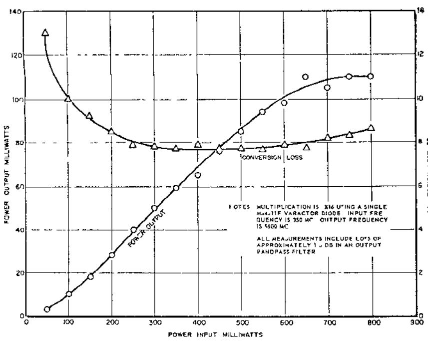

Fig. 4—Efficiency vs drive as obtained with a selected MS4511F diode.

excursion of 0.5 inch), with no change in electrical performance. Power variation for a temperature change from 25°C to 70°C averages ±0.7 db with an additional power drop of 1.3 db up to 100°C. The power output, however, remains constant from 0°C to 25°C.

While these results are typical, substantially higher efficiencies have been obtained with specially selected diodes. Conversion losses as low as 7.7 db, including a 1.5-db output-filter loss, have been repeatedly achieved. A plot of efficiency vs drive obtained with a MS4511F diode is shown in Fig. 4.

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Application of a Fast Microwave Switch to High-Peak-Power Plasma Diagnostic Experiments*

Introduction

The purpose of this communication is to report a unique method which eliminates difficulties encountered when observing a microwave pulse of high energy transmitted through a plasma. It has become increasingly important to observe the characteristics of low-pressure plasmas being irradiated with high power microwave pulses. Knowing the time dependency of electron density during the time in which the high power pulse is irradiating, the plasma gives an insight into recombination, diffusion, degree of ionization, etc.

Experimental Problem Encountered

The experimental setup is schematized in Fig. 1. The plasma is irradiated with pulses of peak power of approximately 0.1 to 1 Mw at 5.5 Gc, a PRR of 60 and a width of 5 μsec. The em plane wave is incident on the bottle and the full power of this wave travels through the bottle during the "formative time lag" of the gas. The gas used in our case is H_2 at a pressure of 1 mm of Hg. Following this time lag, the gas ionizes and the transmitted power is attenuated severely. The pick-up horn receives a pulse as shown in Fig. 2 where t_i refers to the time at which the gas is ionized. This is similar to the spike and flat leakage familiar in TR tubes. The flat leakage is approximately 35–40 db below the spike. The time variation of electron density can be deduced from the instantaneous attenuation of the flat part of this signal. Thus, it is desirable to display the signal on a CRO. This was impossible to do, since the relative magnitudes of the spike power (hundreds of kilowatts) and the flat power (watts) are as shown in Fig. 2. Any attempt to observe the flat part of the transmitted signal simultaneously with the spike resulted in crystal burnout.

What is required is a component that will separate the high-power spike from the low-power flat, allowing the flat to emerge independent of the spike from a single port. The spike may then be discarded by feeding it to a high power dummy load.

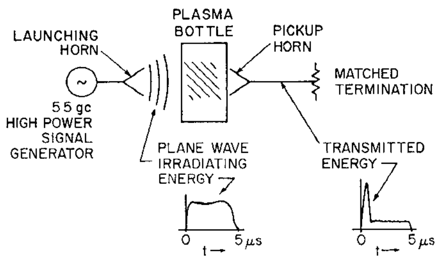

Fig. 1—Simplified schematic of plasma diagnostic experiment.

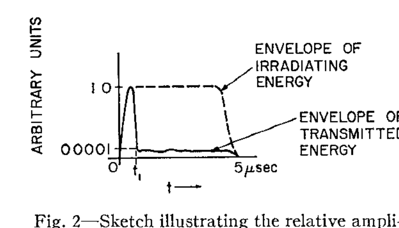

Fig. 2—Sketch illustrating the relative amplitudes of the spike and the flat portion.

Use of Switch to Separate Spike from Flat

Depicted in Fig. 3 is the additional microwave circuitry necessary to accomplish the separation of the spike and the flat portions. The critical component is the fast-acting broadband, high-peak-power switch.[1] The switch is capable of hold-off powers in excess of a megawatt at short pulse widths and, hence, its usefulness in high power plasma diagnostics. The RF dynamic switching time is 20–30 nsec. Fig. 3 also depicts the various waveforms at the three ports of the circulator. The spike emerges at D at full peak power. The switch and associated circuitry is shown in Fig. 4.

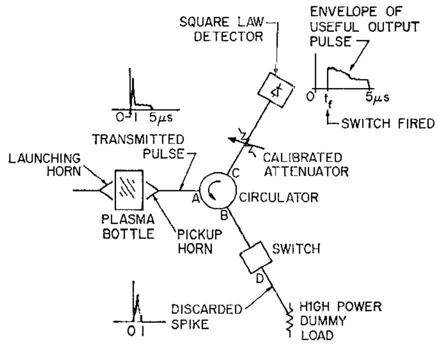

Fig. 3—Simplified schematic of improved experimental setup employing circulator and fast-acting high power switch.

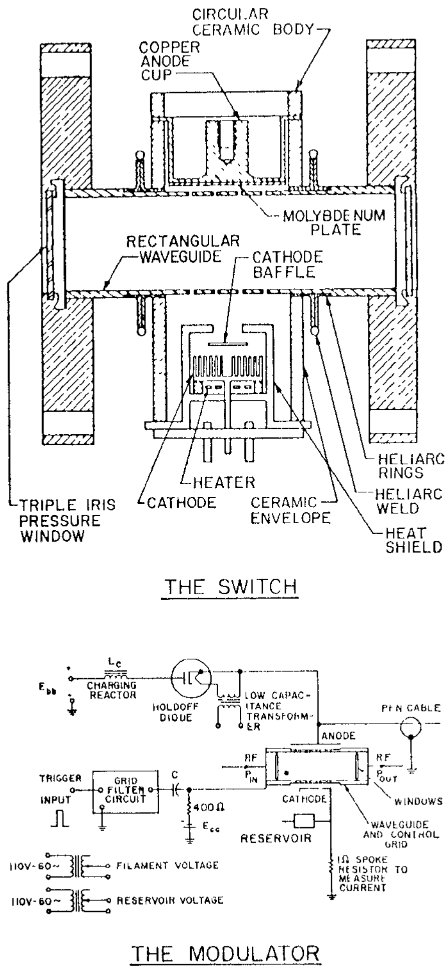

Fig. 4—The switch and associated circuitry.

The experimental arrangement operated satisfactorily. The results are best shown by the two oscillograms of Figs. 5 and 6. Depicted in Fig. 5 are the RF detected envelopes emerging at ports A, C and D. Peak-power levels in this oscillogram are 140 kw. Note that the switch is fired after the spike

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[1] H. Goldie, "A fast broadband high power microwave switch," *Microwave J.*, vol. VI, pp. 76–81; August, 1963.

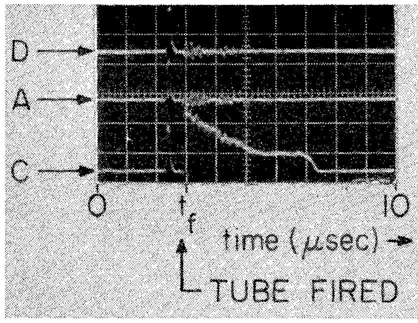

Fig. 5—Oscillogram of detected RF envelopes. D) The upper trace oscillographs the spike which is allowed to pass through the switch tube, demonstrating the hold-off capability of the switch. The spike peak power level is 130 kw. A) The center trace depicts the power received by the pick-up horn. The flat leakage is about 35–40 db below the peak power level of the spike. The spike peak power is approximately 140 kw. The flat leakage cannot be seen on this trace but reference may be made to Fig. 2. C) The lower trace is the desired waveform. The small spike appearing at the left is due to the reflections of the switch when cold (VSWR ≈1.07) and has a peak amplitude of approximately 80 w. The important portion follows after the switch has been fired. It can be seen that the waveform attenuates slowly with increasing time illustrating an increasing concentration of charge density in the plasma. The attenuation remains constant in the final portion of the pulse marking the onset of equilibrium conditions in the plasma. This latter part of the pulse has a power level of approximately 40 w. These oscillograms yield no information on the afterglow.

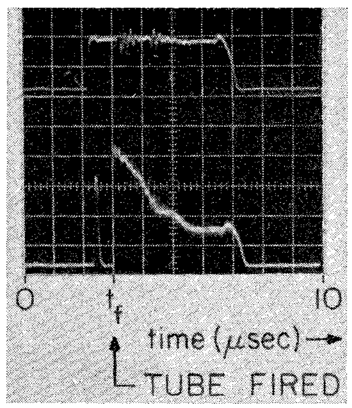

Fig. 6—Oscillogram of detected envelopes. The upper waveform is the detected envelope of the signal irradiating the bottle and creating the plasma. The pulse is 5 μsec in width, occurs at a PRR of 60 pps, has a peak power level of 230 kw and a frequency of 5.5 Gc. The lower trace is the detected RF envelope at port C of the circulator. The instantaneous attenuation of the lower trace relative to the upper trace, now easily available, is of critical importance in plasma diagnosis.

travels through the switch exhibiting the hold-off capability of the device. The switch may be fired at any time during the RF pulse. This allows a useful flexibility in the event that the spike width varies. The flat portion of the transmitted pulse is reflected when the tube fires. Switch losses are constant during the switching time and are known. The tube remains on for 30 μsec. This flat portion, when displayed on a CRO, yields the useful information. The attenuation of the flat portion relative to the irradiating pulse power at one instant of time is found by noting the over-all losses of the system including the plasma. The system is then calibrated by removing the gas from the bottle and measuring the attenuation at the same instant of time. With the system calibrated, the CRO then displays db attenuation against time over the entire flat portion. This information is then related to the electron concentration. Fig. 6 depicts the flat portion of the transmitted pulse displayed directly under the irradiating pulse. Explanations are given in the caption.

Conclusion

The use of the fast acting (20–30 nsec) high-peak-power (~1 Mw) switch in conjunction with a three-port circulator has allowed us to 1) separate, in a clean manner, the spike of energy transmitted through a plasma bottle during the formative time lag from the flat low level (~35–40 db below the spike) portion and 2) display the flat portion superimposed under the irradiating pulse in order to obtain instantaneous attenuation against time. The component which is necessary to do this is described by Goldie.[1] The switch electrical characteristics may also be found by referring to Goldie.[1]

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Dominant Mode Propagation in Ge and Si with Carrier Density Decaying Exponentially in Time*

Nag and Das[1] have recently made a theoretical study of microwave propagation in a semiconductor-filled rectangular waveguide when the semiconductor has a time dependent carrier density. They have assumed ϵ and σ to be time dependent in the wave equation for the TE_{01} mode wave and obtained a solution for the electric field E_x by perturbation techniques for small changes in carrier density. An equivalent propagation constant can be obtained for Germanium and Silicon by solving the wave equation for E_x, assuming no time variations in ϵ and σ, and then later inserting their time dependence. This is an implicit physical assumption in an earlier work of Jacobs, *et al.*[2]

Consider the case of X band propagation or $\omega = 2\pi \times 10^{10}$ cps in Ge or Si having a lifetime $\tau_c = 10^{-6}$ sec. In one microwave period of duration, $T = 10^{-10}$ sec, the fractional change in the *excess carrier* conductivity is

$$\frac{\sigma_1[e^{-t/\tau_c} - e^{-(t+T)/\tau_c}]}{\sigma_1 e^{-t/\tau_c}} \cong \frac{T}{\tau_c} = 10^{-4}. \quad (1)$$

The fractional change in the total conductivity would be even smaller. For longer lifetimes[2,3] and higher frequencies, T/τ_c would be smaller than the value obtained above. If we define the propagation constant in a semiconductor-filled guide as $j\Gamma$, then Γ is given by

$$\Gamma = [\omega^2\mu\epsilon - (\pi/a)^2 - j\omega\mu\sigma]^{1/2}. \quad (2)$$

Using the time dependence for σ and ϵ as given by (3) of Nag and Das,[1] (2) may be written as

$$\Gamma = [\omega^2\mu\{\epsilon_s - \epsilon_1 e^{-t/\tau_c}\} - (\pi/a)^2 - j\omega\mu\{\sigma_s + \sigma_1 e^{-t/\tau_c}\}]^{1/2} \quad (3)$$

or

$$\Gamma = \gamma_s\left[1 - \frac{\omega^2\mu\epsilon_1 + j\omega\mu\sigma_1}{\gamma_s^2}\cdot e^{-t/\tau_c}\right]^{1/2} \quad (4)$$

where

$$\gamma_s = [\omega^2\mu\epsilon_s - (\pi/a)^2 - j\omega\mu\sigma_s]^{1/2}.$$

For small changes in carrier density, (4) can be approximated by

$$\Gamma = \gamma_s\left(1 - \frac{\omega^2\mu\epsilon_1 + j\omega\mu\sigma_1}{2\gamma_s^2}\cdot e^{-t/\tau_c}\right). \quad (5)$$

For Ge and Si at X band frequencies or higher, the time dependent propagation constant obtained by Nag and Das[1] can be shown to be equivalent to that of (5). From their work, Γ can be written as

$$\Gamma = \gamma_s(1 + j\alpha_2 e^{-t/\tau_c}) \quad (6)$$

where $j\alpha_2$ can be written as[4]

$$j\alpha_2 = -\frac{\mu}{2\gamma_s^2}\left[\omega^2\epsilon_1\left\{1 - \frac{1}{\omega^2\tau_c^2}\left(1 + \frac{\sigma_1\tau_c}{\epsilon_1}\right)\right\} + j\omega\sigma_1\left\{1 + \frac{2\epsilon_1}{\sigma_1\tau_c}\right\}\right]. \quad (7)$$

For Ge and Si, the values of the terms in the brackets {} both tend to unity. For $\omega = 2\pi \times 10^{10}$ cps and $\tau_c = 10^{-6}$ sec, $\omega^2\tau_c^2 \cong 4 \times 10^9$. The ratio of ϵ_1 to σ_1 is given by[5]

$$\frac{\epsilon_1}{\sigma_1} = \frac{\left\langle \frac{\tau^2}{1 + \omega^2\tau^2} \right\rangle}{\left\langle \frac{\tau}{1 + \omega^2\tau^2} \right\rangle} \quad (8)$$

where τ is an energy dependent relaxation time and the brackets ⟨⟩ denote weighted averages over energy. For a constant relaxation time, $\epsilon_1/\sigma_1 = \tau$. A reasonable room temperature estimate of τ is 10^{-13} sec; thus, we choose $\epsilon_1/\sigma_1 = 10^{-13}$ sec. Then it is readily seen that

$$\frac{1}{\omega^2\tau_c^2}\left(1 + \frac{\sigma_1\tau_c}{\epsilon_1}\right) \cong 2.5 \times 10^{-3}, \quad (9a)$$

$$\frac{2\epsilon_1}{\sigma_1\tau_c} \cong 2 \times 10^{-7}. \quad (9b)$$

For higher frequencies and longer lifetimes, (9a) and (9b) are even smaller quantities.

* Received September 30, 1963.

[1] B. R. Nag and P. Das, "Microwave propagation in semiconductors with carrier density varying in time," IRE Trans. on Microwave Theory and Techniques, vol. MTT-10, pp. 564–567; November, 1962.

[2] H. Jacobs, F. A. Brand, J. D. Meindl, S. Weitz, R. Benjamin and D. A. Holmes, "New microwave techniques in surface recombination and lifetime studies," Proc. IEEE, vol. 51, pp. 581–592; April, 1963.

[3] S. Deb and B. R. Nag, "Measurement of lifetime of carriers in semiconductors through microwave reflection," *J. Appl. Phys.*, vol. 33, p. 1604; April, 1962.

[4] The typographical error in the final term of (11) of Nag and Das[1] has been corrected in (7) of this communication.

[5] R. A. Smith, "Semiconductors," The Syndics of the Cambridge University Press, London, England, pp. 217–218; 1961.