Pulsed- and DC-Charged PCSS-Based Trigger Generators

Steven F. Glover, Senior Member, IEEE, Fred J. Zutavern, Michael E. Swalby, Michael J. Cich, Guillermo M. Loubriel, A. Mar, and Forest E. White, Member, IEEE

Abstract—Prior to this research, we have developed high-gain GaAs photoconductive semiconductor switches (PCSSs) to trigger 50–300 kV high-voltage switches (HVSs). We have demonstrated that PCSSs can trigger a variety of pulsed-power switches operating at 50–300 kV by locating the trigger generator (TG) directly at the HVS. This was demonstrated for two types of dc-charged trigatrons and two types of field distortion midplane switches, including a ±100 kVdc switch produced by the High Current Electronics Institute used in the linear transformer driver. The lowest rms jitter obtained from triggering an HVS with a PCSS was 100 ps from a 300 kV pulse-charged trigatron. PCSSs are the key component in these independently timed fiber-optically controlled low jitter TGs for HVSs. TGs are critical subsystems for reliable and efficient pulsed-power facilities because they control the timing synchronization and amplitude variation of multiple pulse-forming lines that combine to produce the total system output. Future facility-scale pulsed-power systems are even more dependent on triggering, as they are composed of many more triggered HVSs, and they produce shaped pulses by independent timing of the HVSs. As pulsed-power systems become more complex, the complexity of the associated trigger systems also increases. One of the means to reduce this complexity is to allow the trigger system to be charged directly from the voltage appearing across the HVS. However, for slow or dc-charged pulsed-power systems, this can be particularly challenging as the dc hold-off of the PCSS dramatically declines. This paper presents results that are seeking to address HVS performance requirements over large operating ranges by triggering using a pulsed-charged PCSS-based TG. Switch operating conditions that are as low as 45% of the self-break were achieved. A dc-charged PCSS-based TG is also introduced and demonstrated over a 39–61 kV operating range. DC-charged PCSS allows the TG to be directly charged from slow or dc-charged pulsed-power systems. GaAs and neutron-irradiated GaAs (n-GaAs) PCSSs were used to investigate the dc-charged operation.

Index Terms—Fiber-optic triggers, high-voltage triggers, low jitter triggers, photoconductive semiconductor switches (PCSSs), pulsed-power trigger generators (TGs), triggering pulsed-power switches.

I. INTRODUCTION

FUTURE PULSED-POWER systems will continue to advance in modularity, size, efficiency, and pulse-forming capability. As the number of switches in large-scale systems increases into thousands [1] and as the rise time and pulsewidth requirements get shorter, the requirements for synchronization increase. Programmable pulse shaping [2]–[6] will require independently triggered high-voltage switches (HVSs) or groups of HVSs, resulting in separate trigger lines (i.e., cables, fibers, etc.) between each HVS and the trigger generator (TG). Large numbers of trigger lines and TGs can significantly increase the cost and space requirements for a given system. Pulse shaping that is achieved through independent triggering of HVSs also places greater demand on the performance of the HVSs. HVSs that are triggered later in time may be triggered at lower percentages of self-break than the switches that are triggered earlier in time [2]. Because of this condition, TGs that enable a larger range of operation from the HVS may be crucial to programmable pulse shaping.

High-gain photoconductive semiconductor switch (PCSS)-based TGs [7]–[9] address several of the issues encountered with multimodule pulsed-power systems. The 100 ps jitter capabilities [10], [11] exceed the rise time and jitter requirements for most proposed systems. Both the TG cost and space requirements could be reduced because the optical trigger energy for PCSSs is four orders of magnitude smaller than the optical trigger energy required for direct laser triggering of conventional HVSs (3 μJ versus 30 mJ [8], [12]). Lower optical trigger energy requirements allow fiber-optic triggering with multimode fibers and semiconductor lasers that are significantly smaller, less expensive, and much more versatile system components than high-voltage cables or line of sight optics. The small footprint of PCSS allows the TG to be located directly at the HVS while being remotely controlled with low profile fibers [13]. Finally, high-gain PCSS device lifetime testing under pulse-charged conditions has demonstrated that, if PCSSs are held within appropriate design limits (20 A/filament for 10 ns long pulses), devices can live for up to 10⁸ pulses [14]–[16], which is beyond the lifetime limits of components in most pulsed-power systems.

DC-charged PCSSs can offer more compact and more simplified TG designs but often at reduced voltages. DC-charged PCSSs have been developed for 0.1–1.0 kV applications [17]. Extending this voltage range up to 100 kV would make higher voltage dc-charged PCSSs more practical, but concerns with dark current leading to self-triggering have limited these efforts.
Dark current is produced by intrinsic, injected, avalanche, and ambient photocarriers. The lattice defects that are produced with neutron irradiation act as recombination and scattering sites, which reduce the dark carrier density and mobility [18]. Herein, conventional PCSS devices that are dc charged up to 39 kV/cm and n-GaAs PCSSs charged to 61 kV/cm [9], [18] are utilized in TGs.

This paper presents work that takes advantage of the submillijoule laser trigger energy required for high-gain PCSS to create circuits that are capable of triggering HV pulsed-power switches with nanosecond jitter under pulsed- and dc-charged conditions. The laser pulse that is used to trigger the PCSSs with ~500 ps rms jitter consisted of 70 μJ (measured at the fiber output) of 532 nm light that is about 5 ns wide [19]. The rms jitter is defined as

\[
\text{rms jitter} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (t_i - \bar{t})^2.}
\]  

The laser light was passed through a multimode 600 μm-diameter 5 m long fiber [20]. Note that, in these experiments, the laser energy was not minimized (by concentrating it into the desired filament path) to previously achieved levels of ≤ 10 μJ [8].

**TABLE I**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 )</td>
<td>2.5 kΩ</td>
<td>( R_8 )</td>
<td>10 Ω</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>10 kΩ</td>
<td>( C_1 )</td>
<td>600 pF</td>
</tr>
<tr>
<td>( R_3 )</td>
<td>223 Ω</td>
<td>( C_2 )</td>
<td>100 pF</td>
</tr>
<tr>
<td>( R_4 )</td>
<td>230 Ω</td>
<td>( L_1 )</td>
<td>700 nH</td>
</tr>
<tr>
<td>( R_5 )</td>
<td>1 MΩ</td>
<td>( \text{sw}_{1} )</td>
<td>P/E 81B trigatron</td>
</tr>
<tr>
<td>( R_7 )</td>
<td>100 MΩ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{1}\)These values do not include parasitics.

The laser light was passed through a multimode 600 μm-diameter 5 m long fiber [20]. Note that, in these experiments, the laser energy was not minimized (by concentrating it into the desired filament path) to previously achieved levels of ≤ 10 μJ [8].
and 15–20 kV on $R_1$, the charge voltage is divided as follows: 30 kV on the switch trigger electrode and to an open circuit. When the PCSS TG is triggered, Fig. 3. This plot shows the PCSS TG output pulse delivered to an HCEI switch closure was 2.9 ns rms at a 61 kV charge on the HCEI switch. The total jitter is measured from the commanded trigger signal to current through the HCEI switch with initial charges of 61 and 76 kV on $C_2$. The HCEI switch during these tests was operated with dry air and 26 psig for all experiments listed in Table II. This placed the switch at 90% of the self-break when charged to ±100 kV. Note that trigger pulses that are less than the 61 and 76 kV charge on $C_2$ were delivered to the switch because approximately 3.75–5 kV is dropped across the 0.75–1 cm PCSS (in the on state), and 15 kV is dropped across $R_3$, $R_4$, and $L_1$ to limit the PCSS current. This can be seen in the TG outputs shown in Fig. 3. Operating the HCEI switch at lower percentages of the self-break not only increases the jitter but also increases the delay until the switch closes (runtime), as shown in Fig. 4.

The total delay jitter from the commanded trigger to HCEI switch closure was 2.9 ns rms at a 61 kV charge on $C_2$ and with the HCEI switch at 90% of the self-break. 14.2 ns of rms jitter was obtained with the HCEI switch at 45% of self break and 76 kV on $C_2$. This is an extremely important result because the operating range of the HVS is a critical parameter for pulsed-power systems that are being designed for pulse shaping [5]. Only one HVS prefire was observed in these data sets, and there was no indication of damage to the PCSSs.

III. DC-CHARGED TG

Incorporating the pulsed-charged trigger circuit from Fig. 1 into a system design is not an optimal solution for slowly charged systems. Eliminating the need for pulse charging would simplify the circuit through the removal of $C_1$ and $sw_1$. Unfortunately, the dc hold-off capability of GaAs is less than the hold-off for pulse-charged PCSSs due to dark current limitations. Research using n-GaAs PCSSs has demonstrated reduction in dark currents and an increase in dc hold-off [17], [18].

This section looks at the performance of a dc-charged PCSS-based TG. The pulse-charging TG circuit was modified, as shown in Figs. 5 and 6, by removing the trigatron $sw_1$ and $C_1$ and by increasing the values of $R_2$ and $R_8$. The initial circuit parameters in the dc TG are provided in Table III. For some of the tests, the total current limiting resistance in series with the PCSS ($R_3 + R_4$) was increased by changing $R_3$. For the initial test with a nonirradiated PCSS, the power supply was continuously left on during the 50 shots. For all following experiments, the power supply voltage $v_{ps}$ was ramped up for over 8.6 s and then was held constant for 1.1 s until the triggering of the circuit. The power supply was turned off 0.3 s after triggering. This charging cycle was chosen to match the charging cycle for a new 5 MA pulsed-power system that is under development by Sandia, which is called Genesis [5].

Five 1 cm PCSS devices were tested in this circuit: one nonirradiated and four irradiated, with $4.42 \times 10^{14}$ Mev Si equivalent dose [8], [9]. Table IV shows the PCSS device numbers and the initial voltages of the PCSS and the HCEI switch, which was set at 90% of the self-break. It also shows the total current limiting resistance for the PCSS and the total system range and rms jitter. These results are considered preliminary due to the limited testing achieved on each device. More testing is required to achieve a sufficient statistical accuracy. Prefires that are observed in these experiments were due to self-triggers of the PCSS, not the HCEI switch.

Subnanosecond jitter of the trigger circuit, the laser, and the PCSS was demonstrated by the results from device #2, which was tested into a 2.5 kΩ load rather than the HCEI switch, as shown in Fig. 7. Fig. 8 shows plots of the waveforms across the 2.5 kΩ load resistor. These results exceeded our expectations for n-GaAs PCSS. This 1 cm-long dc-charged n-GaAs PCSS demonstrated subnanosecond jitter at 57 and 61 kV/cm, approaching the normal operating limits of pulse-charged PCSS. The jitter was 0.5–1 ns for the laser and the PCSS. The laser may have been warming up and introducing more than the 500 ps jitter specification, or the PCSS may have been less than optimally aligned and may not be delivering its previously demonstrated 100 ps of the jitter [10], [11]. Pulse-charged HV PCSSs are typically limited to 65–70 kV/cm to avoid surface flashover at the semiconductor oil interface. Essentially, all of the milestones for this project were met with these tests. With the short time remaining, we focused our resources on demonstrating HCEI triggering with the dc-charged PCSS TG. Due to a limited time, we continued to use single filament triggering, knowing full-well that the results may be affected by the damage accumulating on the switch from excessive current per filament.

All other results, using 450 Ω of current limiting resistance into the HCEI switch trigger electrode, demonstrated total system jitters (command trigger to the HCEI current) ranging from 4.9 to 8.4 ns. A factor of 2–3 increase in jitter was observed, comparing results from devices #1 and #3 to the 2.9 ns of the jitter obtained when pulse charging the PCSS. During this analysis, a new device was installed after each set of 50 dc-charged experiments. The cause of increased jitter may have been due to the increased lock-on voltage due to neutron irradiation and reduced lifetime due to PCSS damage. The large number of PCSS self-triggers for device #3 indicates that a lower TG voltage may have produced better results. Further investigation is necessary, but possible causes of damage include increased likelihood of surface tracking due to the longer
IV. CONCLUSION

Pulsed-power systems containing a large number of switches or independently timed switches can benefit significantly from lower cost high-performance optically controlled TGs that are resident at the switches. This research has demonstrated subnanosecond performance of compact optically controlled pulsed- and dc-charged PCSS-based TGs.

Pulse-charged PCSS TGs demonstrated triggering of a 200 kV switch with a 3 ns total rms jitter at 90% of the self-break and a 14 ns total rms jitter at 45% of the self-break. The PCSS jitter was 700 ps (not optimized), with no signs of PCSS degradation observed during these shots.

time that the PCSS was held at voltage, PCSS prefires, long conduction times, and high filament current levels. Improvements in lifetime may be made by limiting the PCSS current, as demonstrated with device #4, or by triggering the PCSS with multiple filaments. However, reduced trigger pulse rise times can result due to the HCEI trigger pin capacitance which causes higher HCEI switch jitter.

TABLE III

<table>
<thead>
<tr>
<th>Symbol</th>
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<th>Value</th>
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<tbody>
<tr>
<td>$R_1$</td>
<td>2.5 kΩ</td>
<td>$R_7$</td>
<td>100 MΩ</td>
</tr>
<tr>
<td>$R_2$</td>
<td>1 GΩ</td>
<td>$R_8$</td>
<td>1 MΩ</td>
</tr>
<tr>
<td>$R_3$</td>
<td>223 Ω</td>
<td>$C_2$</td>
<td>100 pF</td>
</tr>
<tr>
<td>$R_4$</td>
<td>230 Ω</td>
<td>$L_1$</td>
<td>700 nH</td>
</tr>
<tr>
<td>$R_5$</td>
<td>1 MΩ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 These values do not include parasitics.

Fig. 4. This figure contains plots of HCEI switch current waveforms. There are two key points to notice. The spread in the waveforms increases as the charge on the HCEI switch decreases. Also, note that the delay of the closing of the HCEI switch increases as the charge on the HCEI switch decreases.

Fig. 5. Circuit diagram for the dc-charged PCSS TG.

Fig. 6. Test bed for the dc-charged PCSS TG.
TABLE IV
DC-CHARGED TG THAT IS USED TO TRIGGER AN HCEI SWITCH AT 26 PSIG AND 90% OF THE SELF-BREAK

<table>
<thead>
<tr>
<th>Device</th>
<th>HCEI switch Voltage</th>
<th>$V_{ps}$</th>
<th>$C_2$ Voltage $^a$</th>
<th>Ohms</th>
<th>shots $^a$</th>
<th>range $^a$</th>
<th>total rms jitter $^b$</th>
<th>total rms jitter at PCSS $^b$</th>
<th>rms jitter at PCSS $^b$</th>
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</thead>
<tbody>
<tr>
<td>non-irradiated 1cm gap</td>
<td>±100</td>
<td>45</td>
<td>39</td>
<td>450</td>
<td>47/50</td>
<td>27.8 $^5$</td>
<td>5.02</td>
<td></td>
<td></td>
<td>high hold-off 3 self-triggers</td>
</tr>
<tr>
<td>KF172-035XTA #1 1cm gap, irradiated</td>
<td>±100</td>
<td>45</td>
<td>39</td>
<td>450</td>
<td>49/50</td>
<td>40.13</td>
<td>7.36</td>
<td></td>
<td></td>
<td>high current aging</td>
</tr>
<tr>
<td>KF172-035XTA #2 1cm gap, irradiated</td>
<td>---</td>
<td>60</td>
<td>52</td>
<td>2950</td>
<td>48/49</td>
<td>3.8</td>
<td>---</td>
<td>1.07 $^7$</td>
<td></td>
<td>demonstrates TG capability,laser jitter dominates</td>
</tr>
<tr>
<td>KF172-035XTB #3 1cm gap, irradiated</td>
<td>---</td>
<td>65</td>
<td>57</td>
<td>2950</td>
<td>49/50</td>
<td>4.1</td>
<td>---</td>
<td>0.86 $^4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KF172-035XTB #4 1cm gap, irradiated</td>
<td>±100</td>
<td>70</td>
<td>61</td>
<td>450</td>
<td>43/50</td>
<td>35.1</td>
<td>8.39</td>
<td></td>
<td></td>
<td>7 self-triggers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70</td>
<td>61</td>
<td>450</td>
<td>43/50</td>
<td>35.1</td>
<td>8.39</td>
<td></td>
<td></td>
<td>150 ns risetime 7 self-triggers</td>
</tr>
</tbody>
</table>

$^1$ 1cm PCSS gap, 70μJ of laser energy out of the fiber. The HCEI switch was at 90% of self-break. Irradiated devices received 4.42E14 MeV Si eq.

$^2$ Performance as measured includes the laser, PCSS, and HCEI switch. Or for device #2 (with no HCEI switch installed) to the PCSS output voltage.

$^3$ Fifty shots were taken for each experiment. The difference in the number of shots represents the number of pre-fires except for device #2 where shots were missed due to data acquisition issues.

$^4$ This reduction in jitter for these three measurements is due to changes in laser performance which we suspect to be due to the laser warming up.

$^5$ The power supply was continuously connected to the circuit for these shots allowing current to flow through the PCSS for longer periods of time. This is expected to have shortened the lifetime of this device and possibly resulted in higher jitter than what would have otherwise been measured.

$^6$ $C_2$ voltage is estimated using 2 GΩ of PCSS leakage resistance [18].

$^7$ This jitter includes the jitter of the laser and the PCSS.

DC-charged PCSS TGs delivered output pulses with 560 ps rms jitter to a 2.5 kΩ load. These pulses triggered a 200 kV switch at 90% of the self-break with 4.9 ns total rms jitter. Both GaAs and neutron-irradiated GaAs PCSS were utilized, but further research is necessary to fully characterize performance versus neutron dose and to identify the causes of the observed damage.

ACKNOWLEDGMENT

The authors would like to thank all of their colleagues who have contributed to this paper. In particular, special recognition must be made for R. (Dave) Clovis, L. Lippert, and L. Martin at the Sandia National Laboratories Annular Core Research Reactor for expediting the neutron irradiation of key materials for this research.

REFERENCES


From 2000 to 2004, he worked as a Senior Electronic Technician on a pulsed-power system for Science Applications International Corporation at the Defense Threat Reduction Agency’s magnetic flyer plate facility, Kirtland AFB, Albuquerque. In 2004, he joined Ktech Corporation, Albuquerque, as a Senior Electromechanical Technician working with Sandia National Laboratories (SNL), Albuquerque. Since May 2005, he has been a Principal Technologist with the Directed Energy Special Applications group, SNL, where he works on developing photoductive-semiconductor-switch-based trigger generators as well as RF testing and evaluation.
Michael J. Cich received the M.Sc. degree in materials science and engineering from the University of Illinois, Urbana, in 1998 and the Ph.D. degree from the University of California, Berkeley, in 2002. His thesis work was on defect formation in GaAs during the oxidation of aluminum arsenide.

He joined Sandia National Laboratories, Albuquerque, NM, as a Postdoctoral Appointee in 2002, where he is currently a senior member of the technical staff in the RF/Optoelectronics division. His research has focused on compound semiconductor processing for HBTs, MEMs, and lasers.

Dr. Cich is a member of the American Association for the Advancement of Science.

Guillermo M. Loubriel received the Ph.D. degree in solid state physics from the University of Pennsylvania, Philadelphia, in 1979.

Since then, he has been with Sandia National Laboratories (SNL), Albuquerque, NM, where he is currently the Manager of the Directed Energy Special Applications Department. This group covers the areas of high-power microwave (HPM) sources; compact pulsed power; radio frequency propagation, effects, and testing, including electronic warfare; antenna research and development; and semiconductor RF devices, including photoconductive semiconductor switches. He has over 118 publications and 4 patents in these areas. His areas of research have included the study of the following: 1) high-power ultrawideband radar for ground and foliage penetration (modeling and experiments); 2) linear and high-gain semiconductor switching; 3) HPM vulnerability and effects for DOE and DoD customers; 4) generation of high-power pulses for compact pulsed power; 5) longevity of metal contacts to semi-insulating Si and GaAs; 6) switching of high currents for firing sets; 7) ion sources for particle beam fusion accelerators, including defects and flashover in alkali halides; and 8) surface science. He is a member of the Advisory Board of the Electrical and Computer Engineering Department, University of New Mexico, Albuquerque.

Dr. Loubriel is a member of the American Physical Society. He received the DOE/NNSA's Defense Programs Award for Excellence award in 2004 and an SNL Award for Excellence for managing a turn-around in the HPM program in 2002.

A. Mar, photograph and biography not available at the time of publication.

Forest E. White (M’05) was born in Las Vegas, NM, October 12, 1947. He received the B.S. degree in electrical engineering from the University of New Mexico, Albuquerque, in 1977.

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