A DC Triggered High-Speed High-Power Microwave Spark Gap Switch

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***Abstract*—Operation of a microwave spark gap switch triggered with a short high-voltage pulse is described. *C*-band power of 1 MW peak and 4μs pulse width was switched in less than 10 ns at 100 pps with less than 0.3 dB arc loss in air at atmospheric pressure. Use in a cavity resonator to give an efficient pulse compression circuit is described. Switch recovery and turn off data are given.**

Introduction

THE RAPID SWITCHING of high-peak-pulsed microwave powers is a matter of great technical interest. A microwave spark gap, triggered by a pulse of intense ultraviolet light [1], [2], has recently been reported for this purpose. Nanosecond switching times were achieved in this way, but the RF power levels, which could be reliably switched, apparently were restricted to values near (or somewhat in excess of) the self-breakdown power of the spark gap. (The self-breakdown power is defined as the minimum peak-pulsed power at which an occasional breakdown of the gap will occur without an external triggering source.) This, in turn, tends to limit the pulse width to narrow pulses.

In contrast with the above, the switch to be described here is triggered by a short high-voltage dc pulse which makes rapid switching possible over a wide range of RF power levels and pulse widths. The pulsed dc field is made appreciably larger than the dc self-breakdown field to obtain fast switching. Thus, the RF peak power levels that can be switched rapidly range from values above this breakdown strength (for narrow pulses) to values in the mW region depending on the mode of operation. (In the low power range, other switching techniques would probably be more suitable.)

Switch Description and Associated Circuits

The microwave configuration of the switch, which was designed for operation in the 5200–5800 Mc/s range, is shown in Fig. 1. The spark gap consists of two opposed hemispherical stainless steel domes attached to the broad walls of a section of waveguide. The trigger electrode is a stainless steel rod capped by a small stainless steel sphere. It is inserted into the waveguide through a dielectric bushing in one of the side walls and is positioned so that its spherical tip is centered in the gap. With the above geometry, it is possible to obtain an intense, concentrated spark directly across the gap, which essentially has the effect of converting the equivalent lumped capacitance of the central gap region to an inductance. (The diameter of the rod is made slightly smaller than the spherical cap to prevent discharges between the rod and the hemispheres.) This sudden change in circuit reactance accounts for the good microwave switching characteristics of the gap configuration.

The insertion VSWR (voltage standing-wave ratio) of the spark gap section is in excess of four. To transmit microwave power past the switch in the untriggered condition requires that the spark gap section be incorporated into a resonant structure resembling a transmission cavity. The ensuing insertion loss would approach 1 dB. However, by terminating the waveguide section in a shorting plate, a low-loss reflection-type phase shifter can be achieved. This can be used in association with a hybrid junction, to switch power from one arm to the other arm of the hybrid junction (Fig. 2).

To test the switch, the arrangement shown in Fig. 2 was used. The switch assembly, with its shorting plate, terminates one arm of a short-slot hybrid and a second shorting plate terminates the adjacent arm of the hybrid. The second shorting plate is positioned so that, in the absence of a discharge, power incident on port 1 is transmitted with minimum loss to port 2. (The input VSWR is then less than 1.15.) When a discharge is triggered, the incident power is almost entirely reflected back to port 1 because of the resulting quarter-wavelength shift in the effective short position. The remainder of the incident power is partly dissipated in maintaining the discharge and partly lost through port 2. The definitions for arc loss, "cold" insertion loss, and isolation can be understood in terms of this test arrangement.

If it is desired to switch power from one channel to another (instead of reflecting it back to the source), there are two basic arrangements possible. One is to insert a three-port circulator between source and port 1; the other is to use a two-element switch consisting of two similar symmetrically located spark gaps as in Fig. 3. In the circulator configuration, the reflected power, of course, becomes available at the third port of the circulator.

Switching Time

The work of Fletcher [3] and others on impulse breakdown of gases has demonstrated that the formative time lag for breakdown is a function of the overvoltage

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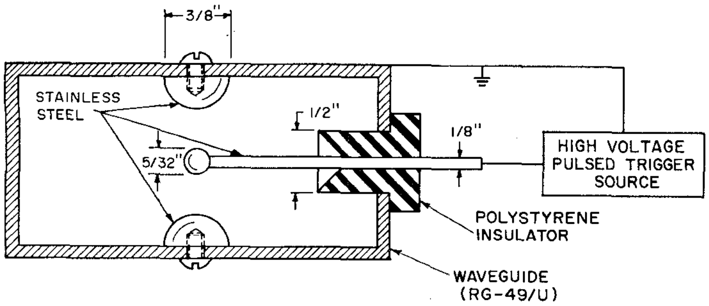
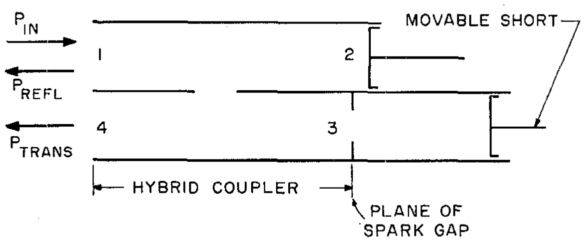


Fig. 1. Schematic of dc triggered microwave spark gap.



TERMINATING SHORTS ARE ARRANGED SO P_{trans} IS MAXIMUM IN ABSENCE OF SPARK. WHEN SPARK IS TRIGGERED P_{trans} DROPS AND P_{refl} RISES. ISOLATION IS DEFINED AS 10 LOG (P_{inc}/P_{trans}) AND ARC LOSS AS 10 LOG (P_{inc}/P_{refl}) FOR SWITCH IN TRIGGERED STATE.

Fig. 2. Test switching arrangement.

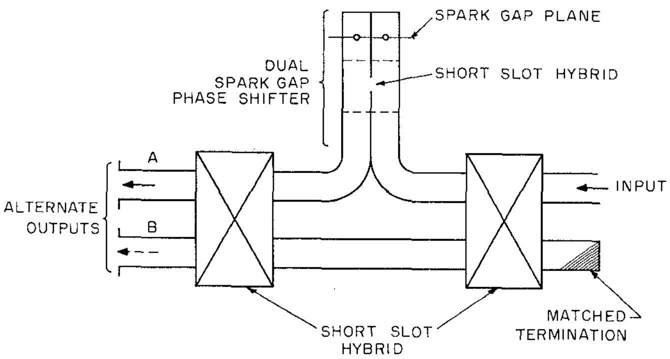
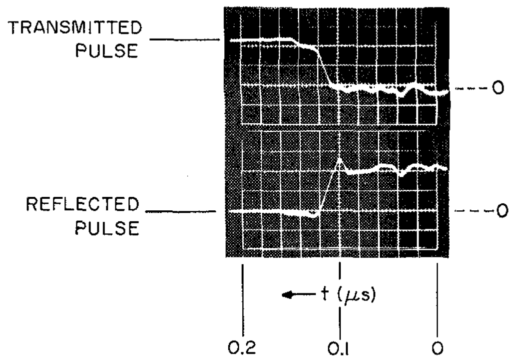


Fig. 3. One possible circuit for SPDT (single-pole, double-throw) switching.

ratio (designated as O.R., the ratio of applied voltage to the threshold breakdown voltage, a number greater than unity). The formative time lag is the time between the application of a voltage and the initial appearance of breakdown. The time between the initial appearance of breakdown and complete breakdown is always less than the formative time, and it is observed as the switching time for the spark gap switch. The reported data for dc pulses indicates that the formative time lags range from 20 to 40 ns for an O.R. of 1.5 down to about one nanosecond for an O.R. of 3.0. The switching times are considerably less than these values. A further reduction in switching time is attained when RF fields are superimposed on the dc trigger fields.

The switch characteristics, measured in a configuration shown in Fig. 2, are summarized herewith:



RF POWER: 600 kw

DC TRIGGER: 15 kv

SCOPE: TEKTRONIX 545A

SWEEP TIME: 20 NANOSECONDS/cm

Fig. 4. Oscillograms of switching by dc triggered microwave spark.

peak RF holdoff power	about one MW (at 4 μs pulse width, 100 pps repetition rate)
RF switching time	less than 10 ns
"cold" insertion loss (unfired condition)	0.1 to 0.2 dB
isolation (as defined in Fig. 2)	~20 dB
arc loss (fired condition)	0.2 to 0.3 dB (at RF levels above 30% of switch holdoff-power capacity)
jitter	none could be observed on a Tektronix 545A scope operated with a horizontal sweep of 20 ns/cm.
gas fill	air

The characteristics of the dc trigger used in these measurements are:

pulse amplitude	10 to 15 kV
pulse shape	one-half sinusoid of 10 to 15 ns
pulse rise time	about 5 ns (estimated)

Switching action during an RF pulse of 2 μs duration is illustrated in Fig. 4 for a peak RF power level of 600 kW. (Because of the expanded time scale, only that portion of the pulse where switching occurs is shown in the figure.)

The bandwidth of the switch for any given setting of shorting plungers appears to be 1 to 2 per cent in the frequency range from 5.4 to 5.7 Gc/s. This was determined from low RF power measurements by using two short-circuiting wires between the sphere electrode and the two hemispheres to simulate the RF circuit behavior of the arc. Microwave impedance measurements with an arc discharge across the gap showed that the circuit performance was indeed equivalent to that of the wires.

RF Self-Switching and Recovery Time

Data were taken on the effect of the residual ionization from a dc spark discharge on "high"- and "low"-pulsed RF power impinging on the spark gap shortly

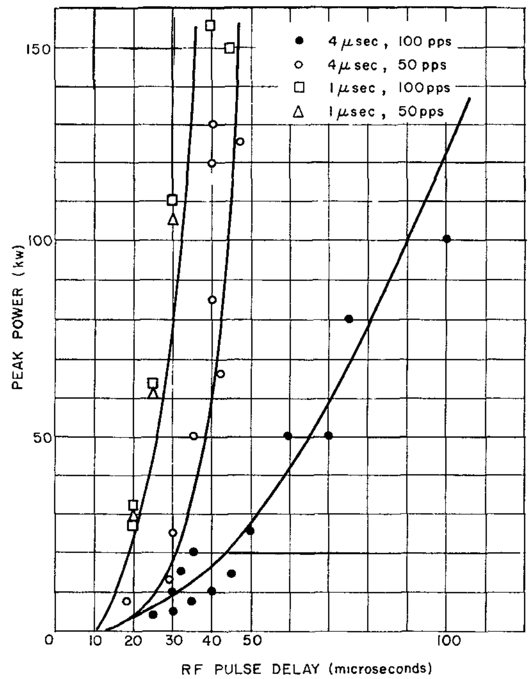


Fig. 5. Maximum time delay behind dc spark discharge for switching vs. peak power.

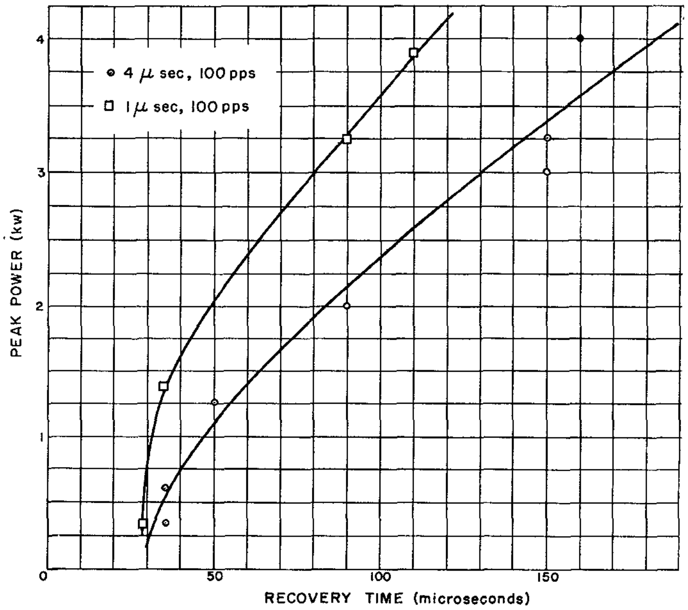


Fig. 6. Recovery time threshold curves.

Note: The recovery time is a measure of how soon an RF pulse may be applied after the initiation of a dc discharge without experiencing distortion or attenuation because of residual ionization from the discharge. The region to the right of each curve gives the allowable time interval between discharge and RF pulse resulting in no distortion or attenuation of the RF pulse. For shorter time intervals, there will be some distortion or attenuation.

after the cessation of the discharge. Threshold curves for RF self-switching at various pulse widths and repetition rates are presented in Fig. 5. These represent the RF level at which the residual ionization in the gap, enhanced by the high RF electric field, may be said to have produced switching of the incident RF pulse. The region to the left of each curve gives the allowable time interval between RF pulse and dc spark within which RF self-breakdown of the gap and almost complete switching of the incident pulse may be obtained. As the peak power, or pulse width, or repetition rate increase, so does the allowable time interval for self-switching. In Fig. 6, curves of recovery time as a function of RF power level are given for one and four microsecond pulse widths. Recovery time is defined as the minimum time one must wait after a dc discharge in order to get a microwave signal past the switching circuit without noticeable distortion or attenuation of the signal by the decaying plasma of the discharge. This is seen asymptotically to approach about 30 μs or less as the signal level is decreased below 100 watts.

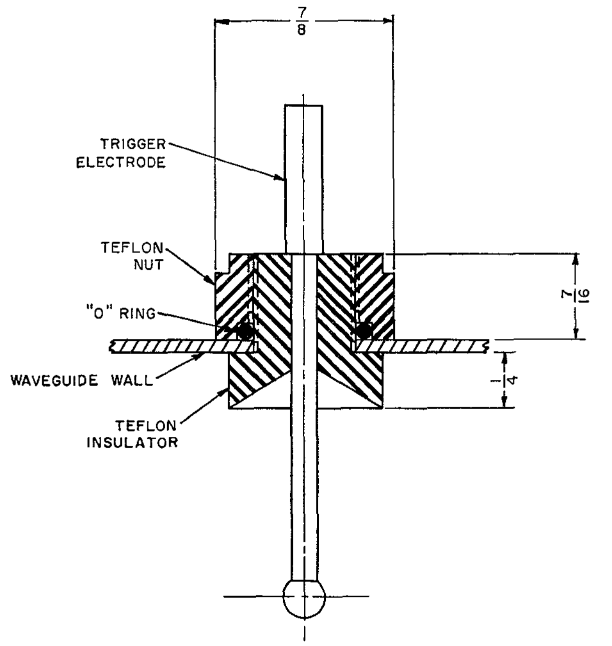


Fig. 7. Trigger for pressurized microwave spark gap switch.

Low-power measurements using an X-band frequency (10 Gc/s) as the probing signal also indicated recovery times in the order of 25 to 30 μs for the 3 dB transmission level through the spark gap region after a microwave discharge.

Switch Pressurization to Increase Holdoff Power

An attempt was made to improve the RF holdoff power of the switch by operating it above atmospheric pressure. The most difficult problem was that of building a suitable insulating bushing to hold the trigger electrode, and to eliminate minute air gaps which could offer discharge paths. The assembly used is shown in Fig. 7. The rod support of the trigger electrode was "frozen" into the insulating dielectric and an "O" ring gasket with retaining nut was used to seal the trigger assembly in the waveguide wall.

At a pressure of 3 atmospheres, it was possible to hold off 2 MW of peak RF power without self-breakdown of the gap. There were occasional RF discharges in the pressure windows, and pressurized shorting plungers, especially after a high-voltage triggering pulse was applied. The latter was from 20 to 30 kV (about twice that required at atmospheric pressure), and caused a corona discharge in the vicinity of the dielectric between the triggering electrode rod support and the outside waveguide wall. Additional work will be required on this problem to attain the RF holdoff level that should be possible with the available trigger voltage (35 kV). (Air was used in all of these experiments.)

Switching Modes

There are several modes of operation of this switch depending on the level of microwave power. At relatively low RF power, the discharge is maintained solely by the dc trigger source. At higher RF power levels, the discharge may be maintained by the two fields or by the microwave field alone as implied in Fig. 5. The speed of switching is determined solely by the rate of rise of the dc trigger voltage and its amplitude. At higher RF powers, the switching time is determined by the superposition of the dc and RF fields, as shown in Table I. When the RF power exceeds the holdoff power, the switch can be triggered during the formative time lag period to attain very short pulses.

TABLE I
THE EFFECT OF SUPERIMPOSED RF AND DC FIELDS ON THE SWITCHING TIME

RF power level ratio[1]	DC voltage ratio[2]	Switching time (with Tektronix 517A) nanoseconds
0.9	2.5	−10
0.9	1.2	10
0.9	1.0	15
0.9	0.9	20
0.9	0.7	20
0.35	2.5	10
0.35	0.9	70
0.20	2.5	12
0.20	0.95	50
0.10	2.5	50
0.10	0.95	100–200

[1] Ratio of input microwave power to holdoff power.
[2] This is the ratio of the direct current voltage expected across the gap to the minimum voltage required for breakdown in the absence of RF power. This ratio is attained if the gap does not start to break down during the nominal rise time of the applied video pulse—about 5 ns.

When dc trigger pulses with relatively long rise times (greater than 0.1 μs) are used, the switching time becomes approximately 0.1 μs for all RF power levels below the holdoff value, and for the condition that the microwave power alone maintains the discharge.

Use in Switching Power out of a Cavity Resonator

The use of this type of switch in a traveling-wave resonator to form a high-power pulse compression circuit has been fully described [1]. Certain problems and complexities of operation associated with the traveling-wave (ring) resonator can be avoided by resorting to a transmission line cavity which can perform the same function with the aid of a fast acting switch. Only one switching element is then required (instead of two as in the ring), and the problem of synchronizing two switches is thereby avoided. Because fewer microwave circuit elements are required, the circuit losses are smaller, and the possible overall efficiency and pulse amplitude magnification are greater. Also, in the traveling-wave resonator, trouble is generally experienced because of the unintentional (and often unavoidable) excitation of a backward wave, the elimination of which requires additional components. This problem does not arise with the cavity. Moreover, since the duration of the output pulse from the cavity is simply the time it takes a wave to travel from one end of the cavity to the opposite end and back, the cavity need be only half as long as a ring which produces an equally long output pulse. This can be a distinct advantage when relatively large pulse widths are required.

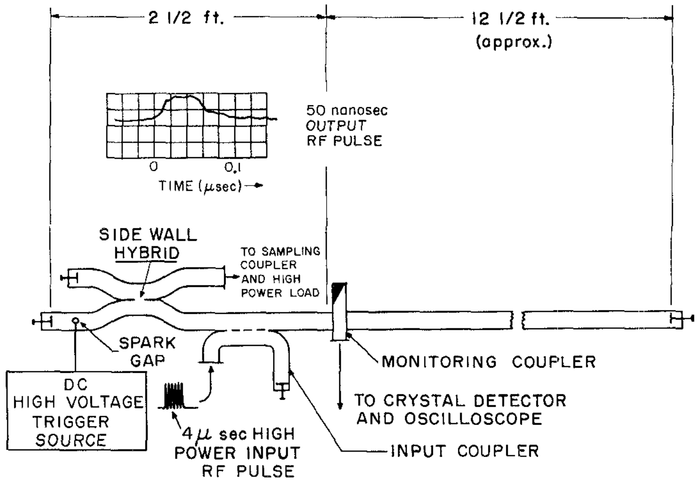


Fig. 8. Arrangement for switching RF power out of cavity resonator.

The chief disadvantages of the cavity, on the other hand, are:

1) Its output power level, as limited by the RF breakdown of the guide, is theoretically one-fourth that of the ring resonator (because the enhanced power is obtained in the form of a standing wave).
2) It initially confronts the source with a mismatch (which, however, decreases as the fields in the cavity build up toward equilibrium), even for critical coupling between source and cavity, whereas the ring resonator can provide a match at all times at critical coupling.

One switching unit was incorporated into a moderately long, copperwalled *C*-band (1 by 2 inches), rectangular waveguide cavity for testing its use in a pulse compression circuit. The experimental arrangement is shown in Fig. 8. The overall length of the resonator, switch and auxiliary components was about 15 feet. A 10 dB directional coupler, whose main arm was terminated in a movable short, and whose auxiliary arm was part of the cavity resonator, constituted the input coupling device. The movable short was adjusted to maximize the energy storage in the cavity. The switch assembly, in the unfired state, simply acts as a terminating short circuit for one end of the cavity. When a discharge is triggered in the spark gap, the stored energy in the cavity is discharged into a high-power load terminating the switch assembly. The envelope of the RF output pulse, as viewed on a Tektronix 545A oscilloscope, is also shown in Fig. 8. The peak value of 0.5 MW attained in the output pulse represented a gain of about 10 dB with respect to the 4 μs RF input pulse. The pulse rise time is seen to be about 14 ns, which is also the response time of the oscilloscope.

Evaluation

The dc triggered spark switch shares the following advantages with the *u-v* triggered type:

1) It is simple to construct and relatively inexpensive to fabricate.
2) It is (or can be made) physically rugged.
3) It can be operated without pressure windows at moderate power levels.
4) The electrodes, which are the only parts of the switch subject to wear, are inexpensive and readily replaced.
5) By pressurization and change of gas fill, the power handling capacity can be increased substantially and wear of electrodes possibly reduced.

Unlike the *u-v* triggered switch, it can handle a wide range of RF power levels, from very low-power levels up to the self-breakdown value, over a wide range of pulse widths (one to 10 μs or more) with very little average dc power consumption. At shorter pulse widths, the holdoff power can exceed the self-breakdown value.

Although some pitting of the electrodes was evident, this did not seem to affect the switch performance to any noticeable extent. The switch was not operated long enough to determine the life expectancy of a set of electrodes, nor was any study carried out to determine the best metals for the electrodes.

Consideration has been given to adapting this switch to a larger size waveguide for operation either at lower frequency (such as L band), or at higher frequencies, which permit the propagation of more than one mode.

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Broadband Binary 180° Diode Phase Modulators

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***Abstract*—The development of two types of broadband binary 180° diode phase modulators is disclosed. One type uses two waveguide paths with a diode switch in each arm to alternate between RF transmission paths. The phase modulation is obtained by an arrangement of *E*-plane and *H*-plane *T* junctions. The other type of phase modulator makes use of the reflection properties of a diode terminating a transmission line in conjunction with a 3-dB coupler or circulator.**

Introduction

THE RECENT EMERGENCE of diode phase modulators makes some microwave systems realizable which previously were not possible or impractical because of the high modulation power required to obtain high-speed phase control. Systems benefiting from this new diode phase-modulator technology include, high-speed electronically scanned microwave antennas and phase modulation radars. This task described here was undertaken as part of an effort to develop a radar phase-modulated at video frequencies. The radar system [1] requires binary phase switching between 0° and 180°. The system has additional flexibility if the phase modulator is broadband.

In the radar system phase-modulated at video frequencies, part of the phase-modulated signal, coupled to the mixer circuit, provides the local oscillator (LO) power. The voltage of the return signal, delayed in time, adds to or subtracts from the LO voltage depending on the relative phase, and produces video output. If the two phase states in the LO have unequal amplitudes, a false signal is generated. Thus, the amplitude in both phase states must be equal and the switching transients must be small to obtain the video response.

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