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FOR

BASIC RESEARCH IN MICROWAVE DEVICES AND QUANTUM ELECTRONICS

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ABSTRACT

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

The construction of the experimental low-frequency model of the frequency multiplier with feedback scheme to enhance the transfer efficiency has been completed. D-c beam testing shows that the tube is aligned satisfactorily. The tube is now awaiting final r-f testing.

Difficulties of brazing a 30 Gc helix into a BeO tube have not been resolved. Techniques involving the use of Fansteel 60 metal are being developed.

Analysis of Amplitude and Phase-Modulated Traveling-Wave Amplifiers

A nonlinear theory of the amplitude and phase-modulated traveling-wave amplifier with a multiple frequency input is developed. Computer results for some typical cases are presented and interpreted.

Study of a D-c Pumped Quadrupole Amplifier

The mechanism of an anomalous gain predicated for the cyclotron-to-synchronous wave interaction is explained in terms of kinetic power relations. Experimental results from other sources give support to this theory.

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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 circuit. A tube based upon the design described in Quarterly Progress Report No. 3 will be constructed. Extreme care will be required in the final assembly of the tube particularly with regard to the alignment of its different parts. D-c beam testing will be conducted prior to the final r-f testing.

B. Investigation of high-thermal-conductivity materials for microwave devices above X-band. Work will be continued to develop a helix loading technique. Other suitable helix materials, e.g., Fansteel wire which has a higher resiliency than tungsten, will be investigated.

C. Analysis of amplitude and phase-modulated traveling-wave amplifiers. The equations presented in the previous progress reports, Nos. 1, 2 and 3, are being programmed for digital computation. Results will be presented in the forms of curves followed by discussions.

D. Study of a d-c pumped quadrupole amplifier. An anomalous gain mechanism for the coupling between a fast cyclotron and a synchronous wave was discussed in a previous report (No. 3). Attempts will be made to explain this type of coupling mechanism by means of the kinetic power theorem. Experimental evidence for this type of operation will be sought.

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 Circuit (C. Yeh, B. Ho)

2.1.1 Assembly of the Experimental Tube. The assembly of the experimental tube has required more time than anticipated due to several modifications incorporated in the multipole magnetron cavity. First, the pole pieces were removed and replaced by coupling flanges onto which straight glass tubes were attached. Then the r-f coupling loop is rearranged so that the cavity can be fitted into a focusing solenoid. The final assembly was quite complicated due to the need for extremely accurate alignment.

One addition to the original design is an ion pump attached to one end of the tube. This addition is necessary in order to maintain as high a vacuum as possible during the life of the tube.

2.1.2 D-c Beam Characteristics. One of the first things to check out before initiating r-f testing is to measure the d-c beam characteristic along the tube. The tube assembly is carefully centered in a solenoid which is capable of delivering up to 1000 gauss of magnetic field. With the input coupler, multipole cavity, feedback coupler and the collector all connected to a common low-voltage power supply, but metered individually, the gun voltages are adjusted for a predetermined magnetic field strength determined by the required cyclotron frequency, until all the electrode currents are zero except that in the collector circuit. A collector current in excess of 200 μa can be obtained. It is then certain that the alignment of the tube is satisfactory and the beam interception is negligible.

The d-c operating conditions are

D-c magnetic field (30 volts, 1 ampere)	250 gauss
First grid voltage	4 volts
First grid current	600 μa
Anode voltage	25 volts
Anode current	50 μa
Input coupler voltage	25 volts
Input coupler current	0
Multipole cavity voltage	25 volts
Multipole cavity current	0
Feedback coupler voltage	25 volts
Feedback coupler current	0
Collector voltage	25 volts
Collector current	150 μa

2.1.3 Future Work. An r-f signal source capable of delivering up to 10 watts at the signal frequency of 680 mc is being constructed. It is expected that r-f testing can be conducted during the next period.

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

2.2.1 Introduction. Efforts during this period have centered on finding a way of overcoming the difficulty encountered in loading a helix into a smooth-bore BeO tube for brazing. Several means are presently being investigated. A detailed description is given below.

2.2.2 Experimental Effort. At the end of the last period the point had been reached where it no longer seemed likely that a heat-treat cycle would be found that would give the tungsten helices the necessary amount of resiliency without excessively embrittling them. An inquiry has been made into the availability of BeO tubing possessing greater dimensional uniformity so that less clearance between the helix and tube is required for loading. Unfortunately, more time than is desirable is required to obtain tubing with the necessary tolerances. Consequently, this will be pursued further only in the event the other alternatives fail.

An investigation was made into the possibility of finding a suitable helix material having a higher resiliency than tungsten which could be used with the BeO tubing presently on hand. A high-temperature spring material, Fansteel 60 Metal*, appears to possess the desired properties. This material is an alloy of 90 percent tantalum and 10 percent tungsten prepared by electron-beam melting techniques. Since some of this wire was immediately available in a diameter of 10 mils, initial tests were performed on this size. A suitable helix was scaled for this wire from the 30 Gc size. The dimensions of this helix are

Mean helix diameter = 0.065 inch,

d_w = 0.010 inch, and

TPI = 32.

A cycle for heat treating this helix was developed which resulted in it being possible to wind the helix on a 0.050 inch mandrel (5 mils undersize) and have it return to its original size (0.075 inch O.D.)

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* Fansteel Metallurgical Corp.

when released. The heat-treat cycle is to fire the helix in air for 15 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. After testing of the spring properties of this wire, tests were run to determine if it was possible to plate it in the manner required for brazing. The outcome of these tests was positive. After conclusion of these tests it was determined that, if the smaller diameter wire behaved in a similar manner, it would possess sufficient resiliency for the loading process.

Attempts were made to obtain the above material in the required 5 mil diameter. However, none was available. Consequently, some 5 mil diameter Fansteel 61 Metal was obtained for testing. This wire consists of 92-1/2 percent tantalum and 7-1/2 percent tungsten prepared by the sintered-metal process. Unfortunately, its behavior after heat treating was similar to that encountered with tungsten, i.e., it is either too brittle to wind down without breaking, or it is too soft to spring back a sufficient amount. The 60 Metal wire is presently on order and will be tested upon its receipt.

Because of the difficulties encountered in this method of preparing this structure, a somewhat different approach is also being investigated. This consists of brazing three BeO helix support rods to the helix and then pressure loading them into a smooth-bore copper tube. The loading technique is presently being developed; the BeO rods are on hand and the copper tubing is slated for delivery in the near future. It is anticipated that a heat-test model of this type will be prepared and tested during the next quarter.

Some work recently completed comparing by means of r-f cold tests the electrical properties of helices brazed into BeO cylinders to those of pressure loaded helices has shown that the performance of the helix is not appreciably degraded by brazing[1]. Consequently, assuming the same thing to be true for the 30 Gc structure, only the heat transfer properties of this geometry will be investigated.

2.2.3 Future Work. Work will be continued on the technique of loading the helix into a BeO cylinder when the Fansteel 60 Metal wire is received. The BeO rod-copper tube structure will be assembled upon receipt of the tubing. Both structures will be heat tested pending their successful fabrication.

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

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

3.1 Introduction. In this report a general analysis is given to describe the nonlinear operation of the traveling-wave amplifier with multifrequency input. The final equations are solved on a digital computer and some of the results are given.

3.2 Derivation of the Equations. The equations that describe the interaction between the circuit and the beam are as follows. The circuit equation is

$$\frac{\partial^2 V}{\partial z^2} - \frac{1}{v_o^2}\frac{\partial^2 V}{\partial t^2} - \frac{2\omega C_o d}{v_o^2}\frac{\partial V}{\partial t} = -\frac{Z_o}{v_o}\left[\frac{\partial^2 \rho}{\partial t^2} + 2\omega C_o d\,\frac{\partial \rho}{\partial t}\right] . \qquad (3.1)$$

The force equation is

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[1] Detweiler, H. K., "Applied Research in Microwave and Quantum Electronics", Final Report, Section II, Electron Physics Laboratory, The University of Michigan; March, 1964.

$$\frac{d^2z}{dt^2} = |\eta| \left(\frac{\partial V}{\partial z} + \frac{\partial V_{sc}}{\partial z} \right) . \qquad (3.2)$$

The conservation of charge is written using a Lagrangian formulation to account for the crossing of electrons, i.e., the beam is assumed to consist of finite particles and the conservation of charge is obtained by stating that the charge contained in a bunch at one position z_o and at time t_o must be conserved at some other position z and a later time t. Hence

$$\rho(z_o, t_o)\, dz_o = \rho(z, t)\, dz . \qquad (3.3)$$

Due to the inherent nonlinearity of the system, it is expected to find components of the circuit voltage, charge density, and current at the harmonic frequencies and cross-modulation frequencies of the input signals together with those having the fundamental frequencies.

In view of the above the expression for the circuit voltage will be written as

$$V(z, t) = \frac{1}{2} \sum_{n=-\infty}^{\infty} \frac{|I_o|\, Z_n}{C_n} A_n(y_1)\, e^{-j\Phi_n(y_1, \Phi_{o1})} , \qquad (3.4)$$

where $y_1 = C_1 z \omega_1 / u_o$,

ω_1 is the frequency of one of the input signals.

Before carrying out the substitution of Eq. 3.4 into the interaction equations, one must find a relation between Φ_n, ω_n and z. This relation is as follows:

$$\frac{\omega_n y_1}{\omega_1 C_1} - \theta_n(y_1) = \omega_n t + \Phi_n(y_1, \Phi_{01}) \quad . \qquad (3.5)$$

Using the definition of y_1 and Eq. 3.4, the left-hand side of the circuit equation becomes

$$\Bigg(\frac{1}{2}|I_o| \left(\frac{C_1\omega_1}{u_o}\right)^2 \sum_n \frac{Z_n}{C_n} \left[\frac{d^2A_n}{dy_1^2} - 2j\frac{dA_n}{dy_1}\left(\frac{\omega_n}{C_1\omega_1} - \frac{d\theta_n}{dy_1}\right)\right.$$

$$\left. + A_n\left\{j\frac{d^2\theta_n}{dy_1^2} - \left(\frac{\omega_n}{C_1\omega_1} - \frac{d\theta_n}{dy_1}\right)^2\right\}\right] + \frac{1}{2}|I_o| \sum_n \frac{\omega_n^2 Z_n}{C_n v_n^2} A_n$$

$$- \frac{|I_o|}{2} j \sum_n \frac{2\omega_n C_n d_n}{v_n^2} \frac{\omega_n Z_n}{C_n} A_n \Bigg) e^{-j\varphi_n} \quad . \qquad (3.6)$$

Since the r-f charge density in the beam is expected to contain components at all possible combination of frequencies the charge density will be written as

$$\rho = \frac{1}{2} \sum_n \rho_n(y_1)\, e^{-j\Phi_n} \quad . \qquad (3.7)$$

It should be noted that the above expression for ρ is <u>not</u> a Fourier series, since in general the Φ_n's are not harmonically related. It is simply a convenient mathematical expression for the charge density. The right-hand side of the circuit equation becomes

$$\frac{1}{2} \sum \frac{Z_n}{v_n} \omega_n^2 \rho_n e^{-j\Phi_n} - \frac{j}{2} \sum 2\omega_n^2 C_n d_n \frac{Z_n}{v_n} \rho_n e^{-j\Phi_n} \quad . \qquad (3.8)$$

Equating 3.6 and 3.8, one obtains

$$\sum_n \left(\frac{Z_n}{C_n} \left\{ \frac{d^2A_n}{dy_1^2} - 2j \frac{dA_n}{dy_1} \left(\frac{\omega_n}{C_1\omega_1} - \frac{d\theta_n}{dy_1} \right) + A_n \left[j \frac{d^2\theta_n}{dy_1^2} - \left(\frac{\omega_n}{C_1\omega_1} - \frac{d\theta_n}{dy_1} \right)^2 \right] \right\} \right.$$

$$\left. + \left(\frac{u_o}{C_1\omega_1} \right)^2 \left[\frac{\omega_n^2 Z_n}{C_n v_n^2} - j \frac{2\omega_n^2 d_n Z_n}{v_n^2} \right] A_n \right) e^{-j\Phi_n}$$

$$= \frac{u_o^2}{|I_o| \, (C_1\omega_1)^2} \sum_n \left(\frac{Z_n}{v_n} \omega_n^2 - j \, 2\omega_n^2 C_n \frac{d_n Z_n}{v_n} \right) \rho_n e^{-j\Phi_n} \quad . \qquad (3.9)$$

The above equation can be separated into n equations by equating terms of like phase on each side of the equation. This can be justified mathematically as follows: If the time average of Eq. 3.9 over a certain period of time is taken (after multiplying both sides by $e^{j\Phi_n}$), and taking the limit as $T \rightarrow \infty$, then both sides go to zero except when n = m.

From the above, it is seen that Eq. 3.9 is valid for each term in the summation.

$\rho_n(y_1)$ is the complex amplitude of the component of charge density at frequency ω_n, and can be written as

$$\rho_n = \rho_{nr} + j\rho_{ni} \quad .$$

Equating the real parts on both sides of Eq. 3.9 (after dropping the summation) and letting $B_n = \omega_n/C_1\omega_1$ gives

$$\frac{d^2A_n(y_1)}{dy_1^2} - A_n(y_1)\left[\left(B_n - \frac{d\theta_n(y_1)}{dy_1}\right)^2 - \left(\frac{u_o}{v_n}\right)^2 B_n^2\right]$$

$$= C_n B_n^2 \frac{u_o}{v_n} \frac{u_o}{|Z_o|} \rho_{nr} + B_n^2 \cdot \frac{u_o}{v_n} \frac{u_o}{|I_o|} 2C_n \cdot C_n d_n \rho_{ni} \quad . \qquad (3.10)$$

Equating the imaginary parts on both sides gives

$$A_n(y_1)\left[\frac{d^2\theta_n}{dy_1^2} - 2C_n d_n B_n^2 \left(\frac{u_o}{v_n}\right)^2\right] - 2\frac{d\,A_n(y_1)}{dy_1}\left(B_n - \frac{d\theta_n}{dy_1}\right)$$

$$= C_n B_n^2 \frac{u_o}{v_n} \frac{u_o}{|I_o|} \rho_{ni} - B_n^2 \frac{u_o}{v_n} \frac{u_o}{|I_o|} - 2C_n d_n \cdot C_n \rho_{nr} \quad . \qquad (3.11)$$

Equations 3.10 and 3.11 give 2n circuit equations.

To find the amplitude of the charge density ρ_n, multiply Eq. 3.7 by $e^{j\Phi_n}$ on both sides and take the time average over a certain period T,

$$\frac{1}{T}\int_0^T \rho\, e^{j\Phi_m}\, dt = \frac{1}{2T}\int_0^T \sum_n \rho_n(y_1)\, e^{-j\Phi_n}\, e^{j\Phi_m}\, dt \quad .$$

Using Eq. 3.7 to express Φ_n and Φ_m in terms of $\omega_n t$, $\omega_m t$ and in the limit as $T \to \infty$, the right-hand side goes to zero unless $n = m$. This is

$$\frac{\rho_m}{2} = \lim_{T \to \infty} \frac{1}{T}\int_0^T \rho\, e^{j\Phi_m}\, dt \quad .$$

The integration can be transformed to integration over phase so that

$$\frac{\rho_m}{2} = \lim_{T\to\infty} \frac{1}{T\omega_m} \int_{\Phi_m(t=0)}^{\Phi_m(t=T)} \rho\, e^{j\Phi_m}\, d\Phi_m \ , \tag{3.12}$$

$$\rho_{mi} = \lim_{T\to\infty} \frac{1}{T\omega_m} \int_{\Phi_m(t=0)}^{\Phi_m(t=T)} \rho \sin\Phi_m\, d\Phi_m \ , \tag{3.13}$$

$$\rho_{mr} = \lim_{T\to\infty} \frac{1}{T\omega_m} \int_{\Phi_m(t=0)}^{\Phi_m(t=T)} \rho \cos\Phi_m\, d\Phi_m \ . \tag{3.14}$$

The relation between variables are found from Eq. 3.5

$$\Phi_n + \theta_n(y_1) = B_n y_1 - \omega_n t \ .$$

Differentiating with respect to t gives

$$\left(\frac{\partial\Phi_n}{dy_1} + \frac{\partial\theta_n}{dy_1}\right)\frac{dy_1}{dt} = B_n \frac{dy_1}{dt} - \omega_n \ .$$

The velocity is defined as $dz/dt = u_t \equiv u_o(1 + 2C_1 u)$, so that

$$\frac{dy_1}{dt} = C_1\omega_1 (1 + 2C_1 u) \ ,$$

$$\left(\frac{\partial\Phi_n}{\partial y_1} + \frac{\partial\theta_n}{\partial y_1}\right) = B_n \frac{(C_1 + 2C_1 u - 1)}{(1 + 2C_1 u)} = \frac{\omega_n}{\omega_1} \frac{2u}{1 + 2C_1 u} \ . \tag{3.15}$$

Now, it is required to express the charge density ρ in a convenient form. This is accomplished by using the continuity equation and the relation between the variables, Eq. 3.15. From Eq. 3.3

$$\rho(z,t) = \rho_o(z_o, t_o) \left| \frac{dz_o}{dz} \right|_t$$

and assuming the beam enters the interaction space unmodulated

$$\rho(z,t) = - \frac{|I_o|}{u_o} \left| \frac{\partial z_o}{\partial z} \right|_t .$$

Define a distance in terms of the time of entrance of a certain electron $z_{oj} = u_o t_{oj}$, also define $\Phi_{o1j} = \omega_1 t_{oj}$, where Φ_{o1j} is the phase of the wave propagating at frequency ω_1 when the jth electron arrives at the interaction space. Thus

$$z_{oj} = \frac{u_o}{\omega_1} \Phi_{o1j}$$

and

$$\left| \frac{\partial z_o}{\partial z} \right|_t = \frac{u_o}{\omega_1} \left| \frac{\partial \Phi_{o1}}{\partial z} \right|_t = C_1 \left| \frac{\partial \Phi_{o1}}{\partial y_1} \right|_t .$$

Since Φ_n is a function of the normalized distance y_1 and the initial phase of the electron, then the total differential of Φ_n can be written as

$$d\Phi_n(y_1, \Phi_{o1}) = \left(\frac{\partial \Phi_n}{\partial y_1} \right)_{\Phi_{o1}} dy_1 + \left(\frac{\partial \Phi_n}{\partial \Phi_{o1}} \right)_{y_1} d\Phi_{o1} ,$$

but from Eq. 3.5

$$d\Phi_n(y_1, \Phi_{01}) = B_n\, dy_1 - \omega_n dt - d\theta_n(y_1) \quad ,$$

and therefore

$$\left(\frac{\partial\Phi_n}{dy_1}\right)_{\Phi_{01}} + \left(\frac{\partial\Phi_n}{d\Phi_{01}}\right)_{y_1} \left(\frac{\partial\Phi_{01}}{\partial y_1}\right)_t = B_n - \frac{d\theta_n}{dy_1} \quad ,$$

$$\left|\frac{\partial\Phi_{01}}{\partial y_1}\right|_t = B_n \frac{1}{1 + 2C_1 u(y_1)} \frac{1}{\left|\frac{\partial\Phi_n}{\partial\Phi_{01}}\right|_{y_1}} \quad ,$$

and the charge density takes the following form:

$$\rho(z, t) = \rho(y_1, \Phi_{01}) = - \frac{|I_0|}{u_0(1 + 2C_1 u)} \frac{\omega_n}{\omega_1} \frac{1}{\left|\frac{\partial\Phi_n}{\partial\Phi_{01}}\right|_{y_1}} \quad . \qquad (3.16)$$

The 2n circuit equations now take the following form:

$$\frac{d^2A_n(y_1)}{dy_1^2} - A_n(y_1)\left[\left(B_n - \frac{d\theta_n(y_1)}{dy_1}\right)^2 - B_n^2 (1 + C_n b_n)^2\right]$$

$$= - C_n B_n^2 (1 + C_n b_n) \frac{2}{T\omega_1} \left[\int \frac{\cos \Phi_n(y_1, \Phi_{01})}{1 + 2C_1 u(y_1, \Phi_{01})} d\Phi_{01} + 2C_n d_n\right.$$

$$\left. \cdot \int \frac{\sin \Phi_n(y_1, \Phi_{01})}{1 + 2C_1 u(y_1, \Phi_{01})} d\Phi_{01}\right], \qquad (3.17)$$

$$A_n(y_1)\left[\frac{d^2\theta_n(y_1)}{dy_1^2} - 2C_n\, d_n\, B_n^2 \cdot (1 + C_n\, b_n)^2\right] - \frac{2dA_n(y_1)}{dy_1}\, B_n - \frac{d\theta_n(y_1)}{dy_1}$$

$$= -C_n\, B_n^2\,(1 + C_n\, b_n)\,\frac{2}{T\omega_1}\left[\int \frac{\sin\,\Phi_n(y_1,\,\Phi_{01})}{1 + 2C_1 u(y_1,\,\Phi_{01})}\, d\Phi_{01} - 2C_n\, d_n \cdot \int \frac{\cos\,\Phi_n(y_1,\,\Phi_{01})}{1 + 2C_1 u(y_1,\,\Phi_{01})}\, d\Phi_{01}\right], \qquad (3.18)$$

where the definition $u_o/v_n = 1 + C_n\, b_n$ has been used.

The force equation

$$\frac{d^2z}{dt^2} = |\eta|\left[\frac{\partial V}{\partial z} + \frac{\partial V_{sc}}{\partial z}\right]$$

will be written in terms of normalized variables previously defined. The following relations are derived:

$$\frac{d^2y_1}{dt^2} = \frac{C_1\omega_1}{u_o}\,\frac{d^2z}{dt^2}\,,$$

$$\frac{d^2y_1}{dt^2} = 2C_1^3\omega_1^2\,(1 + 2C_1 u)\,\frac{\partial u}{\partial y_1}\,,$$

$$(1 + 2C_1 u)\,\frac{\partial u}{dy_1} = \frac{|\eta|}{2C_1^2\omega_1 u_o}\left[\frac{\partial V}{\partial z} + \frac{\partial V_{sc}}{\partial z}\right].$$

Using the expression for $\partial V/\partial z$ previously derived gives

$$(1 + 2C_1 u)\frac{\partial u}{\partial y_1} = \frac{|\eta||I_0|}{4C_1 u_0^2}\sum_n \frac{Z_n}{C_n} e^{-j\Phi_n}\left[\frac{dA_n}{dy_1} - j A_n\left(B_n - \frac{d\theta_n}{dy_1}\right)\right]$$

$$- \frac{|\eta|}{2C_1 \omega_1 u_0} E_{sc} \ .$$

It was shown by Rowe[1] that the space-charge field can be written as

$$E_{sc} = j \frac{\rho(z) R^2}{\epsilon\pi b'^2 \beta} \ .$$

If the expansion of charge density is introduced, one gets:

$$E_{sc} = \frac{j}{\epsilon\pi b'^2}\frac{1}{2}\sum_n \frac{R_n^2}{\beta_n}\rho_n e^{-j\Phi_n} \ .$$

Using Eqs. 3.12 and 3.16,

$$E_{sc} = - \frac{j|I_0|}{\epsilon\pi b'^2 u_0}\sum_n \frac{R_n^2}{\beta_n} e^{-j\Phi_n} \lim_{T \to \infty}\frac{1}{T\omega_n}\int e^{j\varphi'_n}\frac{\omega_n}{\omega_1}$$

$$\cdot \frac{1}{(1 + 2C_1 u)\left|\partial\Phi'_n/\Phi_{01}\right|_{y_1}} d\Phi'_n = \frac{-j|I_0|}{\epsilon\pi b'^2 u_0 \omega_1}$$

$$\cdot \sum_n \frac{R_n^2}{\beta_n}\lim_{T\to\infty}\frac{1}{T}\int \frac{e^{-j(\Phi_n - \Phi'_n)}\, d\Phi'_{01}}{(1 + 2C_1 u)} \ .$$

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1. Rowe, J. E., "A Large-Signal Analysis of the Traveling-Wave Amplifier", Tech. Report No. 19, Electron Physics Laboratory, The University of Michigan; April, 1955.

Taking $\beta_n \simeq \omega_n/v_n$ and using the definitions,

$$\omega_p^2 = \frac{|\eta||I_0|}{\pi\epsilon b'^2 u_0} , \quad \frac{C_n^3}{Z_n} = \frac{|\eta||I_0|}{2u_0^2} ,$$

the force equation becomes

$$(1 + 2C_1 u) \frac{\partial u}{\partial y_1} = \frac{C_1^2}{2Z_1} \sum_n \frac{Z_n}{C_n} e^{-j\Phi_n} \left[\frac{dA_n}{dy_1} - jA_n \left(B_n - \frac{d\theta_n}{dy_1} \right) \right]$$

$$+ \frac{j}{2C_1^2} \left(\frac{\omega_p}{\omega_1} \right)^2 \sum_n \frac{R_n^2}{1 + C_1 b_n} \lim_{T \to \infty} \frac{1}{T\omega_n} \int \frac{e^{-j(\Phi_n - \Phi_n')}}{1 + 2C_1 u} d\Phi_{01}' . \qquad (3.19)$$

In the separation of the circuit equation into n equations the time average has been taken over a certain period and the separation has been possible by taking the limit of the time average as the time interval goes to infinity. A limiting process is necessary, since in general the input signals have no common period. However in the special case, when the frequencies of the input signal are commensurate, there will be a common period and the time average need be taken only over that common period.

Assuming that the frequencies of the input signals are given as $\omega_1 = L_1 \Delta\omega$, $\omega_2 = L_2 \Delta\omega$, $\omega_N = L_N \Delta\omega$, (where L_1, L_2, ... , L_N are integers and $\Delta\omega$ is the greatest common factor), then the common period is equal to $2\pi/\Delta\omega$. The four working equations can be written as follows.

Circuit equations:

$$\frac{dA^2_n(y_1)}{dy_1^2} - A_n(y_1)\left[\left(B_n - \frac{d\theta_n(y_1)}{dy_1}\right)^2 - B_n^2\,(1 + C_n\,b_n)^2\right]$$

$$= -\,C_n\,B_n^2\,(1 + C_n\,b_n)\,\frac{1}{\pi L}\left[\int_0^{2\pi L}\frac{\cos\Phi_n(y_1,\,\Phi_{01})}{1 + 2C_1\,u(y_1,\,\Phi_{01})}\,d\Phi_{01} + 2C_n\,d_n\right.$$

$$\left.\int_0^{2\pi L}\frac{\sin\Phi_n(y_1,\,\Phi_{01})}{1 + 2C_1\,u(y_1,\,\Phi_{01})}\,d\Phi_{01}\right], \tag{3.20}$$

$$A_n(y_1)\left[\frac{d^2\theta_n(y_1)}{dy_1^2} - 2C_n\,d_n\,B_n^2\,(1 + C_n\,b_n)^2\right] - 2\,\frac{dA_n(y_1)}{dy_1}\left(B_n - \frac{d\theta_n(y_1)}{dy_1}\right)$$

$$= -\,C_n\,B_n^2\,(1 + C_n\,b_n)\,\frac{1}{\pi L}\left[\int_0^{2\pi L}\frac{\sin\Phi_n(y_1,\,\Phi_{01})}{1 + 2C_1\,u(y_1,\,\Phi_{01})}\,d\Phi_{01} - 2C_n\,d_n\right.$$

$$\left.\int_0^{2\pi L}\frac{\cos\Phi_n(y_1,\,\Phi_{01})}{1 + 2C_1\,u(y_1,\,\Phi_{01})}\,d\Phi_{01}\right]. \tag{3.21}$$

Force equation:

$$(1 + 2C_1\,u)\,\frac{\partial u}{\partial y_1} = \frac{C_1^2}{Z_1}\sum_n \frac{Z_n}{C_n}\cos\Phi_n\,\frac{dA_n}{dy_1} - \frac{Z_n}{C_n}\sin\Phi_n\left(B_n - \frac{d\theta_n}{dy_1}\right)A_n$$

$$+\,\frac{1}{C_1^2}\left(\frac{\omega_p}{\omega_1}\right)^2\sum_n\frac{R_n^2}{1 + C_n\,b_n}\,\frac{1}{2\pi L}\int_0^{2\pi L}\frac{\sin\,(\Phi_n - \Phi'_n)}{1 + 2C_1\,u}\,d\Phi'_{01}\,. \tag{3.22}$$

Relation between variables:

$$\left(\frac{\partial\Phi_n}{dy_1}\right) + \frac{d\theta_n}{dy_1} = \frac{\omega_n}{\omega_1} \frac{2u}{1 + 2C_1 u} \quad . \qquad (3.23)$$

3.3 Computer Results. The equations presented in this report have been programmed and solved on an IBM 7090 digital computer. Some of the results are shown in Figs. 3.1 through 3.4. The input consists of two signals at frequencies f_1 and f_2. It is assumed that seven signals will propagate on the circuit. These signals have frequencies f_1, f_2, $f_3 = 2f_2 - f_1$, $f_4 = 2f_1 - f_2$, $f_5 = 2f_1$, $f_6 = f_1 + f_2$, and $f_7 = 2f_2$. Only the first four are shown. The output powers in db of the signals at f_1 and f_2 relative to their input power are plotted vs. the normalized distance y_1, while the output powers at f_3 and f_4 in db relative to the input power at f_1 are plotted vs. the same normalized distance y_1.

Figure 3.1 shows the case for $A_1(0) = A_2(0) = 0.0225$, $f_2 = 1.01\ f_1$, $C_1 = C_2 = C_3 = C_4 = 0.05$, $Z_5 = Z_6 = Z_7 = 0.1\ Z_1$, $d_n = 0$, $b_n = 0.076$, $(n = 1,2,3,4,5,6,7)$, $\omega_p/\omega_n = 0$. Figure 3.2 shows the case for $f_2 = 1.05\ f_1$ and all other parameters the same as in Fig. 3.1. Figure 3.3 shows the case for $f_2 = 1.1\ f_1$ and other parameters as before.

It is seen that in the linear portion of the output (up to $y_1 \approx 4$) the intermodulation output at f_3 and f_4 is about 15 db lower than the fundamental output. However for larger values of y_1 when the tube is in saturation or above saturation the intermodulation components get relatively higher. This is of course due to the increased nonlinearity at saturation. In Fig. 3.1 the maximum output of the single frequency input is shown for reference. It is seen that the power output

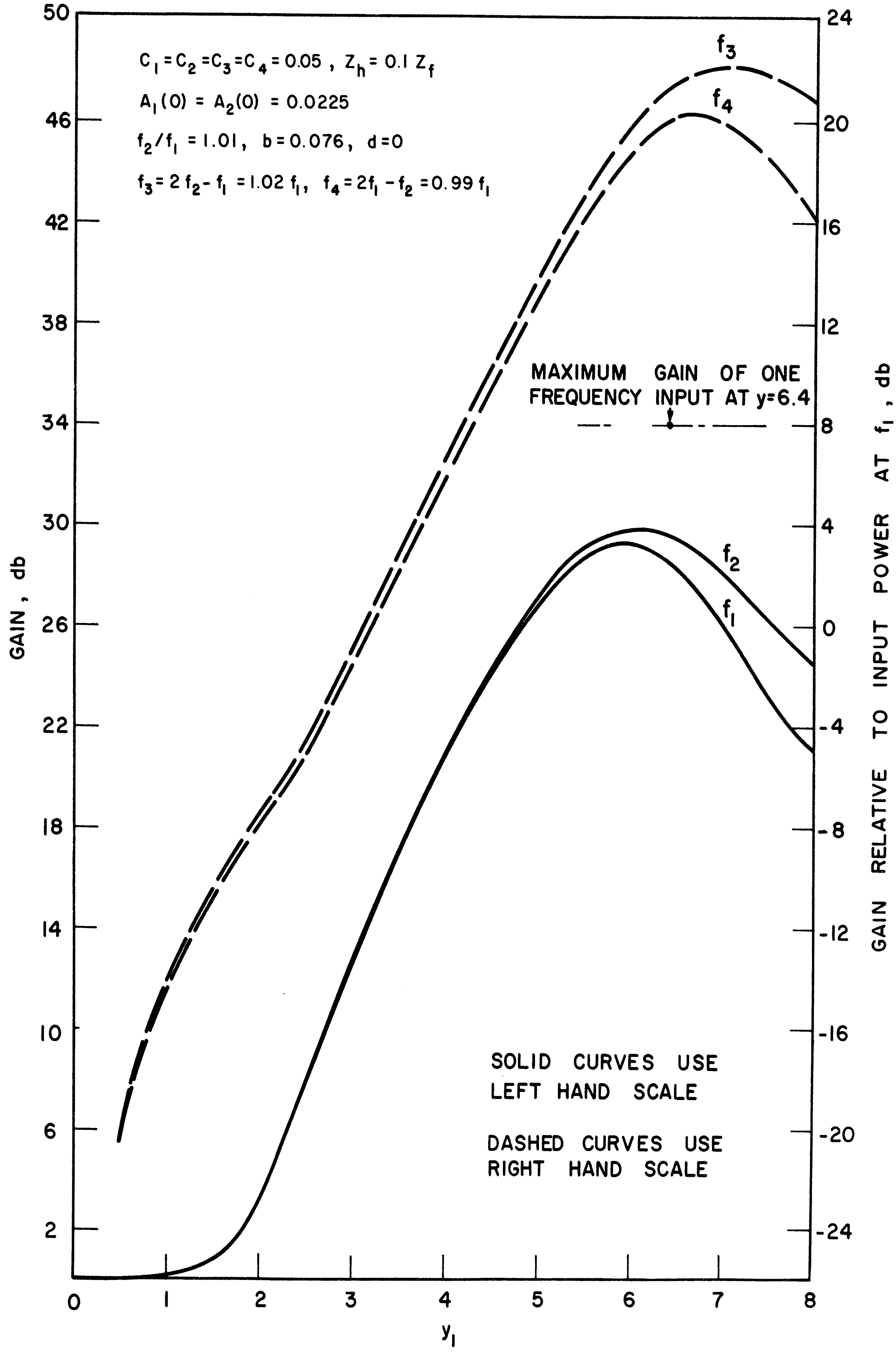

FIG. 3.1 GAIN VS. NORMALIZED DISTANCE.

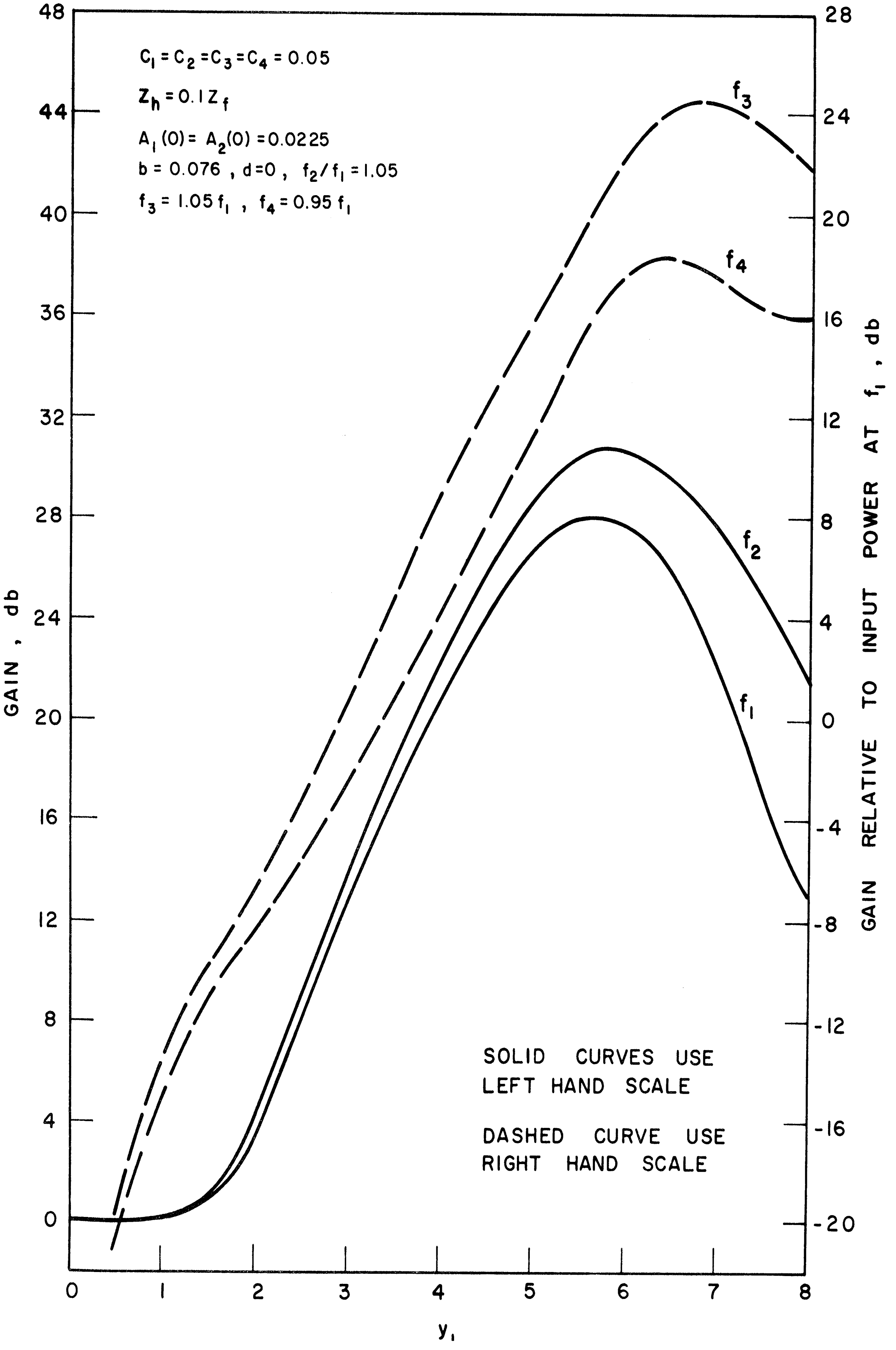

FIG. 3.2 GAIN VS. NORMALIZED DISTANCE.

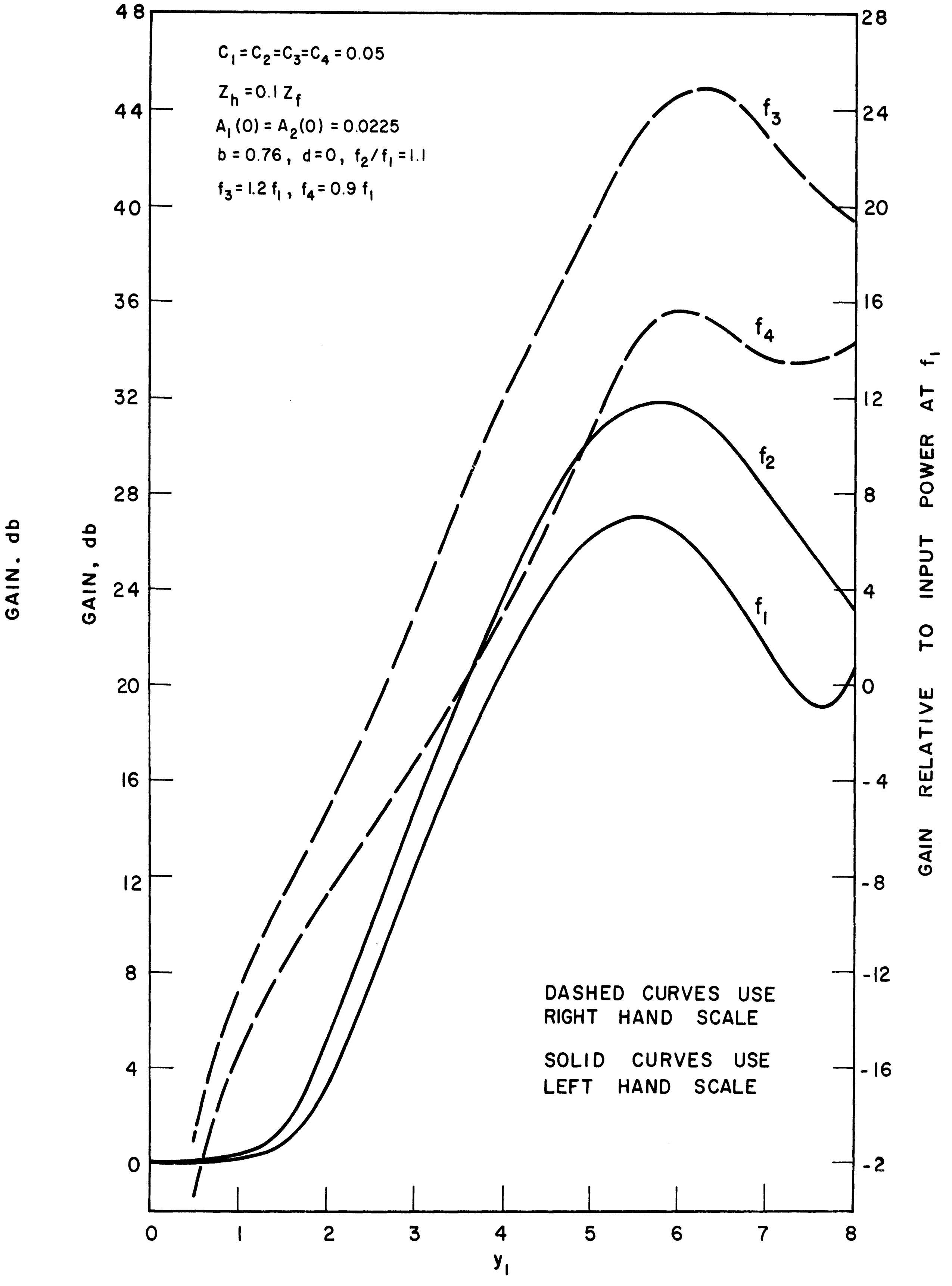

FIG. 3.3 GAIN VS. NORMALIZED DISTANCE.

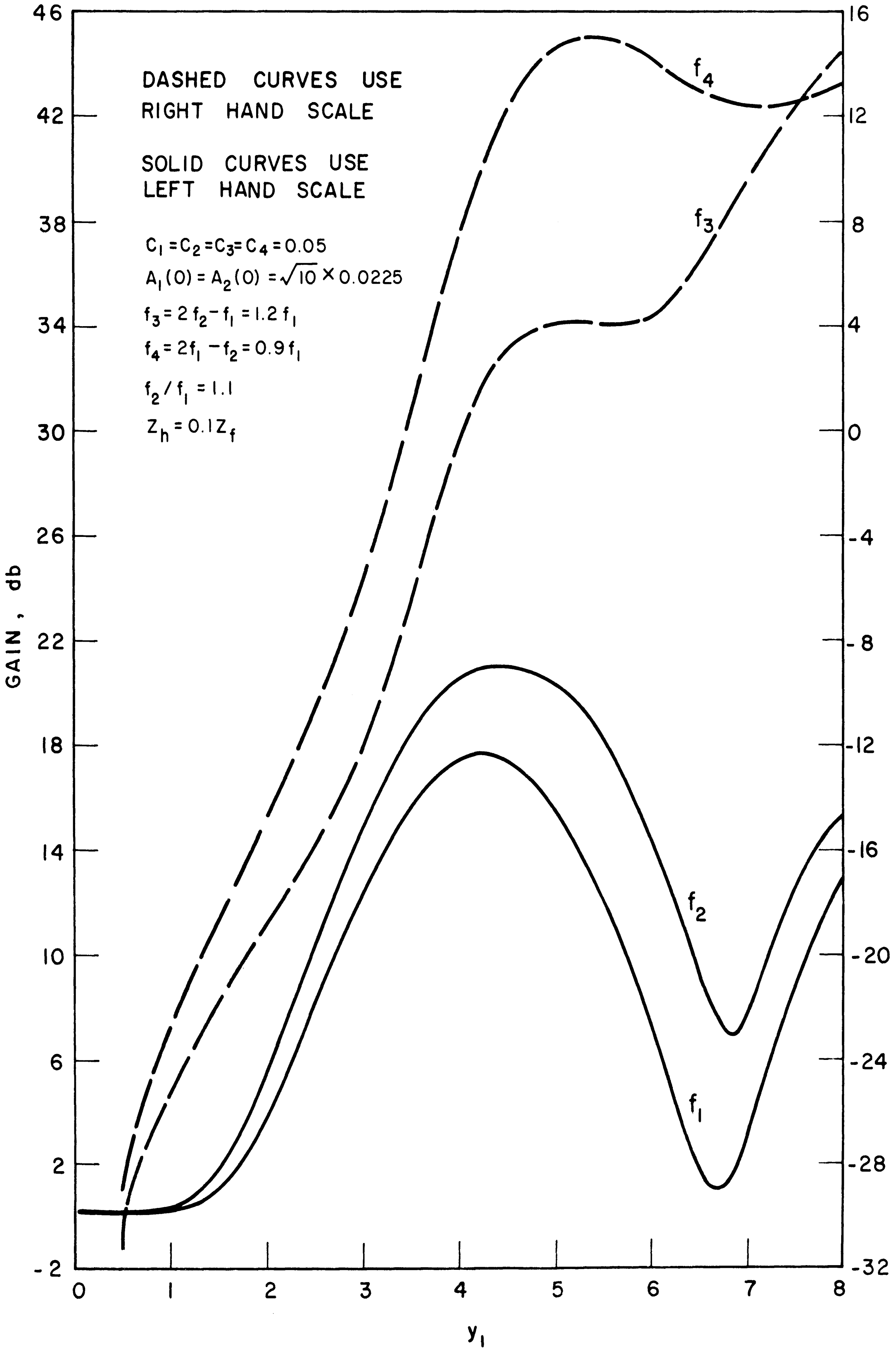

FIG. 3.4 GAIN VS. NORMALIZED DISTANCE.

of the two-frequency input has been reduced by about 4 to 4.5 db from the single frequency input. Also the saturation point occurs at a shorter distance.

Figure 3.4 shows the case in which the input power of each signal is increased by 10 db. It is seen that the saturation point occurs at a shorter distance ($y_1 \approx 4.5$) compared to Fig. 3.3 ($y_1 \approx 5.5$). Also the output at f_1 and f_2 of Fig. 3.4 is 10 db higher than the output of Fig. 3.3 up to $y_1 = 3.25$ above which the output of Fig. 3.4 starts to saturate. It is noticed that the output at f_1 and f_2 (and correspondingly the output at other frequencies) is not the same. This is due to the assumption that $C_1 = C_2 = C_3 = C_4$. Since, practically, the output does not change with frequency in this narrow band, it seems more realistic to assume some variation of C with frequency such that the output at f_1 and f_2 will be the same for equal input power and small frequency difference.

3.4 Future Work. Additional results will be obtained for all interesting values of the input parameters and operating condition of the tube. Also the equations presented in the first quarterly progress report have been programmed and solutions will be obtained in the near future.

Experimental work on an X-band medium power tube is now going on in order to correlate the theoretical results with the experimental ones.

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

4.1 Introduction. In Quarterly Progress Report No. 3 an anomolous gain possibility was reported which occurs when a cyclotron wave is coupled to a synchronous wave of the same kinetic power parity.

Such a coupling mode was previously classified as a passive coupling in which no power gain can be expected. However, in certain types of circuit structures, namely, the staggered and twisted quadrupole structures, high gain is possible under the condition of strong pumping. It was suggested that an explanation of this mechanism be theorized and that some experimental evidence be found to support it. This period has been devoted to these efforts.

4.2 *Kinetic Power Relations in Cyclotron Synchronous Mode Interaction.* Let us focus our attention to a twisted quadrupole structure. For the coupling between cyclotron and synchronous waves, $\beta_q = \beta_c/2$. Conditional coupling between the fast cyclotron wave A_1 and the positive kinetic power synchronous wave A_4 occurs when $2V_p/a^2 > \beta_c^2$. The component waves are found to be

$$a_1 = f_{11} e^{-j[\beta_e-(\beta_c/2) - \sqrt{(\beta_c^2/4) - M}]z} + f_{12} e^{-j[\beta_e-(\beta_c/2) + \sqrt{(\beta_c^2/4) - M}]z}$$

$$+ f_{13} e^{-j[\beta_e-(\beta_c/2) + \sqrt{(\beta_c^2/4) + M}]z} + f_{14} e^{-j[\beta_e-(\beta_c/2) - \sqrt{(\beta_c^2/4) + M}]z} \qquad (4.1)$$

and

$$a_4 = f_{41} e^{-j[\beta_e+(\beta_c/2) + \sqrt{(\beta_c^2/4) - M}]z} + f_{42} e^{-j[\beta_e+(\beta_c/2) - \sqrt{(\beta_c^2/4) - M}]z}$$

$$+ f_{43} e^{-j[\beta_e + (\beta_c/2) - \sqrt{(\beta_c^2/4) + M}]z} + f_{44} e^{-j[\beta_e+(\beta_c/2) + \sqrt{(\beta_c^2/4) + M}]z} , \qquad (4.2)$$

where

$$M = \frac{V_p \eta \beta_c}{u_o \omega_o a^2} .$$

The ω-β plot of these component waves under strong pumping condition $M \geq \beta_c/4$ is shown in Fig. 4.1.

Notice that the phase of the fast cyclotron component waves f_{11} and f_{12} have a value of $-(1/2)\beta_c$ at $\omega = 0$, while f_{14} is on its left at $-1.2\,\beta_c$ and f_{13} is on its right at $0.2\,\beta_c$. If z is increased, f_{11} and f_{12} remain unchanged while f_{14} is shifting toward the left. Similarly the synchronous component waves f_{41}, f_{42} are stationary at $f_c/2$, and f_{43}, f_{44} are shifting toward the left and right respectively.

For a lossless system, the kinetic power carried in each mode is separately conserved, that is to say, $|a_1|^2$ = constant and $|a_4|^2$ = constant. From the ω-β diagram, it can be seen that

$$|a_1|^2 = |f_{11}|^2 + |f_{12}|^2 - |f_{13}|^2 + |f_{14}|^2 , \qquad (4.3)$$

$$|a_4|^2 = -|f_{41}|^2 - |f_{42}|^2 + |f_{43}|^2 - |f_{44}|^2 . \qquad (4.4)$$

The Chu kinetic power theorem states that

$$P = |a_1|^2 + |a_4|^2$$

$$= |f_{11}|^2 + |f_{12}|^2 - |f_{13}|^2 + |f_{14}|^2 - |f_{41}|^2 - |f_{42}|^2 + |f_{43}|^2 - |f_{44}|^2$$

$$= \text{constant} . \qquad (4.5)$$

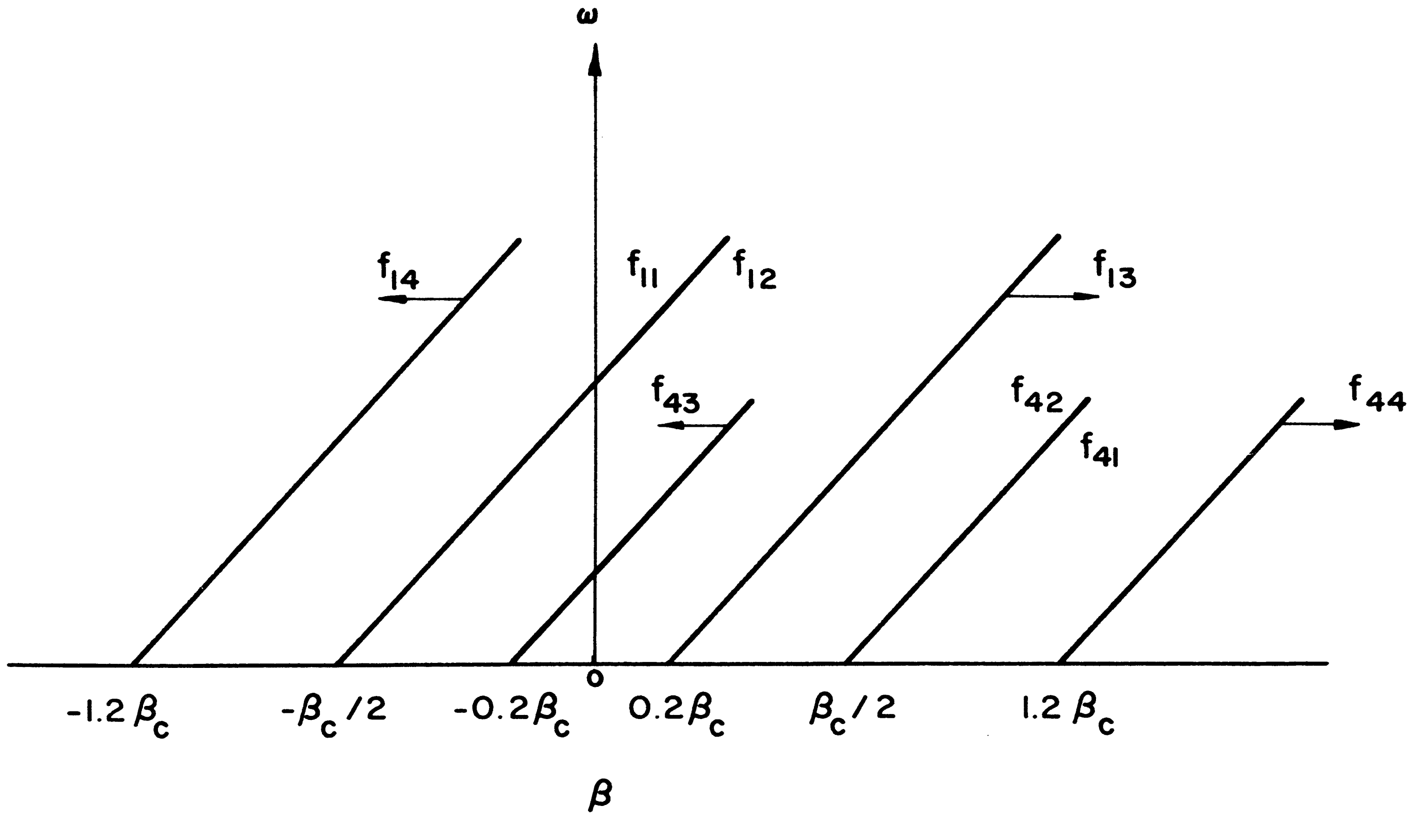

FIG. 4.1 ω-β PLOT OF THE CYCLOTRON-SYNCHRONOUS WAVE INTERACTION IN A TWISTED QUADRUPOLE PUMP STRUCTURE, WITH $M \geq \beta_c^2/4$.

It can be seen from Eqs. 4.1 and 4.2 that the component waves f_{13}, f_{14}, f_{43}, f_{44} have a pure imaginary propagation constant, and thus their amplitudes are constant and so are the squares of the amplitudes. The power theorem is then simply

$$|f_{11}|^2 + |f_{12}|^2 - |f_{41}|^2 - |f_{42}|^2 = \text{constant} \quad , \qquad (4.6)$$

where f_{11}, f_{41} are decaying waves, and f_{12}, f_{42} are growing waves. Therefore, Eq. 4.6 shows that under a lossless system, the rate of growth of f_{12}, f_{42} waves is equal to the rate of decaying of f_{11}, f_{41}. Furthermore, it indicates that f_{11}, f_{12} carry positive kinetic power, while f_{41}, f_{42} carry negative kinetic power. In other words, the so-called positive synchronous wave now carries a net negative kinetic power which can be coupled to the cyclotron wave to produce amplification. Similar reasoning applies to the slow cyclotron-to-negative synchronous wave coupling.

Since the signal input and output are coupled through the use of Cuccia couplers which are isolated from the pump field region, the bandwidth of the amplifier is limited by that of the input and output couplers.

However, a possible wideband operation can be obtained by using a quadrifilar helix as the input and output coupler, and at the same time as the pump field structure, such as is used by Mao and Siegman[1] in their simultaneous r-f and d-c coupled cyclotron amplifier.

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[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.

4.3 Experimental Evidence of the High Gain Transverse-Wave Amplifiers. Thus far, there have been two papers reporting the "unexpected amplifying phenomena" without due explanation[1,2]. In the paper by Saito, Kenmoku and Matsuoka, the observed high gain was the result of reducing the drift voltage to a quarter of its normal operating value. This reduction in drift voltage corresponds to a reduction of the drift velocity to one half of the normal operating value. This operating condition corresponds to the condition for cyclotron-to-synchronous wave coupling at $\beta_q = (1/2)\beta_c$. If this pump voltage remains unchanged under this condition (which is assumed, there is no other place to indicate otherwise), this is precisely the necessary strong pump field condition for the system to exhibit gain. Mao and Seigman reported a similar gain increase in which they have puzzled that according to the operating condition it would indicate a cyclotron-to-synchronous wave coupling from which exponential gain is not possible.

It is our belief that strong pump field will shift the phase of the component waves in this type of coupling to make the exponential gain possible.

5. General Conclusions (C. Yeh)

The experimental low-frequency model of a frequency multiplier with feedback has been constructed. The d-c operating characteristics of this device have been checked and are found to be satisfactory. The device is now awaiting final r-f testing of its workability and efficiency.

---

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

Difficulties encountered in brazing a tungsten helix for operation at 30 Gc into a smooth-bore BeO tube have not been fully resolved. Several other alternative methods are being tried.

A general analysis is given to describe the nonlinear operation of the traveling-wave amplifier with multifrequency input. Computer results for the system are discussed.

The explanation of the anomalous gain phenomena in terms of kinetic power theorem seems reasonable. Strong evidence of the existence of such coupling is found in two entirely unrelated experiments. It is planned to design a tube which will verify this phenomena more directly in the near future.

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The University of Michigan, Electron Physics Laboratory, Ann Arbor, Michigan. BASIC RESEARCH IN MICROWAVE DEVICES AND QUANTUM ELECTRONICS, by H. D. Detweiler, et. al. May, 1964, 29 pp. incl. illus. (Project Serial No. SR0080301, Task 9391, Contract No. NObsr-89274)

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

The construction of the experimental low-frequency model of the frequency multiplier with feedback scheme to enhance the transfer efficiency has been completed. D-c beam testing shows that the tube is aligned satisfactorily. The tube is now awaiting final r-f testing.
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