EVALUATION OF SOLID STATE SWITCHES FOR A SPACE BASED LASER MODULATOR *

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ABSTRACT

Several solid state switch candidates were selected and tested to evaluate their capability to serve in a space based laser modulator application. Two of the SCR's tested surpassed the stringent requirements and were operated at 1300-1400 volts and 2500-2775 amperes with a 4 μs flat-topped pulse. The repetition rate was 6-10 hertz and the turn on di/dt was pushed higher than 16 kA/μs without failure. A saturable magnetic switch was employed to enhance the di/dt capability and minimize the switch losses. A solid state switch assembly would consist of ~ 30 series connected SCR's. When considering weight, efficiency, life, reliability, etc., the solid state switch concept compares favorably to a baseline thyratron system.

INTRODUCTION

The NASA Laser Atmospheric Wind Sounder (LAWS) program requires a 15-20 J/pulse CO_2 laser operating in low earth orbit at 5-20 Hz for more than 1.6×10^9 shots, over a 3-5 year continuous operating life. The G.E. Astrospace [1] and STI Optronics [2] team co-sponsored an IRAD project to evaluate the potential of solid state switches to meet the performance and system requirements for such a laser modulator. A paper study was conducted in order to minimize the number of candidates, and relevant scale tests were performed on each of the selected candidates to determine their performance characteristics and space system compatibility.

PULSED POWER REQUIREMENTS

The bipolar LAWS laser design calls for plus/minus 30 kV PFN's, to be simultaneously switched through the laser head in a series configuration. A simplified view of a positive solid state modulator is shown in Fig.1. External capacitance, that is placed near the laser head to assist with discharge initiation, presents an initial short circuit load to the PFN's and thus dominates the pulse risetime. Breakdown initiates after the head capacitors have charged to ~1.5 times the PFN charge voltage and, since the laser gas ionization is inversely proportional to the head voltage, the discharge resistance drops below normal. This action results in a second fast surge of current before the discharge resistance rises back up to a matched impedance condition. Fig. 2 shows the actual voltage and current waveforms from the thyratron switched STI LAWS prototype laser. The discharge parameters are a strong function of the gas mixture and pressure, and the optimum operating conditions have yet to be determined. However, both modeling and the prototype laser indicate that the voltage, current, di/dt, and pulse length requirements will probably be about 30 kV, 2-2.5 kA, 12-15 kA/μs, and 3.5-4μs, respectively.

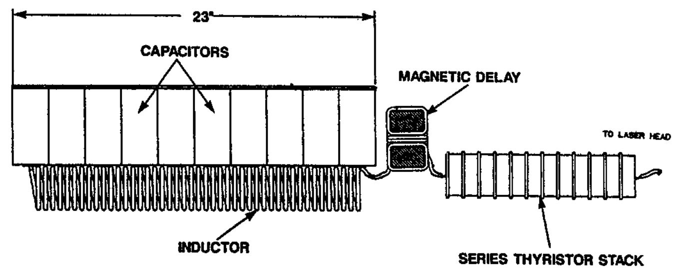

Figure 1. High-Voltage Modulator Side View

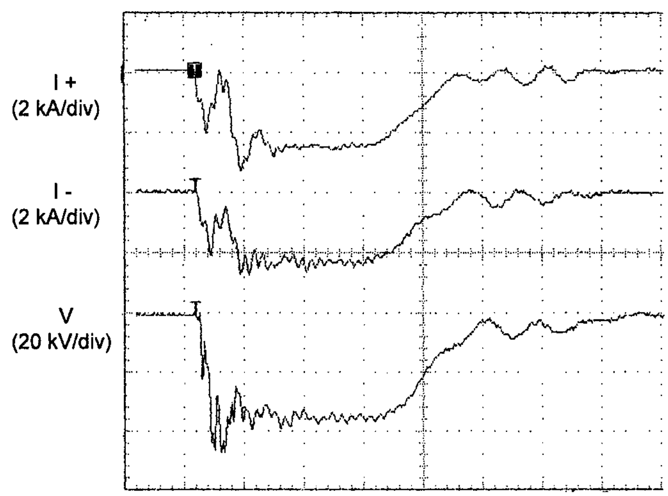

Figure 2. V and I Waveforms From LAWS Prototype Laser

In addition to the electrical pulse characteristics, the pulsed power system must adhere to strict efficiency and weight budgets and meet other specifications regarding lifetime and reliability, and mechanical and environmental concerns. Note that the pulsed power components will reside within the necessary, but otherwise wasted, spaces contained in the laser head. These regions provide not only convenient mechanical support, but they may also be filled with 1-2 atmospheres of recirculating Nitrogen, hence, many of the normal heat removal and high voltage breakdown problems associated with the space environment are virtually eliminated in this design package.

SWITCH CANDIDATES

Low current devices such as MOSFET's and IGBT's were not seriously considered for this switching application because of the complexities of triggering, high voltage insulation, component

* Work conducted for General Electric under NASA contract NAS 8-37589

[1] Currently a division of Martin Marietta.

[2] Mr. McDonald was employed by STI Optronics, Bellevue, WA, at the time this work was conducted. He is currently under contract to the University of Crete, Institute of Plasma Physics.

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Several solid state switch candidates were selected and tested to evaluate their capability to serve in a space based laser modulator application. Two of the SCR's tested surpassed the stringent requirements and were operated at 1300-1400 volts and 2500-2775 amperes with a 4 J.lS flat-topped pulse. The repetition rate was 6-10 hertz and the turn on di/dt was pushed higher than 16 kAIJ.!S without failure. A saturable magnetic switch was employed to enhance the di/dt capability and minimize the switch losses. A solid state switch assembly would consist of - 30 series connected SCR's. When considering weight, efficiency, life, reliability, etc., the solid state switch concept compares favorably to a baseline thyratron system.

15. SUBJECT TERMS

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distribution, current sharing, and potential reliability problems associated with a high part count.

Preferably, the switch assembly will consist of one, or at most two, series stacks of solid state switches that will transfer the normal energy pulse (and a certain percentage of short circuit fault shots) over the life of the program without failure. The search for relevant experimental work led to the high di/dt experiments conducted at the University of South Carolina (USC)[1] and Brown Boveri Co. (ABB)[2,3], to the Copper Vapor Laser Program at LLNL[4], and to unreported work on radar modulators at Westinghouse. USC achieved di/dt's as high as 100 kA/μs by using very high current direct drive triggering into the highly interdigitated gates of inverter grade thyristors. Note that intentionally shorting the amplifying gate structures on IR and Powerex products resulted in their most successful test results. ABB, on the other hand, utilized the amplifying gate in their Reverse Conducting Thyristors (RCT's) to minimize the gate drive requirements. Pre-pulse conditioning, via a magnetic switch delay, played dominant roles in both of these investigations. LLNL furthered the work of ABB by building numerous 20 kV assemblies of ABB RCT's to conduct 1500 A, 1μs sinusoidal, 3 kA/μs pulses at 4.5 kHz. Westinghouse took a different approach by employing stacks of 6-7 of their Reverse Blocking Diode Thyristors (RBDT's) to switch 3-5 kV, 3-5 μs PFN's for radar applications. RBDT's, which do not have a gate and fire with the application of a fast rising high voltage pulse, have demonstrated the conduction of high di/dt pulses with low losses without the assistance of magnetics, but require trigger voltages on the order of, or greater than the holdoff voltage. Conversations with all the major manufacturer's also revealed other potential candidates, including a Gate Turn Off Thyristor, especially designed for closing switch applications, from Meidensa and SCR's from Marconi. Some manufacturers expressed no interest in this program because of the small market potential.

The paper study and telephone survey yielded a lot of insight into the physics of high di/dt, efficient, solid state switching. Not surprisingly, efficiency is inversely related to the voltage standoff and time of recovery, and both efficiency and di/dt capability are directly related to the "active area" at the onslaught of the fast current pulse. Inherent slow plasma velocities inhibit the spread of the active area in silicon devices, a deficiency addressed by the gate structure, and what Marconi appropriately refers to as "priming." The gate must have an abundance of paths and fingers (highly interdigitated is the industry buzz word) that expose large areas to the gate pulse. Note that both direct drive and amplifying gate structures have been demonstrated to perform well, and the optimum approach has not been established. Priming is accomplished with the application of simultaneous primary and secondary methods; consisting of a magnetic switch delay, which holds off the main current pulse and permits the plasma to spread (and the switch resistance to fall) prior to the current surge, and an RC circuit that establishes the A-K current path. The RC circuit also serves double duty as a transient voltage divider and snubber.

Based on both user and manufacturer recommendations, the following switch candidates were selected for testing: 1) the CSR-328-13ia1 RCT from ABB, 2) Three different customized versions of IR's 88-674X series SCR's (on the basis of the TTU work, but with unshorted amplifying gate structures), 3) a specially fabricated version of the TA32914 SCR from Marconi, 4) T62R series RBDT's from Westinghouse, and 5) Meidensha's H10D33YFH closing switch GTO. The ABB SCR's were 1300 V, 52 mm X 25 mm devices; the IR and Marconi SCR's, and the Westinghouse RBDT's were packaged in 35 mm X 15 mm envelopes, and were rated for 1300, 1400, and 1000 volts, respectively; and the Meiden GTO's were 3000 V, 85 mm X 25 mm products.

EXPERIMENTAL PROCEDURE

The test circuit was designed to test switches at 1000-2000 V, and >2000 A, with di/dt's exceeding 10 kA/μs. Four, ten section PFN's were connected in parallel to generate the require 4μsec long flat-top pulse into a short circuit load. The last stage inductance was eliminated in order to simulate the initial current overshoot seen in the prototype laser discharge. An impedance matching End of Line Clipper (EOLC) was employed to absorb the short circuit current pulse and prevent reflections. Switch priming was accomplished with a 2605 CO, Metglas core, which was calculated to yield a 0.75μs delay for a 1000 V charge. Secondary priming included a 10 ohm resistor and a 0.05 μf capacitor, and additional protection was provided via inverse parallel companion diodes. The magnetic core was reset with a DC circuit, and the saturation delay time was varied to determine the impact on the switching efficiency. In the short circuit cases the switch efficiency could be determined to within ~10%, since the capacitance was known, the charge voltage was measured, and the energy deposited in the switch was determined via the $\int vidt$. Matched load cases were run to measure the actual energy deposited in the load resistors, and both methods of determining switch efficiencies were in agreement. The current was measured with a current transformer and the switch voltage was measured with a Tektronix voltage probe. Data was recorded on a LeCroy digital storage oscilloscope, which also performed the math functions necessary to determine the di/dt and energy lost in the switch, or deposited in the switch/load combination. The simplified PFN mechanical layout is demonstrated in Fig 3.

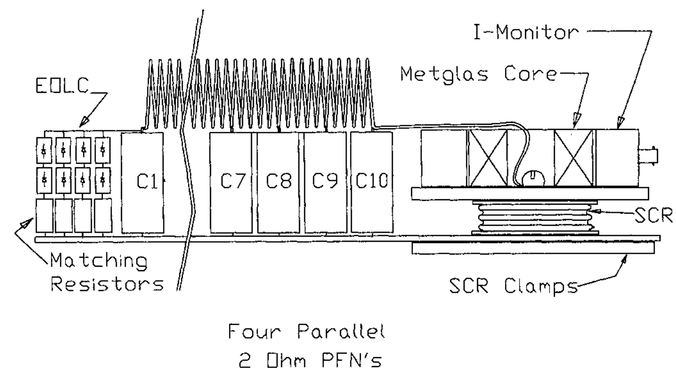

Figure 3. Simplified PFN Mechanical Layout

A command charge and trigger control board was designed to set the pulse repetition rate, regulate the charge voltage setpoint, stop the charge, initiate the trigger pulse, and start the charge again after the switch recovered. The 20 mA supply could provide a maximum of 10 hertz prr, at 1000 V. The board also prevents commencement of the charge cycle and inhibits the trigger pulse until the power supply intermediate storage capacitors are fully charged. This feature was incorporated to accommodate a single shot, with pulse charge, mode of operation.

The trigger generator was designed to provide a fast, high current pulse into the high capacitance SCR gate. A two stage FET step-up circuit amplifies the gate drive. The first stage FET was triggered with a square wave function generator, resulting in a typical output pulse as shown in Fig. 4. Risetimes were on the order of 100 ns, and the pulse duration could be varied to times exceeding the PFN pulse length.

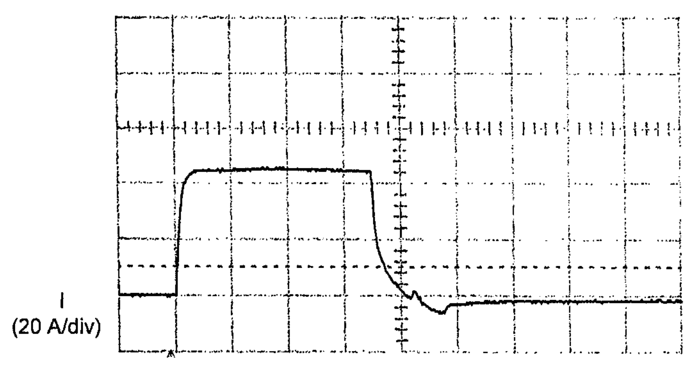

Figure 4. Typical Trigger Waveform.

EXPERIMENTAL RESULTS

ABB 328-13ia

This 1300 V switch accomplished all of our principle objectives and performed well throughout the test program. As shown in Fig. 5, the switch was subjected to over 25,000 pulses at 5 Hz, 1285 V, and 2550 A, with a di/dt of ~15 kA/μs. The peak current exceeded 3440 A.

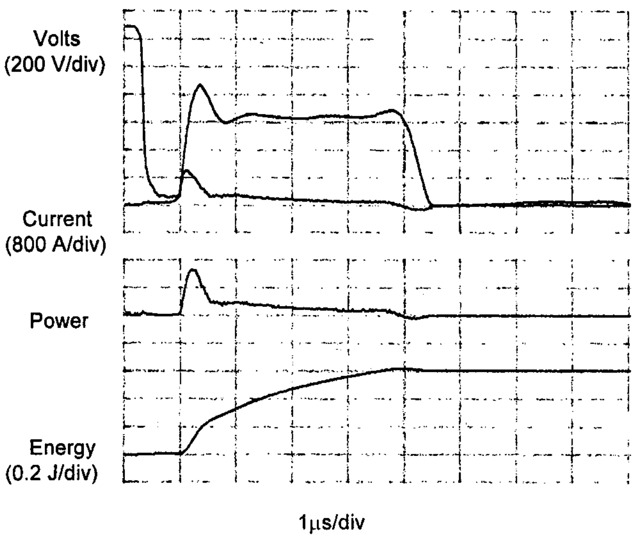

Figure 5. ABB 328-13ia1 RCT: Typical Switch Characteristics

Tens of thousands of shots were taken at other voltage and current levels and only two devices failed during the tests. The reasons have not been determined, in each case they simply failed to hold off voltage the morning following successful test runs. The problems did not appear to be associated with high current or di/dt, and gate trigger problems are suspected.

IR 88-674X

This family of switches failed to meet our requirements on all counts. Fig. 6, demonstrates a large AK voltage drop during conduction, resulting in a very poor switching efficiency. Most devices failed at about 1200 A, and 5 kA/μs. Switching efficiencies did not exceed 80%.

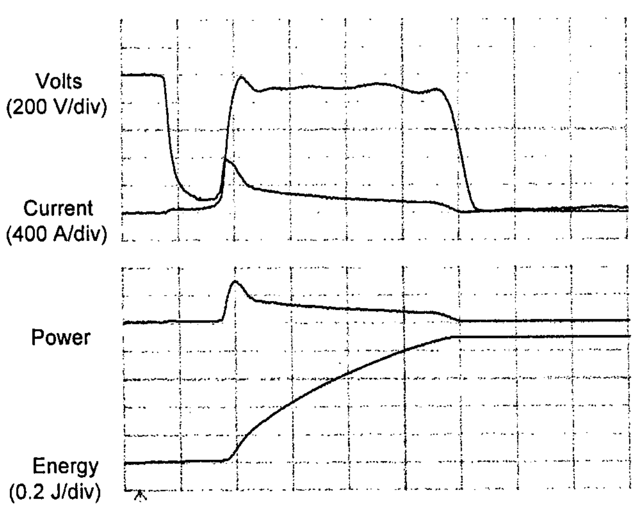

Figure 6. IR 88-674X: Typical Switch Characteristics

MARCONI TA32914 SCR

The Marconi switches met all of our performance specifications and vastly exceeded our expectations. They proved to be the most efficient device tested, and none were damaged in testing even though they were consistently operated at higher voltages and currents, and for more pulses than their competitors. Furthermore, they are one fourth the size and weight of the ABB 328 RCT's, which was the only other candidate to meet our requirements. Fig. 7 displays the Marconi results for a standoff voltage of 1,392 V, a peak current of 3,730 A, a flat-top current of 2,775 A, and a di/dt of 16.5 kA/μs.

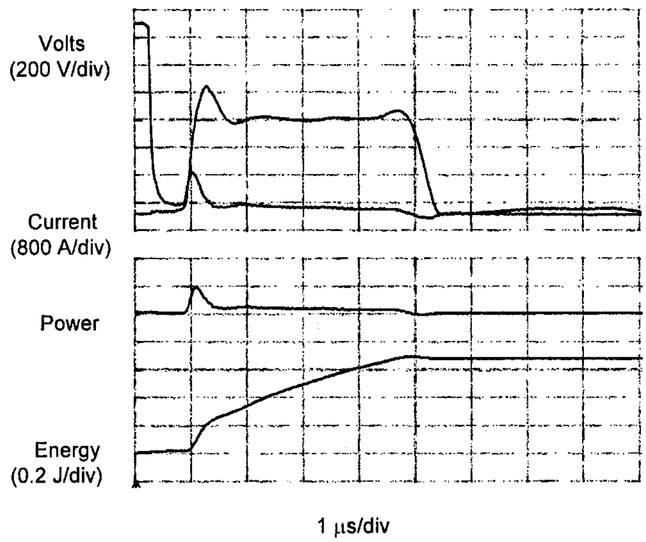

Figure 7. MARCONI TA32914 SCR: Typical Switch Characteristics

Several Marconi switches were tested for 10,000 shots at the above conditions;. Testing at 1,000 V, 2,000 A, and 11 kA/μs exceeded 100,000 shots at 5 hz. No failures were observed, and lifetimes at these conditions are expected to exceed our requirements. Typical switching efficiencies ranged from 92-95%., and were impacted by both the pulse di/dt and the priming delay, which varied inversely with the charge voltage.

The principal advantage of the Marconi was its low initial turn on loss. Note that the dissipated instantaneoμs power in the Marconi is lower than that of the ABB (see Fig. 5), even though all conditions were more stringent for the Marconi, and the priming delay time was slightly shorter. For considerably longer pulses the ABB may prove to be more efficient due to its larger size, but it will be difficult to justify the increase in size and weight.

WESTINGHOUSE T62R RBDT

The primary hope for these devices was that they could be employed in series with SCR's, thus resulting in reduced system trigger requirements. However, the fast dv/dt impulse required to properly initiate conduction in the RBDT's could not be generated with series SCR's in the circuit, and, consequently, the RBDT's failed. There could still be an interest in RBDT's for solid state Marx generator applications, as they have proven to be quite efficient.

MEIDENSHA H10D33YFH GTO

Like the IR SCR's, these switches failed to meet any of our performance specifications. They were easily destroyed, and were characterized by very high turn on losses, as demonstrated in Fig. 8. Switching efficiencies were about 80%

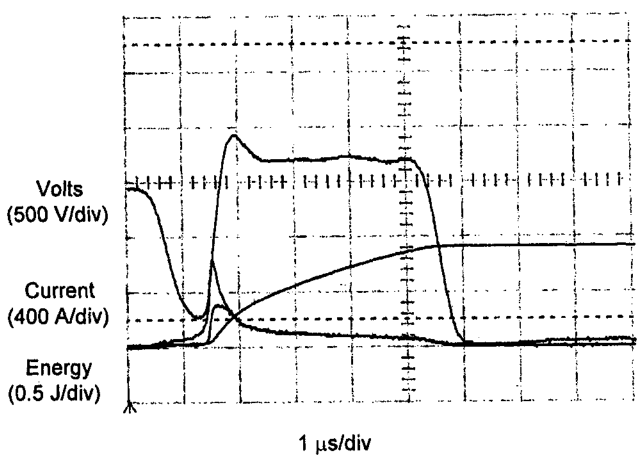

Figure 8. MEIDENSHA H10D33YFH GTO: Typical Switch Characteristics

Marconi SCR vs. Thyratron

The bi-polar drive system requires two 30 kV, type E PFN modulators to be switched in series through the laser head. This comparison assumes the use of two thyratrons versus four Marconi SCR switch assemblies, each consisting of thirty SCR's. Hence there are two parallel output switches for each PFN in the solid state scheme, each of which is capable of conducting the entire load current.

The solid state system has greater conduction losses, and requires more sophisticated transient protection, triggering, and priming circuitry, whereas the thyratron system has much greater "housekeeping" demand, and one of the thyratrons requires a "hot deck" to service the heater, reservoir, grid bias, and trigger. A comparison of the system weights and power requirements is shown in Table 1. The solid state switching components slightly outweigh those of the thyratron system, however, when the additional components (solar panels, battery storage, power converters, etc.) required to provide housekeeping power for the thyratrons are included the Marconi system will be lighter.

WEIGHT AND POWER LOSS COMPARISON

	THYRATRON			THYRISTOR		
ITEM	WEIGHT (kg)	ENERGY LOST PER/PULSE (%)	POWER @ 5 Hz (W)	WEIGHT (kG)	ENERGY LOST PER/PULSE (%)	POWER @ 5 Hz (W)
SWITCH	6.4 (1)	3	36	7.8 (2)	8 (3)	96
MAGNETIC CORE	1	0.1	0.5	2.9	0.4	2
TRIG/GRID BIAS (4)	1.5	0.1	20	6.6	0.4	20
HEATER/RESERVOIR (4)	7.5		500			
RC PRIMING				1.6	1.4	20
OTHER COMMON ITEMS (eg, P.S.'s, Caps,Fault Ckts)	63.7	5.4	310	63.7	5.4	310
TOTAL	80.1	8.6	867	82.6	15.6	448

1. Two Thyratrons.
2. Four stacks of 30 each Marconi 329 thyristors. Two parallel per PFN, times two series PFN's.
3. Includes bleed losses during charge cycle.
4. Floating deck for positive output PFN, includes power supplies, high voltage DC isolation, etc.

NOTE: The power column includes continuous housekeeping losses as well as those associated with the charge and discharge cycles.

Table 1. Comparison of Marconi vs. Thyratron Switched Modulators

Conclusions

The Marconi TA32914 series of SCR appears to be the best overall choice for this application. It is durable, efficient, compact, lightweight, and meets or exceeds all of the program specifications. The parallel switch stack offers redundancy in a critical arena, with little impact to the weight budget. While the ABB RCT met our performance specifications, the Marconi proved to be more efficient for the conduction of short, high di/dt pulses, and is clearly the best choice on the basis of size and weight. The thyratron system, albeit very rugged and immune to faults, loses to the Marconi SCR's because of the thyratrons excessive housekeeping burden and questionable continuous duty life for the three to five year LAWS program. The SCR's also provide an improvement in jitter over the thyratron's, a factor that may prove to be beneficial for trouble free operation in a bi-polar modulator scheme. Note that the switching costs have not been considered since they represent a very small fraction of the overall system and lunch costs. Reliable long life operation is far more critical to this program than the slight increase in initial costs associated with the SCR switch package.

Full scale testing, first into a dummy load, and than into an actual gas discharge load will be required to ascertain the absolute performance capabilities of the Marconi SCR switched modulators. Transient protection, triggering, mechanical layout, and gas load matching will present the most interesting challenges and will require some time to achieve system wide perfection. However I have no doubt that these issues will be successfully addressed and that a solid state switched modulator will represent a significant improvement over the present state of the art in lightweight, long life laser modulators.

Acknowledgments

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References

[1] J.L. Hudgins, V.A. Sankaran, W.M. Portnoy, and K.M. Marks, "High di/dt Switching with Thyristors," Proceedings of the Eighteenth Power Modulator Symposium, pp. 292-298, 1988.

[2] J. Vitins, J. L. Steiner, and A. Schweizer, "Reverse Conducting Thyristors Replace Thyratrons in Sub-microsecond Pulse Generation," Proceedings of the 6th IEEE Pulsed Power Conference, pp. 591-594, 1987.

[3] J. Vitens, et at., "Power Semiconductor Devices for Sub-microsecond Pulse Generation," Proceedings of the Eighteenth Power Modulator Symposium, pp. 299-306, 1988.

[4] G.R. Dreifuerst and B. T. Merritt, "Development and Operation of A Solid-State Switch for Thyratron Replacement," Proceedings of the 8th IEEE Pulsed Power Conference, pp. 191-195, 1991.