OPTICALLY-ACTIVATED GaAs SWITCHES FOR GROUND PENETRATING RADAR AND FIRING SET APPLICATIONS*

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Abstract

Optically activated, high gain GaAs switches are being tested for many different applications. Two such applications are ground penetrating radar (GPR) and firing set switches. The ability of high gain GaAs Photoconductive Semiconductor Switches (PCSS) to deliver fast risetime pulses makes them suitable for their use in radars that rely on fast impulses. This type of direct time domain radar is uniquely suited for the detection of buried items because it can operate at low frequency, high average power, and close to the ground, greatly increasing power on target. We have demonstrated that a PCSS based system can be used to produce a bipolar waveform with a total duration of about 6 ns and with minimal ringing. Such a pulse is radiated and returns from a 55 gallon drum will be presented. For firing sets, the switch requirements include small size, high current, dc charging, radiation hardness and modest longevity. We have switched 1 kA at 1 kV and 2.8 kA at 3 kV dc charge.

I. INTRODUCTION

Our research has focused on optically triggered, high gain GaAs photoconductive semiconductor switches (PCSS) for pulsed power applications.[1] Table I shows the best results obtained with the switches. The GaAs switches used in this experiment are lateral switches made from undoped GaAs of high resistivity $>10^7 \Omega\text{-cm}$ and metallic lands that connect the switch to an energy source and a load. At electric fields above 4 to 6 kV/cm these switches exhibit high gain.[2,3] We have used trigger energies as low as 180 nJ to deliver 48 MW in a 30-50 Ω system.[4] In the "on" state the field across the switch stabilizes to a constant called the lock-on field.

Table I: Results of Tests with High Gain GaAs Switches

Parameter	Best Values	System results
Switch Voltage (kV)	155	100
Switch Current (kA)	7.0	1.26
Peak Power (MW)	120	48
Rise time (ps)	430	430
Trigger Energy (nJ)	2	180
Repetition Rate (kHz)	40,000	1
Lifetime (# pulses)	$> 5 \times 10^7$	5×10^4 (77 kV)

Table I. The middle column describes the best individual results for each parameter and are not simultaneous. The last column describes the result of a single experiment.

II. GROUND PENETRATING RADAR

We seek to develop a GPR system that can be utilized for environmental site reconnaissance and, in particular, for finding buried metallic objects such as 55 gallon drums at depths of up to 10m (and other man-made objects at various depths) in real soils. The primary disadvantages of GPR have been low penetration depth and low signal to clutter. We hope to minimize both of these problems. The penetration depth will be augmented by using: 1) high peak power, high repetition rate operation for high average power; 2) low center frequencies that better penetrate the ground; and 3) short duration impulses. The latter allow for the use of low platforms that increase the power on target relative to a high flying platform (due to the R^4 term in the radar equation, where R is the range to the target). Clutter is minimized by time gating the surface clutter return and using low frequencies (since natural objects are smaller than the wavelengths used here and their cross section is smaller than for higher frequency systems). The factor that makes this work unique is that we will utilize direct

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time domain radar at low frequency and high average power. The soils we intend to study are clay soils with high water content (10 to 20 percent, by weight). Detection of drums buried in non water bearing soils or in sand is relatively easy and, thus, will not be discussed.

A. Method of Moments (MoM) Model

We used a Method of Moments (MoM) model [4] (developed by Dr. L. Carin at Duke University) as a foundation to calculate the expected returns from a buried 55 gallon drum. A tool for the study of electromagnetic scattering from buried objects is the finite difference time domain (FDTD) algorithm which allows scattering to be calculated from rather general environments. However, the FDTD method requires one to grid the entire computational space and, thus, the available computer memory limits the problems it can tackle. The MoM only requires a grid at the target surface while the surrounding media is characterized by a Green's function (which is known for lossy layered media). Also, since MoM is a purely numerical algorithm, it provides insights such as the determination of complex resonant frequencies of targets that are the poles in the MoM solution. The figures show the results of the MoM calculation. Figure 1 and 2 are time and frequency representations of transmitted pulse which has a center frequency of 250 MHz and peak to peak amplitude of 1.5. We calculated returns for drums buried on their side and upright. The results for the worst case are shown in figures 3 (time domain) and 4 (frequency) for an upright 55 Gallon Drum buried 3 m in Puerto Rico soil (10% water content) for normal incidence. Note that the frequency is shifted down and that the peak amplitude is only 0.0045. Thus, it is crucial to radiate high voltages to receive large signals above the noise threshold for water bearing soils.

Figure 1: The radiated pulse as modeled in the MoM calculations.

Figure 2: The frequency content of the radiated pulse modeled in the MoM calculations.

Figure 3: The calculated (MoM) return from an upright drum buried 3 m deep.

Figure 4: The frequency content of the calculated return.

The MoM calculations were continued so that we could calculate the expected returns from our antenna and pulser. Figure 5 shows the transmitted pulse from our system and the fitted Raleigh pulse that was used in the calculations. We calculated returns from a single drum buried in Puerto Rico clay soil with 10% water content in different configurations: 1) a vertical or standing drum whose top is either 1 m, 2 m, or 3 m below the surface, 2) a horizontal or laying-down drum whose top is at either 0.7, 1.7, or 2.7 m below the surface and aligned parallel to the radiated electric field, and 3) a horizontal drum also at the same depths but aligned perpendicular to the radiated electric field. A few of these results are shown in figure 6. First, we want to stress that the returns from the horizontal drums do not depend greatly on polarization. We were concerned with polarization differences that would complicate field searches but that concerns us no longer. Second, the peak amplitudes, in figure 6, for the return relative to the transmitted pulse are as follows: 1.2% for the 2m vertical drum, 0.42% and 0.40% for the horizontal drums at 2.7 m, and 0.32% for the vertical drum at 3 m. Since we can conservatively design a receive system that allows for 60 db to 80 db sensitivity, the above numbers (38 db, 47 db, 48 db, and 50 db) imply that the system we designed is reasonable for the detection of 55-gallon drums in different types of soils, including highly lossy soils such as Puerto Rico clay with 10% water content.

Figure 5: Comparison of modeled waveform and actual transmitted pulse.

Figure 6: Returns from the various configurations: 2 m vertical drum, 2.7 m horizontal drum (parallel and perpendicular polarizations), and 3 m vertical drum.

B. Experiments

We tested the system with the drum in air (not buried), as shown in figure 7. Here we used a TEM horn transmit antenna with flared aperture plates and a high-voltage coaxial balun as the input section. The transmitted pulse has already been shown in figure 5 and has peak frequency content at ~260 MHz with -10 db points at 80 MHz and at 420 MHz and a transmitted field of 11 kV/m at 1 m when the pulser was charged to 30 kV. Note that the EM size of a drum is ~3ns in air ($\epsilon=1$, 330 MHz) and 6.7 ns in soil ($\epsilon=5$, 150 MHz). We tested different receivers: a B-dot monitor (Figure 8), a calibrated D-dot monitor, and a ridge-horn antenna. The results from the D-dot free field sensor show that the receive field was about 30 V/m which was easily detectable (we had to attenuate the signal) and of the order of 15 V. Thus, attenuations of 0.32 % still allow for amplitudes of ~50 mV which we will be able to detect. The transmitted pulse was obtained with a PCSS-driven Frozen Wave Generator (with and without a crowbar switch) pulse forming line.

Figure 7: Photo of system demo in air. Note the 55-gallon drum (right) and receiver (left) which are elevated with wood stands.

Fig 8: Receive waveform for the B-dot receiver.

III. FIRING SETS

The filamentary nature of the current in a PCSS and the current pinching at the metal to semiconductor interface produce very high current densities at the metal-semiconductor interface. We believe that longevity is determined by the current pinching at the GaAs to metal interface. We have improved [5] longevity by spreading the current along the width of the contact and by making the current spread into the GaAs' depth at low currents (~ 10 A) and short pulses (3.5 ns). For firing sets we are interested in currents that range from 80 A to 3 kA and pulse durations that are as high as a few 100 ns. One way to achieve increased longevity is to spread the current into multiple filaments. Figure 9 shows the images of current filaments. On the left the switch was triggered as to produce multiple filaments while on the right, the more normal trigger geometry produces a strong, sharp filament. Longevity tests were carried out both ways, at low and high currents. The diffused triggering geometry shows improvement at low currents but not at 1 kV/1 kA.

Another mechanism that has shown improvements in longevity is neutron irradiation. The great advantage of the neutron irradiation is that it also improves radiation hardness. We have used neutron irradiated GaAs to a dose of $1 \text{ E} 14$ rads to obtain well over 1,000 pulses in forward biased switches at 80 A and over 300 pulses with reverse biased switches. We are currently testing whether a PCSS could trigger a main firing set switch and tested the longevity of the PCSS and the system jitter under these conditions. We tested $400 \text{ }\mu\text{m}$ gap switches forward and reverse biased with neutron doses of $1 \text{ E} 14$ and $3 \text{ E} 14$ rads and 0.5 mm gap n-i-n switches and they all survived for more than 1,000 pulses. At current levels of 80 A, we obtained excellent longevity for this application two different ways: 1) p-i-n forward biased switch ($400 \text{ }\mu\text{m}$ gap) at 480 V and obtained $\sim 2,000$ pulses. 2) n-i-n switch, $500 \text{ }\mu\text{m}$ gap, 540 V, $>10,000$ shots (>700 V hold-off). The system jitter was also tested in a variety of ways and values that range from 1.55 ns to 2.71 ns were obtained. The peak current delivered to the main firing set switch is heavily dependent on inductance. Two circuits were tested: a large strip line circuit with $C=2 \text{ nF}$, $L=30 \text{ nH}$ that resulted in 80 A at 500 V and a small (see figure 10), low inductance, CDU tester circuit $C=1.4 \text{ nF}$, $L=3.8 \text{ nH}$ that also gave 80 A but at 240 V.

Figure 9. Infrared images of the switch during conduction showing multiple, diffuse filaments at left and a strong filament on the right. The outline of the metal contacts runs top to bottom in the figures and they are separated by $400 \text{ }\mu\text{m}$. The current was 40 A.

Figure 10. Small (the SMA connector on the right is 2 mm in diameter), low inductance ($L=3.8 \text{ nH}$) circuit.

IV. SUMMARY

Optically activated, high gain GaAs switches were tested for ground penetrating radar and firing set switches. We have demonstrated that a PCSS based system can be used to produce a bipolar waveform with a total duration of about 6 ns and with minimal ringing. Such a pulse is radiated and returns from a 55 gallon drum obtained. For firing sets, the switch requirements include small size, high current, dc charging, radiation hardness and modest longevity. We have switched 1 kA at 1 kV and 2.8 kA at 3 kV dc charge.

V. REFERENCES

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