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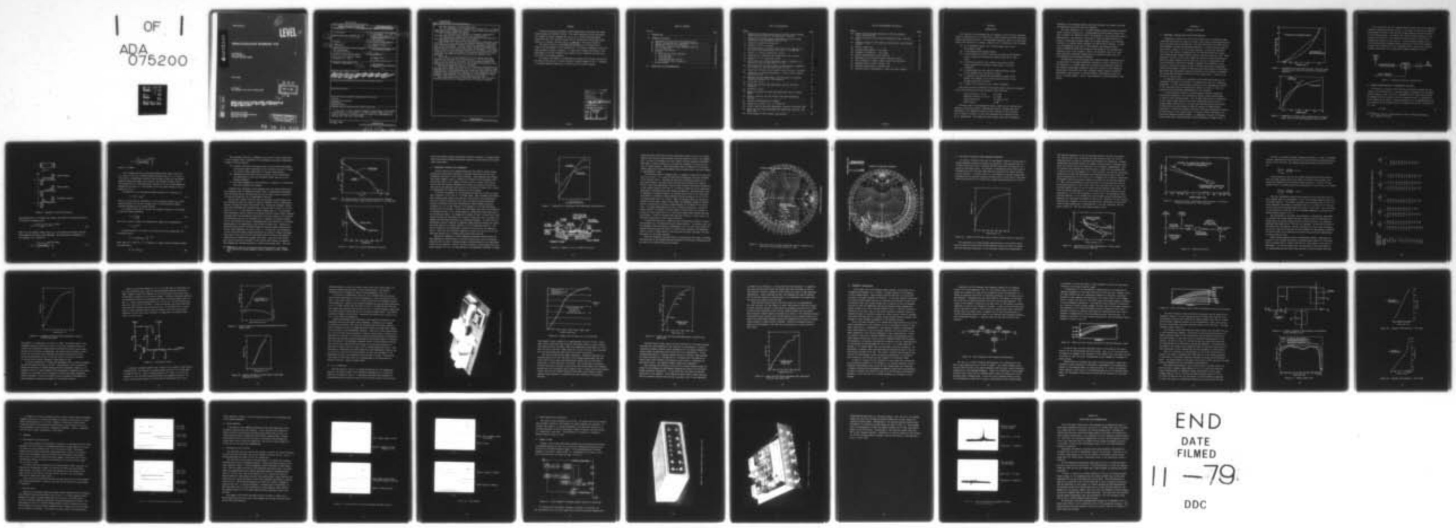

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SINGLE-OSCILLATOR WIDEBAND VCO

D. Mawhinney
RCA Laboratories
Princeton, New Jersey 08540

1 April 1978

Final Report
For the period 1 July 1977 to 15 March 1978

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Washington, D.C 20360

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The effort on this program was aimed at fabricating a low-voltage, high-speed VCO to cover the 11- to 18-GHz frequency range for use in a set-on VCO-type of frequency memory in place of an arrangement requiring three VCOs and a multiplexer.

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The most important accomplishements were:

(1) The development of a low-power VCO covering the 11- to 18-GHz range using a GaAs hyperabrupt junction varactor diode and requiring a very small tuning voltage requirement;

(2) The fabrication of a new type of frequency discriminator which uses the roll-off characteristic of a microwave FET;

(3) Measurements leading to an understanding of the behavior of GaAs hyperabrupt varactors at high input levels.

GaAs hyperabrupt varactors were produced having capacitance ratios in excess of 10:1, but less than the expected frequency tuning ranges were originally obtained from VCOs with these hyperabrupt varactors used as the tuning diode. Special network analyzer measurements with varying levels of input drive power showed the impedance of the hyper-abrupt varactors to be unusually sensitive to the incident power level resulting in a significant reduction in maximum capacitance at levels consistent with those to which the varactors are exposed in the oscillator.

The actual use of the broadband VCO in the memory system was restricted to less than the full band because: (a) the VCO became noisy in several spots in the band; (b) the government-supplied TDA limiter used in conjunction with the FET frequency discriminator had a considerable variation in output vs. frequency.

The overall system was operated in an open-loop configuration with approximately a 30-MHz error over the 12.5 to 16.5-GHz frequency range. Although system pulse measurements and closed-loop tests were not performed because a required error amplifier was not completed during the program, it was estimated that revisions in the discriminator output amplifier would result in a 50-nsec open-loop set-on time.

With these modifications, closed-loop operation over the usable 4000-MHz bandwidth with a frequency error of ± 3 MHz is expected.

PREFACE

This Final Report was prepared at RCA Laboratories, Princeton, New Jersey under Contract No. N00039-77-C-0271. The report describes the work performed on a Single Oscillator Wideband VCO for an 11- to 18-GHz Frequency Memory System from July 1977 through October 1978 in the Microwave Technology Center, under Dr. F. Sterzer, Director and D. D. Mawhinney, the project engineer.

The author wishes to acknowledge the assistance of H. Milgazo and P. Pelka in the development of the wideband VCO. The special hyperabrupt varactors were provided by James J. Napoleon. A. Rosen and B. Dorman contributed to the development of the FET Frequency Discriminator and H. Wolkstein provided valuable advice and program guidance.

The author also wishes to acknowledge the support and direction provided by Ron Wade and Nate Butler of Naval Electronic Systems Command of Mr. T. Timbutake of the Naval Research Laboratory on this and prior related programs.

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SECTION I

INTRODUCTION

The objective of this program was to redesign a set-on VCO type frequency system to operate from 11 to 18 GHz with a single voltage controlled oscillator using a hyperabrupt varactor. The redesigned system was then to be fabricated, tested, and delivered as a single, integrated unit consisting of the following:

(1) An rf amplifier-limiter for a uniform power output over a wide dynamic range.

(2) A discriminator and shaping network.

(3) A follow-and-hold circuit to memorize the applied discriminator output voltage upon appropriate command during the rf input pulse.

(4) A difference amplifier that compares the stored voltage address against the real-time voltage output of the discriminator.

(5) A summing amplifier that adds the sample-and-hold voltage to the feedback error correction voltage.

(6) A linearizer that matches the discriminator output (after holding and summing) to the tuning characteristics of the voltage controlled oscillator.

(7) A single VCO covering the total tunable bandwidth.

The single oscillator wideband VCO frequency memory system was intended to meet the following objective performance specifications:

Set-on accuracy at 50 ns:	$\pm$ 0.5 MHz
Frequency stability at 50 μs:	$\pm$ 2.0 MHz
Input pulse power:	+15 dBm $\pm$ 1.5 dB
Power output:	+5 dBm

The basic work on the wideband VCO using a GaAs varactor had been performed on a previous contract, "Hyperabrupt Varactor Voltage-Controlled Oscillators," No. N00039-75-C-0474, and had resulted in the conclusion that it would be possible to build one high-speed VCO covering the full 11- to 18-GHz band. The single VCO would replace three VCOs originally intended for the frequency memory system and eliminate the complex switching and diplexing which would have been required.

The basic design for a 7- to 11-GHz frequency memory system was developed under a previous contract for a "Locked-Open-Loop VCO Frequency Memory System," (Contract No. N00039-74-C-0227) and adapted to this program with several modifications. The purpose of this type of frequency memory system is to produce a continuous microwave signal at the same frequency as an incoming rf pulse of an unknown threat frequency for ECM deceptive jamming. In addition, developments in the area of FET frequency discriminators under Contract N00039-76-C-0280 were applied to the design of the frequency discriminator used in this program. Some of the pertinent results of these three previously completed programs will be included in this report for both background and explanatory purposes.

The additional work done during this program included continuing effort in application of the GaAs hyperabrupt varactors to obtain operation over the complete 11- to 18-GHz range and to determine the extent and cause of the limited tuning range obtained in practice, revision of the timing and amplification circuits of the basic frequency memory system for improved performance, and extension of the FET frequency discriminator work into the 11- to 18-GHz region. Each of these subjects is also discussed in this report.

SECTION II

TECHNICAL DISCUSSION

A. HYPERABRUPT VARACTOR VCOs FOR ECM APPLICATIONS

Hyperabrupt varactors are used as the tuning diode in wideband voltage controlled oscillators in order to provide a more linear tuning characteristic and an increased tuning sensitivity. Most ECM applications for VCOs require both wideband coverage and high-speed operation. In those systems which require linear tuning, it has often been necessary to add active linearizer circuits to the system to compensate for the inherently nonlinear tuning curve obtained when standard abrupt junction varactor diodes are used. These linearizer circuits can be quite complex and costly for those applications where the tuning response must be rapid (in the tens of nanoseconds) and can be especially difficult to employ in feedback type frequency control circuits. During this program as well as during the previous hyperabrupt varactor VCO program, a number of VCOs have been fabricated and tested which have shown that considerably improved linearity can be achieved in wideband VCOs using GaAs hyperabrupt varactors as the tuning diode. A typical comparison is shown in Fig. 1.

In many applications, the bandwidths and linearities provided by the hyperabrupt VCO would be sufficient to eliminate the need for a linearizer altogether. In other applications, the extent of the compensation required of the linearizer would be substantially reduced as would, in turn, the complexity and operational disadvantages of the linearizer.

A second important feature of the hyperabrupt varactor emphasized during these programs is the considerably reduced tuning voltage needed to cover a given frequency range. For low speed applications, minimization of the tuning voltage swing is relatively unimportant unless there is a voltage supply limitation, but for high speed ECM applications generation of large tuning voltage swings is difficult because of semiconductor limitations. During this program, VCOs built with GaAs hyperabrupt varactors have been shown to have exceptionally low tuning voltage requirements for relatively wideband frequency ranges. A comparison of typical VCO tuning curves using abrupt and hyperabrupt junction varactors is shown in Fig. 2.

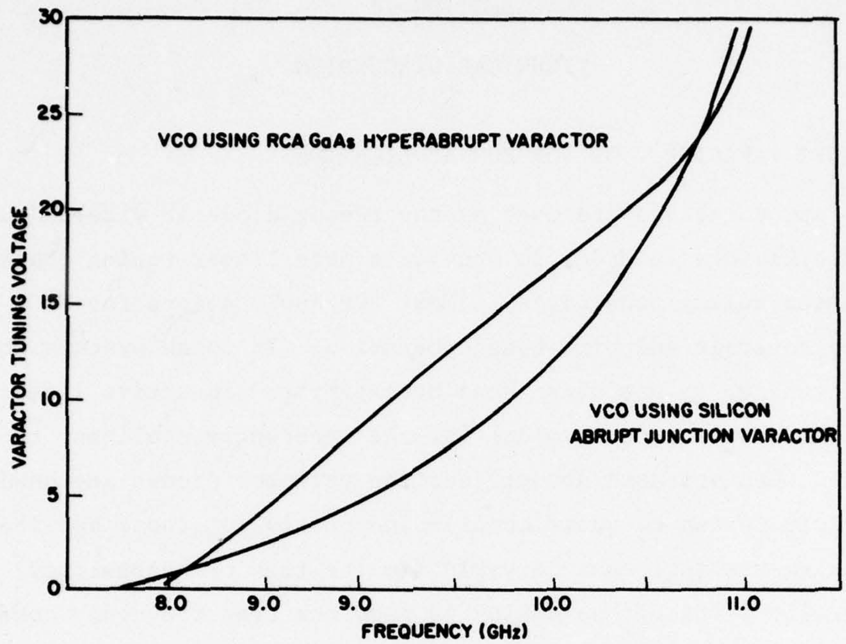


Figure 1. Comparison of tuning characteristics from VCOs using standard abrupt junction varactors and hyperabrupt varactors.

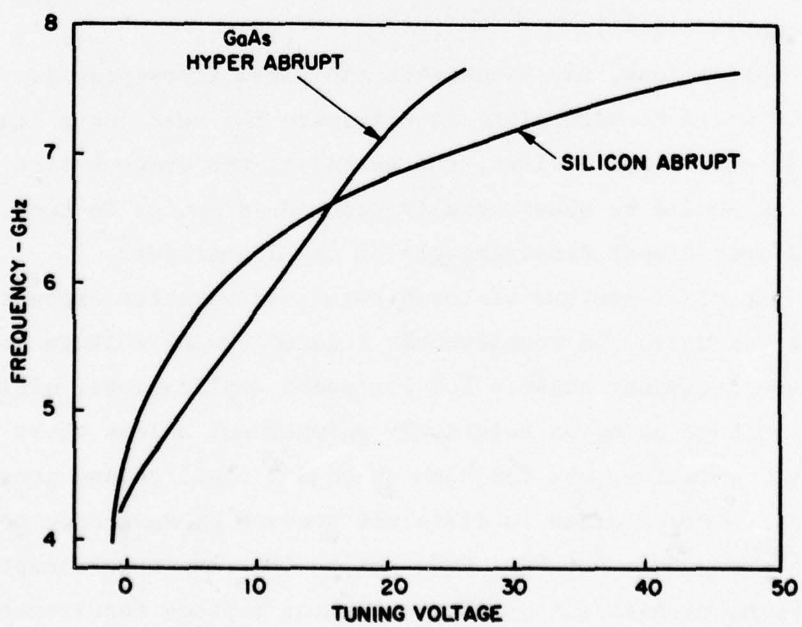


Figure 2. Comparison of tuning voltage requirements of silicon abrupt junction and GaAs hyperabrupt varactor VCOs.

For a set-on VCO type of frequency memory system, such as the simplified open-loop configuration shown in Fig. 3, the output voltage from a wideband discriminator is used to tune the VCO to approximately the same frequency as the incoming signal. The smaller the tuning voltage required, to tune the VCO, the easier it is to design and build amplifier circuits which respond fast enough for rapid set-on. In more complex systems, such as the locked-open-loop frequency memory system with a first order feedback control loop, elimination of the linearizer greatly reduces the stability problems encountered in the high-speed feedback amplifier circuit.

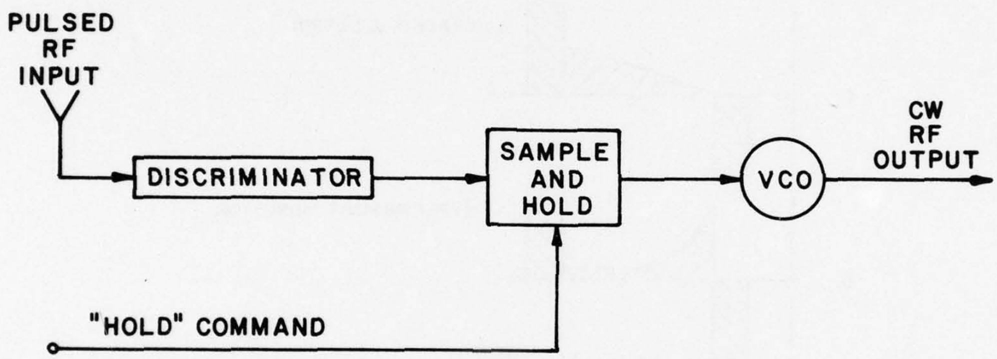


Figure 3. Simplified open-loop configuration.

B. GENERAL CHARACTERISTICS OF HYPERABRUPT VARACTORS

The physics of varactor diodes has been extensively studied and described in the literature [1]. In brief summary, considering the one-sided junction (shown in Fig. 4A) that is comprised of a p^+ layer heavily doped as compared with the n-layer so that the depletion layer is contained entirely within the n-region, a general expression for the doping density (N) as a function of the distance into the n-region from the p^+-n interface at x = 0 is:

$$N = Bx^m \tag{1}$$

1. S. M. Sze, *Physics of Semiconductor Devices*, (Wiley-Interscience, N.Y., 1969), pp 114-116.

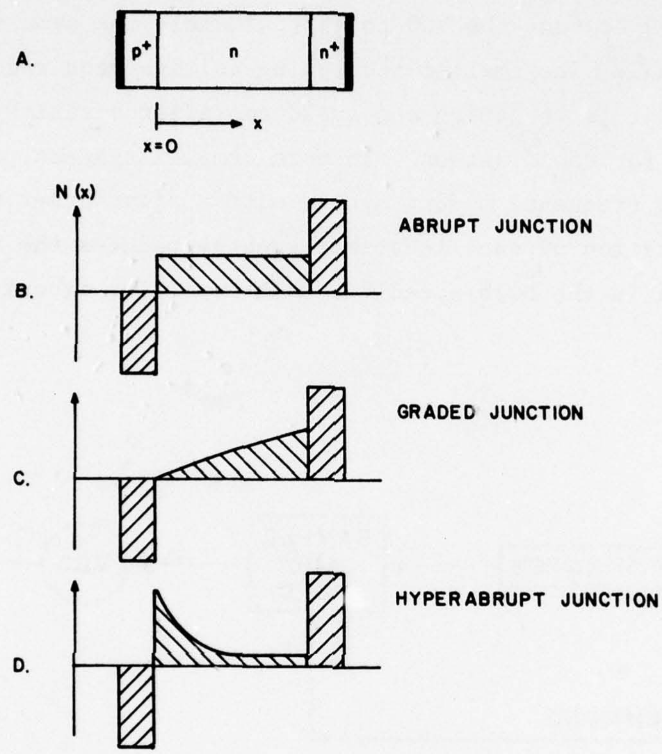


Figure 4. Geometry of p^+-n-n^+ junctions.

upon application of a reverse bias voltage, the width of the depletion layer is varied in accordance with:

$$W = \frac{\varepsilon\ \varepsilon_o (m + 2)\ (V + V_{bi})}{eB}^{1/(m+2)} \qquad (2)$$

where V is the applied reverse bias, V_{bi} is the built-in potential, and the other symbols have their usual meanings. The differential capacitance of the junction, C_j, is given by:

$$C_j = A \left[\frac{e\ B\ (\varepsilon\ \varepsilon_o)^{(m+1)}}{(m+2)(V+V_{bi})} \right]^{1/(m+2)} \qquad (3)$$

$$C_j = A \left[\frac{e\ B\ (\varepsilon\ \varepsilon_o)^{(m+1)}}{(m+2)\,(V+V_{bi})} \right]^{\gamma} \qquad (4)$$

where $\gamma = 1/(m+2)$.

For an abrupt junction, having the doping profile shown by Fig. 4B: $m = o$ and $\gamma = 1/2$; for a linearly graded junction, Fig. 4C: $m = 1$ and $\gamma = 1/3$; and for a hyperabrupt junction, such as shown in Fig. 4D, the doping profile is made very high at the junction and decreases rapidly with x. The doping profile of the hyperabrupt junction can be of various shapes and degrees but the value of γ will exceed 1/2 in all cases and may be in the range of 0.6 to 2.

The generally used capacitance/voltage relation for a varactor is:

$$C_j = K(V - V_{bi})^{-\gamma} \qquad (5)$$

where C_j is the junction capacitance, V is the applied voltage, V_{bi} is the contact potential or built-in voltage, and γ is the previously defined exponent determined by the doping profile.

In a simple series R-L-C circuit, the resonant frequency is determined by the well known expression:

$$fo = \frac{1}{2\pi\ \sqrt{LC}} \qquad (6)$$

that for a circuit in which the inductance is fixed can be expressed by:

$$fo = K_1 C^{-1/2} \qquad (7)$$

By substitution of the value of C_j from (5) into this expression, the following results:

$$fo = K_1 \left[K(V-V_{bi})^{-\gamma} \right]^{-1/2}$$

which only for a value of $\gamma = 2$, reduces to a linear relation between voltage and capacitance:

$$fo = K_2\ (V-V_{bi}) \qquad (9)$$

This idealized linearity, although it can be quite closely approached in low frequency VCOs, is generally not realizable at microwave frequencies because of several factors.

(1) Parasitic and stray capacitances add to the junction capacitance, as does the output capacitance of the oscillator device, to change the actual overall capacitance vs voltage characteristic.

(2) Transmission line effects cause the other circuit capacitances and inductances to vary with frequency rather than act as the assumed constants.

(3) The output parameters of the oscillator, transistor, or T-E device, vary with frequency and loading.

Although exact linearity can be achieved only over limited portions of the frequency range of wideband microwave VCOs, a considerable improvement over the tuning curves resulting from the use of abrupt junction varactors is obtained through the use of hyperabrupt varactors.

The gallium arsenide varactors used for the work of this program were all fabricated during the course of Contract N00039-75-C-0474, "Hyperabrupt Varactor Voltage Controlled Oscillators" [2]. During that program, experiments were performed that indicated that varactors with a value of γ in the order of 0.7 to 1.7 were needed for linear tuning (Fig. 5). The epitaxial GaAs hyperabrupt varactor material was grown using the hydride vapor synthesis technique which was extensively described in the final report of the program. The description will not be repeated, but, in summary, the desired doping profile was obtained by using a programmable gas flow controller to introduce dopant gases at the appropriate rates during the growth run. Desired and measured doping profiles obtained during this process using a Datatrak conductive card programmer are shown by Fig. 6. In addition, the flexibility of this controlled dopant process permitted the growth of complex configurations such as the p^+-n_o-n^+-n-p^+ GaAs wafers used to produce electronically etched varactor diodes with integral heat sinks. The use of such plated heat sink varactors was stressed in the initial work because the improved heat sinking was believed necessary to reduce post-tuning drift. Both the

2. "Hyperabrupt Varactor Voltage-Controlled Oscillators", Final Report, Naval Electronic Systems Command; Contract N00039-75-C-0474, October, 1977.

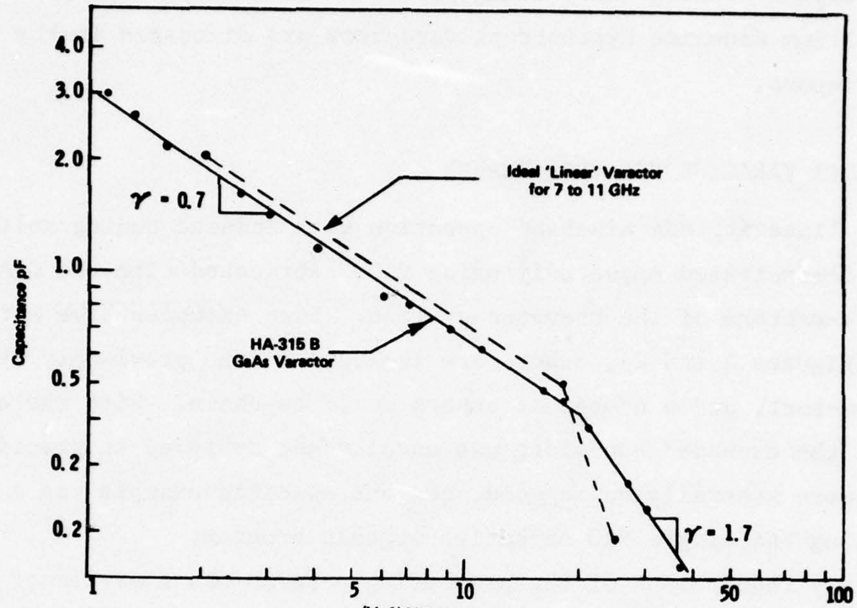


Figure 5. C/V characteristic of HA-315B GaAs varactor and computed C/V curve for ideal tuning varactor for RCA 7- to 11-GHz VCO.

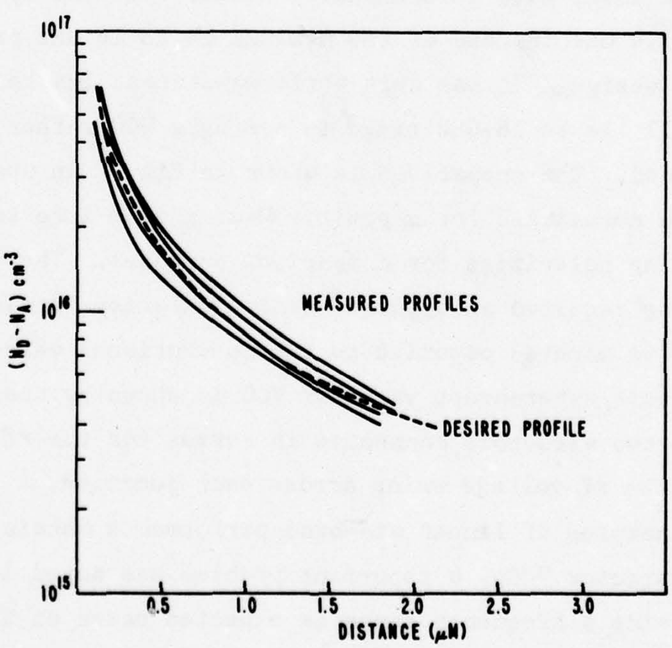


Figure 6. Profile of a typical hyperabrupt varactor.

growth and complex etching and plating processes necessary to prepare plated heat sink gallium arsenide hyperabrupt varactors are discussed in the referenced final report.

C. HYPERABRUPT VARACTOR VCO PERFORMANCE

Overall linearity and wideband operation with reduced tuning voltage swings were demonstrated repeatedly using VCOs fabricated with the GaAs hyperabrupt varactors of the previous program. Some examples have already been shown (Figures 1 and 2), others are included in the previously referenced final report, and a number of others could be shown. With the exception that the expected bandwidth was usually not achieved in practice, the results were generally quite good, and one specific example was a factor in establishing the single-VCO objective of this program.

A delivery requirement of the preceeding program was a series of three VCO's intended to cover the 11- to 18-GHz range. Basic wideband VCO designs with tuning voltage ranges less than 20 V were used for this requirement. One of the three oscillators, built with a plated heat sink hyperabrupt varactor from Wafer 1569, gave exceptionally linear wideband operation covering 12.2 to 17.0 GHz instead of the nominal 14 to 16 GHz previously obtained from this design. It was this performance that led to the objective of covering the full 11- to 18-GHz range in a single VCO rather than three as initially intended. The comparison is shown in Fig. 7 in which the actual tuning voltages are normalized for a positive swing from zero to elimate the offsets and differing polarities for comparison purposes. The VCO with the hyperabrupt varactor required an opposite tuning polarity because the plated heat sink varactor is mounted opposite to the conventional varactor. The circuit design of this hyperabrupt varactor VCO is shown by the diagram of Fig. 8. Note that two varactors connected in series for the rf circuit are used that reduces the rf voltage swing across each junction.

Despite the examples of linear wideband performance obtained from the GaAs hyperabrupt varactor VCOs, a recurrent problem was noted in obtaining operation over as wide a frequency range as expected based on the capacitance ratios of the varactors. Most of the work directed at this problem was done using standard 7.2- to -11.2 GHz VCOs and it was generally difficult to obtain

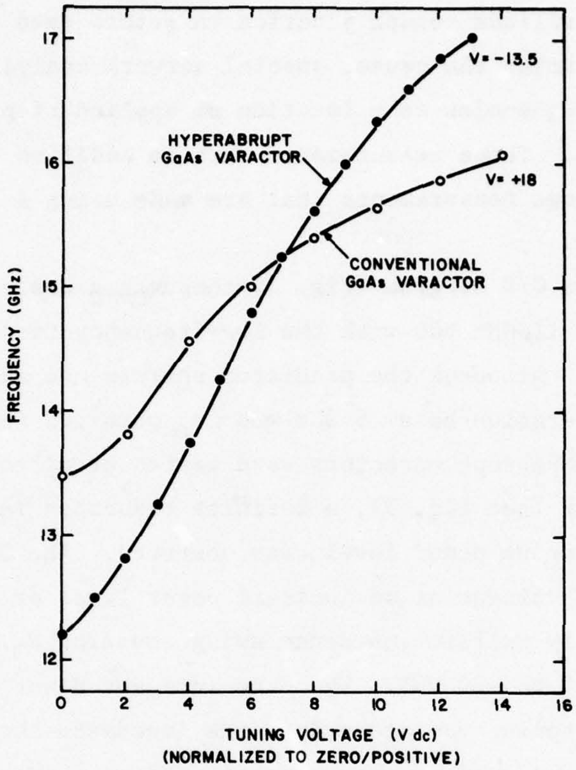


Figure 7. Comparison of conventional and hyperabrupt GaAs varactors.

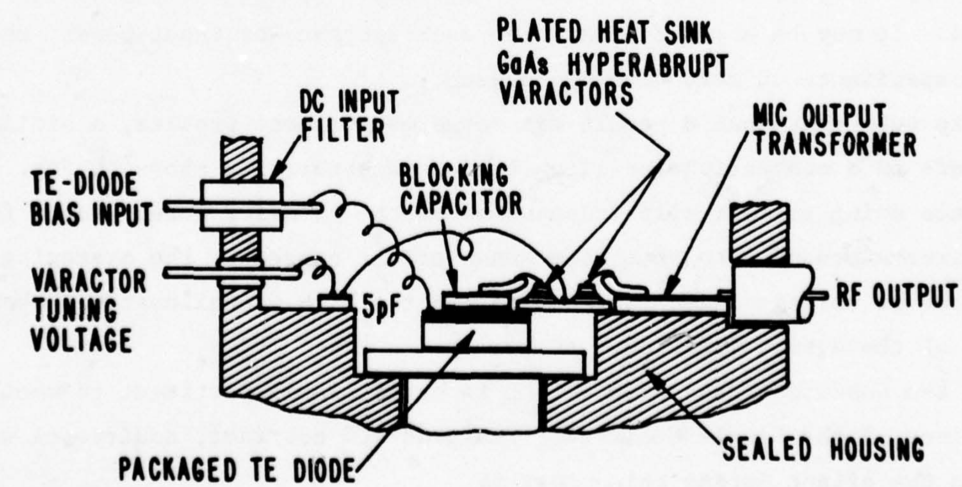


Figure 8. Diagram of 12- to 17-GHz VCO circuit.

operation below 8 GHz with varactor capacitance ratios of from 2 to 4 times greater than those of silicon abrupt junction varactors used in the standard VCO. In order to determine the cause, special network analyzer measurements were made at X-band frequencies as a function of applied rf power level as well as tuning voltage. These measurements were in addition to the conventional capacitance bridge measurements that are made using a low level signal at approximately 1 MHz.

A previously shown C/V diagram (Fig. 5) compares a desired C/V characteristic for a full 7- to 11-GHz VCO with the low-frequency test data obtained on one varactor wafer. Although the predicted performance appears to be more than adequate, operation below 8 GHz was not obtained in a number of trials. When such hyperabrupt varactors were tested at microwave frequencies on the network analyzer (see Fig. 9), a definite reduction in the capacitance swing with increasing drive power levels was observed. The Smith Chart plot of impedance vs tuning voltage at an incident power level of 12.5 mW (solid line) shows a reasonably uniform impedance swing covering an arc of 78° for a voltage change from 0 to -20 VDC. When the incident power is increased to 200 mW, with the same tuning voltage swing, the impedance change (or tuning effect) is drastically reduced to approximately 20° as shown by the dotted line. To further demonstrate the loss of maximum capacitance, a series of points shown by the dashed line were taken at a fixed zero bias voltage at various rf input levels from 1.5 to 200 mW and higher where heating obscured the results. It may be observed that with each increase of input power, the effective capacitance at zero bias was reduced.

To make sure that such a result was not a measurement problem, a similar test was made on a conventional silicon tuning varactor. As shown by Fig. 10, the impedance swing is basically independent of the rf drive level except for a small increase around zero that is a known effect caused by the averaging effect of the rf voltage added to the bias and the highly nonlinear C/V characteristic of the abrupt junction.

Since the bandwidth reduction effect is particularly pertinent to meeting the objectives of the Single Oscillator Wideband VCO contract, additional work was done on the effect during this program.

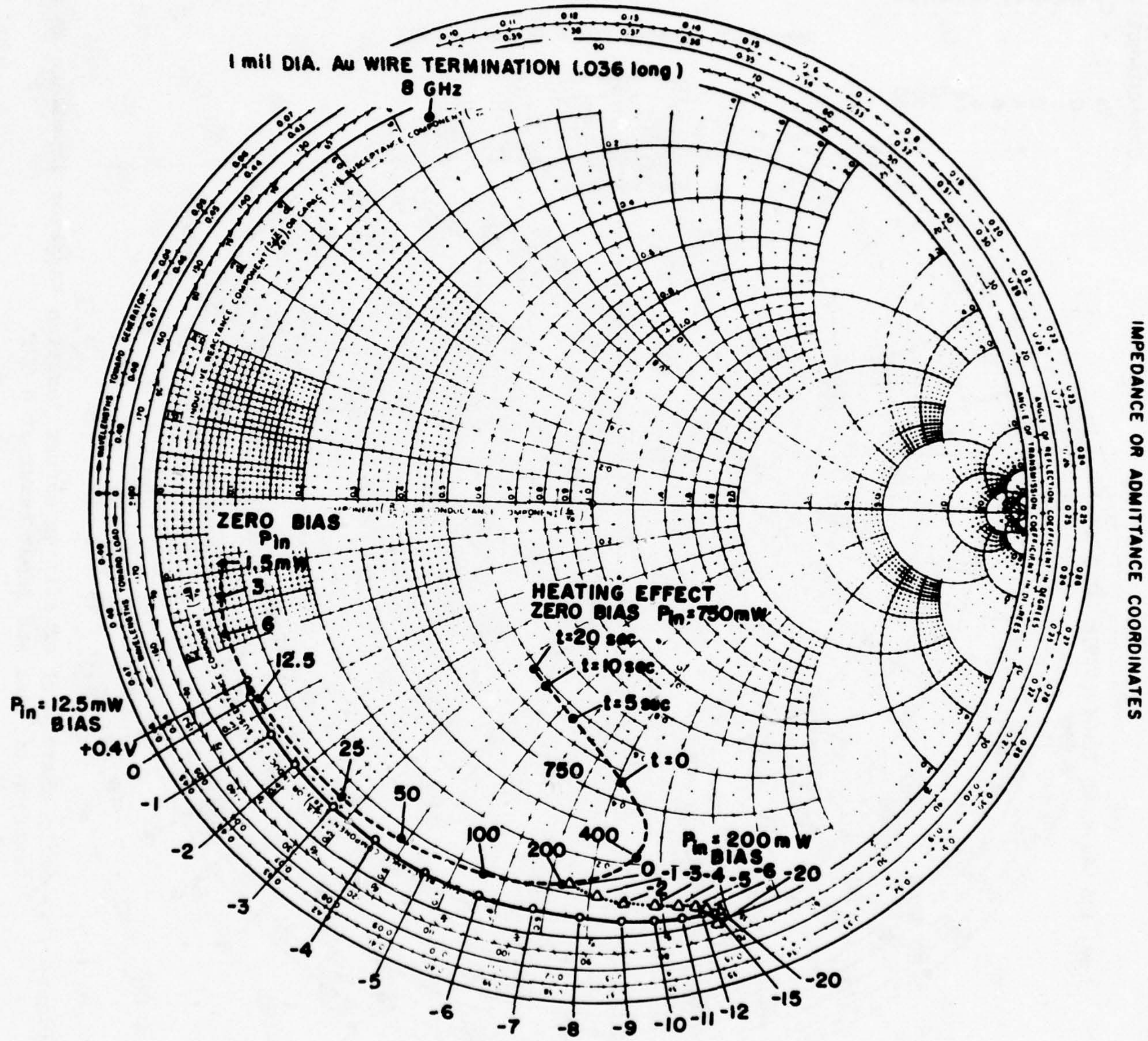


Figure 9. Smith chart plot of GaAs hyperabrupt varactor impedance as a function of bias and input power at 8 GHz.

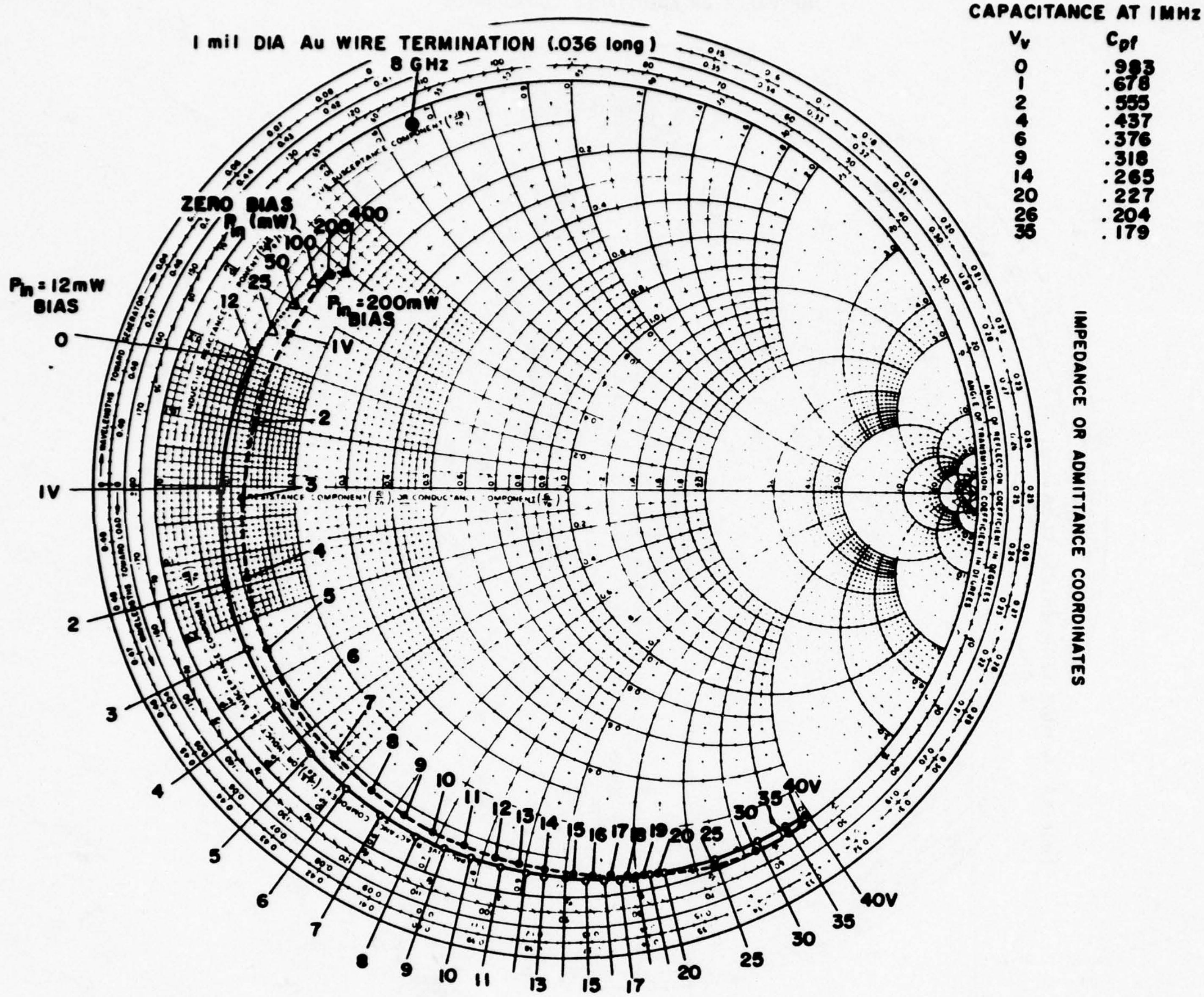


Figure 10. Smith chart plot of silicon abrupt junction varactor impedance as a function of bias and input power at 8 GHz.

D. VCO TESTS TO EVALUATE TUNING BANDWIDTH REDUCTION

In order to further verify and, to some degree, quantify the reduction of tuning bandwidth obtained in practice as compared to that expected from the varactor capacitance ratio, an X-band VCO was constructed and subjected to a series of evaluation tests. The VCO was a transferred-electron diode type of oscillator that was initially fabricated and tested with an abrupt junction silicon varactor. As shown in Fig. 11, the frequency vs tuning voltage characteristic has the typical nonlinear characteristic of this type of oscillator that covers from 8.3 to 11.5 GHz with a tuning voltage swing from 0 to 40 V.

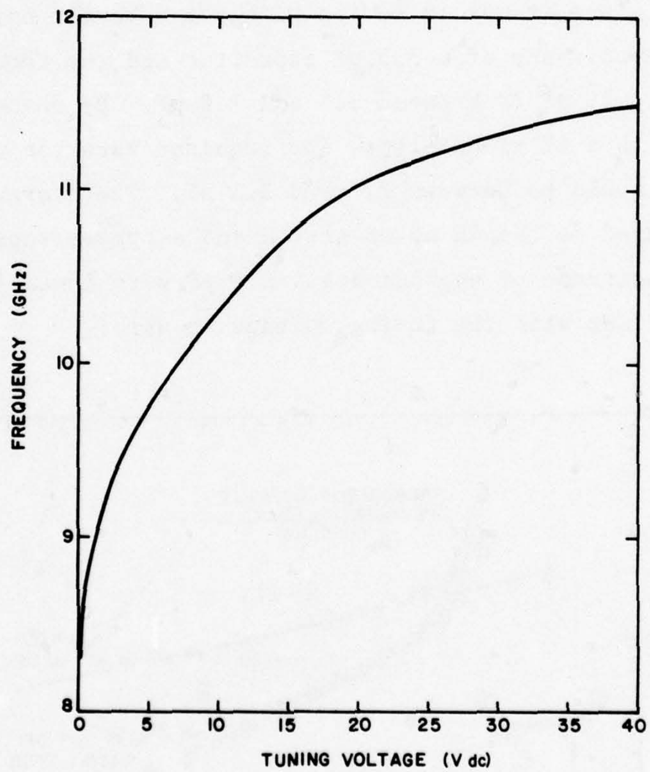


Figure 11. X-band test VCO with silicon abrupt junction varactor installed.

The capacitance vs tuning voltage characteristic of the silicon abrupt junction varactor used in this VCO was measured before and after its removal from the oscillator subsequent to the oscillator tuning curve measurements.

The varactor designated "B" of the four-mesa varactor chip was the specific one that was used, but, as shown by the data plotted in Fig. 12, the C/V characteristics of three of the mesas were measured for comparison. Probable measurement inaccuracies because of leakage current caused the readings taken while the varactor was still connected to be of doubtful significance. With the varactor chip removed, the test data show a normal C/V relationship with a value of 0.47 for the exponent (γ). From this data, the varactor capacitance required for various VCO frequencies was calculated and plotted in Fig. 13, and by extrapolation of this curve, it is estimated that a varactor capacitance of between 9 and 19 pF would be required to produce an oscillating frequency of 7 GHz. Upon reexamination of the oscillator, it became apparent that the dc blocking capacitor of the circuit (Fig. 14), which was only 3.5 pF, was a limiting component since it was in series with the varactor capacitance. The effective series capacitance of a 3.5 pF capacitor and the required varactor capacitance of 10 to 20 pF is between 2.5 and 2.9 pF. By changing the series blocking capacitor to a 40 pF MNS type, the required varactor capacitance for operation at 7 GHz would be between 2.7 and 3.1 pF. Therefore, if the blocking capacitor were changed to the 40 pF as stated and a hyperabrupt varactor with a zero voltage capacitance of approximately 2.9 pF were installed, the VCO should operate at 7 GHz with the tuning voltage at zero.

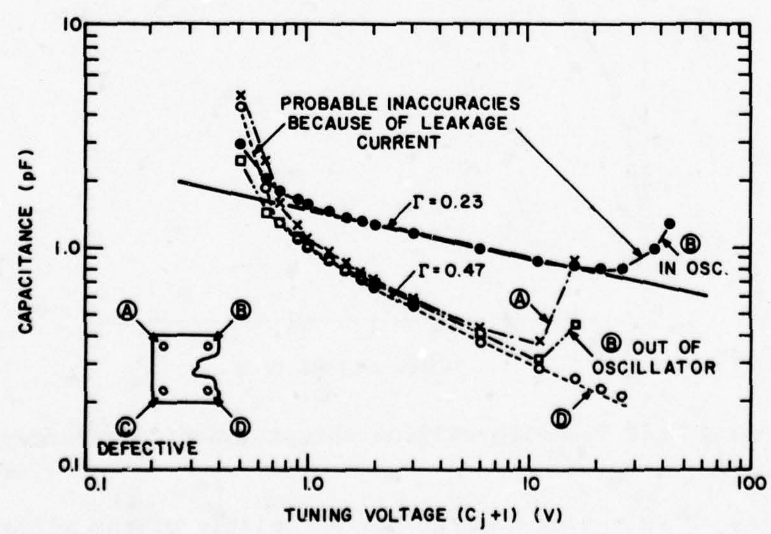


Figure 12. Capacitance vs voltage measurements: silicon abrupt junction varactor from VCO.

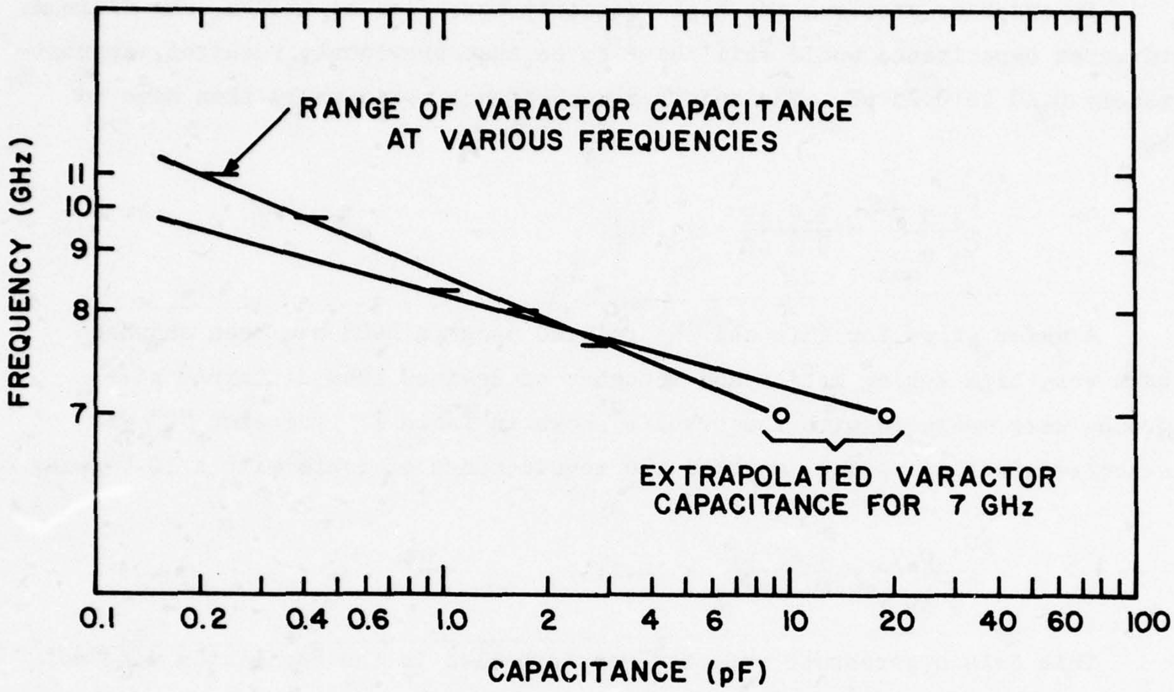


Figure 13. Measured varactor capacitance vs VCO frequency to determine capacitance required for 7-GHz operation.

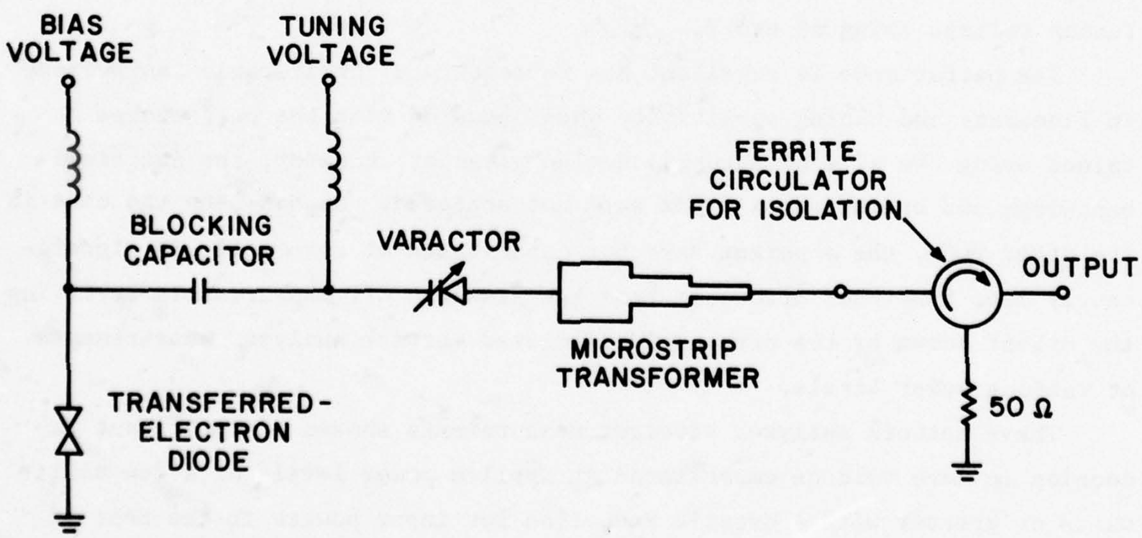


Figure 14. X-band VCO circuit.

In order to preserve the high frequency operation at 11 GHz, the minimum varactor capacitance would still have to be that previously required, approximately 0.20 to 0.25 pF. The required capacitance ratio would then have to be:

$$\frac{C_{j\ 0\ V}}{C_{j\ V_{max}}} = \frac{2.9\ pF}{0.2\ pF} = 14.5:1$$

A wafer grown for this and the related program B408 had been shown to have very high tuning ratios and a number of devices from different size groups were measured with the results shown in Table 1. Varactor "C" was selected since it closely matched the requirements of ratio with a 10 V swing.

$$\frac{C_{j\ 0\ V}}{C_{j\ 10\ V}} = \frac{2.82\ pF}{0.2\ pF} = 14.1:1$$

This GaAs hyperabrupt varactor was installed in the oscillator with no other changes than the replacement of the 3.5 pF blocking capacitor with the 40 pF MNS capacitor. The results are shown by the tuning curve of Fig. 15 in which reasonable performance is obtained from 8 to 11.5 GHz in 15 V with excellent linearity and tuning sensitivity from 8 to 10.5 GHz. Over this range the nonlinearity is about $\pm 1\%$ and this 2500-MHz bandwidth is covered with a tuning voltage swing of 6.5 V.

The performance is excellent and represents a considerable improvement in linearity and tuning sensitivity when compared with the performance obtained using the silicon abrupt junction varactor; however, the increased bandwidth and operation at 7 GHz were not achieved. As has been the case in the other VCOs, the apparent varactor capacitance at zero volts is significantly less than that predicted from the standard C/V measurements verifying the effect shown by the previously discussed network analyzer measurements at various power levels.

These network analyzer varactor measurements showed a significant reduction in zero voltage capacitance at applied power levels of a few milliwatts or greater with a drastic reduction for input powers in the tens of milliwatts. In the test X-band VCO, characterization test data taken on the transferred-electron diode which was used in the VCO showed the diode

TABLE 1. C/V MEASUREMENTS ON GaAs VARACTORS FROM WAFER B 408

Varactor Chip Diodes from Wafer B408	JAR 1.0–1.5		JAR 2.5–3.0		JAR 3.5–4.49		JAR 4.5–5.49		JAR 5.5–7.49		JAR >7.49	
Tuning Voltage	A	B	C	D	E	F	G	H	I	J	K	L
+0.5	2.43	1.68	29.50	4.84	3.92		3.97	.19	1.52			
+0.35	2.90	2.85	4.21	4.24	5.46		5.71	8.37	9.81		12.32	
+0.25	2.61	2.42	3.62	3.62	4.86		5.06	7.42	8.72		10.94	
+0.1	2.29	2.11	3.09	3.07	4.21		4.36	6.41	7.54		9.47	
0	2.17	1.95	2.82	2.80	3.91		4.03	6.04	6.98		8.78	
-0.25	1.83	1.67	2.33	2.31	3.29		3.37	4.97	5.87		7.38	
-0.5	1.61	1.47	1.98	1.95	2.87		2.92	4.30	5.12		6.43	
-0.75	1.45	1.32	1.74	1.68	2.56		2.59	3.80	4.57		5.72	
-1.0	1.31	1.20	1.53	1.45	2.30		2.32	3.41	4.09		5.13	
-2.0	.98	.87	.91	.77	1.62		1.62	2.28	2.93		3.67	
-5.0	.36	.30	.31	.26	.53		.49	.64	1.00		1.18	
-10.0	.18	.15	.20	.17	.25		.25	.36	.42		.53	
-15.0	.15	.08	.20		.20		.18	.28	.32			
-20.0	.15											

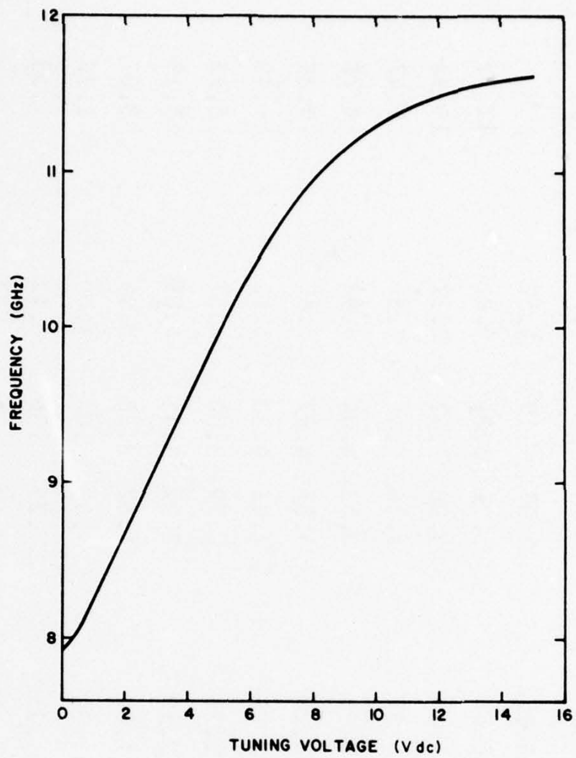


Figure 15. X-band test VCO with GaAs hyperabrupt varactor VCO B408 installed.

was capable of a peak power of 87 mW at 7.2 GHz. The output power of the assembled oscillator was in the order of 25 mW and, assuming as much as one-half the difference between maximum available and actual output power was lost in the circuit or mismatched, the varactor was subjected to about 30 mW. As may be seen from observing the network analyzer Smith chart plot shown previously as Fig. 9, with an input of 30 mW about one-half of the low level varactor impedance tuning range is lost.

It would be desirable to repeat the measurement with an equally wideband but very low power TE diode in the VCO. Unfortunately, very low power TE diodes are difficult to obtain having sufficient bandwidth; however, it is feasible to build a lower frequency VCO using bipolar transistors that would operate at a low power level to determine if wider percentage bandwidths could be obtained. Such an oscillator could be followed by broadband frequency doublers to obtain the required X- and Ku-band outputs.

Based on a previous design for a 2.4- to 5.2-GHz VCO, an oscillator circuit was fabricated using a pair of GaAs hyperabrupt varactors from Wafer B408. Figure 16 shows the schematic of this oscillator circuit which used an HP bipolar transistor as the active element. Excellent broadband operation was obtained as shown by the frequency and power vs tuning voltage curves of Fig. 17. With a tuning voltage input of 0.5 to 13.5 V, the VCO covered more than full octave (2.9 to 6.0 GHz). As may be observed, the output power was much less than obtained from the TE diode VCO. If the same ratio of output power to total applied varactor power is assumed, each of the two series varactors in this lower power oscillator is subjected to an applied power level of 2 mW or less.

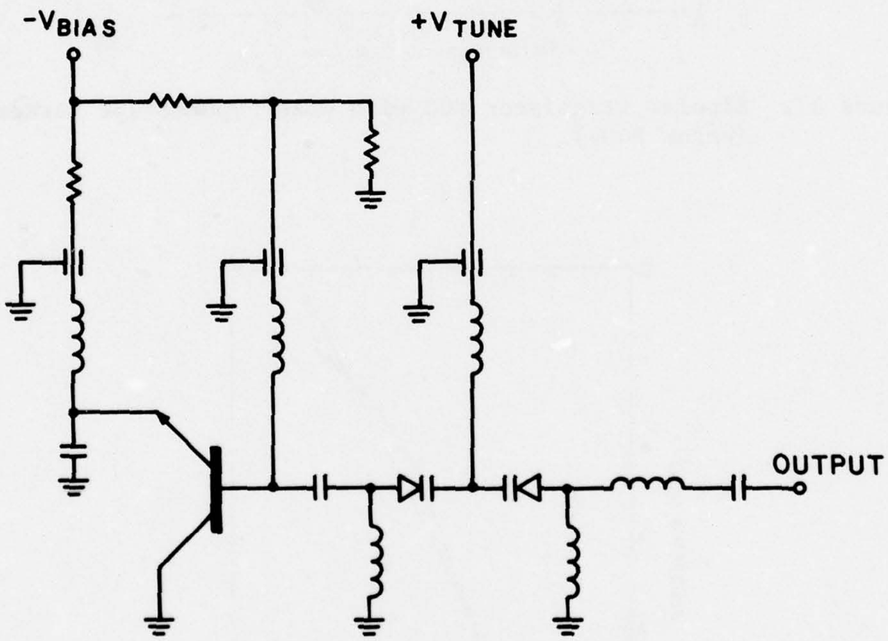


Figure 16. Oscillator circuit.

By adding a frequency doubler and a filter to the output of this bipolar transistor VCO, the frequency vs tuning voltage for the 7- to 11-GHz range is shown by Fig. 18. Only a voltage swing of 4.5 V (from 3 to 7.5 V) is required to tune the entire range over which the linearity is ±7.5%. Of course, the low power output of the VCO and the conversion loss of the

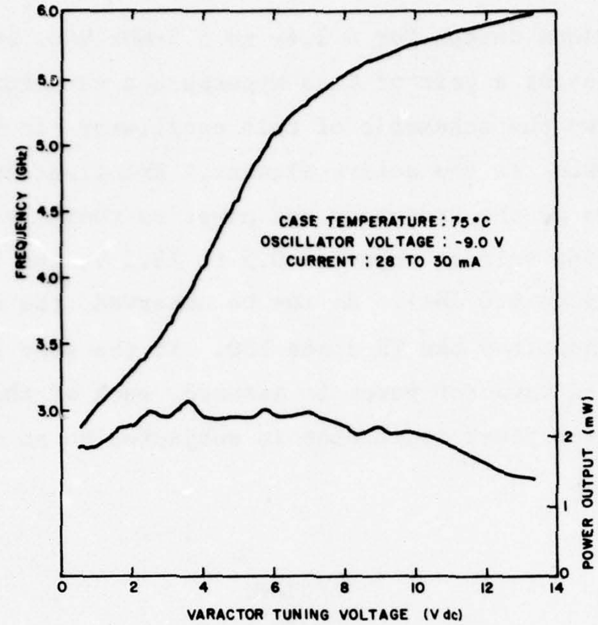


Figure 17. Bipolar transistor VCO with GaAs hyperabrupt varactor (Wafer B408).

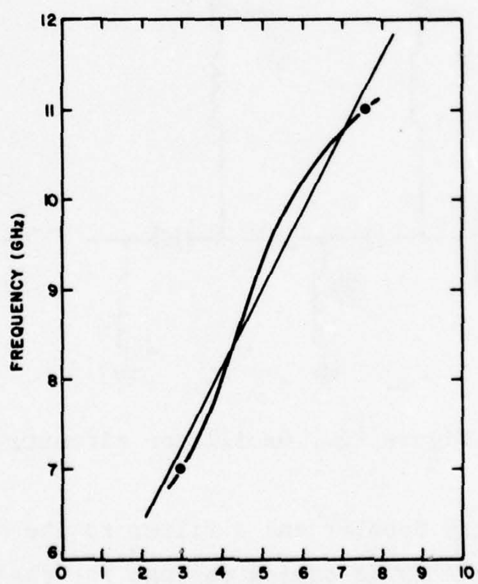


Figure 18. Bipolar transistor VCO and doubler using GaAs hyperabrupt varactor.

doubler results in a very low overall output level which would need to be increased through amplification for most applications. The complete VCO/double/filter assembly is shown by the photograph of Fig. 19.

To be able to consistently cover the 11- to 18-GHz band with the presently proven technology, we would now propose to build an oscillator covering, in the linear region, 2.7 to 4.5 GHz followed by two broadband doublers and an amplifier. Based on the results obtained from the previously mentioned 2.4- to 5.2-GHz VCO that was the basis for the 3- to 6-GHz VCO and that had the tuning curve shown by Fig. 20, the full 11- to 18-GHz frequency range would be covered linearly within ±2% with a 5-V tuning voltage swing. This should virtually eliminate the need for a linearizer and require only a gain of 10 for a 0.5-V output discriminator.

Further experimental and theoretical work should be performed on this bandwidth reduction with power level phenomena. Probably, it is caused by conduction electrons that cross the junction when the reverse polarity bias is overcome by the rf voltage swing and disperse the high space charge in the vicinity of the hyperabrupt junction. Since the carrier concentration is a low value away from the junction, there is little force to oppose this dispersion in contrast to the abrupt or graded junctions where the dispersion away from the junction would be restrained by the greater number of carriers that are present. The bandwidth reduction effect is noted before rectification currents are measured and the voltage at the varactor terminals is monitored to assure that the cause is not a voltage regulation effect. The reduction in capacitance with power observed in the hyperabrupt varactor may be of use in a new type of filter-limiters in which the impedance of the hyperabrupt varactor is determined by the incident rf power. There may be other uses for this effect that is a disadvantage in the application of specific interest - linear, wideband VCOs.

E. 11- to 18-GHz VCO

The VCO design for the 11- to 18-GHz VCO needed for this program was basically the same as that of the previously described 12- to 17-GHz VCO shown by the diagram of Fig. 8. A specially selected Varian VSU-9202 CJ transferred-electron diode was used as the oscillator device with test data

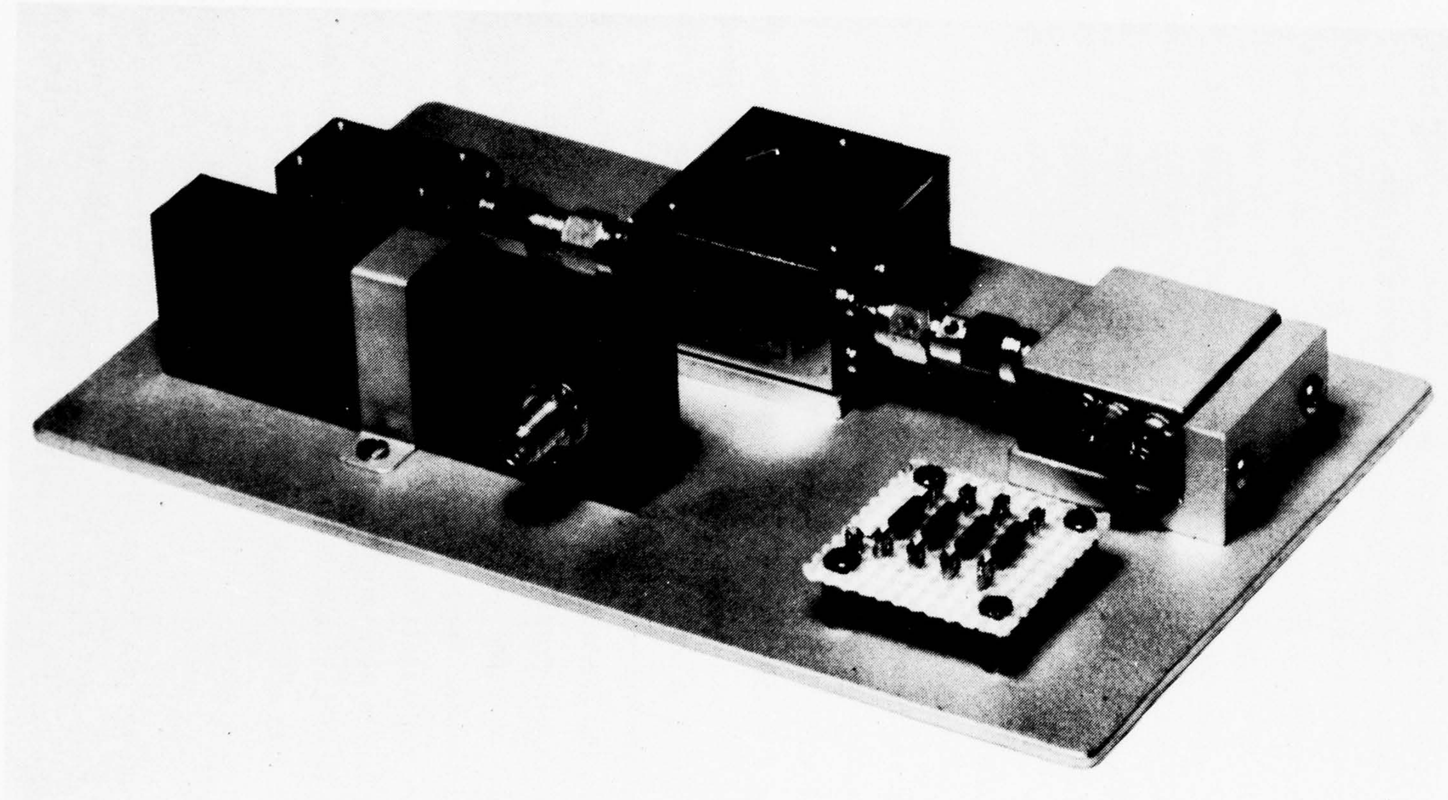


Figure 19. Complete VCO/doubler/filter assembly.

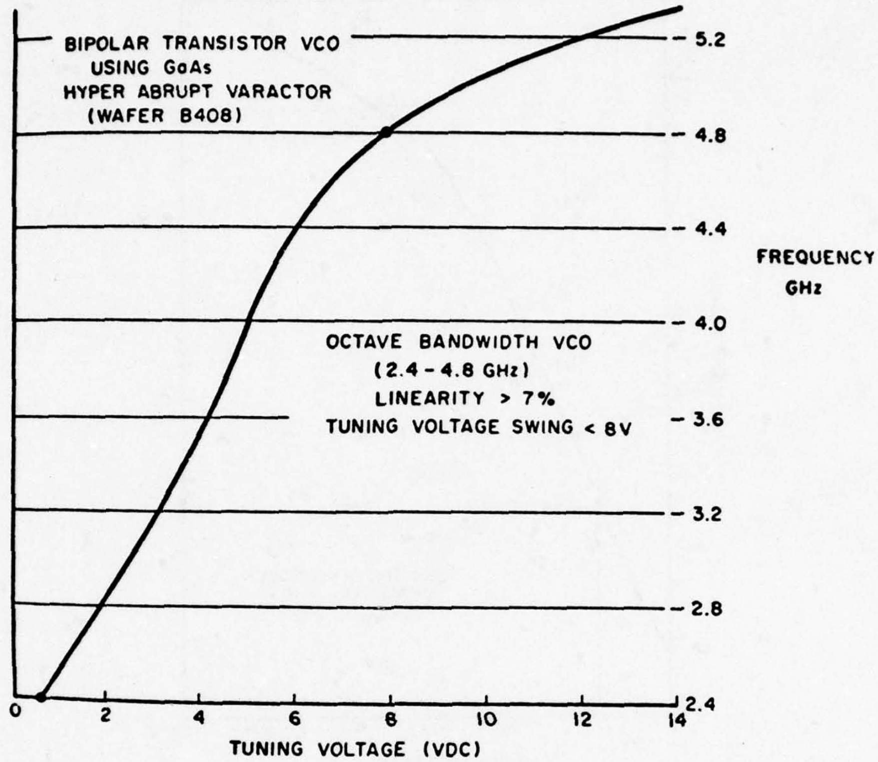


Figure 20. Tuning curve of basic 2.4- to 5.2-GHz VCO.

indicating an output capability of approximately 125 mW at 16 GHz. After some initial tests with GaAs varactors from Wafer 1334II, a pair of plated heat sink varactors from Wafer 1569, with approximate capacitances of 0.8 pF and 0.12 pF at 0 and 20 V respectively for a ratio of 6.7:1, were installed with the interconnecting leads and tabs as short as possible.

The initial results were highly promising. Continuous operation was obtained from 10.9 to 18.4 GHz with a 21-V tuning voltage swing, and the first 6 GHz of this range was exceptionally linear with an 11-V signal sufficient to cover from 10.8 to 16.8 GHz. The initial data was obtained directly from an x-y recorder, that was fed from an EIP Model 351C frequency counter and a D-A converter, and is shown as Fig. 21 where three points marked "noise" and one point marked "spurious" show where the frequency counter response jumped because of conditions that were verified on the spectrum analyzer.

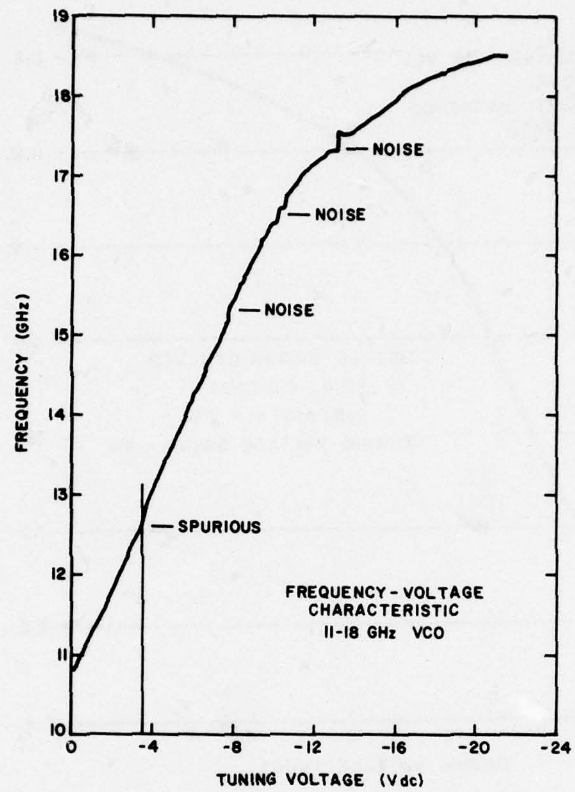


Figure 21. Initial test VCO using PHS hyperabrupt varactors from wafer 1569.

Some additional tuning, mostly precise selection of T-E diode operating bias and heat sink temperature, was tried and it was possible to obtain a continuous frequency counter output throughout the full range although the output signal was generally quite noisy even for a wideband VCO. In the intended application, a frequency memory system for deceptive ECM purposes, the noisy FM output of a few MHz was not a problem since the addition of analog noise would probably be necessary in most cases to compensate for some set-on error. The spurious signal dropout was eliminated.

After running the oscillator on and off for several months during the course of the program, the performance degraded and finally the oscillator became completely inoperative. It was found that the varactor bond had opened and it was repaired. This problem recurred several times, and each time the operation became less and less acceptable until it was impossible to rebond to the varactors. At this point they were replaced. It appeared that some problem existed with the plated heat sink processing of some of the varactors causing a tendency to bond failure with time at high operating temperatures. After replacing the VCO, the bandwidth was reduced somewhat but the VCO was capable of covering most of the bandwidth even though there were many noisy points across the band.

After the most recent repair, the VCO covered 11.0 to approximately 18.2 GHz (see Fig. 22), but there is a small skip around 15 GHz and a region of noisy operation around 17.5 GHz where the frequency counter will not work. The VCO in the system now covers the full range intended, but has several small frequency regions where the operation is erratic. This frequency-voltage characteristic was recorded with the VCO mounted in the frequency memory system at the established operating (controlled) temperature but with an external tuning voltage to permit easier recording. Possible continuing efforts to improve the performance of the VCO will be discussed in a later section of this report.

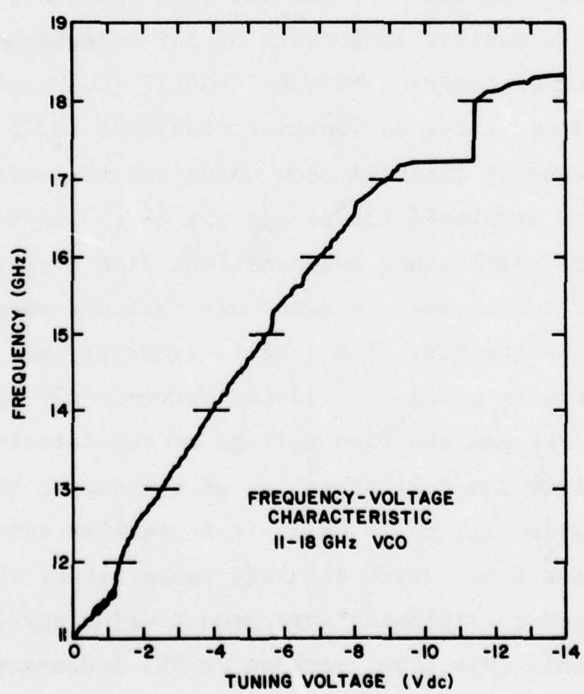


Figure 22. Final test VCO using replacement PHS hyperabrupt varactors from wafer 1569.

F. FREQUENCY DISCRIMINATOR

In the basic set-on VCO frequency memory system, the function of the frequency discriminator is to provide a voltage related to the frequency of the incoming signal. This voltage is stored and used to tune the VCO as close to the same frequency as possible. In the more complex locked-open-loop VCO frequency memory system, the frequency discriminator is also used to provide a real time output voltage that is related to the VCO frequency and that is used for comparison with the previously stored incoming frequency voltage in an error reducing feedback circuit. Absolute accuracy is necessary in the first case; in the latter system the feedback correction reduces the need for absolute accuracy but there remains a need for minimum fine grain structure and for a single valued relation between frequency and voltage to avoid unstable performance in the feedback circuit.

One of the main problems of the conventional interferometer type of frequency discriminator is the tendency to have a considerable amount of fine grain structure as a consequence of the necessary lengths of transmission line, which produce in- and out-of-phase addition and cancellation of the small mismatches of the various components of the interferometer. During the course of the work on Contract N00039-74-C0227 (Locked-Open-Loop Frequency Memory System) and later on Contract N00039-76-C0280 (FET Frequency Discriminator), a frequency discriminator using the roll-off characteristics of a microwave FET was developed for use in the 7- to 11-GHz range that, because of the overall small size, had excellent fine grain linearity. Additionally, a greater output voltage swing was obtained because of the amplification provided by the FET. The overall linearity was reasonably good and the F/V characteristic could be adjusted conveniently by varying the drain voltage of the FET and the bias voltage of the detector diode.

In order to utilize the full potential of the single VCO covering the total objective bandwidth (11 to 18 GHz), it is equally necessary to have a frequency discriminator that covers the full range rather than requiring a complex switching and multiplexing arrangement using three discriminators. In order to achieve this objective, work on an FET frequency discriminator intended to cover the full 11- to 18-GHz bandwidth was included in this program.

Basically, the FET frequency discriminator consists of the elements shown in the block diagram of Fig. 23. The limiter, which is a separate module not included as a part of the integrated circuit discriminator, is needed to eliminate the effects of amplitude variations on the output of the discriminator. Depending upon the output VSWR of the limiter, an isolation may or may not be required between the limiter and the discriminator. The output of the limiter is applied to the gate input of FET through a blocking capacitor to allow for dc biasing of the gate. A short section of microstrip line is included in order to provide room for positioning a small metallized ceramic chip as an input tuner to augment the roll-off characteristics of the FET and thereby produce an input to the detector that decreases uniformly with increasing frequency. A Schottky diode in chip form is used as the detector.

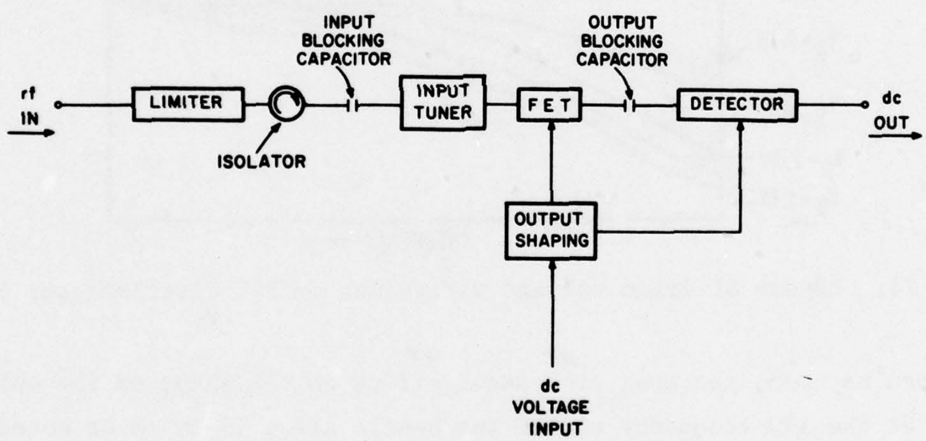


Figure 23. Block diagram of FET frequency discriminator.

For the 11- to 18-GHz frequency discriminator it is desirable for the FET to have usable gain up to 15 GHz or higher. The overall maximum output from the FET would be at the lowest frequency with the power output decreasing towards zero at the maximum frequency. Within the constraints of the desired linearity the greater the low frequency power output the larger will be the detected output voltage swing. In the VCO set-on frequency memory system, it is desirable to start with as large a discriminator output voltage swing as possible to reduce the amount of gain necessary to drive the VCO tuning varactor over the same frequency range.

Linearization of the discriminator characteristic is accomplished by shaping arrangements at the input and output of the FET chip. However, while the *input* network uses the conventional approach of selecting a microwave matching circuit geometry and adjusting it for linear output it was thought better to adjust the *output* of the FET by purely electronic means, as opposed to circuit-geometry approaches. The large FET output impedance variability, as a function of drain voltage changes, provides such an adjustment mechanism. The elimination of an output-matching microwave transmission line helps to eliminate a source of multiple reflections and discontinuities that tend to introduce irregularities in the discriminator output characteristic. An example of the effect of drain voltage variations on the discriminator output response is shown in Fig. 24.

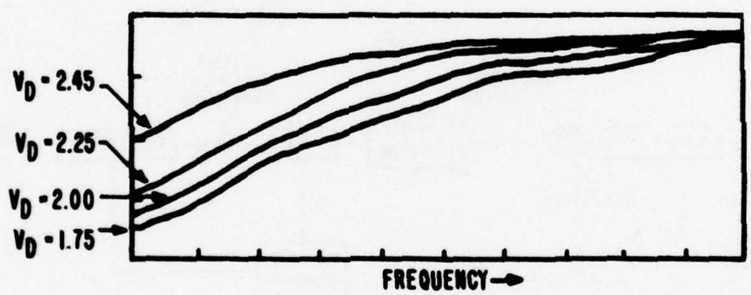


Figure 24. Effect of drain voltage variations on FET discriminator output.

As can be seen, the most pronounced effect on the shape of the output curve is at the low-frequency end of the band. Also, it is to be noted that in addition to changes in the linearity of the output curve, the slope can also be varied, so that the output voltage swing can be changed as a function of drain voltage.

Another means of affecting the shape of the discriminator output (as a function of input frequency) is afforded by adjustments in the forward-bias current of the detector diode, as depicted in Fig. 25. Here, the greatest effect appears to take place at the high-frequency end of the operating band. Again, the adjustment affects both the slope and the linearity of the video output.

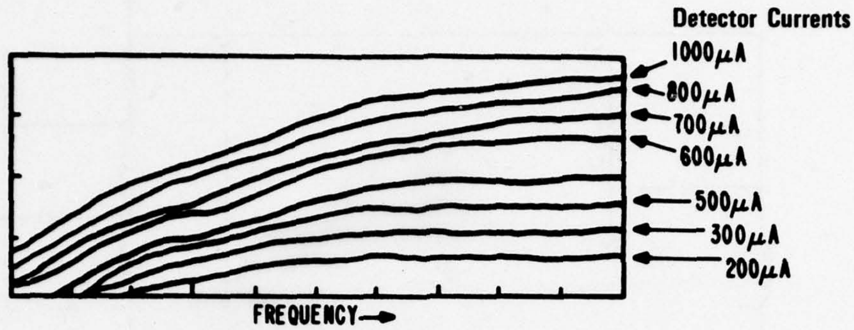


Figure 25. Effect of detector bias on FET discriminator output characteristic.

The effectiveness of these electronic adjustments and the apparent complementary nature of the two approaches (drain voltage affecting the lower frequencies, detector bias affecting the high-frequency end) led us to adopt the electronic "shaping" approach at the discriminator output, while using the more conventional microwave matching network at the FET input. The basic scheme is shown in Fig. 26.

Two 4-stage tunnel-diode amplifier type limiters were available for use in the discriminator assembly. The better of the two was selected but the usable frequency range of the discriminator was substantially reduced by the nonuniformity of the output power vs frequency characteristic of the limiter. As shown in Fig. 27, the TDA limiter was tested alone and with two combinations of an additional isolator and adapters. The difference in the shape of the output curves among the three is relatively small and the level difference can be accounted for by the attenuation of the isolator.

There is a variation of approximately 0.5 dB across the band that in itself would cause a frequency error (850 MHz out of the 7-GHz bandwidth) if there was no corrective capability afforded by tuning the FET discriminator. The rapid changes in the power output below 13 GHz- and above 15.5-GHz limit the bandwidth of the discriminator substantially.

The overall discriminator output characteristic is shown by Fig. 28 with the input frequency range limited to 12.5 to 15 GHz over which the output characteristic is nominally linear and produces a total output voltage swing of 1.24 V. Over the extended frequency range of 12.5 to 17.5 GHz, as shown by Fig. 29, the output of the discriminator amplifier is 1.58 V but there is a significant departure from linear above 16 GHz.

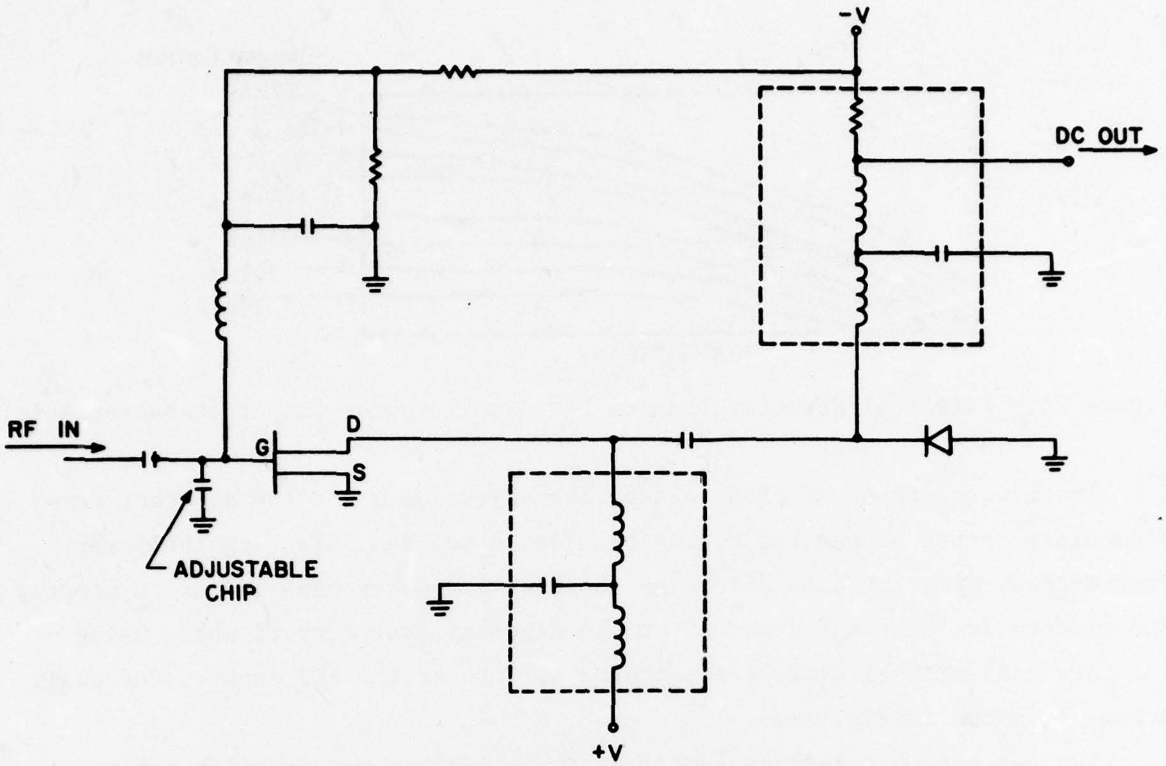


Figure 26. Schematic diagram of FET frequency discriminator output shaping circuit.

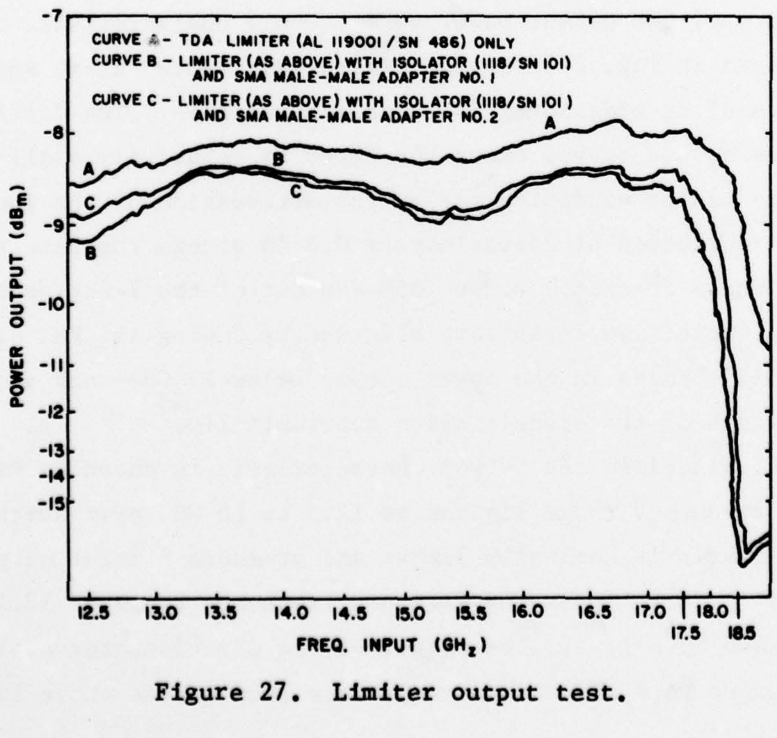


Figure 27. Limiter output test.

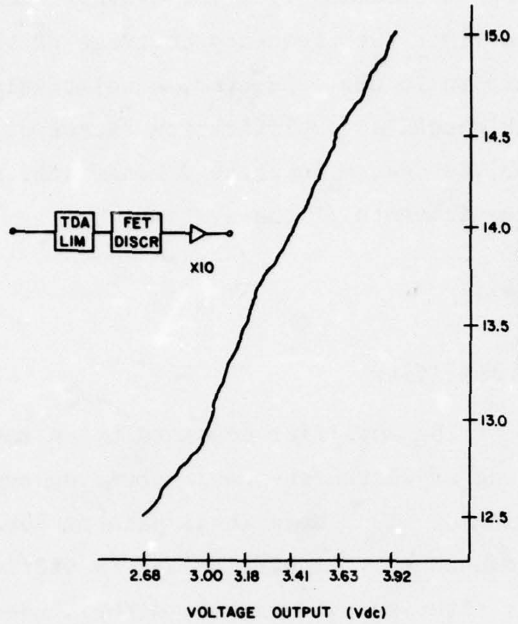


Figure 28. Frequency discriminator - low range.

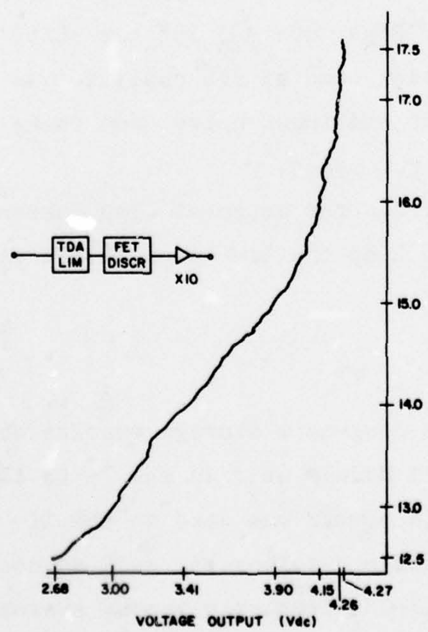


Figure 29. Frequency discriminator - full range.

In summary, the results obtained from the overall limiter-FET discriminator assembly were such as to limit the frequency coverage of the system to a bandwidth covering about 12.5 to 16 GHz. However, a relatively large voltage swing was obtained which needed an amplification factor of about 10 to tune the hyperabrupt varactor VCO over a comparable bandwidth. This is compatible with the set-on speed requirements of the system.

G. CIRCUITS

1. Discriminator Ouput Amplifier

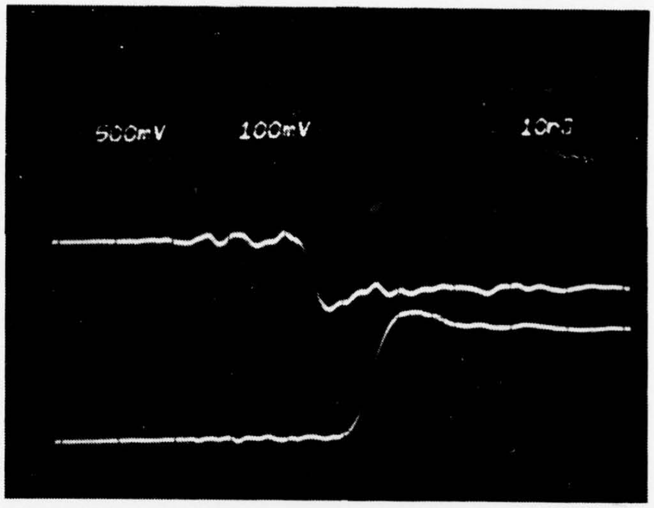
The initial design of the amplifier consists of an integrated circuit video amplifier (SE 592) driving an ultrahigh-speed hybrid op-amp (MSK 785) in order to produce an output swing of ±10 V at a total gain of 30X. Interaction between the two stages caused some ringing which was difficult to suppress. Since it was determined, after the VCO and the discriminator were tested, that a gain of 10 would provide sufficient signal to drive the VCO from the discriminator output, the circuit was modified to use only the first stage set to a gain of 10X.

The input and output waveforms of the discriminator output amplifier are shown by the photograhps of Figs. 30a and 30b for short and long duration input pulses. The output rise time of the amplifier is fast enough to preserve the 20-ns rise time of the input pulse, and there is no noticeable droop with a 750-ns long input pulse.

This circuit also provides the detector bias current for the discriminator and balancing adjustment to keep the low level SE 592 within its linear range of operation.

2. Track and Hold

Based on the excellent long-term storage results obtained from the Computer Labs THC-0030 Track and Hold Module used in the 7- to 11-GHz frequency memory system, this type of voltage memory was used in the 11- to 18-GHz system. It is an inverting stage with provisions for gain adjustment and offset. For application in the 11- to 18-GHz frequency memory system, the gain was set to unity because of the input/output comparison that is made as the error voltage for the feedback correction. The offset was used to match the discriminator



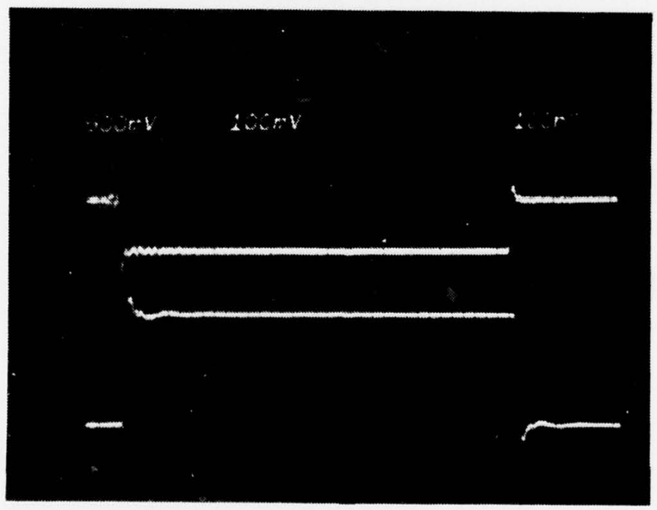
Rise Time

10 ns/div

Input Pulse
100 mV/div

Output Pulse
500 mV/div

(a)



Long Pulse
100 ns/div

Input Pulse
100 mV/div

Output Pulse
500 mV/div

(b)

Figure 30. Revised discriminator-output amplifier.

output amplifier voltage to the VCO tuning voltage at the low-frequency end of the usable bandwidth.

3. Error Amplifier

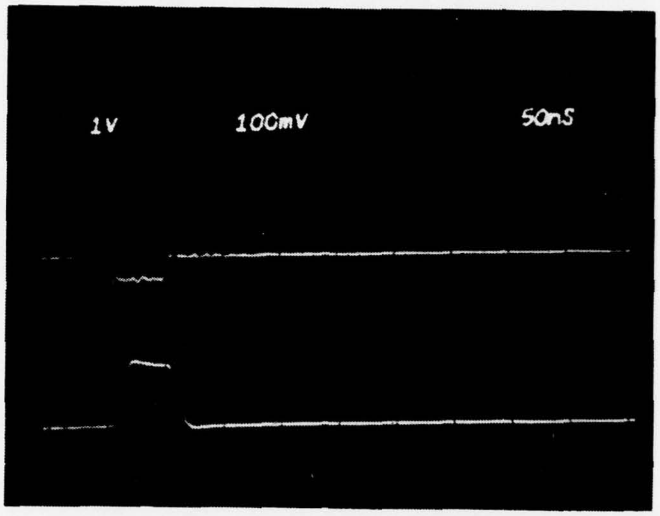
A new type of error amplifier using an SE 592 video amplifier IC was initially installed with poor results. It was replaced with an MSK 760 hybrid IC which would function the same as the circuit used in the 7- to 11-GHz frequency memory system that had a 600-ns settling time. Further work should be done on the SE 592 circuit to eliminate the problems and obtain faster error correction capability. The circuit using the MSK 760 IC was left in the open-loop configuration.

4. Threshold and Gate Circuit

The threshold and gate circuit was revised to provide for faster switching of the track and hold module and the rf feedback PIN-diode switch. The resulting waveforms are shown in Fig. 31a through 31d.

The circuit was tested with a pulse generator to simulate the incoming detected pulse from the threshold detector. Figure 31a shows the gain of the input amplifier stage, a 733-μA integrated circuit differential video amplifier. With the input pulse set to the threshold sensitivity limit, the input signal is approximately 50 mV and the amplified signal is somewhat greater than 1.5 V with a rise time in the order of 15 ns. Figure 31b shows the delay between the input signal and the 74121 multivibrator output and Fig. 31c shows the total delay from input to the "hold" command output which is approximately 55 ns. The difference between the "hold" and "switch" commands is shown by Fig. 31d. It may be necessary, if further work is authorized, to add some video cable to delay application of these signals, which initiate the feedback mode, until the input signal has been processed, stored, and settled.

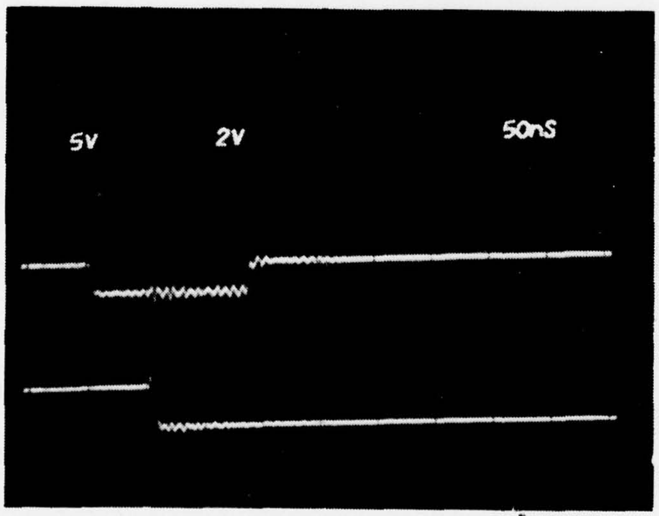
The length of the "hold" mode may be set to 10,100, or 1000 μs by a switch mounted on the front panel which changes the external capacitor value of the 74121 multivibrator.



Input Signal (Approx 50 mV)

Output of Amplifier Stage
(Approx 1.5 V)

(a)

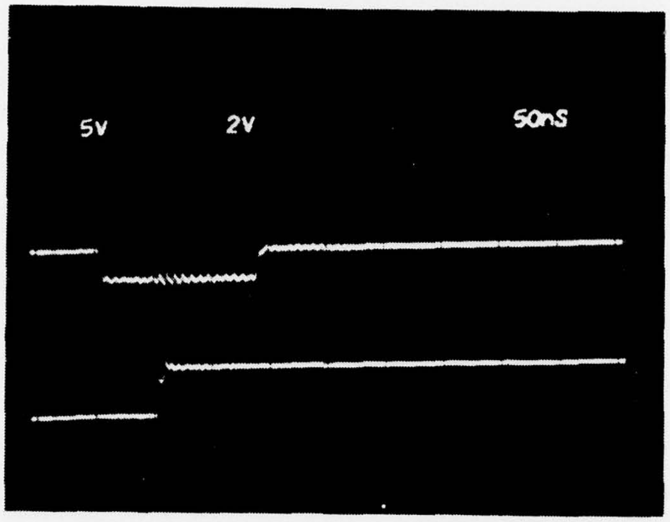


Input Signal (Scope probe connected ahead of 10X pad)

Output of Multivibrator

(b)

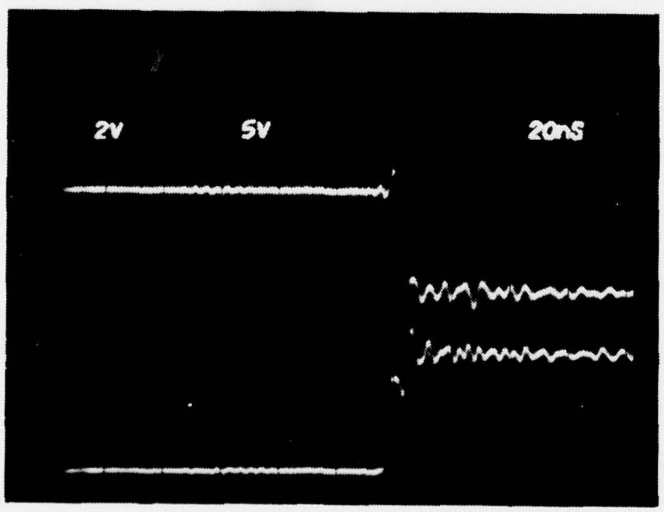
Figure 31. Waveforms after revising threshold and gate circuit.



Input Pulse (Sampled ahead of 10X pad)

"Hold" Output

(c)



"Switch" Output (2 V/Div)

"Hold" Output (5 V/Div)

(d)

Figure 31. (Continued).

5. Power Supplies and Accessories

The overall system operates from 115 Vac. To convert this to the various bias voltages required by the system, 5 dc power supplies are included. To maintain the system at a constant temperature, all parts are mounted on an isolated baseplate on which are mounted a number of heaters which are driven by a temperature controller. The temperature is sensed by a thermistor mounted directly under the VCO.

H. OVERALL SYSTEM

Because of the earlier mentioned bandwidth and error amplifier problems, the frequency memory was left in an open-loop configuration operating over the 12.5- to 16.0-GHz frequency range. In this configuration, the block diagram of the unit is shown in Fig. 32. Photographs of the unit, in and out of the enclosure, are shown by Figs. 33 and 34.

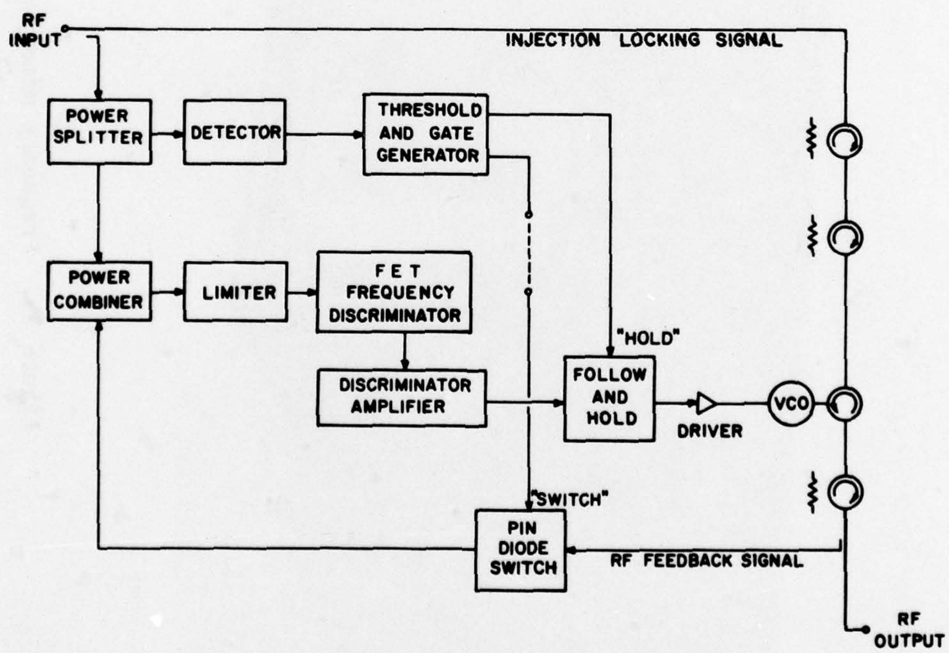


Figure 32. Block diagram of frequency memory system (as delivered).

To evaluate the input/output frequency tracking of the system, the unit was tested with a CW input signal and the input and output signals were

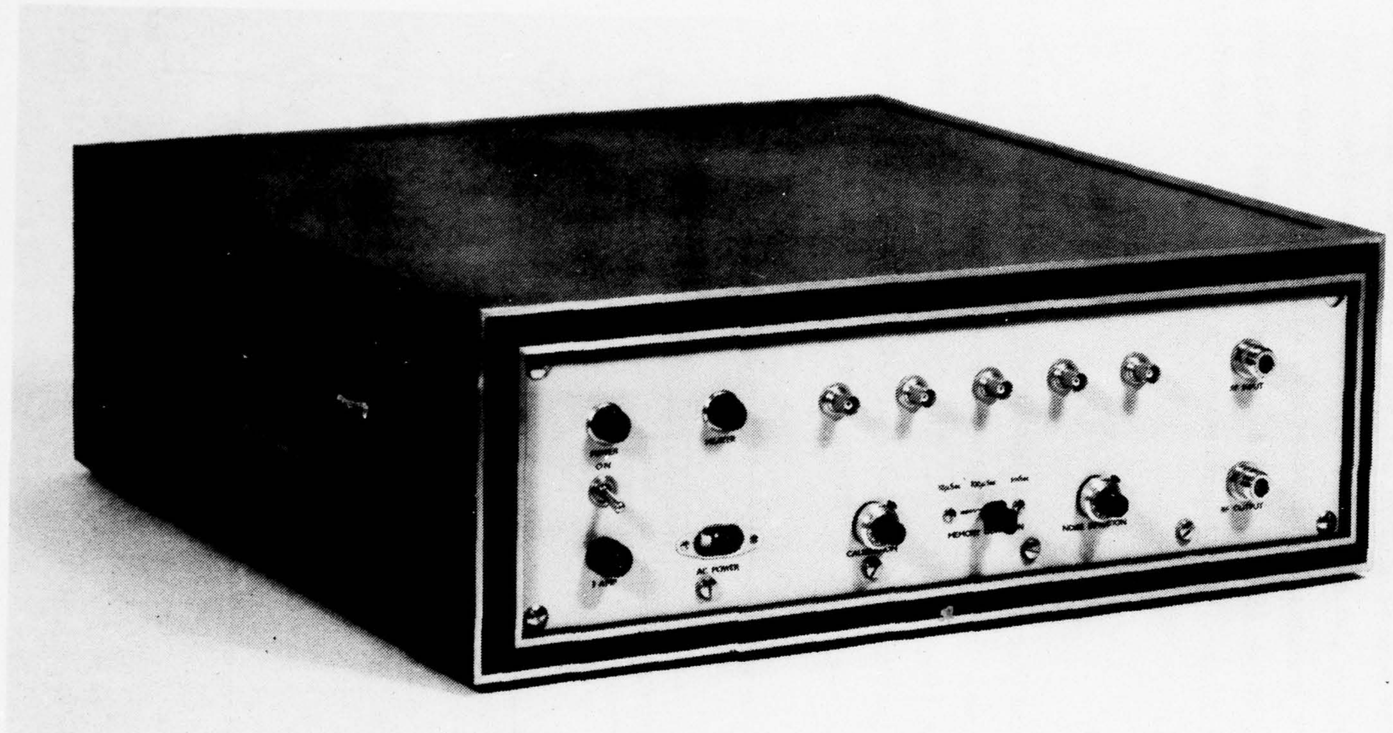


Figure 33. Frequency memory system, external view.

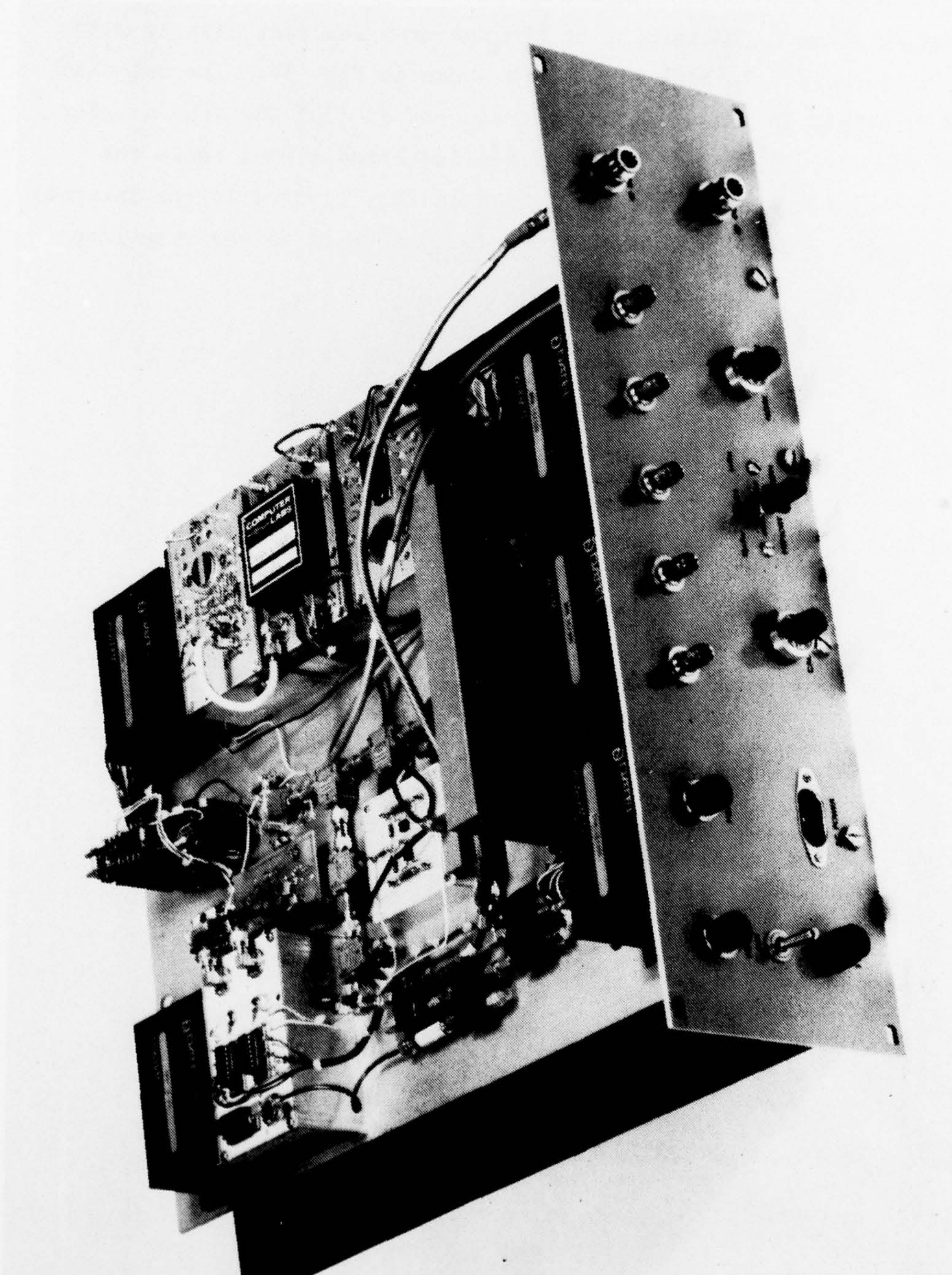
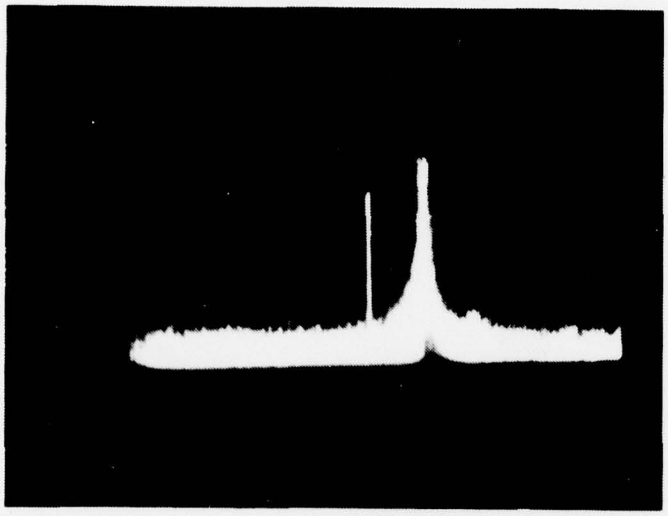


Figure 34. Frequency memory system, internal view.

simultaneously monitored on a spectrum analyzer. Over the 12.5- to 15.5-GHz range, the open-loop tracking was within 30 MHz which is well within the injection locking range. Photographs of the spectrum analyzer display with and without the injection locking signal are shown in Fig. 35. The unlocked error is approximately 15 MHz at an input frequency of 13.5 GHz (the noisier signal is the VCO output). Application of the injection signal locks the VCO to the incoming frequency. Locking is, of course, limited to the interval of time the incoming pulse is present, and the VCO reverts to the open-loop error at other times.

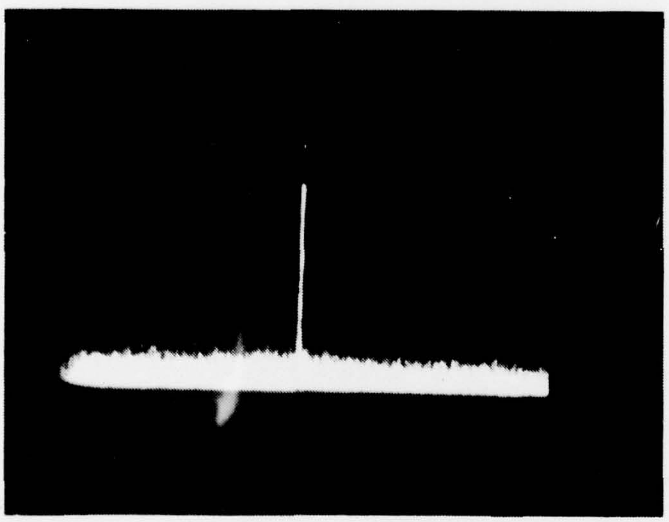


Without Injection
Locking Signal

Input Freq. 13.5 GHz

Dispersion 10 MHz/Div.

(a)



With Injection
Locking Signal

Input Freq. 13.5 GHz

Dispersion 10 MHz/Div.

(b)

Figure 35. Spectrum analyzer photographs of input and output signals.

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

One of the major objectives of this program was to demonstrate that, by using GaAs hyperabrupt varactors, the full 11- to 18-GHz band could be covered by a single VCO with a relatively low tuning voltage swing. Although subsequent deterioration reduced the useful range of the VCO in the overall frequency memory system where it was installed, the full range was covered initially. Even after the performance degradation occurred, the VCO operated linearly over a wide range and with a very small tuning voltage requirement such that it was able to track an FET discriminator over a 12.5- to 16-GHz bandwidth without a linearizer.

Additional information concerning the tuning bandwidth limitations experienced with the use of hyperabrupt varactor was obtained. Operation at low rf power levels appears to be the only method of obtaining the wide tuning range which the large varactor capacitance ratio of the hyperabrupt varactor predicts.

An FET frequency discriminator operating in the 11- to 18-GHz frequency band was constructed and installed. It proved difficult to cover the complete 7-GHz wide band and the TDA limiter was a major problem in reducing the usable bandwidth.

In order to improve the overall operation of the 11- to 18-GHz frequency memory system, it is recommended that the system be GFE'd back to RCA until September 1979 so that additional work can be done. This work would be to improve the operation of the VCO by replacing it with a transistor-multiplier type VCO described in this report, to further optimize the FET discriminator and possibly extend the coverage from 12.5 to 17 GHz (the TDA limiter is not adequate for any greater range), and to get the error amplifier circuit working so that the feedback mode can be made functional. This work will also possibly include adding improvements that are determined by the work presently being done on the 7- 11-GHz frequency memory system.

An additional study and experimentation program is recommended on the rf power level effects on the capacitance ratio of the hyperabrupt varactor. This program would also study possible uses for the effect, such as in limiters or power sensitive switches.