A HIGH-EFFICIENCY 59- TO 64-GHz TWT FOR INTERSATELLITE COMMUNICATIONS

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ABSTRACT

The design of a 75-Watt, 59- to 64- GHz TWT with a predicted overall efficiency in excess of 40% is described. This intersatellite communications TWT, designated the Hughes Aircraft Company Model 961HA, employs a coupled-cavity slow-wave structure with a two-step velocity taper and an isotropic graphite multistage depressed collector (MDC). Because the RF efficiency of this TWT is less than 8%, an MDC design providing a very high collector efficiency was necessary to achieve the overall efficiency goal of 40%.

INTRODUCTION

The development of a space qualifiable, high-power, high-efficiency coupled-cavity TWT for use in future intersatellite link systems operating in the V-band frequency bandwidth of 59- to 64-GHz is near completion. The goal of this program, funded under NASA Contract NAS3-25090, was to produce a PPM-focused coupled-cavity TWT, designated as Hughes Aircraft Company Model 961HA, capable of operating at saturated RF output power levels of 30- and 75-W, with an overall efficiency exceeding 40% over the 5-GHz bandwidth. Table I shows the general characteristics of this TWT. The unique features are the high bandwidth for a coupled-cavity slow-wave structure and the high output power and overall efficiency at V-band frequencies.

Fabrication of the first of two TWTs, 961HA S/N 1, has been completed. Minimum saturated RF output power of 75 W was achieved over 4 GHz of bandwidth under low duty pulse operation. However because of excessive beam interception, CW operation could not be achieved. If the beam interception can be sufficiently reduced in 961HA S/N 2, currently under fabrication, it is expected that the overall efficiency at CW operation will exceed the 40% goal.

CHARACTERISTIC	HIGH-POWER MODE	LOW-POWER MODE
Frequency, GHz	59 to 64	59 to 64
RF output power, W	75*	30*
RF efficiency, %	5.2*	3.5*
Cathode voltage, kV	19.2	19.3
Cathode current, mA	75	45
Perveance, $A/(V)^{3/2}$	0.028×10^{-6}	0.017×10^{-6}

* Minimum value over bandwidth

Table I. General characteristics of Hughes TWT Model 961HA.

ELECTRON GUN

The electron gun employs an M-type cathode operating at 2.0 A/cm^2, consistent with the long lifetime requirement of 10 years. With a perveance of only 28 nanopervs, the gun is designed to produce a 75 mA beam in the high-power mode with a cathode voltage of -19.2 kV. To enable the gun to also provide a 45 mA beam for low-power mode operation, two anodes are utilized. The first is the control anode which operates at approximately ground potential for high-power mode operation and at approximately -5 kV for low-power mode operation. The second is the ion trap anode which operates at a fixed positive voltage of +200 V.

RF CIRCUIT

The RF circuit consists of a total of 169 cavities distributed over three sections. For high interaction impedance and efficiency, the cylindrical cavities have ferrules. To further increase efficiency, the phase velocity (cavity period) was reduced in two steps to 98 and 96 percent of the original value toward the end of the output section.

The circuit design is a refinement of that of Hughes Model 961H, developed in an earlier program (1). The 961HA design corrects a slot mode oscillation problem in the 961H design which was caused by the interception of the beam voltage line with the slot mode dispersion curve at the upper cutoff. To eliminate this problem in the 961HA, the slot mode was shifted down in frequency by narrowing the radial width of the coupling slot and decreasing the slot angle.

MULTISTAGE DEPRESSED COLLECTOR

The use of a multistage depressed collector (MDC) to convert spent electron beam kinetic energy into potential electric energy, thus reducing the power consumed by a TWT, is well established (2). Because the RF efficiency of the 961HA is less than 8% and the program goal was to achieve an overall efficiency in excess of 40%, it was critical to design an MDC with very high collector efficiency. The general characteristics of the MDC are shown in Table II.

Type	Axisymmetric, with one electrode at cathode potential
Number of depressed stages	4
Electrode material	Machined isotropic graphite
Active size	3-cm diam by 5-cm long
Cooling	Conduction to baseplate

Table II. General characteristics of multistage depressed collector for Hughes TWT Model 961HA.

The design procedure for the MDC involved three major steps. In the first step, the NASA 2.5-dimensional large-signal coupled-cavity computer model (3,4) calculated the interaction of the RF circuit field and the magnetic focusing field with the electron beam. In the model, the beam is simulated by a series of 24 disks extending over an axial distance of an RF wavelength, with each disk divided into three axially symmetric rings (the innermost ring is a disk). The RF circuit fields and electron ring trajectories are determined from the calculated axial and radial space-charge, RF, and PPM focusing forces as the rings pass through the sequence of cavities. The model was used to determine the trajectories of each of the rings at the RF output (5).

The second step in the MDC analysis was the modeling of the electron ring trajectories in a short transition tunnel with PPM focusing located between the RF output and the MDC. (The purposes of the transition tunnel are to make room for the output circuit assembly and to provide spatial isolation between the RF output and any backstreaming current from the MDC.) The same computer model that simulated the trajectories in the TWT RF circuit was used in the transition tunnel. The transition tunnel was designed to be of length equal to three magnetic half-periods and of radius equal to a 50% expansion of the RF circuit tunnel radius. Fig. 1 shows the simulated electron ring trajectories at the end of the RF circuit and through the transition tunnel for the high-power mode case at 61.5 GHz.

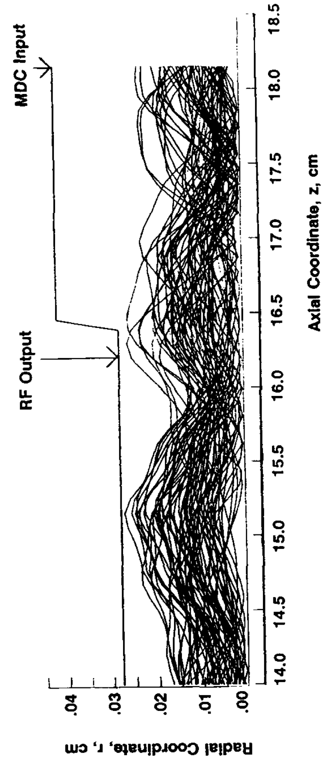

Fig. 1. Computed electron ring outer radii trajectories for the high-power mode at the end of the RF circuit and in the transition tunnel. Dashed vertical lines indicate zeroes of the periodic-permanent-magnet focusing field.

The third step of the MDC design procedure involved the calculation of the electron ring trajectories after the spent beam exits the transition tunnel and enters the MDC. This was accomplished with Herrmannsfeldt's electron trajectory program (6) in which each electron ring trajectory was treated as a continuous ray of current. The trajectory calculations were continued until the current rays impacted the MDC electrodes. The effect of secondary-electron emission from electrode surfaces was analyzed by injecting reduced charges at the points of impact of the primary current rays and tracking their trajectories to their final termination within the MDC or TWT. Based on the final location of the primary and secondary charges, a calculation was made of the collected current, recovered power, and dissipated power at each of the collector electrodes and, if back-streaming occurs, at the TWT itself.

Based on these results, the MDC design was optimized for the high-power mode by primarily using the beam-RF interaction model results from saturated operation at midband. The MDC geometry, the applied optimum potentials, the equipotential lines, and the charge trajectories in the final MDC design are shown in Fig. 2 with the TWT operating in the high-power mode at saturation at 61.5 GHz. The collector efficiency (percentage of power recovered from spent beam) is 94.7%. Optimizing the collector potentials for low-power mode operation also results in a collector efficiency of 94.7%. Contributing to this very high value were the relatively small velocity spread in the beam, a large MDC/beam radius ratio, and the effective suppression of low energy secondary-electron-emission current by the use of machined isotropic-graphite electrode surfaces (7).

The corresponding saturated overall efficiencies at 61.5 GHz are calculated to be 48.6% for the low-power mode and 51.0% for the high-power mode. The TWT computer analysis almost certainly underestimates the actual RF circuit and beam interception losses; therefore, the computed overall efficiencies of about 50% are overly optimistic. Recomputing the more realistic overall efficiencies with the assumptions of 2% DC beam interception and an effective circuit efficiency of 80% at 61.5 GHz (5) gives values of 38.6% for the low-power mode and 44.8% for the high-power mode.

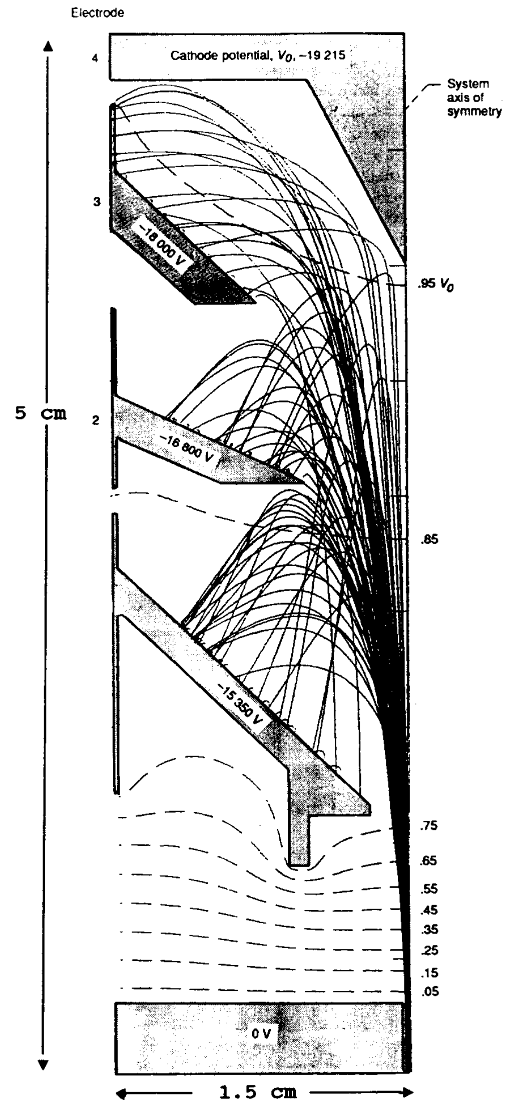

Fig. 2. Computed charge trajectories and equipotentials in the multistage depressed collector at 61.5 GHz, with operation at optimum voltages in the high-power mode.

EXPERIMENTAL RESULTS

Experimental results under low duty pulse operation have been obtained for the 961HA S/N 1 TWT. Fig. 3 shows that minimum saturated output power of 75 W was achieved over 4 GHz of bandwidth. However there are large gain variations due to a high mismatch in the output section. Also, the beam focusing of S/N 1 could not be improved beyond 89%, making CW operation impossible.

Table III shows the measured efficiencies of S/N 1 compared to the calculated values. Because of the excessive interception of 11% at RF saturation, the overall efficiency of 32.2% is much lower than the design goal value of 40%.

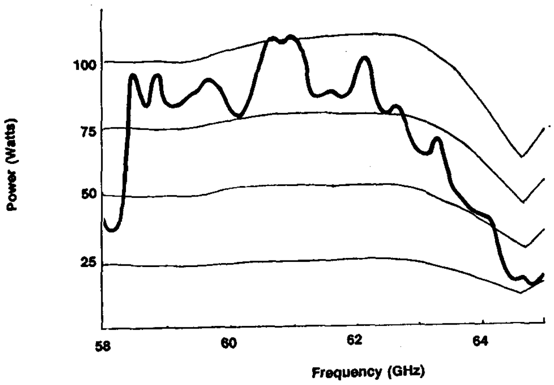

Fig. 3. Experimental saturated RF output power for 961HA S/N 1 at 0.5% duty pulse, high-power mode operation with cathode voltage at -19.2 kV and cathode current at 67.0 mA.

Efficiency	Measured	Calculated
RF	7.95%	6.99%
Collector	93.9%	94.3%
Overall	32.2%	44.8%

Table III. Measured versus calculated efficiencies for 961HA S/N 1 at high-power mode operation. Measured values taken at optimum frequency of 60.7 GHz. Calculated values are at midband frequency of 61.5 GHz.

CONCLUSIONS

Despite a high degree of electron interception by the slow-wave circuit, operation of the 961HA S/N 1 TWT at a low duty cycle produced a minimum RF output power of 75 W over a bandwidth of 4 GHz. Measurements indicated a very high MDC efficiency of 93.9%, very close to the computed value. Thus if the DC beam interception design goal value of 2% can be obtained with S/N 2, currently under fabrication, it is expected that the overall efficiency at CW operation will exceed the 40% goal. This would result in a high-bandwidth, high-power, high-efficiency TWT operating at V-band frequencies.

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