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QUARTERLY PROGRESS REPORT NO. 5

FOR

BASIC RESEARCH IN MICROWAVE DEVICES AND QUANTUM ELECTRONICS

This report covers the period May 1, 1964 to August 1, 1964

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ABSTRACT

A new frequency multiplier tube that will have a better overall conversion efficiency has been designed. The enhancement in efficiency is derived from the fact that a section of d-c pumped quadrupole amplifier is added to boost the feedback signal to a workable level before introducing it onto the input coupler. Theoretical calculation indicates that enhancement in efficiency up to 100 percent can be realized.

The technique for loading a helix into a BeO tube is being developed and the best test has proven it to be moderately successful.

Equations for the modulation products of two-signal analysis of the amplitude- and phase-modulated traveling-wave amplifier have been programmed and computed. Experimental results on the measurement of an X-band traveling-wave amplifier with two inputs are presented. Final discussion and conclusions await further theoretical computations.

A large-signal analysis of the d-c pumped quadrupole amplifier has been initiated. Equations of motion and the energy relations are derived assuming a specific pump field and neglecting the space-charge forces. From the trajectory of the beam and the energy relation between the beam and the quadrupole, a more exact criterion for the existence of the anomalous gain discussed in previous reports can be established.

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LIST OF ILLUSTRATIONS

PERSONNEL

Scientific and Engineering Personnel		Time Worked in Man Months*
J. Rowe	Professors of Electrical Engineering	.20
C. Yeh		1.75
M. El-Shandwily	Research Associate	1.53
B. Ho	Research Assistant	1.53
Service Personnel		5.17

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* Time Worked is based on 172 hours per month.

INTERIM SCIENTIFIC REPORT NO. 5
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 circuit. The enhancement of the theoretical efficiency of the frequency multiplier by feedback is handicapped by the low efficiency of the Cuccia couplers. A scheme will be devised in which the feedback signal is amplified by a d-c quadrupole section before inducing it into the input coupler.

B. Investigation of high-thermal-conductivity materials for microwave devices above X-band. Work to develop a helix loading technique using a higher resiliency Fansteel wire will continue. Heat tests will be conducted to determine the dissipation of the structure.

C. Analysis of amplitude- and phase-modulated traveling-wave amplifiers. The theoretical results prescribed in the previous progress reports (Nos. 1, 2 and 3) will be programmed for digital computation. Experimental measurement will be made with an X-band amplifier. Correlation of theoretical and experimental results will be presented.

D. Study of a d-c pumped quadrupole amplifier. Further study of the criterion for the realization of the anomalous gain in a d-c pumped quadrupole amplifier will continue. Searching for experimental evidence in direct support of the theory is continuing.

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

2.1 Study of Frequency Multiplication in Angular Propagating Circuit

(C. Yeh and B. Ho)

2.1.1 Introduction. The frequency multiplier tube built during a previous reporting period underwent a series of preliminary d-c testing and was found to be satisfactory. R-f testing is scheduled to follow. Unfortunately, during one of the procedures in assembling the tube into the magnetic coil, a lead was hit accidently which caused a slow leak to develop and burned out the heater. Instead of resealing the tube, it was decided to redesign it completely. This is because several new thoughts have developed during the r-f testing which, when used in the new tube, could enhance its operation greatly.

2.1.2 Points to Be Considered in Designing a New Tube. From the d-c and r-f testing carried out on the old tube, the following was learned:

1. In order to develop a high r-f field at the input coupler, a resonant circuit should be built right onto the coupler.

2. Since there are three successive interaction regions along the drifting beam, a real fine beam of diameter not greater than 1 mm is desirable.

3. A higher beam voltage, higher than have been used in the old tube, (25 volts) is desirable in order to obtain a better beam focusing.

4. The enhancement in overall efficiency of the frequency multiplier with feedback is still too low to be of any practical use.

In view of this discussion it was decided to redesign the tube so that the above mentioned points could be taken care of. Accordingly, cold tests were made to find a suitable resonant configuration to be added to the input as well as the output couplers; a multi-anode high performance gun has been obtained; the axial dimensions of the interaction region have been increased to accommodate the increase in beam voltage; and a new scheme to enhance the efficiency has been developed.

2.1.3 Design Procedure for the High Efficiency Cyclotron-Wave Frequency Multiplier. The scheme to further increase the overall efficiency of the frequency multiplier needs further investigation.

Due to the inherent low efficiency of the Cuccia coupler, a maximum of about 25 percent, the overall efficiency of the frequency multiplier is limited to about four percent without feedback and five percent if feedback is used. Such a low efficiency of operation is of course far from satisfactory. In order to improve the efficiency, a d-c quadrupole amplifier is introduced in the feedback loop. By varying the gain of the quadrupole amplifier, the overall efficiency of the frequency multiplier can be improved up to 100 percent. In other words, a self-sustained oscillation can also be obtained.

The block diagram of the operating system is shown in Fig. 2.1. If G represents the power gain of the quadrupole amplifier*, then the power relationships of the individual blocks are as follows:

$$P_L = \eta_3 P_T$$

$$P_T = \xi P_m$$

$$P_e = (1 - \xi) P_m$$

$$P_2 = \eta_2 P_e$$

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* Other notations are the same as in a previous report (Quarterly Progress Report No. 2, November, 1963).

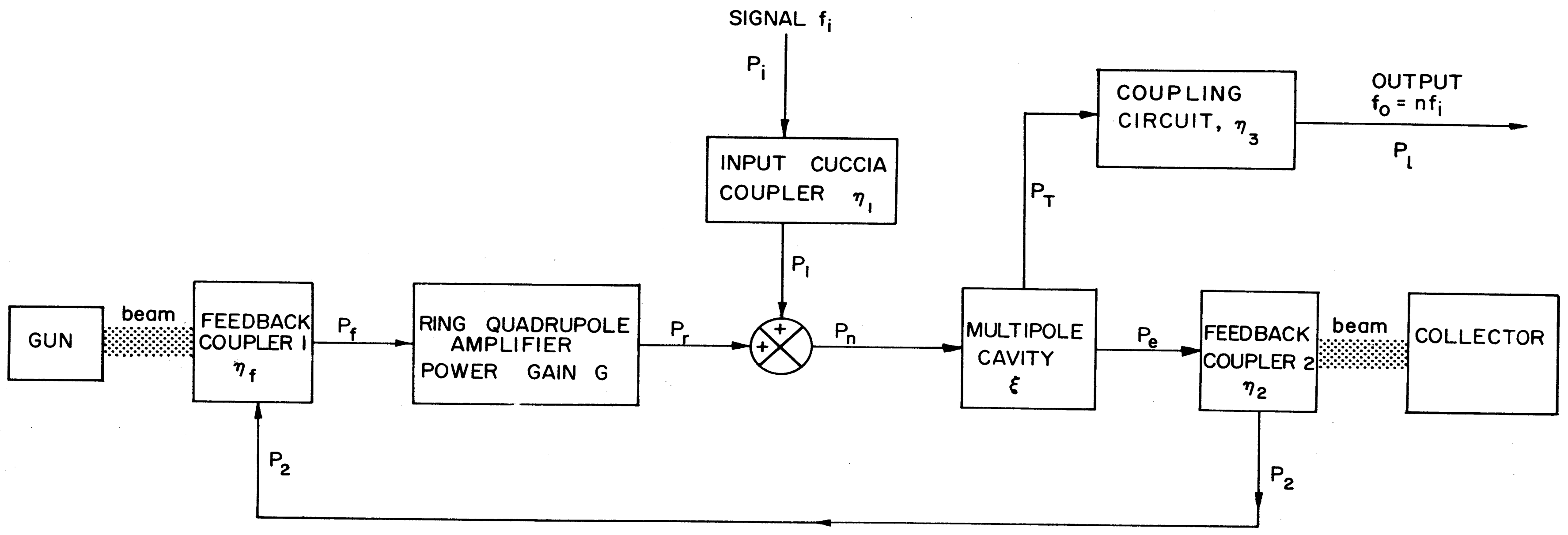


FIG. 2.1 BLOCK DIAGRAM OF A CYCLOTRON-WAVE FREQUENCY MULTIPLIER WITH FEEDBACK AND QUADRUPOLE AMPLIFIER.

$$P_f = \eta_f P_2$$
$$P_r = G P_f$$
$$P_1 = \eta_1 P_i$$
$$P_m = P_r + P_1 = P_r + \eta_1 P_i$$

The overall efficiency is then

$$\eta = \frac{P_L}{P_i}$$

$$= \frac{\eta_1 \eta_3 \xi}{1 - G \eta_f \eta_2 (1-\xi)} . \qquad (2.1)$$

Use the typical values of η_1, η_2, η_f, η_3 and ξ as follows:

$\eta_1 = \eta_2 = \eta_f =$ efficiency of Cuccia coupler ≈ 0.25 ,

$\eta_3 =$ coupling circuit efficiency ≈ 0.75 ,

$\xi =$ multipole cavity efficiency ≈ 0.22 ;

then the overall efficiency as a function of d-c quadrupole power gain G becomes

$$\eta = \frac{0.043}{1 - 0.052\,G} . \qquad (2.2)$$

A plot of η vs. G of Eq. 2.2 is shown in Fig. 2.2. It is seen that the efficiency of the multiplier increases rapidly with the gain of the quadrupole amplifier. At a gain value of 18, 100 percent efficiency is attainable.

The advantage of introducing such a quadrupole amplifier in the feedback loop is not only to improve the overall efficiency of the device, but also to provide a simple means to control the high frequency power output.

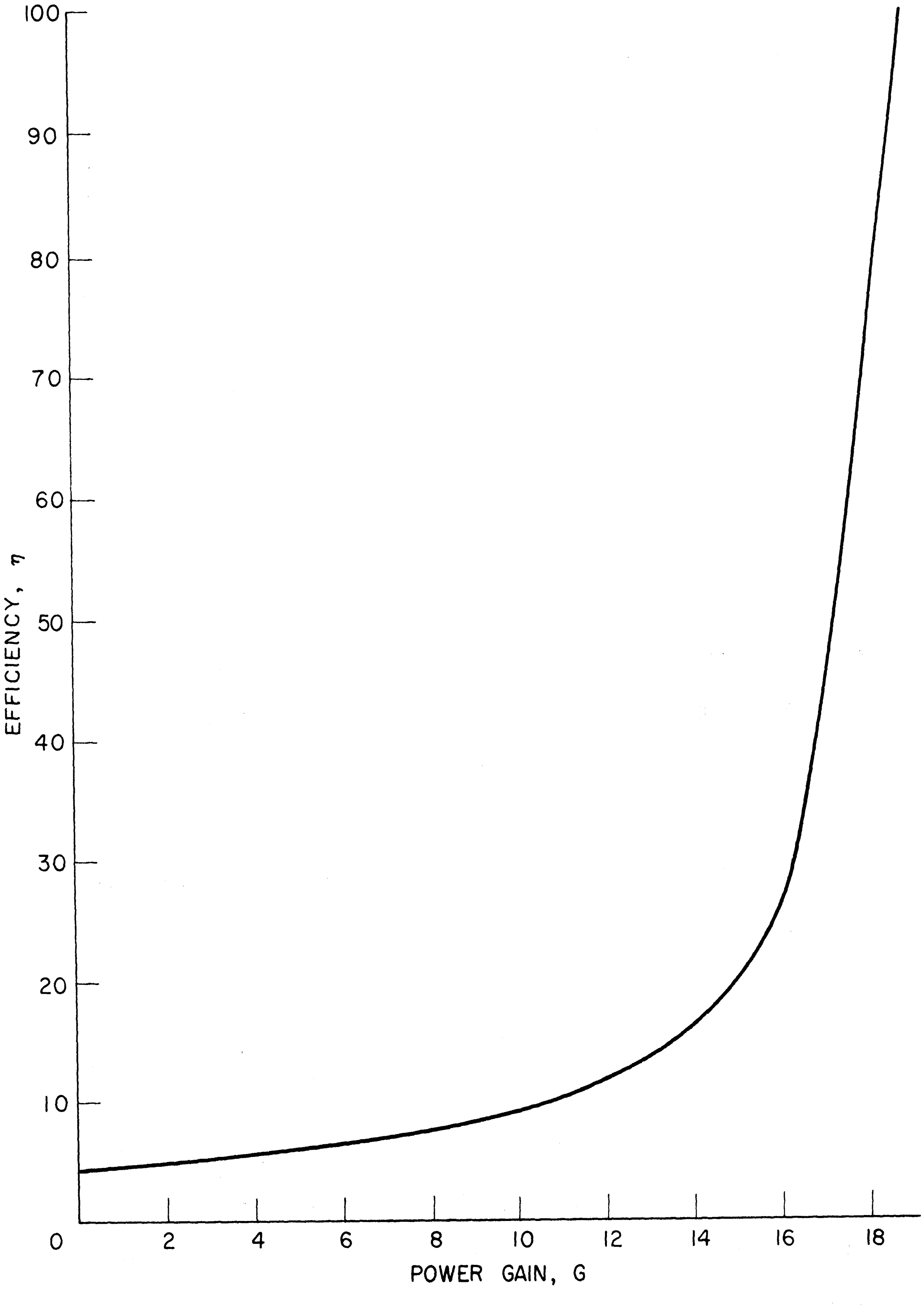


FIG. 2.2 OVERALL EFFICIENCY VS. FEEDBACK QUADRUPOLE AMPLIFIER POWER GAIN G WITH $\eta_1 = \eta_2 = \eta_f = 0.25$, $\eta_3 = 0.75$, $\xi = 0.22$.

2.1.4 Design Data for the High Efficiency Cyclotron-Wave Frequency Multiplier.

1. Multipole cavity. The resonators are of hole and slot type. The radius of the hole is 0.236 inch, and the length and width of the slot are 0.236 inch and 0.079 inch respectively. The resonant frequency is computed to be 2.24 kmc. There are eight holes and slots. The diameter between vane tips is 0.456 inch and the block length is 1.4 inch.

2. Input frequency f_i.

$$f_i = 2.24/8 \text{ kmc} = 560 \text{ mc} \quad .$$

3. Strength of axial magnetic field B.

$$B = \frac{\omega_c}{\eta} = 200 \text{ gauss} \quad .$$

4. Maximum r-f beam power P_m. The vane tip radius is 0.228 inch. In order to avoid high beam current interception in the multipole cavity, a maximum beam rotational radius would be

$$r_m = 0.228 \times 0.9 = 0.205 \text{ inch} \quad .$$

The corresponding r-f beam power is then

$$P_m = 11.22\, I_o\, f_{mc}^2\, r_m^2$$
$$= 238 \text{ mw} \quad .$$

A beam current of 250 μa is assumed.

5. Required signal power P_i. Assuming the Cuccia coupler has an efficiency of $\eta_1 = 0.25$, then the required signal power is

$$P_i = \frac{P_m}{\eta_1} = 951 \text{ mw} .$$

6. Beam voltage V_o. From the plot of output power vs. number of revolutions M in the multipole cavity, in Quarterly Progress Report No. 2, a value of M = 4 can be used.

The period of the cyclotron frequency is

$$T_c = 1.78 \times 10^{-9} \text{ sec} .$$

The total time duration T_m in the multipole cavity region is

$$T_m = M T_c = 7.12 \times 10^{-9} \text{ sec} .$$

The beam velocity then should be

$$u_o = \frac{\ell}{T_m} = 5 \times 10^6 \text{ m/sec} .$$

The required beam voltage is

$$V_o = \frac{1}{2\eta} u_o^2 = 71 \text{ volts} .$$

7. Couplers. Cold tests have been performed in investigating the method of coupling the signal to the beam. It is found that a resonant circuit formed by the coupler capacitance in parallel with a small inductance is satisfactory. The signal is fed to the taper of the inductance coil. A small trimmer type tuning device is attached to the coupler such that all the couplers in the system can be tuned to the same cyclotron frequency.

The coupler dimensions are:

	Signal Coupler	Feedback Coupler
Coupler plate length (inch)	1.37	1.09
Coupler plate separation (inch)	0.46	0.362
Coupler plate width (inch)	0.5	0.5
Plate length to separation ratio	3.0	3.0

8. Ring quadrupole amplifier. The gain expression for ring quadrupole cyclotron-synchronous wave amplifier is given in Table 4.1 in Quarterly Progress Report No. 3 as

$$\text{Gain} = 20 \log \cosh \frac{2\eta V_p n \pi}{\omega_c^2 a^2} .$$

In order to obtain high gain at short pump length and low pump level, the ring radius should be kept small. Two sections of ring structure are used in cascade. The design data are:

	First Section	Second Section
Operating frequency (mc)	560	560
No. of period	4	4
Approximate pump voltage (volts)	60	80
Ring radius (cm)	0.35	0.54
Voltage gain	2.95	1.59
Power gain	8.7	2.53

The voltage gain vs. ring radius for pump voltages of 60 and 80 volts are plotted in Figs. 2.3 and 2.4 respectively.

The period of the ring structure can be calculated as follows: Beam voltage V_o = 71 volts, and the corresponding beam velocity u_o = 5×10^6 m/sec. For cyclotron-synchronous wave amplification it is

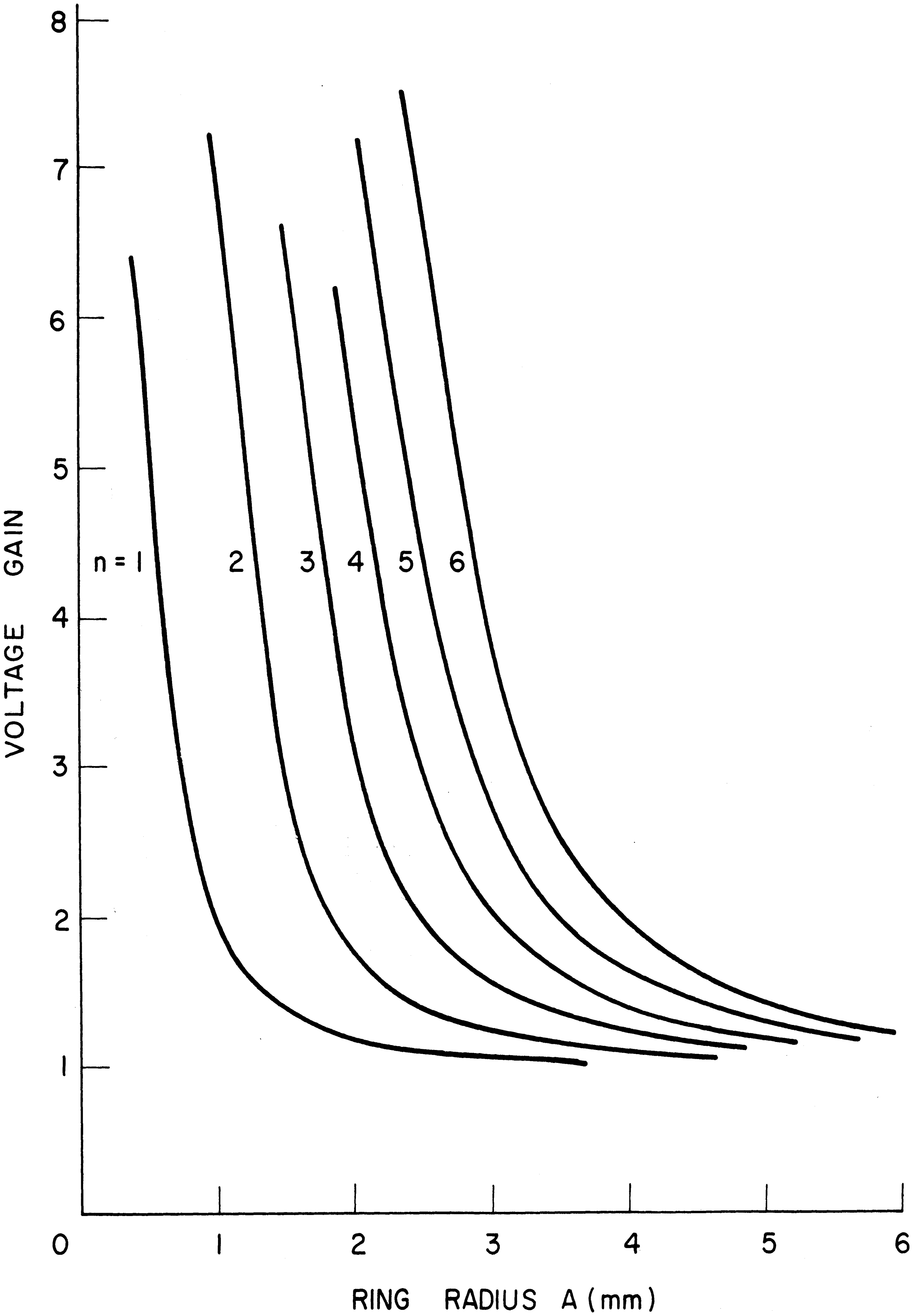


FIG. 2.3 VOLTAGE GAIN VS. RING RADIUS OF THE QUADRUPOLE AMPLIFIER FOR V_p = 60 VOLTS, f = 560 mc.

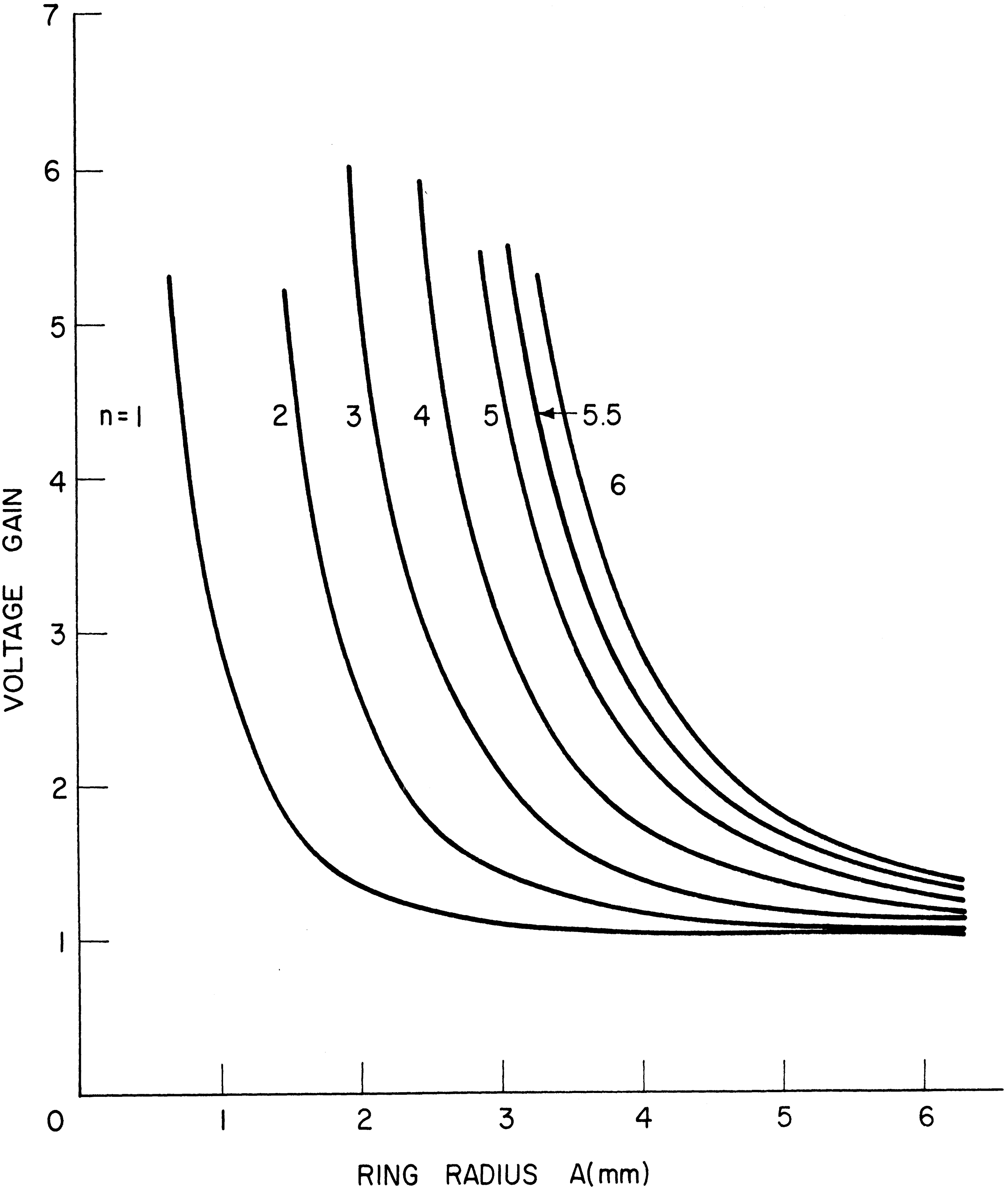


FIG. 2.4 VOLTAGE GAIN VS. RING RADIUS OF THE QUADRUPOLE AMPLIFIER FOR V_p = 80 VOLTS, f = 560 mc.

required that $\beta_c = \beta_q$. Therefore the ring structure should have a separation of

$$\lambda_q/2 = T_c u_o/2 = 0.4465 \text{ cm} .$$

9. Overall efficiency. As shown in Fig. 2.2, the overall efficiency can be varied from four percent, with feedback power gain G of unity to 100 percent, with a power gain equal to 17.56. Equation 2.2 also shows that there exists a possibility of self-sustained oscillation, provided the gain of the quadrupole amplifier is greater than the critical gain of 17.56. If such a condition is satisfied, the device becomes a high-frequency oscillator. The power output of the oscillator is controlled by the d-c voltage at the pump field of the ring structure.

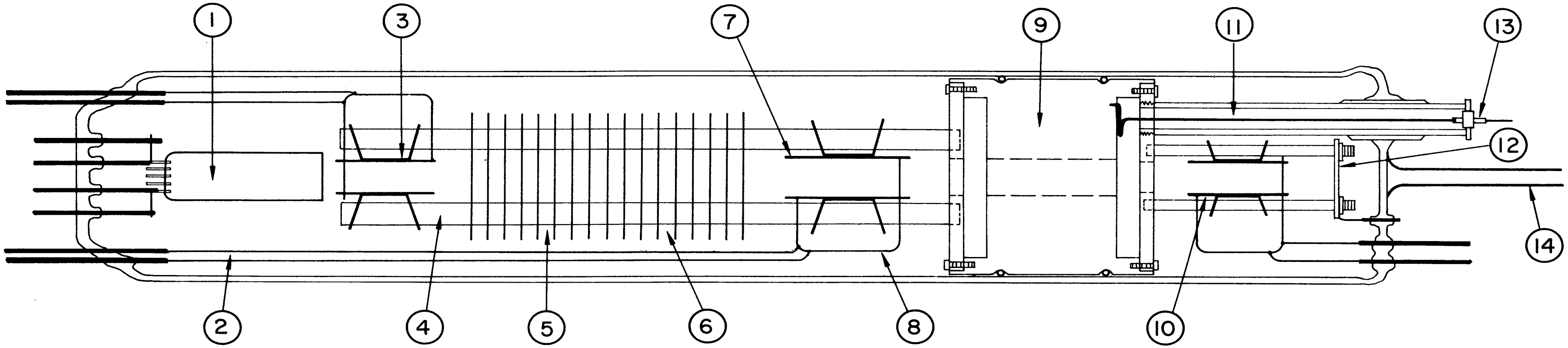
The complete assembly of the tube is shown in Fig. 2.5.

2.1.5 Future Work. The parts of the tube are in the process of machining. It is hoped that the tube will be assembled and processed during this working period.

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

2.2.1 Introduction. During this period marked progress was made in developing a technique for loading a helix into a smooth-bore BeO tube for brazing. Several structures were prepared using Fansteel Type 60 Metal helices and these were subsequently heat tested. Efforts were continued on developing the BeO rod-metal tube structure. A detailed account of the work is given below.

2.2.2 Experimental Effort. At the beginning of this period a shipment of 5 mil diameter Fansteel 60 Metal wire (90 percent tantalum and 10 percent tungsten prepared by the electron-beam melting process)



1. MULTI-ANODE GUN
2. SIGNAL TRANSMISSION LINE
3. FEEDBACK COUPLER
4. CERAMIC ROD
5. FIRST SECTION OF Q.A.
6. SECOND SECTION OF Q.A.
7. SIGNAL CUCCIA COUPLER
8. RESONANT CIRCUIT FOR THE COUPLER
9. MULTIPOLE CAVITY
10. FEEDBACK COUPLER
11. OUTPUT COAXIAL LINE
12. COLLECTOR
13. OUTPUT
14. ION PUMP

FIG. 2.5 SCHEMATIC DIAGRAM OF A CYCLOTRON-WAVE FREQUENCY MULTIPLIER.

was received. A program was undertaken to determine a heat-treat cycle which would give a 30 Gc helix wound out of this wire the desired amount of resiliency. For loading the helix into a BeO tube for brazing it was necessary that a helix having the dimensions

Mean helix diameter = 0.030 inch,

O. D. = 0.035 inch,

d_w = 0.005 inch and

TPI = 64

be 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. After extensive testing a heat-treat cycle was found which gave nearly the desired results in that, on the average, 2 mils of spring back were obtained. The 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.

Using the brazing[1] and loading[2] techniques described previously and the above heat treatment for the 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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[1] Detweiler, H. K., et al., "Basic Research in Microwave Devices and Quantum Electronics", Quarterly Progress Report No. 1, Electron Physics Laboratory, The University of Michigan, Ann Arbor, p. 27; September, 1963.

[2] Detweiler, H. K., et al., "Basic Research in Microwave Devices and Quantum Electronics", Quarterly Progress Report No. 2, Electron Physics Laboratory, The University of Michigan, Ann Arbor, p. 6; November, 1963.

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 heating with d-c power and determining the mean helix temperature rise from its change in electrical resistance. The results are shown in Fig. 2.6. 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; higher power handling capabilities only await a better quality BeO tube. Even with the relatively poor tubes used it is seen from the experimental data that this structure is capable of dissipating 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. Therefore no further work on this structure is planned during the next quarter.

The copper tubing for the BeO rod-metal envelope structure was received during this quarter. Unfortunately, after attempts to deform this undersize tubing, i.e., smaller I. D. than the O. D. of the helix with the BeO support rods on its outside, in such a way to admit the helix and rods, the tubing did not spring back sufficiently when released to obtain the desired pressure contact. Consequently, some stainless

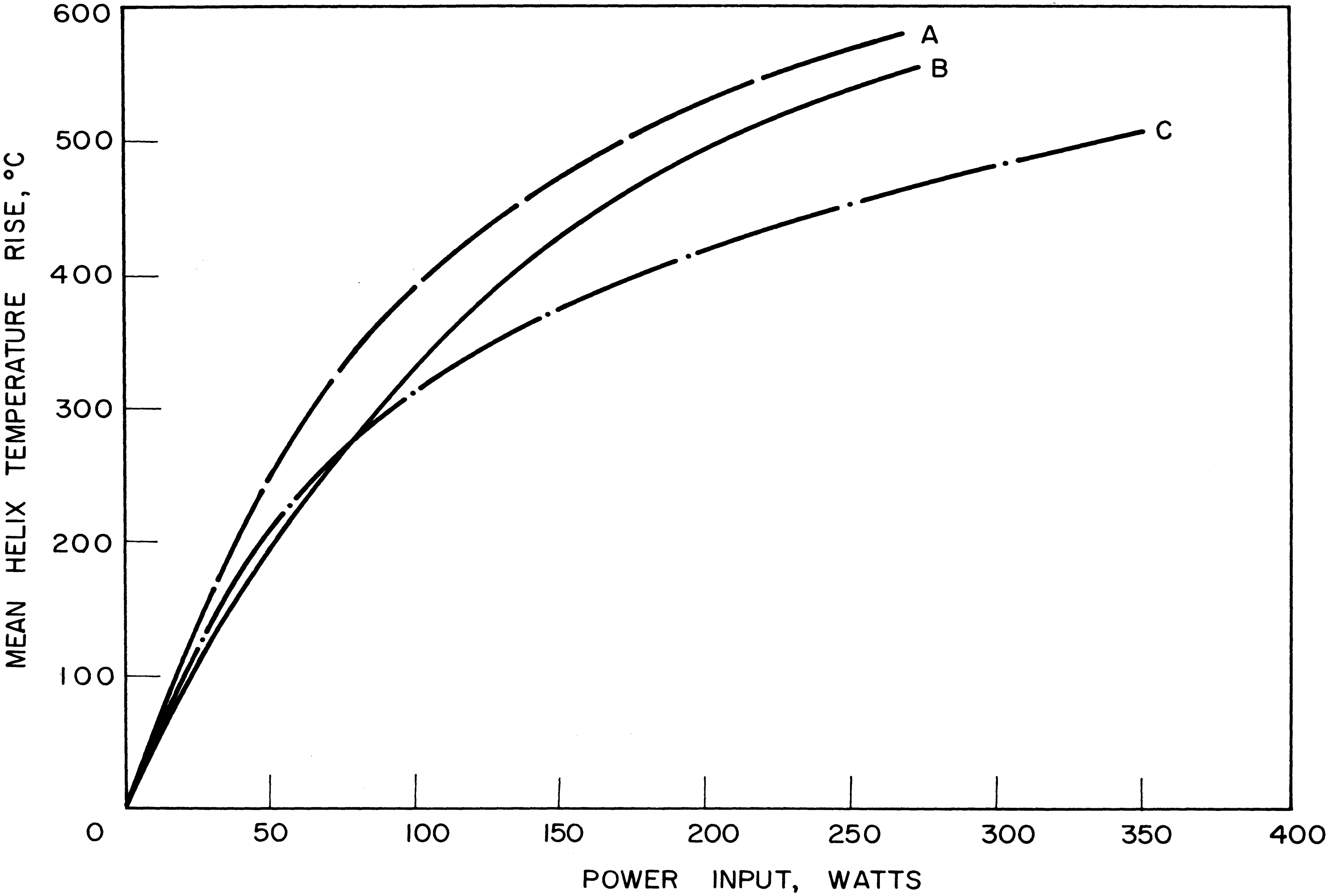

FIG. 2.6 MEAN HELIX TEMPERATURE RISE VS. POWER OUTPUT FOR THREE BRAZED HELIX-BeO TUBE STRUCTURES.

steel tubing has been ordered and further tests will be conducted upon its receipt. A jig for accomplishing the brazing of the BeO rods to the helix has been made and brazing tests are presently being conducted.

2.2.3 Future Work. Work will be continued on the development of the BeO rod-metal envelope helix support structure. This structure will be heat tested upon its successful fabrication.

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

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

3.1 Introduction. In the previous progress reports, the problem of multi-frequency input signals has been treated by three different methods. Each method has its advantages and limitations. In this progress report, some of the theoretical and experimental results will be presented and discussed.

The theoretical results presented in this report are the solutions of the equations in the first quarterly progress report. (An error was found in those equations and was corrected before solution.) Figures 3.1, 3.2 and 3.3 show the output-input characteristic for a traveling-wave amplifier with two input signals. The input power at f_b is kept constant while that at f_a is varied. The abscissa is the input power at f_a relative to $C_a I_o V_o$ in db. The ordinate is the output power at f_a and the generated signal at $2 f_a - f_b$ relative to the constant input power at f_b in db.

It is seen from these figures that the generated component at $2 f_a - f_b$ increases more rapidly with input power at f_a than the output at f_a. Also for the same input power, the output at $2 f_a - f_b$ increases more rapidly with distance along the tube than the output at f_a.

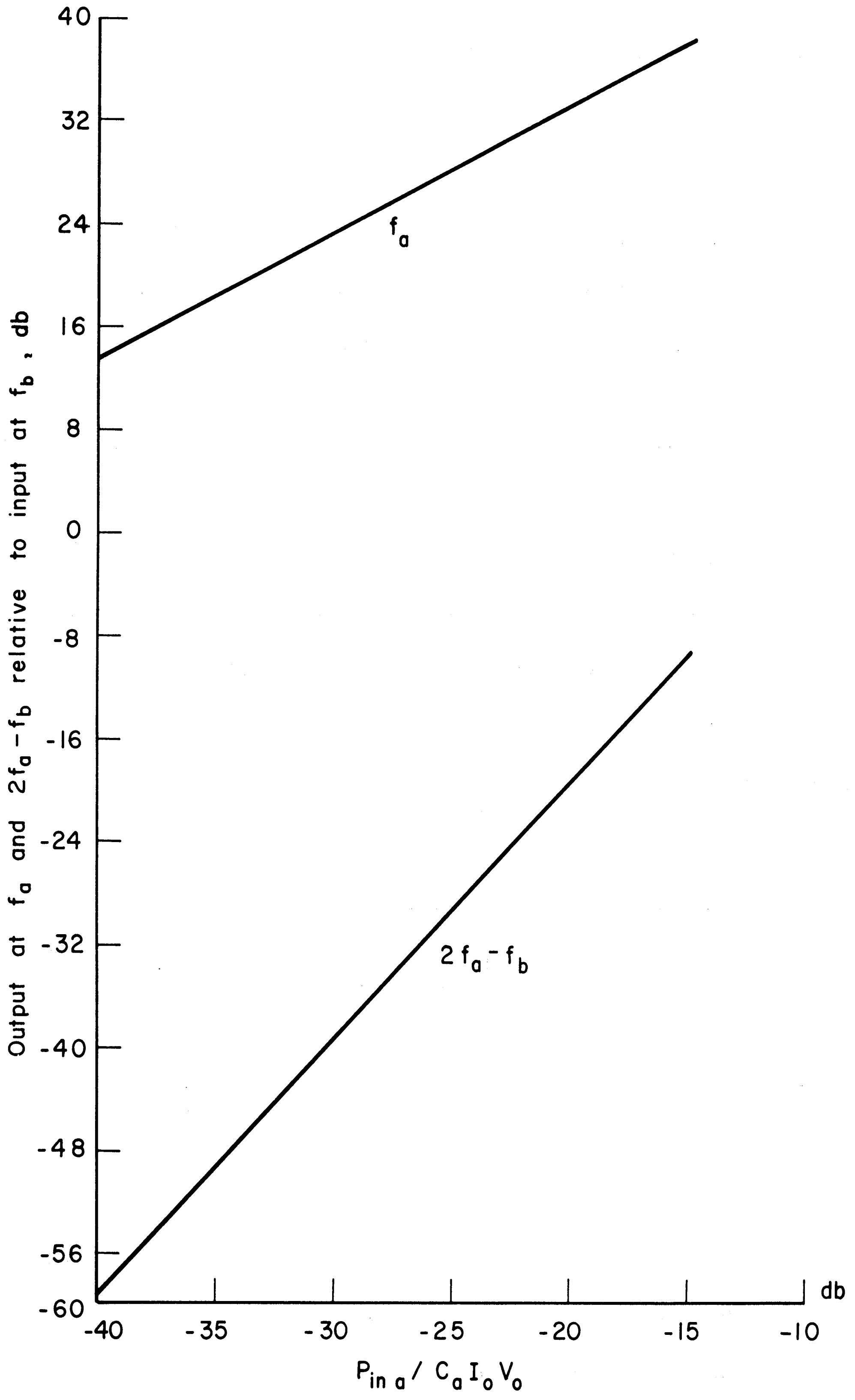

FIG. 3.1 OUTPUT AT f_a AND $2f_a - f_b$ VS. INPUT POWER AT f_a IN NORMALIZED UNITS FOR $f_a/f_b = 1$, $C_a = C_b = 0.05$, $d = b = QC = 0$, $\zeta_a = 3$, $P_{inb}/C_b I_o V_o = -40$ db.

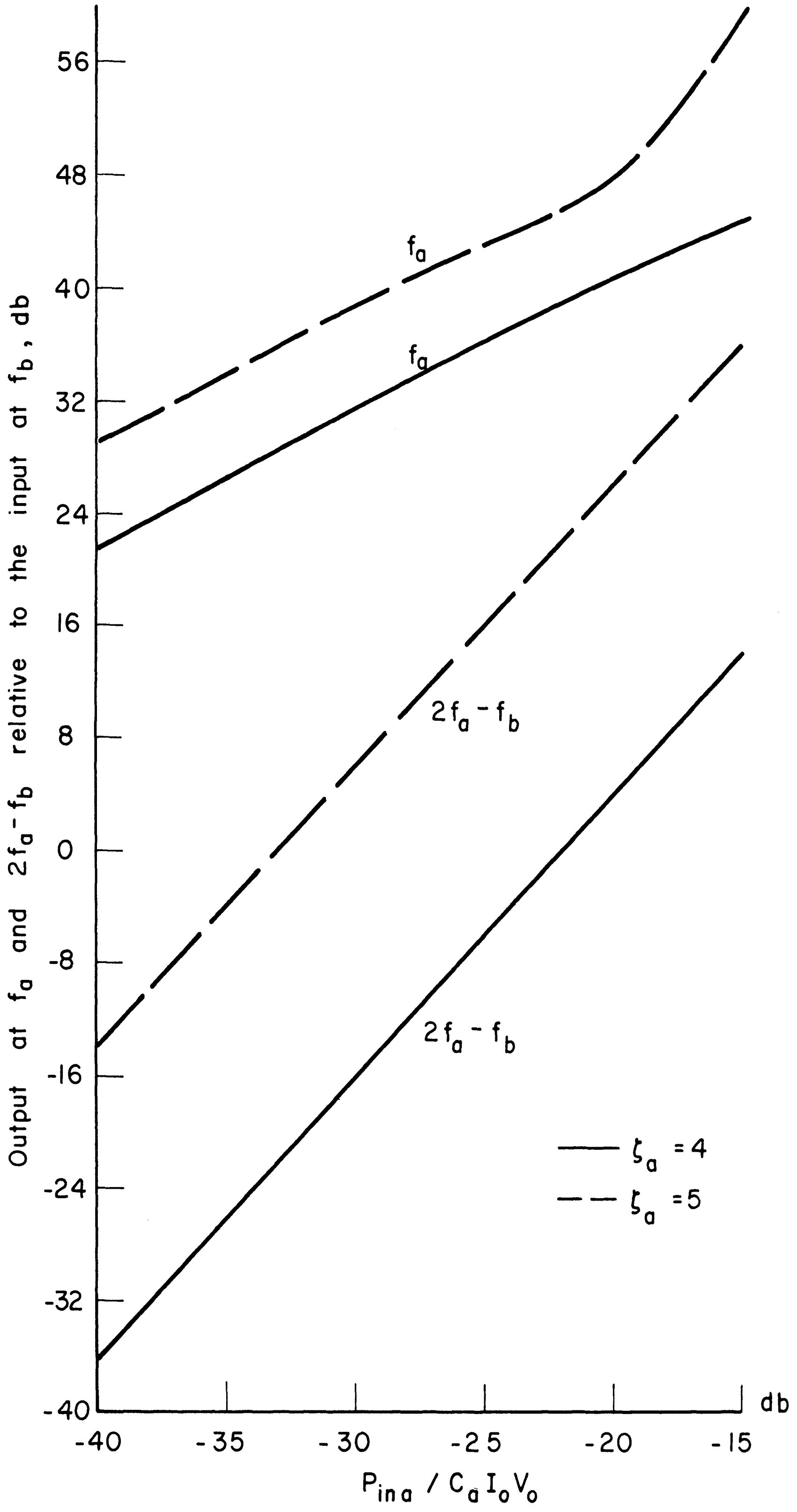

FIG. 3.2 OUTPUT AT f_a AND $2f_a - f_b$ VS. INPUT POWER AT f_a IN NORMALIZED UNITS FOR $f_a/f_b = 1$, $C_a = C_b = 0.05$, $d = b = QC = 0$, $\zeta_a = 4.5$, $P_{inb}/C_b I_o V_o = -40$ db.

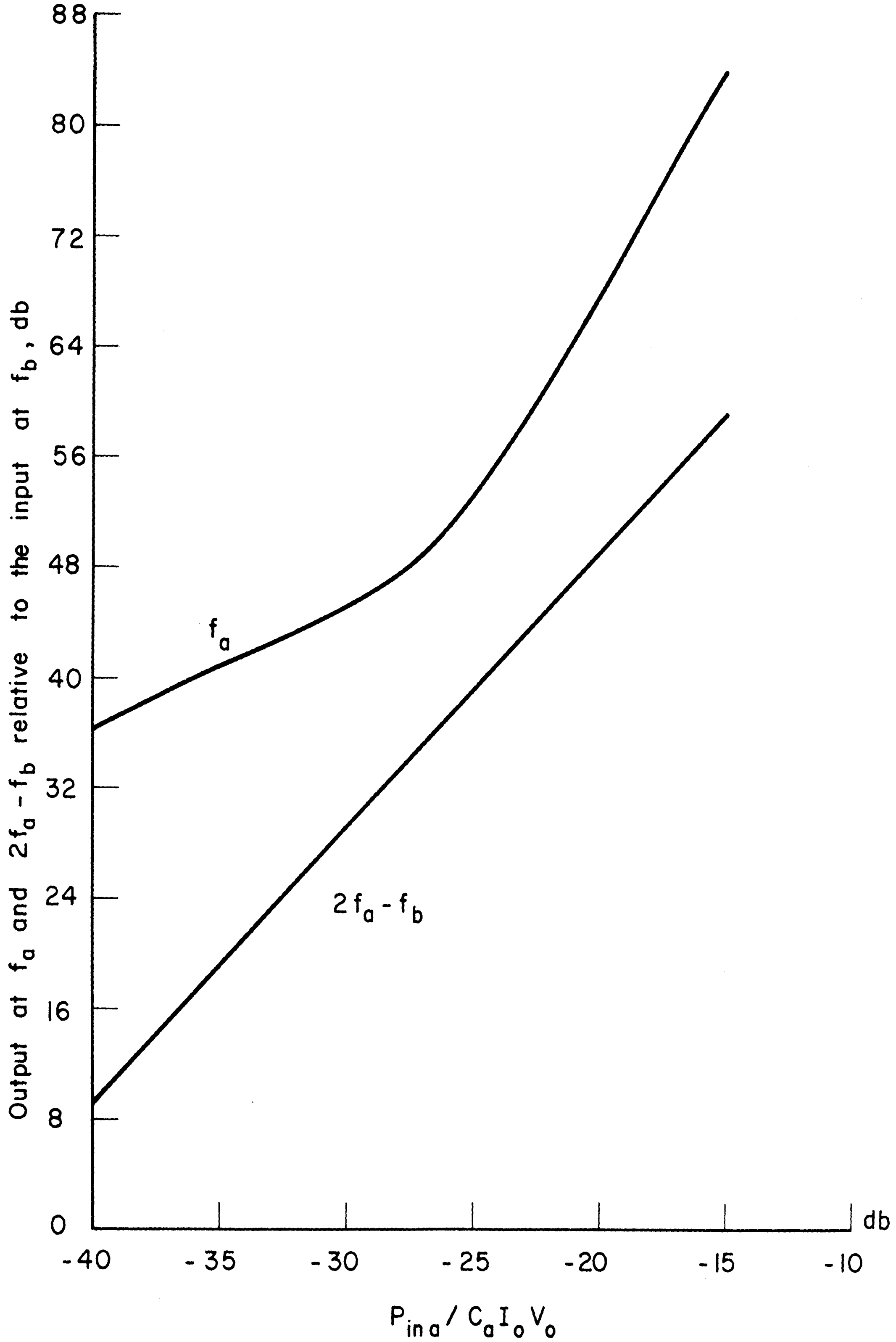

FIG. 3.3 OUTPUT AT f_a AND $2f_a - f_b$ VS. INPUT POWER AT f_a IN NORMALIZED UNITS FOR $f_a/f_b = 1$, $C_a = C_b = 0.05$, $d = b = QC = 0$, $\zeta_a = 6$, $P_{inb}/C_b I_o V_o = -40$ db.

The figures show that for ζ_a ($\equiv \beta_a C_a z$) = 5 and 6, the output at f_a for high input power increases at a higher rate than the usual small-signal increase. In these regions the analysis does not hold. This is because the nonlinear terms are no more negligible. The analysis was based on the assumption that the nonlinear terms are small.

Figures 3.4 and 3.5 show the variation of the cross-modulation factor with the input power at f_a. The cross-modulation factor T' is defined as $1 - |1 - T|$, where T is the complex cross-modulation factor as defined in the first quarterly progress report.

It is seen that the cross-modulation T' changes with the input power at f_a. For $\zeta_a = 3$, it is almost independent of P in a. However, for $\zeta_a = 4, 5, 6$, it decreases with increase of P in a. The rate of decrease depends on the length of the tube and on the input power. For $\zeta_a = 4, 5$ the rate of decrease is very, very small for small input power; but it gets larger for large input power. Again, the calculation of T' for $\zeta_a = 5, \frac{P \text{ in } a}{C_a I_o V_o} > -20$ db and $\zeta_a = 6, \frac{P \text{ in } a}{C_a I_o V_o} > -30$ db are doubtful due to nonlinearity.

<u>3.2</u> <u>Experimental</u> <u>Results</u>. Some results of the measurements made on an X-band, medium power, traveling-wave amplifier with two input signals are shown. Figures 3.6, 3.7, 3.8, 3.9 and 3.10 show the output of the generated components at $2f_a - f_b$ and $2f_b - f_a$ relative to the output at f_a in db vs. the total input power for various values of V_o respectively. The input power at f_a is 10 db higher than the input power at f_b. It is seen that the relative output of the two generated signals at $2f_a - f_b$ and $2f_b - f_a$ varies linearly with the input power.

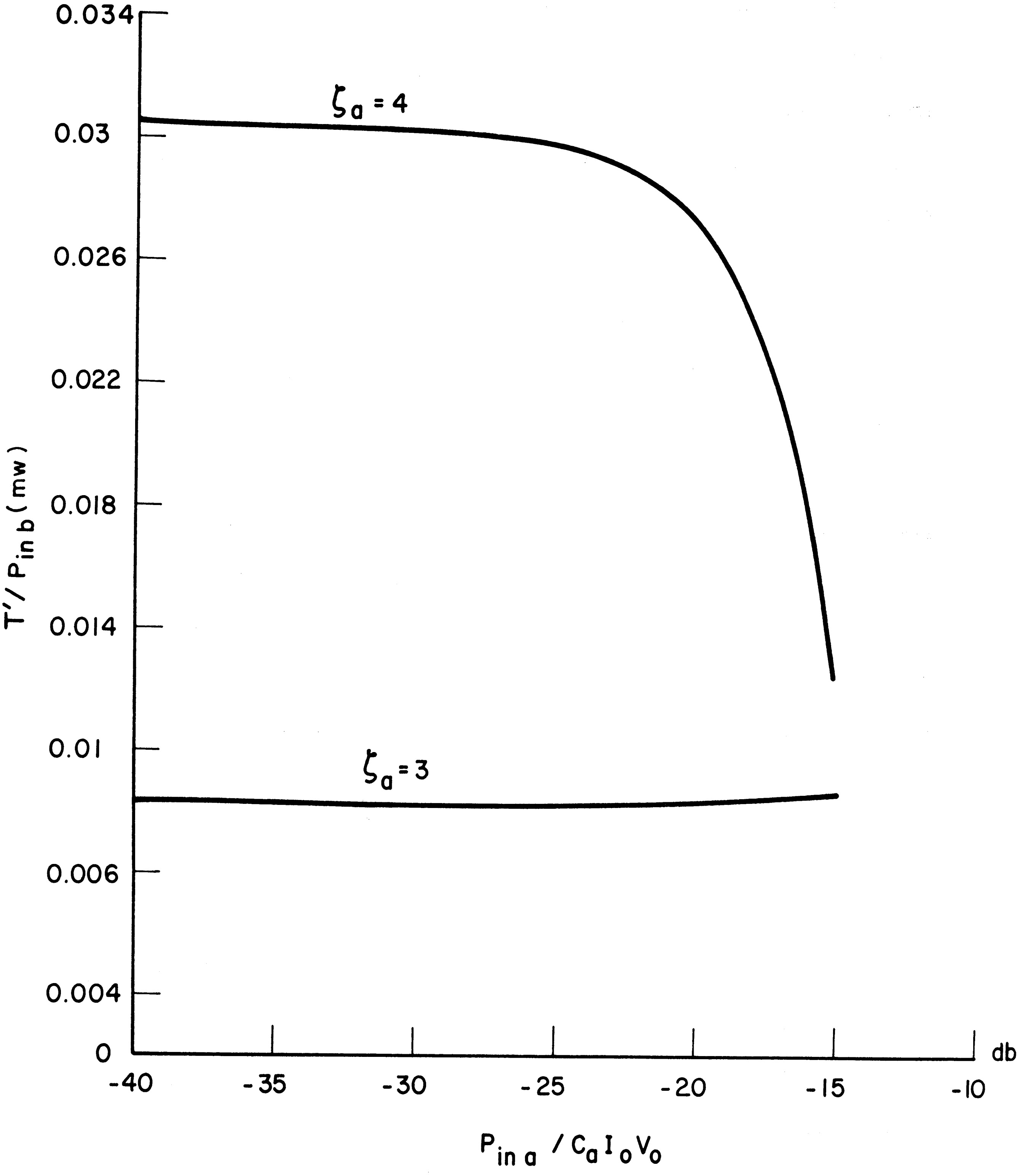

FIG. 3.4 CROSS-MODULATION FACTOR VS. INPUT POWER AT f_a FOR $f_a/f_b = 1$, $C_a = C_b = 0.05$, $d = b = QC = 0$, $P_{inb}/C_bI_oV_o = -40$ db, $\zeta_a = 3.4$.

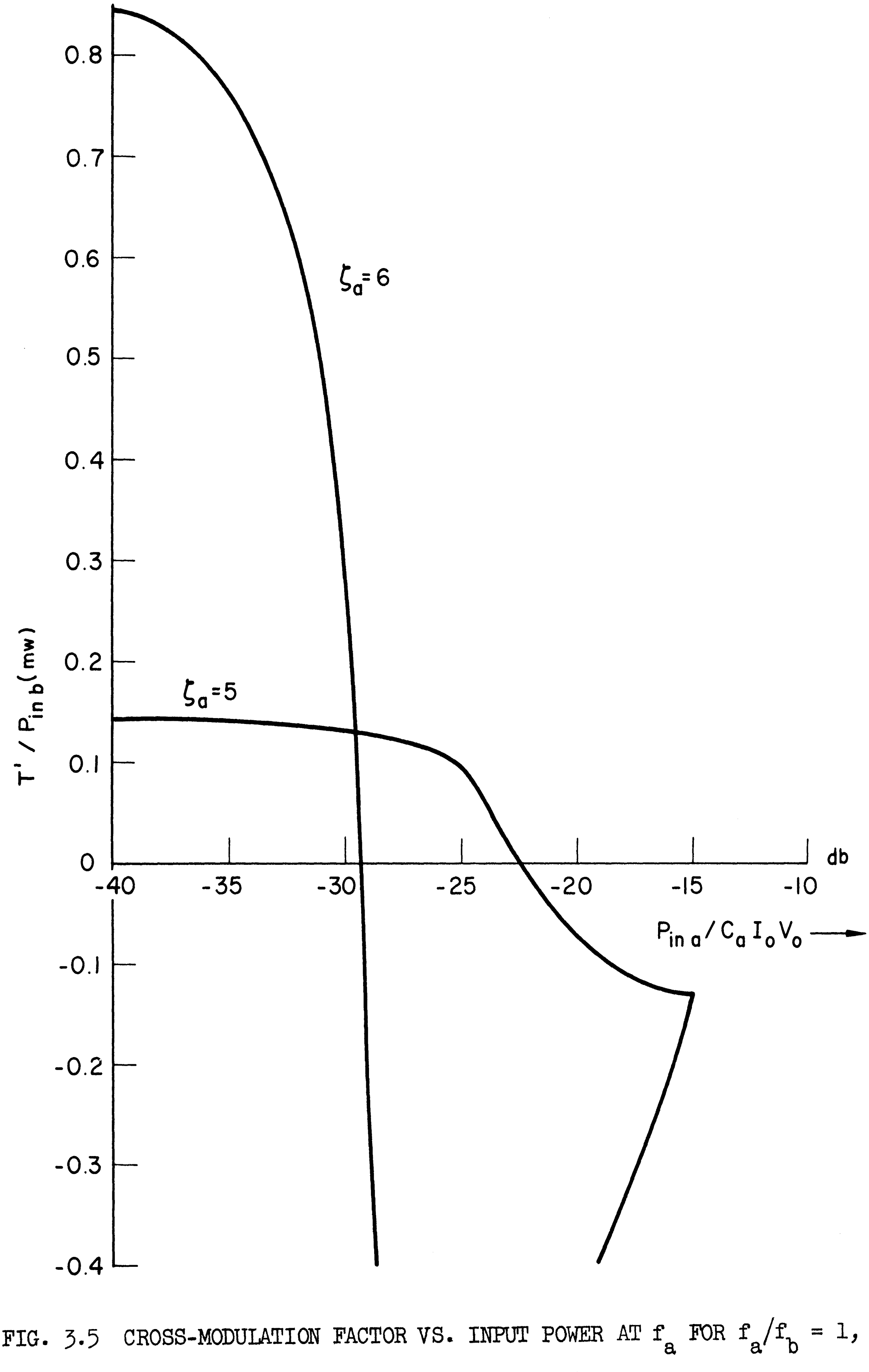

FIG. 3.5 CROSS-MODULATION FACTOR VS. INPUT POWER AT f_a FOR $f_a/f_b = 1$, $C_a = C_b = 0.05$, $d = b = QC = 0$, $P_{inb}/C_b I_o V_o = -40$ db, $\zeta_a = 5.6$.

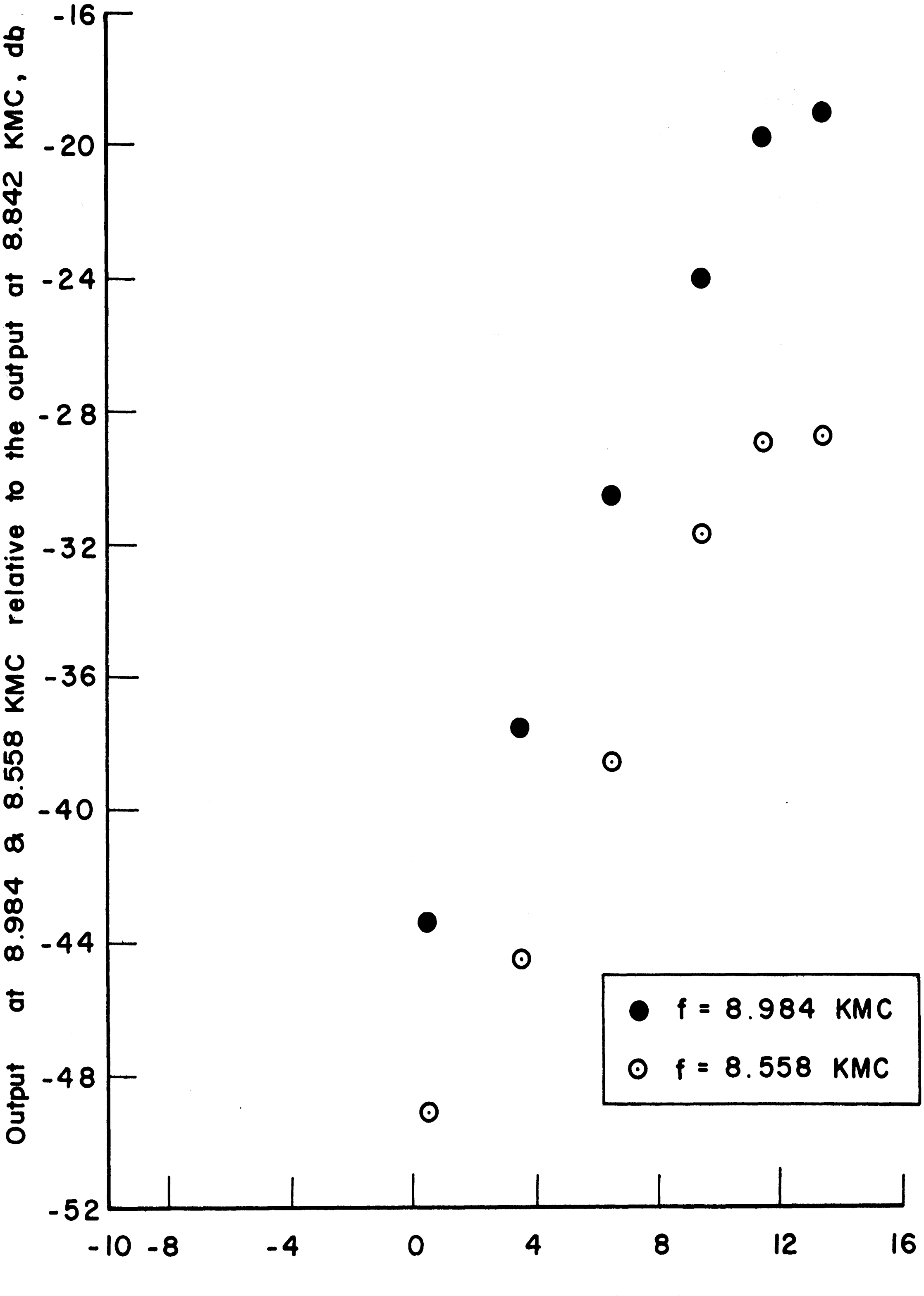

FIG. 3.6 EXPERIMENTAL OUTPUT VS. INPUT POWERS FOR V_0 = 2200 VOLTS, I_0 = 29 ma, f_a = 8.842 kmc, f_b = 8.700 kmc, INPUT POWER AT f_a IS 10 db HIGHER THAN THAT AT f_b.

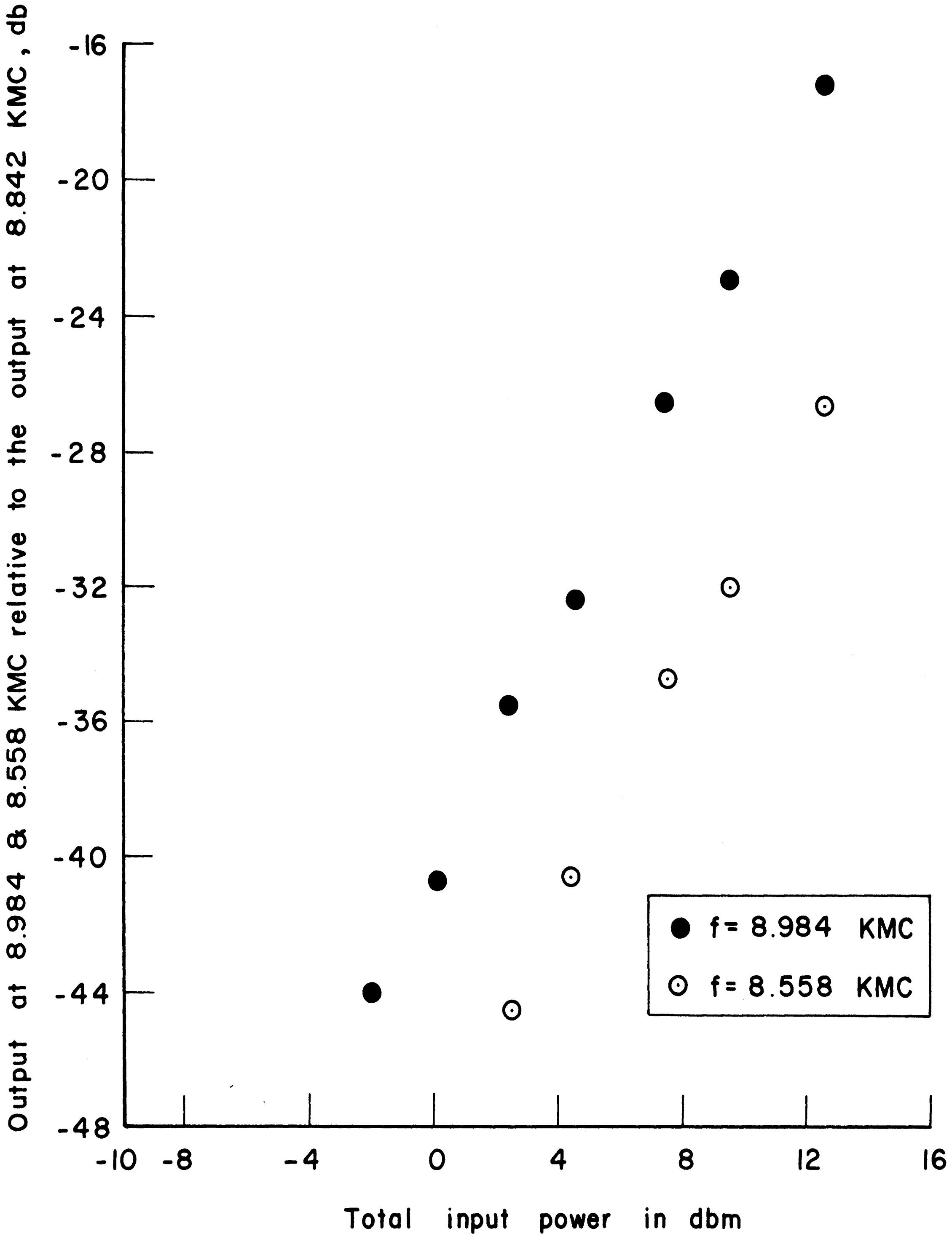

FIG. 3.7 EXPERIMENTAL OUTPUT VS. INPUT POWERS FOR V_o = 2300 VOLTS, I_o = 27 ma, f_a = 8.842 kmc, f_b = 8.700 kmc, INPUT POWER AT f_a IS 10 db HIGHER THAN THAT AT f_b.

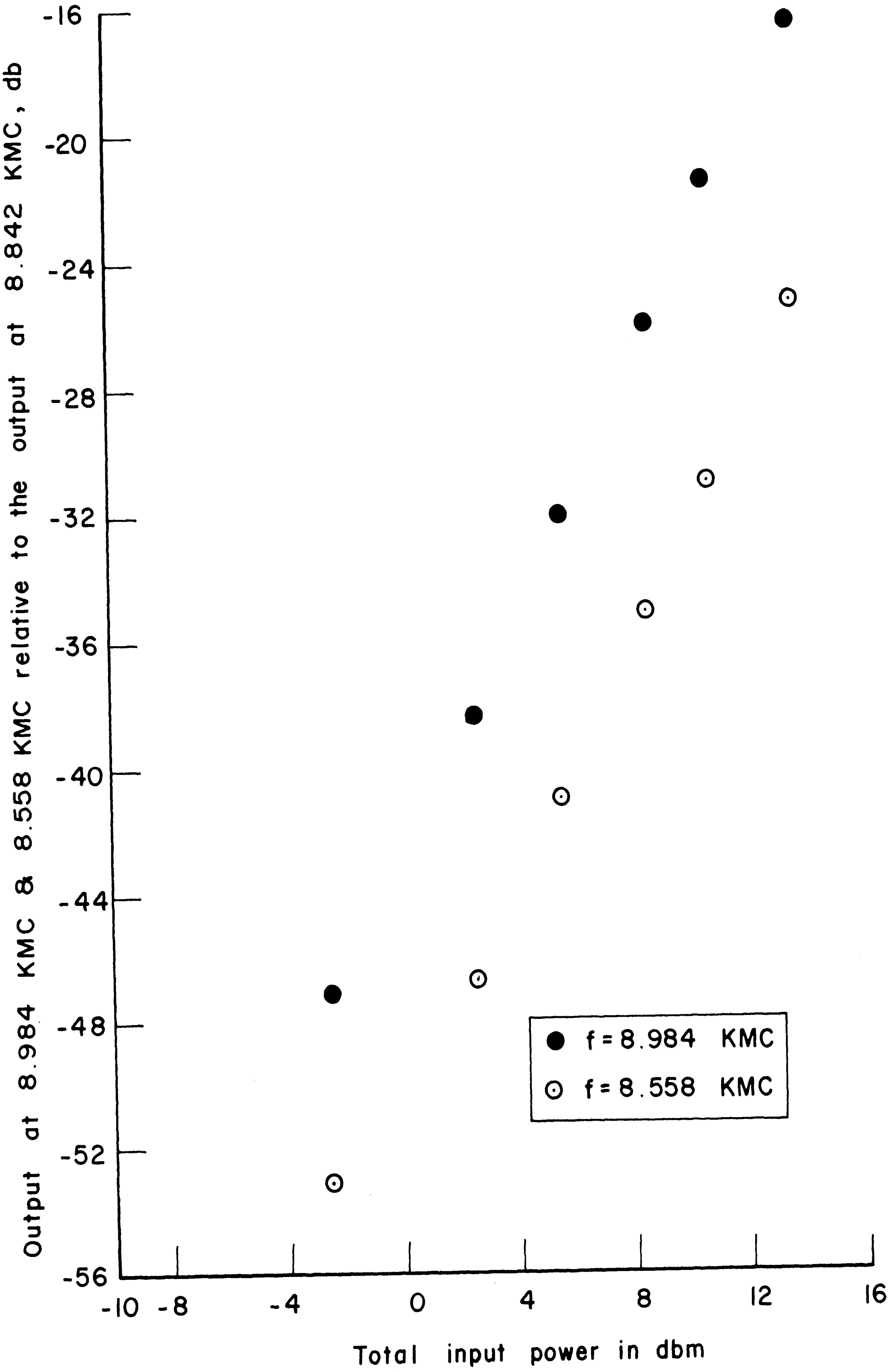

FIG. 3.8 EXPERIMENTAL OUTPUT VS. INPUT POWERS FOR V_o = 2400 VOLTS, I_a = 29 ma, f_a = 8.842 kmc, f_b = 8.700 kmc, INPUT POWER AT f_a IS 10 db HIGHER THAN THAT AT f_b.

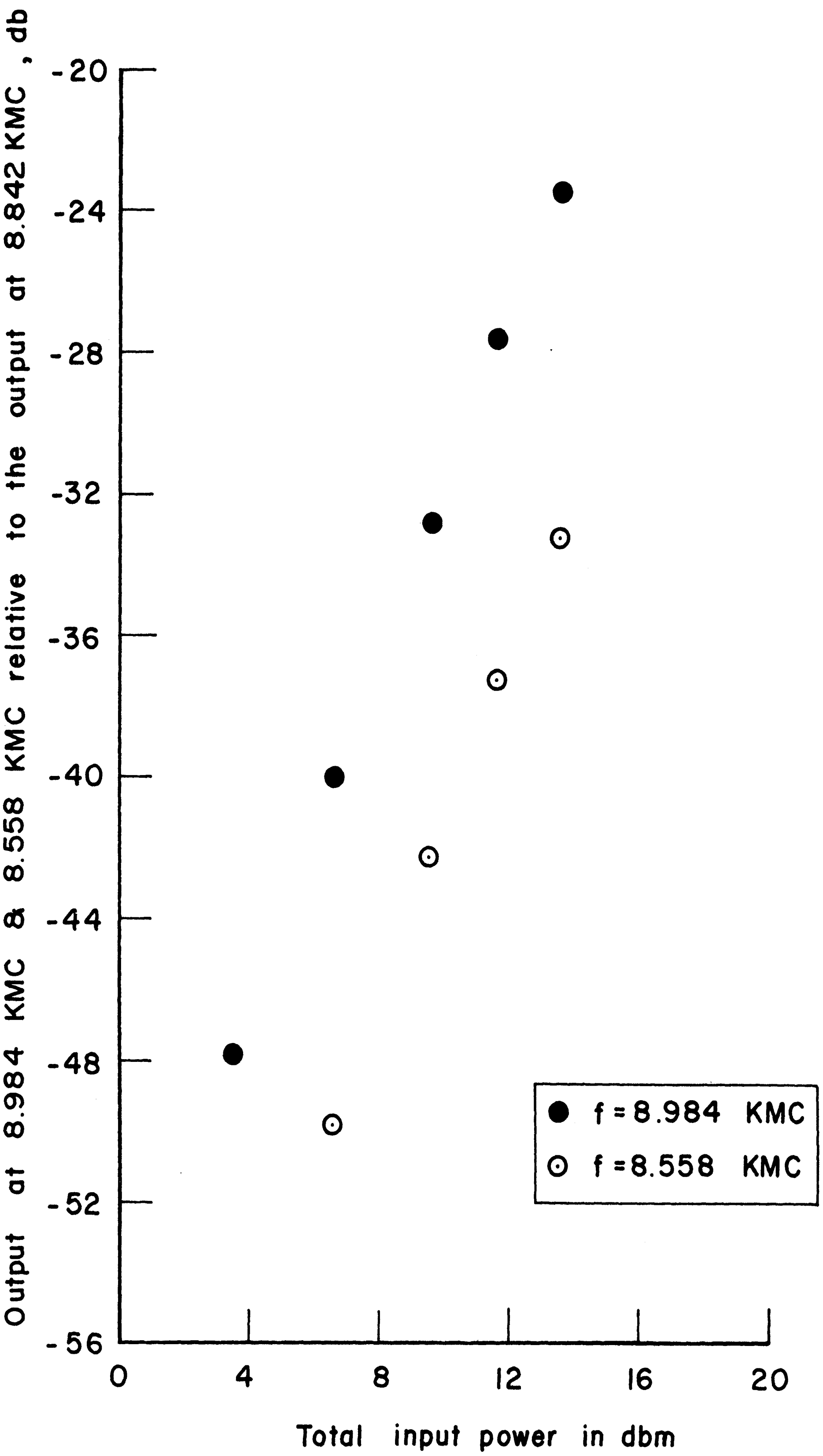

FIG. 3.9 EXPERIMENTAL OUTPUT VS. INPUT POWERS FOR V_o = 2500 VOLTS, I_a = 31 ma, f_a = 8.842 kmc, f_b = 8.700 kmc, INPUT POWER AT f_a IS 10 db HIGHER THAN THAT AT f_b.

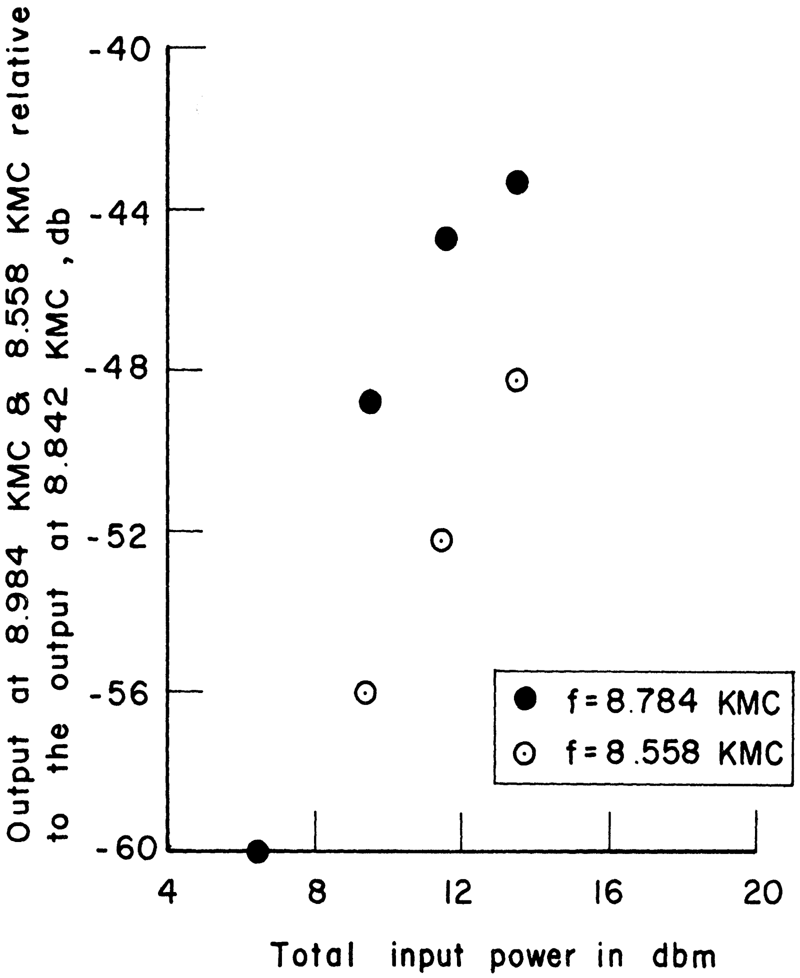

FIG. 3.10 EXPERIMENTAL OUTPUT VS. INPUT POWERS FOR V_o = 2600 VOLTS, I_a = 33 ma, f_a = 8.842 kmc, f_b = 8.700 kmc, INPUT POWER AT f_a IS 10 db HIGHER THAN THAT AT f_b.

The helix voltage for maximum small-signal gain is about 2400 v. Figure 3.11 shows the output at $2f_a - f_b$ and $2f_b - f_a$ relative to the output of f_a vs. the helix voltage (the same as the beam voltage). The input at f_a is 10 db higher than the input at f_b and the total input power is 7.5 dbm. These figures indicate that in order to get low-cross-modulation components the tube should be operated at a d-c voltage lower than the value that gives maximum small-signal gain. Although the output at the input frequencies will be lower, there still is an advantage of getting much lower cross-modulation components.

Figure 3.12 is the same as Fig. 3.11 except the input power at f_a is 20 db higher than the input power at f_b and the total input power is 8 dbm. It shows the same general behavior as Fig. 3.11.

3.3 Future Work.

1. Additional results will be obtained for the equations presented in the first progress report and will be compared with the experimental measurements.

2. It is believed that there is an error in the computer program of the large-signal analysis presented in the fourth progress report. The program is being checked. After the correction is made, the results will be compared with the experimental results.

3. The analysis by the Boltzmann transport equation method will be programmed and the results will be compared with the other two methods.

4. Experimental work will continue to study the behavior of the tube with three or four input signals.

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

4.1 Introduction. In a previous progress report (No. 4), it was mentioned that the unexplained gain observed in the experiments

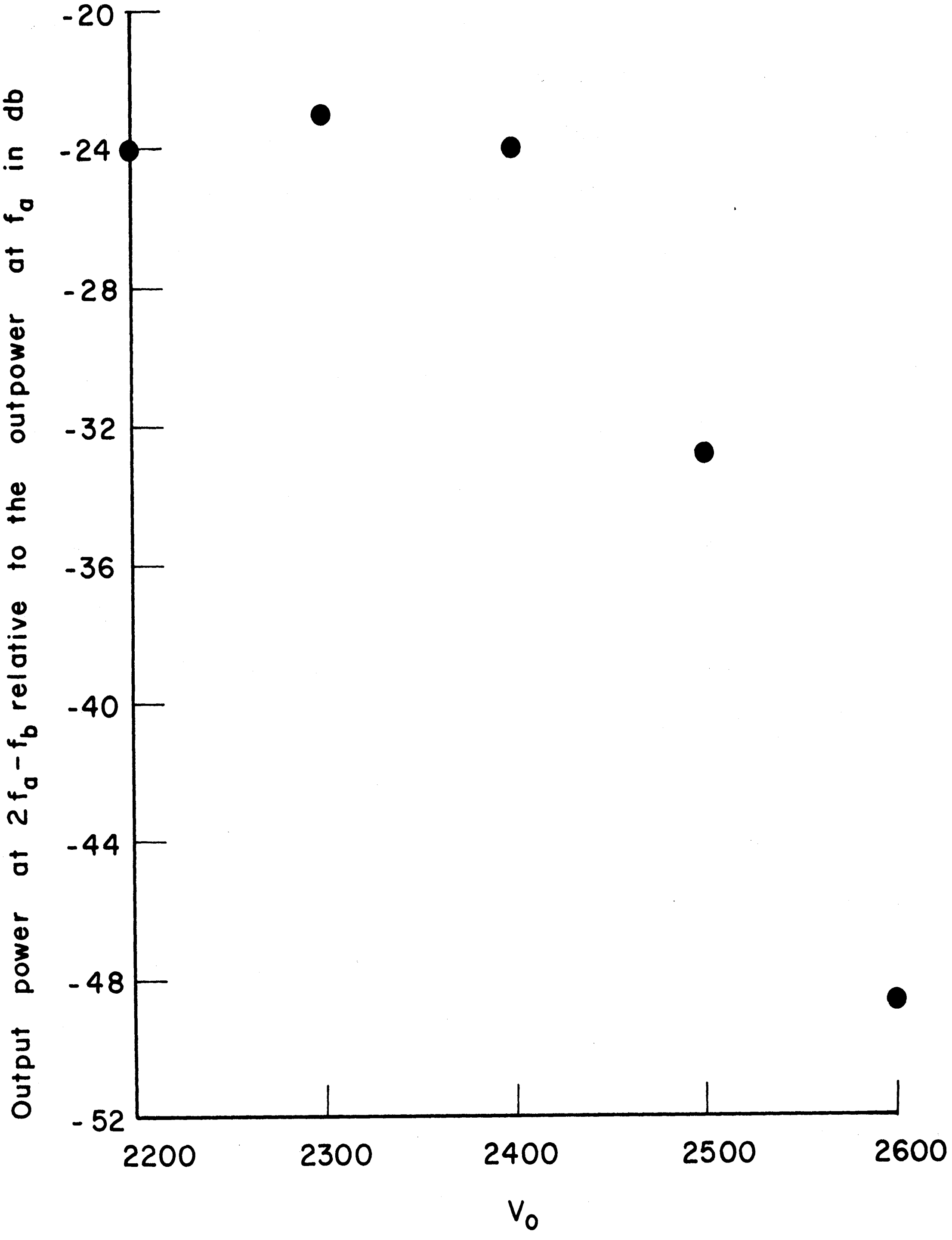

FIG. 3.11 OUTPUT POWER VS. D-C BEAM VOLTAGE FOR TOTAL INPUT POWER OF 9.5 dbm, f_a = 8.842 kmc, f_b = 8.700 kmc, INPUT AT f_a IS 10 db HIGHER THAN THAT AT f_b.

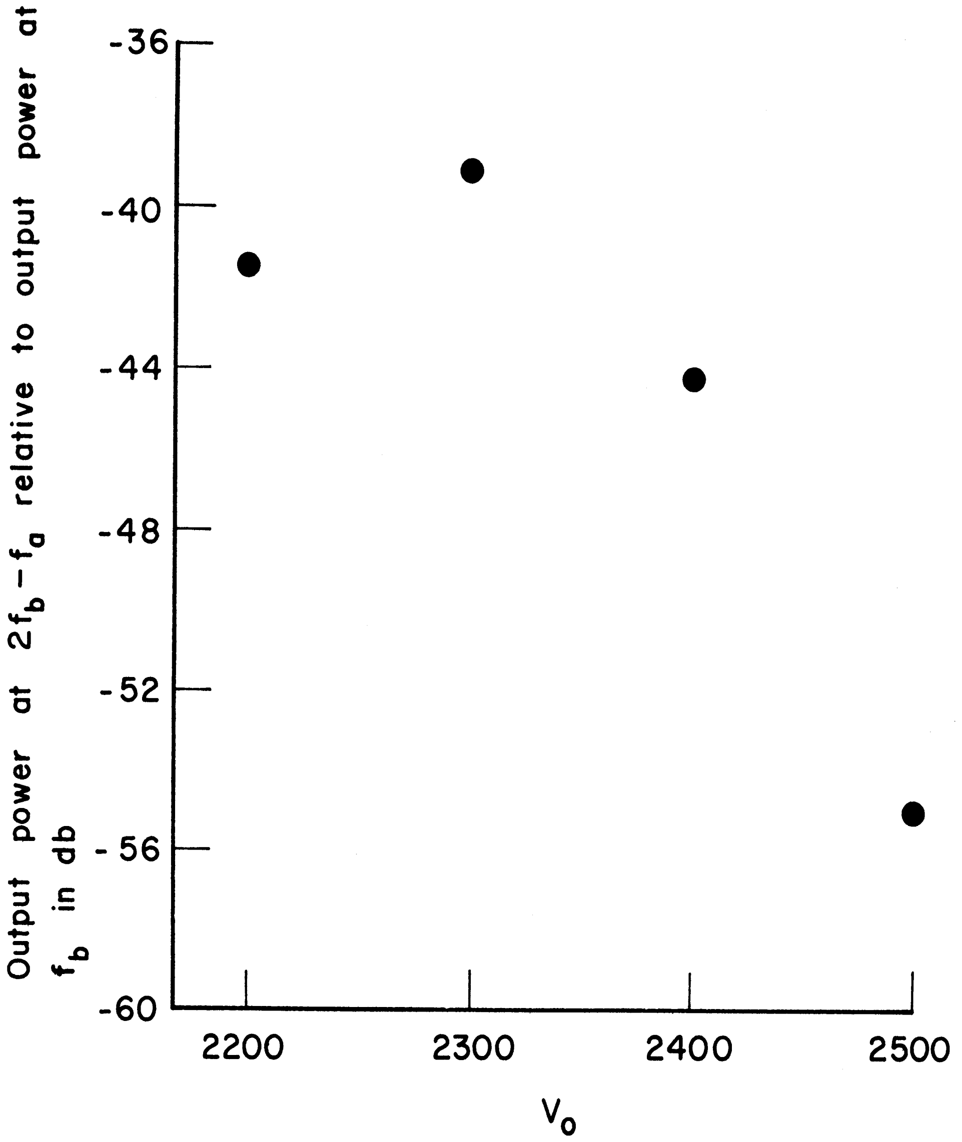

FIG. 3.12 OUTPUT POWER VS. D-C BEAM VOLTAGE FOR TOTAL INPUT POWER OF 8.0 dbm, f_a = 8.850 kmc, f_b = 8.710 kmc, INPUT AT f_b IS 20 db HIGHER THAN THAT AT f_a.

on d-c quadrupole amplifiers by Mao and Siegman[1] and Saito, Kenmoker and Matsuoka[2] suggested the possibility of cyclotron-to-synchronous wave coupling discussed in this report. Careful check on the conditions for this coupling mechanism reveals that one of the conditions, $\beta_q = (1/2)\,\beta_c$, is exactly what is needed for cyclotron-to-synchronous wave coupling. However, the strong pumping criterion, $M \geq V_p \eta\, \beta_c / u_o \omega_c a^2$, does not check out quantitatively. The anomalous gain in their experiments occurred at a much lower pump field than that predicted by this theory. It is postulated that under the strong pumping field condition, nonlinearity may set in to destroy the simple theory based upon linear analysis. In this period, a large-signal theory based upon the particle dynamics will be developed. By computing the trajectory of the individual electrons, it is hoped that a more exact pumping field requirement can be derived.

4.2 Large-Signal Analysis of a D-c Pumped Quadrupole Amplifier.

For a large-signal analysis, the coupled-mode theory discussed in the previous analysis is not adequate; the motion of individual electrons has to be considered. The equations of motion can be written as

$$\ddot{r} - r(\dot{\theta})^2 = -\eta\,[E_{sc-r} - \frac{\partial V}{\partial r} + B_z\, r\,\dot{\theta}] \quad , \qquad (4.1)$$

---

[1] Mao, S. and Siegman, A. E., "Cyclotron Wave Amplification Using Simultaneous R-f Coupling and D-c Pumping", International Congress on Microwave Tubes, pp. 268-276; 1960.

[2] Saito, S., Kenmoker, M. and Matsuoka, T., "D-c Pumped Cyclotron Beam Tubes Using Quadrifilar Helix", International Congress on Microwave Tubes, pp. 244-248; 1962.

$$r\ddot{\theta} + 2\dot{r}\dot{\theta} = -\eta\,[E_{sc-\theta} - \frac{1}{r}\frac{\partial V}{\partial \theta} - B_z\dot{r}] \qquad (4.2)$$

and

$$\ddot{z} = -\eta\,[E_{sc-z} - \frac{\partial V}{\partial z}] \;, \qquad (4.3)$$

where the dot indicates the time derivative. E_{sc-r}, $E_{sc-\theta}$ and E_{sc-z} are the components of space-charge field. V is the pumping field potential and B_z is the axial magnetic field intensity. Assuming a d-c pumped quadrifilar field which can be represented by the following expression,

$$V = A\,J_2(kr)\,\sin\,(2\theta - 2\beta_q z) \;, \qquad (4.4)$$

where A and k are constants, $J_2(kr)$ is the Bessel function of the first kind of the argument kr and order two. β_q is the wave number of the twist of the helical winding. Thus

$$\frac{\partial V}{\partial r} = A\,\frac{\partial}{\partial r}\,J_2(kr)\,\sin\,2(\theta - \beta_q z) \;,$$

$$\frac{1}{r}\frac{\partial V}{\partial \theta} = \frac{2A}{r}\,J_2(kr)\,\cos\,2(\theta - \beta_q z) \;,$$

$$\frac{\partial V}{\partial z} = -2A\,\beta_q\,J_2(kr)\,\cos\,2(\theta - \beta_q z) \;. \qquad (4.5)$$

Insert Eq. 4.5 into Eqs. 4.1, 4.2 and 4.3 which gives, assuming zero space-charge force,

$$\ddot{r} - r\dot{\theta}^2 + \omega_c r\dot{\theta} = \eta\,A\,\frac{\partial}{\partial r}\,J_2(kr)\,\sin\,2(\theta - \beta_q z) \;, \qquad (4.6)$$

$$r\ddot{\theta} + 2\dot{r}\dot{\theta} - \omega_c\dot{r} = 2\eta\,\frac{A}{r}\,J_2(kr)\,\cos\,2(\theta - \beta_q z) \qquad (4.7)$$

and

$$\ddot{z} = -2\eta\, A\, \beta_q\, J_2(kr) \cos 2(\theta - \beta_q z) \quad . \tag{4.8}$$

Transforming these equations into a moving coordinate system (actually in a rotating system), i.e., let $\Phi = \theta - \omega_c t$, then

$$\ddot{r} - r\dot{\Phi}^2 - r\,\omega_c\dot{\Phi} = \eta\, A \frac{\partial}{\partial r} J_2(kr) \sin 2(\Phi + \omega_c t - \beta_q z) \quad , \tag{4.9}$$

$$r\ddot{\Phi} + 2\dot{r}\dot{\Phi} + \dot{r}\omega_c = 2\eta \frac{A}{r} J_2(kr) \cos 2(\Phi + \omega_c t - \beta_q z) \tag{4.10}$$

and

$$\ddot{z} = -2\eta\, A\, \beta_q\, J_2(kr) \cos 2(\Phi + \omega_c t - \beta_q z) \quad . \tag{4.11}$$

Introduce the normalization factors

$$\rho \triangleq r/r_m \quad ,$$

$$\tau \triangleq \omega_c t \quad ,$$

$$\zeta \triangleq z/r_m \quad ,$$

and change the time variable to τ, where $r_m = u_o/\omega_c$ is the largest radius of rotation of the beam within which the conservation of energy holds true. v_o is the axial beam velocity, Eqs. 4.9, 4.10 and 4.11 become respectively,

$$\frac{d^2\rho}{d\tau^2} - \rho\left(\frac{d\Phi}{d\tau}\right)^2 - \frac{d\Phi}{d\tau}\rho = M \frac{d}{d\rho} J_2(ku_o\rho/\omega_c) \sin 2(\Phi + \tau - \zeta) \quad , \tag{4.12}$$

$$\frac{d^2\Phi}{dt^2} + \frac{2}{\rho}\frac{d\rho}{d\tau}\frac{d\Phi}{d\tau} + \frac{1}{\rho}\frac{d\rho}{d\tau} = 2\frac{M}{\rho} J_2(ku_o\rho/\omega_c) \cos 2(\Phi + \tau - \zeta) \tag{4.13}$$

and

$$\frac{d^2\zeta}{d\tau^2} = -2M\, J_2(ku_o\rho/\omega_c)\, \cos 2(\Phi + \tau - \zeta) \quad , \qquad (4.14)$$

where $M = \eta\, A/u_o^2$ is the pump field constant and a simplified condition $\beta_q = \omega_c/u_o$ has been used.

ρ, Φ and ζ define the trajectory of the beam. These quantities will be programmed for digital computation. The results will be used for further discussion.

4.3 Energy Relations. A few words may be said about the energy relations between the electron beam and the d-c field in the quadrifilar helix. Equations 4.12, 4.13 and 4.14 may be used to derive this energy relation. Multiply Eq. 4.12 by $dp/d\tau$, Eq. 4.13 by $\rho^2(1 + d\Phi/d\tau)$ and Eq. 4.14 by $d\zeta/d\tau$ and perform the integration with respect to τ, and add all three equations; the result is

$$\left(\frac{d\zeta}{d\tau}\right)^2 + \left(\frac{d\rho}{d\tau}\right)^2 + \rho^2\left(1 + \frac{d\Phi}{d\tau}\right)^2 = 8M\, J_2(ku_o\rho/\omega_c)\, \sin 2(\Phi + \tau - \zeta) \quad , \qquad (4.15)$$

where the first term on the left-hand side of Eq. 4.15 is related to the axial energy, the two remaining terms on the same side are related to the rotational energy of the beam. The term on the right-hand side of Eq. 4.15 is related to the energy supplied by the d-c pump.

4.4 Future Work. In the next quarter, the beam trajectory and the energy relation will be studied for the purpose of establishing a pump field condition for the anomalous gain.

5. General Conclusions (C. Yeh)

Due to an accident which happened to the tube under test, a new one has to be constructed. However, the testing results from the original tube serve well as a guide to the design and construction of the new version of the frequency multiplier. Several improvements are incorporated in this new design. First, the mechanical design is simplified by mounting all the elements except the gun onto the cavity structure so as to simplify the alignment procedure during enveloping. Second, a section of d-c pumped quadrupole amplifier is added in the feedback loop to enhance the feedback signal before it is combined with the input signal. In this way, the overall efficiency is greatly enhanced. The improved version of this tube is now under construction.

A successful technique for loading a helix into a BeO tube for brazing has finally been developed. The brazed helix-BeO tube structures designed for 30 Gc operation is heat tested. Although a perfect thermal contact between the helix and BeO has not been achieved as is indicated by the testing results, the structure is capable of dissipating about 170 watt/inch at a mean helix temperature of 500°C.

The nonlinear analysis of the amplitude and phase-modulated traveling-wave amplifier with two input frequencies presented in Quarterly Progress Report No. 1 has been programmed and the results of computation are presented in the form of graphs in Figs. 3.1 through 3.5. Experimental results made on an X-band medium power traveling-wave amplifier with two input signals are presented in Figs. 3.6 through 3.10. Direct comparison between the theoretical and experimental results can be made from these curves. The comments and discussion will await other theoretical computations now in progress.

The strong pumping criterion predicted by the simple linear theory for the anomalous gain in a d-c pumped quadrupole amplifier stimulate the necessity to go into a large-signal analysis of the trajectory of the beam in the quadrupole section of the tube. The equations of motion have been derived in terms of a moving coordinate system and an energy relation is also given. These equations are to be programmed for digital computation and the results will enable one to find a more exact criterion for strong pumping.

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The University of Michigan, Electron Physics Laboratory, Ann Arbor, Michigan. BASIC RESEARCH IN MICROWAVE DEVICES AND QUANTUM ELECTRONICS, by H. K. Detweiler, et al. August, 1964, 37 pp. incl. illus. (Project Serial No. SR0080301, Task 9391, Contract No. NObsr-89274)

A new frequency multiplier tube that will have a better overall conversion efficiency has been designed. The enhancement in efficiency is derived from the fact that a section of d-c pumped quadrupole amplifier is added to boost the feedback signal to a workable level before introducing in onto the input coupler. Theoretical calculation indicates that enhancement in efficiency up to 100 percent can be realized.

The technique for loading a helix into a BeO tube is being developed and the best test has proven it to be moderately successful.

Equations for the modulation products of two-signal analysis of the amplitude- and phase-modulated traveling-wave amplifier have been programmed and computed. Experimental results on the measurement of an X-band traveling-wave amplifier with two inputs are presented. Final discussion and conclusions await further theoretical computations.

A large-signal analysis of the d-c pumped quadrupole amplifier has been initiated. Equations of motion and the energy relations are derived assuming a specific pump field and neglecting the space-charge forces. From the trajectory of the beam and the energy relation between the beam and the quadrupole, a more exact criterion for the existence of the anomalous gain discussed in previous reports can be established.

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1. General Introduction
2. Generation and Amplification of Coherent Electromagnetic Energy in the Millimeter and Submillimeter Wavelength Region
3. Analysis of Amplitude and Phase-Modulated Traveling-Wave Amplifiers
4. Study of a D-c Pump Quadrupole Amplifier
5. General Conclusions

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