HIGH-POWER, SHORT-PULSE FORMING CIRCUITS

R. Tan, M. Berry, and R. Garver

Harry Diamond Laboratories
Adelphi, Maryland

Abstract

Fast-rise, short microwave pulses at 100 kW peak power have been obtained. Arc-activated expanders have been developed in coaxial transmission line at S-band and in waveguide at X-band that provide fast-rise rf pulses (1 to 10 ns) from slow-rise inputs. These expanders are placed on the output of 1-MW magnetrons to provide fast-rise pulses in the 50- to 100-kW range. When the expander is followed by a single shunt Zo/2 transmission line as a pulse-forming network, it provides short pulses with fast risetimes and fast falltimes. These pulse-forming networks also suppress "front porch" leakage caused by the finite isolation of the expanders.

Introduction

Fast-rise-time pulses of high performance radars may be able to pass through TR tubes and diode limiters before these devices turn on, thereby potentially damaging receiver front ends. Further, the pulse leaking past a TR tube may be quite short in length and significantly high in power (10 to 100 kW). Studying the spike leakage and damage level of thicker I-region PIN diodes as limiters is necessary so that we can optimize them to potect receivers. There is also a need to characterize the damage threshold of receiver components for very short leakage pulses. To carry out these tests, we require pulses with a nanosecond rise time and variable (10 to 100 ns) pulse width. Two devices were needed for this study. The first device is an expander, which provides high isolation during low incident power and low insertion loss during high incident power. The resulting rf pulse has a rise time on the order of 1 ns. The expanders reported here were designed to operate with a standard magnetron output (of 20- to 100-ns rise time). The second device required is an rf envelope generator. Given a long rf pulse with a fast rise time as input, the envelope generator will produce an output rf pulse of any desirable width. These devices were built in S- and X-bands. The expanders are broadband, self-acting structures, and are in-line devices.

Other devices capable of providing fast rise times in the kilowatt region were considered but were not practical for various reasons. These devices include diode switches, laser-switched semiconductors, switched waveguide cavities, and transmit-receive (TR) tubes. A diode switch can operate only at low power levels, but it must be followed by expensive traveling-wave tube (TWT) amplifiers to obtain high power levels. The laser-switched semiconductor can operate in the megawatt region, but it requires a large and expensive laser system to be brought into the same location as the large and expensive high power source. The switched waveguide cavity requires a microwave source with high spectral purity. The reflected pulse from a TR tube gives a fast rise time at high power levels but is limited because TR tubes are narrow-band devices, are made only in waveguide, and work only at limited specified power levels.

Given a long, fast-rising pulse, expanders have been made to work in the laboratory; they provide the desired short, fast-rising pulse, but they have not been reduced to practical, well-engineered working devices. They suffer from very short lifetimes because of point wear; moreover, all the design parameters have not yet been fully explored to provide a device that can work with any desired parameters and without constant adjustment.

Coaxial S-Band Expander

The coaxial expander was built in a 10-cm air line. The center conductor was cut in half, and points were ground on each side of the gap, making this a series spark gap (fig. 1). This device is wide band since it is built in a coaxial structure. The capacitance between the tips had to be low so that the isolation will be high at low power. The points on the tips were sharpened to decrease the capacitance. The impedance of the tips was evaluated with the network analyzer to measure the isolation versus frequency; then the capacitance was calculated from those measurements using the diode switching (for a series impedance R+jX) equation (1):

$$\alpha = 10 \log[(\frac{R}{2Z_0} + 1)^2 + (\frac{X}{2Z_0})^2] , \qquad (1)$$

where α is the attenuation in decibels. Since the structure is purely reactive (capacitive), α becomes

$$\alpha = 10 \log[1 + (\frac{X}{2Z_0})^2] . \qquad (2)$$

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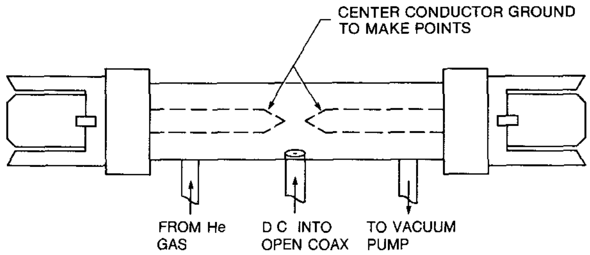

Fig. 1. Coaxial expander built with the use of a General Radio 10-cm air line.

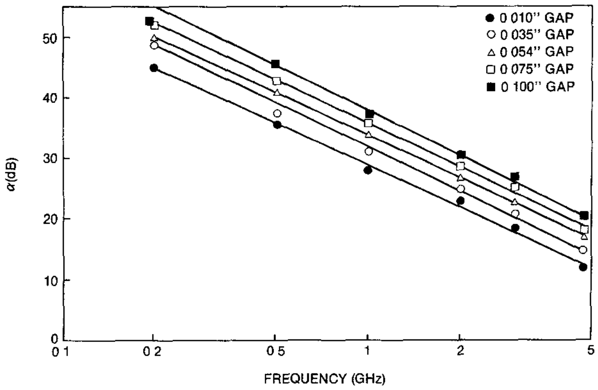

Fig. 2. Isolation versus frequency for tip angle of 42°.

Solving this for C equation (2) gives

$$C = \frac{1}{2\pi f X} = \frac{1}{4\pi Z_0 f \left[10^{\alpha/10} - 1\right]^{1/2}}, \qquad (3)$$

From the measured isolation (attenuation) the capacitance can be calculated. The lower the capacitance, the higher the isolation at low power and the lower the arcing threshold. An example of the isolation versus frequency for different gaps (and the same angle) is shown in figure 2. The isolation was measured at 3 GHz, and the capacitance was calculated using (3). From this example and other measurements, figure 3 shows a graph of capacitance versus gap for different angles of the points (sharpness).

The expander was tested in the high-power test setup shown in figure 4. At high power, the expander passed the full signal but it was attenuated, indicating that the spark gap was not firing, even for gaps as small as 0.010 in. The next step was to evacuate the expander and inject helium gas to promote arcing. The expander now worked but was very random. To overcome this problem, free electrons were provided with the use of a piece of semirigid coaxial line (as in fig. 1) biased to give a glow gas discharge. The primer required several hundred volts and drew 8 mA. The resulting pulses are shown in figure 5, but the rise time was between only 3 and 10 ns. The coaxial connectors were arcing in shunt, shorting out the rest of the pulse (as in fig. 5)

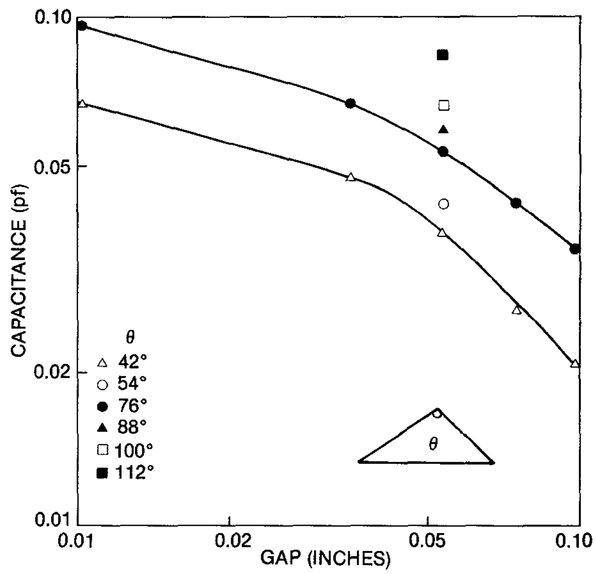

Fig. 3. Capacitance versus gap width for different tip angles.

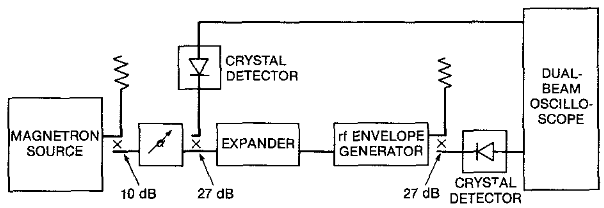

Fig. 4. High-power test setup.

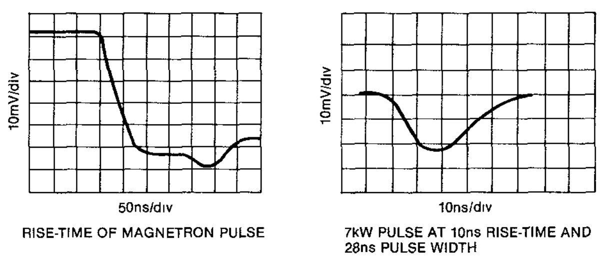

Fig. 5. Input and output of S-band expander.

and limiting us to a very short pulse width. In a newly built version, the connectors are not in the low-pressure environment, but the spark gap is (as in fig 1). This version eliminates the coaxial transitions and also seals off the vacuum to just the arcing section. This stopped the connectors from arcing, and the expander passed the entire pulse with the fast rise time.

Stripline S-Band Expander

The stripline S-band expander is narrow band and is built in stripline with a spark gap terminal protection device (TPD) used as a switch.

The TPD is a type 72/200 coaxial surge arrester manufactured by M-O Valve Company. The TPD arcs in shunt at 150 to 200 Vdc and provides low insertion loss at low power levels, for fre-

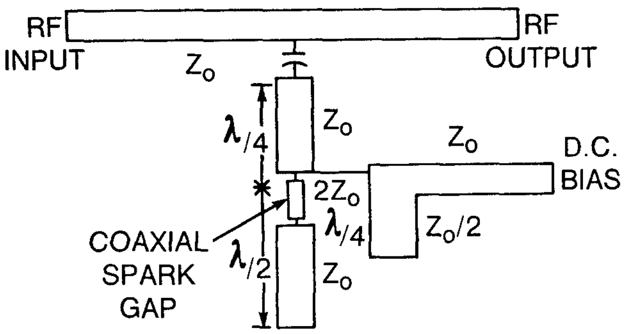

Fig. 6. Circuit diagram of stripline S-band expander.

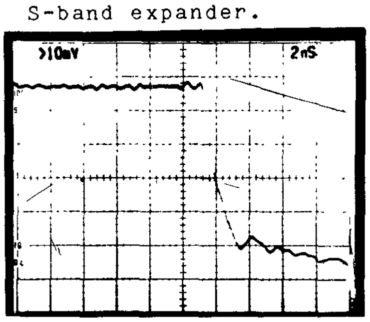

Fig. 7. 10 watt output of stripline expander with a 2ns rise time.

quencies up to 5 GHz.

The stripline circuit, shown in figure 6, was designed to operate at 2.74 GHz. When the coaxial spark gap is conducting (at high power) it is a short circuit which is transformed to an open circuit across the main transmission line, thus providing low loss. At low power it is a through device (low insertion loss) and the open circuit $\lambda/2$ away appears at the TPD. This is transformed by the $\lambda/4$ to a short across the main transmission line, which reflects incident power. The circuit was tuned while observing the responses on a network analyzer. The insertion loss at 2.74 GHz with the TPD shorted to ground was 0.1 dB and the isolation with the TPD open circuited was 18 dB. In order to drive the TPD to a low impedance we turned it on with a 1000-V fast-rise-time video pulse, (<1-ns rise time), generated by a charged line and reed switch. When the TPD is arcing with this voltage pulse, it appears as a 1- to 2- ohm resistor to ground.

The expander was tested with a 10-W cw input. The resulting rf output is the 10-W step with a rise time of 2 ns (as shown in fig. 7). High power tests were made with a 1-µs rf pulse up to 5 kw but the video pulse used had a rise time of >15 ns. The rf pulses under 500 W had rise times of about 10 ns. The rf pulses greater than 500 W turned on the TPD and resulted in no pulse shaping. It is suspected that the slow video pulse results in the slow rf rise times. To prevent the rf from turning on the TPD, a TPD with higher breakdown should be used. With a high-voltage fast-rise-time video pulse generator that can be synchronized with the rf pulse and a higher threshold TPD, it may be possible to obtain the desired fast-rise-time rf pulses at the kilowatt level. For this device to provide fast rise times without the video pulse, the arc should be made to occur at a high impedance point so that the moderate resistance (20-V drop) of the self-generated arc provides a very low insertion loss.

X-Band Expander

The X-band expander was realized in waveguide. A coaxial line is used for transforming the spark gap ($\lambda/4$ transformer) to the waveguide. Insertion loss and isolation were calculated using equations (4) and (5):

$$\eta = 20 \log \frac{B}{2Y_0} = 20 \log\left[\frac{Y_Q}{2Y_0} \tan(90 - 0.45BW)\right] , \qquad (4)$$

$$\delta = 10 \log\left[1 + \left(\frac{B}{2Y_0}\right)^2\right] = 20 \log\left[1 + \left\{\frac{Y_Q}{2Y_0} \cot(90 - 0.45BW)\right\}^2\right] , \qquad (5)$$

where η is the isolation in decibels (dB), δ is insertion loss in dB, Y_0 is characteristic admittance of the waveguide in mhos, Y_Q is the admittance of the $\lambda/4$ transformer in mhos, B is the susceptance in mhos, and BW is the bandwidth in percent. Equation (4) represents the isolation of the expander during the low-power state. Equation (5) represents the insertion loss during the high-power state (during arcing); these equations are plotted in figure 8. The dimensions of the coaxial structure were determined using figure 8 and equation (6):

$$Z_0 = 60 \ln\left(\frac{b}{a}\right) , \qquad (6)$$

where b is the radius of the outer conductor and a is the radius of the inner conductor. For 40-dB isolation, 7-percent BW, and about 0.25-dB insertion loss, $Z_Q/Z_0 = 0.1$ is taken from figure 8. Therefore, with $Z_0 = 400$ ohms for X-band waveguide, the impedance of the coaxial structure must be 40 ohms. The expander was fabricated using standard machine screws with tungsten tips to withstand repeated arcing.

The X-band expander was placed in the high-power setup, where the input and output power were measured with crystal detectors (as in fig. 4). Figure 9 shows the input and output waveforms of the expander. The oscilloscope photo shows the output pulse with a rise time on the order of 1 ns. The expander did not give 1- to 2-ns rise-time pulses on a consistent basis; 5- to 10-ns rise-time pulses were more common. The expander also did not arc consistently. On some pulses no arcing occurred; therefore, there was no output. To solve this problem, we tried several things. First, helium gas was injected into the waveguide in an attempt to increase the speed of the arc (and decrease the rise time). The use of helium did not improve the speed. Second, springs were placed on the screws to provide pressure on the threads. This improved the repeatability of the output, but pulses were still missing. This

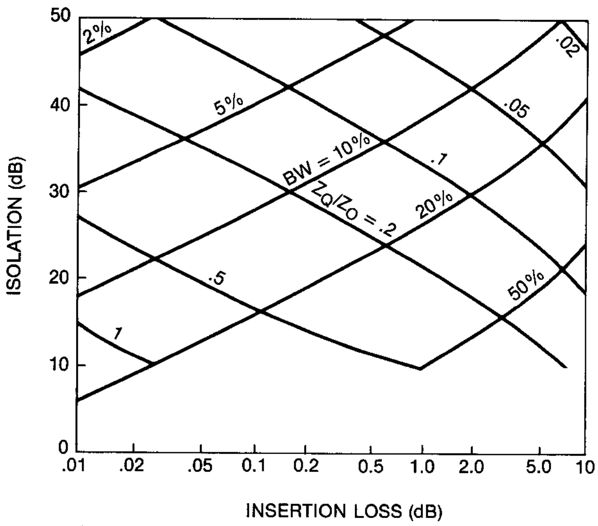

Fig. 8. Insertion loss versus isolation for X-band expander.

phenomenon is not unusual with arcing devices since the initiation of a spark gap is caused by the random presence of electrons.

Pulse Shaping Network

The nanosecond rf envelope generator works on the principle of having a parallel, shorted line with half the characteristic impedance of the input and output. The device was made with an H-plane cross in X-band waveguide. Parallel waveguide lines are terminated in variable shorts. For ease of explanation, we will say arms 2 and 3 have been shorted, and arms 1 and 4 are the input and output arms, respectively. The incident power is divided at the junction: one-fourth being reflected, one-fourth being transmitted (out arm 4), and one-fourth in each of the side arms.

The power traveling down arms 2 and 3 will be reflected at the shorts, where their phase will be inverted. The inverted power from both side arms, each with a magnitude of one-fourth the input power, will reach the intersection, and now one-half of this inverted power from each arm will go down arms 1 and 4. The length of arms 2 and 3 are equal and adjusted in phase so that the power in arm 4 will be cancelled, ending the rf pulse. The output has a pulse width equal to the time that it takes the rf pulse to travel down arms 2 and 3 and back. The rf envelope generator uses voltage cancellation to form the output rf pulse. The advantage in using the rf envelope generator is that it works with conventional rf sources, and unlike cavity methods does not need an input with high spectral purity. Figure 10 shows the output pulse with the expander in cascade with the nanosecond rf generator, giving a 10-ns pulse width.

The envelope generator has another benefit in that it suppresses "front porch" power associated with fast-rising pulses. When the rise time or fall time is slow, the phase of the short circuits on the stubs provides a measure of suppression.

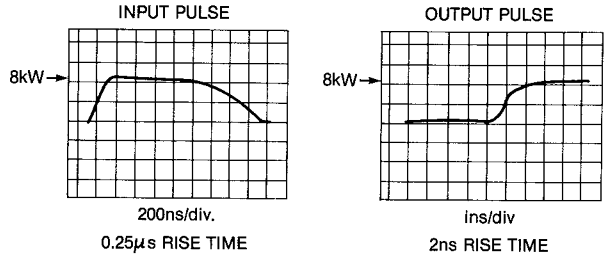

Fig. 9. High-power response of X-band expander.

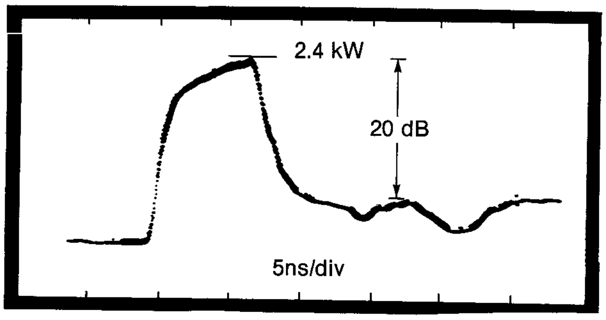

Fig. 10. Output pulse of expander in cascade with nanosecond rf envelope generator.

When the pulse rise time is T and the delay of the arm is t, the suppression is 20 log T/t. Therefore the envelope generator not only gives a pulse of controlled length, but enhances the definition of the pulse above preceding power.

Conclusions and Recommendations

The expanders and pulse-forming network described here work well with standard magnetrons. The expanders are broadband, with exception of the S-band stripline expander (X-band works from 8 to 12 GHz, and the coaxial version works from dc to 5 GHz). The rf envelope generator can be built in waveguide, stripline, or in a coaxial line to make it a wide-band device. All these devices, except the stripline device, are completely adjustable for tuning, which helps them as wide-band devices. However, several problems need to be addressed. Consistency of the arcing is a major problem--radioactive material can be used to stabilize the arc and lower the arcing threshold. On the coaxial S-band expander, the evacuated section must be separated from the connectors to stop them from arcing in shunt. Different TPD's should be tried in the stripline S-band expander so that it will operate at higher power levels. (A nanosecond rf envelope generator for S-band has yet to be made and tested.) On the X-band expander, variable pressures and/or a piece of arcing semirigid coaxial line could be used to give more consistent output. The X-band nanosecond rf envelope generator works very well and needs no modification. The design parameters of both devices need to be well characterized so that well-engineered devices can be made for laboratory experiments.