DIVERSIFIED TECHNOLOGIES, INC.

# SOLID STATE RADAR MODULATORS

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***ABSTRACT***
*Hundreds of radar systems operating within DOD and at commercial sites utilize tetrodes or thyratrons/ PFNs for high PRF pulse modulation. While these systems remain operationally viable, the vacuum tube modulators are expensive to maintain, and their relatively short lifetimes constitute a significant operational expense. In addition, the number of reliable suppliers of vacuum switch tubes is diminishing, resulting in higher prices and longer procurement cycles. In some cases, replacements for obsolete switch tubes are simply not available from any supplier.*

*Diversified Technologies, Inc. (DTI) has successfully developed and demonstrated a highly efficient and reliable new approach to solid state switching that can be used in radar transmitters. The key to this development is the Solid State Switch Module shown in Figure 1. This is an encapsulated series switch module approximately 7"x7"x2" It is rated to 9kV, 30A, with very low insertion loss (10-20 ohms). Higher currents, up to 100 A peak, are also possible at lower voltage ratings per module (nominally 5 kV). Multiple switch modules can be combined in series and parallel to meet a wide range of power switching requirements. Since these modules are individually isolated and protected, they can be used for both cathode pulsed and grid/mod-anode pulsed radar systems.*

*There are two major benefits to the radar system from use of these solid state switch modules. The first is improved transmitter performance, with a wider range of operating parameters (pulse width, PRF, pulse agility, and pulse-to-pulse consistency). The second is the major cost reductions of operating these transmitters. These cost savings result from the inherent reliability of these switch modules versus conventional switch tubes, and the elimination of numerous auxiliary components for operation of the switch tubes themselves. DTI has successfully demonstrated this technology's application to transmitters with TWTs, klystrons, magnetrons, and CFAs.*

This paper describes how these Solid State Switch Modules have been used as components for both new and upgraded radar transmitters.

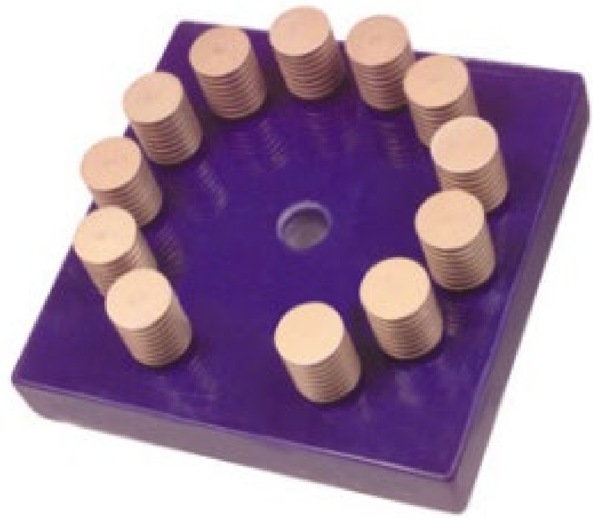

*Figure 1: 9kV, 30A Solid State Switch Module Approximately 7" x 7" x 3"*

## BACKGROUND – HIGH POWER SOLIDSTATE SWITCHING

The non-ideal characteristics of conventional, vacuum tube switches include a large effective voltage drop, limited current capability and speed, high maintenance requirements, and complex driving and protection circuitry. Nonetheless, vacuum tubes have provided a nearly exclusive solution to the problem of high-voltage switching because no cost-effective alternatives were available. As future systems require higher voltage and power, the use of switch tubes becomes increasingly impractical due to their inherent voltage and current limitations.

### Solid State Modulator Principles

In its simplest configuration, solid-state technology provides a fast, high current series switch, or circuit breaker. These switches typically open and close in less than 100 – 500 nS, depending on their power rating.

When used as a Pulse Modulator, the opening and closing of the switch is controlled by a command signal at low voltage. The result is a stream of high power pulses into the load, each with rapid rise and fall times, and extremely consistent pulse-to-pulse characteristics. Because these solid state modulators do not use resonant circuits, each pulse can be arbitrarily sized. This allows complete pulse width and separation flexibility - from 1 µs to DC - on a pulse to pulse basis.

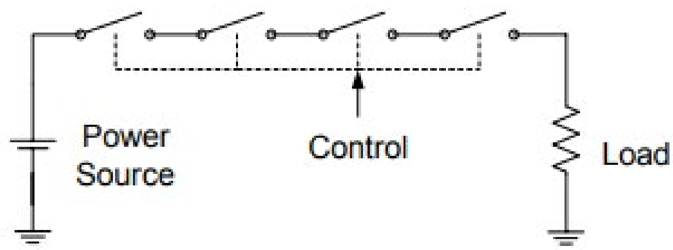


*Figure 2: Solid state modulator components. The switches are in series.*

Systems having high voltage and/or high current requirements can be constructed by stacking switch modules in various series and parallel configurations. Figure 2 shows the basic design of a solid state series modulator. This concept provides the flexibility of a modular design, with no inherent limit to voltage handling. However, it also necessitates the formidable task of ensuring that the load is shared equally between devices so that no single device sees harmful or destructive voltages. An external gate drive controls all modules simultaneously. The gate drives must be highly synchronized to accomplish this. DTI has developed and patented the technology to achieve this synchronization, which has been demonstrated at up to 160 IGBTs in series, and up to six IGBTs in parallel. For most radar applications, high voltage switching can be provided by an assembly of one to ten switch modules.

## AN/SPG-60 MODULATOR UPGRADE

The AN/SPG-60 fire control radar is an Xband, klystron system which is a key component in the GFCS MK-86 shipboard weapons control system, is in service on more than 30 US Navy ships. The Naval Surface Warfare Center, at Port Hueneme, CA contracted with DTI for the development of a replacement solid state modulator for the radar (Figure 3). The original design's vacuum switch tubes, monitoring and housekeeping circuits were a major contributor to the overall AN/SPG-60 failure rate. The goal was to decrease the failure rate of the transmitter by improving its overall reliability, reducing maintenance requirements, and improving power handling capabilities.

DTI combined two of the solid state switches shown in Figure 1 into a modulator / transmitter assembly rated at 18 kV, 30 A, and 35 kHz. The upgrade included a new 15 kV switching cathode power supply, and an improved filament supply, to reduce stress on the klystron. The components of the upgrade replaced a 4CX5000 switch tube, pulse transformer, and linear power supply in the original AN/SPG-60 transmitter (Figure 3-circled area). The upgrade also eliminated the need for traditional switchtube housekeeping circuits, such as heater supplies. The entire modulator upgrade was designed to be field-retrofitted quickly

*Figure 3: AN/SPG-60 transmitter with DTI solid state modulator installed in middle cabinet.*

Klystron pulses from this transmitter upgrade are shown in Figure 6 and Figure 4. Figure 6 shows a single klystron pulse, at 13.5 kV, and 8 microseconds pulse width. The rise and fall times of this pulse are primarily limited by the capacitance of the klystron cathode and its leads, and are approximately 100 nS. The impact of this capacitance is shown in the charging current spike seen at the leading edge of the pulse. Figure 4 shows a pulse train at 25 kHz, demonstrating the pulse-to-pulse consistency of this modulator.

Preliminary test results are very promising. The solid state modulator has increased the calculated MTBF of the AN/SPG-60 transmitter cabinet by a factor of more than twenty. The limiting component is now the service life of the klystron, about 10,000 hours. This means the overall MTBF of the system has improved by a factor of more than six. Further, the increased reliability is estimated to reduce maintenance labor by 200 hours annually per system, and total spare parts costs by $280K annually. Significant improvements in system uptime are also expected.

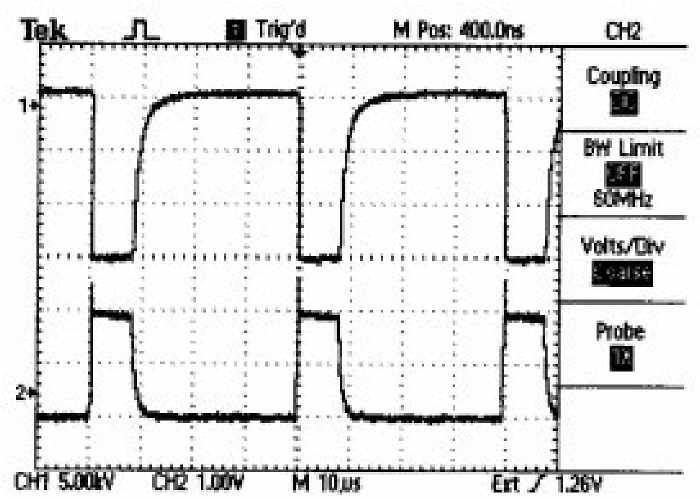

*Figure 4: AN/SPG-60 train, 15kV, 25 kHz, 8 µs*

The new solid state design is also much more efficient than the original design. It has reduced the transmitter cabinet's 440 V / 400 Hz input power requirements by nearly three amps, and led to an 80% heat reduction within the transmitter cabinet itself. DTI's design also allows most maintenance to be conducted from the inner door (see Figure 3), without requiring access to the high voltage components.

## NRL 94 GHZ GYROKLYSTRON

Under a Small Business Innovation Research (SBIR) contract from the Naval Research Laboratory, DTI is building a complete transmitter for NRL's recently demonstrated 94 GHz gyroklystron, which provides approximately 10 kW of RF power. The overall transmitter design is shown in Figure 8, and includes a 65 kV cathode power supply and a high PRF solid state modulator. In 1999, DTI demonstrated a prototype 20 kV, 100 kHz modulator for this transmitter. DTI further demonstrated a 400kHz capability at lower voltage, (Figure 7) far exceeding both the 5 kHz level NRL was able to achieve with conventional switch tubes, and the 100 kHz design goal.

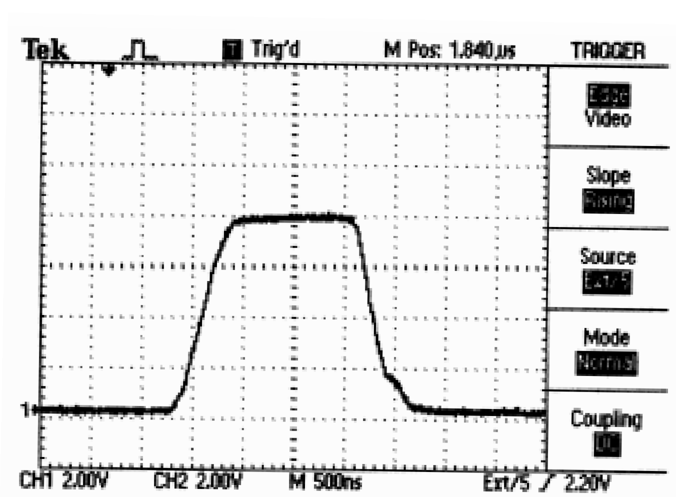

*Figure 5: Transmitter pulse 8kV, 100kHz, 1.5µs*

This significant increase in speed was achieved with less than 8% of the expected CV2 f losses inherent in hard switched designs. As an additional benefit, the transmitter system features a solid state series switch to eliminate the need for a crowbar, providing enhanced protection to the gyroklystron itself. The complete transmitter system is scheduled for delivery to NRL in mid 2001.

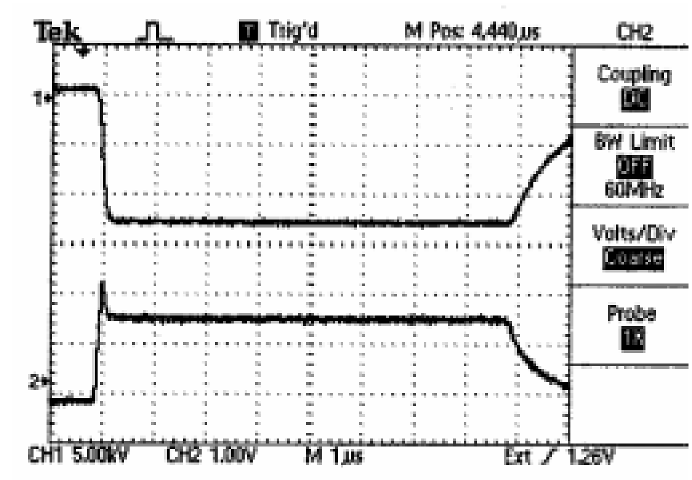

*Figure 6: AN/SPG-60 Pulse, 13.5kV, 25 kHz, 8 µs*

## CONCLUSIONS

The use of solid state modulators in high frequency radar transmitters is a very recent reality. This approach has major benefits to both new radar designs, and to the upgrade and operation of existing systems. Many shortcomings of older vacuum tube technologies (reliability, efficiency, cooling, and flexibility) can be ameliorated, and new, previously unreachable

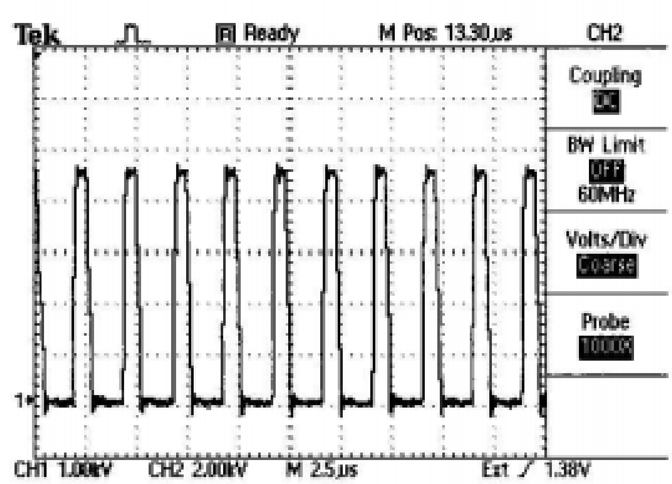

*Figure 7: 4.5kV, 400kHz pulse*

performance levels can be attained. The modular, flexible design of the switch modules aids successful deployment in other radar designs and high power devices.

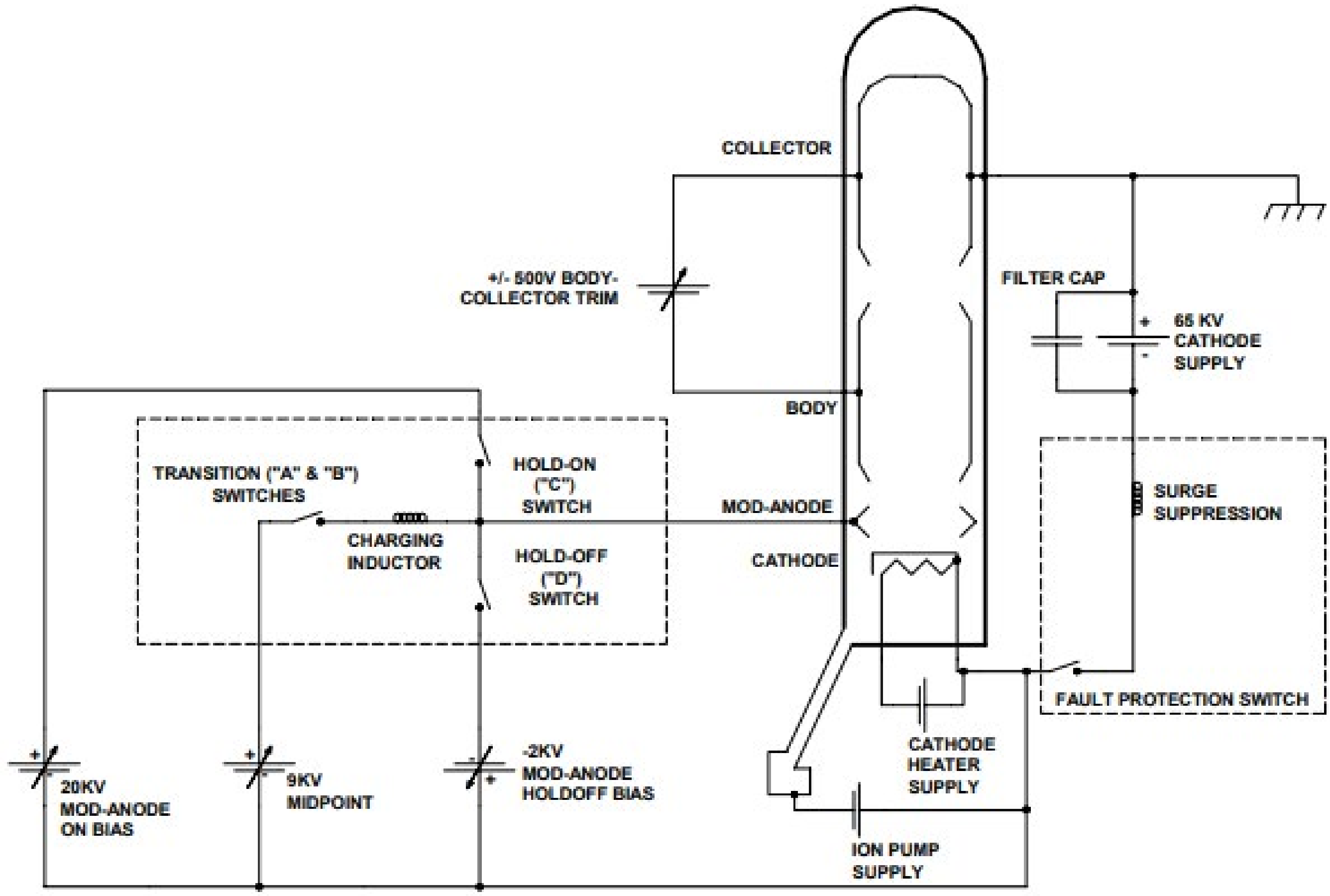


*Figure 8: Schematic of NRL gyroklystron modulator.*