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AN ELECTRONICALLY-TUNED, PULSED COAXIAL MAGNETRON FOR KU-BAND.(U)
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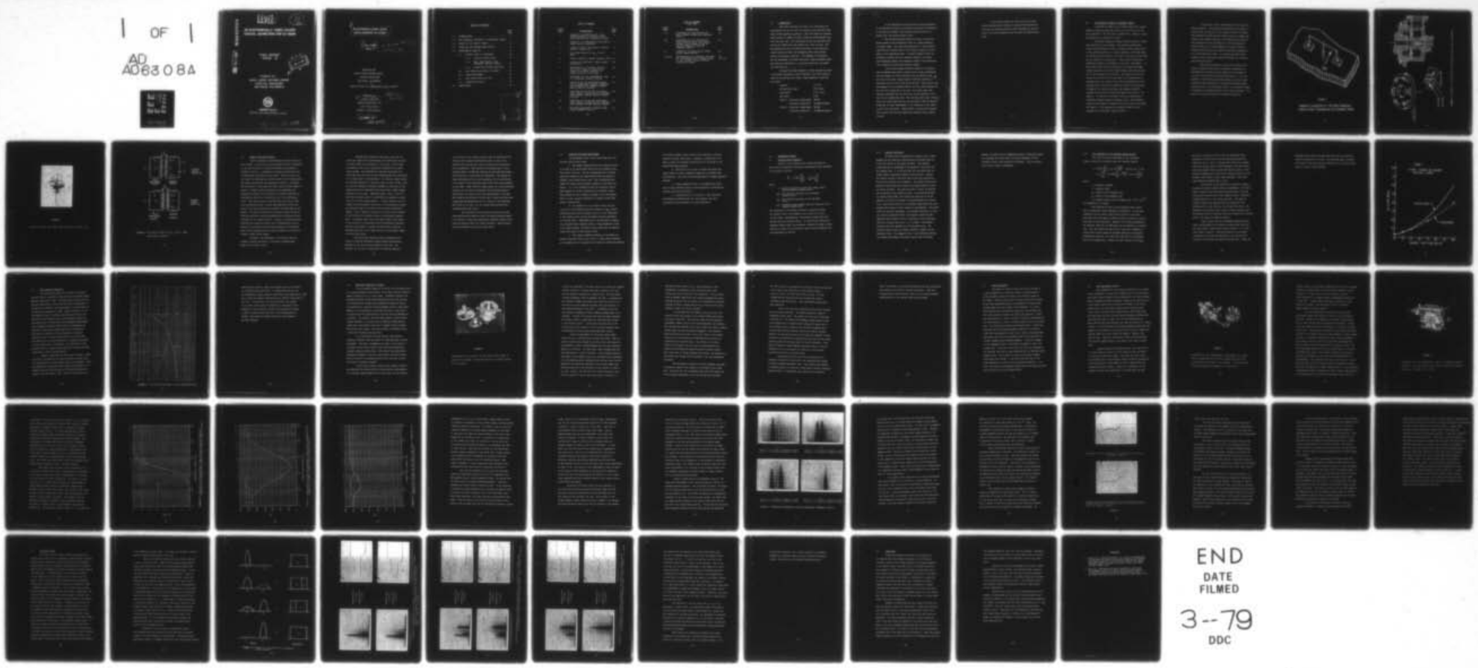

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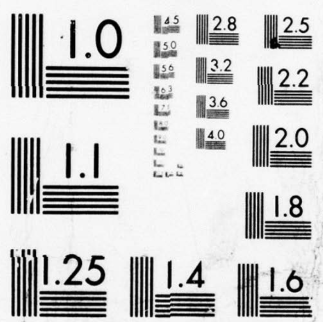


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

# AN ELECTRONICALLY TUNED, PULSED COAXIAL MAGNETRON FOR KU-BAND

FINAL REPORT
PHASE II



Prepared for:

NAVAL OCEAN SYSTEMS CENTER
CATALINA, BOULEVARD
SAN DIEGO, CALIFORNIA

varian-beverly

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FINAL REPORT. Jul 76-Jul 77, on

PHASE II Phase 2,

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SEPTEMBER 1977

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## 1.0 INTRODUCTION

This report describes the effort on a continuation program supported by the U.S. Navy to develop an electronically tuned, pulsed coaxial magnetron oscillator. The first phase was conducted under Contract No. N00123-75-C-0911 during the period between June, 1975, and June, 1976. The continuation effort was conducted under Contract No. N00123-76-C-1476 between July, 1976, and July, 1977. The program was under the technical direction of the Naval Electronics Laboratory Center (now designated Naval Ocean Systems Center) in San Diego, California. The emphasis on the program was the development of suitable electronic tuning techniques rather than upon tube fabrication to a particular electrical and mechanical specification.

Although the primary emphasis on these programs was aimed at developing appropriate tuning techniques, there were technical goals for an electronically tuned, coaxial magnetron, which were as follows:

| | |
|---|---|
| Frequency | 16.3 GHz |
| RF Peak Power Output | 60 kW (min.) |
| Pulse Width | 0.5-2.0 μsec. |
| Duty Cycle | 0.001 |
| Option A - Electronic Tuning Range | 300 MHz |
| Electronic Tuning Rate | 50 MHz/millisecond |
| Option B - Electronic Tuning Range | 100 MHz |
| Electronic Tuning Rate | 100 MHz/microsecond |

It was desirable that the electronic tuning technique(s) to be developed be capable of performing both Option A and Option B. If this was not possible, then alternate solutions were to be offered that could perform either option.

The technical approach adopted by Varian utilizes PIN diodes mounted in the stabilizing cavity of a coaxial magnetron to produce tuning. The diodes and associated d.c. bias coupling leads form an LC network that is an RF circuit coupled to the RF fields of the stabilizing cavity. Discrete frequency shifts are obtained by altering the bias conditions applied to the diode. The accompanying change in RF impedance coupled to the stabilizing cavity produces the associated frequency change.

In the first program electronic tuning of an operating tube was demonstrated using a coupled circuit tuning configuration that was thought to be most appropriate for intrapulse tuning. In one tube an electronic tuning range of 10 MHz was obtained at a peak power level of 30 to 50 kW across the band. These results were encouraging so far as showing viability for the tuning technique but were not fully understood at the time. The tuning range under operating conditions was only about half of that measured at cold test for the nonoperating tube. Also the peak power output variation across the tuning range from the tube was greater than was expected based upon cold test measurements of the variations of the loaded $Q_L$ and circuit efficiency. Similar kinds of results were obtained with a second tube that was tested that contained twelve coupled circuits.

In the second program the effort has been directed toward understanding the reasons for these differences between cold test and operating tubes and toward obtaining an electronically tuned coaxial magnetron that will meet the program objectives.

## 2.0 THE TECHNICAL APPROACH TO ELECTRONIC TUNING

A detailed discussion of the tuning concept for a coaxial magnetron using PIN diodes was given in the final report for the first program.[1] That will not be repeated here. However, a brief description of the concept is in order.

Electronic tuning was obtained using PIN diodes as switchable capacitors in an LC network. The network is inductively coupled to the RF magnetic field of a $TE_{011}$ circular electric mode in the stabilizing cavity of a coaxial magnetron. PIN diode chips are affixed in pairs directly to the wall or end plate of the cavity and are joined by a coupling loop. A bias lead is attached in a symmetrical fashion to the midpoint of the loop. See Figure 1. In the reverse biased state the diode chips are essentially lumped element capacitors, and in the forward biased state they function as low loss resistors for RF current. The coupled circuits are mounted in the cavity so that the plane of the coupling loop is perpendicular to the radius of the cavity and therefore are also perpendicular to the radial RF magnetic fields of the $TE_{011}$ mode. RF magnetic flux lines of the $TE_{011}$ mode passing through the coupling loop provide the interaction between the circuits. See Figure 2. In practice, the coupled circuits are fabricated as independent elements mounted on separate studs. The individual studs are then mounted in recesses in the cavity wall or end plate. See Figure 3. This approach will eventually permit low cost assembly of the individual coupled circuits.

An equivalent circuit representation of the concept is shown in Figure 4. By switching electronically from reverse to forward bias, the character of the coupled circuits is changed. The reactance reflected into the primary circuit is changed, and tuning of the resonant frequency of the $TE_{011}$ mode is achieved. This technique was used successfully in the first program to electronically tune a coaxial magnetron to produce 10 $MH_z$ of tuning at Ku-band using six coupled circuits while operating at 40 to 50 kW peak power output. In a second tube with twelve coupled circuits, electronic tuning was obtained over 20 MHz at lower peak power levels.

This tuning technique is suitable for pulse-to-pulse tuning in quantized steps where the selected frequencies are determined by the coupled circuit design and by the number of circuits in the forward and reverse biased states. It is also possible to obtain intra-pulse tuning during a pulse for pulse compression radar application by successively switching diodes from the reverse to forward biased states. An incremental change in frequency is obtained with each circuit that is switched. The result is a staircase profile for frequency versus time.

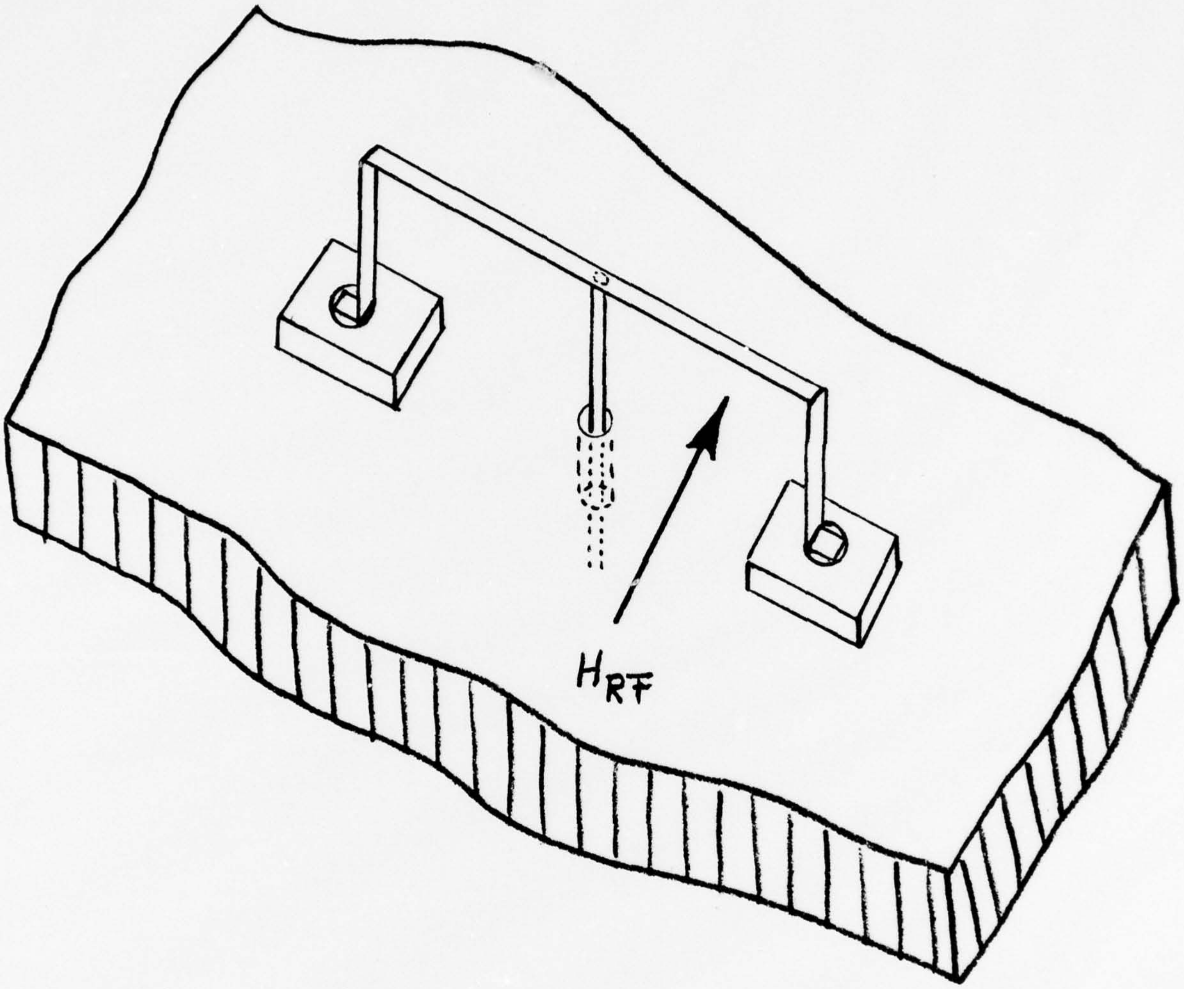


FIGURE 1

SCHEMATIC ILLUSTRATION OF A PIN DIODE CONTROLLED, COUPLED CIRCUIT CONFIGURATION FOR ELECTRONIC TUNING

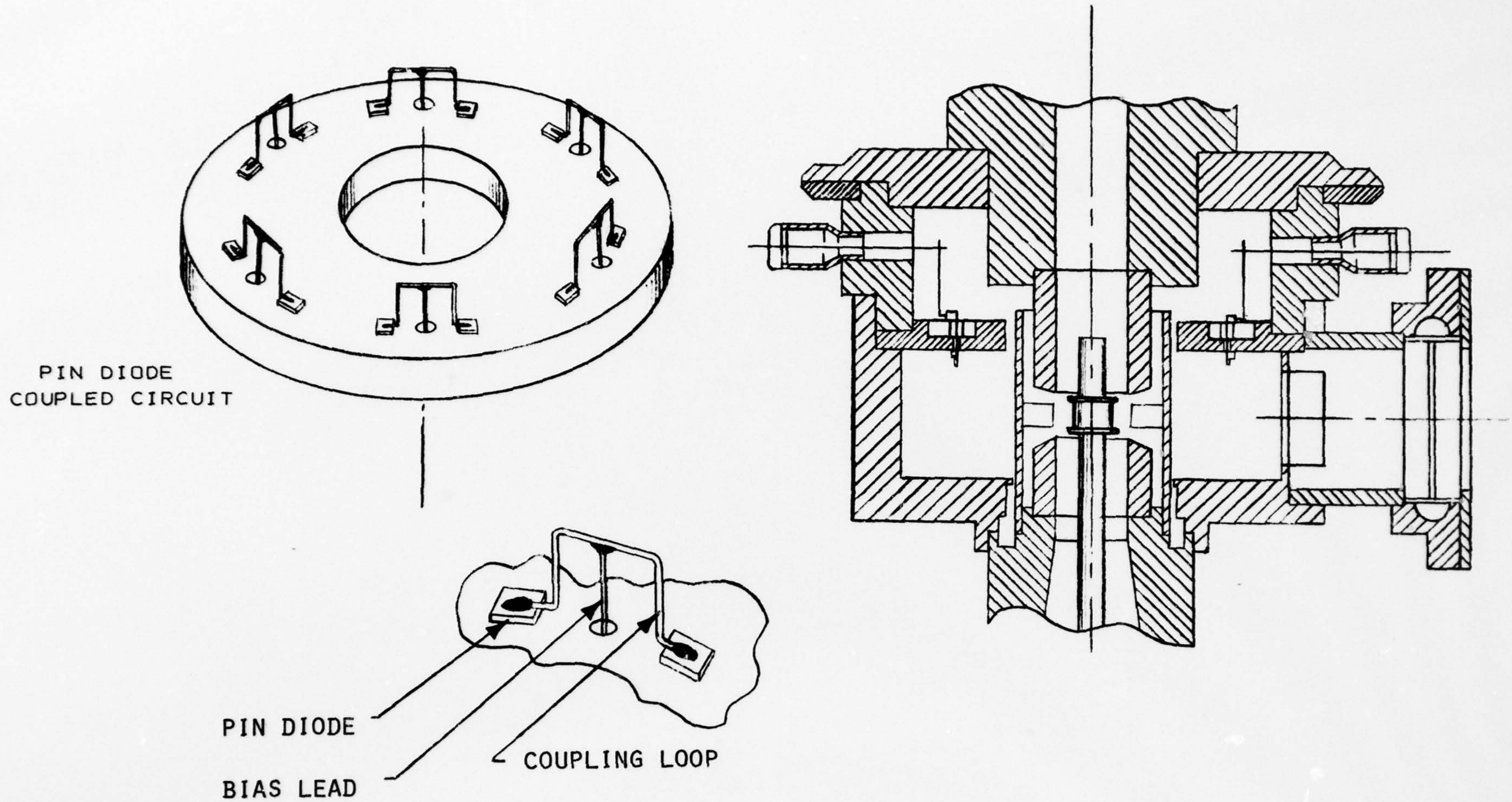


FIGURE 2--SCHEMATIC ILLUSTRATION OF ELECTRONIC-TUNED COAXIAL MAGNETRON

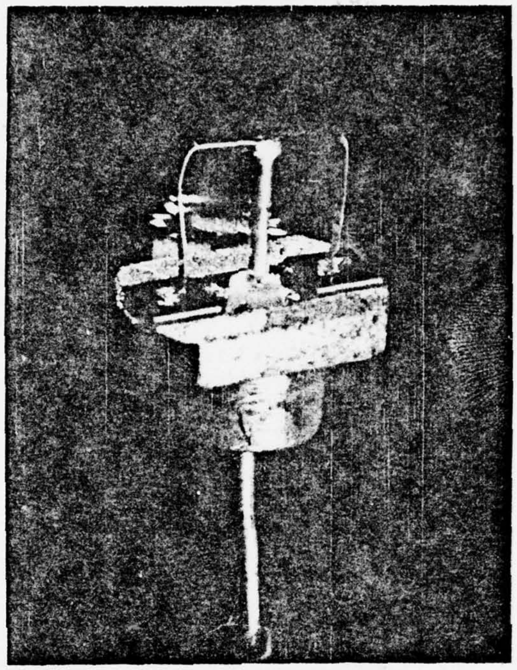

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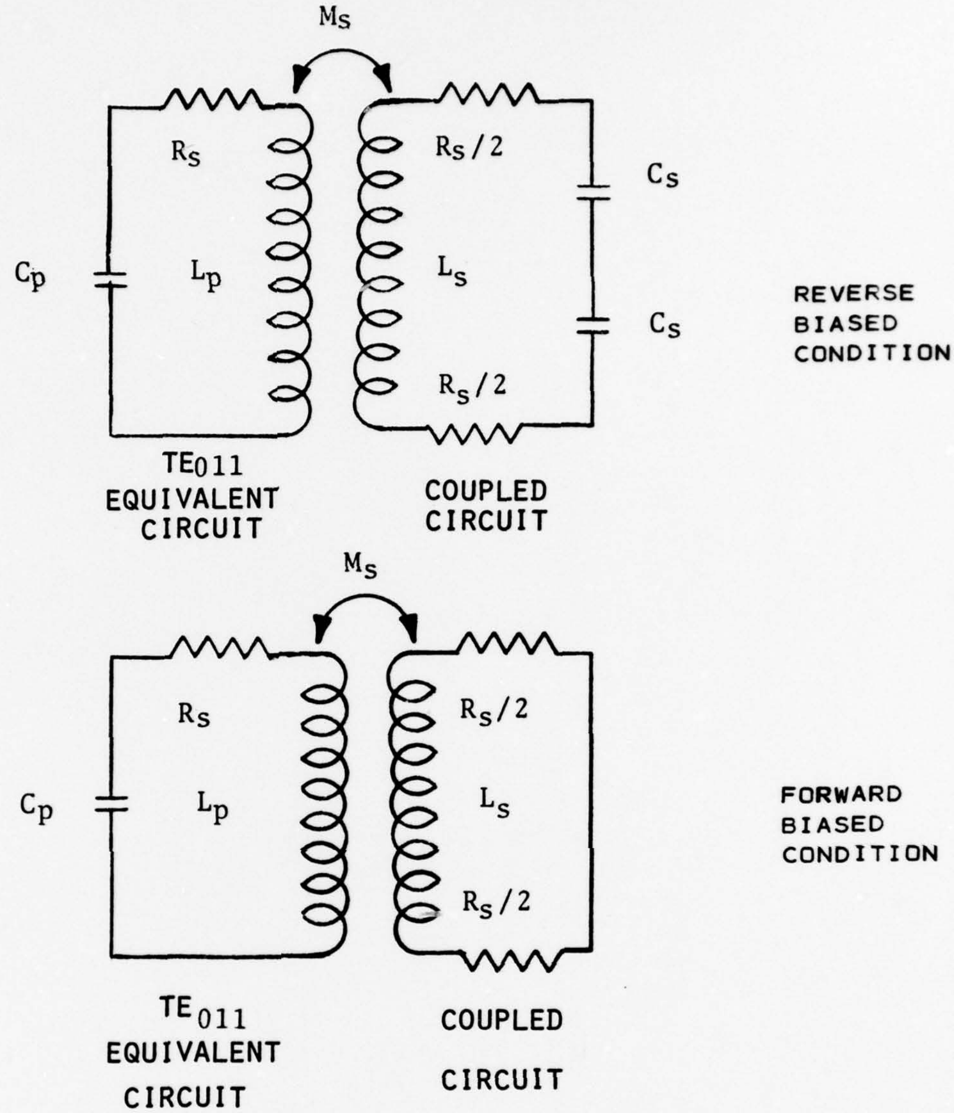
FIGURE 3

CLOSE UP VIEW OF PIN DIODE, COUPLED CIRCUIT TUNING STUD.




<u>FIGURE</u> 4--PIN DIODE TUNING OF $TE_{011}$ CAVITY MODE. EQUIVALENT CIRCUITS.

## 3.0 STATUS AT THE END OF PHASE I

Several significant accomplishments were made during the first program. An electronic tuning technique that was investigated at cold test initially at S-band was modified and successfully extended to Ku-band. A mathematical analysis was made based upon a lumped element equivalent circuit model. This has proved to be very useful for designing the coupled circuits and for interpreting the results obtained with the experimental vehicles. Techniques were developed for fabricating the small coupled circuits needed at Ku-band. A simple biasing configuration was established that inhibited RF leakage from the magnetron and thereby minimized any consequential reduction of the internal $Q_o$ for the stabilizing cavity. The coupled circuits using PIN diode chips were successfully incorporated within a vacuum-tight magnetron and were subjected to all normal fabrication procedures including bake-out and exhaust. Two tubes were operated at peak power levels as high as 50 kW and electronic tuning was demonstrated by switching the bias conditions of the coupled circuits. Finally, the analytical model indicated that different coupled circuit configurations would be required for inter-pulse and intra-pulse tuning, but some experimental results suggested that it might be feasible to do both with a single coupled circuit design.

In general, the development of the tuning concept is regarded as having proceeded in a relatively straightforward fashion in the Phase I effort.

Although much progress had been made, there were two areas that needed better understanding and clarification in order to obtain further the advancement of the concept. One of these was related to the actual tuning shift obtained with a coupled circuit design. The experimentally observed tuning shift was about twice the value that had been intended based upon calculation, i.e. a tuning shift of approximately 3 to 4 MHz per coupled circuit was obtained compared to a calculated value of about 1.8 MHz. Even so, this was considered reasonable agreement at this point in the program because the computations were made using a lumped element equivalent circuit model. Agreement within a factor of two for such small frequency shifts at 16,300 MHz was considered a verification of the basic design approach. It meant, however, that the reasons for the discrepancy would have to be established to permit the analytical model to be used for more accurate quantitative designs. This is important because the electrical stress applied to the PIN diodes is directly related to the obtained frequency shift. A frequency shift that is too small causes little stress to that diode but is unattractive from an applications viewpoint because a large number of coupled circuits would be required. A frequency shift that is too large can lead to catastrophic damage to the PIN diode chips.

The second area requiring further investigation was related to observed differences between tuning characteristics measured at cold test and those measured at hot test. For instance, for one tube a tuning shift of 19 MHz was measured at cold test for five coupled circuits, and the variation of the loaded $Q_L$ with tuning was sufficiently small so that it was expected that the peak power output variation with tuning would not be significant. When tested as an operating tube, a total frequency shift of 10 MHz was obtained, and the peak power output varied from 29 to 43 kW across the tuning band. The reasons for these differences were not fully understood, but it was believed to be related to the excessively high values of RF voltage applied to the diodes. These large RF voltage values for a given operating condition for the tube are consistent with the large values of tuning shift per coupled circuit that was measured at cold test. This viewpoint was partially verified with a second tube where the tuning range was demonstrated to be a function of the operating power level of the tube, e.g. the tuning range decreased with increasing peak power output.

The conclusion was that diodes with better peak power characteristics were needed and that the design procedures needed to be refined to obtain more quantitative agreement between calculated and measured values for tuning excursions. These features have been addressed in the second phase effort.

## 4.0 PLANS FOR THE SECOND PHASE EFFORT

The development effort on the second phase was to be directed toward several areas.

A. The design configurations for the coupled circuits to be used in the second phase effort was to be different from that used in the first. The new configuration was to provide capacitive loading in the reverse biased state and inductive loading in the forward biased state. This configuration was termed the "below series resonance" geometry in the reports on Phase I. It is the configuration that the equivalent circuit model suggests to be most appropriate for interpulse tuning. This requires the use of smaller secondary circuit inductances which, in turn, requires fabrication of coupled circuits with smaller coupling loops.

B. The parameters of the coupled circuit that are critical are the coupling coefficient between the $TE_{011}$ coaxial stabilizing cavity and the coupled circuit, the self inductance of the coupled circuit and the switchable junction capacitance of the diode chips. Experiments were to be performed to compare the calculated and/or measured values of these parameters as used in the lumped element, equivalent circuit model with the apparent values they exhibit in the coaxial cavity.

C. The voltage breakdown properties of PIN diodes are measured typically using a sixty cycle A.C. power supply contained as an integral part of a standard curve tracer for solid state devices.

The voltage breakdown values could be quite different at Ku-band because of transit time effects. Therefore, attempts were to be made to assess the breakdown characteristics of the diodes at the desired operating frequency.

D. Efforts were to be made to develop PIN diodes with larger values of reverse breakdown voltage and to decrease their RF resistance. This effort was performed mainly on company-sponsored programs.

E. Coaxial magnetrons were to be assembled and tested with the most promising coupled circuit geometries for meeting the technical objectives of Option A.

F. Consideration was to be given to other electrical and mechanical considerations that could optimize the tube's acceptability and performance for system application.

# 5.0 EXPERIMENTAL RESULTS

## 5.1 Coupled Circuit Parameters

Analysis of the coupled circuit tuning technique predicts that the tuning shift produced by switching the bias conditions of the diodes is given by:

$$\frac{\Delta f}{f} = \frac{1}{2} a^2 X_{LP} \left[ \frac{1}{X_{LS}} - \frac{1}{X_{LS} - X_{CS}} \right]$$

where:

- $a$ = coupling coefficient between the coaxial cavity and the secondary coupled circuit
- $X_{LS}$ = self inductive reactance of the secondary coupled circuit
- $X_{CS}$ = net capacitive reactance of the PIN diode chips
- $X_{LP}$ = equivalent lumped element inductive reactance of the primary coaxial cavity

The resistance of the secondary circuits is neglected because the coupled circuits are designed to have values for Qo that are very large. Experimentally, the measured tuning shifts were greater than the calculated values. To obtain better quantitative agreement between theory and experiment, attempts were made to establish proper values for the secondary coupled circuit parameters that were appropriate at Ku-band.

### 5.1.1 Coupling Coefficient

The model used for analyzing the coupled circuit tuning assumed that the diodes and coupling loops were affixed directly to the flat surface of the cavity end plate. The coupling coefficient then is determined by the geometry of the cavity and the coupling loop. It is believed that the calculated value for a under those circumstances should be quite accurate. However, the coupled circuits in the tubes used in the first phase effort did not quite conform to this geometry. The coupled circuits were mounted on studs which were located in an annular groove cut into the cavity end plate. The groove was used to locate the position and orientation of the coupled circuits. It was speculated that the annular groove might cause sufficient distortion of the RF magnetic flux lines to increase the coupling between the circuits. If so, this could account for the increased tuning shifts that were obtained with coupled circuits mounted in this geometry. This possibility was tested by experiment. The resonant frequency of a cold test cavity was measured without any coupled circuits and then remeasured using coupled circuits consisting of several mounting studs with coupling loops only; i.e., no diodes. The measured frequency shift was compared with the calculated value. The observed frequency shift was smaller instead of larger than the calculated value. This suggested that, if any difference existed, the coupling coefficient was actually smaller than calculated.

However, the result was not unambiguous because a difference between the calculated and actual value of the self inductance for the secondary circuit could confound the experiment. This was checked with a second series of experiments.

5.1.2 Self Inductance of the Secondary Coupled Circuit

The value for the self inductance of the rectangular coupled circuits was calculated using the following equation.

$$L = 0.02339 \left[ (S_1 + S_2) \log \frac{2S_1S_2}{b+c} - \log (S_1 + g) - S \log (S_2 + g) \right] + 0.01016 \left[ 2g - \frac{S_1+S_2}{2} + 0.447\ (b+c) \right] \mu H$$

where:

$b$ = conductor thickness

$c$ = conductor width

$S_1$ = height of the rectangular loop

$S_2$ = width of the rectangular loop

$g$ = diagonal length of the rectangular loop = $(S_1^{\,2} + S_2^{\,2})^{1/2}$

All dimensions are in inches.

This equation is valid at low frequencies where current flow is essentially uniform throughout the conductor. At very high frequencies the skin effect causes the RF current to crowd into thin layers near the conductor surface and this can lead to a slightly lower value of self inductance. However, for the small dimensions of the conductor used here, the difference was not expected to be significant. Also, the formula was derived for a loop with a conductor of uniform cross section around the periphery whereas in the mounting configuration used here, the cavity wall forms part of the conductor path of the coupling loop. However, the wall currents in the $TE_{011}$

mode flow in concentric circles, hence no significant radial spreading of current flow on the wall between the diodes was expected to occur. Also, to preserve this feature the coupling loops size was kept small so that RF magnetic field lines associated with coupled circuit current flow would not have a circumferential component which could lead to energy conversion to non-resonant, non-circular, electric mode components. This would cause additional unwanted loss to occur.

The validity of this equation for electronic tuning at Ku-band was tested in another series of experiments. For these a number of square loops were formed using gold tape of the same cross section that was used in the coupled circuits. These were attached directly to a flat cavity end plate. The change in resonant frequency was measured when this tuning plate was substituted for a flat end plate in a Ku-band test cavity. The experiment was performed using a range of square coupling loops. The measured values of frequency shift were compared with calculated values. The results are shown in Figure 5.

These results show quite reasonable agreement between theory and experiment for the range of coupling loop sizes that have been tested in diode switch coupled circuits; i.e., 0.065 x 0.065 inches or smaller. Calculated values for the coupling coefficient and for the self inductance of the loop are both involved in calculating the expected frequency shift. Hence the agreement between theory and experiments show that the calculated values are appropriate at Ku-band. The remaining suspect parameter is the value of the diode junction capacitance in the reverse biased state to be used at this frequency.

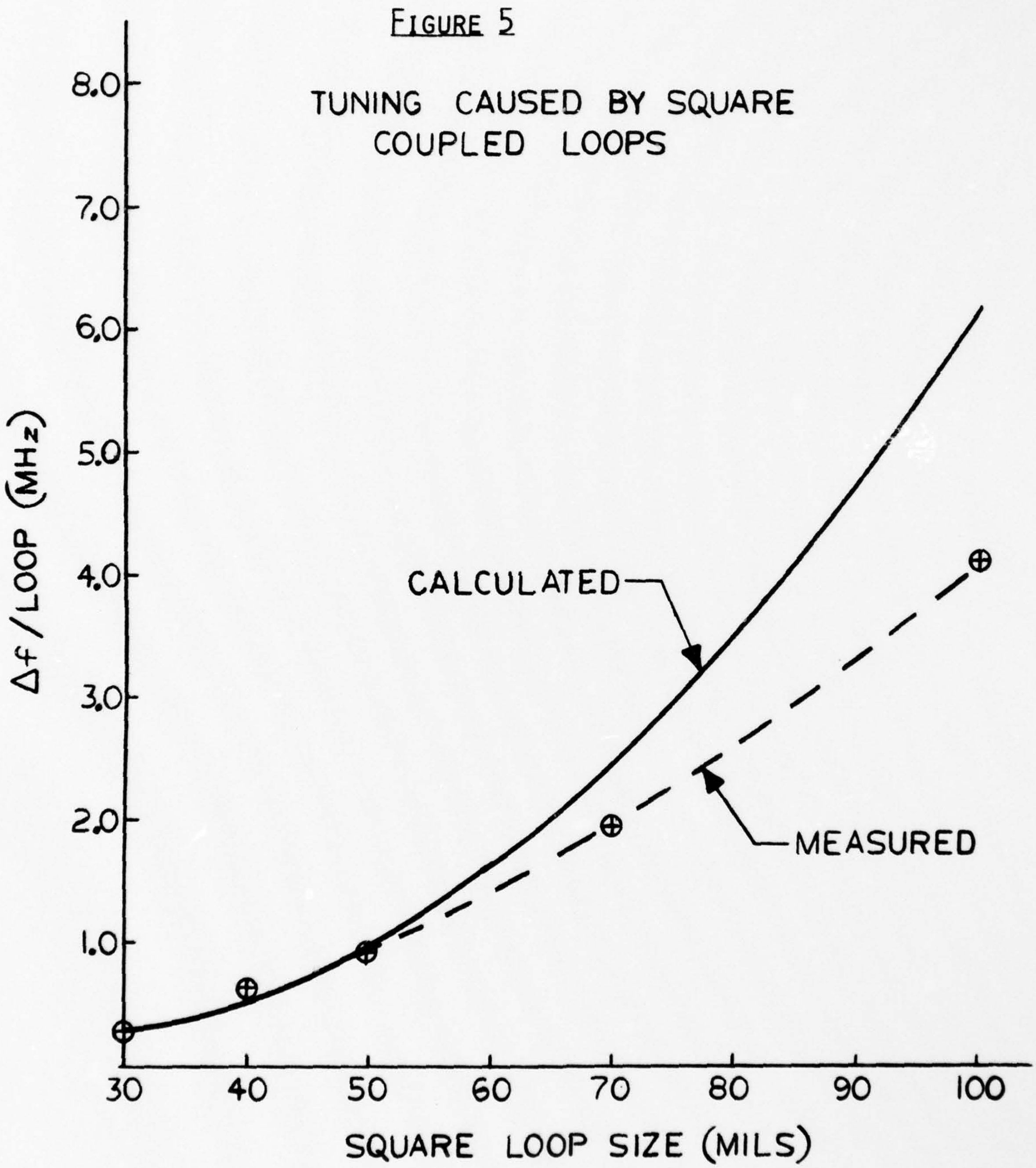


FIGURE 5
TUNING CAUSED BY SQUARE COUPLED LOOPS
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
Δf /LOOP (MHz)
CALCULATED
MEASURED
30
40
50
60
70
80
90
100
SQUARE LOOP SIZE (MILS)

### 5.1.3 Diode Capacitive Reactance

The junction capacitance of PIN diodes are measured typically using a capacitance bridge which has an internal signal generator operating at 1 MHz. The diode theory predicts that the junction capacitance at full reverse bias will be independent of frequency and, therefore, the value measured at Ku-band should be the same as that measured at 1 MHz. Indeed, this may be so, but this measured value of the diode capacitance when used in the equivalent circuit model does not yield agreement between the calculated value of tuning shifts and experimental measurements. Since reasonable agreement between theory and experiment was obtained for inductively loaded loops only, it was decided arbitrarily to assign all of the discrepancy to having an inaccurate value of junction capacitance for use at Ku-band. This ignores the fact that distributed or fringing capacitances or other effects may be contributory. The equivalent circuit model was used as a guide to enable empirical selection of diode capacitance to obtain a desired result.

Figure 6, taken from the final report of Phase I, shows the effect of variation of the diode capacitive reactance upon the tuning shift for a fixed coupled circuit loop geometry. Since the experimental tuning shifts were larger than expected, it is apparent that the effective value of junction capacitance was smaller at Ku-band than at 1 MHz. This also has the effect of

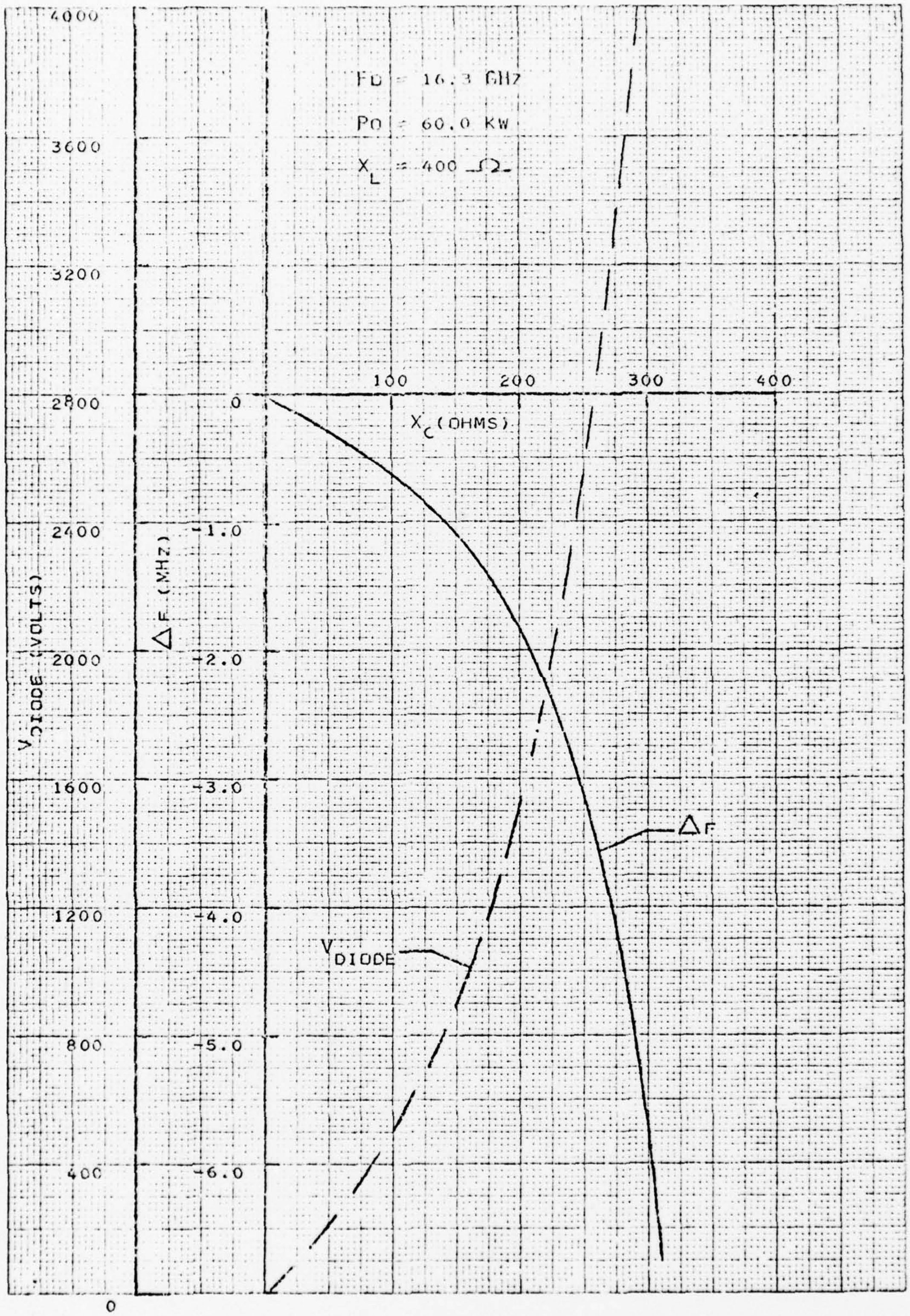



FIGURE 6 - CALCULATED ELECTRONIC TUNING CHARACTERISTICS

subjecting the diodes to larger than planned values of RF voltage at a prescribed peak power level. An appropriate diode for use was determined by using a range of capacitance values (measured at 1 MHz) with a fixed loop geometry and measuring the obtained tuning shift on cold test. A tuning shift curve such as Figure 6 was assumed to be correct and was used to interpolate or extrapolate values leading to a final selection. Several iterations were necessary to obtain a selection each time that a loop configuration was changed. This empirical method worked quite well although it was time consuming.

## 5.2 High Power Evaluation of Diodes

It was considered important to acquire more information about the voltage breakdown characteristics of the diode than that obtained merely by using a 60 c.p.s. curve tracer. Published literature and marketing brochures by some diode manufacturers state that the sum of the reverse bias voltage and the applied RF voltage can exceed the manufacturers' specified voltage breakdown values to some extent. However, no firm guidelines are provided and there is some reason to believe that this characteristic could vary from one manufacturer to another. For instance, some PIN diodes exhibit a sharp reverse voltage breakdown at a precise value of negative voltage whereas others show a more gradual transition of leakage current increase with reverse bias voltage. This latter effect is sometimes called a "soft knee" breakdown characteristic.

It is conceivable that these devices could function completely different from one another in a high peak power, Ku-band environment. Therefore, arrangements were made to test diodes in a Ku-band, coaxial cavity resonator that could be illuminated by a pulsed, high peak power source. This differs from some similar experiments attempted in the first phase effort in that the diodes would be tested in a configuration more nearly like that in which they would be intended to operate.

A fixed tuned, Ku-band, coaxial cavity (shown in Figure 7) was fabricated that duplicated the circular electric mode geometry of the Ku-band coaxial magnetron to be used later as a test vehicle

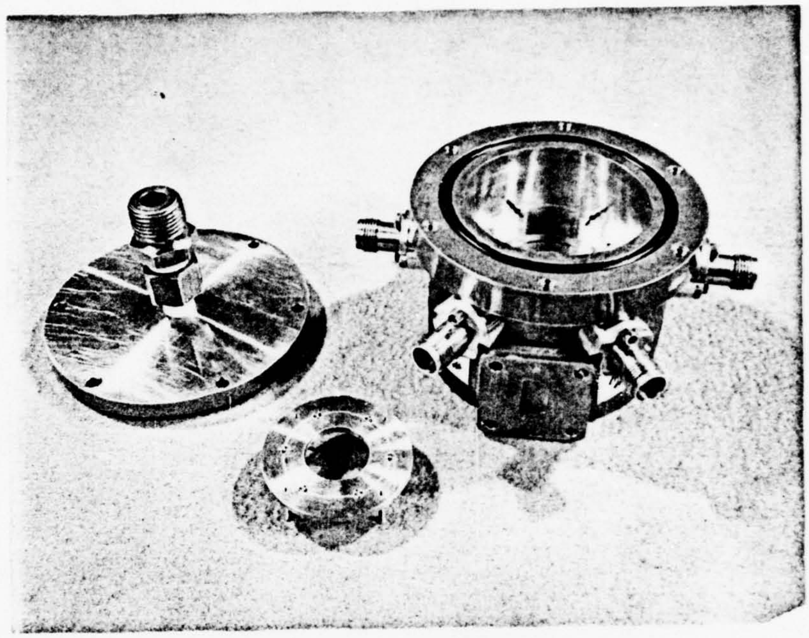


FIGURE 7

PHOTOGRAPH OF A KU-BAND, COAXIAL TEST CAVITY USED TO SUBJECT PIN DIODES IN COUPLED CIRCUITS TO LARGE VALUES OF RF VOLTAGE.

for hot test operations. The center post of the cavity was a smooth cylinder instead of a regular anode and no absorbers were used such as ordinarily contained in a regular tube. The same output coupling arrangement from the magnetron was used. A coupling loop was attached to sample the signal level inside the cavity to be sure that the driver magnetron frequency was tuned precisely to the resonant frequency of the cavity. A removable cavity end plate permitted changing the diode coupling configurations to be evaluated. A header region above the cavity end plate contained six coaxial connector feedthroughs for connecting bias voltage to the coupled circuits. A cover plate was fitted with an "O" ring seal and a pipe connector so that the whole assembly could be pressurized to avoid arcing during high power testing.

Cold test measurements of the cavity tester showed values for $Q_E$ of 1,100 and for $Q_O$ of more than 10,000. When the coupled circuits were included in the test cavity, the values for $Q_O$ decreased to 4,000 to 8,000 dependent upon the bias conditions applied to the diodes. In either case, these configurations have very high values of circuit efficiency. The RF voltage applied to the diodes in the coupled circuits are calculated from a knowledge of the illuminating power transferred into the test cavity and the mechanical and electrical properties of the circuits under test. Equations developed in the equivalent circuit analysis of Phase I are used. However, the high values of circuit efficiency, even with the coupled circuits in the cavity, made it difficult to determine precise values for $Q_0$. This uncertainty is then transferred to uncertainty in the calculated value of RF voltage since $Q_0$ is involved in the computation. This situation could be markedly improved for any further experiments by either lowering the $Q_0$ for the test cavity or by decreasing the external coupling to obtain a higher value for $Q_E$ so that the test cavity loading is closer to critical coupling.

To high power test the diodes in the test cavity, all coupled circuits were placed in full forward biased state except the circuit under test. This was done using the bias switching arrangement normally used for cold test measurement and evaluation. Bias voltages were applied to the circuit under test using a separate voltage supply and bias switching arrangement. This provided a means for measuring any pulse current that flowed in the coupled circuits due to rectification or breakdown when the cavity was illuminated with pulsed RF power. The polarity of the pulse current in the diode circuit was used to identify whether the diodes were rectifying the applied RF pulse or whether reverse bias current due to voltage breakdown was flowing. The magnitude of the reverse bias voltage could be adjusted to set the experimental conditions.

The experimental procedure for diode assessment consisted of applying a negative bias voltage to the coupled circuit under test. The cavity was then illuminated with an RF drive signal and the RF voltage superimposed on the bias voltage was calculated.

The bias voltage was decreased until rectified current was observed. In all cases it was found that the bias voltage could be reduced to only a few volts before this occurred. The bias voltage was then increased until the reverse bias current increased during the RF pulse. This established reverse breakdown conditions.

Only a few tests were performed and the results obtained were not wholly consistent. The diodes tested had a range of breakdown voltage values. The reasons for this will be discussed in Section 5.3. For diodes with breakdown voltage values of only a few hundred volts it appeared that combined RF voltage and d.c. bias voltage values in excess of the specified breakdown value could be applied before reverse current flow could be observed. However, the calculated values of RF voltage were somewhat in doubt because of the uncertainty in measured $Q_0$ values for the test cavity resulting from the very high values of circuit efficiency. Tests made with diodes of high breakdown values were erratic. This was believed to be due to arcing as the results of the poor diode passivation that will be discussed later.

Although the few tests that were performed were not completely successful in this effort, the technique shows promise of being a valuable development tool. This could be very helpful in assessing diodes for electronic tuning without having to fabricate operating tubes. Q measurements give values for the resistive loss of the diodes at the operating frequency band and tuning shifts give values of the effective junction capacitance. High power testing will give more realistic values for the voltage breakdown characteristics in the intended operating environment.

## 5.3 Diode Development

The number of coupled circuits that can be included in a coaxial magnetron for electronic tuning is limited primarily by the tolerable Q reduction caused by the resistive losses of the diodes. Therefore, some effort was spent during this program by the diode engineering group at Varian/Beverly to develop high voltage diodes with lower values of RF resistance. To do this, they concentrated on using higher resistivity silicon wafers and which were physically thinner than those used previously. Diodes were fabricated with a range of values for junction capacitance for test and evaluation to select the proper value for use in a Ku-band tube. This selection procedure was described before. Diodes were developed which had voltage breakdown values well in excess of 1,000 volts when measured in wafer form. However, when passivated, metallized, and diced into individual chips it was found that the voltage breakdown values degraded markedly. It was not uncommon for the breakdown values of some diodes to degrade to only a few hundred volts. These were satisfactory for cold test experiments, but obviously could not be used satisfactorily in a high peak power, operating tube. This accounts for some of the erratic behavior during high power testing. It was also found that some of the diodes degraded as a result of tube processing procedures. It is clear that these new developmental diodes were not as useful as those that were used in the first program effort.

5.4 Tube Fabrication and Test

Upon completion of the extensive evaluation of the coupled circuit parameters, two tubes were assembled for hot test operation. Both tubes utilized coupled circuits designed for the below resonance mode of operation providing capacitive loading to the coaxial cavity in the reverse biased state and inductive loading in the forward biased state. The tubes each contained twelve tuning circuits. In the first tube each circuit produced about 1 MHz tuning shift. The diode chips that were used had reverse breakdown voltage values near 1500 volts while in wafer form, but this deteriorated to about 350-400 volts when separated into chips and mounted into coupled circuits. It was speculated by the diode engineering group that this might be due to moisture on the diode surface and that a significant recovery might occur after bakeout and exhaust. However, this did not occur. Therefore, this placed a limit on the RF voltages that could be applied safely to the diodes in the reverse biased state.

Figure 8 shows the experimental tube. This tube differs in format from that used on the first program in that the header for the bias connectors is larger. The reason for this is that it was planned that a multiterminal connector would be incorporated into the tube body of later models to allow a simple method for connecting the bias voltages. However, for convenience, it was decided for these first experiments to continue using the same

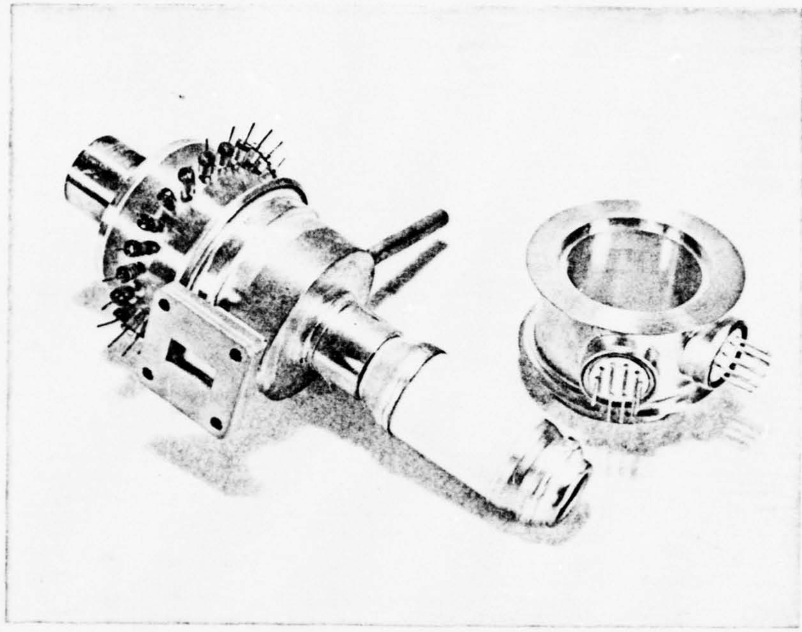


FIGURE 8

PHOTOGRAPH OF THE EXPERIMENTAL, ELECTRONICALLY-TUNED, COAXIAL MAGNETRON WITH COAXIAL CONNECTORS USED FOR ATTACHING BIAS VOLTAGE TO THE DIODES. THE NEW HEADER WITH MULTICONNECTOR TERMINALS IS ALSO SHOWN.

coaxial connector feedthrough arrangement used on the first program, but with the larger header that could later be adapted to plug-on connectors. By doing this it was also possible to make an early assessment of a permanent magnet configuration suitable for a final tube. A sample header with plug-on connectors is also shown in the figure. The experimental tube in a permanent magnet package is shown in Figure 9.

Cold test measurements were made on this tube after fabrication, bakeout and exhaust but before hot test evaluation. The total frequency shift obtained by all twelve tuning circuits was the same 13-14 MHz that was measured before exhaust. Tuning curves and variations in Qo were measured as a function of forward bias current. This was done to determine if any devastating effects occurred as the coupled circuit was tuned through the series resonant condition. It should be recalled that early in the development of this concept, this was a point of concern when considering this kind of coupled circuit configuration for intrapulse tuning. The first measurement made was to show the tuning change as a function of forward bias current. The resonant frequency of the tube was measured by a wavemeter in the cold test reflectometer used for Q measurements. The tuning shift for each circuit is just a little more than 1 MHz so that it would be difficult to measure a tuning curve very accurately for a single coupled circuit. As an alternative, a compromise was made by switching all twelve circuits simultaneously. It is assumed that each circuit will contribute about 1/12 of the

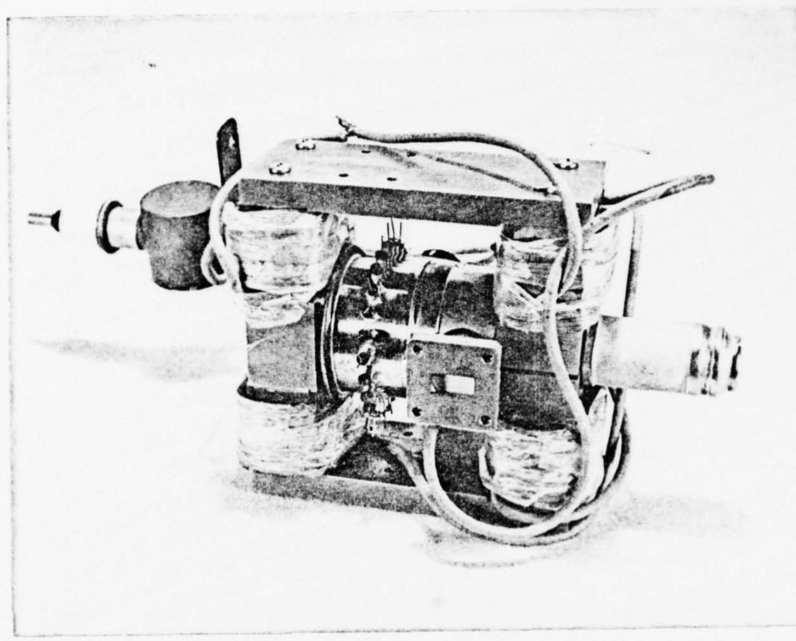


FIGURE 9

PHOTOGRAPH OF THE EXPERIMENTAL TUBE IN A PERMANENT MAGNET PACKAGE. THE WIRE WOUND COILS USED TO CHARGE THE MAGNETS ARE STILL ATTACHED TO THE TUBE.

total effect. The results are shown in Figure 10. It is observed that frequency tunes upward with forward bias current as expected. (Contrarily, a downward tuning curve is obtained for an above resonant coupled circuit.) It is also observed that a smooth, continuous frequency change is obtained and that the frequency transition is essentially completed at 20,000 microamps. This corresponds to a forward bias current of about 1.0 milliamps through each of the 24 diode chips in the 12 coupled circuits. Since the final bias current through each of the diodes will be of the order of 100 milliamps or more, it is apparent that the frequency transition is completed quite early in any switching cycle. This effect was also observed in the first program for the tuning circuits designed for above resonance operation.

Measurements were also made of the variation in Qo as a function of forward bias current. Measurements were again made as all twelve circuits were switched simultaneously to correlate with the tuning curve shown in Figure 10. The results are shown in Figure 11. It is seen that Qo decreases in value during the tuning change and then recovers to almost the original value measured at full reverse bias voltage. The low value in Qo occurs at about the same forward bias current value corresponding to the midpoint in the frequency transition. Even though it was not feasible to measure the frequency tuning transition during the switching of a single circuit, it was possible to measure the change in Qo. The results are shown in Figure 12. It is seen that

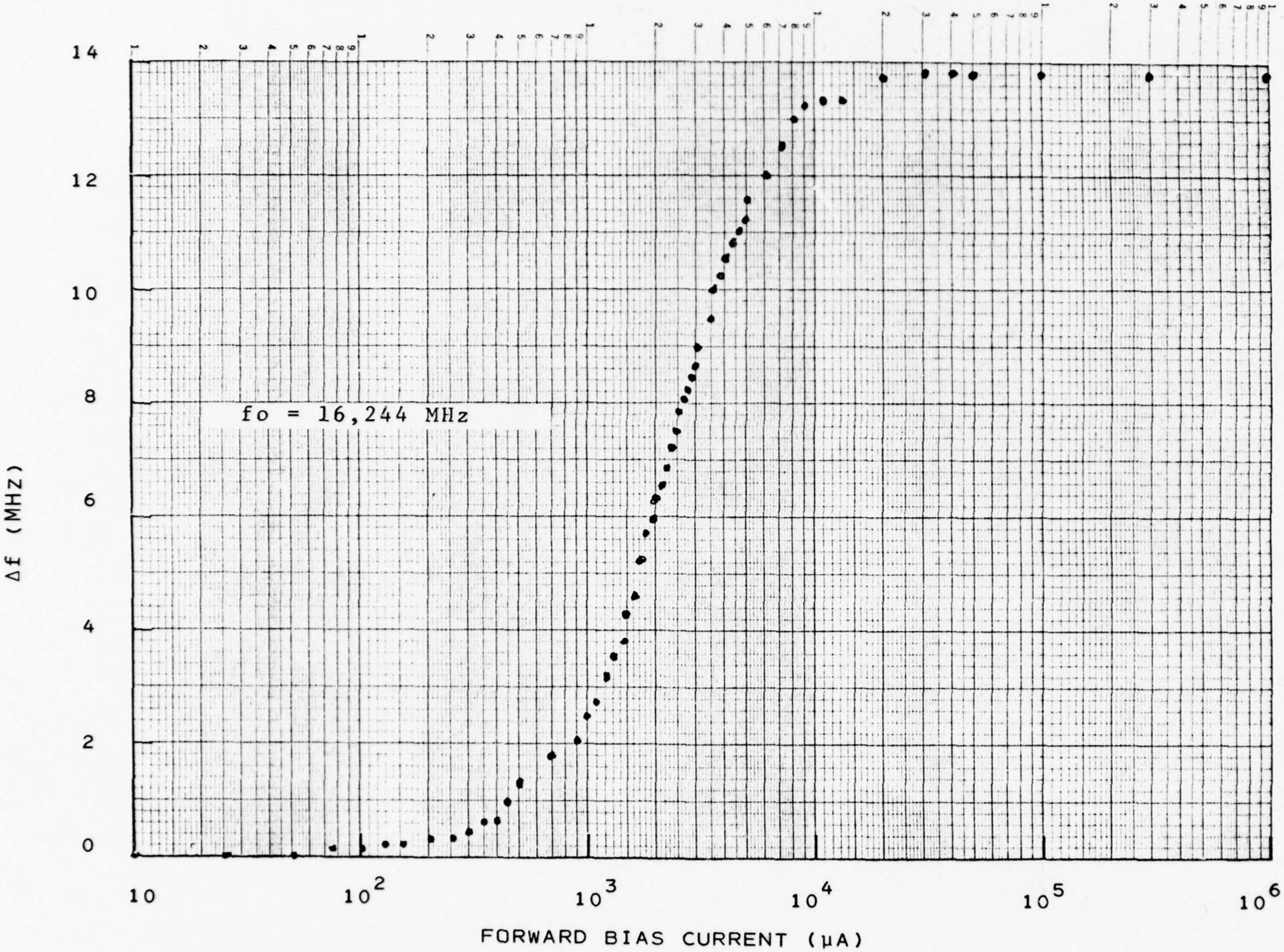



FIGURE 10--VARIATION OF THE ELECTRONIC-TUNED COAXIAL MAGNETRON RESONANT FREQUENCY WITH FORWARD BIAS CURRENT THROUGH TWELVE COUPLED CIRCUITS.

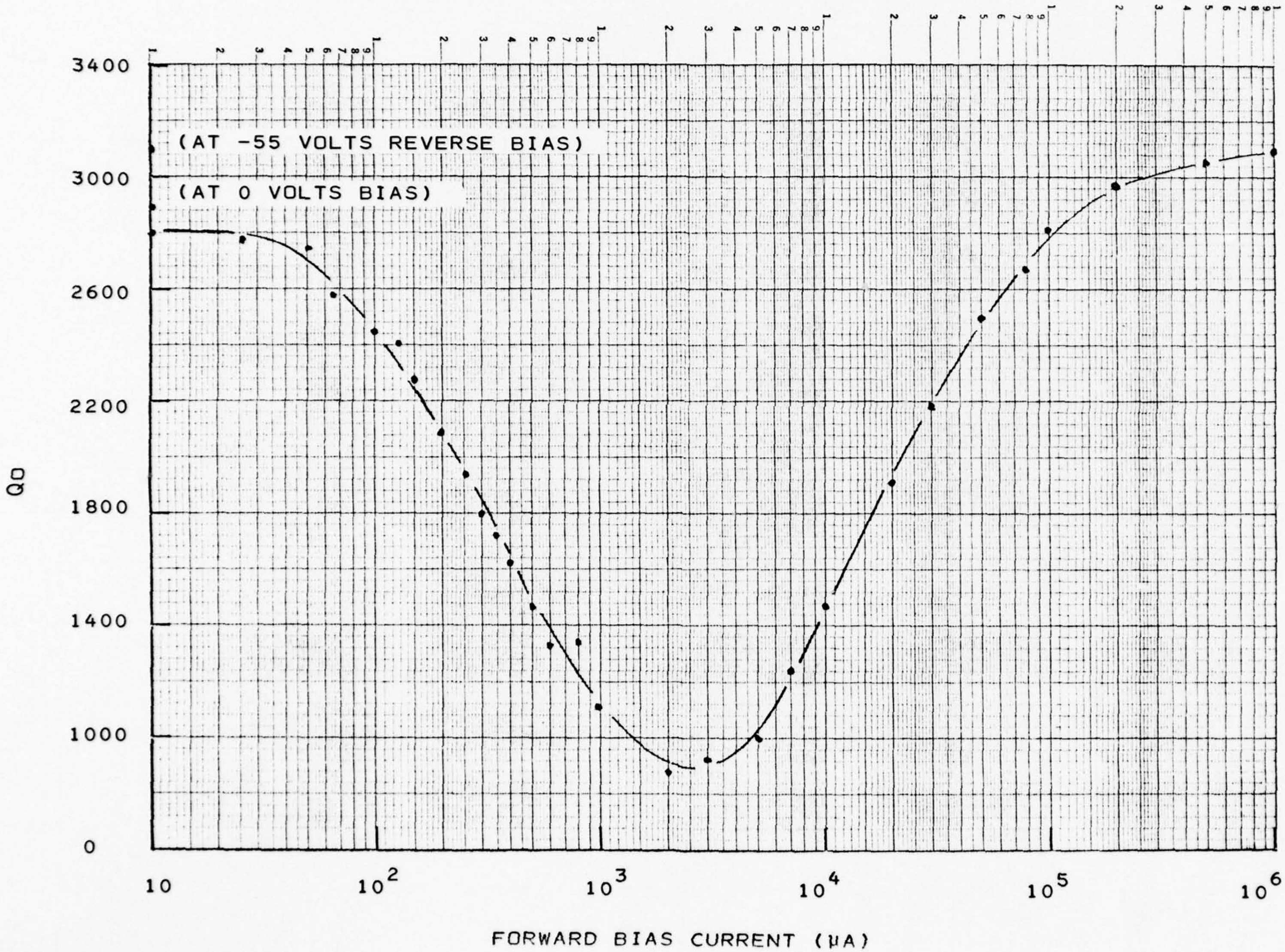



FIGURE 11--VARIATION OF Qo FOR THE ELECTRONIC-TUNED COAXIAL MAGNETRON WITH FORWARD BIAS CURRENT THROUGH TWELVE COUPLED CIRCUITS.

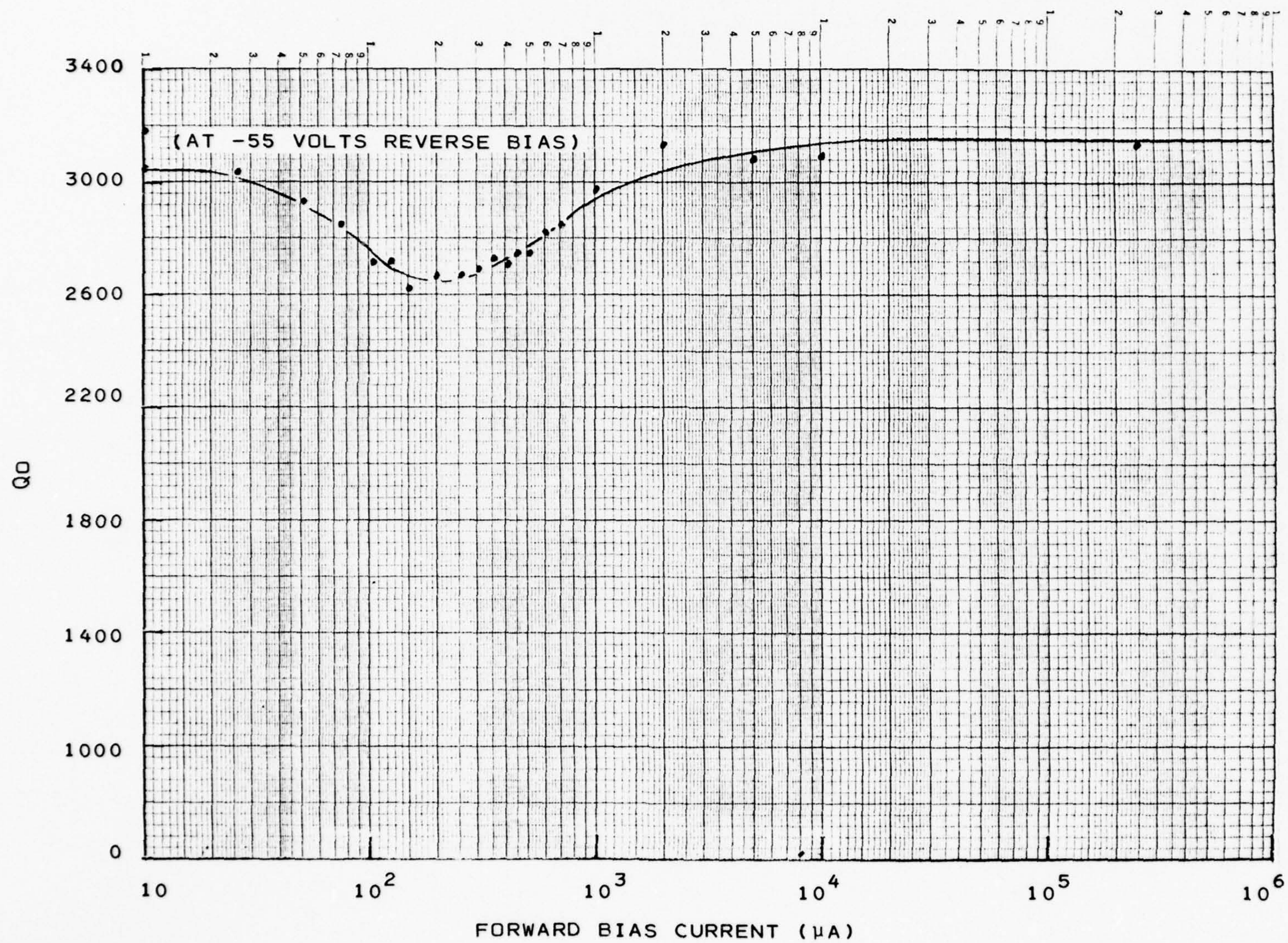


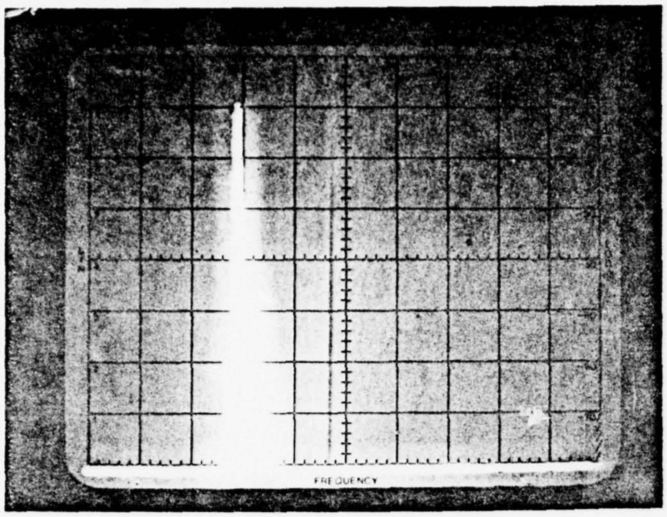

FIGURE 12--VARIATION OF Qo FOR THE ELECTRONIC-TUNED COAXIAL MAGNETRON WITH FORWARD BIAS CURRENT FOR ONE COUPLED CIRCUIT.

degradation in Qo is not too great when a single-coupled circuit is switched even though the circuit passes through a series resonant condition during the transition. The reason for this is that the resistive component of the diode complex impedance is very large at this point and limits the current flowing in the circuit even though the net reactance is zero. Qo recovers to a higher value as the forward bias current is increased to its full value and the diode series resistance decreases to its ultimately low value of about one ohm. These cold test results are very significant and gave further credibility to the belief that a single coupled-circuit geometry could be optimized for interpulse electronic tuning which could also be used for intrapulse tuning. Some simple experiments to further demonstrate this feasibility were performed with this tube and will be described in Section 5.5

This tube was operated at hot test and the peak power output was deliberately limited to 2-3 kW to be compatible with the measured value of reverse breakdown voltage. The vehicle used for these tests was a modified VMU-1000 magnetron. This tube normally has a power output of 60-80 kW or more. It was necessary to preload the cathode modulator and to decrease the magnetic field in order for the tube to operate at the 2-3 kW peak power level. Under these conditions, the output spectrum was deteriorated from normal. This is caused by the fact that the RF voltages on the anode at this low power level are not sufficiently intense to provide proper control of the circulating electron stream. Nevertheless, the tube was tuned electronically across the 12-13 MHz bandwidth using the 12 coupled circuits (fo = 16,244 MHz). There was no unaccountable change in power output with tuning. This was expected based upon cold test measurements of the tube after bakeout and exhaust. The small changes in power output that occurred with tuning for this tube were consistent with the measured changes in loaded $Q_L$ and circuit efficiency. In other words, both cold test and hot test results were in agreement at this power level. This is in contradistinction to the results obtained during the first phase of this effort in which the operating, electronically-tunable bandwidth was only about half of that measured at cold test and the power output varied unexpectedly by about 1.7 dB. The reason for this improvement is that the effect of the coupled circuit parameters are now much better understood and the fact that the tube operation was limited to a set of conditions compatible with the calculated values for the coupled circuit and PIN diode limitations.

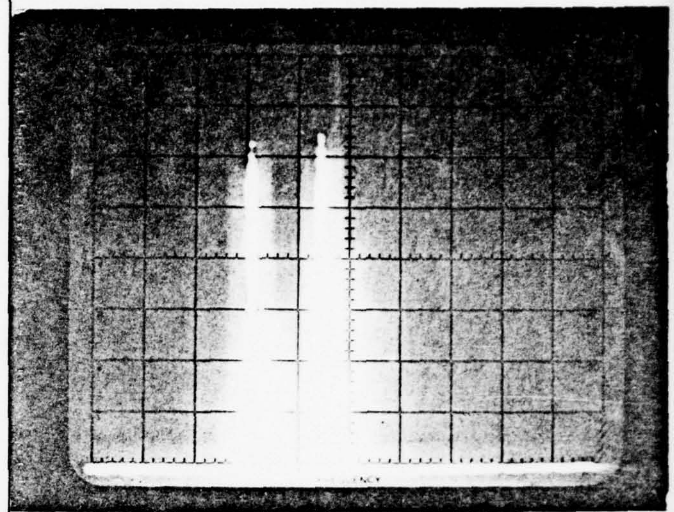
During the first phase effort the bias conditions on the diodes were altered using manually operated toggle switches. Electronic tuning was demonstrated with the operating tube, but the tuning rate was obviously very slow. As an adjunct to the present program, company funds were used to assemble a low voltage, electronically-driven switch that could be attached to the manually operated, bias switching circuitry. This was suitable for use with the low bias voltages needed for operating the tube at 2-3 kW peak power operation. With this device it was possible to demonstrate frequency shifting on a pulse-to-pulse basis as well as intrapulse tuning. In the "off" state for the electronically-driven switch, all coupled circuits remained in the reverse bias state regardless of the bias setting selected by the manual toggle switches. However, those coupled circuits for which the toggle switches were set for the forward bias condition were then turned "on" during the time intervals that the electronically-driven switch was activated. By activating the electronically-driven switch on alternate pulses for the magnetron, it was possible to demonstrate interpulse tuning. The frequency shift occurred between that frequency corresponding to all circuits in their reverse biased state to a frequency determined by whatever number of toggle switches were in the forward biased position.

Figure 13 shows some of the experimental results. The figure shows photographs of the linear oscilloscopic display of a broadband spectrum analyzer. Four conditions are shown. For Figure 13A, all toggle switches were in the reverse biased state so that the same frequency (fo = 16,272 MHz) was generated by the magnetron regardless of the status of the electronic switch. For Figure 13B, six toggle switches remained in the reverse biased state and six were set in the forward biased position. On one pulse the electronic switch remained inoperative and the same frequency was generated



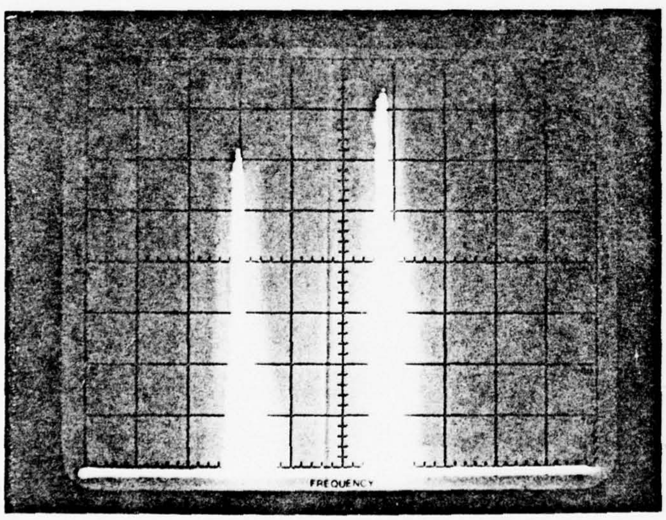

A

PULSE 1--12 CIRCUITS REVERSE BIASED
PULSE 2--12 CIRCUITS REVERSE BIASED



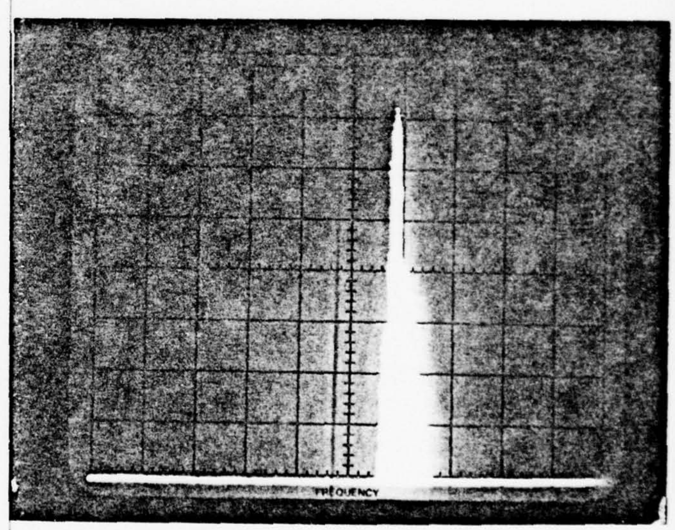
B

PULSE 1--12 CIRCUITS REVERSE BIASED
PULSE 2-- 6 CIRCUITS FORWARD BIASED




C

PULSE 1--12 CIRCUITS REVERSE BIASED
PULSE 2--12 CIRCUITS FORWARD BIASED



D

PULSE 1--12 CIRCUITS FORWARD BIASED
PULSE 2--12 CIRCUITS FORWARD BIASED

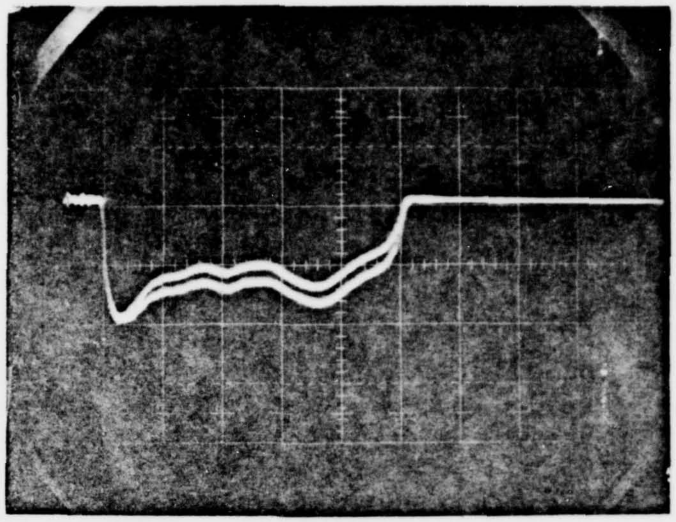
FIGURE 13--SPECTRUM PHOTOGRAPHS SHOWING INTERPULSE FREQUENCY AGILITY

as in Figure 13A. On the next pulse, the electronic switch was activated just prior to cathode pulsing the magnetron and remained "on" for the full cathode pulsed period. For this pulse the magnetron output was at a frequency fo plus approximately 6.5 MHz. Similarly for conditions of Figure 13C, with twelve toggle switches in the forward biased position, the magnetron output frequency alternated between fo and fo plus about 13 MHz. For conditions of Figure 13D, the repetition rate of the drive pulse to the electronic switch was doubled so that all coupled circuits were forward biased for each magnetron pulse. The output frequency of each pulse was fo plus 13 MHz. In all of these tests the coupled circuits were returned to and remained in the reverse biased condition during the inter-pulse period. Conditions were changed only for the time duration of the magnetron pulse. Hence these test results are a demonstration of a completely electronic-tuned coaxial magnetron such as would be used in a system application.

It is apparent from inspection of the spectrum photographs that this performance is not typical of a coaxial magnetron. As noted before, this is the result of operating this particular magnetron in a set of conditions that is far from normal power output for the tube. Spectrum photographs shown in the report from the first phase effort are much more typical where the PIN diode-tuned coaxial magnetron was operated at peak power levels of 30-45 kW. Moreover, this same technical approach to electronic tuning was explored by others in a Ku-band tube specifically designed for operation at a peak power output of 1.0 kW.[2] There, too, electronic tuning was successfully demonstrated. Oscilloscopic photographs of the spectrum output of this tube were typical of a coaxial magnetron because the tube was operated in its intended range of characteristics. The same kind of performance would be expected at 60 kW power output from a tube with a coupled circuit design and PIN diodes that were optimized.

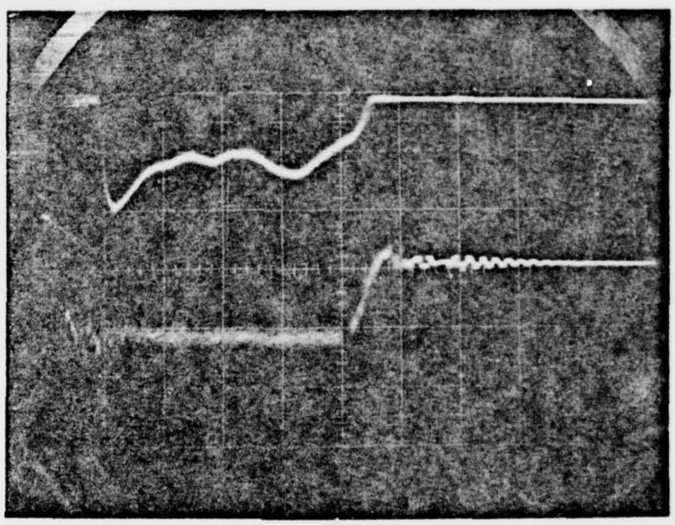
Figure 14A shows the detected RF output pulse during the interpulse tuning mode of operation. The difference in power output on alternate pulses is clear. This occurs because the loaded $Q_L$ and overall circuit efficiency for the magnetron cavity are not the same at the two frequencies. This effect can be minimized or eliminated by a more judicious choice of coupled circuit parameters. The upper trace in Figure 14B shows the detected RF output pulse of the magnetron and the lower trace shows the current pulse delivered by the electronic switch to the coupled circuits. The temporal overlap of the current pulse with the magnetron power output is clearly seen.

Upon completion of these tests attempts were made to operate the magnetron at higher power levels. This, of course, applies more RF voltage to the diodes in the reverse biased state. The tube became gassy and the diodes were subsequently damaged. This is similar to what has occurred before then tubes were operated such that the diodes were exposed to excessive RF voltages. No



A

PHOTOGRAPH OF THE DETECTED RF PULSE DURING INTERPULSE FREQUENCY AGILITY



B

PHOTOGRAPH OF THE DETECTED RF PULSE TOGETHER WITH THE SAMPLED FORWARD BIAS CURRENT PULSE TO THE PIN DIODES TO SHOW THE TEMPORAL OVERLAP.

FIGURE 14

further tests were made with this tube.

The tube was rebuilt using diode chips that had been coated with an inorganic resin commonly used in the semiconductor industry. The purpose was to try to preserve for the diode chip the high voltage breakdown characteristics that could be demonstrated while in wafer form.

The tube was assembled with 12 coupled circuits using these diodes. The 12 circuits gave a total frequency shift of approximately 18 MHz at cold test. The diode breakdown voltage was measured after bakeout, exhaust, and heater activation just prior to hot test evaluation and was found to be equal to or to exceed 800 volts for all coupled circuits. These same values were also measured before exhaust. Calculations indicate that this should have been adequate for proper tuning at an RF power output level of 30-40 kW.

The tube was delivered to hot test and operated at low peak power levels. When the diodes were operated in reverse bias the tube was observed to outgas severely. The reason for this is not understood. After operating for about a half hour at low peak power levels (3-5 kW), the tube became extremely gassy and RF performance degraded severely. The tube was removed from the test set and the voltage breakdown characteristics of the coupled circuits were measured. Three circuits showed very low resistance in the reverse direction and two showed resistance values of only a few megohms. The rest were normal.

The tube was then moved to the cold test set and evaluated. Very low values for Qo were measured so long as these damaged circuits were reverse biased, but increased to normal values if they were switched to forward bias. This condition prevailed whether the remaining circuits were in a forward or reverse biased state. Moreover essentially the same tuning range could be obtained at cold test when all of the diodes were switched from reverse to forward bias as was obtained prior to the tube operation. This mode of failure appears to be different from any that have occurred heretofore. It is not known if this was associated with the resin coating of the diodes.

Although the new developmental PIN diodes showed lower resistive losses in the magnetron (leading to higher values for Qo), it is clear that they did not function as well in a tube environment as those that were used in the tubes in the first phase program. In hindsight it now appears that it would have been better to continue working with those when optimizing the selection of the coupled circuit parameters for this effort. It is believed that these would have permitted proper tube operation and electronic tuning at power levels of 40-60 kW. This belief is based on the fact that operation was demonstrated in the first program at power levels of 30-50 kW even though the coupled circuit and diode parameters were such that excessive RF voltages were applied to the diodes.

At this point in the program the contract funds were completely expended. In addition, the microwave silicon diode engineering and manufacturing facility at Varian (Beverly, Massachusetts) was sold and transferred to Microwave Associates (Burlington, Massachusetts) and was no longer available as an on-site supplier. However, some additional work was done using company funds. High voltage PIN diodes were obtained from Microwave Associates. These were Cermachip™ PIN diode chips (model MA-47401). These have a special impervious, hard glass passivation which allows them to preserve their high voltage breakdown characteristics. However, they do appear to be somewhat more lossy than those supplied by the Varian diode engineering group. Chips were selectively chosen to have the proper value of junction capacitance to provide the correct tuning shift when incorporated in a coupled circuit. The tube was rebuilt with twelve coupled circuits using these diodes. The tube was baked, exhausted, and pinched off. The coupled circuits were then checked and all found to have reverse voltage breakdown in excess of 800 volts. A total of 20-21 MHz tuning was obtained with all twelve coupled circuits. The tube is now ready for test. At the time of the writing of this report, there are no additional funds available to complete the cold test and hot test evaluation of this tube.

## 5.5 Intrapulse Tuning

All of the cold test results obtained during the first program using coupled circuits designed for above-resonance operation and during this program for circuits designed for below-resonance operation showed that the frequency tuning transition is completed when about one milliampere of forward bias current is passing through each diode chip. In addition most of the variation in loaded Q is also completed at a bias current of four or five times this amount. These results gave strong indication that an intrapulse tuning mode of operation was quite feasible even though the loaded Q degraded during the transition. It was believed that an appropriately designed bias current pulse with a fast, leading edge, rise time would cause the diodes to be moved through the critical loss region so quickly that the magnetron operation would not be impaired and the diodes would not be damaged. Although it was not part of the original plan for this program, it proved feasible to use the electronically-controlled switching arrangement described before to perform a simple demonstration of intrapulse electronic tuning. This was done by changing the temporal alignment of the diode forward bias current pulse with respect to the magnetron cathode pulse. It should be recalled that PIN diode characteristics are such that it is possible to switch them more rapidly from a reverse biased state to forward bias than it is in the reverse direction. Hence intrapulse tuning was accomplished by progressively advancing the time of the leading edge of the forward bias current pulse into the time duration of the magnetron RF output pulse. No attempt has been made to investigate the reverse tuning sequence at hot test.

Figure 15 illustrates schematically what would be expected to occur in the ideal case. Figure 15A illustrates the detected RF output pulse and the main lobe of a spectrum analyzer display when the diode switching cycle occurs after the magnetron pulse. In this case, the diodes are reverse biased for the whole pulse. Power is generated only at frequency $f_1$ during the whole pulse. Figure 15B shows what occurs when the diodes are switched for a small portion of time near the end of the magnetron pulse. Power is now generated at two frequencies. The main lobe of the spectrum at $f_1$ is now lower in amplitude because less total energy is generated at $f_1$ during the pulse and the spectrum at this frequency is broader because of the narrower pulse length for $f_1$. A small amount of energy is generated at the second frequency $f_2$. Therefore, the spectral display at that frequency shows a main lobe that is smaller in amplitude and wider in frequency spread than that at $f_1$. Figure 15C illustrates what occurs when the diode switching occurs at the early part of the magnetron pulse. It is the reverse of that shown in Figure 15B. Figure 15D shows what occurs when the diodes are forward biased during the entire magnetron pulse.

Figures 16 A, B, and C show the experimental results. The photographs show the detected RF output pulse and the relative timing of the diode forward bias current pulse. Increasing current magnitude is shown by a downward deflection on the oscilloscopic display.

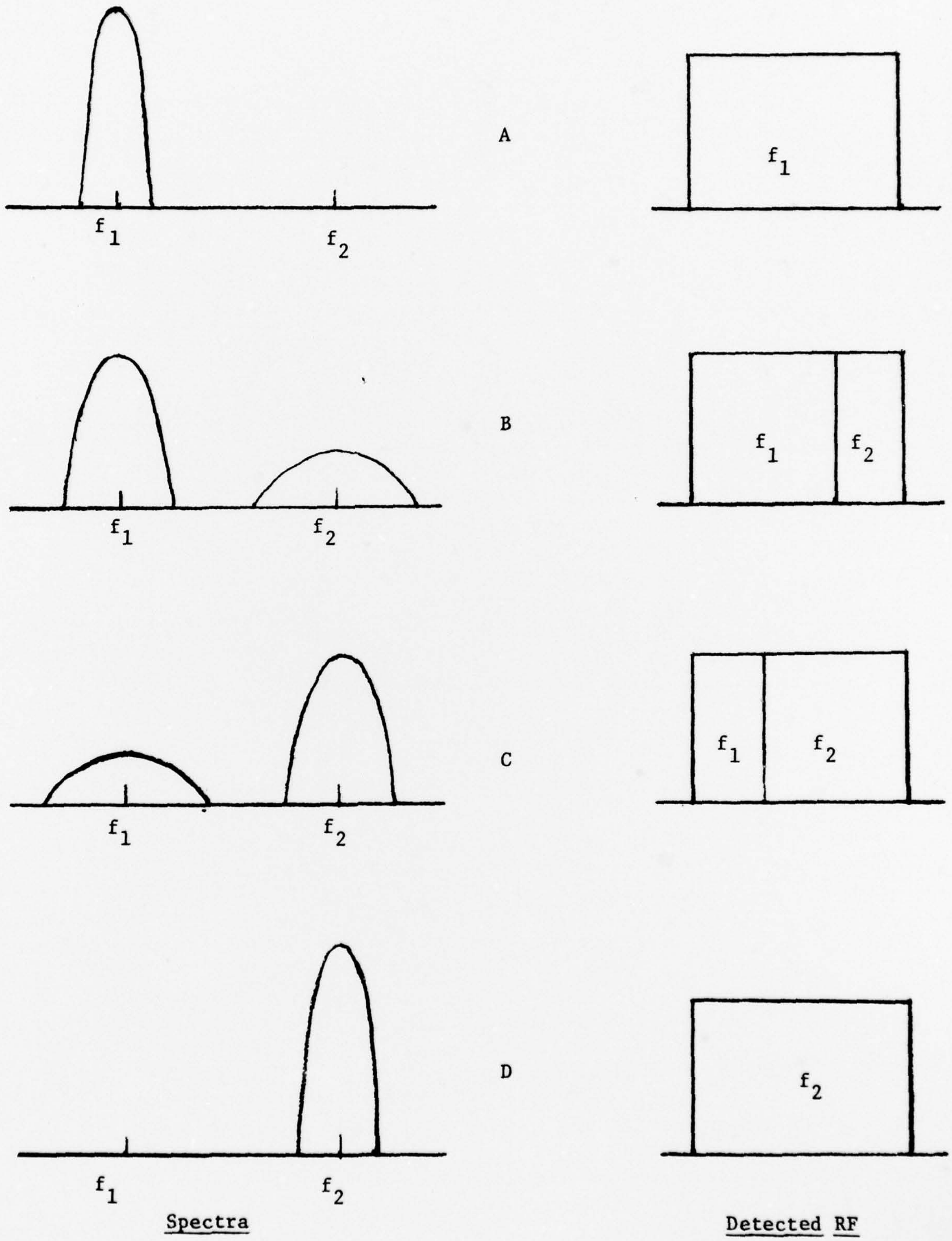
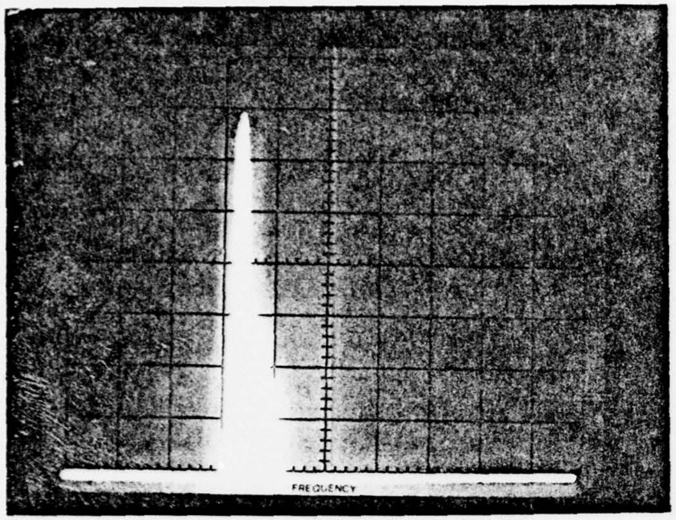
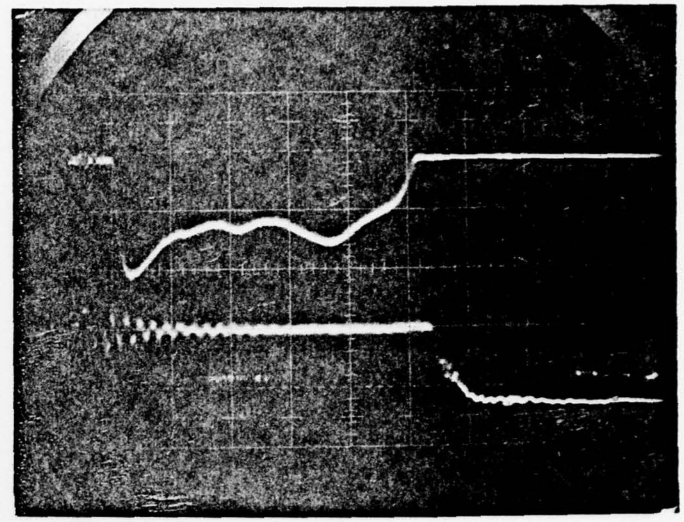
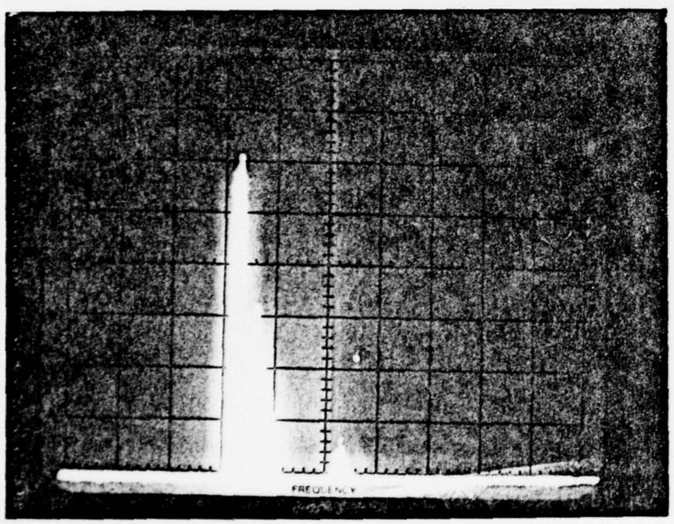



FIGURE 15--SCHEMATIC ILLUSTRATION OF INTRAPULSE TUNING EFFECTS.




REVERSE BIAS
2.5 µSEC.
FORWARD BIAS
0.0 µSEC.






REVERSE BIAS
2.0 µSEC.
FORWARD BIAS
0.5 µSEC.

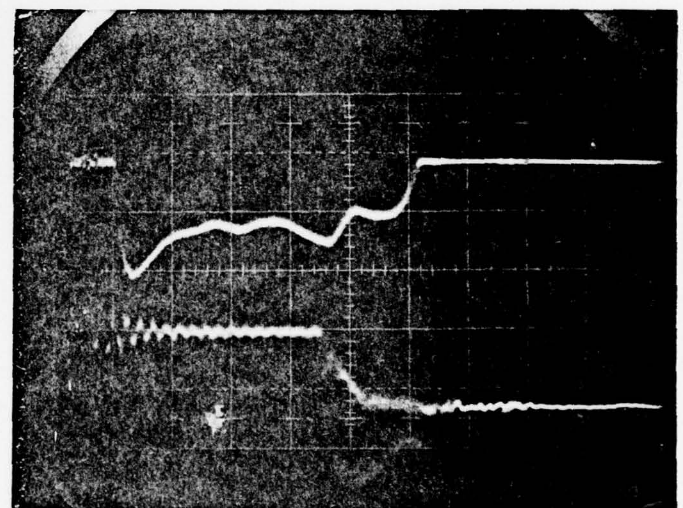
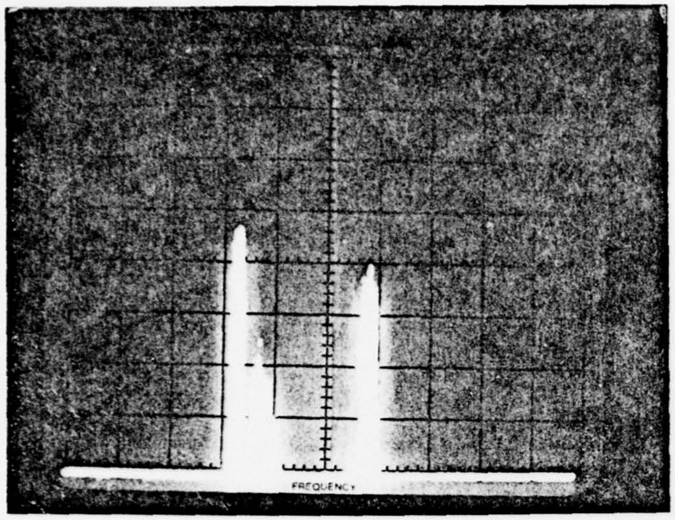
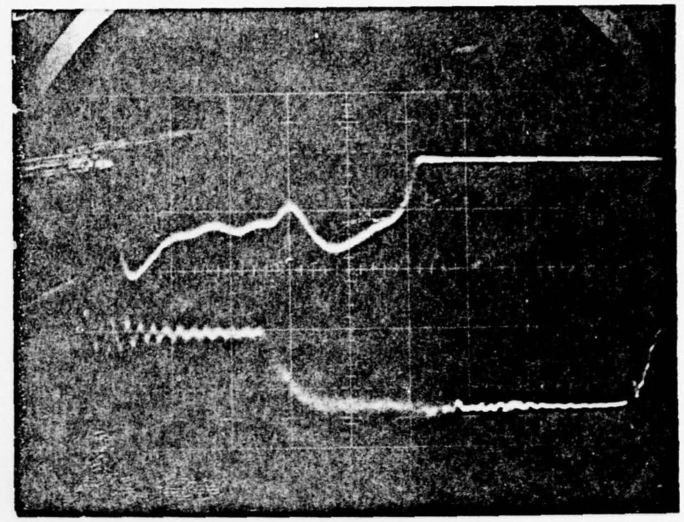
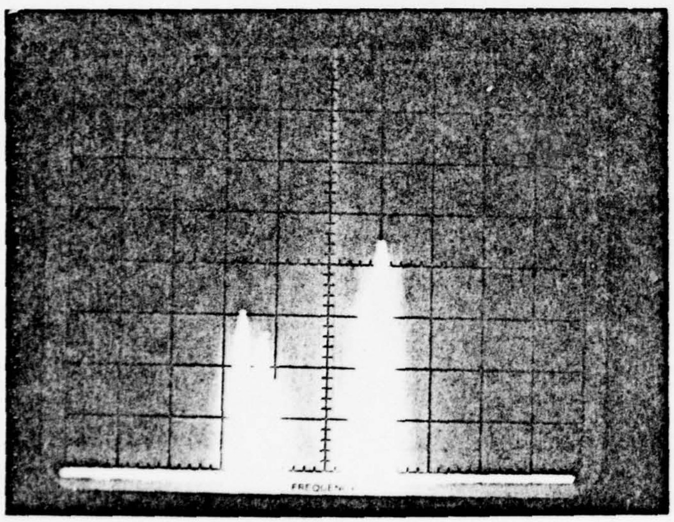


FIGURE 16A--PHOTOGRAPHS OF RF SPECTRA, DETECTED RF, AND FORWARD BIAS CURRENT PULSE TO THE COUPLED CIRCUITS DURING INTRAPULSE TUNING.
SCALE: 5 MHZ/CM 2.0 DB/CM




REVERSE BIAS
1.5 μSEC.
FORWARD BIAS
1.0 μSEC.






REVERSE BIAS
1.0 μSEC.
FORWARD BIAS
1.5 μSEC.

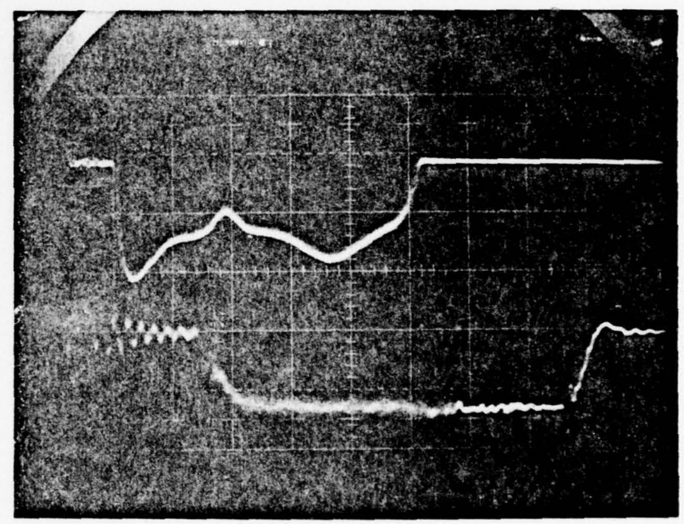
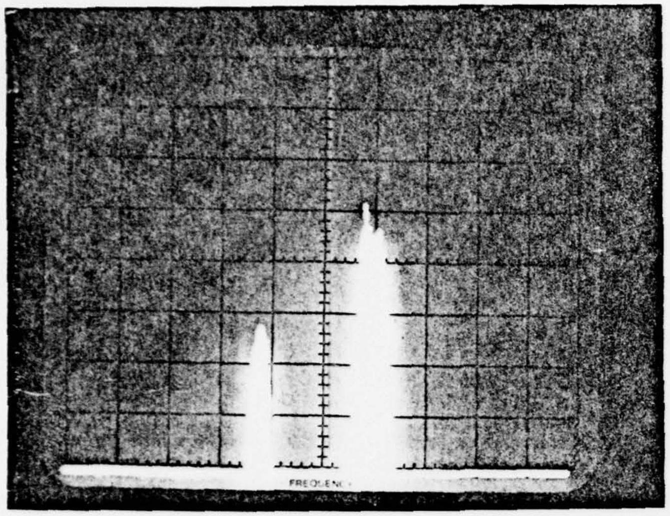
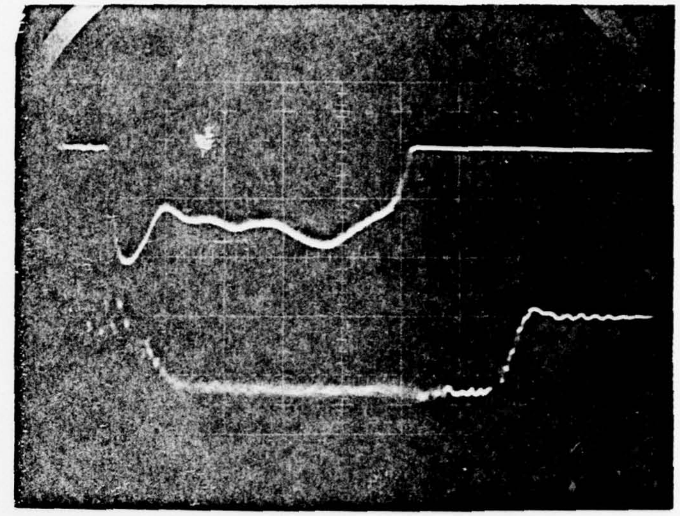
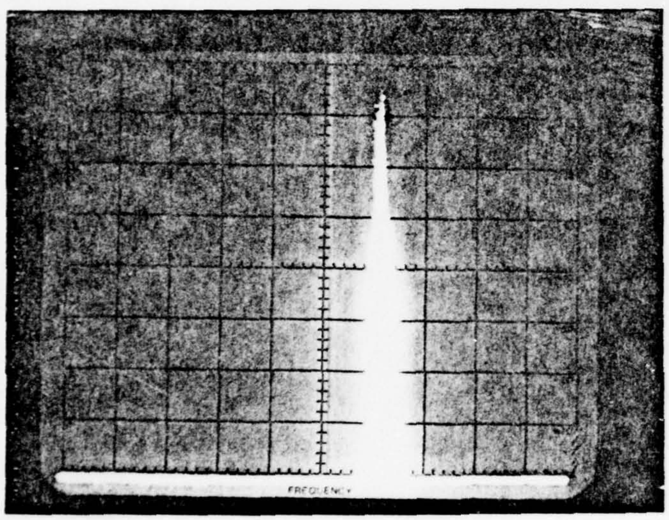


FIGURE 16B--PHOTOGRAPHS OF RF SPECTRA, DETECTED RF, AND FORWARD BIAS CURRENT PULSE TO THE COUPLED CIRCUITS DURING INTRAPULSE TUNING. SCALE: 5 MHZ/CM 2.0 DB/CM



REVERSE BIAS
0.5 μSEC.
FORWARD BIAS
2.0 μSEC.





REVERSE BIAS
0.0 μSEC.
FORWARD BIAS
2.5 μSEC.

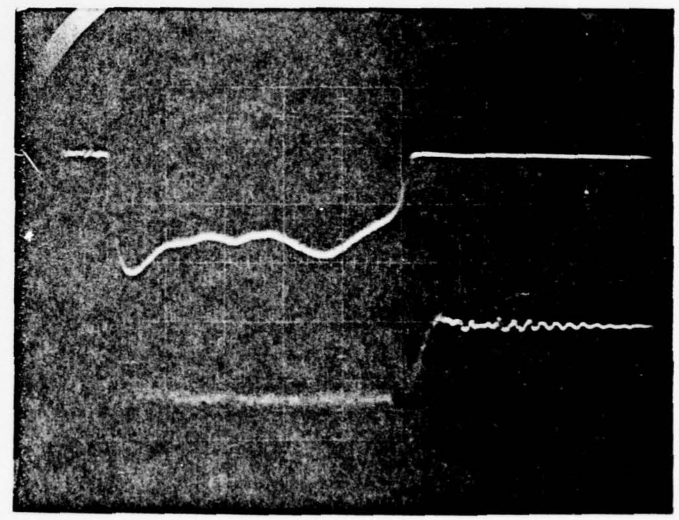


FIGURE 16C--PHOTOGRAPHS OF RF SPECTRA, DETECTED RF, AND FORWARD BIAS CURRENT PULSE TO THE COUPLED CIRCUITS DURING INTRAPULSE TUNING. SCALE: 5 MHZ/CM 2.0 DB/CM

The figures show the sequence as the diode forward biased time duration is advanced progressively from after the magnetron pulse to complete overlap. It can be seen that the rise time of the diode bias current pulse is about 0.25 microseconds. This is not very fast, but even so the perturbation in the amplitude of the RF output pulse does not seem severe during the switching transition. It should also be remembered that to obtain a clear demonstration of this effect in this experiment all twelve of the coupled circuits were switched simultaneously during this transition. In practice, for a radar application, it is most likely that intrapulse tuning would be accomplished by sequential switching of only one coupled circuit at a time to obtain a pulse compression effect. Therefore, the perturbation in the amplitude of the RF output pulse would be significantly less than seen here.

The transition in spectral power from $f_1$ to $f_2$ in the experiment is clearly shown. No significance should be attached to the actual spectrum shapes shown in these figures for reasons that were discussed in the previous section. The experiment is admittedly primitive but it would be premature to try to do more at this time. A properly performed experiment can only be done after a satisfactory electronically-tuned magnetron and appropriately designed switching circuitry are available.

These results are interpreted as giving still further credibility to the belief that a PIN-diode coaxial magnetron can be used for interpulse tuning as well as intrapulse tuning. It is specifically noteworthy that a single coupled-circuit geometry designed for interpulse tuning can also be used for intrapulse tuning. This was one of the original program objectives.

## 6.0 CONCLUSIONS

During this program the validity was reaffirmed for the analysis that was developed previously for the PIN diode-switched, coupled circuit tuning technique for a coaxial magnetron. It was shown, however, that some cut and try trimming procedures are necessary at Ku-band to get the degree of quantitative agreement between calculated and epxerimental results that is necessary for proper operation of the diodes. In particular, it seems that the value of junction capacitance that is measured at 1 MHz is somewhat different from the value that is effective at Ku-band. Procedures were developed for selection of the correct diode chips to be used. With this approach, agreement between cold test measurements and hot test operation of the tube was shown at low peak power output levels from the magnetron.

Attempts to develop improved high voltage PIN diodes with lower RF resistive losses were unsuccessful. Diodes were fabricated that had thinner layers of intrinsic semiconductors between the P and N junctions which did, indeed, have lower loss than those used previously. The reverse breakdown voltage for these diodes when still in the wafer format was measured to be greater than 1000 volts. However, this value degraded significantly when the wafers were diced into individual chips. The reason for this was that the passivation procedures used on the diodes was not satisfactory. These shortcomings placed limitations on the RF capabilities of the diodes and restricted the operating magnetron tests that could be performed. Meaningful tests could only be performed at low peak power levels to restrict the RF voltages applied to the diodes when in the reverse biased state.

Electronic circuitry was assembled that allowed a simple demonstration of pulse-to-pulse, electronically-tuned, frequency agility. This is the first time that this has been accomplished for a PIN diode-tuned magnetron. Intrapulse tuning was also demonstrated using this electronic circuitry. Both interpulse tuning and intrapulse tuning were demonstrated using the same coupled circuit configuration.

Based upon the results of the preceeding program and the advances in understanding of the coupled circuit properties made during this program, it is believed that a Ku-band coaxial magnetron can, indeed, be developed that will tune electronically over at least 50-100 MHz. This will require about fifty PIN diode-switched, coupled circuits. Operation over this bandwidth at 50-60 kW peak power output seems obtainable. Even more of a power-bandwidth product is feasible with advances in high voltage, low loss PIN diode characteristics.

# References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2. Wynn, A.P., (Microwave Associates, Watsonville, California) "Diode-Magnetron Cavity", Informal technical report prepared for the United States Naval Electronics Laboratory Center, San Diego, California, Contract No. N00123-76-C-1804 (April 1977).