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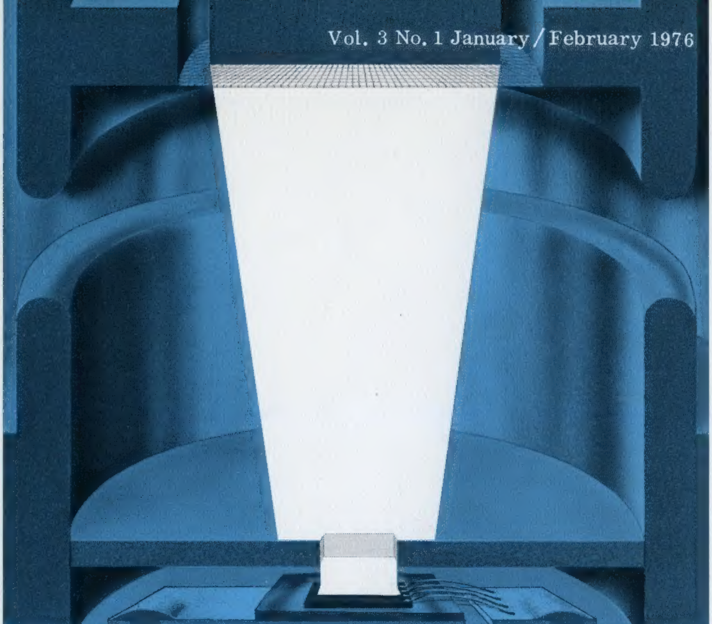


ELECTRON BOMBARDED SEMICONDUCTORS

For Fast Rise Time Modulators

Demand for modulators exhibiting faster rise time, shorter time delay and variable pulse width in electronic warfare and commercial applications has made previously used modulator types less effective. The electron bombarded semiconductor (EBS), which is essentially a semiconductor diode within the same envelope as a modulated electron beam, is now out-performing vacuum tubes and semiconductor devices as rf amplifiers or modulators.

EBS devices can employ one of three types of electron beam control: density, deflection or velocity modulation. The EBS described in this article is of the density modulated type and is designed for high-speed switching applications. They have achieved current- and voltage-switching rates of 4×10^{10} amperes/second and 2×10^{11} volts/second, respectively. This high-output current and voltage capability is producing a signal with nanosecond rise time and time delay. The high-speed, high-voltage characteristics of EBS modulators can be used in many diverse applications such as deception repeater-jamming systems, ultrasonic transducers, density modulated CRT displays and short-pulse radars.

WATKINS-JOHNSON COMPANY
Tech-notes

ELECTRONIC WARFARE

- SHORT-PULSE RADAR MODULATORS
- DECEPTION REPEATER JAMMERS
- LASER RANGING

LABORATORY INSTRUMENTATION

- PULSE GENERATORS
- CHARGED PARTICLE BEAM CHOPPERS
- TIME-OF-FLIGHT MASS SPECTROMETERS

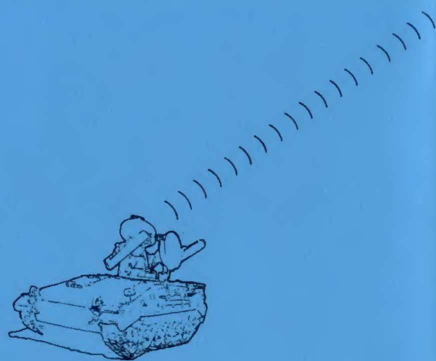
MATERIALS TESTING

- ULTRASONIC TRANSDUCER DRIVERS
- X-RAY TUBE MODULATORS

COMMUNICATIONS

- LASER MODULATORS
- CRT VIDEO DISPLAYS

Table 1. Scientific and technological EBS applications.



EBS Performance in a Modulator Application

The EBS is a hybrid amplifier using an electron beam to control the flow of current in a semiconductor diode. Unique capabilities of the EBS device include the generation of nanosecond rise and fall time output pulses, greater than 100 amperes output current, up to 1,000 volts output, and greater than 10 kilowatts pulsed output power. Some of the many diverse areas of science and technology where these high performance switching characteristics may be applied are listed in Table 1.

Many of the EBS characteristics as a high-speed switching device are illustrated by its application in an ECM deception repeater-jamming system as shown in Figure 1. The objective of this deception jammer is to repeat the radar pulse from a hostile radar while introducing subtle modifications to mask the real radar echo, and thus create erroneous information rendering the hostile radar system ineffective. The jamming pulse must be transmitted at the same frequency as the hostile radar pulse, and at a sufficiently high-power level compared to the radar return echo (jam-to-signal level) to mask the radar return echo pulse. Also, it is vital that the jamming pulse be transmitted with a short time delay after the radar return echo to prevent jamming signal recognition by the hostile radar. Components of a modern repeater jammer are also shown in Figure 1. The jammer consists of receiving and transmitting antennas, signal processing, EBS modulator and a TWT amplifier chain. Output power from the power TWT amplifier is typically 1-20 kilowatts peak.

Threat radar inputs normally arrive

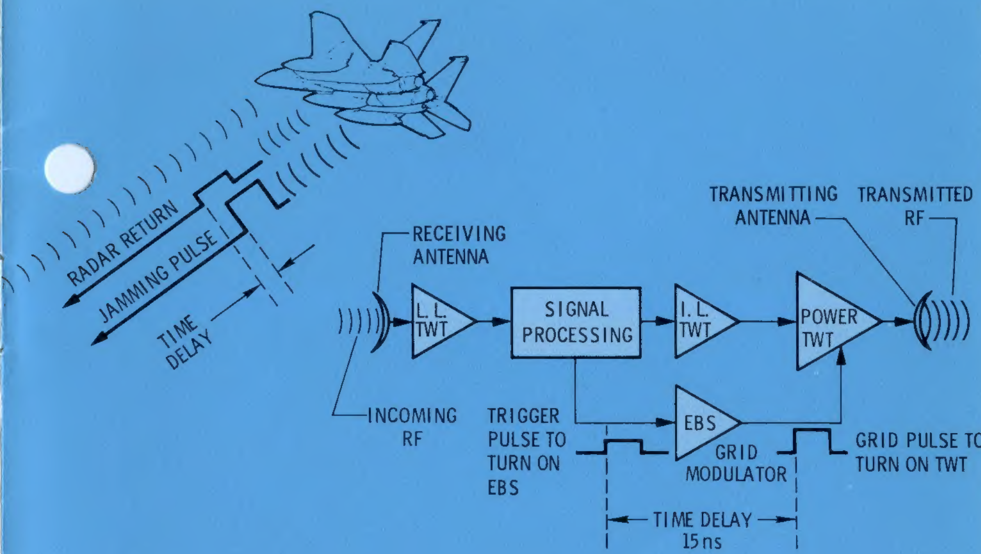


Fig. 1. The Deception Jammer retransmits a sufficiently high-power jamming pulse to mask the real radar return echo from a threat radar system. The Repeater Jammer illustrated uses a low-level, intermediate-level and power TWT amplifier chain, and an EBS modulator to obtain minimum time delay between the real and retransmitted rf signal.

on a random basis. Therefore, in order for the repeater jammer to respond to these random inputs with a short time delay, either the TWT amplifier chain must be in continuous operation, or provision must be made for rapid turn on and turn off of the power TWT amplifier. The use of a pulsed TWT amplifier is preferred if high peak powers are to be transmitted, since the cost, power consumption, and size of CW amplifiers are prohibitive in most ECM systems. In order to make the repeater jammer completely effective, the modulator output voltage must be large enough to completely turn off the TWT and prevent rf "leakage" when no jamming pulse is transmitted. In addition, the modulator must supply a fast rise time grid pulse to turn on the TWT and produce the amplified jamming pulse with minimum time delay.

Increasingly stringent requirements on modulator time delay, rise time, pulse width and duty cycle make the previously used modulator types such as the transisitor, vacuum tube, and electron multiplier tube less effective. EBS modulators provide a superior combination of performance capabilities. Their high output current and voltage characteristics result in a rise time as short as 10 nanoseconds with a total EBS modulator time delay as low as 15-20 nanoseconds. Pulse repetiton rates in the megahertz range are being achieved, and EBS modulators have operated at duty cycles up to 50 percent. The EBS is extremely versatile in performance, fully compatible with military environments, and a total modulator can occupy less than 1/25 cubic foot.

EBS Operation

The same EBS characteristics which improve ECM modulators are also

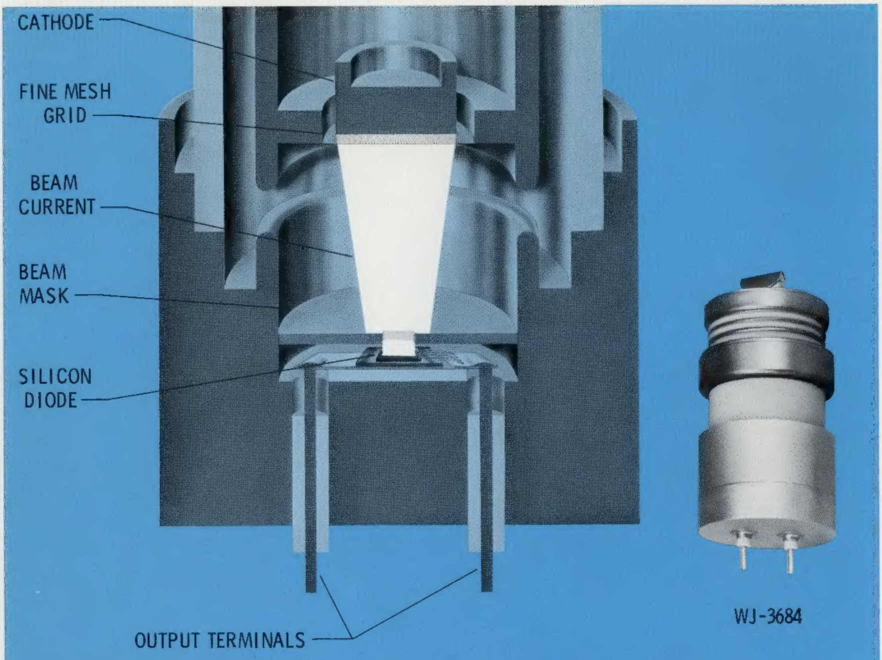


Fig. 2. Components of the density modulated EBS consist of a directly heated cathode, control grid, and a pn junction diode target. The output is obtained by making one contact to the diode surface exposed to the electron beam, and a second connection to the opposite side of the diode. A grid voltage as low as 5 volts will cause high-energy electrons to strike the diode and produce an output voltage up to 400 volts. Actual size of the WJ-3684 EBS is 3¼ inches long by 1¼ inches in diameter.

attractive for many other high-speed, high-power switching applications. Each EBS modulator application imposes different requirements on load impedance, voltage output, power level, and output rise time. Matching the EBS to different applications requires knowledge of the EBS principle of operation and its circuit characteristics.

The EBS used in modulators are of the density modulated type shown in Figure 2. Control of the electron beam is provided by a high-transconductance intercepting grid electron gun which varies the *total* current bombarding the diode. When the grid is biased in beam cut-off, only a small diode leakage current (less than 1mA) flows in the external circuit. When the beam is turned on, the diode is bombarded with high-energy electrons. These 10-15 kilovolt electrons penetrate the top contact of the back-biased pn junction diode, and produce a greatly amplified current in the diode by impact ionization. A grid voltage swing of 10-20 volts, and in some cases, as low as 5 volts can control an output current of 5-100 amperes. In essence, the device is a power triode with an active high-gain anode, where density modulation of the electron beam is provided by voltage inputs applied to the grid.

Diode Structure and Current Amplification

Figure 3 illustrates the diode structure used in the WJ-3684 EBS. A shallow pn junction (approximately .3

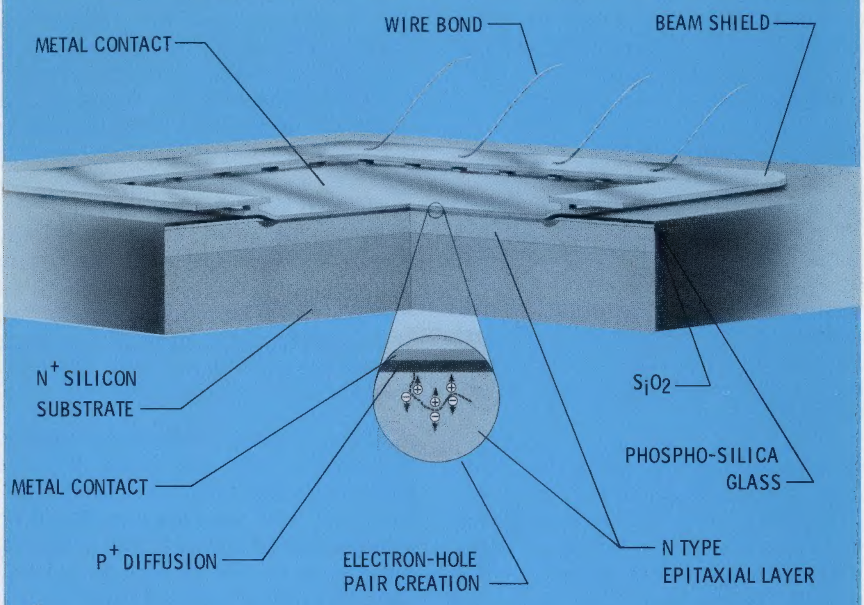


Fig 3. A magnified view of the pn junction diode showing carrier-pair creation. Current multiplication in the reverse-biased diode occurs within the shallow pn junction. Incident high-energy electrons produce one electron-hole carrier pair in silicon for each 3.6 volts of beam energy. Carrier-pairs produced within the first few microns of the pn junction are quickly separated by a high electric field. Positive (hole) charges are immediately returned to the top metal contact, whereas, negative (electron) charges drift under the influence of the high electric field to the contact on the opposite surface.

μm) is covered by a thin metalization layer which can be penetrated by the incident electrons. Surrounding this thin metalization is a pillar-supported beam shield which protects the edge of the pn junction and oxide passivation layers from electron beam bombardment.

Current amplification in the diode is given by the equation:

$$a = \frac{V_K - V_1}{3.6V}$$

where V_K is the cathode supply voltage and V_1 is the voltage loss in penetrating the junction of the diode (typically 3-5 kV). Typical current amplification values range from 1,500 to 3,000 and permit milliamperes of electron beam current to control amperes of current in the output circuit. This large output current results in nanosecond rise times when the EBS is used to modulate capacitive loads such as the grid of power TWT amplifiers. The transconductance of the electron gun is multiplied by the diode current amplification, resulting in an overall transconductance as high as 3 mhos.

The capabilities of the semiconductor diode can be tailored to meet a wide range of requirements. Diodes designed for high-current operation have delivered over 200 amperes of peak current. Other diode designs have produced output pulses of over 1,000 volts. Practical upper limits on current-and voltage-switching rates appear to be approximately 5×10^{11}

amperes/second or volts/second, respectively. A current switching rate of 4×10^{10} amperes/second, and voltage switching rate in excess of 2×10^{11} volts/second have been achieved.

Static Characteristics

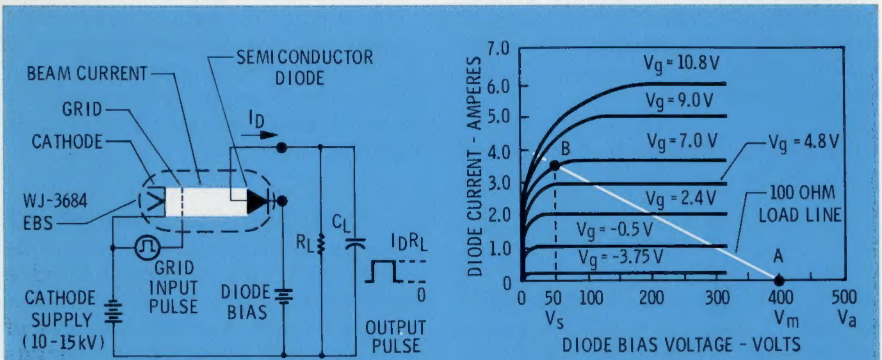
Figure 4a illustrates a schematic of the EBS and bias circuitry required to produce a positive output pulse in an external load. The grid voltage controls the amount of beam current striking the reverse-biased diode, and the external load (R_L) provides the path for greatly amplified diode current, I_D.

Static operating characteristics of this EBS circuit are shown in Figure 4b. The curves of diode current versus diode bias appear for different values of grid voltage. These characteristics may be divided into three regions of device operation: saturation, active, and avalanche breakdown. The maximum EBS operating voltage is limited by the avalanche breakdown voltage of the diode, V_a, and application of a voltage greater than V_a will result in damage to the diode. As a result, the EBS is not operated in this region, and the device output is limited to typically 80 percent of the avalanche voltage.

For diode bias voltages between V_s and V_m, the EBS is in the active region and acts as a high-impedance current source. In the active region, the EBS is a video amplifier with output proportional to the input. As an example, if the WJ-3684 shown in Figure 2 is connected to an external 100 ohm load impedance, a peak output pulse of 350 volts will be produced by changing the grid voltage from −6 to +7 volts. This change in grid voltage corresponds to a shift on the load line from point A to point B of the characteristic curves. The peak output power during this 350 volt pulse is over 1.2 kilowatts.

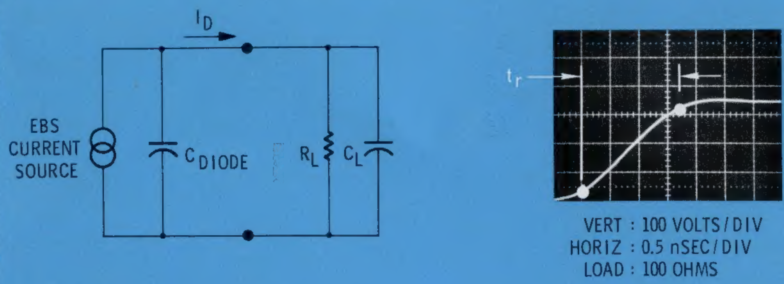
While operating in the active region, carriers within the diode drift at saturated velocity rather than by diffusion at low velocities as in other semiconductor devices. As a result, there is no carrier storage time other than the subnanosecond carrier transit time across the diode. Therefore, an EBS can be turned on or turned off extremely fast. In fact, in the active region, the EBS is a broadband video amplifier capable of generating kilowatt pulses with nanosecond rise times.

A saturation region exists for diode bias voltages less than V_s, in which substantial carrier storage time may arise. Operation in the saturation region reduces the internal power



a) Schematic circuit **b) Static characteristics**

Fig. 4. A simplified schematic of the density modulated EBS and its static characteristics.



a) Dynamic response equivalent circuit with load impedance R_L and C_L.

b) The WJ-3684 EBS rise time with R_L = 100 ohms.

Fig. 5. Dynamic equivalent circuit and rise time characteristics.

dissipation, and the EBS output voltage is less sensitive to variations in grid drive and beam supply voltages. However, the fall time will be greater than the rise time due to internal charge storage. If a slower fall time can be tolerated, it is generally preferred to drive the EBS into the saturation region to minimize power dissipation.

Dynamic Characteristics

For nanosecond pulses, the operation of the EBS cannot be predicted solely from static characteristics. The EBS dynamic response may be obtained by referring to the equivalent circuit shown in Figure 5a. In the active region, the EBS responds as a current source and the output pulse rise and fall time are given by the equation:

$$t_r = 2.2\, R_L(C_{Diode} + C_L)$$

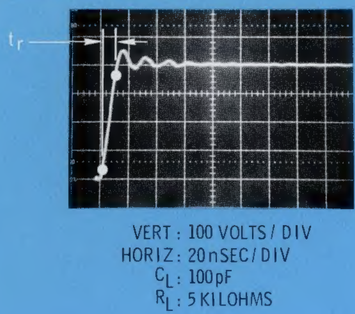
where the rise time, t_r, is the time it takes the voltage to rise from 10 percent to 90 percent of its final value. In the circuit of Figure 4a, the WJ-3684 has a rise time of less than 3 nanoseconds when R_L = 100 ohms, and is shown in Figure 5b. When an external capacitive load of 50 pF is added to the circuit shown in Figure 5a, the rise time increases to 12 nanoseconds.

The fast rise time characteristics of the active region can be useful in numerous applications. Fast rise time pulses with variable amplitude can be used in laboratory instrumentation, to drive electro-optic modulators, to drive ultrasonic transducers, or to density modulate CRT displays at high speeds.

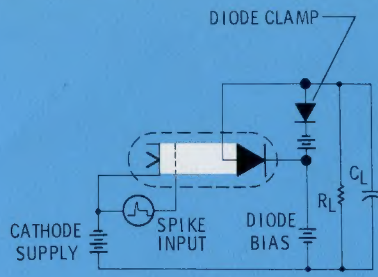
Resistive Pull-Down

High-peak power and fast rise times are highly desirable in many applications. However, in other applications such as the TWT grid modulator, it is more desirable to obtain the fastest possible rise time into a capacitive load while minimizing the power consumed. Fast rise time pulses are obtained by operating the EBS in a saturated switching mode, rather than in the active region.

To operate in the saturation mode, a higher resistance, typically 5 kilohms, replaces the 100 ohm load. An input pulse applied to the EBS now produces maximum diode output current flow into the load capacitance until the voltage across it approaches the diode bias voltage. The EBS diode is driven hard into the saturation or charge storage region. Under this condition, the rise time is given approximately by the equation:



a) Fast rise time Pull-Up



b) Diode Clamp circuit

Fig. 6. The fast rise time output with the EBS in a saturated switching mode. Adding a Diode Clamp reduces the turn off time.

$$t_r = .8(C_{Diode} + C_L)\frac{V_p}{I_p}$$

where V_p is the peak output voltage, and I_p is the peak output current of the EBS.

In practice, the resulting rise time is approximately 2½ times faster than the rise time for the same EBS operating within the active region with a fixed capacitive load. This reduction is caused by diverting less current into the higher shunt load resistance. Power dissipation during the pulse is given by the equation:

$$P = \frac{V_p^2}{R_L}.$$

Power dissipation is inversely proportional to the load resistance; therefore, increasing the load resistance by a factor of 50 (100 ohms to 5 kilohms) results in reduced power dissipation by a factor of 50.

The price paid for this reduction in rise time and power dissipation is slower turn off time. The same high resistance contributing to the faster rise time during turn on produces a slower fall time. The output pulse fall time is controlled by the RC time constant of the external load, just as the rise and fall time within the active region. Neglecting the effect of charge storage in the diode, the effect of load resistance on fall time is given by the equation:

$$t_f = 2.2\ R_L(C_{Diode} + C_L)$$

where the fall time, t_f, is now the time it takes the voltage to fall from 90 percent to 10 percent of its final value. Increasing the load or pull-down resistance from 100 ohms to 5 kilohms actually increases the fall time by a factor of 50. Figure 6a illustrates the fast rise time obtained when an input pull-up is applied to the EBS operating in the saturation region. A rise time of 6 nanoseconds is produced for a load impedance of 100 pF shunted by 5 kilohms.

Since the diode is driven into saturation, carrier storage time must also be considered. In severe cases, charge storage may add microseconds to the fall time. One method of reducing charge storage is the addition of a diode clamp to the EBS bias circuit, Figure 6b. The diode clamp prevents the EBS diode from entering the saturation region, and prevents the build up of stored charge. Once the input rise time (pull-up) is complete, it is advantageous to reduce the input voltage to a holding level. The required pulse shape can be accomplished by passing the input pulse through a passive RC differentiating network to add a spike to the leading

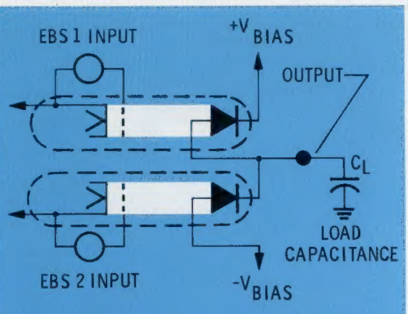


Fig. 7. Two EBS used in a Pull-Up/Pull-Down Modulator produce both minimum rise and fall time.

edge. When the input voltage is dropped to a holding level, the current circulating through the clamp circuit decreases, resulting in less dissipated power.

The use of a diode clamp and choice of a "pull-down" resistance of intermediate value allows a trade-off between fall time and power dissipation. This trade-off is satisfactory in applications, such as, some TWT grid modulators where fast rise time and low power dissipation are of primary importance, and fall time is secondary.

Active Pull-up/Pull-down

In many applications, fast rise and fall time, as well as power dissipation, are critical. Short-pulse radar systems, for example, may require very fast rise and fall time modulation. Fast rise and fall time, and low power consumption are also critical in ECM systems operating at a high pulse repetition frequency (PRF) and high duty cycles. These requirements may be satisfied by combining two EBS in an active pull-up/pull-down configuration as shown in Figure 7. The grid input to EBS 1 is driven with a spike, followed by a holding level to achieve a very fast-rise time and reduced power dissipation. Fast turn off is achieved by removing the signal to EBS 1 and applying a second spike signal input to EBS 2.

Although the pull-up/pull-down modulator configuration requires two EBS, it provides both minimum rise and fall time. Output pulse widths can be reduced to values only slightly greater than the rise time, and the duty cycle can approach 100% due to the low power dissipation. Maximum pulse repetition frequency is limited by the power dissipation whenever the load capacitance is charged or discharged. Power dissipation in the EBS due to charging or discharging the load capacitance depends on the pulse repetition frequency, and is given by the equation:

$$P = \tfrac{1}{2}(2C_{Diode} + C_L)\, V^2 \times PRF.$$

In practical modulator applications, the power dissipated due to load capacitance charging typically accounts for 80% of the EBS diode dissipation.

The pull-up/pull-down modulator is well suited to control power TWT's used in deception jammer systems. Table 2 shows the performance characteristics of a modulator when two WJ-3684 EBS are operated in the pull-up/pull-down configuration. Total modulator time delay is due to the delay of the input circuitry, (t_i), internal EBS delay and the rise time of TWT grid capacitance, and is given approximately by the expression:

$$t_{delay} = t_i + t_{EBS} + .9(2C_{Diode} + C_{TWT})\,\frac{V_p}{I_p}.$$

In this application, the total time delay of the modulator is estimated at

TWT LOAD CAPACITANCE - pF	50
OUTPUT VOLTAGE - VOLTS	350
PULSE RISE TIME - NANOSECONDS	6-8
TIME DELAY - NANOSECONDS	15
PULSE BURST MINIMUM INTER PULSE SPACING - NANOSECONDS	50
MAXIMUM PULSE REPETITION RATE - MHz	2.5

Table 2. Pull-up/Pull-down Modulator performance.

less than 15 nanoseconds while the input circuitry contributes 6 nanoseconds and the internal EBS time delay is less than 2 nanoseconds. The total time delay achieved in practical modulators is between 12 and 20 nanoseconds. The high PRF capability results from the rated EBS power dissipation of 12 watts.

EBS Reliability

EBS modulators have accumulated a calculated mean-time-to-failure (MTTF) of over 20,000 hours at 60 percent confidence level based on life tests conducted over the past three years. However, the operating environment in specific applications may impose unusual requirements which must be considered if this high reliability is to be achieved. For example, in the TWT grid modulator application the EBS must survive when exposed to high-voltage arcs initiated by the TWT. In a well designed TWT amplifier, the energy available in the TWT power supply is minimized, and provision made for rapid turn off of the power supply. Even so, the modulator must be immune to substantial voltage transients.

A transient suppression technique using a small resistor (5 ohms) in series with the EBS diode, and shunted by a power diode, is shown in Figure 8. During normal operation the power diode remains reverse biased and has little effect on modulator performance. During an arc, however, the

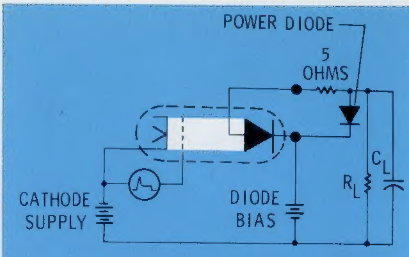


Fig. 8. An Arc-Suppression circuit provides reliable operation even for large voltage transients such as TWT arcs.

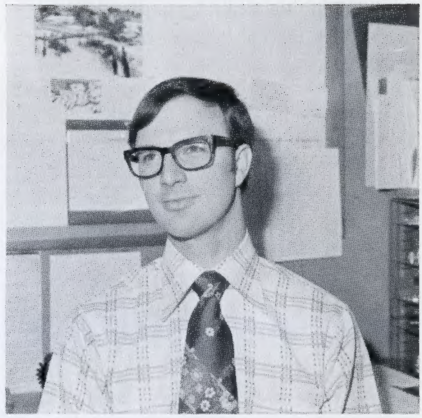
diode becomes forward biased and diverts much of the transient energy from the EBS diode. When power diodes are placed across both EBS in the pull-up/pull-down modulator, protection is provided for transients of either polarity. This technique, combined with spark gaps normally placed at the TWT grid, is effective in preventing modulator damage due to TWT arcing.

Capabilities

In the modulator applications and circuits illustrated, the WJ-3684 was chosen to represent the performance of a typical EBS. Performance characteristics of other EBS are shown in Table 3. The output current capability for these devices ranges from 4 to 100 amperes, and output voltage capability ranges from 100 to 1000 volts. As development continues, additional devices having greater current, voltage, and peak power capability will become available.

CHARACTERISTIC	WJ-3680	WJ-3681	WJ-3684	WJ-3652
PEAK OUTPUT VOLTAGE - VOLTS	1000	750	400	100
PEAK OUTPUT CURRENT - AMPERES	3.5	7.0	3.5	100
OUTPUT RISE TIME - NANOSECONDS	30	12	10	6
DELAY (10% INPUT - 10% OUTPUT)-NANOSECONDS	3	3	3	3
DIODE POWER DISSIPATION - WATTS	15 MAX.	15 MAX.	12	—
LOAD RESISTANCE	2.5 kOHMS	2.5 kOHMS	2.5 kOHMS	1 OHM
LOAD CAPACITANCE - pF	50	50	50	—

Table. 3. High-voltage and high-current EBS characteristics.



Authors:

Bruce Bell

Mr. Bell has been a member of W-J's Tube Division technical staff since his graduation from Stanford University in 1973 with a BS in Physics. Mr. Bell is now Project Engineer responsible for the design, development, and testing of the EBS high-voltage and high-current pulse amplifiers. He has designed and developed the WJ-3680-2 and WJ-3680-3 high-voltage pulse amplifiers, and the WJ-3652, a high-current pulse amplifier. He is also Project Engineer of a 2 kilowatt pulsed rf amplifier operating in L-Band, and the development and testing of low-pass rf amplifiers operating up to 20 watts CW. Bruce is a member of the IEEE.

Richard Knight

Mr. Knight has been engaged in the development of the EBS since joining W-J's Tube Division in 1970. At present, he is Head, EBS R&D Section responsible for research, development and reliability of future EBS devices. As Project Engineer, he developed a number of grid-controlled EBS for fast rise time switching of high-current and high-voltage outputs. As Program Manager, he has been responsible for the development of broadband deflected beam EBS amplifiers. Before joining W-J, Dick received his BS in Physics from Indiana University, and his MS in Physics from the University of Illinois, 1970. Dick is a member of the IEEE.

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