An Experimental Gyro-TWT

ROBERT S. SYMONS, FELLOW, IEEE, HOWARD R. JORY, MEMBER, IEEE, S. J. HEGJI, MEMBER, IEEE, AND PATRICK E. FERGUSON

Abstract—**Three experimental gyro traveling wave tubes (TWT's) have been built and tested. All tubes used a fundamental cyclotron resonance interaction with the circularly polarized TE_{11}^{0} dominant waveguide mode. The tubes differed in the length of the single circuit section and in the amount of distributed loss used. The experiments were conducted at 5 GHz, with the object of producing a design that could be scaled to 94 GHz. Results on the third experiment include measurements of stable gain as high as 24 dB small signal and 18 dB saturated. A saturated power output of 120 kW at a total beam efficiency of 26 percent was measured with a 3-dB saturated power output bandwidth of 6 percent. The design features of the tubes and the experimental results are described fully.**

I. Theory

RECENTLY Seftor *et al.* [1] and Barnett *et al.* [2] have described a gyro-TWT using a hollow electron beam interacting with a TE_{01}^{0} waveguide mode. It is also possible to use other waveguide modes. There are at least two good reasons for building a gyro-TWT using a dominant waveguide mode, and in addition there is a third reason for using the circular waveguide TE_{11}^{0} degenerate dominant-mode pair.

Studies of the dispersion relation for gyro-TWT's indicate that once the beam line intersects the waveguide dispersion hyperbola for a particular mode, there will be gain in that mode, even if the cyclotron frequency is substantially above the cutoff frequency. Hence, a higher order waveguide mode gyro-TWT is almost certain to amplify in lower order waveguide modes if these modes are excited by structure or beam asymmetries. Second, the smaller the waveguide cross section, the higher will be the electric fields for a given power flow. Since the degree of bunching and the power removed from the beam are each a function of the electric field, then, as in a conventional traveling wave tube, the gain parameter will be greater if the electric field is produced by a small power flow than if it is produced by a large one.

A waveguide mode which exists as an orthogonal degenerate pair is desirable in a gyro-TWT because the electrons are orbiting and can interact continuously if they are in a circularly polarized field. One can think of the circularly polarized TE_{11}^{0} mode as being made of the two degenerate linearly polarized TE_{11}^{0} modes excited in space and time quadrature. If a certain power flow in one of the modes produces a certain field, and this power is then divided between the two orthogonal modes, the field of each mode will be $1/\sqrt{2}$ times as large. As a result, an orbiting electron will encounter an integral of $E\cdot dl$ over one cyclotron period which is $2/\sqrt{2}$ times as large as that it would encounter in a guide containing a single linearly polarized mode with the same power flow. The interaction impedance is proportional to $\langle E\rangle^2/P$ in which $\langle E\rangle$ is the time average of the electric field and P is the power flow in the waveguide. The impedance is therefore twice as large for circular polarization as for linear polarization.

The above conclusions were based upon inferences drawn from dispersion relations calculated by various authors [3]–[7] for other beam-waveguide geometries. Recently, however, Chu, Drobot, Szu, and Sprangle [8] have published the dispersion relation for this specific geometry. With a little algebra it is possible to give the mode coupling factor in their equation a striking resemblance to Pierce's C^3. That is

$$\bar{\omega}^2-(\bar{k}^2+1)=-\frac{1}{4\pi^2\beta_{\parallel}}G_bZR \cdot\left(\beta_{\perp}^2\frac{(\bar{\omega}^2-\bar{k}^2)}{\left(\bar{\omega}-\bar{k}\beta_{\parallel}-s\bar{\Omega}\right)^2}-\frac{\left(\bar{\omega}-\bar{k}\beta_{\parallel}\right)Q_{sm}}{\left(\bar{\omega}-\bar{k}\beta_{\parallel}-s\bar{\Omega}\right)H_{sm}}\right) \tag{1}$$

in which $\bar{\Omega}=\Omega/\omega_n$, $\bar{\omega}=\omega/\omega_n$, $\bar{k}=k/k_n$, Ω is the electron cyclotron frequency, ω is the operating frequency, ω_n is the waveguide cutoff frequency, and k_n is the normal wavenumber which is equal to ω_n/c. G_b is the dc beam conductance equal to the beam current I_b divided by the beam voltage, V_b, $\beta_{\parallel}$, and $\beta_{\perp}$ are the axial and transverse beam velocities normalized with respect of the velocity of light, and

$$R=[V_b/V_n]/[1+V_b/V_n] \tag{2}$$

in which $V_n=mc^2/e=511\,000$ V is a measure of the rest mass energy. The factor R is the efficiency with which energy modulation is turned into angular velocity modulation. (This is analogous to the factor of $1/2$ which comes from the square root relation between electron velocity and electron energy in conventional linear beam tubes.) The circuit impedance Z for TE_{mn}^{0} modes is given by

$$Z=\frac{4\pi^2\eta_1H_{sm}(x,y)}{\pi x_{mn}^2K_{mn}}=\frac{(\lambda_nE)^2v_g}{2Pc} \tag{3}$$

Manuscript received June 17, 1980; revised October 7, 1980. This work was supported by Rome Air Development Center for the Defense Advanced Research Projects Agency and the Ballistic Missle Defense Advanced Technology Center under Contract F-30602-78-C-0011.

R. S. Symons, H. R. Jory, and P. E. Ferguson are with Varian Associates, Inc., Palo Alto, CA 94303.

S. J. Hegji was with Varian Associates, Inc., Palo Alto, CA 94303. He is now with Logic Applications Corporation, Sacramento, CA.

0018-9480/81/0300-0181$00.75 ©1981 IEEE

in which η_1 is the characteristic impedance of free space and H_{sm}, which is related primarily to the integral of the tangential electric field on the electron around its orbit, is given by

$$H_{sm}(x, y)=[J_{s-m}(x)J_s'(y)]^2. \quad (4)$$

As shown above, Z can be thought of as the ratio of the square of the normalized strength, $\lambda_n E$, of the multipole component of the electric field (which is responsible for interaction at the harmonic s) divided by the power flow P and normalized with respect to the ratio of c to v_g, the group velocity of the unperturbed waveguide mode (λ_n is the free-space wavelength at the waveguide cutoff frequency).

The factor Q_{sm} which arises primarily out of the radial forces of the multipole fields on the orbiting electrons results in damping. This is given by

$$Q_{sm}(x, y)=2H_{sm}(x, y)+y\Big[J_{s-m}^2(x)J_s'(y)J_s''(y) + \frac{1}{2}J_{s-m-1}^2(x)J_s'(y)J_{s-1}'(y)-\frac{1}{2}J_{s-m+1}^2(x)J_s'(y)J_{s+1}(y)\Big] \quad (5)$$

and K_{mn} which relates to the power flow in the waveguide is given by

$$K_{mn}=J_m^2(x_{mn})-J_{m-1}(x_{mn})J_{m+1}(x_{mn}). \quad (6)$$

In the above expressions $x_{mn}=k_n r_w$, $x=k_n r_0$, and $y=k_n r_c$ in which r_w is the waveguide radius, r_0 is the hollow beam radius (i.e., the radius of the cylinder which is the locus of the guiding centers of the electrons), and r_c is the cyclotron radius.

The roots of (1) give the propagation characteristics of the growing wave

$$H_z=H_{z0}\exp[j(\omega_r t-kz)+\omega_i t]$$

or

$$H_z=H_{z0}\exp[j(\omega t-k_r z)+k_i z] \quad (7)$$

in which ω_r and ω_i are the real and imaginary parts of a complex ω solved for as a function of real wavenumber k, and k_r and k_i are the real and imaginary parts of a complex wavenumber solved for as a function of real frequency. It does not matter much how one solves the equation because the temporal growth rate ω_i is related simply to the spatial growth rate k_i by the equation

$$k_i=\omega_i\left(\frac{\partial\omega_r}{\partial k}\right)^{-1}=\frac{\omega_i}{v_g}. \quad (8)$$

In this case v_g is the group velocity of the unstable wave.

Fig. 1 shows the normalized frequency ω_r/ω_n and the normalized temporal growth rate ω_i/ω_n as functions of normalized wavenumber k/k_n. The cyclotron resonance maser instability is described by the complex conjugate values of ω/ω_n for $0<k/k_n<0.5$. The complex conjugate values of ω/ω_n for $|k/k_n|>\omega/\omega_n$ (i.e., for waves slower than the velocity of light) are frequently referred to as the Weibel instability. Convincing physical arguments can be made that this beam instability (beam break-up) actually can occur. However, the assumptions made in the derivation of (1) are violated for $|k/k_n|>\omega/\omega_n$, so the numerical values shown in Fig. 1 should not be trusted in this region. Fig. 2 shows the gain in decibles/meter derived from the spatial growth rate k_i as a function of frequency for the parameters we used in the experimental tubes we built and for electrons with a perpendicular momentum 1.5 times the parallel momentum. From our gun calculations we believe this momentum ratio is close to the experimental values.

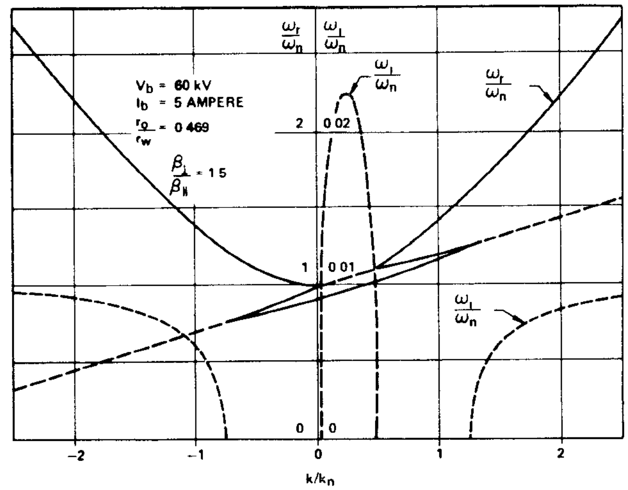

Fig. 1. Roots of dispersion relation.

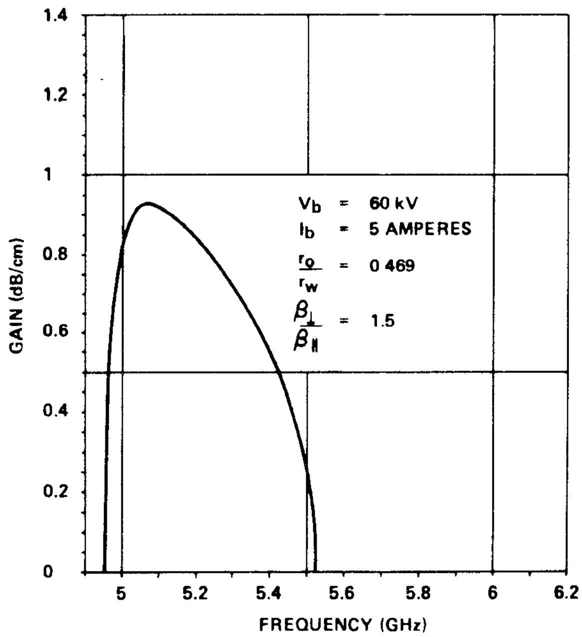

Fig. 2. Calculated gain in decibles/centimeter versus frequency.

II. Experiment

All three experimental tubes were designed to operate at a beam voltage of 60 kV with a beam current of 5 A peak. Modulating anode pulsing was used. All had a structure rather like the third tube shown sectioned in Fig. 3 and pictured in Fig. 4. All tubes used two abrupt rectangular waveguide to circular waveguide input transitions at 90° to each other in order to match into the two orthogonal TE_{11}^0 modes that can exist in the circular waveguide. A capaci-

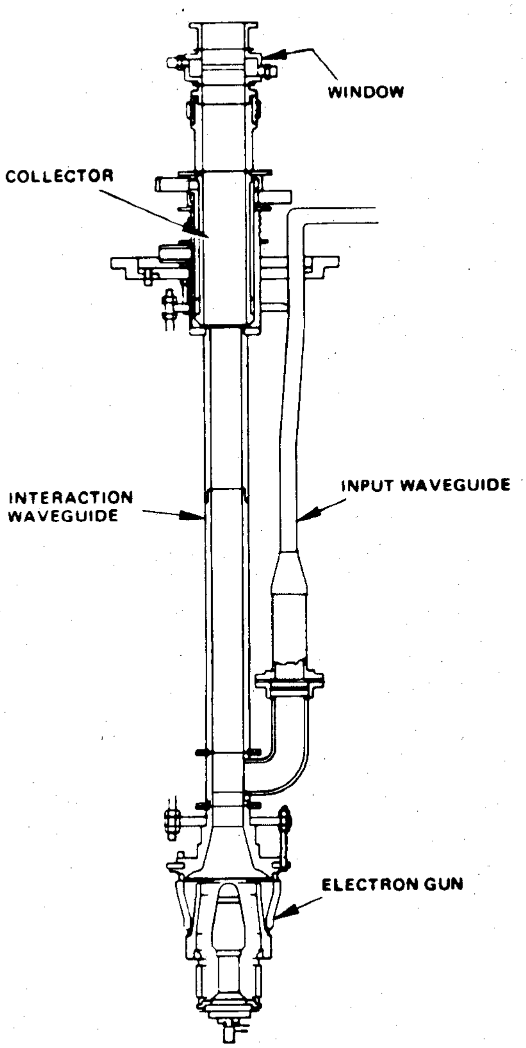

Fig. 3. Section of gyro-TWT.

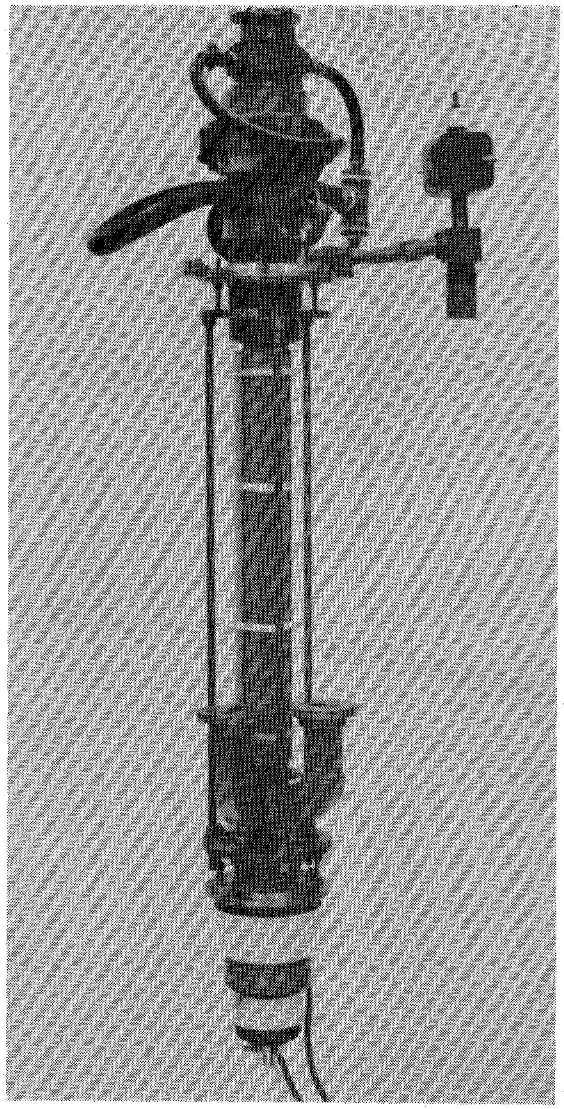

Fig. 4. Gyro-TWT (photo).

tive post in the rectangular waveguide near the junction helped the match. The output window was at the end of the circular cylindrical collector.

Transverse field permanent magnets deflected electrons to the collector wall before they could reach the window. The first tube used coaxial input windows followed by coax to waveguide transitions in vacuum. The second and third tubes used waveguide windows and all-waveguide drive lines which gave a slightly better match. However, the most significant differences in the three tubes were in circuit length, circuit cutoff frequency, and the amount of distributed loss used. Table I shows these differences.

The first tube showed a net gain of about 3 dB. At magnetic fields somewhat above the highest value which gave stable gain, the tube broke into oscillations which tuned smoothly from 4.8 to 5.2 GHz as the magnetic field was increased. One to 2 kW of peak power was delivered out of the inputs when the tube oscillated in this manner. At lower magnetic fields the tube oscillated at frequencies between 8.05 and 8.55 GHz which we believe resulted from an interaction of the second cyclotron harmonic with the TE_{21}^0 mode.

TABLE I

Tube No.	Length	Cutoff Frequency	Distributed Loss
1	8″	4.8	None
2	17″	4.8	None
3	17″	5.0	6-10 dB over first two-thirds of length

The second tube was increased in length so the interaction region was about 17 in. The tube oscillated at the same frequencies for the same magnetic field settings as did the first tube. The power delivered into the output load for the TE_{11}^0 oscillation was 40 kW for 300 kW of beam power and the oscillation power coming out of the input ports was 10 dB less. At 2.5 A of beam current, and a 45-kV beam voltage, the tube gave a stable gain of 17 dB at 4.9 GHz. At 50 kV and 4.0 A with the gun magnetic field adjusted

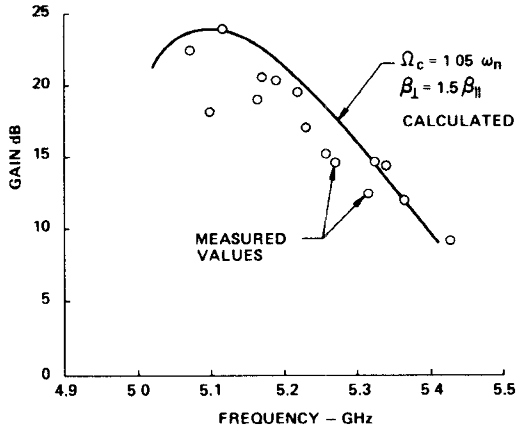

Fig. 5. Comparison of calculated and measured gain.

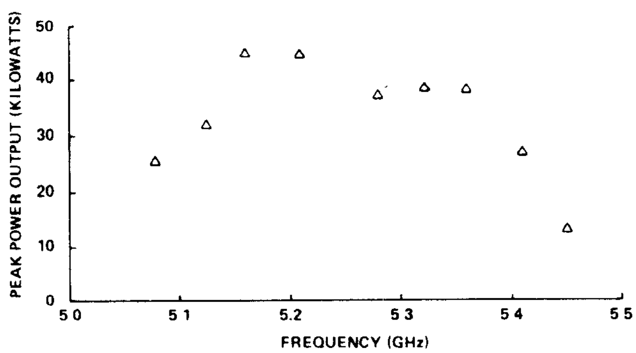

Fig. 6. Saturated power output.

for lower transverse energy, stable operation across the band could be achieved, and the gain decreased from about 12 dB at 4.9 GHz to 5 dB at 5.1 GHz with a great deal of fluctuation over this frequency interval due to the lack of distributed loss. Under the same operating conditions the saturated output power was 11 to 13 kW.

In order to increase the stable gain and reduce problems with reflections, a third tube was built with distributed loss. Kanthal was applied to the first two-thirds of the circuit and the cutoff of the interaction waveguide was moved from 4.8 to 5 GHz so that the hot bandwidth of the tube would be more nearly centered in the frequency range over which the input matches were best. This tube exhibited much improved performance. It demonstrated stable gain at full beam power. A maximum stable gain of 24 dB small signal and 18 dB saturated was observed, and the fluctuations due to match problems were largely eliminated. Fifty kilowatts peak output power was also observed with an efficiency of 16.6 percent. Fig. 5 shows the measured small signal gain compared to the gain calculated for a ratio of perpendicular to parallel momentum of 1.5. The calculated curve is based upon Fig. 2 with a launching loss assumed to be 9 dB. An additional launching loss of 3 dB is also subtracted. This loss occurred because only one drive line was excited and so half the drive power went into a circularly polarized wave rotating in the wrong direction (by using a short-slot hybrid to drive both inputs, this loss can be avoided). An additional 3 dB was subtracted to allow for circuit loss. Fig. 6 shows the saturated power output as a function of frequency. The 3-dB saturated power bandwidth is 6 percent. The data in Figs. 5 and 6 were taken without any adjustment of parameters. More recent measurements indicating 120 kW at 26-percent efficiency were made after careful optimization of current regulated magnet supply settings with a beam voltage of 65 kV and a beam current of 7 A. Design work has been done on electron beams suitable for use in this gyro-TWT scaled to 94 GHz. It appears that suitable beams can be achieved.

ACKNOWLEDGMENT

The authors wish to thank Ms. P. Walchli for doing the computer work associated with the design of the electron gun, A. Nordquist for his contributions in connection with the small signal gain computer programs and R. Morwood for adapting the NRL large signal programs to run on our computer.

REFERENCES

[1] J. L Seftor, V L. Granatstein, K. R. Chu, P. Sprangle, and M. Read, "The electron cyclotron maser as a high-power traveling-wave amplifier of millimeter waves," *IEEE J Quantum Electron.*, vol. QE-15, pp. 848–853, 1979.

[2] L. R Barnett, K R. Chu, J. M. Baird, V L. Granatstein, and A T. Drobot, "Gain, saturation, and bandwidth measurements of the NRL gyrotron travelling wave amplifier," in *IEDM Technical Dig.*, pp. 164–167, Dec. 1979.

[3] V. V Zheleznyakov, "On the instability of a magnetoactive plasma under high-frequency electromagnetic perturbations. I ," *Izv. VUZ Radiofizika*, vol. 3, no. 1, p. 57, Jan 1960.

[4] A. V Gaponov and V. K. Yulpatov, "Interaction of helical electron beams with the electromagnetic field in a waveguide," *Radiotekh. Elektron* , vol. 12, no. 4, p. 627, 1967; also, *Radio Eng. Electron Phys* , vol. 12, no. 4, pp. 582–587, Apr. 1967.

[5] E. Ott and M. Manheimer, "Theory of microwave emission by velocity-space instabilities of an intense relativistic electron beam," *IEEE Trans. Plasma Sci.*, vol. PS-3, pp. 1–5, Jan. 1975.

[6] P. Sprangle, and A. T. Drobot, "The linear and self-consistent non-linear theory of the electron cyclotron maser instability," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 528–544, June 1977.

[7] K. R. Chu, and A. T. Drobot, "Theory and single wave simulation of the gyrotron traveling wave amplifier operating at cyclotron harmonics," NRL Memorandum Rep. 3788, Aug. 1978.

[8] K. R. Chu, A. T. Drobot, H. H. Szu, and P. Sprangle, "Analytic scaling of efficiency for the gyrotron traveling wave amplifier operating at cyclotron harmonics," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 313–317, Apr. 1980.