Abstract—The high-harmonic gyro-traveling wave tube (gyro-TWT) is a high-power (≥ 1 kW) millimeter wave amplifier based on the synchronous interaction of a beam of large-orbit axis-encircling electrons with a high-order cylindrical waveguide mode. Since the interaction occurs at a high harmonic of the cyclotron frequency, the intense magnetic fields required for the conventional fundamental-mode gyro-TWT are not required. A proof-of-principle experiment designed to demonstrate the interaction of a 150-mA 350-keV electron beam with the TE_m_ mode of a cylindrical waveguide is described. Principal results include a small signal gain of 10 dB, an interaction bandwidth of 4.3 percent, and a saturated power transfer from electron beam to wave of 0.5 kW. Additional measurements include the dependence of gain on electron beam current and the measurement of the beam's y, β_m, and Δ P_s. Sufficient agreement between the experimental results, simulation codes, and an analytic description of the interaction is demonstrated to permit the design of high-performance millimeter wave amplifiers.

I. INTRODUCTION

THERE IS currently considerable interest in the development of high-power millimeter wave amplifiers. Proposed applications for these amplifiers include high resolution and imaging radar, high information density communications, nondestructive testing of dielectric materials, and RF sources for the next generation of particle accelerators and fusion experiments. Conventional electron tubes require electron beams and electromagnetic fields required for the conventional fundamental-mode gyro-TWT. These fields can be provided by superconducting magnets, pulsed solenoids, and Bitter magnets; however, many of the proposed applications for these amplifiers would have difficulty tolerating the weight, size, fragility, or cost of these magnet systems.

An alternative configuration which allows for millimeter wave operation in reduced magnetic fields is the large-orbit high-harmonic gyro-TWT. This device shares many of the advantages of the conventional gyro-TWT; however, the magnetic field requirements for millimeter wave operation are only 0.1–2.0 T. In many cases, these fields may be obtained using compact permanent magnets, allowing for an extremely small, lightweight, and portable system.

Early work in the application of the high-harmonic interaction was undertaken in the 1960's and 1970's [22], [23]. Experimental results on high-harmonic gyrotron oscillators have included the operation of an eleventh-harmonic 84-GHz tube with an output power of 6 W [22], a third-harmonic 1.5-kW 26-GHz tube with a conversion efficiency of 15 percent [24], and an eleventh-harmonic 26-GHz tube with an output power of 1.5 kW [25]. This work has recently been extended to high-harmonic gyrotron amplifiers with experimental results indicating a
small gain of 45 dB and an output power of 0.6 kW in a fifth-harmonic four-cavity device operating at 11.3 GHz [26].

II. PRINCIPLES OF OPERATION

The high-harmonic gyro-TWT [27] is a device which combines the operating principles of the linear beam TWT with those of the high-harmonic gyrotron gyrotrotron to form a broadband amplifier that does not require small-diameter electron beams or intricate machining procedures. A schematic of the high-harmonic gyro-TWT is shown in Fig. 1. An axis-encircling large-orbit electron beam of random phase and uniform velocity enters an interaction region which consists of a smooth-walled cylindrical waveguide. The input signal is introduced into the waveguide in the form of a TE_{m1} mode. The azimuthal electric field of this mode modulates the perpendicular velocity of the electrons when approximate synchronism between the wave and the electron beam is maintained. Because of the relativistic dependence of the cyclotron frequency, those electrons which gain energy slip back in phase, while those electrons which lose energy move ahead in phase. As the electrons travel through the waveguide, this phase slippage gives rise to spatial bunching of the electrons.

The electrons are in resonance with the wave when

$$\omega - k_1 v_y - n \Omega_e = 0$$  \hspace{1cm} (2)

where \(k_1\) is the axial wavevector and \(v_y\) is the electron's axial velocity. In the absence of the electron beam, the dispersion relationship of the waveguide mode is

$$\omega^2 - k_1 v_y^2 - \omega_{\text{acc}}^2 = 0$$  \hspace{1cm} (3)

where \(\omega_{\text{acc}} = q_n c / r_n\) is the TE_{m1} mode's cutoff frequency, \(r_n\) is the waveguide's radius, \(q_n\) is the \(n\)th zero of \(J_n(z)\), and \(J_n\) is the derivative of the Bessel function of the first kind of order \(n\). Broadband amplification occurs when the cyclotron resonance line is tangent to the waveguide's dispersion curve or, equivalently, when the electron's axial velocity equals the wave's group velocity. This condition is met if

$$n \Omega_e / \omega_{\text{acc}} = \gamma_1^{-1}$$  \hspace{1cm} (4)

where \(\gamma_1 = [1 - \beta_2]^{-1/2}\) and \(\beta_2 = v_y / c\). The strongest growing frequency is then expected to satisfy

$$\omega / \omega_{\text{acc}} = \gamma_1.$$  \hspace{1cm} (5)

Historically, several methods have been used to analyze the coupling between the beam and waveguide modes. The earliest work on the cyclotron maser instability involved a quantum mechanical interpretation [28], [29]. In these studies, the energy states for the orbiting electrons were calculated and then an expression for the transition probability was used to find the power flow from beam to wave. A kinetic treatment of the interaction, based on the linearized Vlasov equation, has also been used [30], [31]. However, an interpretation which provides significant physical insight is the macroscopic fluid model presented by Lau [11].

In Lau's model, an infinitesimally thin shell of monoenergetic axis-encircling electrons interacts with a cylindrical waveguide TE_{n1} mode. The dispersion relation for the interaction is found to be

$$(\omega - n \Omega_e - k_1 v_y)^2 (\omega_{\text{acc}}^2 - k_1^2 v_y^2)$$

$$= -4 \beta_2^2 \left[ \frac{1}{I_1} \left[ \frac{q_n c}{r_n} \right]^2 \frac{1}{q_n^2} \left( \frac{J_n(q_n r_n / r_n)}{J_n(q_n)} \right)^2 \right]$$  \hspace{1cm} (6)

where \(\beta_2 = v_y / c\) and \(I_1 = 4 \pi e_0 \beta_1 \gamma m_e c^2 / e = \beta_1 \gamma 17 \text{kA}\) is the Alven current.

The spatial growth rate of the wave may be obtained by solving (6) for the imaginary part of \(k_1\). Since this equation is fourth-order in \(k_1\), complex solutions can be obtained numerically using a computer program. The operation of a gyro-TWT is complicated by the existence of a launching loss. This launching loss occurs because all of the input power does not couple to the desired mode. By adopting the formalism of Pierce, Caplan has derived a general expression for the initial amplitude of the growing wave in a gyro-TWT [32]:

$$\frac{E_1}{E_1(z = 0)} = \frac{\delta_1}{(\delta_1 - \delta_2)(\delta_1 - \delta_3)}$$  \hspace{1cm} (7)

where the three \(\delta_s\) are the imaginary parts of the three forward-wave wavevectors which are solutions to (6). \(E_1\) and \(\delta_1\) correspond to the growing wave. Equations (7) may be used to calculate the launching loss for arbitrary electron beam parameters.

III. DESCRIPTION OF THE SIMULATION CODE

The computer code used to study the high-harmonic gyro-TWT was originally written by Ganguly and Ahn [13] to analyze a rectangular waveguide gyro-TWT operating at the fundamental cyclotron frequency. The code was modified to allow the study of a high-harmonic gyro-TWT interacting with high-order azimuthal TE cylindrical waveguide modes. The modified code could treat any transverse azimuthal or radial mode. In solving the particle/field interaction, the code assumed that the beam electrons follow test-particle orbits in the combined dc magnetic and RF fields. Particle orbits were solved by using the fully relativistic equations of motion. Equations for the guiding center position and phase angle, along with
the transverse and longitudinal momentum, were used. The current generated by the electron beam was then used as a time-dependent source term in the RF field equations. In solving for the RF field, the transverse profile was assumed to be described by a cold-cavity cylindrical waveguide mode. The variation of the RF field amplitude and phase was calculated from Maxwell's equations after time-averaging over the RF field period and spatial-averaging over the waveguide cross section. This self-consistent system of equations for the particles and RF field was solved numerically, with the power gain being computed as the change in the time-averaged RF power obtained by integrating the longitudinal component of the Poynting vector over the waveguide cross section.

IV. THE RF ACCELERATOR

Equation (6) indicates that the coupling between the electrons and the wave is proportional to $|\beta_{\perp} J_{0}(q_{\perp} r_{\perp} / a)|^2$, which can be shown to approximately equal $|\beta_{\perp} J_{0}(n\beta_{\perp})|^2$. It is therefore apparent that optimum interaction calls for very energetic electrons. Several methods for the production of high-$\beta_{\perp}$ axis-encircling electron beams are now under study at various laboratories. For the experiments described herein, gyroresonant RF acceleration was chosen.

In our gyroresonant RF accelerator, a low-energy pencil-like electron beam is passed through a cylindrical cavity resonator which supports a large amplitude TE$_{111}$ circularly polarized mode. The electrons gain energy from the electric field of the mode and spiral outward under the influence of a longitudinal magnetic field to form a hollow, cylindrical, rotating helix whose thickness is roughly the original diameter of the input beam.

This method of beam acceleration [33]-[36] has been shown to be a simple and efficient means of producing electron beams which are appropriate for high-harmonic gyro-tubes [24]. Experimental results have included the acceleration of 200-mA electron beams to 500 keV and peak efficiencies of up to 55%. The fact that gyroresonant RF acceleration does not require high dc voltages is an added benefit which complements the overall aims of the high-harmonic gyro-tube concept.

V. EXPERIMENTAL CONFIGURATION

The interaction waveguide consisted of a 1.0-m length of 2.94-cm-radius cylindrical aluminum waveguide. The design frequency of 16.2 GHz for the desired eighth-harmonic amplifier was chosen using the analytic model of the interaction and also the acceleration characteristics. The desired TE$_{81}$ mode was introduced using the "azimuthal phase velocity coupler" shown in Fig. 2. In this coupler, a rectangular waveguide is wrapped around the cylindrical waveguide, whose radius is such that the wavelength in the rectangular waveguide is equal to the circumference of the rectangular guide midplane divided by $n$. Coupling is established using apertures in the shared wall.

A second identical coupler was used to extract the amplified wave. Cold tests indicated that the couplers launched a circularly polarized wave, with a reflection coefficient of 0.15 at each coupler. Since the expected gain of the device was low, the value of the transmission coefficient was not critical. A reflection of 0.15 at the couplers does not induce oscillation unless the gain exceeds 16.5 dB. Since the expected gain was approximately 10 dB, the quality of coupler achieved was deemed to be adequate.

The gyro-TWT was placed in a vacuum chamber within the bore of a laboratory solenoid. The field was tapered by 15% between the accelerator and the gyro-TWT to increase the axial velocity of the electrons, which lowers the sensitivity of the device to spatial ripple in the magnetic field profile. A peak-to-peak spatial ripple of 1.8% was measured within the interaction region. This ripple was caused by the solenoid actually being comprised of discrete pancake magnets.

The RF diagnostics consist of calibrated crystal detectors and attenuators for the measurement of input and output power, and a heterodyne receiver for the measurement of the output signal's frequency. The electron beam current was measured using a current collector and current transformers. After propagating through the gyro-TWT, the beam passed into either a uranium glass fluorescent witness plate for the determination of the electrons' Larmor radius, or the geometric pitch analyzer shown in Fig. 3 to determine the axial velocity. The first plate incorporated a wedge-shaped radial slit which permitted a fraction of the electron beam to pass. This portion of the beam continued along its helical path until it encountered a second identical aperture plate, followed by a current collector. If the distance between the plates corresponded to an integral number of complete electron orbits, then the electrons were collected by the collector. By translating aperture plate 1 with respect to aperture plate 2 and observing the distances between the plates at which the current collected by the collector is maximized, the pitch of the helix could be determined. This information, together with the magnetic field strength and the electrons' Larmor radius, yields $r_{1}$, $\Delta r_{1}$ may be obtained if one deconvolves the width of the maxima from the width of the radial slit using a Fourier integral. This use of apertures to determine beam properties is similar in principle to one used previously by Barnett [37] and, more recently, by McAdoo et al. [38].
VI. EXPERIMENTAL RESULTS

The dependence of the observed small signal gain on frequency for three operating points is shown in Fig. 4. The measured electron beam parameters for these operating points are summarized in Table I. The magnetic field represents the average magnetic field strength within the interaction region. The bandwidth in Fig. 4(a) is 4.3 percent. Optimum amplification occurred for a value of $n\omega_0$, slightly smaller than that required for grazing incidence of the cyclotron and waveguide modes. A center frequency of 16.25 GHz corresponds to $\omega_0/\omega_{ci} = 1.036 \pm 0.3\%$, whereas from (5) the tangent intersection, and thus peak gain, should occur for $\omega_0/\omega_{ci}$ with $1.059 \pm 1\%$.

The peak gain in Fig. 4(c) is 10.4 dB. When the magnetic field was lowered past this point, sporadic oscillations with a peak amplitude of approximately 50 W and a frequency of approximately 15.8 GHz were observed. The reflection coefficient for each coupler was approximately 0.2 at this frequency. As a result, gain values as low as 14 dB may have led to oscillations caused by external feedback. Alternatively, the oscillations may have been due to an absolute instability.

Fig. 4 also shows the predicted gain for the experimental parameters using the analytic dispersion relationship for the interaction (6) and subtracting the theoretical launching loss found using (7). The predicted peak gain including launching loss was 16 dB, or 5.6 dB higher than the observed peak gain. It is believed that this discrepancy was caused by the spatial ripple of the magnetic field in the interaction region and by the existence of axial velocity spread in the electron beam.

Fig. 4(b) and (c) also indicates an extremely interesting phenomenon. For certain values of frequency, net absorption of the wave energy was observed. One explanation for the net absorption of wave energy by the electron beam relates to the launching loss. In the initial portion of the interaction region, some of the input wave energy serves to bunch the electron beam. If the gain of the interaction for a particular operating point is sufficiently low, then a large distance is required before positive net gain results. In the operation described in the preceding, the interaction may have been terminated before net positive gain could be achieved.

Fig. 4. Gain as function of frequency for operating points corresponding to the following: (a) $B = 0.1115$ T; (b) $B = 0.1111$ T; and (c) $B = 0.1107$ T. Experimental data (circles) are compared to analytic theory (solid line). Experimental uncertainty is $\pm 1$ dB.

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TABLE I

ELECTRON BEAM PARAMETERS FOR THE OPERATION SHOWN IN FIG. 4
A second explanation for the observed data is based on the presence of velocity spread in the electron beam. Although electrons with low \( v_1 \) have a positive mismatch \( (\Delta \omega = \omega - k_l v_1 - n \Omega, > 0) \) with the wave, and yield net energy transfer to the wave, there may be more electrons that have a negative mismatch with the wave \( (\Delta \omega < 0) \), and hence absorb the wave energy. The overall energy transfer may therefore be from the wave to the electrons. This is most likely to occur when the beam line is above the waveguide line. In the experiments, net absorption of the wave energy appears to have occurred for this situation for the portion of the spectrum where the beam line is above the waveguide line. (Though the magnetic field in Fig. 4(b) is larger than in Fig. 4(c) and smaller than in Fig. 4(a), \( \Omega \), in Fig. 4(b) is actually smaller than in Fig. 4(c) and larger than in Fig. 4(a). This is due to a property of the gyroresonant RF accelerator \[36\]. The accelerator’s output \( \gamma \) increases faster than the magnetic field over most of the accelerator’s magnetic field window.) Since this absorption effect involves the distribution function of the electrons, it is not included in the fluid description of the interaction. The quantitative analysis of this situation requires a kinetic treatment, and is currently being considered by other investigators in the field.

In Fig. 5, the experimental data for the parameters indicated in Table I(a) are plotted together with the predictions of the simulation codes for velocity spreads of 0, 3, and 5%. The solution indicates that the higher frequency waves (larger \( k_l \)) are damped by the beam’s spread in axial velocity. The axial velocity spread as determined through Fourier deconvolution of the data collected by the geometric pitch analyzer and shown in Fig. 6 was 3.5 ± 2 percent. The agreement between the experimental and simulation results is quite good.

The observed gain is plotted as a function of electron beam current in Fig. 7. Fig. 7 also shows the net analytical small-signal gain, found by subtracting the launching loss from the gain given by (6), and the results from numerical simulation of beams with velocity spreads of 0, 3, and 5%. The analytical theory is verified by the cold-beam simulation to within \( \pm 2 \) dB, and the simulation with a 3% spread fits the observed data to within 3 dB.

Spurious output signals were observed as the beam parameters were varied slightly from optimum. The observed frequencies together with their possible source are summarized in Table II.

The output signal at 17.4 GHz is of specific interest since it appears to be related to the \( \mathrm{TE}_{11} \) interaction. The presence of oscillation at this frequency is not surprising when one considers that the bandwidth of the interaction for strong beam to wave coupling extends above the pass-band of the \( \mathrm{TE}_{10} \) rectangular to \( \mathrm{TE}_{11} \) circular waveguide couplers. At 17.4 GHz, the transmission of each coupler was 0.5. Thus only 6 dB of gain was required at this frequency to induce oscillations.

It is surprising that strong oscillations at frequencies corresponding to the \( n = 9 \) and \( n = 11 \) modes were not observed. If parameters are chosen so that gyro-TWT operation occurs for a given harmonic, then excitation of gyro-BWO modes would be expected at higher harmonics. Several factors may have contributed to this situation.
First, the interaction strength decreases for increasing mode number. This may explain why oscillations were not observed for mode numbers higher than 10. Oscillations at the $n = 10$ mode may have been favored over oscillations at the $n = 9$ mode because the observed frequency of 19.9 GHz corresponds to the seventh harmonic of the accelerator RF drive frequency. The accelerator acts to prebunch the electrons at the accelerator drive frequency; thus the beam is partially bunched at harmonics of this frequency. It has been shown that this prebunching action can significantly enhance a gyro-interaction [39].

A rough estimate of the maximum possible efficiency is given by the change of $\gamma$ by which the electrons advance in the wave by $180^\circ$, which can be written as

$$\pi = [n\Omega, (\Delta \gamma / \gamma) + k_l \Delta n_l] \tau$$  \hspace{1cm} (8)

where $\tau$ is the effective duration of the interaction—in this case, the temporal growth rate. It can be shown that the efficiency is then given by

$$\eta = \frac{\Delta \gamma}{\gamma} = 2\pi \beta_R \frac{\Delta \gamma}{\gamma} \left( \frac{\gamma}{\gamma - 1} \right) \left( \frac{c k_l}{\omega_{pe}} \right)$$ \hspace{1cm} (9)

where $k_l$ is the spatial growth rate. For our parameters, the predicted maximum efficiency is 3.5%, whereas simulation of a cold beam yields a peak efficiency of 2.2%.

The saturation characteristics of the amplifier are shown in Fig. 8. The dependence of the observed output power and implied conversion efficiency on the input power are shown together with simulation results for velocity spreads of 0, 3, and 5 percent. Experimental uncertainty of output power is ± 10 percent.

The potential of a higher frequency, scaled device is of tremendous interest. This proof-of-principle experiment was designed to demonstrate the basic operation of the high-harmonic gyro-TWT, and was not intended to be an optimized device. It is clear from the previous discussion that work must be done before one can construct an amplifier which exhibits high performance. However, optimization could result in a wideband amplifier which operates in the millimeter wave at very conservative magnetic field strengths. A 94-GHz tube, for example, operating at the eight cyclotron harmonic with a $\gamma = 1.6$ electron beam would require only 0.7 T of magnetic field.

The RF accelerator for this amplifier would operate at 16 GHz. The increased ohmic losses which one encounters at higher frequency are not a problem in the case of the gyro-TWT. In fact, it has been shown that wall loss can be beneficial, in that it may help to stabilize the amplifier by damping the backward wave [5]. [6]. By improving the beam-to-wave coupling by increasing the electron-beam current to 1 A and energy to 500 keV, an output power of 30 kW with 6-percent efficiency and a gain of 3 dB/cm should be feasible as predicted by theory in (6) and (9). The efficiency can be enhanced by tapering the magnetic field so that electrons remain in resonance as they lose energy [19]. Still higher efficiencies would be obtained through the use of beam-energy recovery techniques.

In summary, the high-harmonic interaction has been applied to a gyro-TWT amplifier. The goal of this work...
was not to produce an optimized high-gain device. Rather, the intention was to develop an understanding of the interaction picture and to demonstrate the viability of the high-harmonic gyro-TWT amplifier. Significant agreement between the experimental results and the predictions of analytic theory and simulation was obtained. This knowledge now permits the design of high-performance millimeter-wave amplifiers based on the high-harmonic gyro-interaction.

ACKNOWLEDGMENT

The authors would like to thank Prof. K. R. Chu for valuable discussions, and E. R. Kroy and H. Cao for their technical assistance. In addition, the authors would like to express their appreciation to W. H. Proud of Proud Services Corp. for his assistance in the restoration of the Hughes Aircraft Co. FLAMR radar transmitter, which was used in the saturation studies. This paper is based in part on a dissertation submitted by D. S. Furuno to the University of California, Los Angeles, in partial fulfillment of the requirements for the Ph.D. degree.

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