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QUARTERLY PROGRESS REPORT NO. 7

FOR

BASIC RESEARCH IN MICROWAVE DEVICES AND QUANTUM ELECTRONICS

This report covers the period November 1, 1964 to February 1, 1965

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ABSTRACT

The experimental results obtained on power dissipation for a 30 Gc TWA helix structure mounted in high-thermal-conductivity beryllium oxide are summarized. Two structures were investigated and a power dissipation of 170 watts/inch was realized for a BeO tube structure and 32 watts/inch for a BeO rod-copper tube structure at a mean helix temperature of 500°C.

The analysis and measurement of cross-modulation products for S- and X-band O-type traveling-wave amplifiers with multiple input signals have been extended to cover the effect on input signal modulations on the output spectrum. These studies are also being extended to cover other types of amplifiers; i.e., the crossed-field amplifier and the tunnel-diode amplifier.

A preliminary discussion of the results of the large-signal electron trajectory computation for a d-c pumped quadrupole amplifier is included.

The work on fabricating a low frequency (600 - 2400 mc) multiplier tube is in progress.

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LIST OF ILLUSTRATIONS

PERSONNEL

Scientific and Engineering Personnel		Time Worked in Man Months*
J. Rowe	Professors of Electrical Engineering	.10
C. Yeh		.91
M. El-Shandwily	Research Associate	2.74
H. Detweiler	Assistant Research Engineers	1.38
W. Rensel		.37
A. Heath	Research Assistants	.88
B. Ho		.79
A. Cha	Assistants in Research	.33
E. Fronczak		.02
R. Ying		1.30
Service Personnel		6.42

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* Time Worked is based on 172 hours per month.

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FOR

BASIC RESEARCH IN MICROWAVE DEVICES AND QUANTUM ELECTRONICS

1. General Introduction (C. Yeh)

The broad purpose of this project is to investigate new ideas in the area of microwave devices and quantum electronics. The program is envisioned as a general and flexible one under which a wide variety of topics may be studied. At present, the following areas of investigation are in progress:

A. Study of frequency multiplication in an angular propagating structure. Fabrication of a low-frequency multiplier tube which multiplies a 600 mc input signal to a 2400 mc output signal with adjustable feedback control is in progress and extensive testing will follow.

B. Investigation of high-thermal-conductivity materials for microwave devices above X-band. This phase of the investigation has been concluded and a final summary on the experimental findings is given.

C. Analysis of amplitude- and phase-modulated traveling-wave amplifiers. Experimental work on the cross-modulation measurements on an S-band traveling-wave amplifier is continuing. This work will include the effect of various types of input modulation signals on the cross-modulation products.

D. Study of a d-c pumped quadrupole amplifier. Electron trajectories in a d-c pumped quadrupole structure will be studied by solving the equations of motion for the different modes of operation of the amplifier. Large-signal analyses are also being studied and computer results will be presented.

Two new areas of investigation have been initiated and these are:

A. Investigation of the cross-modulation products in a wideband tunnel-diode amplifier. Theoretical and experimental work will be carried out to investigate the correlation between physical parameters of the diode and the modulation products.

B. Large-signal analysis of the crossed-field amplifiers with multi-frequency input signals. An analysis similar to that of the O-type traveling-wave amplifier will be carried out for the crossed-field amplifier to investigate the cross-modulation products with multiple input signals.

2. Generation and Amplification of Coherent Electromagnetic Energy in the Millimeter and Submillimeter Wavelength Region

2.1 Study of Frequency Multiplication in an Angular Propagating Structure (C. Yeh and B. Ho)

The work on fabrication of the experimental low-frequency multiplier tube is progressing. The winding of a quadrifilar helix presented some problems in obtaining the desired uniformity. A method of winding and annealing the helices so that they will remain in shape after being taken from the winding mandrel is being developed.

The cavity has been tested for resonance and the coupling to the undesired modes has been minimized by properly adjusting the coupling loop to the cavity. The resonant frequency of the cavity is 2379.5 mc. The first noticeable undesired mode is separated by 137 mc. With a reasonable cavity Q, it would not be difficult to discriminate against this undesired mode.

2.2 Investigation of High-Thermal-Conductivity Materials for Microwave Devices Above X-Band (H. K. Detweiler)

2.2.1 Introduction.

The purpose of this study has been to investigate the use of high-thermal-conductivity materials in microwave devices above X-band. Because of its very high-thermal conductivity and adequate electrical properties, primary consideration has been given to beryllium oxide. In particular, the use of this material for the improvement of the average power handling capability of the helix slow-wave structure has been studied. Two types of helix support structures utilizing beryllium oxide have been investigated. In one type of structure the helix is brazed into a smooth-bore BeO tube. The other consists of the helix with three BeO rods brazed to it, supported inside a metal tube. During the past quarter, this investigation has been completed with the conclusion of tests on the BeO rod-metal tube structure. The results of these tests together with a summary of the important points of the entire study are reported below.

2.2.2 Experimental Effort.

A previous theoretical and experimental investigation of the use of beryllium oxide as the helix support structure material demonstrated that a considerable improvement in the power handling capability of the helix can be achieved in this manner[1]. Experimental testing of these structures, while demonstrating an improvement, also showed the importance of obtaining good thermal contact between the helix and beryllium oxide. Regions of poor contact

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[1] Detweiler, H. K., Dolph, C. L. and Rowe, J. E., "Applied Research on High-Thermal-Conductivity Materials for Use in Microwave Tubes", Final Report, Contract No. AF33(616)-7542, Electron Physics Laboratory, The University of Michigan, Ann Arbor; December, 1961.

resulted in the development of hot spots and a power handling capability somewhat less than expected. Subsequently, a technique was developed to braze the helix to the BeO for improved thermal contact[2]. A problem common to the assembly of both types of helix structures studied was the modification of this brazing technique to fit the needs of the particular application. In each case it was also necessary to devise a means for loading the helix assembly into its tube in such a way as to assure good thermal contact. The details of the techniques will be presented below in connection with the structures to which they were applied.

The first structure to be discussed will be the one in which a helix is brazed into a smooth-bore BeO tube. The particular structure on which tests were performed was designed for operation at a frequency of 30 Gc.

The technique used to braze the helix into a BeO tube is summarized here. Before any plating operations are begun all heat treatments of the helix (e.g., those performed to give the resiliency required for loading) must be completed. A tungsten or molybdenum helix is first plated with a rhodium flash to a thickness of a few microinches to provide a good base for subsequent copper plating. For a tantalloy helix this step is omitted. The helix is then copper plated to the desired thickness (experimentally determined). Next, the helix is titanium coated by vacuum deposition. A titanium thickness of one half that of the copper, which gives an approximate weight ratio of 4 to 1 copper to titanium, has produced satisfactory brazes. Finally, after loading the helix into

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[2] Detweiler, H. K., "Applied Research in Microwave and Quantum Electronics", Interim Scientific Report No. 2, pp. 2-27, Contract No. AF33(657)-8050, Electron Physics Laboratory, The University of Michigan, Ann Arbor; February, 1963.

the tube, it is vacuum fired at about 1030°C for a period of three minutes. The system pressure during brazing should be less than 5×10^{-5} torr. This technique has produced strong, consistent brazes between BeO and helices made of tungsten, molybdenum, and tantalloy.

A series of tests was run to determine the proper amounts of copper and titanium for brazing the 30 Gc helix. It was found that quite satisfactory brazes were obtained when using a copper plating 0.1 mil thick and a 0.05 mil-thick coating of titanium. While these amounts were not critical, for appreciably smaller values brazing did not occur and for much larger values excessively large fillets were formed.

The loading technique used for assembling this structure was to first wind the helix on a mandrel so that the helix outside diameter exceeded the inside diameter of the tube by approximately 2 mils. After heat treating the helix to set it (the heat-treat cycle depending upon the helix material), it was wound on a smaller size mandrel so that its O. D. was about 2 to 2-1/2 mils smaller than the tube I. D. This amount of clearance was necessary so that the titanium coating on the helix would not be rubbed off during loading. It was then inserted into the tube and released.

In attempting to perform the operation outlined above it was discovered that the usual helix materials (tungsten and molybdenum) did not have sufficient resiliency to spring back the desired amount when normally heat treated. An extensive series of tests was carried out on tungsten helices in hopes of improving their resiliency. The results were negative. They seemed to indicate that when the point is reached where the helices are no longer so brittle that they break when being wound down, they do not possess sufficient resiliency to spring back more than approximately 1-1/2 mils. Similar difficulties were encountered with Fansteel 61 Metal*, a wire consisting of 92-1/2 percent tantalum and 7-1/2 percent tungsten, prepared by the sintered-metal process.

Success was finally achieved using Fansteel 60 Metal* wire (90 percent tantalum and 10 percent tungsten prepared by the electron-beam-melting process). A 30 Gc helix would out of this wire having the dimensions

Mean helix diameter = 0.030 inch,

O. D. = 0.035 inch,

d_w = 0.005 inch and

TPI = 64

was able to spring back to an outside diameter of 0.0335 inch (corresponding to the I. D. of the BeO tube) when wound down to 0.031-0.0315 inch for the loading operation. The required heat-treat cycle is to fire the helix in air for eight minutes at 538°C in order to oxidize the surface and then fire for 30 minutes at 1200°C in a vacuum to diffuse the oxide into the metal for hardening. The helix can then be plated with copper and titanium, loaded into the BeO tubes and fired for brazing.

Using the brazing and loading techniques described previously and the above heat treatment for the Fansteel 60 Metal helix, several brazed helix-BeO tube structures were prepared and heat tested. The dimensions of the structures are

Helix: Mean helix diameter = 0.0285 inch,

d_w = 0.005 inch,

TPI = 64,

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* Fansteel Metallurgical Corporation.

BeO Tube: I. D. = 0.0335 inch,
O. D. = 0.094 inch and
Length = 2.08 inches.

The copper and titanium thicknesses used are 0.085 mil and 0.056 mil respectively.

Heat tests were conducted on three structures by applying d-c power and determining the mean helix temperature rise from its change in electrical resistance. The results are shown in Fig. 2.1. It is seen that the cooling is not strictly conduction cooling alone, i.e., the curves are not straight lines. Therefore, noticeable radiation cooling is taking place. This indicates that perfect thermal contact between the helix and BeO has not been achieved. This is due mainly to a lack of dimensional uniformity of the inside diameter of the BeO tube, which can be corrected by the use of better tubing. It is felt that the above techniques can be used to prepare the desired BeO tube structure; the realization of higher power handling capabilities only awaits a better quality BeO tube. Even with the relatively poor quality tubes used it is seen from the experimental data that this structure is capable of dissipating appreciable power, e.g., about 170 watts/inch at a mean helix temperature of 500°C. Consequently, it is felt that this has been shown to be a satisfactory high-power r-f structure; hence, no further tests have been conducted.

For the purpose of exhibiting the possible further improvement in power handling capability achievable through better quality tubing and perhaps a refinement of techniques, a comparison of the above

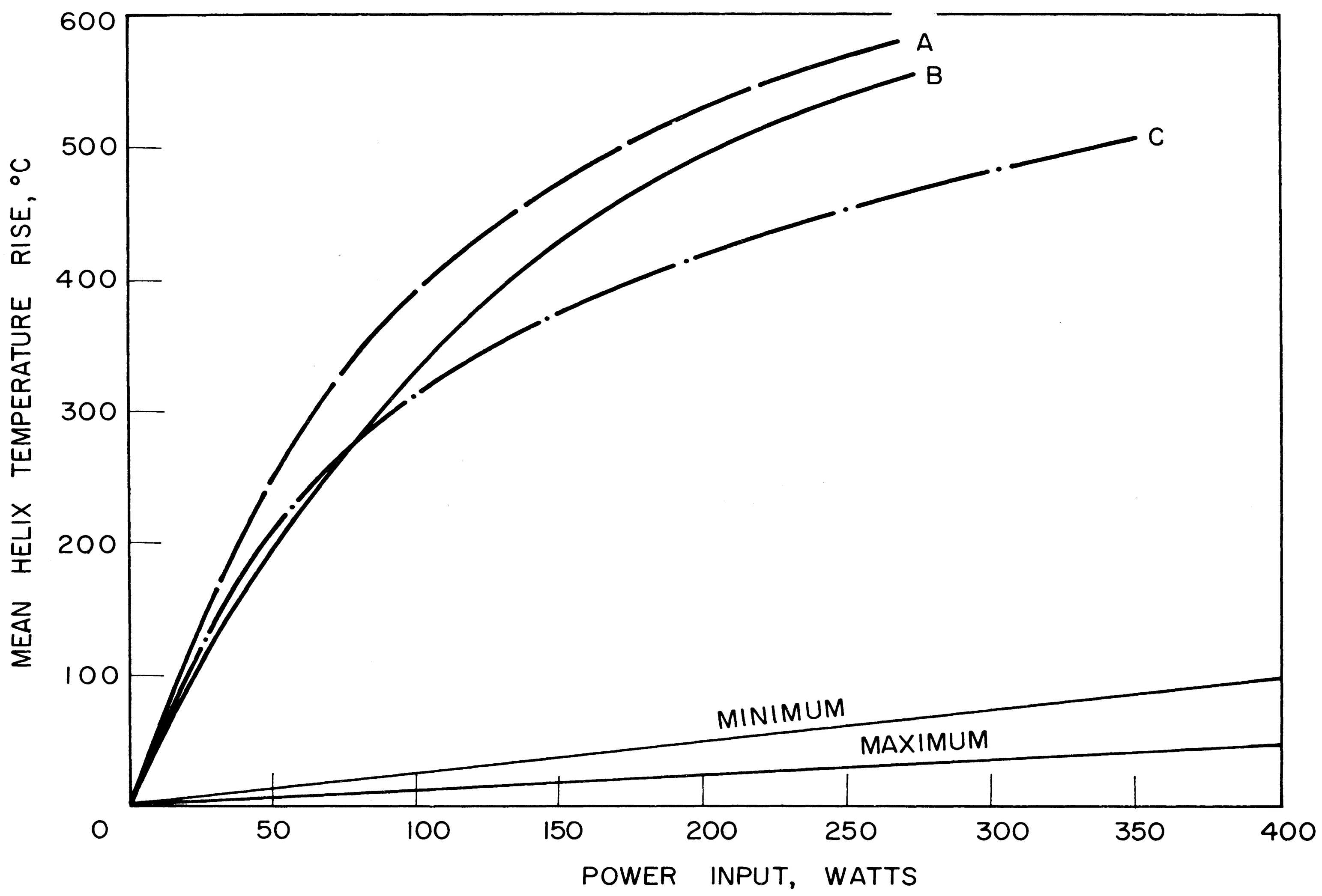

FIG. 2.1 MEAN HELIX TEMPERATURE RISE VS. POWER INPUT FOR THE BRAZED HELIX-BeO TUBE STRUCTURE.

experimental results to theoretical predictions reported elsewhere[3] can be made. It is shown there that the power dissipated by a helix at uniform temperature, T, through a cylinder with thermal conductivity, k_c, whose outer surface is held at a temperature, T_1, is given by

$$P = \frac{\pi\, k_c\, d_{oh}\, [1 - w_c\, (TPI)]\, L}{t_w \cos\psi\, \ln\left[\dfrac{1}{w_c\,(TPI)}\right]} (T - T_1) \quad , \tag{2.1}$$

where d_{oh} = outer diameter of the helix,

w_c = width of contact between the helix wire and the cylinder,

(TPI) = helix turns per inch,

L = length of the structure,

t_w = wall thickness of the cylinder and

ψ = helix pitch angle.

For the particular structure considered the parameters have the following values with the indicated tolerances:

k_c = 2.5 ± 0.5 watts/in.-°C,

d_{oh} = 0.0335 inch,

w_c = 1 ± 0.5 mil,

TPI = 64,

L = 2.08,

t_w = 0.030 inch and

$\cos\psi = \cos 9.9° = 0.985$.

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[3] Detweiler, H. K. and Rowe, J. E., "Evaluation of High-Thermal-Conductivity Ceramics for Cooling R-f Structures", Tech. Report No. 78, Contract No. AF33(615)-1553, Electron Physics Laboratory, The University of Michigan, Ann Arbor, pp. 34-35; October, 1964.

An upper and lower bound can be obtained by calculating the predicted power dissipation for the extreme values of the parameters. Carrying out these calculations it is found that

$$P_{max} = 8.6 \, (T - T_1) \tag{2.2}$$

and

$$P_{min} = 4.2 \, (T - T_1) \quad . \tag{2.3}$$

These relations are plotted as the straight lines designated as maximum and minimum, respectively, on Fig. 2.1. These curves indicate that a further increase in power handling capability is possible.

Problems similar to those encountered in assembling the first type of structure were met with the BeO rod-metal envelope structure. The techniques employed for solving these difficulties will be discussed now.

The helix (tungsten) is first wound so that its outside diameter plus twice the BeO rod diameter exceeds the metal tube inside diameter by about one mil. The helix-BeO rod assembly will then be larger than the tube I. D. for the pressure-loading operation. After firing the helix to set it, it is rhodium and copper plated and titanium coated as described above. The amounts of these materials used for brazing a helix into a BeO tube were found to be appropriate also for this brazing operation. For brazing, the helix and BeO rods are supported in a stainless steel jig with the rods equally spaced around the helix outside diameter. The assembly is then vacuum fired at 1030°C for 1-1/2 minutes.

For loading the helix-BeO rod assembly, a copper tube is placed in a jig consisting of three adjustable knife-edged blades equally spaced around the tube diameter. When these blades are tightened down on the tube, the portions of the tube between adjacent blades expand elastically outward. It was found to be possible to insert a helix-rod assembly which was originally one mil larger in diameter than the tube I. D. by deforming it in this way. After insertion of the assembly, the blades were released and a good pressure contact obtained between the rods and the copper tube. For a properly assembled structure it was not possible to remove the helix and rods without breaking the rods and crushing the helix.

During the past quarter two structures were prepared by the above techniques and heat tested. The dimensions of the various components are

Helix: O. D. = 0.031 inch,
d_w = 0.005 inch,
TPI = 64,
BeO rods: diameter = 0.030 inch,
Copper tube: I. D. = 0.090 inch and
O. D. = 0.110 inch.

The structures were each 4-7/8 inches long with helix plating thicknesses 0.102 mil of copper and 0.11 mil of titanium.

As before the helices are heated by d-c power and the mean helix temperature determined from the change in the electrical resistance of the helix. The results for these tests are shown as curves A and B in Fig. 2.2. Again, the cooling is not strictly conduction cooling since the curves are not straight lines. Hence, noticeable radiation cooling is taking place indicating that perfect thermal contact has not been achieved. Since the helix-BeO rod assemblies were examined before their insertion into the tubes and found to have each rod brazed to the helix

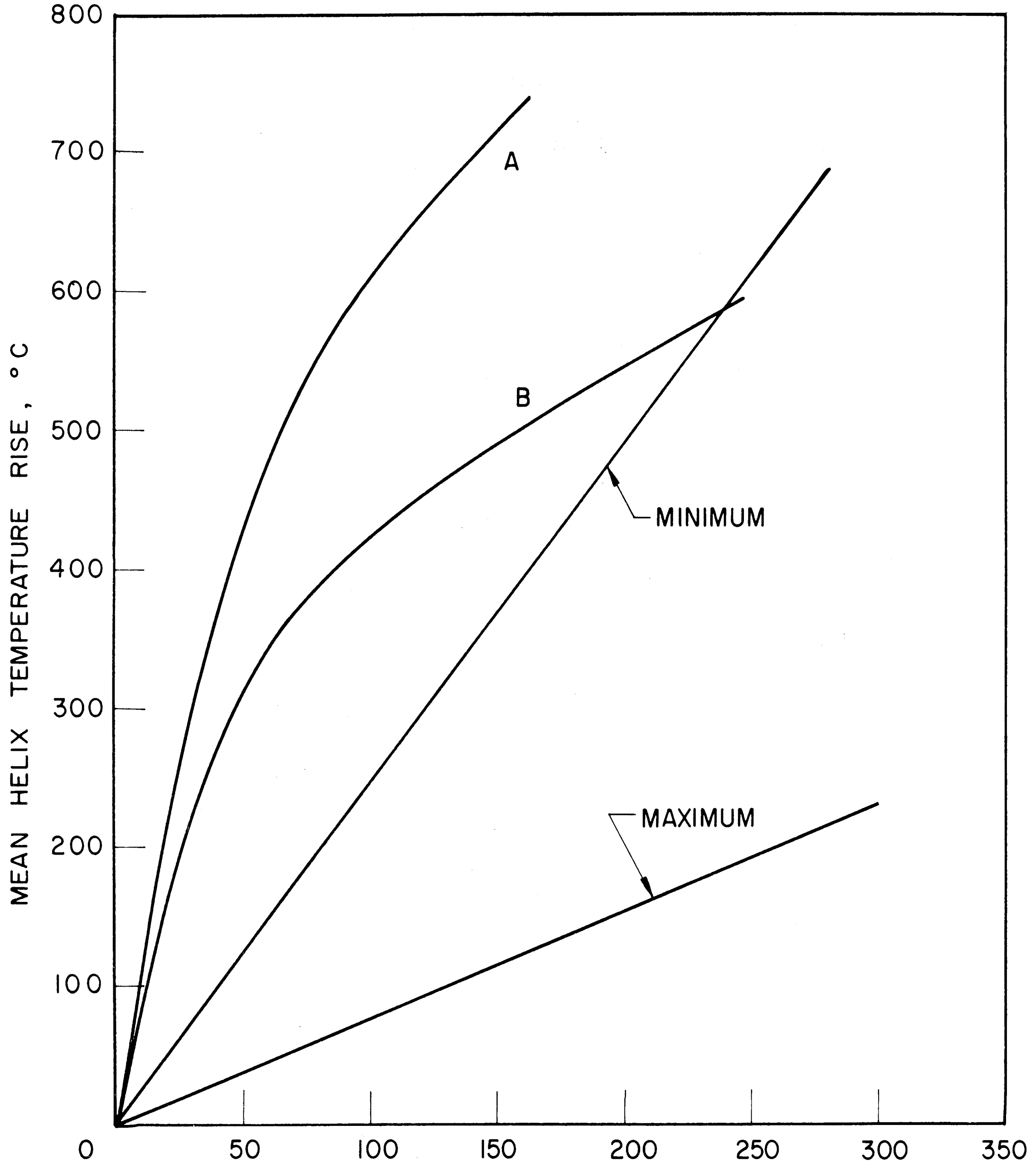

FIG. 2.2 MEAN HELIX TEMPERATURE RISE VS. POWER INPUT FOR THE BeO ROD-COPPER TUBE STRUCTURE.

at each turn, it is suspected that the poor contact exists at the pressure contact between the rods and the copper tube, not between the helix and rods. The theoretical analysis of power handling capability for this structure presented below supports this suspicion.

The differential heat conduction equation in the absence of sources or sinks is

$$dT = -\frac{P\,dz}{k\,A_T} , \tag{2.4}$$

where T = temperature,

z = distance from the apex of the heat tube,

k = thermal conductivity,

A_T = total cross-sectional area for heat flow and

P = power flow through A_T.

Now apply this equation to the temperature drop across the BeO rods. Then

$$A_T = 3(\mathrm{TPI})\,L\,A , \tag{2.5}$$

where L = structure length and

A = cross-sectional area of one heat flow tube.

Assume an elliptical contact area between the helix and rod with the semi-minor and semi-major axes a_o and b_o, respectively, and that the heat flow tube remains elliptical in cross section. Then

$$A(z) = \pi\,a(z)\,b(z) , \tag{2.6}$$

where a(z) and b(z) are the semi-minor and semi-major axes, respectively, at the distance z. Substitution gives

$$dT = -\frac{P}{3\pi(\mathrm{TPI})\,L\,k}\,\frac{dz}{a(z)\,b(z)} . \tag{2.7}$$

Assuming that halfway through the rod the heat flow tube has expanded to one half the rod diameter results in

$$\tan\alpha = \frac{b_o}{z_1} = \frac{d_r/2}{z_2} , \tag{2.8}$$

where α = angle of the heat flow tube in the plane of the major axis,

d_r = rod diameter,

z_1 = distance from the heat flow tube apex to the helix-rod contact and

z_2 = distance from the heat flow tube apex to the middle of the rod = $z_1 + d_r/2$.

It can then be shown that

$$z_1 = \frac{b_o d_r}{d_r - 2b_o} , \tag{2.9}$$

$$z_2 = \frac{d_r^2}{2(d_r - 2b_o)} \tag{2.10}$$

and

$$\tan\alpha = 1 - \frac{2b_o}{d_r} . \tag{2.11}$$

Assume

$$\frac{b(z)}{a(z)} = \frac{b_o}{a_o} \tag{2.12}$$

and since

$$\frac{b(z)}{z} = \tan\alpha, \tag{2.13}$$

one can write

$$a(z) = \frac{a_o}{b_o} b(z) = \frac{a_o}{b_o} z \tan \alpha \quad . \qquad (2.14)$$

Substituting Eqs. 2.13 and 2.14 into Eq. 2.7 gives

$$dT = - \frac{P}{3\pi(TPI)\, Lk \left(\frac{a_o}{b_o} \right) (\tan \alpha)^2} \frac{dz}{z^2} \quad . \qquad (2.15)$$

If the total temperature drop across the rod, ΔT_1, is twice the drop from the contact point to the rod center, a doubling of the value of the integral of Eq. 2.15 between z_1 and z_2 yields

$$\Delta T_1 = \frac{2P}{3\pi(TPI)\, Lk \left(\frac{a_o}{b_o} \right) (\tan \alpha)^2} \left(\frac{1}{z_1} - \frac{1}{z_2} \right) \quad . \qquad (2.16)$$

There is also a temperature drop across the BeO rod-copper tube interfaces. For a pressure-type contact of this sort

$$P = H A_c \Delta T_2 \quad , \qquad (2.17)$$

where P = power flow across the interface,

H = heat transfer coefficient,

A_c = contact area and

ΔT_2 = temperature drop across the interface.

For contact between the three rods and the tube

$$A_c = 3 w_c L \quad , \qquad (2.18)$$

where w_c = width of contact area for one rod and

L = length of the structure.

Combining Eqs. 2.17 and 2.18 results in

$$\Delta T_2 = \frac{P}{3w_c \, L \, H} \ . \tag{2.19}$$

The total temperature drop from the helix to the outside of the metal tube is then the sum of Eqs. 2.16 and 2.19, i.e.,

$$\Delta T = \Delta T_1 + \Delta T_2 \ . \tag{2.20}$$

In this last statement it is assumed that there is negligible temperature drop across the brazed contact between the helix and rods.

The above results can be used to check the experimental results. The various parameters with their tolerance or uncertainties are

$2a_o$ = 0.005 ± 0.001 inch,

$2b_o$ = 0.009 ± 0.001 inch,

k = 2.5 ± 0.5 watts/in.-°C,

TPI = 64,

L = 4-7/8 inches,

d_r = 0.030 inch,

w_c = 1.5 ± 0.5 mil and

H = 40 ± 10 watts/in^2-°C.

For the parameter values which give a maximum cooling limit

$$\Delta T_{1_{max}} = 0.075P \ ,$$

$$\Delta T_{2_{max}} = 0.685P \text{ and}$$

$$\Delta T_{max} = 0.76P \ . \tag{2.21}$$

Similarly the minimum limit is

$$\Delta T_{1_{\min}} = 0.17P,$$

$$\Delta T_{2_{\min}} = 2.28P \text{ and}$$

$$\Delta T_{\min} = 2.45P \quad . \tag{2.22}$$

These equations are plotted as the straight lines on Fig. 2.2 designated as maximum and minimum. The experimental results come close to these theoretical predictions, however, some improvement is still possible.

An interesting aspect of Eqs. 2.21 and 2.22 is that they predict that the primary temperature drop occurs across the pressure contact between the BeO rods and the copper tube. If such was the case the helix and rods would all heat up to nearly the same temperature during testing. This was observed during the tests and is a clear indication of the advantage accrued by brazing as compared to a pressure fit, since there would be an almost negligible temperature drop across a brazed joint between the BeO rods and the metal envelope.

It is also significant that this structure has been demonstrated to have a power dissipation capability in the range of 100-200 watts. Noteworthy also is the brazing of BeO rods along a five-inch length of a helix of these small dimensions.

Comparing the power dissipation capability of this structure to that of the BeO tube structure, it is seen that this one, of course, has a lower capability due to less contact area between the helix and its support structure. At a temperature of 500°C, for instance, the former structure can dissipate 170 watts/inch, whereas, this structure dissipates only 32 watts/inch. However, this structure will exhibit better electrical characteristics. It is important to note that a helix supported in either structure will be capable of dissipating considerably more power than when supported in any of the conventional ways.

Originally r-f cold tests of the electrical properties of these structures had been planned. However, other work[4] at S- and X-bands demonstrated that a helix pressure loaded into a BeO structure possesses satisfactory electrical properties and that these properties are not appreciably degraded by brazing. Consequently, assuming the same to be true for the 30 Gc structures, the need for the r-f cold tests was eliminated and only their heat transfer properties were investigated.

2.2.3 Conclusions. Both structures have demonstrated a high-power dissipation capability; 170 watts/inch for the BeO tube structure and 32 watts/inch for the BeO rod-copper tube structure at 500°C mean helix temperature. The distribution of the temperature drop in the latter structure has shown the advantage of a brazed contact over a pressure contact. It has been shown how to braze a 30 Gc helix into a smooth-bore BeO tube and how to braze BeO rods to a 30 Gc helix and pressure load this into a copper tube. Since the structures have adequate r-f properties they have been shown to be satisfactory high-power r-f structures.

3. Analysis of Amplitude- and Phase-Modulated Traveling-Wave Amplifiers

(M. E. El-Shandwily and J. E. Rowe)

3.1 Introduction. During this period, work was carried out on the following items:

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[4] Detweiler, H. K., "Applied Research in Microwave and Quantum Electronics", Final Report, pp. 2-58, Contract No. AF33(657)-8050, Electron Physics Laboratory, The University of Michigan, Ann Arbor; March, 1964.

a. Large-signal analysis of the multi-signal traveling-wave amplifier.

b. Experimental work on traveling-wave amplifiers with two input signals carrying modulation.

c. Writing a summary technical report.

The work accomplished on each of the above items is reported briefly in the following section.

3.2 Results.

3.2.1 Large-Signal Analysis. It was reported in Quarterly Progress Report No. 6 that there was some difficulty in obtaining the required accuracy to get correct results from the large-signal analysis. The computer program has been rewritten using double precision arithmetic to attain the required accuracy in the computation. No results have been obtained at this time.

3.2.2 Experimental Effort. The experimental results reported so far were obtained with sinusoidal input signals. It is interesting to carry out similar tests when the input signals are modulated. Also, the behavior of the traveling-wave amplifiers with multi-frequency input signals in the presence of band-limited noise needs to be investigated. Experimental work is now going on to study these effects.

3.2.3 Summary Technical Report. A summary technical report on the nonlinear operation of the traveling-wave amplifier with multi-frequency input signals is being prepared. It is expected that it will be ready by the end of the next quarter.

4. Study of a D-c Pumped Quadrupole Amplifier (C. Yeh and B. Ho)

In a previous program report (No. 5) the equations of motion for the large-signal analysis of a d-c quadrupole amplifier employing cyclotron-to-cyclotron wave interaction have been derived. These equations were programmed for digital computer solution during this reporting period. Although the detailed evaluation of the data is not yet completed, a few pertinent points can be observed from the tabulated data.

A. The trajectories of the electrons injected at different entrance angles show a strong tendency to phase focusing. Electrons entering the quadrupole structure at all angles tend to group into two spokes.

B. There is one particular entrance angle at which the radius of rotation is largest. This is the most favorable entrance angle for the electrons.

C. The radius of rotation increases with the pumping parameter.

D. The time required for the radius of rotation to become a maximum decreases with increasing pumping field strength.

E. With a small pumping field strength, the maximum radius of rotation never reaches a value such that $\rho/\rho_m = 1$.

F. With a strong pumping field strength, ρ/ρ_m may exceed unity.

G. The axial parameter does not coincide with the time parameter τ. This indicates that the axial velocity is not strictly constant along the axis of the system.

Detailed evaluation awaits the completion of all possible variations of the parameters and plotting of the data.

A similar computing program for the equations of motion of the large-signal analysis of d-c quadrupole amplifier employing cyclotron-to-synchotron wave interaction derived in Quarterly Progress Report No. 6

is in progress. It is intended to compare these two modes of operation and to seek an explanation of the anomalous gain mechanism previously reported.

5. Investigation of the Cross-Modulation Products in a Wideband Tunnel-Diode Amplifier (C. Yeh)

5.1 Introduction. During recent years, tunnel-diode amplifiers have been developed to realize low-noise figures (3.5 db) and wide frequency range operation (octave bandwidth) in the microwave spectrum. Their existence challenges the exclusive position enjoyed by the traveling-wave tubes only a few years ago. However the gain-bandwidth and the ultimate noise figure achievable by a tunnel-diode amplifier are still somewhat below that obtainable in a well designed TWA. Yet its small size, light weight, simple low-voltage d-c supply are definitely advantages over the TWA in many applications.

Among the many problems needing investigation in the application of the wideband tunnel-diode amplifier to communication engineering is a study of the cross-modulation products appearing at the output. It is anticipated that since the operation of a tunnel-diode amplifier depends upon the negative resistance characteristic of the diode, whose linearity can be controlled through the proper choice of materials and appropriate doping, the problem of cross modulation is not as acute as in the case of the TWA. In the latter case the nonlinearity in operating characteristics is derived from the complicated interaction mechanism between the beam and the circuit waves and hence is more susceptible to operating conditions, such as the input power level, output load impedances, etc.

5.2 Procedure for the Study. A tentative schedule for the study of the cross-modulation problems in wideband tunnel-diode amplifiers is as follows:

a. To derive an expression for the negative resistance of the tunnel-diode characteristic linking its linearity or nonlinearity to the material properties of the diode and its doping concentration. Since the volt-ampere characteristic of a tunnel diode depends upon the forward and reverse current at operating d-c bias voltage, and the former are functions of the tunneling probability, the Fermi-Dirac probability of occupancy, the densities of states in conduction and valence bands, the material and its doping concentration can affect its characteristic drastically.

b. To investigate theoretically the effect of temperature on the diode characteristic.

c. Use the negative resistance characteristic of the diode thus derived to obtain expressions for the cross-modulation products when two or more input signals are applied simultaneously. Input signals with various types of modulations can be studied.

d. Experimentally determine the negative resistance characteristic. Approximate this characteristic by a mathematical expression and compute the cross-modulation products using this expression. Compare the results with "c".

e. Experimentally measure the cross-modulation product using various input combinations and various modulation forms. Compare the results with that obtained in "c" and "d".

It is not necessary that the above steps be followed in sequence.

5.3 Future Work. The following steps have been initiated:

a. A literature survey and formulation of the theory.

b. A wideband tunnel-diode amplifier will be purchased to carry out the experimental study.

6. Nonlinear Analysis of the Crossed-Field Amplifier with Multi-Frequency Input Signals (M. E. El-Shandwily and J. E. Rowe)

The crossed-field device offers certain advantages for some system applications in view of its inherently high efficiency and relative low phase sensitivity. A study of the nonlinear operation of the injected-beam forward-wave crossed-field amplifier with multi-frequency input signals was initiated during this period. A small-signal nonlinear theory similar to that for the O-type amplifier is nearly completed. After the theoretical analysis is finished, numerical results will be obtained from a digital computer.

In the future an experimental program will be initiated and nonlinear calculations will be considered.

7. General Conclusions (C. Yeh)

The experimental work on two types of helix mounting in high-thermal-conductivity beryllium oxide for a 30 Gc TWA has been reported. Both structures have demonstrated a high-power dissipation capability; 170 watts/inch for the BeO tube structure and 32 watts/inch for the BeO rod-copper tube structure at 500°C mean helix temperature.

The measurement of cross-modulation products in an O-type traveling-wave amplifier with multiple input frequency signals has been extended to cover input modulations of different types, i.e., if the input signals are sinusoidally modulated, phase modulated etc. The effect of noise modulation will also be studied.

Preliminary results on the large-signal trajectory computations for a d-c quadrupole amplifier using a cyclotron-to-cyclotron mode of operation are being evaluated. A similar computation for the other mode of operation, i.e., the cyclotron-to-synchrotron mode, will be carried out for comparison.

Two new areas of investigation have been initiated--the investigation of cross-modulation products in a wideband tunnel-diode amplifier and the nonlinear analysis of a crossed-field multi-signal input amplifier.

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A preliminary discussion of the results of the large-signal electron trajectory computation for a d-c pumped quadrupole amplifier is included.

The work on fabricating a low frequency (600 - 2400 mc) multiplier tube is in progress.

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