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STRAPPED MULTIFILAR HELIX TWT STUDY.(U)
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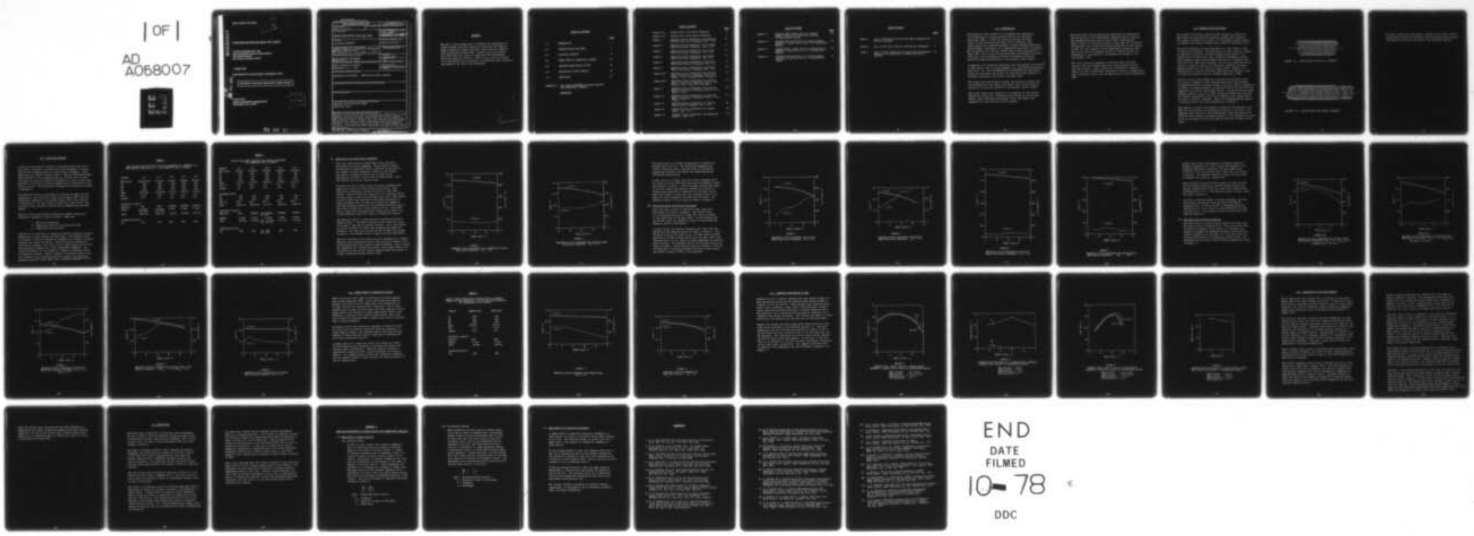

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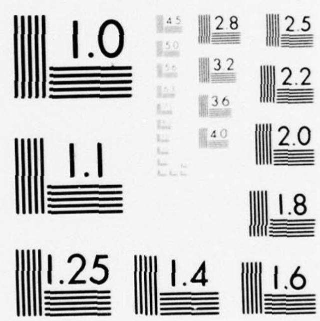
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Report N00173-76-C-0001

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STRAPPED MULTIFILAR HELIX TWT STUDY

LITTON SYSTEMS, INC. dba
Litton Industries Electron Tube Division
960 Industrial Road
San Carlos, California 94070

1 JUNE 1978

Final Report for Period April 1976-March 1978

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The goal of this program was to determine the feasibility of using strapped multifilar helices in traveling wave tubes at higher operating voltages and power levels than was possible with existing helix-type tubes. Several cold test circuits were fabricated and tested by comparison with conventional helix and ring-loop circuits. None of the circuits was found to be satisfactory for inclusion in an operating tube, therefore this phase of the effort was terminated.

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ABSTRACT

The goal of this program was to determine the feasibility of using strapped multifilar helices in traveling wave tubes at higher operating voltages and power levels than was possible with existing helix-type tubes. Several cold test circuits were fabricated and tested by comparison with conventional helix and ring-loop circuits. None of the circuits was found to be satisfactory for inclusion in an operating tube, therefore this phase of the effort was terminated.

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1.0 INTRODUCTION

The purpose of this contract is to determine the feasibility of the technique of using multifilar helices for traveling wave tubes (TWTs), so that the operating voltage and power levels of existing helix-type tubes can be increased. This study program was originally proposed to Naval Research Electronics System Command, Washington, DC, by Microwave Associates, Burlington, MA in December 1975, and the contract was awarded subsequently in April 1976. The initial work was performed by Microwave Associates from April 1976 to February 1977 and the progress during this period was reported previously in nine monthly letter reports.

In February 1977, Microwave Associates sold the business and assets of TWT product lines to Litton Systems, Inc., Electron Tube Division, San Carlos, CA. Thus the project was interrupted for nine months during the transition period when the facilities and personnel of Microwave Associates were moved to the West Coast.

The project was reactivated at Litton, San Carlos in October 1977 and continued for five months until March 1978, and the progress during this period was reported in four monthly letter reports.

This study program was scheduled to be completed in nine months. Theoretical evaluation, construction and evaluation of cold test models, match experiments and design of hot test models were scheduled for the first half of this program.

The second half of this project was scheduled for construction and hot-testing of two experimental high-power TWTs to evaluate the strapped multifilar helix circuit under investigation. After a number of cold-test circuits of this type were assembled and measured, none of them was found satisfactory for hot testing to meet the time schedule for the experimental high-power TWTs. Due to the lack of encouraging results to justify further investigation, it was decided to discontinue the project at the end of March 1978.

This final report was prepared to describe these cold test circuits built and tested during this study program and their cold test results. These circuits are evaluated by comparing them to two more conventional interaction circuits, a simple helix and a ring-loop circuit, for the application in similar high-power TWTs.

2.0 STRAPPED MULTIFILAR HELIX

The concept of multifilar helix for TWT interaction circuit has been known for many years and extensive studies were conducted by a number of people in the past. A bibliography on this subject is compiled and listed in chronological order as references (1-9).

The unique advantage of helix-type TWTs over other types of TWTs is their wide bandwidth. The application of simple helices, however, is limited to relatively low beam voltages mostly below 10 kV, because helix circuits have lower interaction impedance, limited power handling capability and higher possibility of backward wave oscillation at higher beam voltages. The use of a multifilar helix circuit is known to improve the interaction impedance and power-handling capability over that of a simple helix. However, the multiplicity of circuits introduces additional mode problems, some of which may interfere with the intended operation of TWTs.

One way to solve this problem is to provide the multifilar helix with proper strapping so that undesired modes may be discouraged or suppressed without excessive change in the main mode of propagation. A variety of strapping methods for multifilar helix circuits has been suggested and tried by other people before. During the present study program, however, only two of these strapping methods were selected for further experimental study, one of which is axial strapping and the other is helical strapping. These two strapping methods applied to bifilar helices are shown schematically in Figure 1.

The objective of this study program included the hot-testing of two TWTs for the evaluation of interaction circuits of this type. The operating beam voltage of these experimental tubes was specified at 20-22 kV, which required the phase velocity of the interaction circuit to be in the range of 0.25-0.20 times the velocity of light in free space.

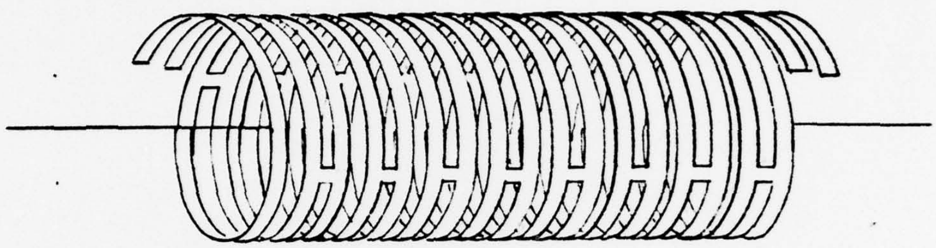

FIGURE 1(a) - BIFILAR HELIX WITH AXIAL STRAPPING

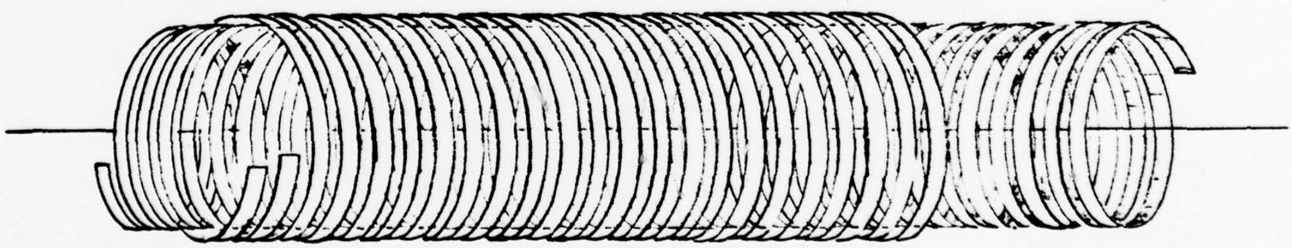

FIGURE 1(b) - BIFILAR HELIX WITH HELICAL STRAPPING

In order to meet this requirement, a number of cold test circuits of multifilar helix have been built and tested during this project, the results of which are described in the following sections.

3.0 COLD TEST CIRCUITS

A total of ten cold-test circuits of multifilar helix were built and tested, including 4 circuits with axial strapping, 5 circuits with helical strapping and one circuit without strapping. Their dimensions are listed in Tables A and B. The cold test measurements were conducted in the frequency range of 2-8 GHz on all of them. The phase velocity and interaction impedance of these circuits were measured by conventional methods commonly used for helix-type interaction circuits. The measurement techniques are described in detail in Appendix A.

The measured results are presented by plotting the phase velocity normalized to the velocity of light in free space, V_p/C, and the interaction impedance at the circuit radius, K(a), as a function of frequencies. The same format of plotting is used for all test circuits so that different circuits can be compared and evaluated easily.

There are three basic factors affecting the phase velocity and interaction impedance of these circuits. These are:

1. main helix dimensions
2. supporting dielectric materials and sizes
3. conducting shield envelope

Therefore it is difficult to compare and evaluate different circuits unless some of these factors are kept equal. Also another factor to consider is that the interaction impedance is a function of phase velocity and circuit dispersion. Thus when similar interaction circuits are compared, the circuit with a higher phase velocity and less dispersion usually has a lower interaction impedance. The circuit dispersion can be reduced by a number of techniques known as dispersion shaping. Special shaping of dielectric supports and use of vanes on the conducting shield are some of the techniques frequently applied in many TWTs with an extended bandwidth (10-15).

TABLE A

LIST OF COLD TEST CIRCUITS WITH AXIAL STRAPPING (A-1 THROUGH A-4) AND WITHOUT STRAPPING (A-5). ALL DIMENSIONS ARE IN INCHES.

CIRCUIT	A-1	A-2	A-3	A-4	A-5
Main Helix	Quadrifilar	Trifilar	Bifilar	Bifilar	Bifilar
ID	.234	.234	.295	.295	.295
OD	.264	.264	.315	.315	.315
MD	.249	.249	.305	.305	.305
Tape	.015x.027	.015x.020	.01x.05	.01x.05	.01x.05
TPI	4.125	7.14	4.0	6.0	4.0
Length	2.9	3.0	6.0	6.0	6.0
Dielectric Support					
Material	BeO	BeO	Alumina	Alumina	Alumina
Number	3 blocks per turn	3 blocks per turn	3 rods	3 rods	3 rods
Size	.06x.135	.06x.135	.09 dia.	.09 dia.	.09 dia.
Conducting Shield					
ID	.412	.412	.500	.500	.500

TABLE B

LIST OF COLD TEST CIRCUITS WITH HELICAL STRAPPING.
ALL DIMENSIONS ARE IN INCHES.

CIRCUIT	B-1	B-2	B-3	B-4	B-5
Main Helix	Bifilar	Bifilar	Unifilar	Unifilar	Unifilar
ID	.291	.291	.265	.291	.291
OD	.311	.311	.315	.311	.311
MD	.301	.301	.290	.301	.301
Tape	.01x.05	.01x.02	.025x.05	.01x.05	.01x.05
TPI (1)	4.0	10.0	4.0	10.0	10.0
Length	6.0	6.0	6.0	6.0	6.0
Strapping Helix					
ID	.281	.281	.245	.281	.281
OD	.291	.291	.265	.291	.291
TPI (2)	32.0	32.0	32.0	32.0	20.0
Tape	.005x.02	.005x.015	.01x.015	.005x.015	.005x.015
Dielectric Support					
Material	BeO	Alumina	(a) Alumina (b) BeO	Alumina	Alumina
Number	3 rods	3 rods	3 rods	3 rods	3 rods
Size	.09 dia.	.09 dia.	(a) .125 dia. (b) .09 dia.	.09 dia.	.09 dia.
Conducting Shield					
ID	.500	.500	(a) .564 (b) .500	.500	.500

(A) Multifilar Helix With Axial Strapping

Four cold test circuits of multifilar helix were built and tested with axial strapping. These circuits consist of multiples of identical helices connected to one another by a number of axial conductors, which are tape straps. The number of straps per helix turn is equal to the multiplicity of helix, such as four for quadrifilar, three for trifilar and two for bifilar helix.

The first two test circuits built with axial strapping were quadrifilar helix (A-1) and trifilar helix (A-2). They were made by machining a series of slots on a thin metal tubing. These circuits were supported in a conducting shield by three pieces of BeO block per each helix turn. This method of helix support was developed by Microwave Associates for other high-power TWTs, by which the interaction impedance and power handling capability are increased effectively while the circuit dispersion is kept minimum (16-19). These TWTs have a higher tube efficiency and a higher power output with a wider bandwidth than other tubes of conventional design.

The measured results on these two test circuits are shown in Figures 2 and 3. The phase velocity in both cases was found to be higher than that of present interest. Also, this method of circuit assembly is rather time-consuming and expensive. Therefore, the cold test circuits can not be made long enough to permit a non-resonant method of phase velocity measurement.

Thus the following test circuits were all assembled by a simpler method in which multifilar helices were wound on a mandrel first and strapping tapes were brazed on them afterward. These circuits are supported by a conventional method, using three ceramic rods of circular cross section, equally spaced around the helices in a plain conducting shield without vanes.

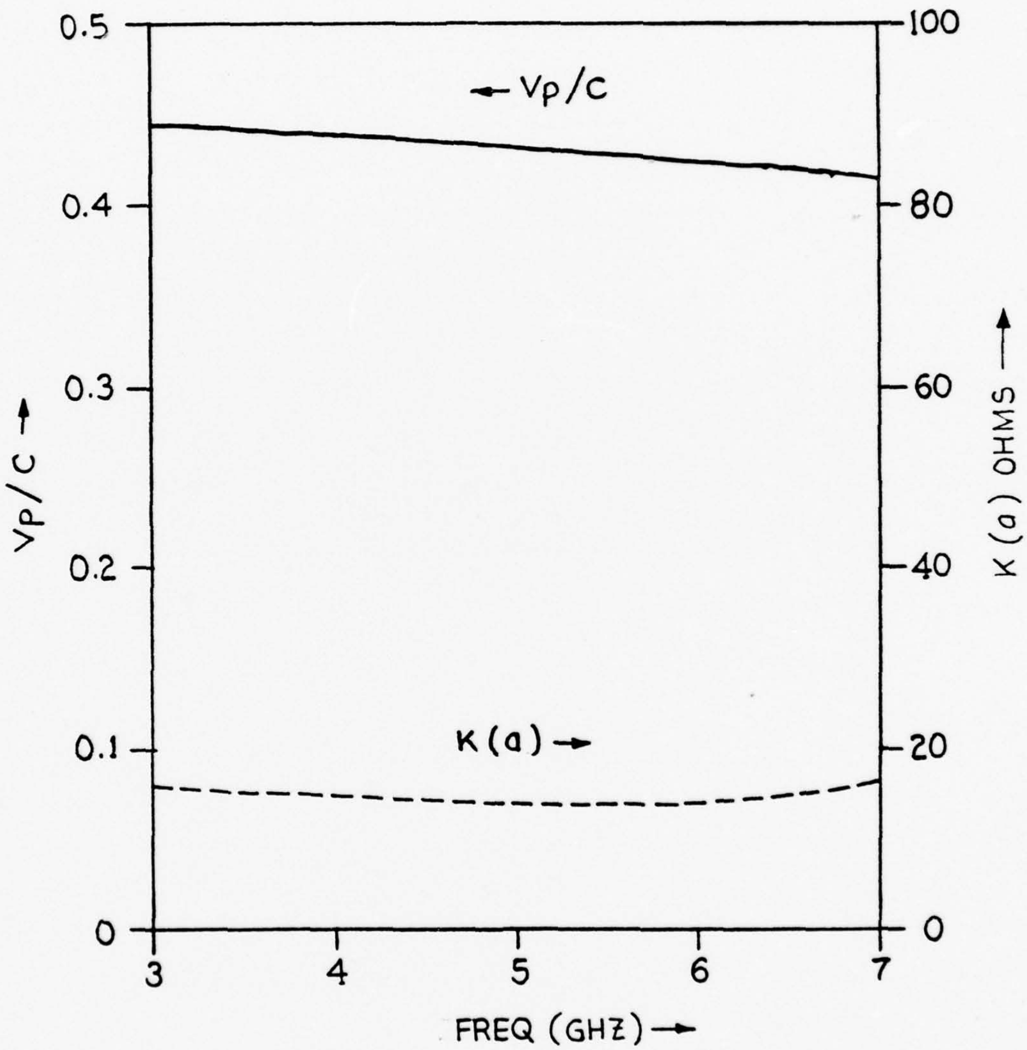

FIGURE 2

MEASURED CIRCUIT PARAMETERS FOR QUADRIFILAR CIRCUIT WITH AXIAL STRAPPING. TPI = 4.13

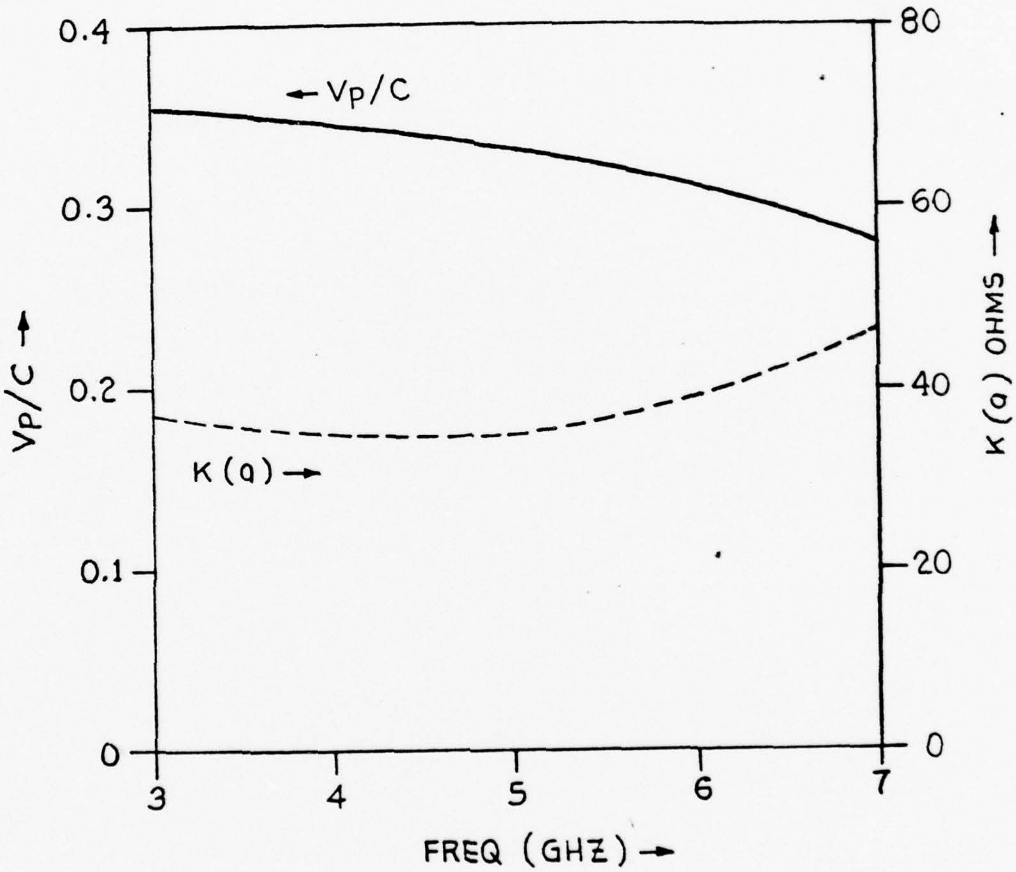

FIGURE 3

MEASURED CIRCUIT PARAMETERS FOR TRIFILAR HELIX
WITH AXIAL STRAPPING. TPI = 7.14

The first step is to design the main helix to obtain the desired phase velocity. The interaction impedance and circuit dispersion may be improved later by varying the supporting dielectric rods and/or the conducting shield for desired applications.

A test circuit of bifilar helix with axial strapping (A-3) was built in the way described above and the measured results are plotted in Figure 4. Since the phase velocity was found to be still higher than desired, another test circuit of bifilar helix with axial strapping (A-4) was built with a helix TPI (number of turns per inch) increased from 4 to 6, while all other parameters are kept same as before. The measured results on this circuit are shown in Figure 5.

(B) Multifilar Helix with Helical Strapping

Five cold test circuits of multifilar helix were built and tested with helical strapping. The helical strap is a contrawound helix with a large TPI, which is brazed to the inside wall of the main helix. It was assumed that the helical strap can simulate a series of ring straps and should be easier to fabricate.

A bifilar helix with helical strapping (B-1) was built and tested with the measured results as shown in Figure 6. After the phase velocity was found to be too high for the present application, another bifilar helix (B-2) was built with a TPI increased from 4 to 10, while all other parameters are kept the same as before. The measured results on this test circuit are shown in Figure 7, which indicate that the increase of TPI did not help much in reducing the phase velocity of this circuit and further increase of TPI is not practical.

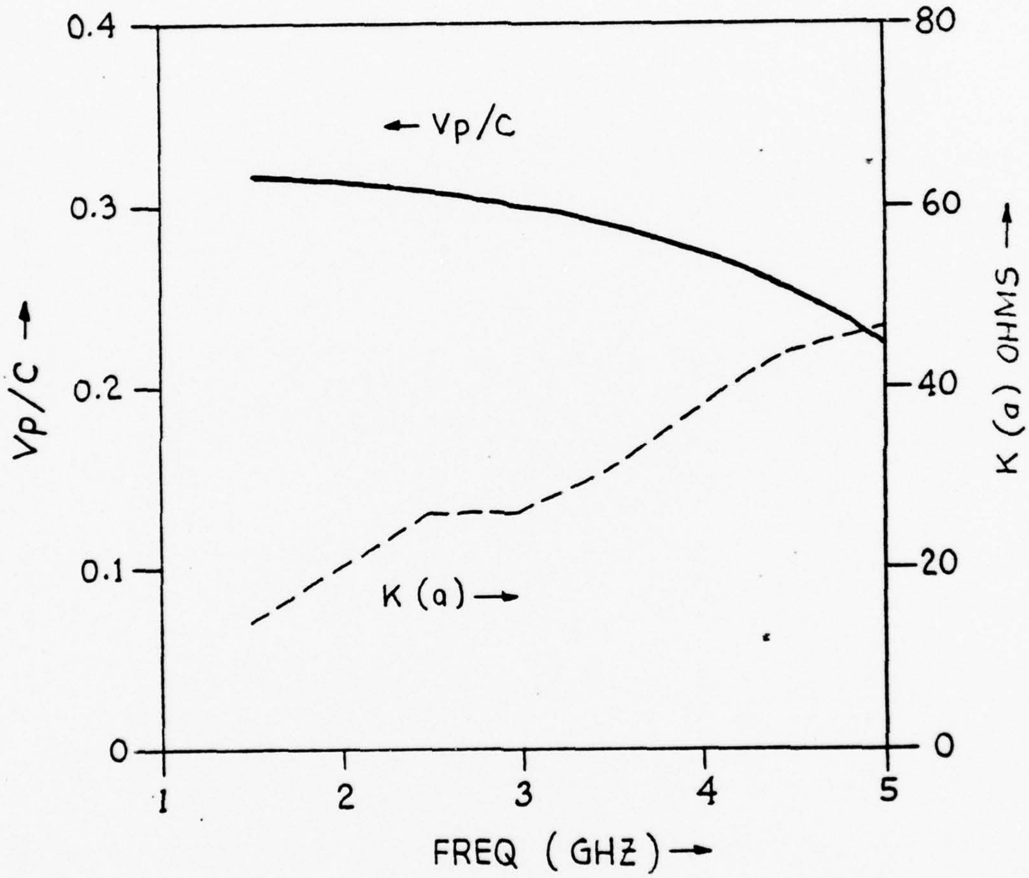

FIGURE 4

MEASURED CIRCUIT PARAMETERS FOR BIFILAR HELIX WITH AXIAL STRAPPING. TPI - 4.0

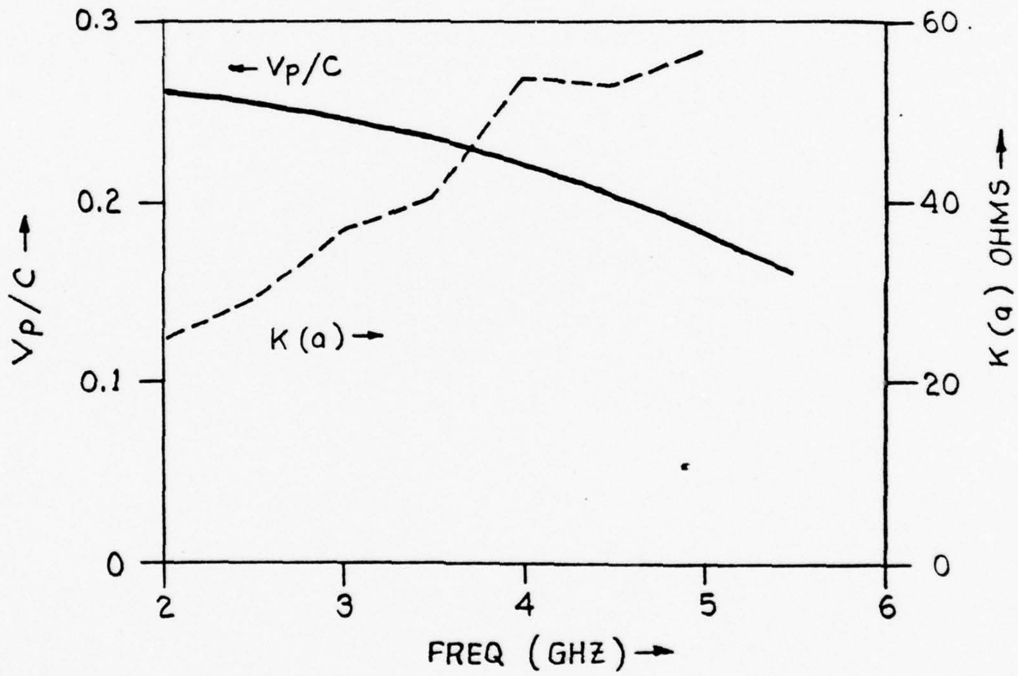

FIGURE 5

MEASURED CIRCUIT PARAMETERS FOR BIFILAR HELIX WITH AXIAL STRAPPING. TPI = 6.0

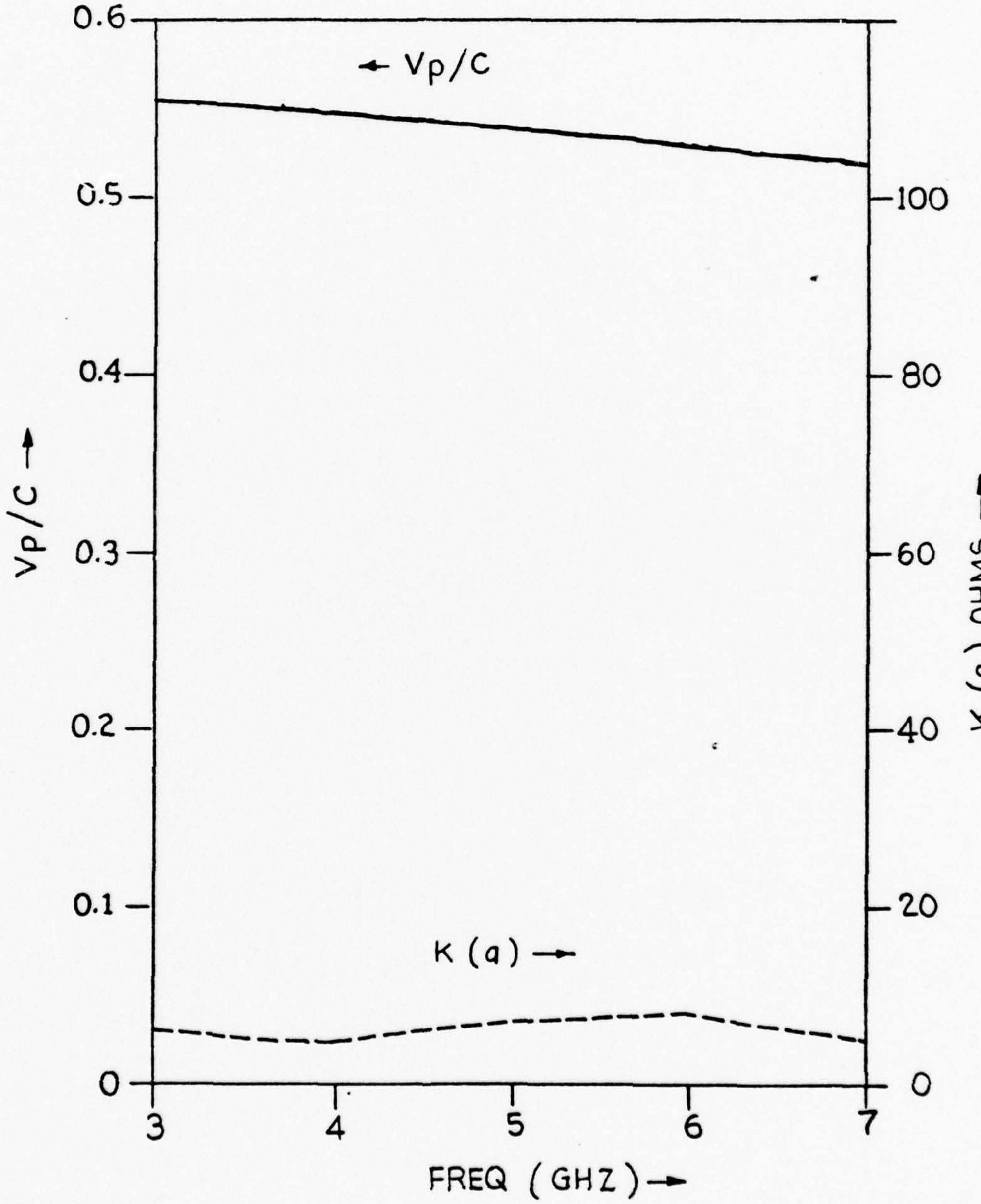

FIGURE 6

MEASURED CIRCUIT PARAMETERS FOR BILFIAR HELIX WITH HELICAL STRAPPING. TPI - 4.0

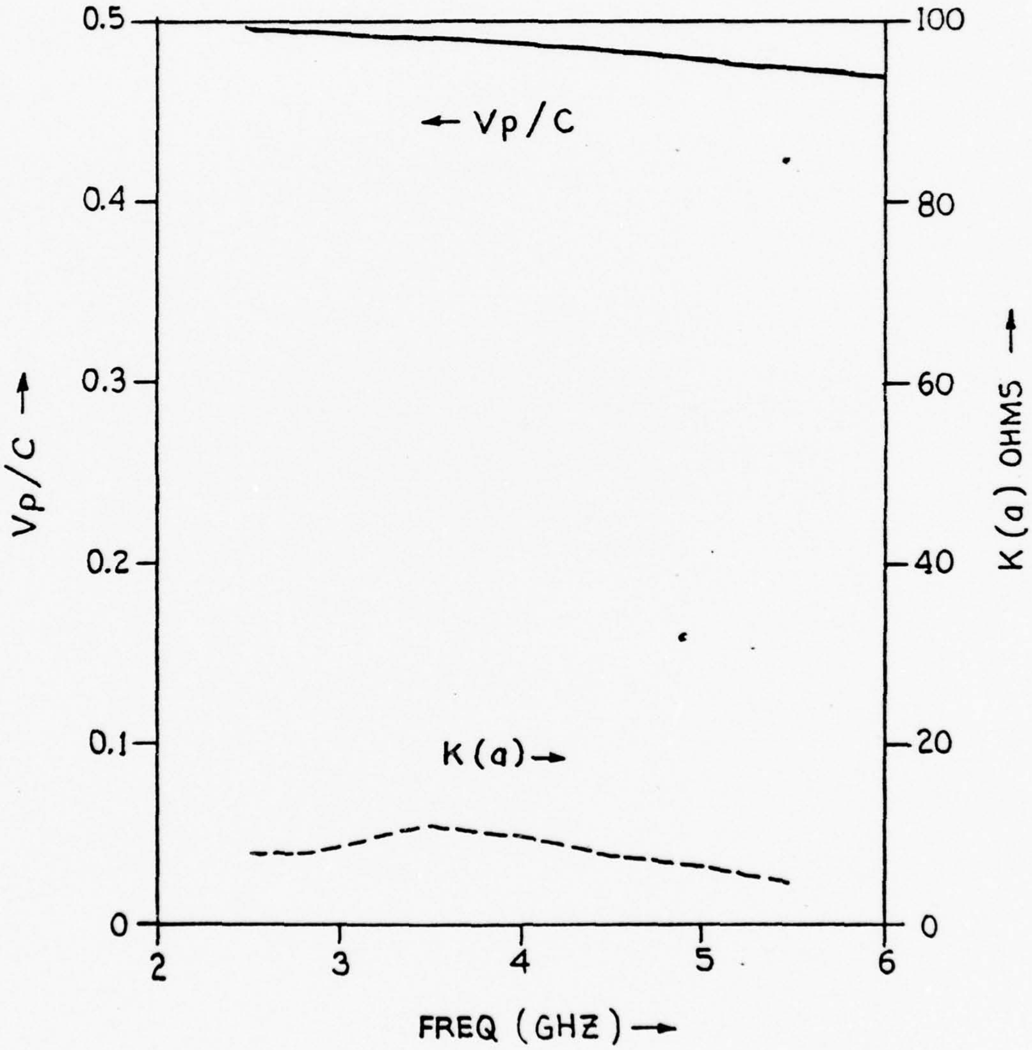

FIGURE 7

MEASURED CIRCUIT PARAMETERS FOR BIFILAR HELIX WITH HELICAL STRAPPING. TPI = 10.0

Another test circuit investigated is unifilar helix with helical strapping (B-3). This circuit was measured in two different supporting structures, (a) with alumina rods (.125" dia.) and (b) with BeO rods (.090" dia.), as listed in Table B. The measured results in these cases are shown in Figures 8(a) and 8(b), respectively.

Since the phase velocity of this circuit is still too high for the present application, another unifilar helix with helical strapping (B-4) was built with a TPI of main helix increased from 4 to 10. The measured results of this circuit are shown in Figure 9.

In order to find the effect of helical strapping, one more test circuit of unifilar helix was built with helical strapping (B-5), in which the TPI of strapping helix was reduced from 32 to 20, while all other parameters are kept the same as B-4. The measured results of this circuit are shown in Figure 10.

(C) Multifilar Helix Without Strapping

One test circuit of bifilar helix similar to A-3 was built and tested without strapping (A-5). This circuit was built to serve two purposes, one of which is to determine the effect of strapping by comparing the same circuit with and without strapping, and the other is to use this circuit to try any other method of strapping for further study. The measured results on this circuit without strapping are shown in Figure 11.

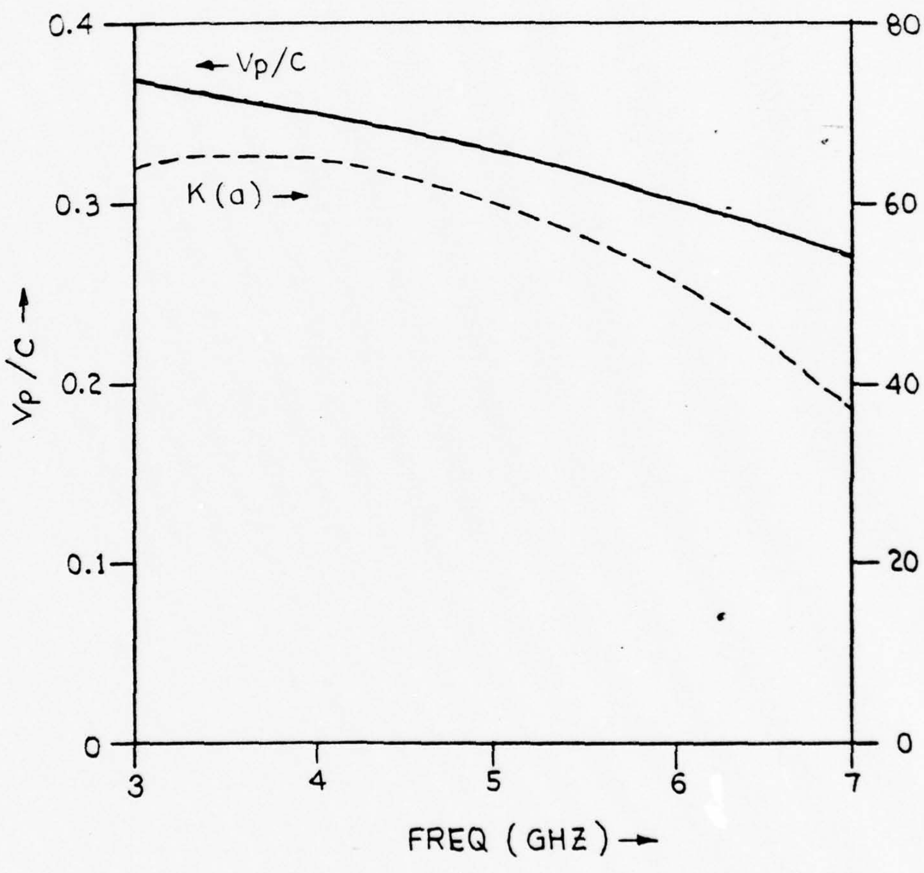

FIGURE 8(a)

MEASURED CIRCUIT PARAMETERS FOR UNIFILAR HELIX WITH HELICAL STRAPPING. $TPI_{(1)}=4.0$, $TPI_{(2)}= 32.0$
ALUMINA RODS (.125 DIA.)

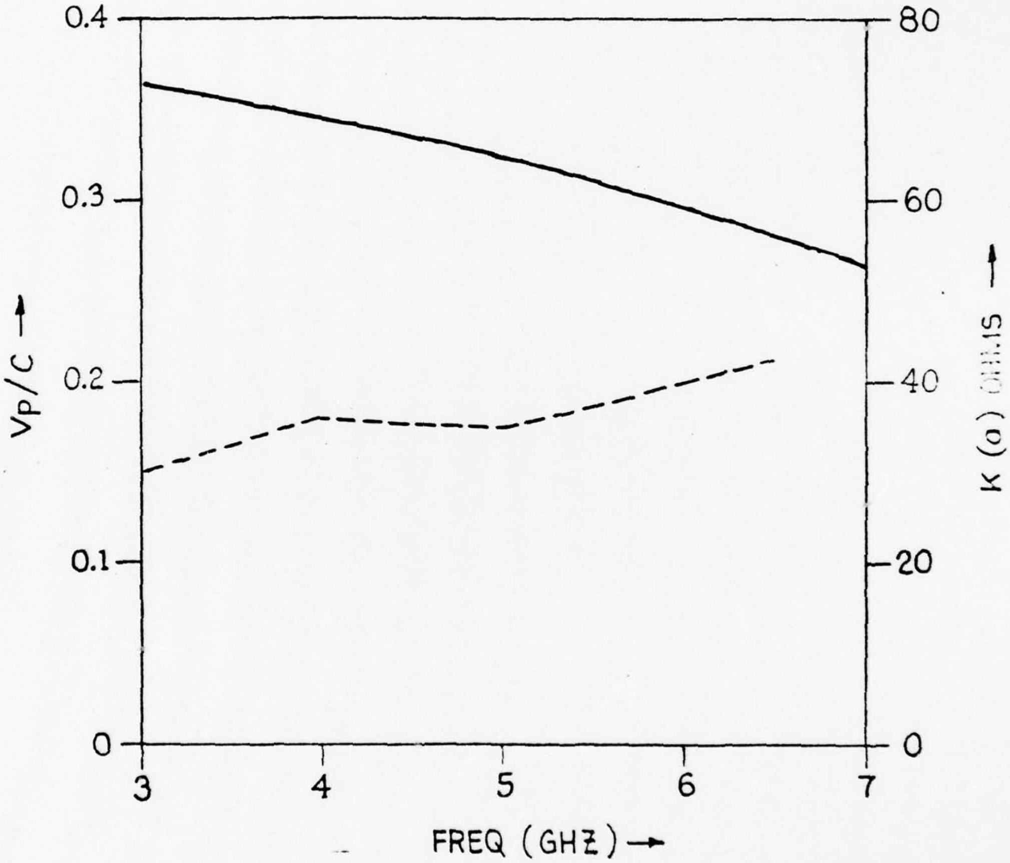

FIGURE 8(b)

MEASURED CIRCUIT PARAMETERS FOR UNIFILAR HELIX WITH HELICAL STRAPPING. $TPI_{(1)} = 4.0$, $TPI_{(2)} = 32.0$

BeO RODS (.090 DIA.)

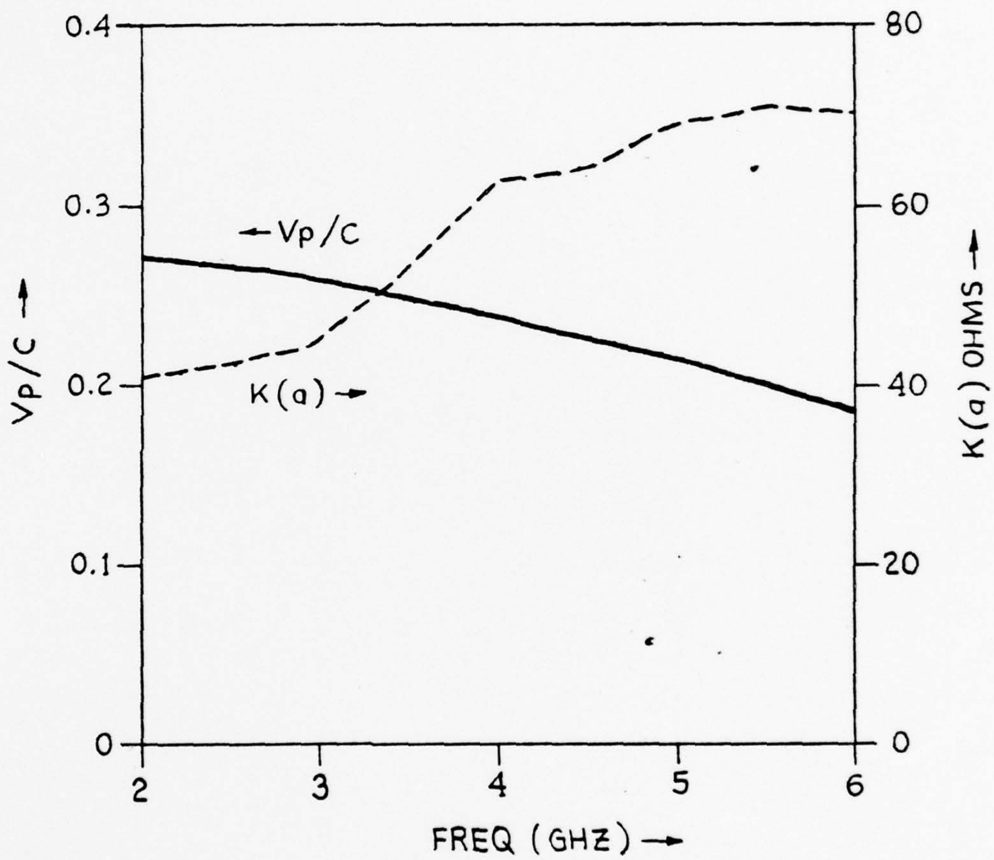

FIGURE 9

MEASURED CIRCUIT PARAMETERS FOR UNIFILAR HELIX WITH HELICAL STRAPPING. $TPI_{(1)} = 10.0$, $TPI_{(2)} = 32.0$

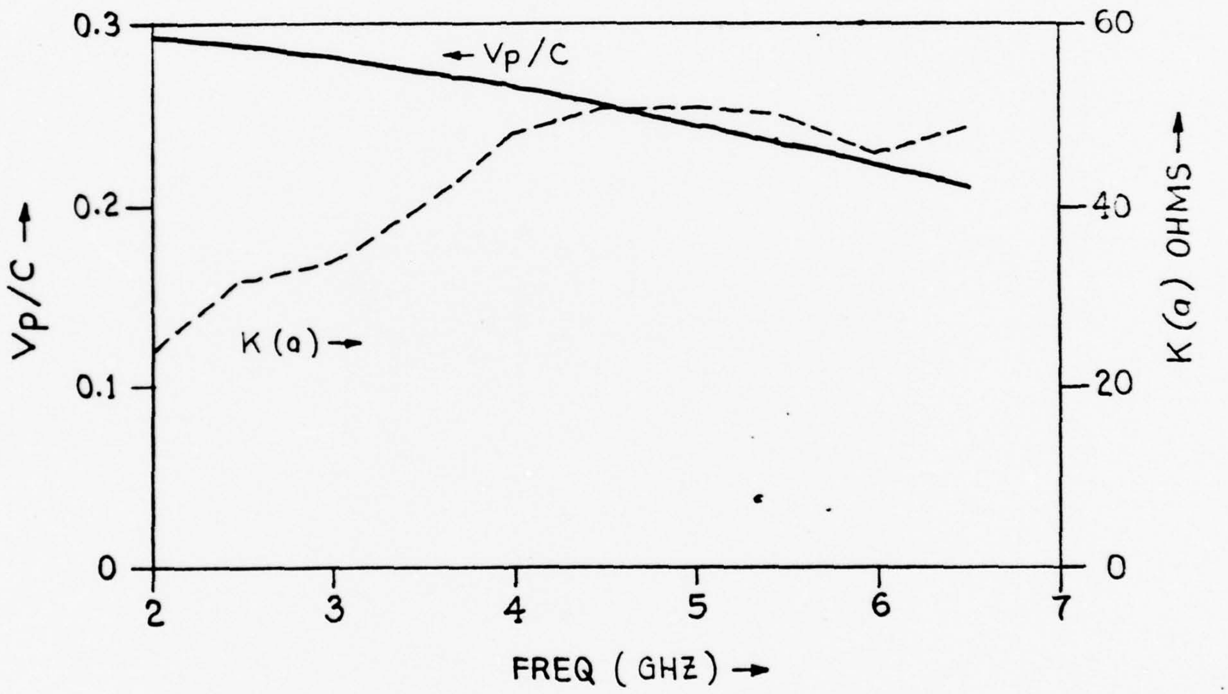

FIGURE 10

MEASURED CIRCUIT PARAMETERS FOR UNIFILAR HELIX WITH HELICAL STRAPPING. $TPI_{(1)} = 10.0$, $TPI_{(2)} = 20.0$

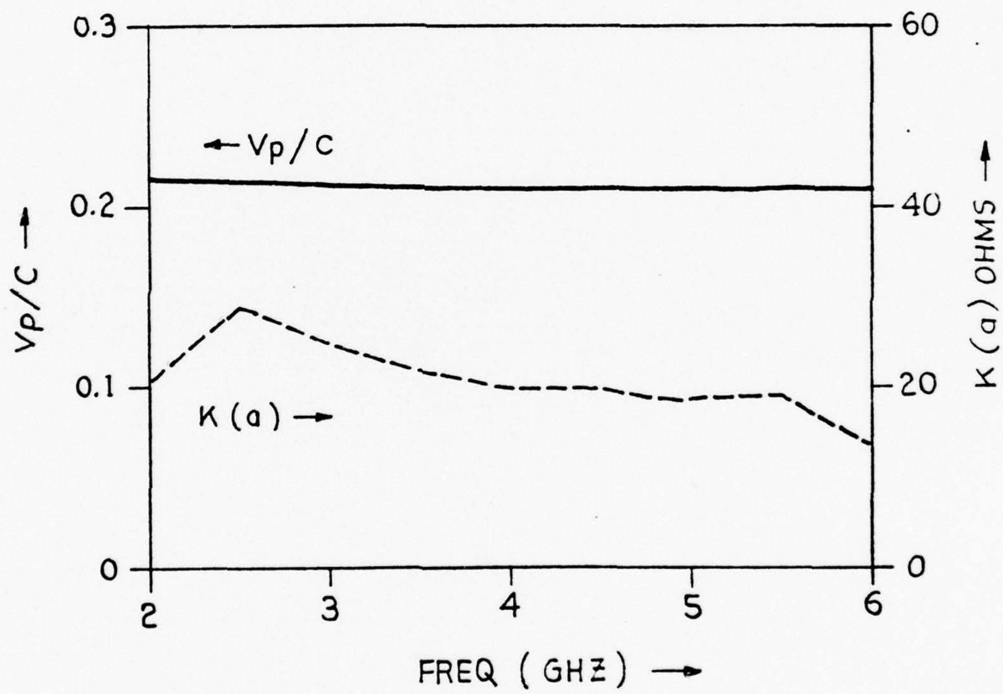

FIGURE 11

MEASURED CIRCUIT PARAMETERS FOR BIFILAR HELIX WITHOUT STRAPPING. TPI = 10.0

4.0 OTHER TYPES OF INTERACTION CIRCUIT

There are various other types of interaction circuits commonly used in many high-power TWTs. Since these tubes have been developed, built and in use for many years, the characteristics of these circuits are known and well understood. Two of these commonly used circuits are the simple helix and ring-loop circuit. Simple helices are suitable for these applications where a wide bandwidth is required with a limited power output, while ring-loop circuits are preferred when a higher power output is desired with a limited bandwidth.

The phase velocity and interaction impedance of these two types of circuit can be predicted from their physical dimensions by using computer models. The computed results have been verified already for many different cases by comparing to measured data for actual interaction circuits.

A simple helix and a ring-loop circuit were chosen as a basis for the comparison and evaluation of strapped multifilar helix circuits under investigation. These are typical circuits of conventional design and their circuit dimensions are listed in Table C. The computed phase velocity and interaction impedance for the computer models of these circuits are shown in Figures 12 and 13, respectively.

TABLE C

LIST OF OTHER INTERACTION CIRCUITS USED AS COMPUTER MODELS FOR THE EVALUATION OF MULTIFILAR HELIX CIRCUITS. ALL DIMENSIONS ARE IN INCHES.

CIRCUIT	SIMPLE HELIX	RING LOOP
ID	.280	.240
OD	.300	.300
MD	.290	.270
Tape	.01x.05	.02x.03
TPI	4.0	8.23
Length	10.0	8.0
Dielectric Support		
Material	BeO	BeO
Number	3 rods	3 rods
Size	.09 dia.	.09 dia.
Conducting Shield		
ID	.500	.465

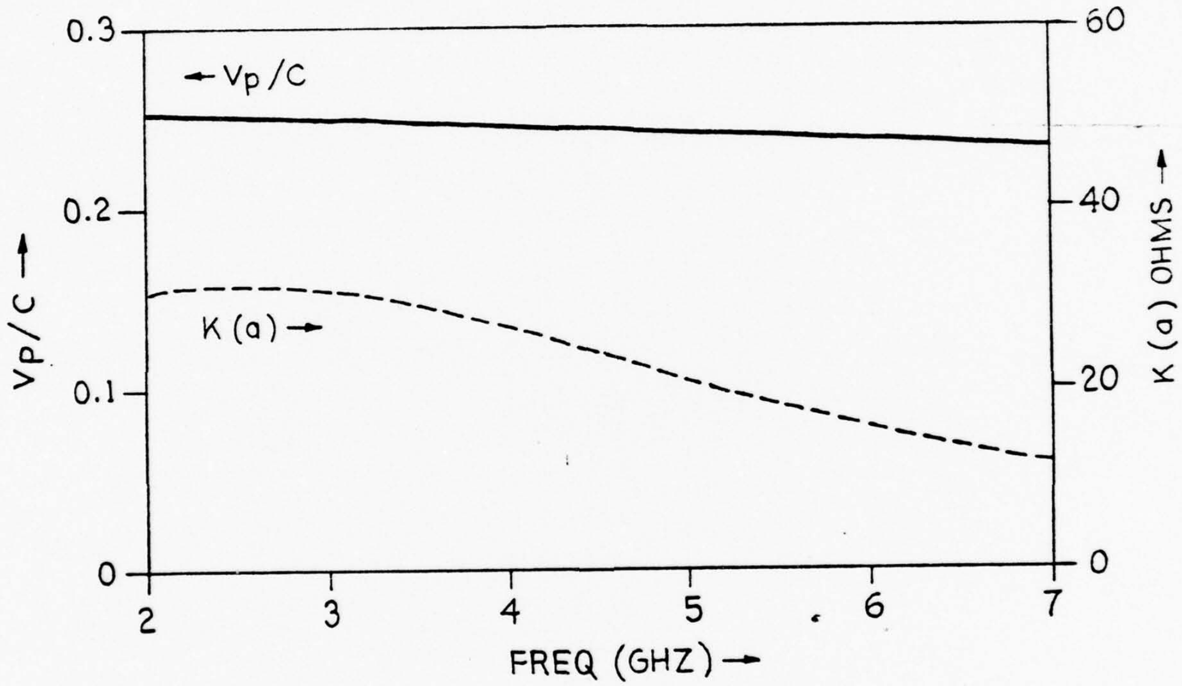

FIGURE 12

COMPUTED CIRCUIT PARAMETERS FOR SIMPLE HELIX.
TPI = 4.0

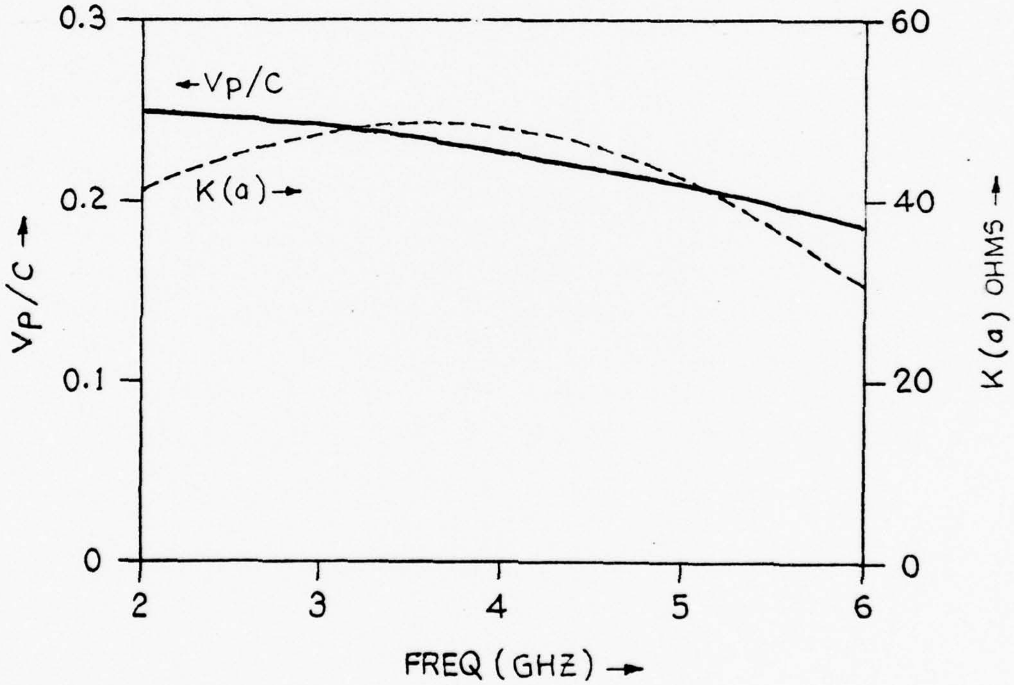

FIGURE 13

COMPUTED CIRCUIT PARAMETERS FOR RING-LOOP CIRCUIT. TPI = 8.0

5.0 COMPUTER-AIDED DESIGN OF TWTs

Nowadays the use of digital computers has been widely accepted in many engineering fields and the computer-aided design of TWTs is commonly in use also (20-23). Many important tube characteristics such as gain, bandwidth, output power, tube efficiency, harmonic power, amplitude and phase distortion, overdrive characteristics and stability, can be predicted and optimized by effective use of computer-aided design techniques. This reduces the number of trials and errors, and minimizes the time and cost of tube development.

Sample tube designs were made assuming the simple helix and ring-loop circuit described in the preceding Section 4.0. The small signal gain and tube efficiency are plotted in Figures 14 and 15 for the helix tube and in Figures 16 and 17 for the ring-loop tube. The bandwidth, tube efficiency and circuit length can be compared for the two tubes using these figures. In the case of the helix tube, it is essential to include the effect of harmonic interaction in the large signal calculations. The computed tube efficiency is shown for both fundamental and second harmonic frequencies in Figure 15.

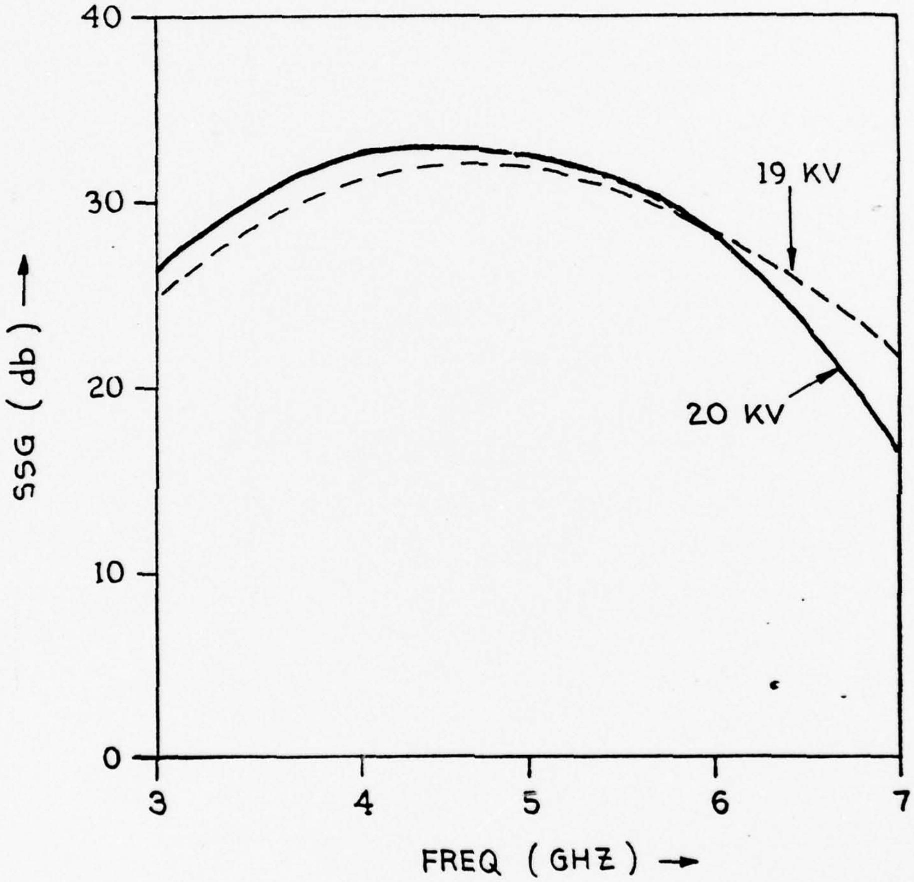

FIGURE 14

COMPUTED SMALL SIGNAL GAIN OF A SAMPLE DESIGN, ASSUMING A SIMPLE HELIX CIRCUIT OF CONVENTIONAL DESIGN.

Beam Voltage	= 19, 20 kV
Beam Current	= 3.67, 3.96 A
Beam Perveance	= 1.4 μP
Filling Factor	= 0.5

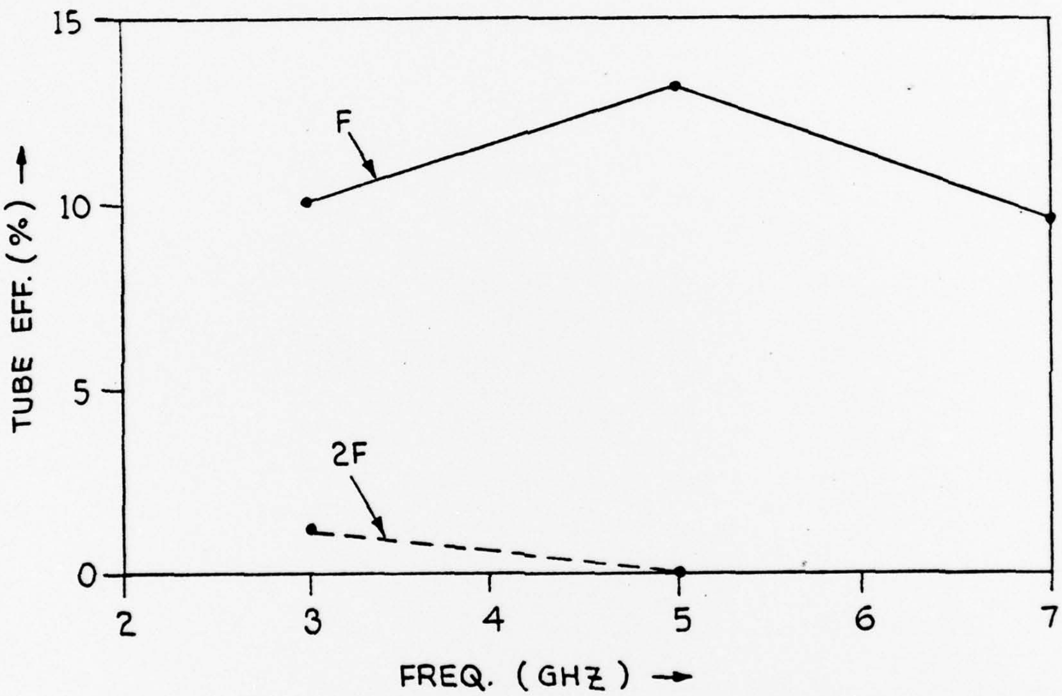

FIGURE 15

COMPUTED TUBE EFFICIENCY OF A SAMPLE DESIGN, ASSUMING A SIMPLE HELIX CIRCUIT OF CONVENTIONAL DEISGN.

Beam Voltage = 20 kV
Beam Current = 3.96 A
Beam Perveance= 1.4 μP
Filling Factor= 0.5

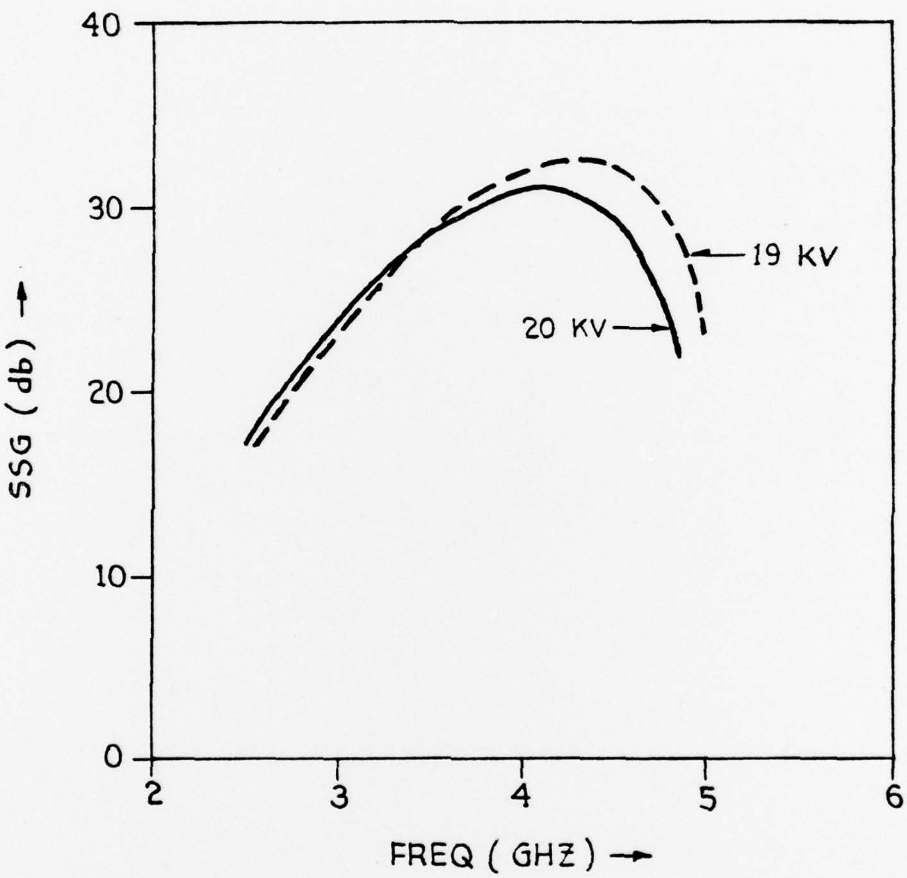

FIGURE 16

COMPUTED SMALL SIGNAL GAIN OF A SAMPLE DESIGN, ASSUMING A RING-LOOP CIRCUIT OF CONVENTIONAL DESIGN.

Beam Voltage = 19, 20 kV
Beam Current = 3.67, 3.96 A
Beam Perveance = 1.4 μP
Filling Factor = 0.5

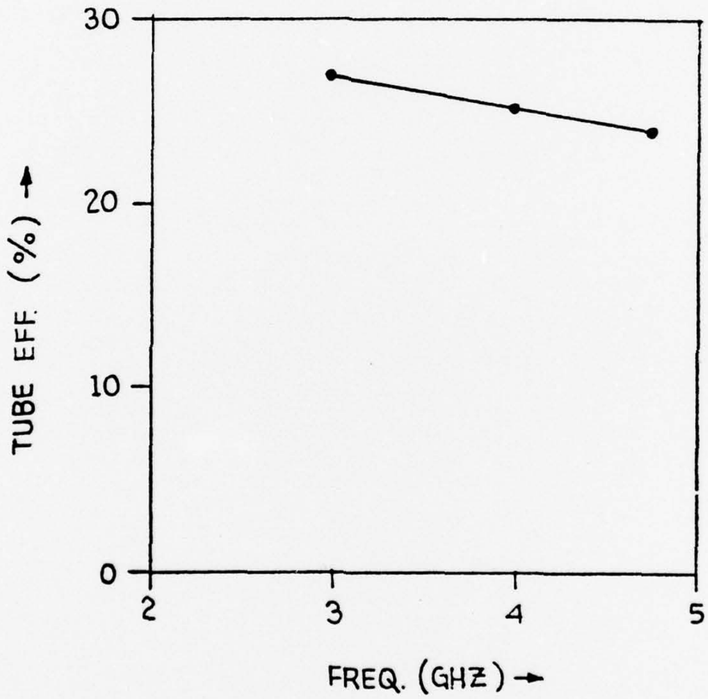

FIGURE 17

COMPUTED TUBE EFFICIENCY OF A SAMPLE DESIGN, ASSUMING A RING-LOOP CIRCUIT OF CONVENTIONAL DESIGN.

Beam Voltage = 20 kV
Beam Current = 3.96 A
Beam Perveance = 1.4 μP
Filling Factor = 0.5

6.0 EVALUATION OF COLD TEST RESULTS

One of these cold test circuits was to be chosen for the experimental TWTs with a beam voltage of 20-22 kV. A number of requirements must be considered for this selection such as correct phase velocity, less circuit dispersion, higher interaction impedance, higher power capability, ease of fabrication and matching to a coaxial line.

The first two cold test circuits with axial strapping, the quadrifilar helix circuit (A-1) and the trifilar helix circuit (A-2), are not suitable because their phase velocity is too high for the specified beam voltage. Comparing these circuits to bifilar helix circuits, the fabrication will be more difficult because of a larger number of straps required. The matching to a coaxial line is also expected to be a problem, because 3 or 4 individual transmission lines instead of just 2 must be balanced properly at the input/output terminals. Therefore, bifilar helix circuits are preferred for the present application.

When a bifilar helix circuit is considered with either axial strapping or helical strapping, the choice is axial strapping because the phase velocity was found too high for the present application with helical strapping.

The helical strapping could be used if the main circuit is a unifilar helix rather than a bifilar helix. The choice between the bifilar helix with axial strapping (A-4) and the unifilar helix with helical strapping (B-4) can be determined by comparing the measured data shown in Figures 5 and 9. The phase velocity is about the same but the interaction impedance is measured higher with the unifilar circuit and the circuit dispersion is also less with the unifilar circuit.

Initial testing of matching to a coaxial line of 50 ohms was tried on these two circuits. The preliminary results are quite similar for both circuits and little difficulty of matching is expected in either of them. Considering all these factors, the unifilar helix with helical strapping (B-4) is the best choice among the cold test circuits of strapped multifilar helices.

When this circuit (B-4) is compared to other types of interaction circuits, namely a simple helix and a ring-loop circuit, it is found that this circuit is very similar to the ring-loop circuit, except this circuit is more dispersive and has a little higher interaction impedance. Considering the difference of dielectric support and conducting shield, the circuit characteristics are about same for this circuit (B-4) and the ring-loop circuit. However, the ring-loop circuit is easier to fabricate and has a higher power handling capability than the other. Thus the ring-loop circuit is better than the unifilar helix with helical strapping in the present application.

The ring-loop circuit being considered here is assumed to have a conventional design with three BeO rods in a plain conducting shield. The characteristics of this circuit can be improved further by more advanced designs, using BeO blocks rather than rods and additional vanes in the conducting shield. However, even with further improvement on the ring-loop circuit, the available bandwidth is expected to be less than that which can be achieved by use of a simple helix.

Therefore if the required bandwidth is wider than the ring-loop tube can provide and the required power output is greater than the helix tube can handle, then a reasonable choice will be a bifilar helix circuit without strapping. In this case, the problem of tube stability must be solved by other means such as mode loading, circuit loss or velocity tapering. These techniques have been developed in recent years for some high-power high-voltage TWTs using simple helix circuits, which can be applied to bifilar helix circuits as well (24-29).

Since the bifilar helix circuits have the same bandwidth as a simple helix but higher interaction impedance and power handling capability, the use of the bifilar helix circuit without strapping will be a worthwhile effort to advance the state of the art in high power helix-type TWTs.

7.0 CONCLUSIONS

Multifilar helix interaction circuits have been investigated for use in TWTs so that the operating voltage and power levels of existing helix-type tubes could be increased. One of these circuits was to be used to build experimental TWTs at a beam voltage of 20-22 kV.

Two types of strapping methods, axial strapping and helical strapping, have been tried on a number of cold test circuits. It was found that either strapping method does affect the circuit characteristic, increasing the phase velocity and circuit dispersion. The resulting circuits are rather dispersive and their characteristics are similar to that of ring-loop circuits.

The best circuit selected from all cold test circuits is a unifilar helix with helical strapping (B-4). Even this circuit is not as good as a ring-loop circuit of conventional design, which is quite discouraging.

The choice of interaction circuit in existing high-power TWTs is determined by whether the primary objective is the bandwidth or power output. A simple helix is chosen for wider bandwidths, while a ring-loop circuit is preferred for higher power levels and tube efficiencies. The strapped multifilar helix circuits studied in this project were found quite similar to ring-loop circuits but not better. If a wide bandwidth and a higher power output are desired, the use of bifilar helix without strapping may be considered.

In either case, further work is necessary before experimental TWTs can be designed and built. In the case of ring-loop circuits, the dielectric support and conducting shield must be optimized in order to reduce the circuit dispersion. Various shapes of BeO blocks and loading vanes on the conducting shield can be tried to achieve this objective. In the case of bifilar helix without strapping, suppression of undesired modes will be most important. Frequency selective loss, proper velocity taper or some other methods of mode loading must be applied to ensure stable operation of TWTs.

Thus it was concluded that the original schedule of this study program could not be met without further delay in cold testing. The available cold test data are not sufficient to justify building experimental TWTs at this time. However, two possibilities are still open for further development in this area of investigation. One is to improve the ring-loop circuit with optimized supporting structures, and the other is to use the bifilar helix with an effective mode loading.

APPENDIX A

COLD TEST MEASUREMENT OF PHASE VELOCITY AND INTERACTION IMPEDANCE

1.0 Measurement of Phase Velocity

(A) Resonant Method

If the cold test circuit has a plane of symmetry, a pair of conducting plates are placed as shorting planes at both ends of the test circuit. A series of resonant frequencies can be measured on this test circuit by means of probes loosely coupled to the circuit. The number of resonant frequencies for each mode of transmission is proportional to the number of periods in the test circuit. These frequencies are plotted on a ω-β diagram as a function of phase shift. The phase shift for each resonant frequency can be determined by moving a small perturbing object through the circuit and checking standing-wave patterns on the circuit. Once the ω-β diagram is completed, the phase velocity is given by

$$\frac{V_p}{C} = \frac{2\pi F}{C \cdot \beta}$$

V_p/C : Normalized Phase Velocity

F : Frequency

C : Velocity of Light in Free Space

β : Phase Shift

(B) Non-Resonant Method

Some interaction circuits such as a simple helix, do not have a plane of symmetry and a non-resonant method of phase velocity measurement must be used. In this case, the cold test circuit is made sufficiently long so that a good termination can be provided at one end. The other end of the test circuit is connected to a signal generator through a directional coupler, by which the reflected signal can be measured. A small perturber is moved through this test circuit and the reflected power is recorded as a function of distance the perturber travels. The wavelength can be determined directly from this plot and the phase velocity is given by

$$\frac{V_p}{C} = \frac{F}{C} \lambda$$

V_p/C : Normalized Phase Velocity
C : Velocity of Light in Free Space
F : Frequency
λ : Wavelength

2.0 Measurement of Interaction Impedance

A common method of measuring interaction impedance of a test circuit is to place a dielectric rod of small diameter on the axis. The resulting change of circuit velocity or phase shift is the measure of interaction impedance at that location.

If the resonant method is used, the frequency shift due to the rod is measured for each of the resonant frequencies. The interaction impedance on the axis can be determined as a function of the frequency shift, size of rod and dielectric constant of the rod material (30,31).

If the *non-resonant* method is used, the phase velocity measurement is repeated with and without the dielectric rod on the axis. The frequency shift can be determined from the ω-β diagram thus obtained for the circuit with and without the dielectric rod.

The resonant method is preferred if possible, because measurement of wavelength is not as accurate as measurement of resonant frequencies.

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