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A LONGLIFE, HIGHVOLTAGE, SHORTPULSE  
GENERATOR BASED ON OPTICALLY ACTIVATED  
BULK AVALANCHE SEMICONDUCTOR SWITCH

PHASE II SBIR

FINAL REPORT

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By

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## I. INTRODUCTION

Power Spectra, Inc. has conducted a program to demonstrate that the proprietary switches which Power Spectra developed under its internal funding can be used to produce a pulsed electrical source with the following characteristics:

Pulse Width (FWHM)	100 ps
Pulse Amplitude	1 kV
Pulse Repetition Frequency (PRF)	1 kHz
Lifetime	1000 hrs

Concurrently with this demonstration Power Spectra continued its switch development program. At each stage of development, switches were tested under the SBIR Phase II program to demonstrate the required capability.

## II. BACKGROUND

Power Spectra, Inc. under private funding, has developed a unique high power, efficient microwave frequency semiconductor switch. This Bulk Avalanche Semiconductor Switch (BASS) utilizes optically-triggered avalanche in bulk semi-insulating gallium arsenide to provide the on-state conductivity.

The very high avalanche gain ( $>10,000$ ) makes this switch ideal for high power, high frequency applications requiring high optical efficiency. The switch is triggered with a semiconductor laser which eliminates the requirement for large, delicate and inefficient lasers required by other light-activated switches. Power Spectra has developed proprietary techniques to eliminate filamentary avalanche and to ensure long switch life.

The elimination of large lasers also ensures that the switch is capable of operation at high PRF. Semiconductor lasers have been modulated at microwave frequencies and the recombination time which determines the switch recovery in GaAs is on the order of 10 ns. Thus operation at multi-megahertz PRF should be possible.

The avalanche risetime in GaAs is theoretically 15 - 30 ps. This allows the generation of pulses as narrow as 30 - 60 ps in GaAs materials using the avalanche process.

The voltage hold-off of bulk switches is determined by the thickness and resistivity of the material. Nominally, the breakdown electric field of GaAs is 400 kV/cm. In practice, fields as high as 200 kV/cm are readily achievable. The intrinsic resistivity of semi-insulating GaAs is  $10^8$  ohm-cm. Even large switches at high voltage will have a large off-state resistance and therefore low leakage current.

### III. SBIR PHASE II SWITCH REQUIREMENTS

The pulse characteristics which were to be demonstrated in this program required a pulse width of 100 ps and a peak amplitude of 1 kV. The PRF was 1 kHz and the lifetime 1000 hours.

These requirements raised several issues as far as switch and diagnostic development were concerned. The test geometry which was chosen consisted of a 50 $\Omega$  transmission line pulse-forming section and a 50 $\Omega$  transmission line output section feeding the pulse to a 50 $\Omega$  diagnostic system. The output pulse amplitude from this configuration is one-half of the charging voltage; therefore, a 1 kV output would require charging the switch to a minimum of 2 kV.

The 100 ps pulse width presented a significant diagnostic and configuration problem. The major issue is that in order to measure a 1 kV or greater pulse the signal needs to be attenuated by greater than x 1000. This is due to the fact that the only systems capable of measuring the fast pulse are sampling oscilloscopes. The input of the sampling scope is limited to about  $\pm$  0.5 V. Attenuators capable of supporting > 1 kV and reducing the amplitude x 1000 have poor pulse risetime. Another problem with the diagnostic technique is that the sampling scope requires a 70 ns pretrigger. This requires low pulse jitter and a highly stable trigger source. For clean signals this requires that the trigger noise contamination be much less than the pulse width.

The configuration issue requires that the switch which couples the pulse to the output line have a small impedance mismatch to the line. An impedance mismatch results in a degraded pulse shape and lifetime.

For lifetime testing at 1 kHz for 1000 hours the switch is required to achieve  $3.6 \times 10^9$  charging and firing cycles. This places a stress on the peripherals which must last an equal duration. The peripherals include the voltage supplies, transmission line components, trigger pulsers, counters, etc. The 1000 hours at 1 kHz require continuous testing for approximately one and a half months. This process can be accelerated by operating the switch at a higher PRF.

#### 1 kV Pulse Output

The 1 kV pulse output was met easily by the switches we developed under our internally funded program. During the period of the SBIR Phase II, we improved the switch hold-off voltage to 15 kV DC.

#### 100 ps Pulse Width

The switch test configuration is shown in Fig. 1. The risetime performance of the cables and attenuators was measured by passing a nominally 30 ps risetime pulse from the Tektronix S-52 pulse generator through each component individually. The overall response was obtained by combining the individual component risetimes in gaudrature:

$$RT = \sqrt{\sum RT_i^2}$$

The output risetime of the switch was determined by a similar procedure:

$$RT_{sw} = \sqrt{RT_{meas}^2 - RT^2}$$

Due to the large attenuation value which was required, the measurement error in the attenuation allowed us to only establish an upper-limit on the pulse risetime. A representative pulse is shown in Fig. 2. The derived input pulse risetime is less than 50 ps.

The fall time of the pulse is distorted by the response of the attenuators as well as the parasitic capacitance of the charging resistor. This could be optimized by correctly matching the charging resistor coupling to the input pulse charge line; however, for the purposes of meeting a 100 ps pulse width this was not necessary.

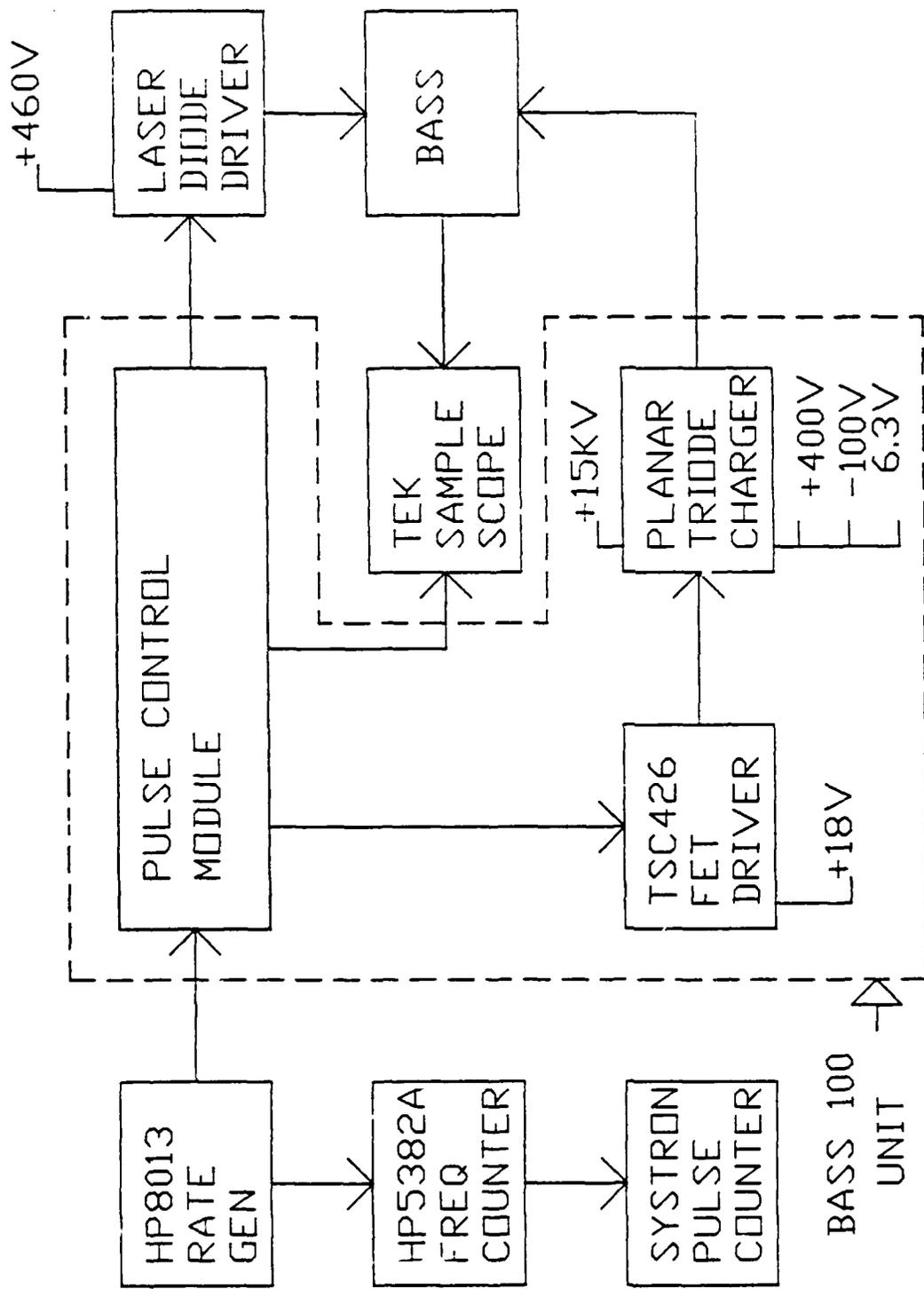
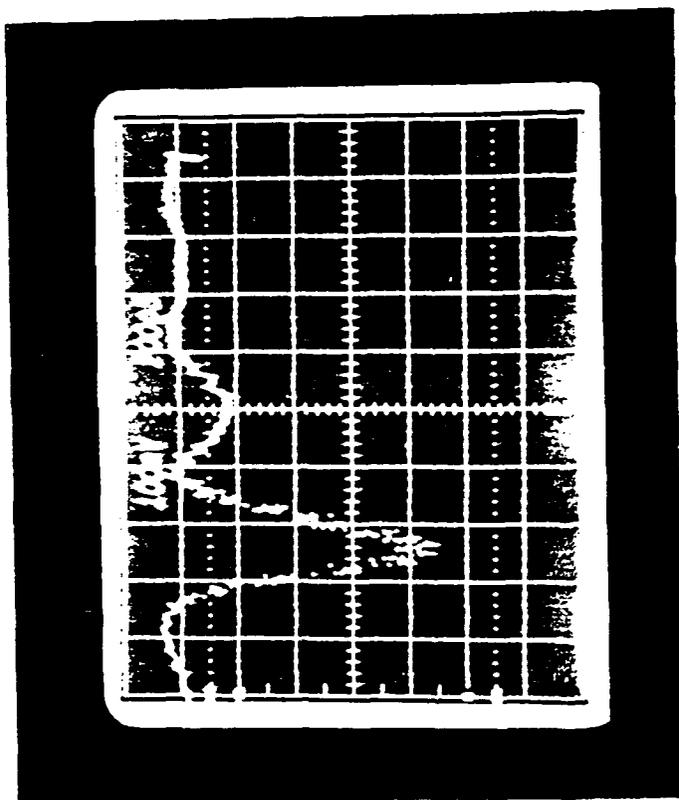


Figure 1. Test Setup for BASS Lifetime and Performance



1000 v/div  
200 ps/div

Figure 2. A Typical BASS Pulse

The FWHM of the pulse shown in Fig. 2 is 200 ps and its amplitude is 4 kV. For diagnostic purposes there was no point in attempting to reduce the pulse width further since it would have led to a reduction in pulse amplitude. This clearly demonstrates that the switch can easily achieve a 100 ps pulse width at 1 kV; however, we are diagnostics-limited in being able to demonstrate it.

The configuration problem and diagnostics problem were mitigated by using the switch in a 50 ohm circuit. The limiting risetime of the switch can be verified by reducing the line impedance. This makes the switch impedance a more sensitive determinant of the pulse shape. For these tests the impedance mismatch at the switch was reduced by utilizing a stepped transmission line. This is illustrated in Fig. 3.

Under these conditions no degradation in the risetime was seen as the impedance was reduced to 16.5 ohms. This serves to confirm that the switch risetime is not the limiting factor in the pulse width.

#### Jitter

The avalanche process has an exponential growth and is expected to have relatively low inherent jitter. The laser diode which triggers the BASS has a higher potential for jitter, however the major source of jitter is the input trigger electronics.

The pulse output in Fig. 2 shows very little jitter in the pulse. This is evidenced by the narrow sampled trace on the scope. When it is recognized that each dot on the scope trace is the result of an individual pulse the remarkably low jitter of the system becomes evident. In fact, the trigger electronics account for most of this jitter.

The laser diode jitter was controlled by utilizing a high power avalanche driver with less than 100 ps risetime.

#### Reliability

Various BASS materials, contact configurations, and operating conditions were tested for lifetime under the SBIR Phase II program. Some interesting correlations were found with certain device types and operating conditions, ultimately resulting in much improved pulse lifetimes. During the course of this program the

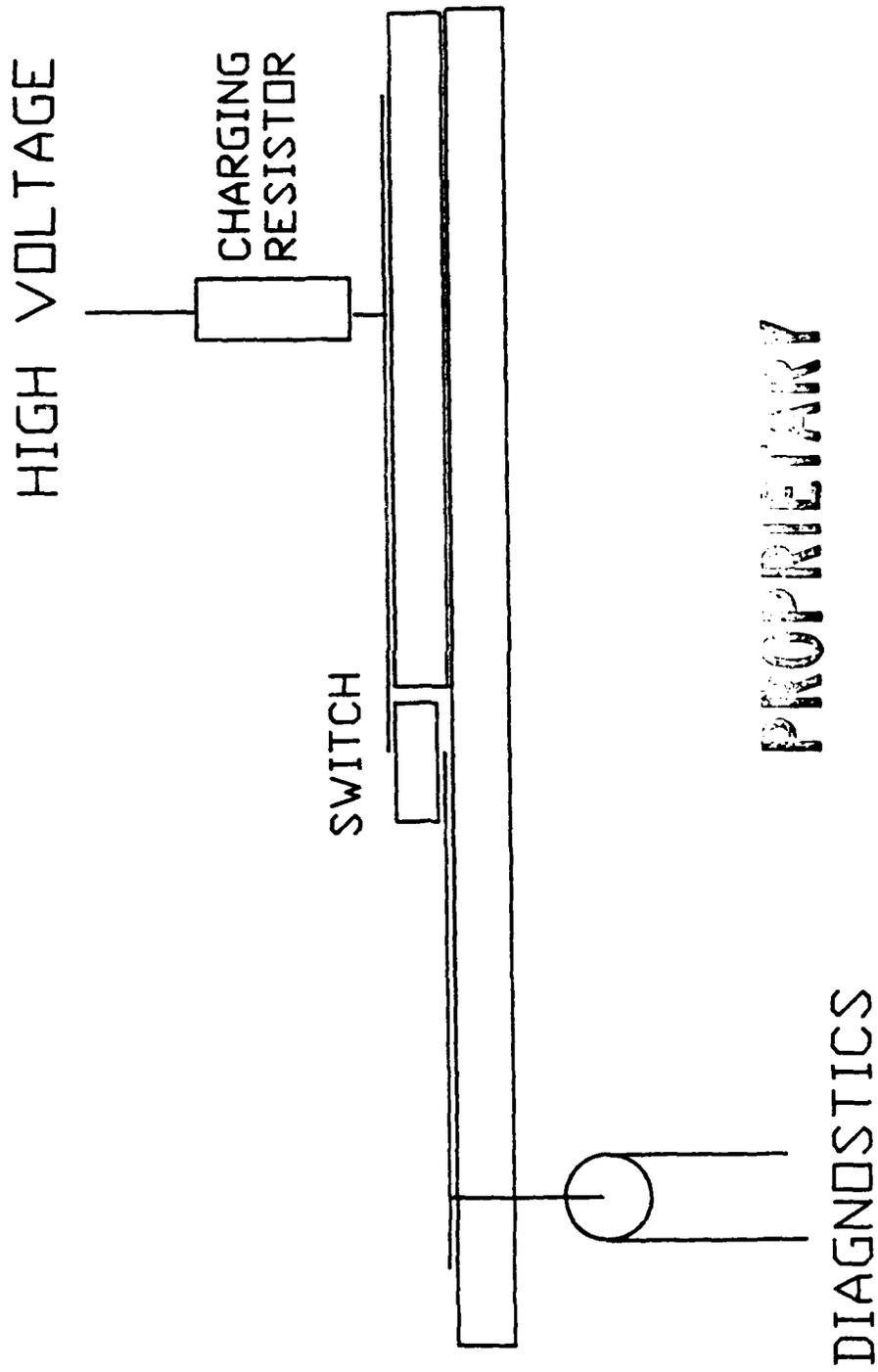


FIG 3. WELL MATCHED CONFIGURATION FOR RISE TIME DIAGNOSTICS

lifetime of BASS devices was observed to increase from roughly 1 million to 500 million shots.

#### Materials Considerations

During this program various devices developed under our internal program and fabricated from a variety of semi-insulating GaAs materials were evaluated:

- o Crystal Specialties undoped horizontal Bridgman
- o Sumitomo indium-doped Czochralski
- o Mitsubishi-Monsanto undoped Czochralski

The Crystal Specialties was of interest because these wafers had a dislocation density of less than  $6,500/\text{cm}^2$ . This low dislocation density was particularly impressive for horizontal Bridgman GaAs, because it was achieved without counter-doping with chromium to achieve semi-insulating material. Normally, counter-doping is necessary to compensate the silicon donors introduced from the quartz boats employed. The innovation of Crystal Specialties was to employ a pyrolytic boron nitride boat to avoid the undesired silicon doping.

Ideally, chromium doping is undesirable because of the probability that all the chromium will not be atomically dispersed. Chromium (and other impurities) can clump together and form aggregates in the bulk. These aggregates are believed to be very detrimental for long-lived BASS devices because they result in field concentrations in the bulk of the device and non-uniform current distributions.

The Sumitomo indium doped material was of interest because the dislocation density could be reduced to less than  $1000/\text{cm}^2$ . Furthermore, the indium doping hardens the lattice making low defect polishing of the surface more easily achieved. A significant potential problem with indium doped GaAs for BASS devices is that the indium itself can aggregate within the lattice and form high field points.

Low dislocations are believed desirable for long-lived BASS operations because dislocations, being line defects, are ideal paths for electromigration and thermal migration of metallic impurities in the BASS device. Obviously, the BASS should be constructed such that metallic impurity migration is minimized.

Our studies of the above materials gave the following results:

<u>Wafer</u>	<u>Type</u>	<u>Efficiency</u>	<u>Shot Lifetime</u>
MT4-15	Crystal Specialties undoped	28-40%	80-520K
MT4-5	Sumitomo indium doped	20-30%	0-250K

The efficiency is defined as twice the voltage appearing across the load divided by the voltage applied before triggering across the BASS device.

We believe that the poorer results on the Sumitomo material observed are attributable to either indium aggregates in the bulk or strained epitaxial contacts. The indium changes the lattice constant significantly, such that there is a lattice mismatch with epitaxial GaAs. Good quality MOCVD epitaxial layers of more than a micron in thickness are very difficult to grow.

The next two runs (MP1 and MP2) were made with Mitsubishi-Monsanto Czochralski material and gave the best overall device lifetime results. A summary of the results from the better of the two runs is shown in Figure 4. As can be seen the lifetimes go as high as 500 million shots. There are various material, device, and operational reasons which, combined, resulted in these outstanding improvements in shot lifetime results. The GaAs material reasons, we believe, are two: very low metallic impurity aggregates in the bulk and superior surface finish. More will be said about the other reasons later.

XMR, Inc. analysed the GaAs materials quality. They have done extensive tests using a proprietary impurity cluster etch and other etches which delineate surface defect structures. On the basis of these tests we believe that the Mitsubishi-Monsanto materials we tested were better in quality. [A good review of XMR work is available in "Subsurface Damage, Near Surface Impurity Drive-in and Bulk Impurity Clusters in Foreign and Domestic LEC Gallium Arsenide Wafers", XMR Technical Report TR-87-1A, January (1988). This research was supported by DARPA under ONR contract No. N0014-86-C-0674.]

Wafer Number	Device	Thick (mm)	MFG	Vout	Life Time (Shots)
MP2-9	082688-6	1	MMK	1500	500,000,000
MP2-9	090288-10	1	MMK	2400	180,000,000
MP2-9	081688-9	1	MMK	2800	110,000,000
MP2-9	081688-10	1	MMK	1920	39,000,000
MP2-5	LT103188-11	1	MMK	1600	8,000,000
MP2-5	LT92788-7	1	MMK		4,500,000
MP2-5	LT92788-4	1	MMK	2850	3,000,000
MP2-5	LT92788-1	1	MMK	2700	1,000,000
MP2-9	090188-5	1	MMK	2500	920,000
MP2-9	090188-5	1	MMK	2500	900,000
MP2-5	LT92788-9	1	MMK	3840	310,000
MP2-9	081688-3	1	MMK	2400	300,000
MP2-9	090188-5	1	MMK	1100	210,000
MP2-9	081688-6	1	MMK	2500	200,000
MP2-9	090188-5	1	MMK	2200	190,000
MP2-5	LT103188-10	1	MMK	2000	180,000
MP2-9	081688-12	1	MMK	1980	170,000
MP2-9	081688-4	1	MMK	1920	150,000
MP2-9	081688-5	1	MMK	1725	90,000
MP2-5	LT92788-2	1	MMK	2450	72,000
MP2-5	LT92788-8	1	MMK	2400	36,000
MP2-9	082688-6	1	MMK	2880	8,000
MP2-9	081688-1	1	MMK	3070	5,000
MP2-9	090188-5	1	MMK	1500	0

Figure 4. Lifetime Results of BASS Devices Constructed with low Mitsubishi Monsanto Wafers

It should be pointed out that surface defects seem to be very detrimental to the lifetime of BASS devices for reasons similar to those for impurity aggregates. Surface defects can cause high field points to occur in the bulk near the surface which result in non-uniform current densities in the BASS device after turn on.

#### Device Considerations

There are several options for the types of contacts to a BASS device. Very early BASS devices were constructed with both top and bottom contacts constructed exclusively by ion implantation. The lifetime of these devices was extremely limited, and we soon switched to a structure in which the top contact was epitaxial and the bottom contact was ion implanted. The idea was that the bottom contact did not need to be epitaxial because it was coated with a thick metallic contact region. The top contact by contrast must be open in the center so that the device can be light triggered. A thick top epitaxial contact is needed to keep the contact spreading resistance low.

The other major option is to manufacture the device in such a way that both top and bottom contacts are epitaxial. This type of structure in fact gave the best results. The best implanted devices gave 8 million shot lifetimes for room temperature operation versus 110 million shot lifetimes at room temperature for all epitaxial contact BASS devices made with similar material. It is believed that the improvement in lifetime for the all epitaxy contact structure results from various factors:

- o Isolation of the metallic contact from the active areas
- o Removal of the defect regime implicit in a partially annealed ion implanted contact
- o Buffering of the mechanical stress induced in the device from the die attachment operation

#### Operational Considerations

An operational consideration is the temperature of the device heat sink. Our heat sink was alumina, since only pulsed heat dissipation was important. We found that the best device lifetime with a heat sink at 25 °C was 180 million shots, whereas at +5°C the best lifetime was

500 million shots. This behavior can be understood from simple activation energy arguments. Many failure mechanisms in GaAs have active energies on the order of 1.6 eV in contrast to many failure mechanisms in silicon which are usually lower in activation energy. With a failure mechanism whose active energy is 1.6 eV, the shot lifetime can be expected to increase approximately an order of magnitude for every 12°C decline in temperature. Our results are consistent with temperature behavior of many GaAs failure mechanisms.

#### PRF

The 1000 hour lifetime requirement would have required half a working year to test at 1 kHz. We raised the repetition frequency to 5 kHz in order to reduce the testing time. The 5 kHz maximum PRF was limited by our laser diode driver.

#### IV. SUMMARY

Power Spectra has successfully demonstrated the meeting of all but one of the goals for this pulser demonstration. We have exceeded the output voltage requirement by a factor of six. We have demonstrated the feasibility of achieving the 100 ps pulse width. We have exceeded the PRF by a factor of five. The only area where we failed to meet our goals is in the lifetime demonstration. Here we fall approximately a factor of seven short of the 1000 hour life. Nevertheless, we have demonstrated that the BASS is a usable technology for applications which cannot be satisfied by any other switch.

#### V. FURTHER WORK

Our internal switch development continues to address the lifetime issue. As a consequence of the successes we have had on this applications, new areas of interest have opened up in the Government and private sectors. Thus this SBIR program has been extremely successful in meeting its goal of exposing a new technology with enormous potential to the Government and the private sectors.