SFD Report No. 33-IDR-6

January 1965

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DEVELOPMENT OF AN X-BAND CW CROSSED-FIELD AMPLIFIER

by
G. K. Farney
J. Hentschel

Sixth Interim Development Report
for period
1 October 1964 to 31 December 1964

Contract NObsr-89503
Index No. SF0100201 ST 9294

NAVY DEPARTMENT
BUREAU OF SHIPS, ELECTRONICS DIVISION

S•F•D laboratories, inc.
Union, New Jersey

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INTERIM DEVELOPMENT REPORT
FOR
DEVELOPMENT OF AN X-BAND CW CROSSED-FIELD AMPLIFIER

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ABSTRACT

Effects of radiation and the cumulative random errors have been detrimental factors influencing the match to the new slow wave circuits under investigation. The radiation problems have been minimized by the use of shielded transmission lines as the means of coupling. An analysis of small random errors resulted in the construction of a higher voltage circuit having only 60 sections. This circuit has been matched and should be hot tested in mid-January 1965.

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1.0 INTRODUCTION

As outlined in Contract NObsr-89503, the purpose of this project is divided into two phases. During Phase I, a detailed investigative study of the design techniques required to improve interaction structures for application in a broad band crossed-field amplifier is to be performed. The investigation will emphasize the following characteristics of the interaction structures:

(a) bandwidth
(b) thermal dissipation
(c) electronic interaction impedance
(d) mode patterns

In Phase II, the design criteria for the interaction structures determined during Phase I are to be applied to the design of a crossed-field CW amplifier. Some of the specified performance charactersitics are as follows (minimum requirements):

(a) frequency - 7 Gc to 11 Gc
(b) power output - 2000 watts
(c) gain - 30 db
(d) efficiency - 50%
(e) anode voltage - 10 kv (max)

Authorization for work on the project was given by Bureau of Ships, Washington, D. C., effective 28 June 1963.

During the present report period, a change in the direction of effort was made. Work on the reactively loaded interdigital line (RLIL) circuits was postponed because of matching difficulties encountered at these frequencies and the promising features of a new circuit. Emphasis was placed on this new type slow wave circuit briefly mentioned in the Fifth Interim Development Report. This circuit will be referred to as the helix coupled vane circuit. A full description of the circuit is given in Section 2, Discussion of Circuits.

While no tubes were hot tested during this report period, four circuits intended for hot tubes were fabricated. The non-uniformity of the first low voltage circuit brought to focus the complications of random errors as a function of circuit length and spacing (see Section 4). A second low voltage circuit, identical in design to the first, has since been made, which appears excellent mechanically. On the basis of random error factors, however, two higher voltage circuits, having greater vane to vane spacing and fewer sections were designed and built. Indeed these higher voltage circuits, less critical to tolerances, appear to have less severe matching problems. One of these circuits has been adequately matched and will be evaluated in a hot tube in January 1965.

2.0 DISCUSSION OF CIRCUITS

The reactively loaded interdigital line has been used at L-band, demonstrating crossed-field amplifier operation over an octave bandwidth. Comparable operation has been obtained at C-band. However, attempts to use this circuit at X-band have not been so successful. The difficulty stems from the lack of complete accuracy in control of mechanical dimensions on a very fine grain circuit. This difficulty is exaggerated by the multiple periodic nature of this particular slow wave circuit. It is well known that satisfactory circuit matches are difficult to achieve on slow wave circuits of a multiple periodic nature unless absolute accuracy is maintained in holding mechanical dimensions. The low synchronous voltage required for this application has led to the use of a 0.030" period circuit composed of 0.015" metal vanes and 0.015" slots. Mechanical deviations of 0.001" can result in impedance changes of more than 5%. This, coupled with the random errors introduced into the circuit during fabrication, has led to severe matching problems at X-band. For this reason, a new slow wave circuit with a single cell periodic nature which has been under study on a continuing company sponsored program is now being investigated on this program.

The helix slow wave circuit has long been known to be capable of very wide bandwidth at constant phase velocity. However, it has not received much attention on crossed-field devices because of its low inherent thermal capability. Attempts have been made in the past to raise the thermal capability of the helix slow wave circuit by mounting the helix on stub supports. In the past, this has always had the effect of narrowing the useful bandwidth of the helix. The reason for this can be traced to the relative dimensions that have been used for the helix and the stub supports. Wide bandwidth can be maintained, provided the impedance of the stub supports is large compared to the impedance of the helix. There are practical limitations to the small dimensions with corresponding high impedance that can be used for the stub supports. The impedance of the helix as used in traveling wave tubes is large, and it has not been practical to obtain stub supports of much higher impedance. It is for this reason that stub supported helix circuits in the past have been comparatively narrow band. On the other hand, the impedance of the helix could be reduced relative to that of the stub supports in order to obtain the desired bandwidth. This could be done by using large diameter wire for the helix or by using coiled strip line. This has not been done for beam type traveling wave tubes because it results in reduced electronic interaction impedance; that is, the RF fields within the helix are reduced in magnitude. However, this does not need to be a limitation for a crossed-field tube. Electronic interaction can take place with the high impedance stub support element rather than with the low impedance helix. This is shown in schematic form in Figure 1. For this arrangement, the rugged thermal capability of a customary vane circuit is maintained, but a circuit with much wider bandwidth is achieved.

The concept used here is to increase the bandwidth of the narrow-band vane circuit with its excellent thermal properties by the use of a low impedance helix to couple the elements. This is opposed to the customary point of view that the stub support elements increase the thermal properties of the helix but reduce its bandwidth. Figure 2 is a photograph of the X-band version of this circuit, presently being investigated. A dispersion curve for this circuit is shown in Figure 3.

Once the concept of permitting electronic interaction to occur with the high impedance support elements instead of with the helix is recognized, there are several alternate forms of the slow wave circuit that come to mind. One of the most obvious is the helix coupled ladder line shown in Figure 4. Again, by proper choice of

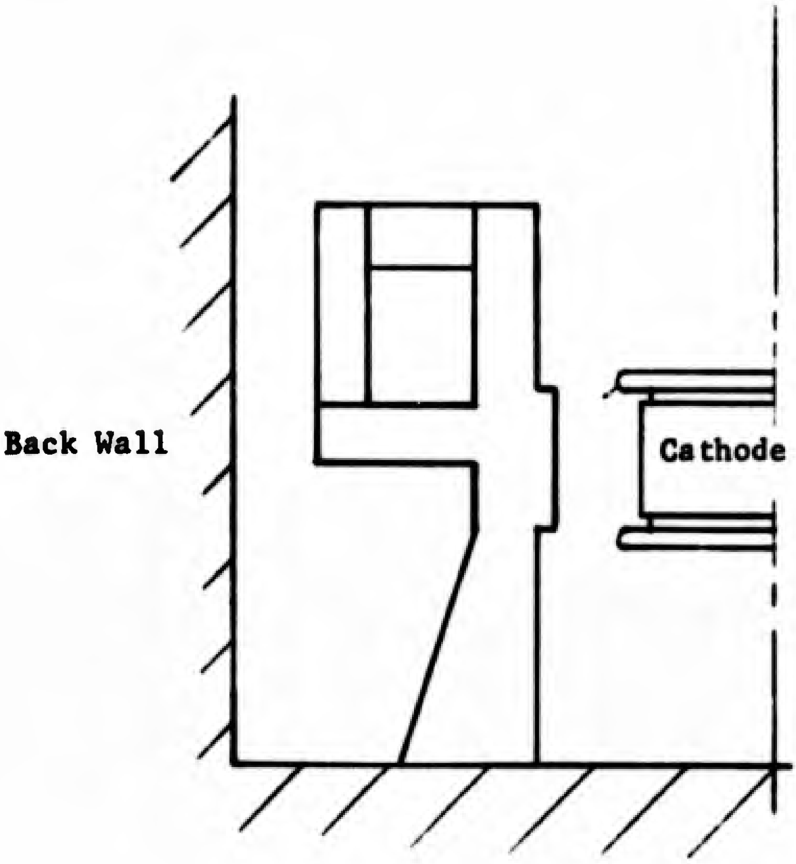

FIGURE 1 SKETCH OF HELIX COUPLED VANE CIRCUIT

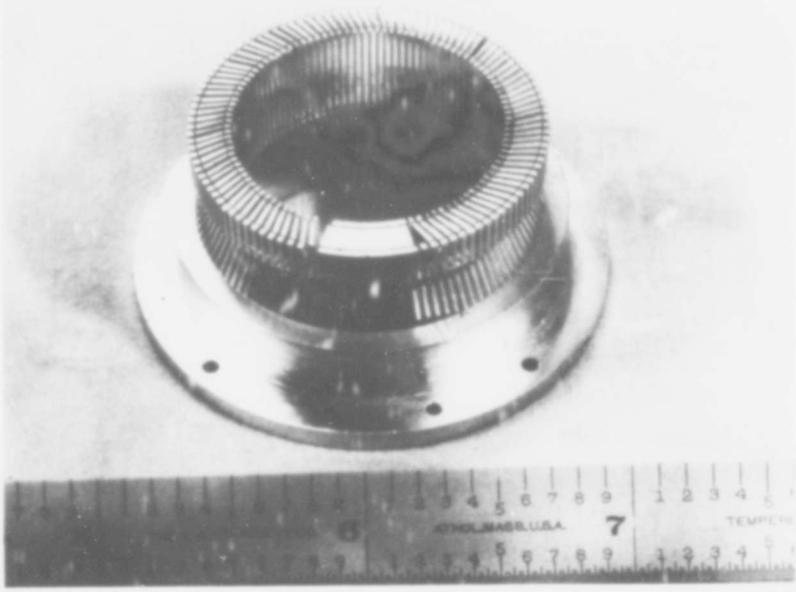

FIGURE 2 PHOTOGRAPH OF X-BAND HELIX COUPLED VANE CIRCUIT

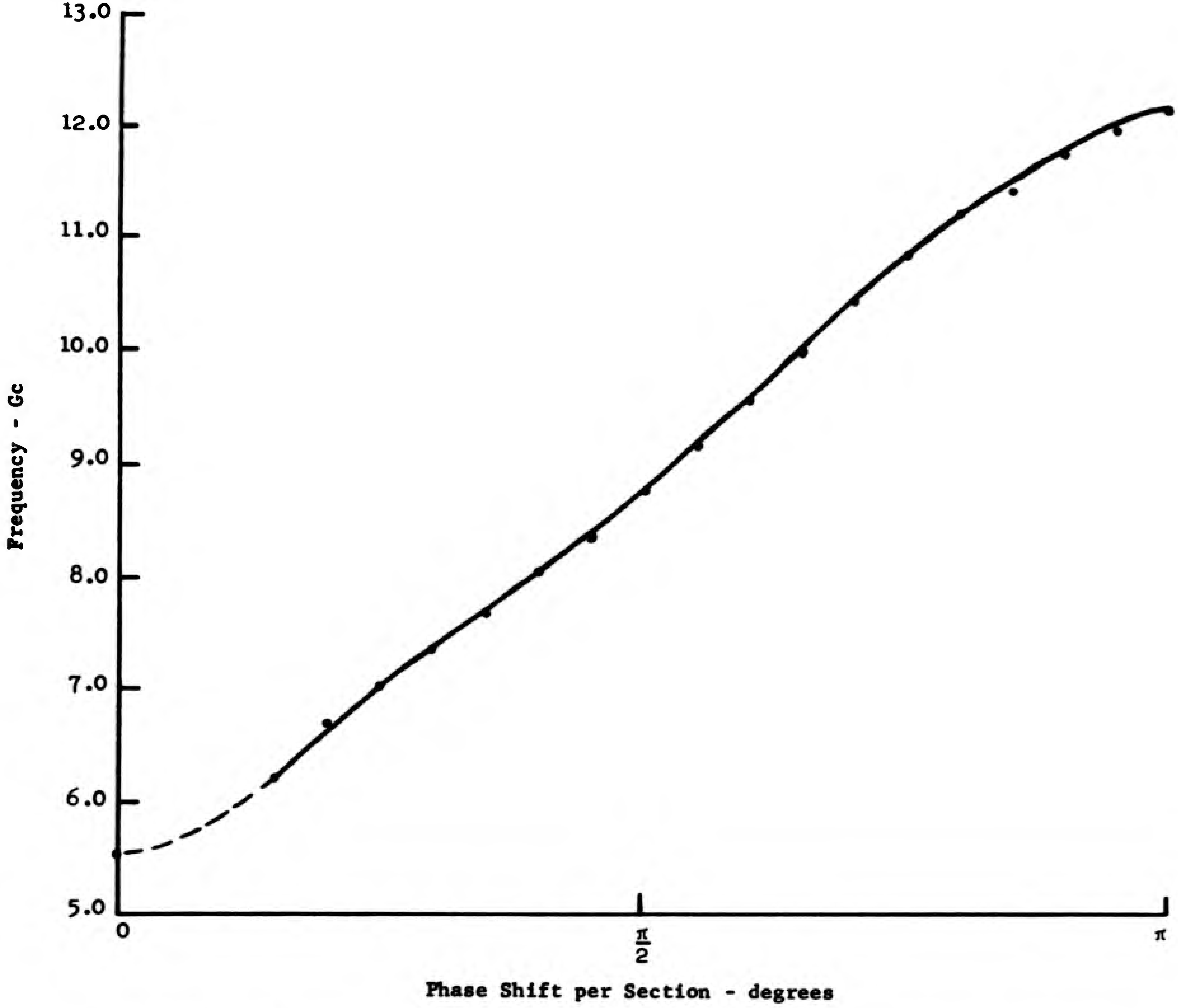

FIGURE 3 MEASURED DISPERSION CURVE OF 0.050" PERIOD HELIX COUPLED VANE CIRCUIT

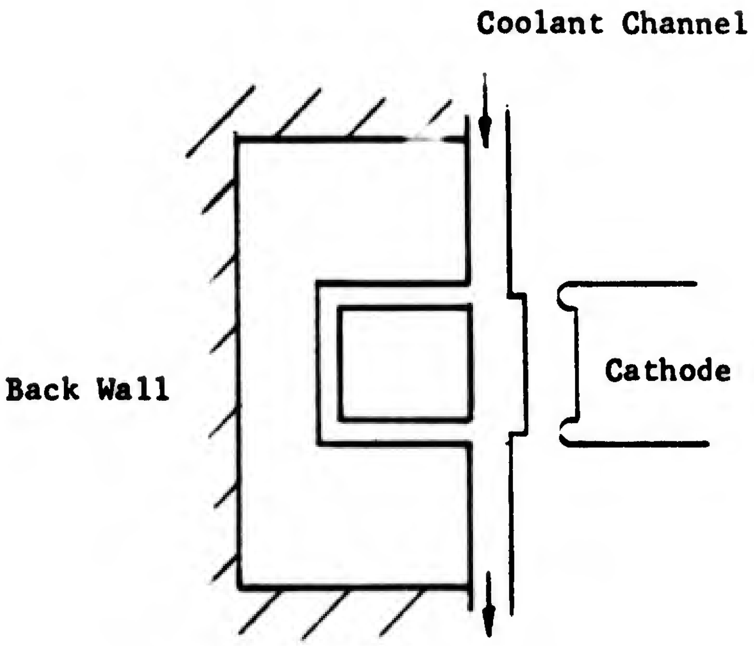

FIGURE 4 SKETCH OF HELIX COUPLED LADDER LINE

the dimensions of the helix relative to that of the ladder line, a circuit with very wide bandwidth can be achieved. This type of circuit will be particularly useful at lower frequencies for high average power applications for coolant can be pumped directly through the bars of the ladder line. However, this is not practical for the present program. Other variations of these two basic circuit concepts will occur to the reader.

3.0 COLD TEST OF HELIX COUPLED VANE CIRCUITS

The first circular version of the helix coupled vane circuit had a pitch of 0.030" with 100 active sections, plus a short drift space for space charge debunching, similar to the reactively loaded interdigital line. Initial matching studies were made using the arrangement used to match the linear version of this circuit. This matching technique is shown in Figure 5a. These preliminary tests showed that several of the circuit brazes were poor. Efforts to correct the defects were not completely satisfactory and the circuit conditions, even after repair, can only be described as poor.

With a cathode simulator in place, energy was coupled across the drift space directly to the output. This is one of several undesired transmission paths which needed to be eliminated before proper amplifier operation could be expected. It was found that such coupling could be reduced by selectively locating the position of the matching tapers. However, even with this transmission path minimized, the energy was not confined to the slow wave circuit but radiated freely.

Again the coaxial match was considered as it had been for the reactively loaded interdigital line circuits. By the use of a coaxial match, RF can be brought to the desired point of the circuit with a minimum of radiation. This is, of course, due to the inherent shielding properties of the outer sleeve of the coaxial line. Preliminary studies with coax indicated that indeed radiation was reduced. However, even with less radiation, it did not appear that a match could be achieved because of the obvious variation in the circuit itself. Because of this, a detailed analysis of random and systematic errors was made (see Section 4). This indicated that, to evaluate the circuit itself, it would be best to reduce the number of sections and increase the pitch of the circuit. On this basis, new circuits were ordered which had the number of sections reduced from 100 to 60 and

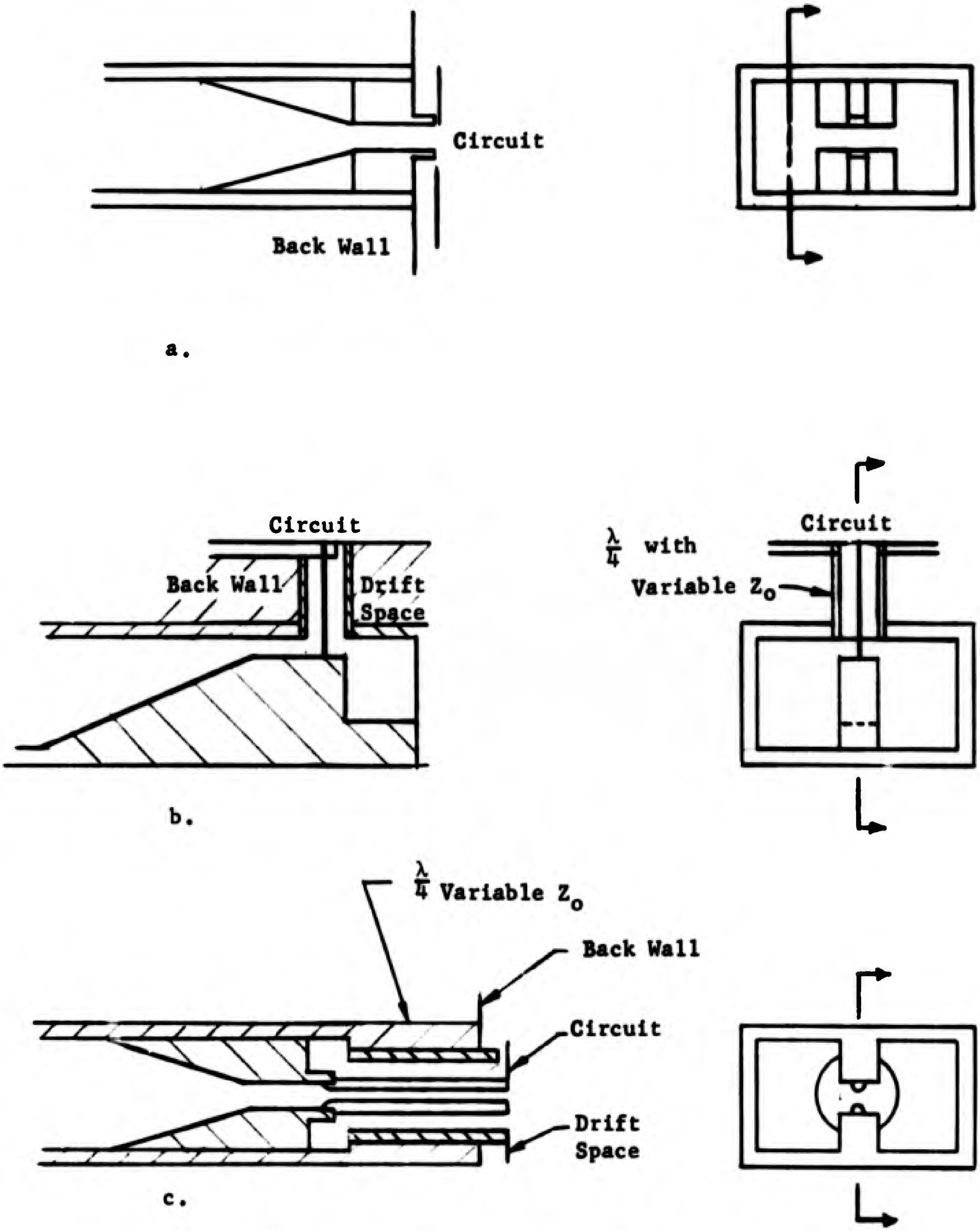

FIGURE 5 MATCHING TECHNIQUES USED WITH HELIX COUPLED VANE CIRCUIT

the pitch increased from 0.030" to 0.050". This design would result in inherently high peak power tubes, operating at higher voltages, but the circuit usefulness could be evaluated more quickly.

While awaiting the higher voltage circuits, matching studies continued with the 0.030" period circuit in a cold test body. In the body, the circuit had a greater tendency to radiate into free space even with a coaxial match. A dummy anode was substituted to verify that energy could be coupled readily into the helix-back wall region with a coupling probe used to match the slow wave circuit. The outer coaxial sleeve was shorted to the dummy anode and to the back wall as it was in the previous test with the slow wave circuit. Indeed energy was coupling into this helix-back wall spacing and then radiating out. In previous tubes with similar matching arrangements, such spacings could not be excited because this propagating mode was cut off. However, this configuration establishes a geometry between the circuit and the back wall which resembles a half section of single ridge waveguide (see Figure 1). Calculation of the cut-off frequency of such a ridge guide indicated that it could propagate well below the circuit itself. Preliminary data (see Figure 6) indicated that energy was being transmitted through these undesired back wall-circuit spacings only 10 db down from the reference level even when the drift space was shorted. Corrective measures consisted of making contact to the helix with the center pin and outer sleeve on adjacent turns and of bringing the cutaway portion of the outer sleeve to within 0.020" of the slow wave circuit. By these changes, the effective transmission through this circuit-back wall spacing was reduced to the 30-40 db region in the band of interest (see Figure 7). These data were taken by terminating the energy on the slow wave circuit and measuring transmission from input to output. Loading the back wall region reduced this transmission.

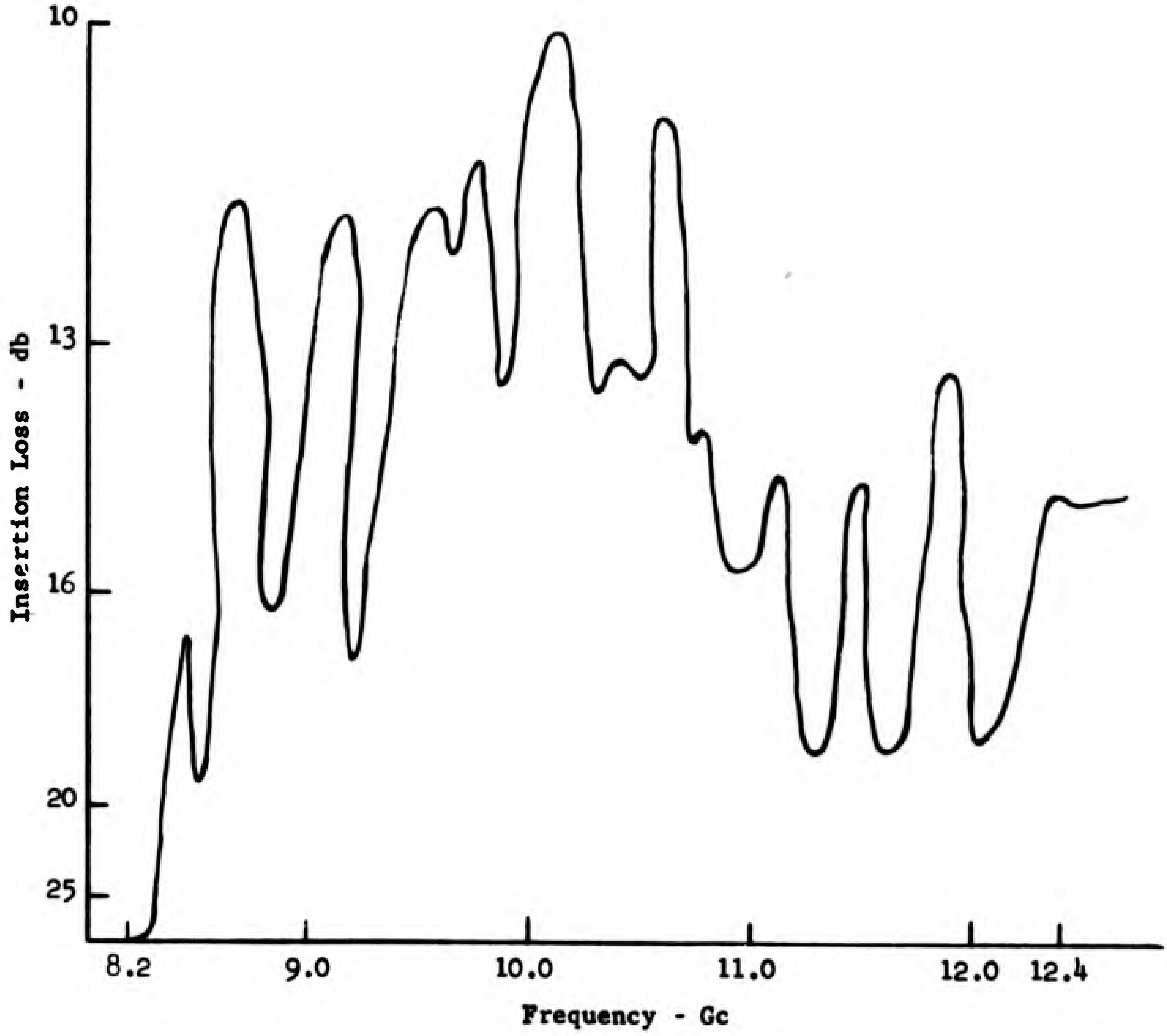

FIGURE 6 UNDESIRED TRANSMISSION THROUGH 0.050" HELIX BACK WALL SPACING WITH COAXIAL SLEEVE CONNECTED IN STANDARD MANNER

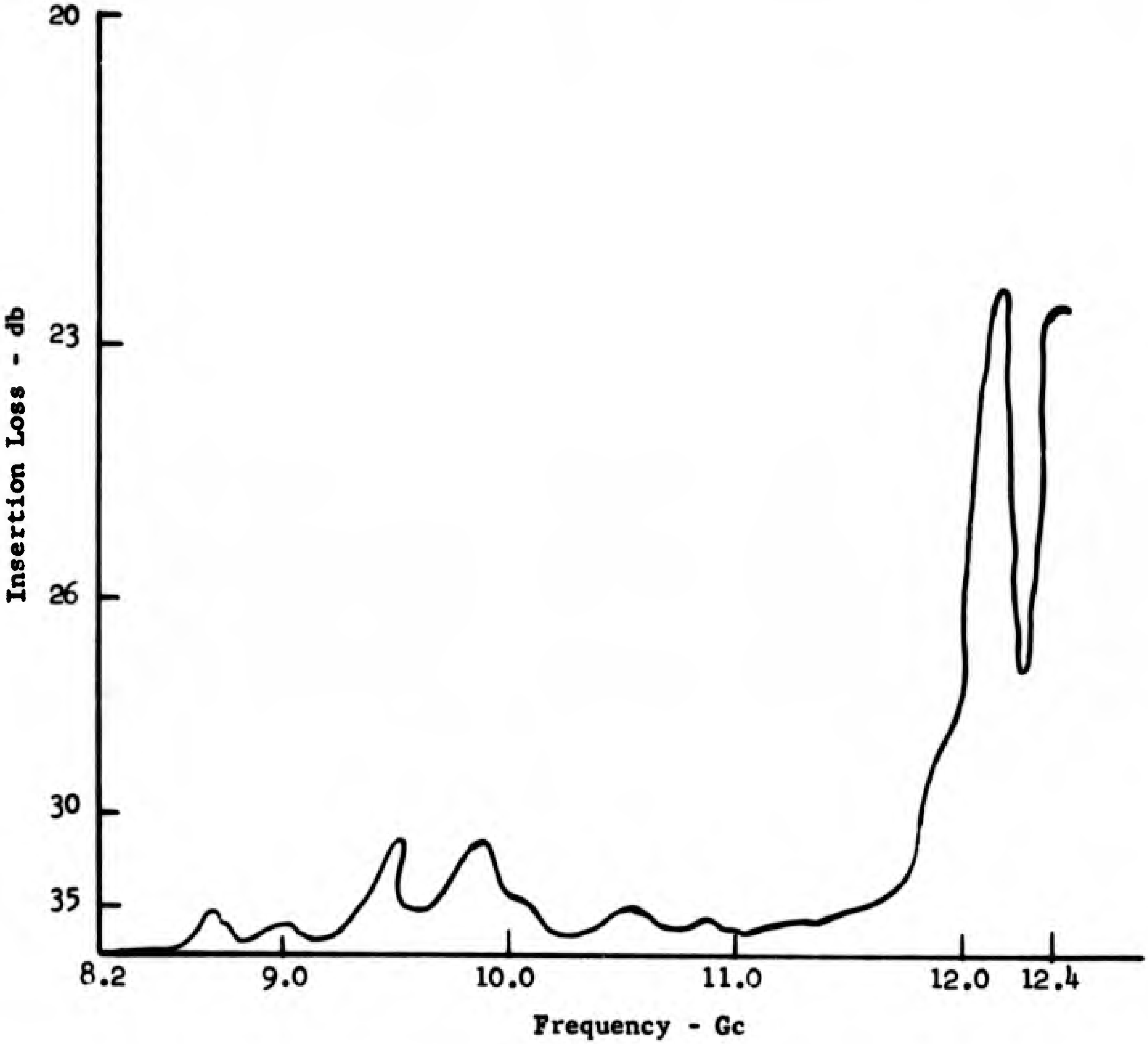

FIGURE 7 UNDESIRED TRANSMISSION THROUGH 0.050" HELIX BACK WALL SPACING WITH 0.020" EXTENSION OF SLEEVE AND CENTER PIN OF COAXIAL LINE CONNECTED TO ADJACENT TURNS OF THE CIRCUIT

With energy confined to the slow wave circuit, it was then possible to begin meaningful quantitative matching studies using arrangements suitable for use in a hot tube. Such a technique (see Figure 5b) uses a single ramp linear taper to single ridge guide having an impedance approximately equal to that of the slow wave circuit. A mode transformation is then made to coaxial line, again having the approximate impedance of the slow wave circuit. For matching purposes, this coaxial line is $\lambda/4$ long and has removable sleeves to adjust the match. The actual connection to the slow wave circuit is made as previously described with the inner and outer conductor making contact to the circuit on adjacent turns. The method tested has the helix itself shorted as shown in Figure 8 with the connection to the coax located a nominal $\lambda/4$ from this short. A new approach, not yet tried, eliminates the short in the helix by bringing the end of the helix directly into the coaxial line as the center conductor. Such a match appears to have greater bandwidth potential.

The 0.030" period helix coupled vane circuit was estimated to have a surge impedance of 66 ohms based on open strip line approximations. The transitions were designed accordingly and tested back-to-back, separated by a finite length of 66 ohm coaxial line. The results showed that this transition to coax was excellent over the frequency range of 8.5 Gc to 12 Gc as shown in Figure 9.

Fairly good matches have been made to the circuit using these transitions when the slow wave circuit is terminated by "ecco-sorb". However, the large number of sections with the cumulative tolerance error of this poor low voltage circuit prevents a good match. This was verified by modifying the cold test body to allow the matching technique to be evaluated into the full 100 sections of the circuit, or into only 40 or 17 sections of the circuit. As the number of sections was reduced, the match appeared to improve as did the uniformity of transmitted power. It appears that the surge impedance of this circuit is higher than estimated.

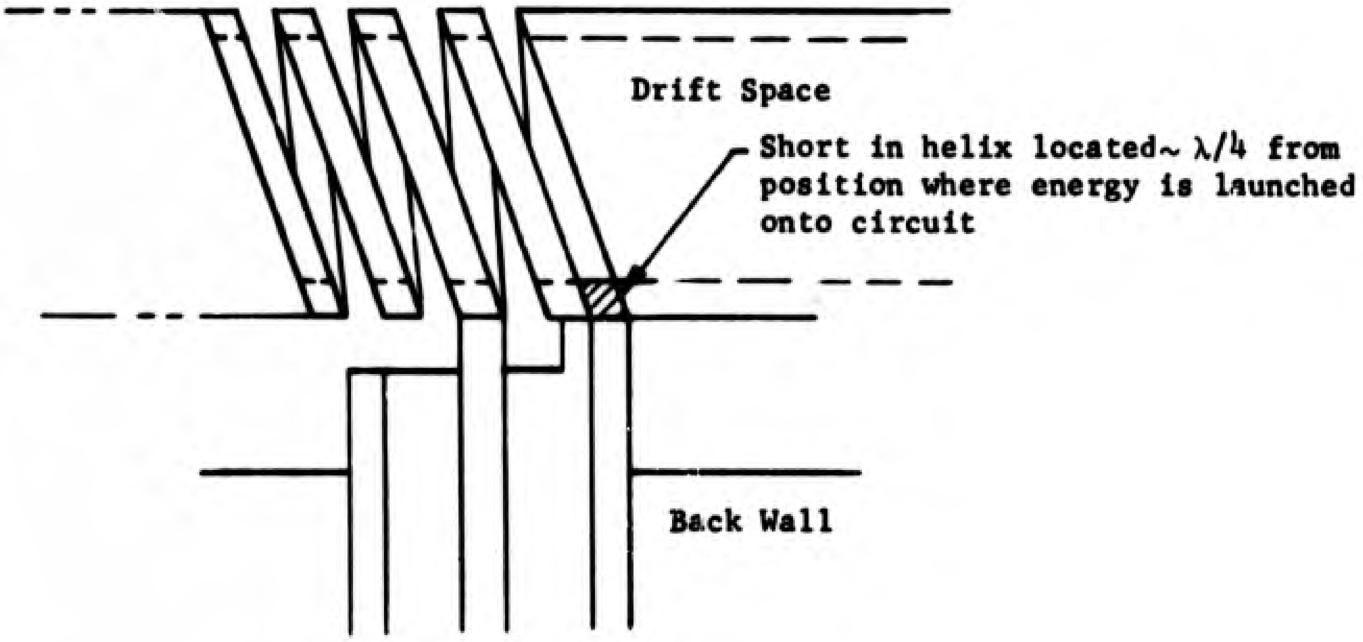

FIGURE 8 DETAILED VIEW OF COAXIAL CONNECTION TO SLOW WAVE CIRCUIT

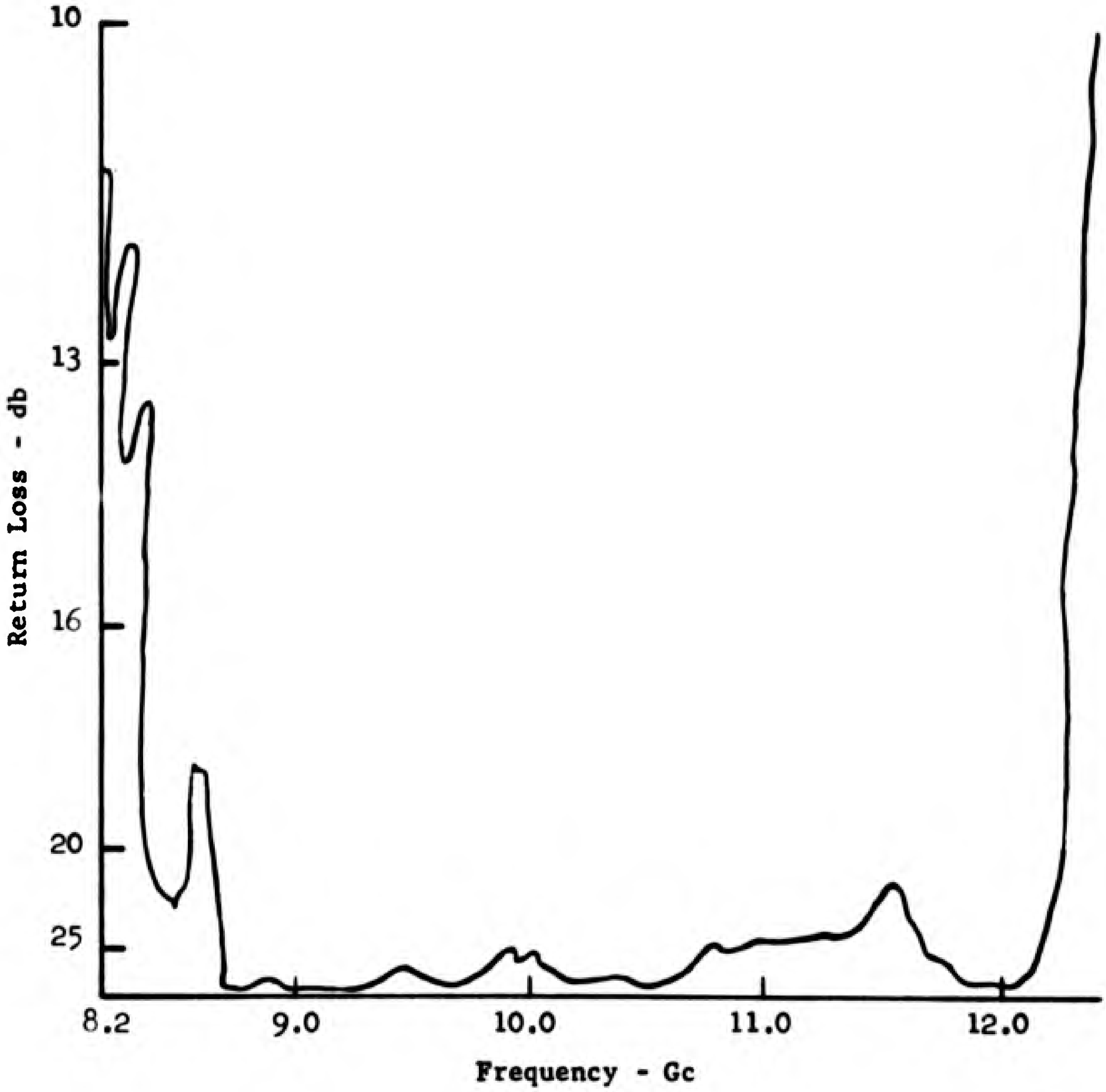

FIGURE 9 RETURN LOSS FROM TWO WAVEGUIDE TO COAXIAL TRANSITIONS (SEPARATED BY LENGTH OF COAXIAL LINE EQUAL TO ESTIMATED IMPEDANCE OF 0.030" PERIOD CIRCUIT)

The first 0.050" period circuit available was designed to use a shielded pair, balanced transmission line matching technique using double ridge tapers (see Figure 5c). This is similar to the preliminary matching technique (Figure 5a), except that the undesired transmission paths are effectively shielded from the strip line used to launch energy onto the circuits. The same basic approach of estimating impedances and the use of $\lambda/4$ line for final impedance tailoring is used for this technique as is used for the coaxial technique. Here the end of the helix wire is brought directly to one of the two wires of the shielded pair (see Figure 10) so that $\lambda/4$ shunt impedances are minimized and maximum bandwidth capability is maintained. As with the 0.030" period circuit, the surge impedance of this 0.050" period circuit was again higher than estimated. The intended adjustment to obtain a match was to increase the diameter of the shielding sleeve. However, the maximum diameter available already indicated that some radiation into the back space was taking place. Rather than increase the intermediate $\lambda/4$ impedance further and increase radiation, the impedance of the double ridge ramp was decreased in an effort to make the $\lambda/4$ impedance the proper geometric mean impedance. The results were very good as indicated by the match obtained in Figure 11. Note that the match designated "Input" is different from that designated "Output". This is due to an asymmetry of the circuit end conditions caused by the location of the choke supports for interaction and the mechanically convenient points of coupling. To overcome this, minor adjustments of the pertinent dimensions are needed at the input and the output ports.

This match is considered to be very satisfactory for the initial test of this circuit and therefore the circuit has been released for final assembly. Body parts and cathode assemblies requiring only final machining had been prepared so that a hot tube using the actual cold test circuit should be available in mid-January

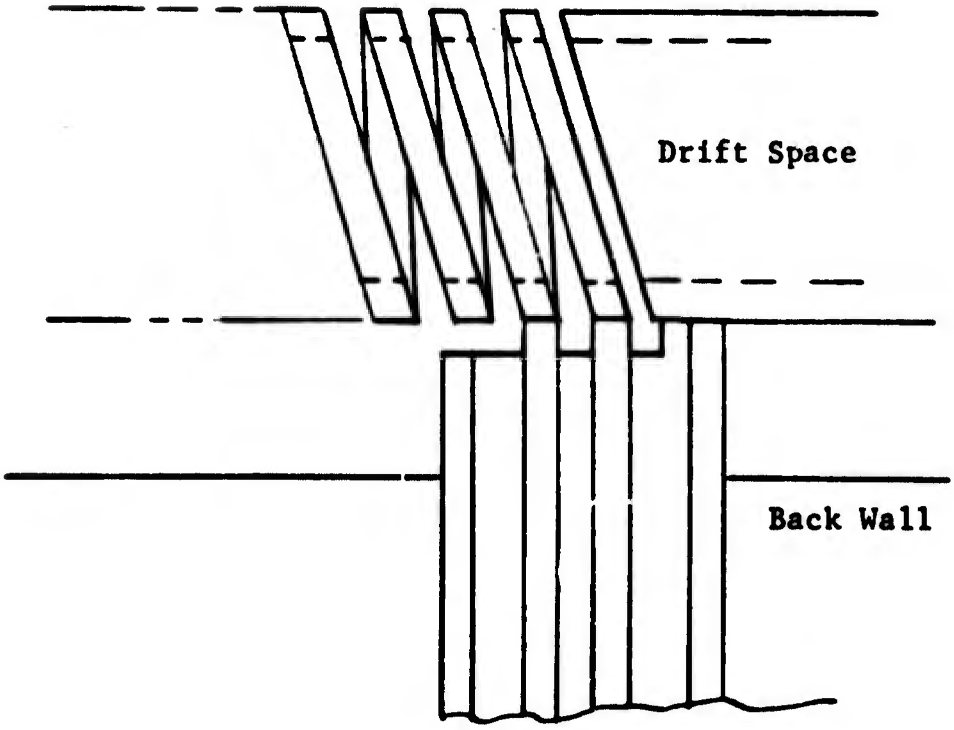

FIGURE 10 DETAILED VIEW OF SHIELDED PAIR, BALANCED LINE CONNECTION TO SLOW WAVE CIRCUIT

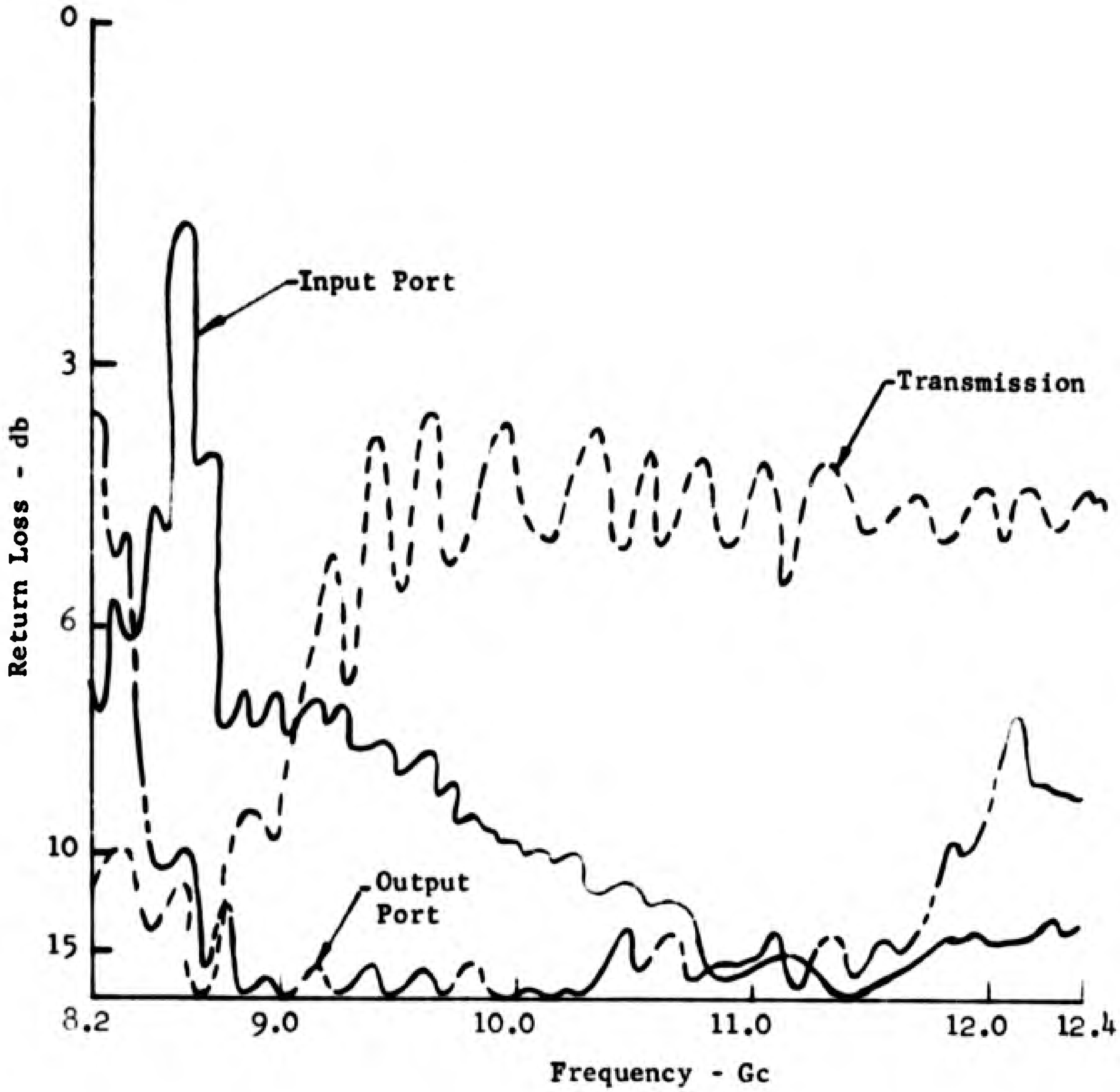

FIGURE 11 MATCHING DATA OBTAINED WITH 0.050" PERIOD HELIX COUPLED VANE CIRCUIT USING SHIELDED PAIR, BALANCED LINE MATCHING TECHNIQUE (CIRCUIT TERMINATED BY "ECCOSORB")

1965. It should be noted that this first test is intended to evaluate the helix coupled vane circuit as a suitable amplifier circuit. It is basically a higher voltage design and, therefore, will result in a higher peak power device than any other tested on this program. On this basis, it was felt that any attempts to reduce the current to levels suitable for CW operation at the levels set for this program would merely becloud the evaluation of this slow wave circuit. Therefore, primarily high peak power pulse techniques will be used to evaluate this vehicle. If warranted, some CW operation will be attempted.

4.0 STUDY OF RANDOM AND SYSTEMATIC ERRORS

While the matching of re-entrant crossed-field amplifiers has always been a problem, such matches have not approached the difficulties associated with the matching of the long period structures used in TWT's and BWO's. Such circuits have problems caused by the cumulative effect of small errors. In the past, circuits thermally suitable for re-entrant stream crossed-field amplifiers have limited the useful bandwidth to approximately 20%. In addition, the control of re-entrant space charge has to date limited the noise free gain region of these devices under pulsed conditions to approximately 20 db. Such factors have dictated the number of sections that need be used and the β range over which the circuit need be matched. The utilization of the high efficiency properties of crossed-field devices has also been normally made at very high peak power ratings with corresponding increases in spacings. All of these factors tend to simplify the matching problems of these circuits, although they certainly do not make matching easy. However on this program, the higher gain and lower peak power, coupled with the wide useful bandwidth of these new circuits, have greatly increased the problems of matching.

Some useful equations used to analyze the effects of small errors on interdigital circuits are given below (Ref. 1)

$$\lim_{\theta \to \frac{\pi}{2}} |\gamma_{2n}|^2 = \frac{4\delta^2 n^2}{1 + 4\delta^2 n^2} \qquad \text{(misregister of crown)} \qquad (1)$$

$$|\gamma_n|^2 = n\delta_{rms}^2 \sin^2 \theta \qquad \text{(uncorrelated random errors)} \qquad (2)$$

---

1. CROSSED-FIELD MICROWAVE DEVICES, ed by E. Okress, "The Effect of Tolerance on Interdigital Lines," M. C. Pease, Vol. 1, Academic Press, 1961, p 87 ff

$$|\gamma_n|^2 = 2n\delta_{rms}^2 \sin^4 \theta \quad \text{(correlated random errors)} \tag{3}$$

where γ = reflection coefficient

δ = impedance error from nominal

n = number of stepped impedance errors
$\approx$ number of sections

$$\delta_{rms} = \left\{ \frac{1}{n} \Sigma \, \delta^2 \right\}^{\frac{1}{2}}$$

θ = actual RF phase advance in one section of the primary path

Equation (1) indicates the mismatch expected when the crowns supporting the interdigital line are not registered properly. The more general equation shows that the effect falls off very rapidly away from $\theta = \pi/2$ and therefore other points are ignored. This equation applies to the RLIL and, for proper use, it must be remembered that the number of sections of the interdigital path is half the number of vanes of the RLIL. Also the phase in the interdigital path equals $2\theta/\text{section} - \pi$. Equation (2) applies to uncorrelated changes in impedance which would occur with different slot widths due to random cutting errors. Equation (3) applies to correlated changes in impedance which would occur with a bent vane. The impedance on one side of the bent vane would increase while that on the other side would decrease.

In this section, an attempt will be made to analyze the cumulative effect of hypothetical errors on the 100 section - 0.030" period RLIL, the 100 section - 0.030" period helix coupled vane circuit, and the 60 section - 0.050" period helix coupled vane circuit. For these calculations, it will be assumed that the circuit impedance approximates that of open strip line having the same dimensions as the circuit evaluated and that spacings can be held to ±0.0005" on both the 0.030" and 0.050" circuits. This corresponds to a

$\delta = \delta_{rms} = 0.033$ for the 0.030" circuit and $\delta = \delta_{rms} = 0.02$ for the 0.050" circuit.

Equation (1) applied to the 0.030" period RLIL would give

$$|\gamma_{2n}|^2 = \frac{4(0.033 \times 50)^2}{1 + 4(0.033 \times 50)^2} = 0.915$$

$$\gamma_{2n} = 0.955$$

This would effectively put a stop band at approximately 9 Gc. Reducing the error δ to 0.02 and n to 25 still leaves $\gamma_{2n} = 0.5$. The problems of the stop band are obviously not easily reduced. Equation (2) for uncorrelated random errors seems to apply quite well to the RLIL. Any bent vane would affect only the impedance of that portion of the interdigital path and the impedance of the series reactive element adjacent to it. It would not affect the impedance in an adjacent portion of the interdigital path. The fact that the two crowns are machined separately appears to further remove any correlation of machining defects. Equation (2) then gives

$$\gamma_n = \sqrt{50}\ (0.033) \sin \theta = 0.233 \sin \theta$$

These random uncorrelated errors are then a slow varying function over wide portions of the band which can offer excessive mismatch for a 30 db gain tube. A return loss ripple of no better than 13 db could be expected across the band unless the circuit losses were quite high. This assumes that a perfect match could be made to the nominal circuit impedance at all frequencies. Were these errors correlated, the effect would be

$$\gamma_n = 0.33 \sin^2 \theta$$

with return loss varying more rapidly with frequency and again peaking at mid-band to approximately 10 db return loss. These calculations are plotted against frequency in Figure 12 for the two random error cases.

For the helix coupled vane circuits, the effect of register would not exist and therefore matching throughout the complete band would be much more uniform. However because there are effectively more sections, the reflection coefficient away from the $\pi/2$ point would be worse than the above RLIL circuit by the $\sqrt{2}$ for equal ability to fabricate the structures. By reducing the number of sections to 60 and increasing the period to 0.050", this factor is reduced to 0.65. Plots of these responses are given in Figures 13 and 14.

The general conclusion of this section is that the worst match point of any of these circuits should occur at mid-band. This effect can be appreciably reduced with the helix coupled vane circuits by decreasing the number of active sections and increasing the period of the circuit. However, this is not true with the RLIL, where a stop band remains very pronounced. Away from the stop band, it would appear that the RLIL could be matched better than a helix coupled vane circuit having the same period and number of sections. If the tolerance limit increases to ±0.001, δ approximately doubles for any of these circuits and good circuit matches could not possibly be achieved.

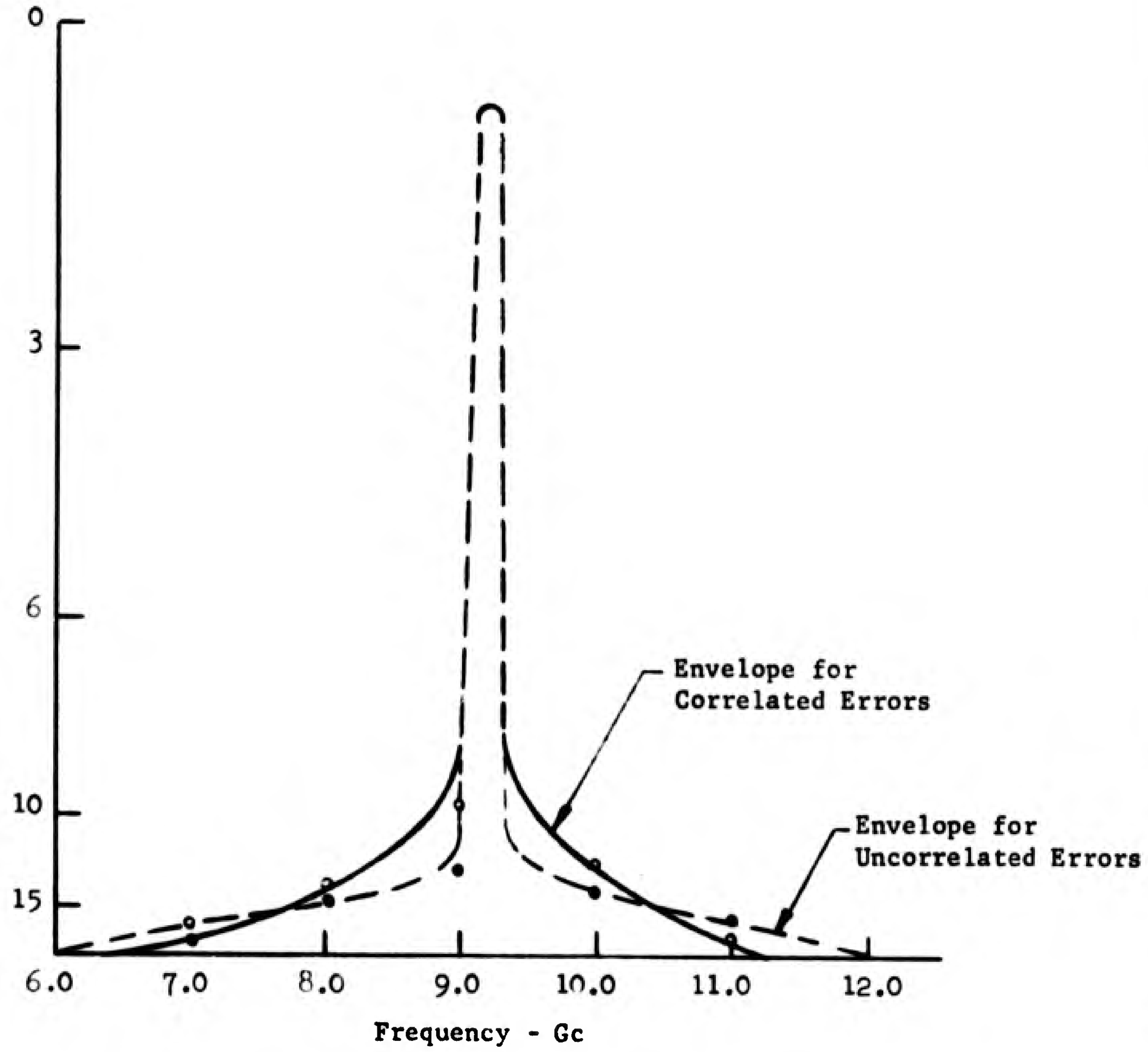

FIGURE 12 CALCULATED MISMATCH OF 100 SECTION 0.030" PERIOD RLIL CIRCUITS DUE TO CUMULATIVE RANDOM ERRORS (± 0.0005" TOLERANCE)

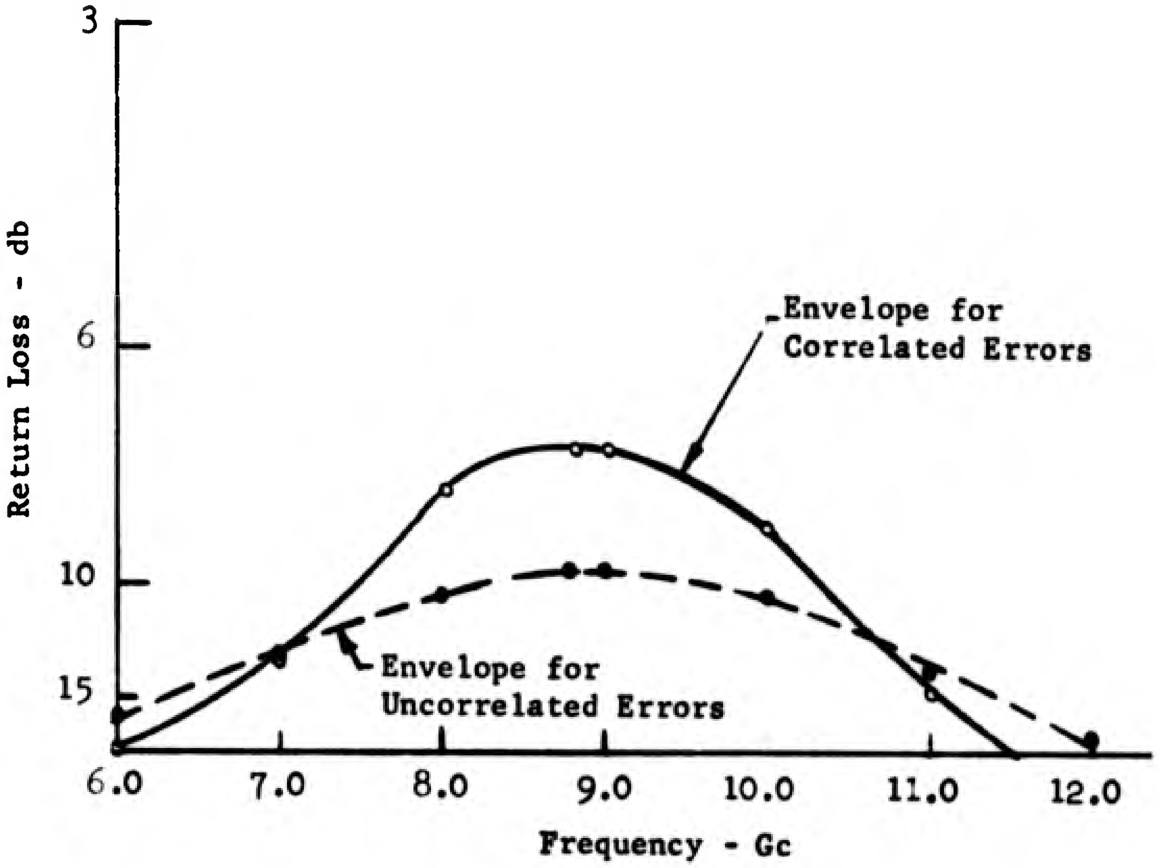

FIGURE 13 CALCULATED MISMATCH OF 100 SECTION 0.030" PERIOD HELIX COUPLED VANE CIRCUIT DUE TO CUMULATIVE RANDOM ERRORS (± 0.0005" TOLERANCE)

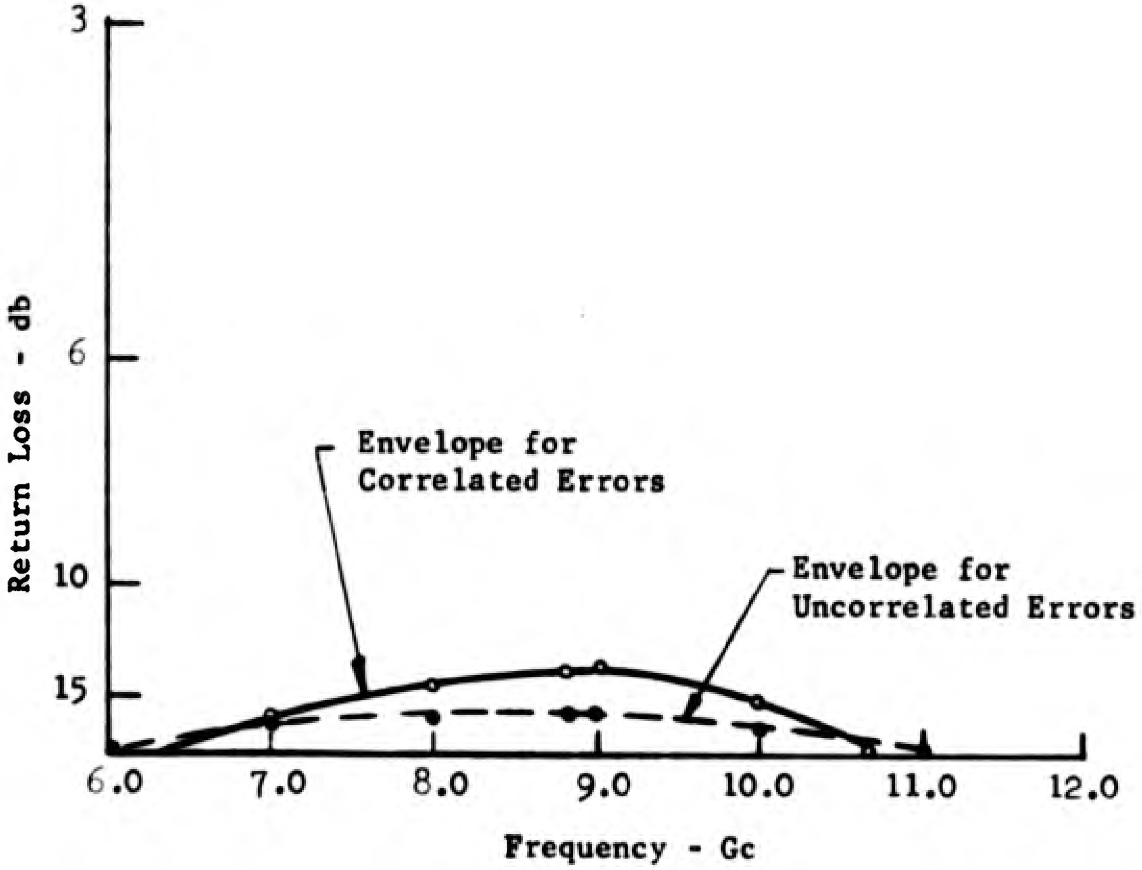

FIGURE 14 CALCULATED MISMATCH OF 60 SECTION 0.050" PERIOD HELIX COUPLED VANE CIRCUIT DUE TO CUMULATIVE RANDOM ERRORS (± 0.0005" TOLERANCE)

5.0 SUMMARY

The matching techniques used on the new slow wave circuit have been very successful. As a result, meaningful data concerning the helix coupled vane circuit should be obtained as a crossed-field amplifier. The experience gained on control of radiation should be useful in obtaining good matches to the other vehicles previously tested.

6.0 FUTURE PROGRAM

Efforts on this program during the next quarterly report period will be directed along the following lines.

1. Complete the fabrication of the first hot tube incorporating the 0.050" period helix coupled vane circuit.
2. Hot test this first tube at high peak power under pulsed conditions to evaluate the circuit.
3. Complete the match to the 100 section, 0.030" eriod helix coupled vane circuit.
4. Build the 0.030" period tube and the second 0.050" period tube, using the helix coupled vane circuits and hot test under normal CW conditions.
5. Rebuild the previous tubes using the crown supported reactively loaded interdigital line if the match can be considerably improved.

7.0 MAN HOURS EXPENDED ON PROGRAM

Summarized below are the man hours expended by the principal engineering and scientific personnel and other personnel in the performance of the program.

	Hours This Quarter	Hours To Date
M. Arnum	0	1682.75
G. K. Farney	5.5	482.5
J. Feinstein	0	44
C. M. Hellenbrand	0	208
J. Hentschel	87	123*
R. Lang	232.5	253.5
L. Lemanski	0	16
R. Springberg	0	993.25
W. C. Sylvernal	27	275
W. Zettler	130	398
Misc Shop & Technical	1278	5269.75
Total	1760.0	9745.75

*Reflects 36 hours charged to project prior to permanent assignment.

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