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# Multi-Filament Triggering of PCSS for High Current Utilizing VCSEL Triggers

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## Abstract

We are developing advanced optically-activated solid-state switch technology for Firing Sets. Advanced switch development at Sandia has demonstrated multi-kA/kV switching and the path for scalability to even higher current/power, resulting in good prospects for sprytron replacement and other even higher current pulsed power switching applications. Realization of this potential requires development of new optical sources/switches based on key Sandia photonic device technologies: vertical-cavity surface-emitting lasers (VCSELs) and photoconductive semiconductor switch (PCSS) devices.

The key to increasing the switching capacity of PCSS devices to 5kV/5kA and higher has been to distribute the current in multiple parallel line filaments triggered by an array of high-brightness line-shaped illuminators.[1] This was limited by commercial mechanically-stacked edge-emitting lasers, which are difficult to scale and manufacture with the required uniformity. In VCSEL arrays, adjacent lasers utilize identical semiconductor material and are lithographically patterned to the required aspect ratio. However, we have demonstrated that good optical uniformity in rectangular-aperture (e.g. 5-by-500μm) VCSELs is difficult to achieve due to the lack of optical confinement in the long dimension.

We have demonstrated line filament triggering using 1-D VCSEL arrays to approximate line generation. These arrays of uncoupled circular-aperture VCSELs have fill factors ranging from 2% to 40%. Using these arrays, we are developing a better understanding of the illumination requirements for stable triggering of multiple-filament PCSS devices. In particular, we are examining the dependence of filament formation versus the illumination fill factor and spatial brightness along the length of the filament. Ultimately, we will apply effective index techniques, pioneered at Sandia for leaky-mode VCSELs, to create a lateral photonic lattice that selects a single transverse mode with high brightness and uniformity for even higher fill factors and illumination unformity.[2] These sources will be developed and tested with complementary PCSS designs employing interdigitated multi-filament contacts for high-power switching.

## I. INTRODUCTION

The PCSS is an optically-activated switch that utilizes avalanche carrier multiplication in bulk gallium arsenide (GaAs) to form persistent filamentary current channels between two electrodes. In this high gain, or "lock-on" mode, on the order of $10^5$ electon-hole pairs are generated for each absorbed optical photon. This enables the switch to be triggered by sources of relatively low optical energy, including diode laser sources. This leads to the promise of extremely compact switching systems that are of relatively low cost, which motivates our interest in incorporating these devices in firesets. The PCSS is also a high-speed device, with subnanosecond risetime and jitter having been demonstrated to great advantange in fireset applications. The PCSS also offers the virtues of semiconductor batch fabrication, which means devices of very small volumes can be fabricated at low cost. Wafer scale fabrication also enables these parts to be manufactured with great uniformity and repeatability. In terms of WR production, it is of great advantage that test and proof parts can come from the same wafer as production parts, a virtue that was exploited to great advantage in the use of the PCSS as a low current optical trigger for a sprytron switch tube.

The long term goal is to improve the capability of the PCSS to multi-kV/kA switching levels with lifetimes greater than 100 shots. This would make it a viable alternative to the sprytron switch tube in fireset applications. There are many advantages that could be gained by such a use of PCSS, including volume reductions that could allow more and new functionalities to be built into firesets. Optical triggering implies greater surety due to the reduced susceptibility to lightning and other types of unintentional discharges, or electromagnetic pickup such as from from EMP and HPM. This technology also avoids potential long-term storage issues of vacuum devices (with ceramic-metal seals) such as leakage and outgassing of internal materials. Finally, this may be an option from relying on a dedicated production line for a such a specialized device as the sprytron switch tube.

## II. MULTI-FILAMENT PCSS OPERATION

Multi-channeling in PCSS devices has been shown to be key in obtaining lifetime improvements at multi-kA current levels[1]. Lifetime at 1kA was increased from 10 shots to 466 by distributing the current amongst 8 parallel filaments. At 3kA, the lifetime was increased to 65 shots, compared to 1 shot obtained using a single filament. It is desired to obtain still greater lifetimes and current levels by further increasing the number of filaments generated

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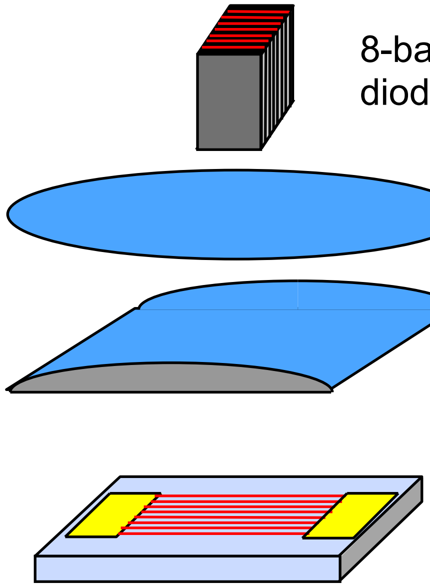


Figure 1. Triggering multiple filaments in a PCSS using a stacked laser array.

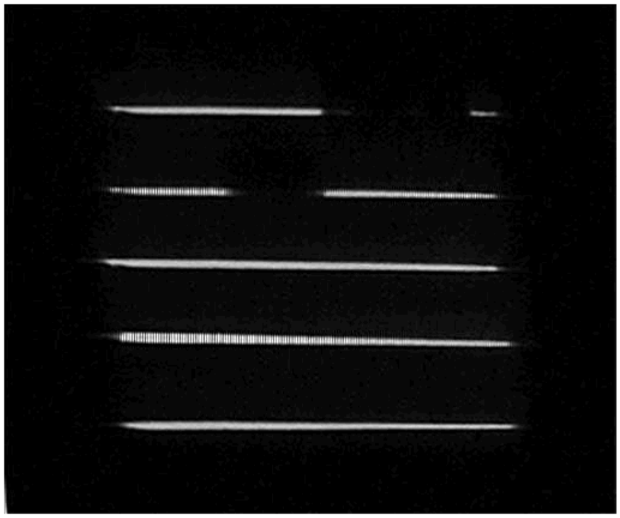

Figure 2. Near-field image of a stacked laser array exhibiting typical dark region defects and misalignment.

to share the current. This approach currrently relies on the use of commercial stacked arrays of edge-emitting lasers (EELs). The near field pattern is an array of lines that is imaged into the gap of the PCSS, as shown in figure 1. Each line triggers a filament that shares the conducted current. The problem in this approach is that the stacked array requires mechanical assembly using a pick and place machine to stack and solder tiny laser chips by an operator manipulating the parts under a microscope. This process produces arrays that are acceptable for many applications that simply require sufficient raw output power, but usually contain defects in terms of alignment or dark regions in some of the lines of the near-field pattern, as show in figure 2. Arrays must be laboriously selected against these defects for use as trigger line generators for multi-filament triggering of PCSS, leading to poor yields of usable lasers. The yield obviously becomes worse with larger arrays. In contrast, Vertical-cavity surface-emitting lasers (VCSELs) offer an attractive alternative to edge-emitting lasers for triggering multiple-filament PCSS devices. While precisely stacking and bonding many edge-emitting laser chips is difficult and costly. VCSEL technology is inherently amenable to the formation of 2-D arrays of lasers on a single chip. This scaling is also applicable to fabrication of longer lines, which is the requirement for illuminating PCSS with longer gaps for higher voltages for other applications. The VCSEL array patterns are defined lithographically in a single die for ease of packaging, eliminating critical mechanical alignment, and allowing flexible definition of the 2-D illumination profile. The challenge is to fabricate VCSELs with very high aspect ratio line-shaped apertures (on the order of 5 by 500 microns) that exhibit very uniform intensity along the length of the line during a short (10-ns) drive pulse. A line-shaped 3 by 500-micron single aperture VCSEL was fabricated, but the device exhibited highly non-uniform output intensity, as shown in Figure 3, due to the hundreds of transverse spatial modes available in the long dimension of the aperture.

To solve the problems of non-uniformity in the long-aperture VCSEL line generator, we have developed linear arrays of VCSELs with conventional circular apertures. These linear arrays create lines of illumination with fill factors ranging from 2 to 40%. The peak optical intensity in the center of each aperture is on the order of 1mW/$\mu m^2$ which is comparable to that of the EEL and further evidenced by the fact that "spot" triggering of PCSS has previously been demonstrated by such VCSELs. The structure also allows the possibility of integrated micro-optics for increasing the fill factor in the linear dimension; however, this would be at the cost of optical intensity. The 40% fill-factor array shown in Figure 3, from wafer EMC7551-A, was specifically designed to yield high slope efficiency, since we anticipated that PCSS triggering would require high optical power. In fact, we demonstrated up to 37% DC electrical-to-optical conversion efficiency, which is the amongst the highest

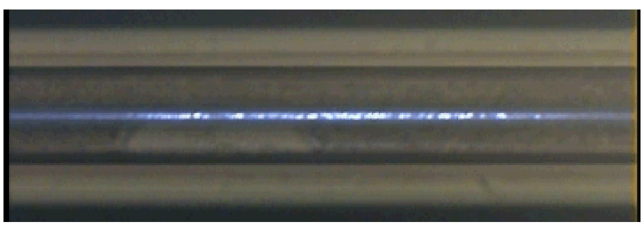

Figure 3. Lasing from a linear aperture VCSEL exhibiting instability and non-uniformity due to lack of optical confinement in the long axis.

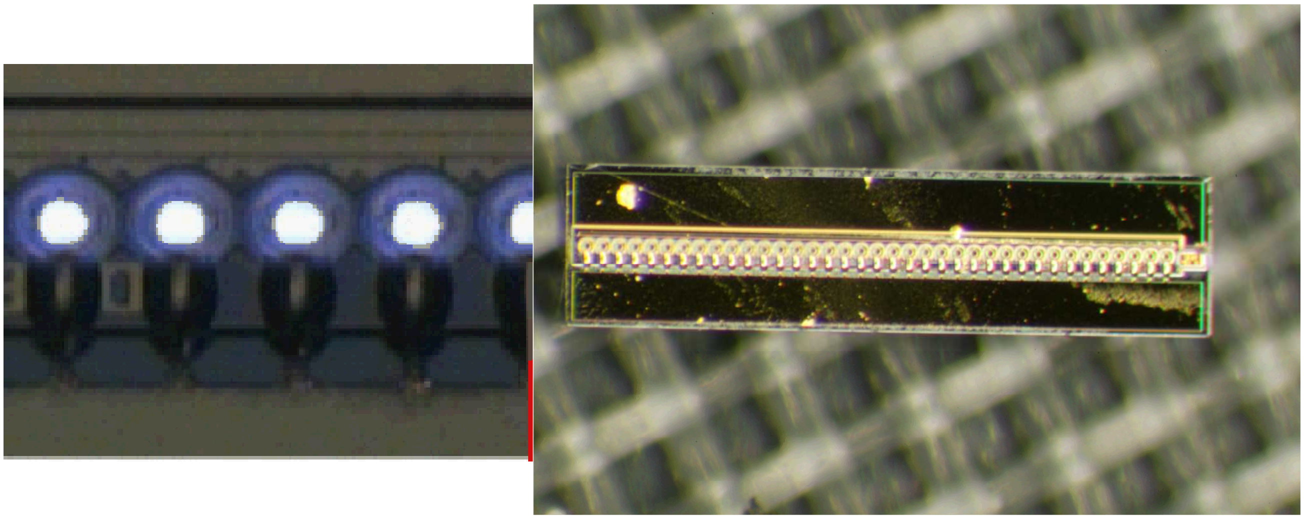

Figure 4. Microphotograph of 40% fill factor array.

achieved from a VCSEL. This is achieved by optimizing (lowering) the top output mirror reflectivity to obtain high output. This comes at the expense of a slight increase in laser threshold current, which is of negligible impact in this application where the devices are operated with short (~10ns) pulses at many times threshold current. The device pitch in this array was only 50µm, which is 5 times smaller than the conventional for electrical probing, which results in a 5 times increase in overall power. This represents the density limit for uncoupled devices using the current fabrication technology, as adjacent devices are now nearly touching each other. For these experiments each array is cleaved into a separate chip and connectorized. In this package, two chips can be installed to form two parallel lines.

The imaging of the VCSEL array into the gap of the PCSS is shown in Figure 5. In this case, a 10% fill factor array is used. The resulting current filament that is triggered is also shown. This filament is well-defined and fairly straight from one contact to the other compared to the lightning-bolt like chaotic shape that spot triggered filaments form. This is important if many parallel simultaneous filaments are to be triggered to distribute current without interfering with each other.

Accomplishing simultaneous dual filaments requires extra care in imaging and focusing of the laser lines in the switch gap. Moreover, careful matching of the arrays was necessary. If one filament forms before the other, the voltage necessary for generating lock-on at the other laser line is dissipated. Therefore, for two filaments to form, the delay time in filament formation must be the same for both laser lines. Figure 6 shows the lock-on delay time (relative to a fixed scope trigger signal) as a function of charge voltage on the PCSS. As expected, the delay time decreases as the voltage is increased until it is too close to the self-break voltage (~10kV in this case), and flattens

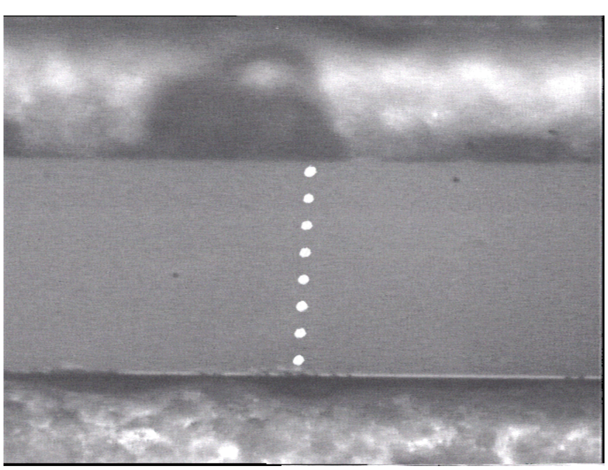

Figure 5b. Imaging of VCSEL array into PCSS gap.

Figure 5b. Resulting triggered linear filament

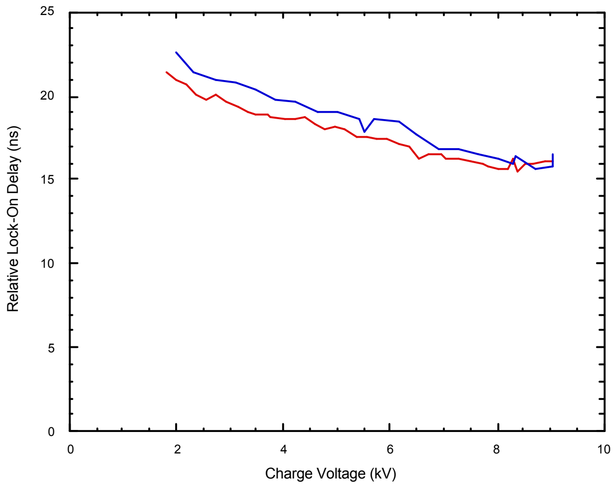


Figure 6a. Filament formation delay vs. charge voltage-well-matched laser array pair.

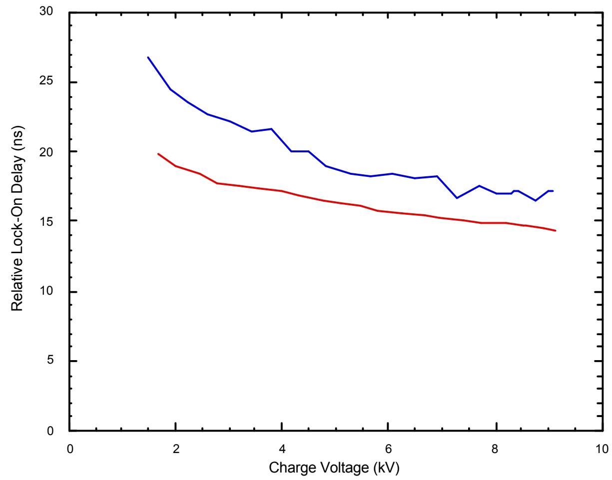


Figure 6a. Filament formation delay vs. charge voltage-poorly-matched laser array pair (~2ns difference).

out at the higher voltages. At these higher voltages, the timing jitter is also lower, and it becomes easier to trigger two filaments consistently. In figure 6a, the arrays are well-matched and are able to trigger dual filaments reliably at the higher charge voltages. In figure 6b, even though each array is itself able to generate a line filament, the consistent (~2ns) mismatch in delay prevents dual filament formation.

Pairs of the 40% fill factor arrays were used in parallel to generate dual trigger lines. The emission of this dual array is shown in figure 7. The lasers were driven with a 275-V 10-ns pulse from the 50-ohm source. The parallel resistance of the 37 VCSELs is approximately 0.5 ohms, from which we estimate a total current supplied to the array of 10.9A (275V*2/50.5). The actual measured optical pulse energy collected by the imaging optics was 120nJ, for a peak power of 12W. The high coupling efficiency of the array to the PCSS was accomplished by using a short focal length (2.75mm) lens with very high numerical aperture (0.65), given the imaging requirements for illuminating the PCSS gap with all 74 emitters.

Figure 8 shows two filaments formed in the PCSS at 8kV charge voltage using the well-matched array pair. With continuing improvements in laser uniformity and performance due to improved fabrication and coupled array device design,[2,3] this bodes well for future use of VCSEL arrays for multifilament (interdigitated) PCSS operating at 5kA and higher for firesets, and also for high voltage PCSS trigger generators[4] for pulsed power.

## III. REFERENCES

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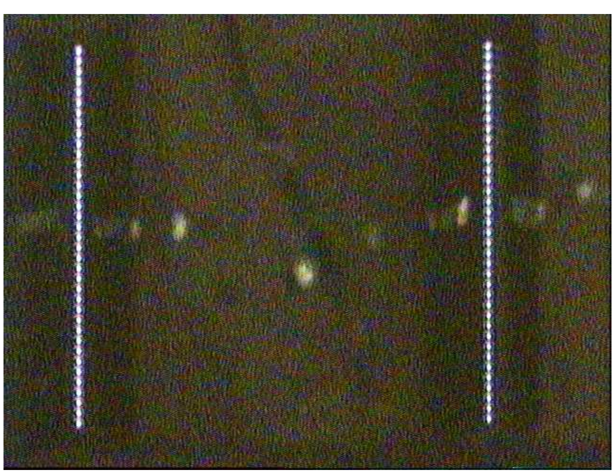

Figure 7. Emission of two parallel linear arrays of VCSELs in connectorized package.

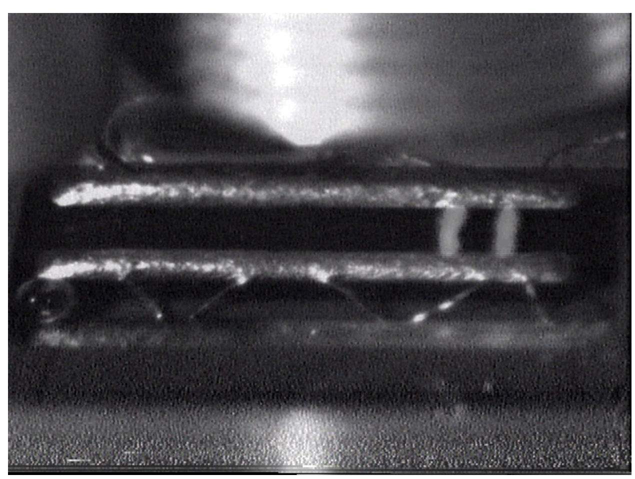

Figure 8. Dual filaments triggered in a PCSS using two linear VCSEL arrays.