differential on the films. Under these conditions the 0.00025 in. films never failed when bombarded with the 0.61-Mev beam of pulsed currents up to 14 ma on a 1.2×10^{-4} duty cycle for periods of one hour and more. The same beam burned a hole in the 0.0005 in. sheet in 15–20 minutes and burned a hole in the 0.001 in. sheet in 2–3 minutes. Consequently, no scattering or debunching data is available for the 0.001 in. sheets.

Experiments were then conducted to find the amount of pressure differential the 0.00025 in. sheets could withstand when bombarded. The Mylar sheet was able to withstand pressure differences of up to 200 mm Hg over an area of 0.318 cm^2 when bombarded with a 0.93-Mev beam of 7-ma pulsed current at a 1.2×10^{-4} duty cycle for one hour or more. The 0.00025 in. sheets can hold one atmosphere over the 0.318 cm^2 before bombardment. However, after bombardment with 11-ma pulsed current for 20 minutes, the Mylar failed after 15–20 minutes at one atmosphere differential.

Mylar sheets with very thin vacuum deposited aluminum coatings were also tested. The aluminum coated Mylar can be used in beam excited cavities to allow passage of the electron beam into the cavity but to prevent the electro-magnetic energy in the cavity from leaking out the beam entrance hole. It was also hoped that the aluminum coating would reduce the heating damage to the Mylar sheets.

The 0.00025 in. sheets were covered with an aluminum coating 4000–5000 A thick. The aluminum caused no noticeable increase in beam scatter or beam debunching. The coating decreased the beam damage only slightly however.

Acknowledgment

Thanks are due to Prof. E. L. Goldwasser of the Physics Department, University of Illinois, for suggesting the use of Mylar in this application.

The Magnetron as a Negative-Resistance Amplifier*

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Summary—**A one-port, nonlinear, crossed-field microwave amplifier which uses a magnetron as a negative-resistance element is described. Such an amplifier is characterized as one using an emitting sole, reentrant beam, and reentrant RF fields. A circulator is required to achieve stable regenerative amplification. The system is analyzed as a negative-resistance amplifier and as a synchronized or forced oscillator. Experimental measurements of gain and bandwidth are illustrated. The effect of varying operating conditions upon these characteristics is indicated. Operation with a solid cathode composed of oxidized beryllium-nickel has been demonstrated.**

I. Introduction

As a means of obtaining microwave amplification at high-power levels, crossed-field or magnetron-type traveling-wave tubes offer high efficiencies not obtainable in other types of devices. Attempts at wide-band magnetron amplifiers [1], [2] have been made in two-port devices, and were characteristically of low gain and high efficiency. This paper describes a one-port, nonlinear, crossed-field amplifier, called the Circlotron amplifier, which uses a magnetron as a negative-resistance element much in the same way that maser and parametric-type amplifiers use "active" materials. The magnetron is tightly coupled to its load so that the self-oscillation is damped. Such amplifiers are regenerative and need have only one coupling hole to the external load. By the addition of a circulator, the amplifier obtains two ports, an efficient means of separating input and output signals, and isolation of the negative resistance from variations in load and source impedances.

In general, small-signal regenerative amplifiers tend to be sensitive to variations in circuit and operating conditions. However, if we drive such an amplifier to large-signal conditions in order to obtain a power device, we find that the amplification becomes nonlinear and the operation more stable. In fact, the larger the nonlinearity, the greater the stability of most negative-resistance devices. Furthermore, frequency synchronization or the suppression of "free" by "forced" oscillations is a peculiarity possible only in nonlinear oscillators. Because of this phenomenon, it is possible to operate a regenerative amplifier under large-signal conditions at and above the threshold of oscillation and obtain stable amplification. In such cases, however, we speak of the

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operation as being in the form of synchronized oscillations rather than regenerative amplification.

There is another property of the cylindrical magnetron which is particularly useful in the amplifier. Because the cathode is part of the resonant circuit, the RF fields cause electrons to back-bombard the cathode, and as a result the required cathode current is supplied by secondary-electron emission. This effect may be used to obtain operation with a cold cathode, for instead of thermionic electrons initiating the buildup of current, as in the conventional magnetron, the input signal, if of sufficient magnitude, triggers the buildup. This type of RF starting allows the use of certain metallic, heaterless cathodes which promise increased operating life.

II. Gain Bandwidth Relations

Fig. 1 shows a schematic diagram of the amplifier. The negative-resistance element is a magnetron oscillator damped by the useful load below the threshold of self-oscillations. This structure retains the cylindrical cathode emitting electrons over the entire length of the slow-wave structure and producing a re-entrant beam. We would expect such a structure to achieve amplification while retaining the advantageous features of the magnetron oscillator—its high efficiency, high-power handling capacity, and low-beam impedance.

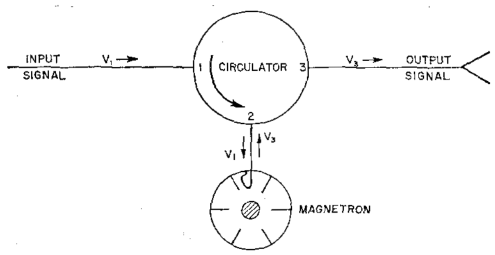


Fig. 1—Schematic diagram of the amplifier circuit.

The RF input signal V_1 is on Arm 1 of the circulator, and impresses an electromotive force on the magnetron while the power-output signal V_3 passes from the magnetron through the circulator to the load on Arm 3. An analysis of this system may be obtained by examining the circuit at the oscillator reference plane on Arm 2. Looking toward the magnetron, we see a resonant circuit shunted by the electronic space charge. Looking toward the circulator, we see an input signal V_1 coming from a matched source.

An equivalent circuit of this arm is shown in Fig. 2. The magnetron anode is represented by a parallel resonant circuit LC. The electronic space charge is represented by an equivalent negative conductance $-g_e$ which includes the internal cavity losses. The reactive loading effects of the space charge are omitted for the sake of simplicity, since its effect on steady-state oscillation is that of a small frequency correction. The voltage V_1 is the RF input-signal incident at the reference plane from the drive generator on Arm 1; the conductance g_0 represents the load on Arm 3 as seen at our reference plane and appears as a matched load because of the isolation effects of the circulator.

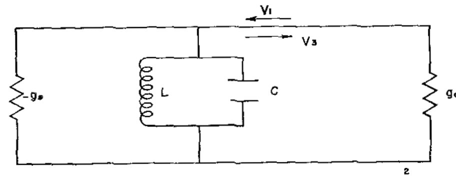


Fig. 2—Equivalent circuit of magnetron arm.

The input-signal incident on the energized magnetron causes a reflection which, because of the negative conductance, is larger than the incident signal. In other words, the reflection coefficient in the direction of the resonant circuit is the voltage gain of the system. Because the input and output admittances for these signals are the same, the power gain K_p is the squared magnitude of the reflection coefficient or,

$$K_p = \left(\frac{V_3}{V_1}\right)\left(\frac{V_3}{V_1}\right)^* = \left|\frac{g_0 + g_e - j\left(\omega C - \frac{1}{\omega L}\right)}{g_0 - g_e + j\left(\omega C - \frac{1}{\omega L}\right)}\right|^2. \tag{1}$$

At the center or resonant frequency $\omega = \omega_0 = 1/\sqrt{LC}$, the voltage gain is given by

$$K_p^{1/2} = K_{p0}^{1/2} = \frac{g_0 + g_e}{g_0 - g_e}. \tag{2}$$

The bandwidth of an amplifier is defined as the frequency difference between points where the power gain has decreased 3 db from its resonant-frequency value. In using this definition for our amplifier, where the power gain is never less than unity, we encounter infinite half-power bandwidths for values of $K_{p0} < 2$. If instead, we consider the frequency dependence of $(K_p - 1)$, which represents the power supplied by the negative conductance, we find that the gain equation is simplified to the equation

$$K_p - 1 = \frac{4g_0g_e}{(g_0 - g_e)^2 + \left(\omega C - \frac{1}{\omega L}\right)^2}, \tag{3}$$

and the half-power fractional bandwidth W_1 of $K_p - 1$ is given by

$$W_1 = \frac{2(\omega_1 - \omega_0)}{\omega_0} \doteq \frac{g_0 - g_e}{\omega_0 C}. \tag{4}$$

Thus, we have the invariant properties

$$(K_{p0}^{1/2} - 1)W_1 = \frac{2g_e}{\omega_0 C} = \frac{2}{Q_{\text{neg}}} \tag{5}$$

$$(K_{p0}^{1/2} + 1)W_1 = \frac{2g_0}{\omega_0 C} = \frac{2}{Q_E},$$

where Q_{neg} is the negative Q, equal to $\omega_0 C/g_e$, and Q_E the external Q, equal to $\omega_0 C/g_0$, of the system.

These gain-bandwidth products show the fundamental constants of the system and indicate that for large gains, the product of voltage gain and bandwidth is a constant. This is the usual relation for a regenerative amplifier. We see from these equations that increasing the negative conductance g_e improves the gain-bandwidth product primarily by increasing gain; while increasing the loading g_0 or decreasing the energy storage of the anode $\omega_0 C$ also improves the gain-bandwidth product, but primarily by increasing bandwidth. These equations, in addition to the conventional magnetron-design equations [3], form the design basis for the negative-resistance-type magnetron amplifier. The design objectives in loading and energy storage are opposite to those of designing a stable magnetron oscillator.

The phase shift between input and output signals is the phase angle of the reflection coefficient $K_p^{\frac{1}{2}}$ which may be derived from (1). The value of phase angle varies from zero at midband frequency to

$$\theta_1 = \pm\left(\frac{\pi}{4} + \tan^{-1} 1/K_{p0}^{1/2}\right), \tag{6}$$

at the half-power frequencies. At large values of gain, θ_1 varies from $+45°$ to $-45°$ over the half-power bandwidth. This small variation in phase shift with frequency, which also implies small time delay between input and output signals, indicates an amplifier with small changes in phase due to variation in operating conditions.

III. Synchronized Oscillator

One of the practical difficulties anticipated with the regenerative amplifier is the possibility of free or self-oscillations; particularly when high gain is desired, operation must be close to the threshold of oscillations. Under certain conditions, the nonlinear effects, however, may result in the free oscillation being damped. The problem of the buildup of free oscillations in a system under the influence of an external signal has been analyzed many times, first by van der Pol [4], and more recently by Slater [5], and others [6]–[11]. The results of these analyses show that in a nonlinear system, the free oscillations which tend to build up may be suppressed by the forced oscillations. The result is observed to be frequency locking or synchronization.

The difference between the synchronized oscillator and regenerative amplifier is mainly in the state of the systems prior to the introduction of external-input signals. In the regenerative amplifier, we start with a system which is below the threshold of oscillations due to the fact that the loading of the system is greater than its internal negative conductance. In the case of the forced or synchronized oscillator, we start with an oscillating system whose amplitude is limited by the nonlinear dependence of negative conductance on amplitude of the oscillation. If an external signal close in frequency is introduced into this oscillator, it can have the effect of reducing the mean value of negative conductance available for the free oscillation because of the nonlinear effects. Should the external signal be increased to that degree where the free oscillation ceases to exist, we have a synchronized oscillator. Thus, for different reasons, both the regenerative amplifier and the synchronized oscillator are below the threshold of oscillation. The difference between them becomes evident when the input signal is removed. The synchronized oscillator will experience an increase in its mean negative conductance and oscillate at its natural resonant frequency, while the regenerative-amplifier signal will be damped.

Over the region of frequency synchronization where the free oscillation is suppressed, the load conductance g_0 is greater than the internal negative conductance $|g_e|$ of the oscillator, and the analysis of Section II is applicable in deriving the gain and bandwidth relations. The synchronized band, moreover, can be shown[1] to be wider than the half-power bandwidth so that operation at half-power frequencies will be free from self-oscillations.

Thus, as a consequence of its nonlinear negative conductance, the magnetron may be operated as an amplifier both below and above the threshold of oscillation—the two regions of operation being indistinguishable as long as the input signal is large enough to suppress the free oscillation. The gain-bandwidth relations derived apply to both conditions of operation.

IV. Experimental Results

Several tubes were built with values of Q_E between 1 and 30. These tubes varied in energy storage and output loading and showed variations in gain-bandwidth product in accordance with theory. All work performed was at X band at peak power outputs between 1 and 30 kw. Most tubes operated over a 5 per cent to 10 per cent bandwidth with power gains between 20 and 8 db, the higher values of gain being obtained over narrower bandwidths. Efficiency was generally above 40 per cent, occasionally above 60 per cent. These data were taken at 0.1 per cent duty factor, with a pulse duration of approximately one μsec.

Our best results to date with respect to gain and bandwidth were obtained in a 12-vane anode design (2J42 magnetron) whose power output as an oscillator under pulsed conditions is approximately 10 kw with anode voltage of 5.5 kv, anode current of 4.5 amperes, and magnetic flux density of 4850 gauss. The unpackaged, modified magnetron is shown in Fig. 3.

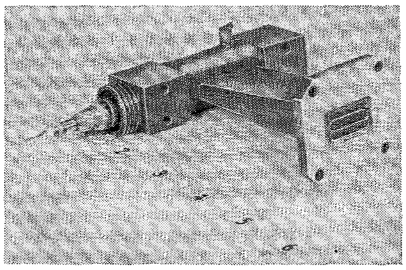


Fig. 3—Unpackaged amplifier.

[1] See [5], p. 207, Eq. 5.5.

The apparatus for testing the magnetron as an amplifier is sketched in Fig. 4. The characteristics of one of the better tubes are shown in Figs. 5–11. Most of the data were taken with a cold cathode, the cathode current being triggered by the input signal. However, in order to obtain gain at small input signal, heater power was required. This is shown in the figures by dotted curves. The cathode used was a standard, oxide-coated, magnetron cathode.

The frequency characteristics are shown in Fig. 5. The anode current was maintained constant at 2 amperes. Plate voltage is 7.5 kv and varies ±5 per cent over the frequency band.

The response of this same tube with variations in input-signal amplitude is shown in Fig. 6. Two conditions are plotted, one with the pulse generator fixed in voltage, the other with the pulse-generator current adjusted for maximum gain. Because these data were taken with the

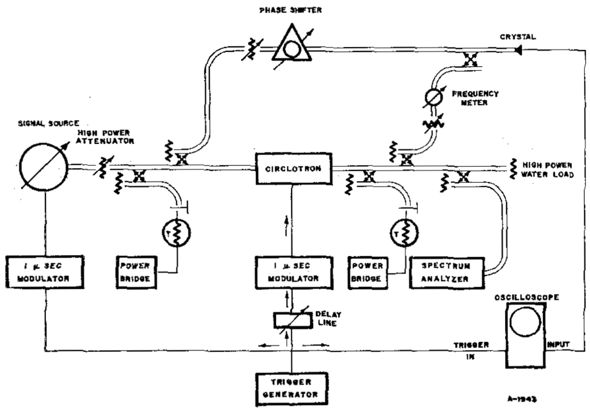


Fig. 4—Schematic diagram of the test circuit.

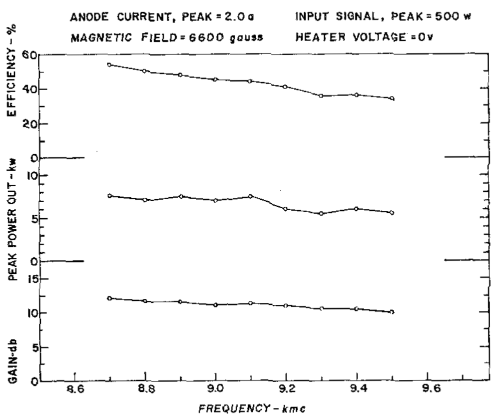


Fig. 5—Characteristics vs frequency. Constant anode current.

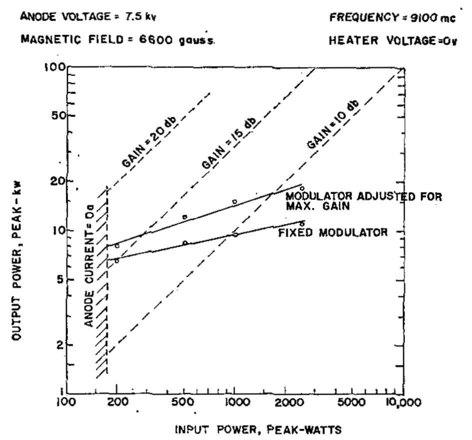


Fig. 6—Drive characteristics.

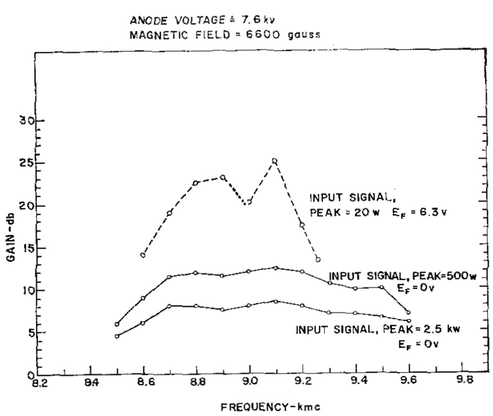


Fig. 7—Maximum gain vs frequency.

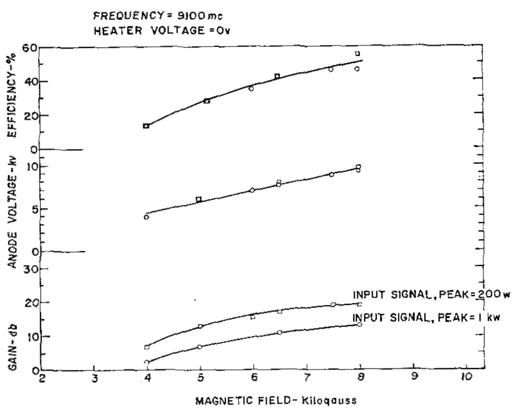


Fig. 8—Characteristics vs magnetic field.

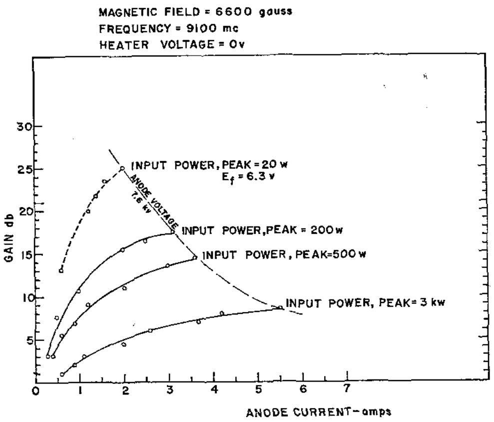


Fig. 9—Gain vs anode current.

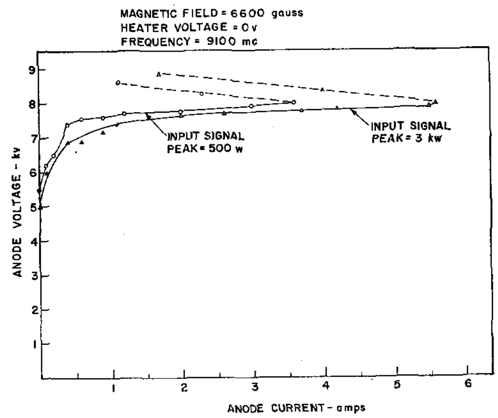
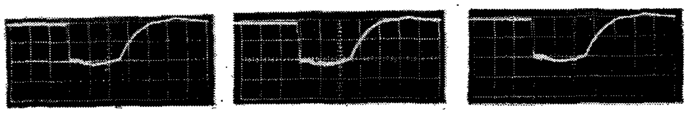
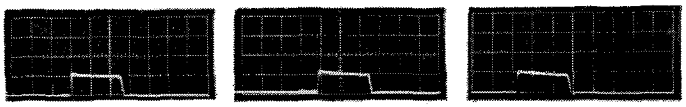


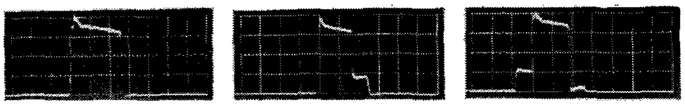
Fig. 10—Anode voltage vs anode current.



(a) Magnetron cathode voltage pulse vs time; 0.5 μsec/div.



(b) RF input signal envelope vs time; 0.5 μsec/div.



(c) RF output signal envelope vs time; 0.5 μsec/div.

Input signal: 9100 Mc; 1 kw, peak; 0.001 duty factor.
Magnetron amplifier: −6.8 kv, peak, cathode voltage; 4 ma, average cathode current; 9 db gain.

Fig. 11—RF pulse envelopes for the magnetron amplifier using an oxidized beryllium-nickel cathode. (a) RF input signal and magnetron cathode are applied simultaneously. (b) RF input signal is applied 0.5 μsec after magnetron-cathode-voltage pulse. (c) RF input signal is applied 0.4 μsec before magnetron-cathode pulse.

magnetron cathode cold, a threshold value of input signal at 170-watts peak had to be exceeded to obtain gain. At values of input signal below the threshold level, the anode current is zero, presumably due to the value of secondary-electron-emission coefficient decreasing below unity as the energy of the impinging electrons decrease toward zero. With heater power applied, the threshold level is decreased to approximately 20 watts of input signal.

In Fig. 7, the frequency characteristics are shown at three different values of input signal amplitude. Note that heater power was required to obtain operation at the 20-watts input signal level. These data were obtained by adjusting anode current for maximum gain at each frequency. At the small magnitude of input signal, the gain is sensitive to changes in amplitude of anode current.

The dependency of maximum gain, plate voltage and efficiency on magnetic field strength is shown in Fig. 8. Plate voltage and efficiency show the same dependencies as do magnetron oscillators.

Fig. 9 shows the variation of gain with anode current at several values of input-signal level. Again heater power was required to obtain the dotted curve at 20 watts of input. It is apparent that the smaller input signals result in higher gain, but with increasing sensitivity to current variations. The data indicates that at constant anode voltage, the negative conductance decreases with increasing current. If we attempt by raising the anode voltage to increase the current through the tube beyond that indicated by this maximum current curve, the result is a decrease in current and in gain as higher anode voltages are applied. This effect is shown in Fig. 10.

V. Cold-Cathode Operation

Experimental results demonstrated that above a threshold value of input signal, it was possible to operate a standard, oxide-coated cathode at room temperature. The anode current is triggered by the RF input signal while the electron back-bombardment phenomenon of the magnetron produces secondary electrons from the cold, oxide-coated cathode. Because thermionic emission is not required for operation of this device, several attractive metallic compounds with large secondary-electron-emission coefficients could be considered in order to obtain a solid, heaterless cathode.

The best results were obtained with cathodes machined from beryllium-nickel rods whose surfaces were oxidized prior to final assembly of the magnetron. Measured power gains were comparable to those obtained with cold oxide-coated cathodes.

Fig. 11 shows photographs of the magnetron cathode-voltage pulse and RF envelopes at three different relative times. In Fig. 11(a) the pulse voltage applied to the magnetron amplifier cathode is simultaneous with, and of the same duration as, the RF input signal.

In Fig. 11(b) the condition is shown where the RF input signal arrives at the amplifier 0.5 μsec after the cathode-voltage pulse is applied to the amplifier. There is no evidence of power output during the interval before the RF input signal appears, although the cathode voltage is applied. (The slight disturbance in the base line before the pulse is present in all the photographs of the RF envelope and is due to pickup in the viewing circuit.) The insertion loss of the nonoperating amplifier is that of the circulator because the magnetron anode reflects nearly all the energy incident on it. Accordingly, the RF input signal appears at the load as a step at the end of the RF output signal.

Fig. 11(c) shows the condition when the RF input signal arrives at the amplifier about 0.4 μsec before the anode-voltage pulse is applied. The first step of the pulse is the input signal reflected from the magnetron; the middle part is the amplified signal, while the last step indicates output power being generated after the RF input-signal pulse. This signal is a noisy oscillation centered at 9050 Mc, the natural resonant frequency of the magnetron. This oscillation may be eliminated if the cathode voltage is stepped down about 3 kv after the input-signal pulse ends.

VI. Conclusion

A high-power, microwave amplifier using a magnetron as a nonlinear, negative conductance has been successfully built and tested. This approach has been established as a means of obtaining wide-band amplification in a structure which retains the advantageous features of the magnetron oscillator—its high efficiency and high-power handling capabilities, as well as its relative simplicity and economy of construction. The power gains obtained are low in comparison with beam-type devices but are comparable to other crossed-field devices.

The experiments with solid, surface-oxidized, beryllium-nickel cathodes show promise of providing a new means for obtaining long-lived, high-duty-cycle operation of crossed-field devices. The possibility of simplifying the cathode-pulse generator is suggested by the RF starting phenomenon illustrated in Fig. 11(b).

Although our work was performed at X band with peak-power output in the order of kilowatts, the principles of the device may be applied at other frequencies and power levels—preferably where there is in existence a magnetron-oscillator design.

Because of the small time delay and small phase shift of the device, this amplifier should find particular application in the transmitter portion of phased array systems. It may also prove to be of considerable importance in regions of the microwave spectrum where high-power amplifiers are not available but magnetron oscillators are. It is hoped also that some of the measurements may serve to increase our knowledge of the magnetron space-charge characteristics.

Acknowledgment

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