient but typically yields a poorer signal-to-noise ratio than conventional, transmission geometry, electro-optic sampling. A Glassman EL03R15 500 V dc power supply was used for the dc field comparison experiments.

III. EXPERIMENTAL RESULTS

Figure 4 compares the measured terahertz electromagnetic field using the pulsed supply with that from the dc supply at the same bias voltage. The characteristics of the terahertz signal do not change with increasing voltage and the dc supply voltage limited the experiment comparison to a maximum voltage of 500 V. The primary advantage here is that by triggering the voltage pulse on alternate laser pulses, an "electronic chopper" is effected allowing a much higher lock-in demodulation frequency than can be achieved with a conventional optical chopper.

The improvement in signal-to-noise ratio (SNR) seen in Fig. 4 (inset), measured as a standard deviation in the base line, is eightfold for a pulse rate of 100 kHz, compared with the mechanical chopper rate of 1.5 kHz. Without this frequency increase, the SNR of the signal is very similar. Also seen in Fig. 4 is a small difference in pulse shapes. The signal derived from the dc bias reaches a slightly lower peak value and decays faster, which could be due to the use of an optical chopper that can partially mask the laser beam before reaching the antenna resulting in unwanted electrical effects. Very little can be read into this behavior—the response of the supply is extremely slow on the time scale of this signal, but the difference may be due to the pulsed supply allowing the charge surge to relax more completely between excitation pulses.

In conclusion, we present a relatively simple high-voltage short-pulse power supply for synchronization with laser pulses at repetition rates up to 100 kHz. Its application gives an improvement in the signal-to-noise ratio of the measured terahertz signal compared with a standard dc supply. This design is relatively inexpensive and has the advantage of not requiring external cooling or heat sinks and can comfortably generate 40 kV pulses at 1 kHz and with heat-sinking can achieve 20 kV at 100 kHz.

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