A LOW-POWER, HIGH-EFFICIENCY Ka-BAND TWTA

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ABSTRACT

The objective of this NASA-sponsored program with the Hughes Aircraft Company is to develop a high-efficiency, low-power TWTA operating at 32 GHz and meeting the requirements for the Cassini Mission to study Saturn, planned for launch in 1995. The required rf output power of the helix TWT is 10 watts, while the dc power from the spacecraft is limited to about 30 watts. This performance level will permit the transmission to Earth of all the data produced in the mission. In order to achieve this efficiency, several novel technologies are incorporated into the TWT. These advances include an advanced dynamic velocity taper (DVT) characterized by a non-linear reduction in pitch in the output helix section of the TWT and a Lewis-designed multistage depressed collector (MDC) employing copper electrodes treated for secondary electron emission suppression. Preliminary program results are encouraging: rf output power of 10.6 watts has been obtained at 14 mA beam current and 5.2 kV helix voltage with overall TWT efficiency exceeding 40 percent.

INTRODUCTION

Ongoing programs at the Lewis Research Center (LeRC) continue to provide the technologies needed for high-efficiency millimeter wave traveling wave tube amplifiers (TWTA's) for planned NASA deep space missions. One of the current objectives of this program is to develop, in a contractual and cooperative effort with the Hughes Aircraft Company, Electron Dynamics Division and the Jet Propulsion Laboratory, a very high-efficiency low-power TWTA operating in the Ka-band (32 GHz) and meeting the requirements for the Cassini Mission to the environment of Saturn planned for launch in late 1995. Parallel contracts were awarded in 1990 to both Hughes and Varian Associates, Inc. for this program; following the acquisition in 1991 of the Varian space TWT product line by Hughes, the two programs were consolidated. The required rf output power of the TWT, which has been given the designation 955 H, is 10 watts, while the dc input power to the power supply, or electronic power conditioner (EPC) is limited to about 30 watts. Hughes has the responsibility for the design of the EPC. Table I presents a listing of the major objective requirements of the TWTA. Achieving these performance goals will more than double the efficiency of Ka-band TWTA's presently available at this power level and will permit the transmission to Earth of all the data produced in the Cassini Mission. Several Lewis-developed efficiency-enhancing technologies are applied throughout the TWTA to accomplish this, including computer-aided design and experimental development efforts. A major LeRC contribution is the design of an advanced helix dynamic velocity taper (DVT) to significantly improve the interaction between the electron beam and electromagnetic wave in the TWT. LeRC also supplied the design of a spent-beam refocusing section and a multistage depressed collector (MDC) and will provide in-house treatment of the electrode surfaces to suppress secondary electron emission. In addition, Hughes has incorporated other performance-improving features, including the reduction of the TWT's interaction section magnet period to provide for better beam quality and a more efficient cathode support assembly to reduce required heater power. Hughes has the responsibility for the thermal and mechanical design of the TWT.

TWT DESIGN FEATURES

In the helical TWT, the electron beam formed in the electron gun passes through the helical interaction section and the final magnetic section where it is focused for optimum entry into the MDC. The spent beam entering the MDC is then collected at potentials depressed from the circuit potential. Efficiency-enhancing features being incorporated in the this TWT are treated in the following paragraphs.

Electron Gun and EPC: The electron gun is a brazed assembly incorporating an M-type cathode. This cathode consists of a sintered tungsten pellet matrix which is impregnated with BaO (5 parts), CaO (3 parts), and Al_2O_3 (2 parts), and is osmium-coated. The electron gun utilizes an isolated focus electrode for electron beam control, enabling the beam to be turned on and off with a voltage swing of only 150 volts rather that full cathode potential in excess of 5000 volts. This enhances EPC efficiency by eliminating the need for additional transformers and circuitry and also reduces EPC mass. For very low-power tubes such as the one being developed in this program, the cathode heater power required has a significant effect on overall efficiency. The cathode ac heater in this TWT uses a single lead wire with the return

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leg being the molybdenum/rhenium cathode support cylinder itself. In addition, the support cylinder wall thickness used in this heater design is 0.0008 inch (as compared to the more typical 0.001 to 0.002 inch) to minimize heat loss from the cathode and thus conserve energy. The net reduction in required heater power is about 0.5 watt relative to more typical designs.

Dynamic Velocity Taper (DVT): The rf interaction (amplifying) section of the TWT consists in part of a section of constant-pitch helix from the signal input point to a sever, followed by another section of helix with a synchronous constant pitch to the beginning of the DVT helix. This pitch distribution (shown as turns-per-inch) is presented in figure 1. The helix pitch in the input section of the tube was designed for optimum gain from small-signal theory (ref. 1). In this section of the helix, the beam/circuit interaction produces modulation, or bunching of the electron beam. Immediately after the sever and preceding the DVT is a short section of constant-pitch helix which causes a gradual growth in signal strength and a tighter bunching of the beam. The DVT used in this TWT is characterized by a continuous, non-linear reduction in helix pitch from its initial synchronous value at the beginning of the output section to near the end of the helix. The circuit was designed using a two-dimensional large-signal computer code originally developed by Detweiler (ref. 2). The reduction in pitch of the DVT slows the circuit wave, resulting in better synchronization between the circuit wave and electron bunches that form in the electron beam than can be realized with a constant-pitch helix (ref. 3). Independently, both Hughes and Varian have computationally modeled this taper effect. The output circuit ends with a short section of helix having a constant pitch equalling that of the end of the DVT, causing the favorable energy exchange to be continued over a greater length. The overall active length of the helix circuit, including the sever, is 4.504 inches (see fig. 1). The helix inside diameter is 0.0232 inch: the material is tungsten/rhenium 0.003 x 0.006 inch tape which is copper-plated to minimize losses. The helix-supporting dielectric material is pyrolytic boron nitride rods which are oriented to provide for minimum losses.

Magnetic Structure (Magnet Stack): The electron beam is contained within the helix of the TWT by means of a magnetic field imposed by a periodic permanent magnet stack. Recently-developed capability to machine samarium cobalt magnets thinner than previously and with good accuracy enables the individual annular magnets to be precisely fitted around the helix barrel. This in turn permits excellent control of axial beam alignment and repeatable tube-to-tube performance. The ability to fabricate thin individual magnets also allows a reduction in magnetic period, which in turn improves beam stability by reducing electron beam scalloping. The samarium cobalt magnets used in this TWT are 0.060 inch thick. Figure 2 displays tube output circuit bodies with recessed magnet slots which contrast the magnet thicknesses of the most recent development tube and an earlier development model. It should be noted that as the magnet material is machined thinner the diameter must increase to produce the required magnetic field to contain the electron beam. This results in a small tradeoff between increased beam quality and TWT mass.

Multistage Depressed Collector (MDC): After it exits the TWT's interaction helix section, the spent beam passes through a refocusing section which is intended to improve the MDC efficiency by debunching the beam. The refocusing section is a short drift tube within a magnet stack and is located between the rf output coupler and the MDC port. The Detweiler program was employed to design the refocusing section to condition the spent electron beam for optimum entry to the MDC (ref. 4). Within the MDC, the beam is slowed by a retarding electric field, and the electrons arrive at the electrodes with reduced energies. Electrons having the highest energies will reach electrodes at or near cathode potential, while those electrons having less energy will be collected on electrodes at lower energies (ref. 5). To attain a high collector efficiency, the collector electrodes must have low secondary electron emission yield. The MDC design was performed with the use of a computer program developed by Herrmannsfeldt, modified to include consideration of the effects of the secondary electron emission characteristics of the collector surfaces (ref. 6). The calculation procedure predicts the electron trajectories and electric field potentials within the cylindrical boundaries of the MDC geometry as shown in figure 3. The MDC will employ oxygen-free, high-conductivity copper electrodes which will be treated at LeRC for secondary electron emission suppression by means of an ion-bombardment process (ref. 7). A scanning electron microscope photomicrograph of the treated surface is shown in figure 5. The surface, which displays sharply lower secondary electron emission properties relative to the untreated surface, is characterized by a dense uniform array of straight-walled blunt projections with average feature height and separation being about 5 and 3 micrometers, respectively.

Program Status and Concluding Remarks: This is an ongoing development program, with new hardware being fabricated and new performance results emerging on a continuing basis. Test results obtained part-way through the program have been very encouraging. Recent tests with a development TWT essentially identical to the one pictured in figure 5 indicate saturated rf output power to be 10.6 watts at near design conditions with overall TWT efficiency of 40.8 percent. Of particular interest to the system designers is the very low AM/PM conversion ratio of less than 1 degree/dB. Some selected results of these tests are presented in Table II. With planned further design modifications, the overall program objective performance goals are expected to be fully realized.

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TABLE I. - OBJECTIVE REQUIREMENTS FOR THE HIGH-EFFICIENCY Ka-BAND TWTA

Frequency, GHz	31.8 to 32.3
Min. sat. rf output power in band, W	10
Max. dc input power to EPC, W	30
Overall efficiency (incl. htr.), %	43
Saturated gain, dB	38.5
Beam transmission at saturation, %	>99
Dispenser cathode type	M
Helix voltage, kV	< 6
Max. heater power, W	3
Beam focusing	periodic permanent magnet
Refocusing system	periodic permanent magnet
Design lifetime, years	>10

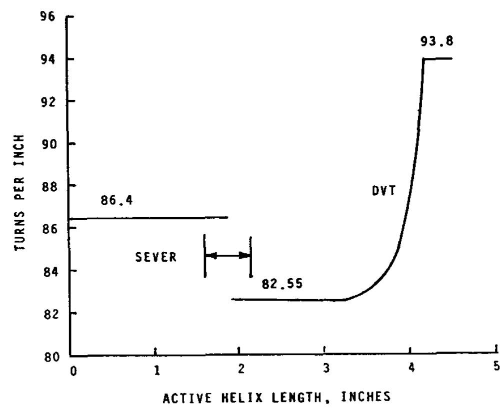

Figure 1. - Helix turns-per-inch distribution for the high-efficiency Ka-band TWT.

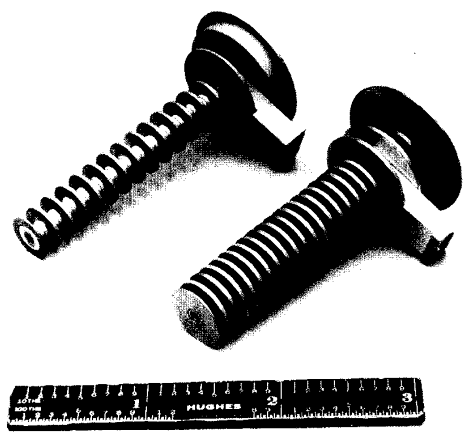

Figure 2. - Ka-band TWT output circuit bodies showing currently-used short-period magnet stack configuration (right) and earlier stack version.

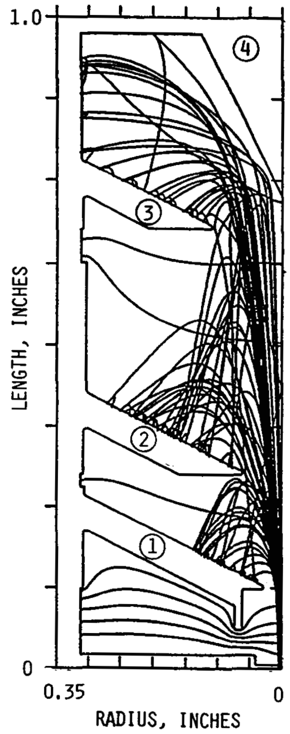

Figure 3. - Computed electron trajectory traces for multistage depressed collector for high-efficiency Ka-band TWT. Stages are numbered (circled) from spent beam entry port. Lines of constant potential are also shown.

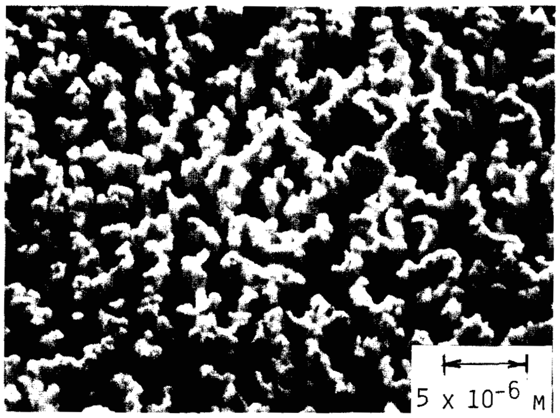

Figure 4. - Scanning electron microscope photomicrograph of molybdenum-masked, ion-textured copper. Angle with surface, 30°.

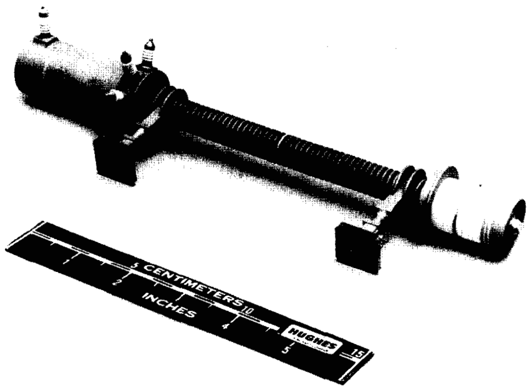

Figure 5. - Development model high-efficiency Ka-band TWT. Multistage depressed collector is at left end of tube.

TABLE II. - SELECTED TEST RESULTS FROM DEVELOPMENT TWT AT 32 GHz, CW

Helix voltage,V		5200
Helix current, mA		0.479
Beam current, mA		14
MDC electrode 1	voltage, V*	2050
	current, mA	2.24
MDC electrode 2	voltage, V	1750
	current, mA	7.73
MDC electrode 3	voltage, V	700
	current, mA	3.64
MDC electrode 4	voltage, V	0
	current, mA	negligible
Saturated gain, dB		36.46
Saturated rf output power, W		10.6
Beam efficiency, %		14.56
Overall efficiency (incl. htr.), %		40.8
Heater power, W		2.988
Phase shift at saturation, deg/dB		less than 1

* MDC electrode voltage shown is difference between helix (cathode) and electrode potentials.