High Power and Efficiency Space Traveling-Wave Tube Amplifiers with Reduced Size and Mass for NASA Missions

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Abstract— **Recent advances in high power and efficiency space traveling-wave tube amplifiers (TWTAs) for NASA's space-to-Earth communications are presented in this paper. The RF power and efficiency of a new K-Band amplifier is 40 Watts and 50% and that of a new Ka-Band amplifier is 200 Watts and 60%. An important figure-of-merit, which is defined as the ratio of the RF power output to the mass (W/kg) of a TWT has improved by a factor of ten over the previous generation Ka-Band devices.**

Index Terms — **Amplifiers, Traveling wave tubes, Space technology, Microwave power amplifiers, Power conditioning, Satellite communication, Millimeter wave power amplifiers, Millimeter wave tubes.**

I. INTRODUCTION

Signals transmitted from spacecrafts orbiting the outer planets or from the vicinity of the lunar surface need to travel enormous distances to ground antennas. In addition, as the distance from the sun increases, the amount of solar energy that is available for conversion to electrical power on board the spacecraft decreases. Hence, there is a need for developing reliable space amplifiers, which are capable of delivering high RF power as well as operating with very high efficiency [1]. In addition, these amplifiers need to be lightweight and small in size. The two possible solutions to this problem are based on either solid-state or microwave vacuum electronics technology. Solid-state devices based on GaAs or GaN high electron mobility transistor (HEMT) technology, when characterized on-wafer using load-pull techniques, deliver only about 2 to 3 watts of RF power at Ka-Band frequencies [2]. Although these devices have efficiencies as high as 35 to 40%, the efficiency of the multi-stage monolithic microwave integrated circuit (MMIC) power amplifier (PA), built around these devices, is on the order of 25 to 30% due to additional circuit losses. In addition, when the output of several MMIC PAs are combined to realize a high power Ka-Band solid-state power amplifier (SSPA), the overall efficiency further drops to 15 to 20% due to combiner losses. Furthermore, the low efficiency results in thermal management issues, which impacts reliability. On the other hand, for space applications, microwave vacuum electronics based devices such as helix traveling wave tubes (TWTs) have demonstrated reliability at higher microwave frequencies with power output in the range of 10 to several hundred watts and corresponding efficiency in the range of 40 to 60 % [3, 4].

Communication from the vicinity of the Moon is considered to be near-Earth while that from the planets of our solar system is considered to be from deep space. The corresponding frequency band designated for near-Earth is 25.5 to 26.5 GHz (K-Band) and for deep space communications is 31.8 to 32.3 GHz (Ka-Band). In this paper, we present the microwave performance of a new K-Band helix TWT for near-Earth communications and also a new Ka-Band helix TWT for deep space communications. Both of these units are manufactured by L-3 Communications, Electron Technologies Inc. (ETI) under contracts from NASA Glenn Research Center (GRC).

II. TWT DESIGN AND MODELING

In the early eighties, the design of TWTs was mainly done through trial and error, which was time consuming and expensive. The advances made in desktop computing and electromagnetic simulation/optimization tools have enabled the first pass design success of modern TWTs. These include the U.S. Naval Research Laboratory's CHRISTINE 3-D Code for high efficiency slow-wave interaction circuit and MITCHELLE 3-D Code for multistage depressed collector design [5]-[7]. In addition, efficient thermal modeling/simulation tools are also available, which have enhanced the power handling capability of TWTs by integrating efficient conduction cooled packages. Furthermore, advances in materials technology have resulted in lightweight, temperature stable, high BH product samarium cobalt permanent magnets, which are used in focusing the electron beam. Moreover, advances in tungsten/osmium cathode technology have resulted in cathode lifetimes exceeding 20 years in space [8].

III. K-BAND AND KA-BAND SPACE TWT REQUIREMENTS

The K-Band TWT was developed for communications from the Lunar Reconnaissance Orbiter (LRO) spacecraft to Earth. The specifications for the model 9835H K-Band TWT are shown in Table I .

The Ka-Band TWT was developed for communications from a spacecraft orbiting any of the outer planets, such as Jupiter or its icy Moons. The specifications for the model 999HA Ka-Band TWT are shown in Table II.

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To transmit data from Jupiter at very high rates on the order of Mb/s, the spacecraft transmitter power has to be on the order of 1 kW. To achieve this kind of power level, the outputs from four of the above TWTs would be combined. Combining efficiency as high as 90% has been demonstrated at Ka-Band frequencies for a two-way combiner.

Both the K-Band and Ka-Band TWTs have four-stage depressed collector circuits for high efficiency. The collector circuits require high voltages, which are provided by a separate electronic power conditioner (EPC), which is attached by an umbilical power cord to the TWT.

Table I
TWT Model 9835H K-Band TWT Specifications

Parameter	NASA Specifications
Frequency Band	25.5-25.8 GHz
Output Power (CW)	40 W min
Saturated Gain	46 dB min
Sat. Gain Flatness	0.5 dB min
AM-to-PM	4.5 deg/dB max
VSWR	2.0:1 max
Overall Efficiency	44 % min
Overdrive	+6 dB
Mass	<1750 gm
Size	37 x 9 x 9 cm
Input/Output Ports	WR-34 waveguide
Operating Life/Mission Life	14/26 months
Environment	Lunar orbit

Table II
TWT Model 999HA Ka-Band TWT Specifications

Parameter	NASA Specifications
Frequency Band	31.8-32.3 GHz
Output Power (CW)	180 W min
Saturated Gain	50 dB min
Sat. Gain Flatness	0.25 dB min
AM-to-PM	4 deg/dB max
VSWR	1.5:1 max
Overall Efficiency	55 % min
Overdrive	+5 dB
Mass	<1750 gm
Size	37 x 9 x 9 cm
Input/Output Ports	WR-28 waveguide
Operating Life/Mission Life	7/20 yrs
Environment	Deep space

IV. K-Band and Ka-Band TWT Measured Performance

A. *Model 9835H K-Band TWT*

Three TWTs were manufactured and characterized and all three meet full specifications, resulting in first pass design success and 100% yield. The measured output power, overall efficiency, and saturated gain of the three TWTs are summarized in Table III.

B. *Model 999HA Ka-Band TWT*

A photograph of the fully packaged Model 999HA TWT is shown in Fig. 1. Three such TWTs were manufactured and characterized, and three units were able to demonstrate 180 watts. The TWT S/N 202 was tested up to 250 watts and set up at 200 watts for additional flight qualification testing. The measured overall efficiency and saturated gain of this TWT exceeded 60% and 55 dB, respectively. The measured characteristics are presented in Figure 2.

Table III
LRO Program Goals and Performance Data of Model 9835H K-Band TWT at f_0 = 25.65 GHz

Performance Parameters	LRO Program Goals
RF Power Output (CW) (Watts)	40
Overall Efficiency (%) (Min)	44
Saturated Gain (dB) (Min)	46
Model 9835H TWT S/N 201	
RF Power Output (CW) (Watts)	41.90
Overall Efficiency (%) (Min)	50.84
Saturated Gain (dB) (Min)	47.85
Model 9835H TWT S/N 202	
RF Power Output (CW) (Watts)	41.79
Overall Efficiency (%) (Min)	45.93
Saturated Gain (dB) (Min)	47.10
Model 9835H TWT S/N 203	
RF Power Output (CW) (Watts)	41.92
Overall Efficiency (%) (Min)	51.15
Saturated Gain (dB) (Min)	47.00

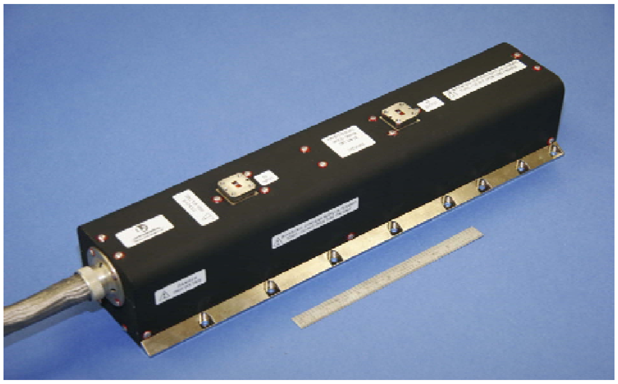

Fig. 1. The Model 999HA Ka-Band space TWT in a conduction cooled package.

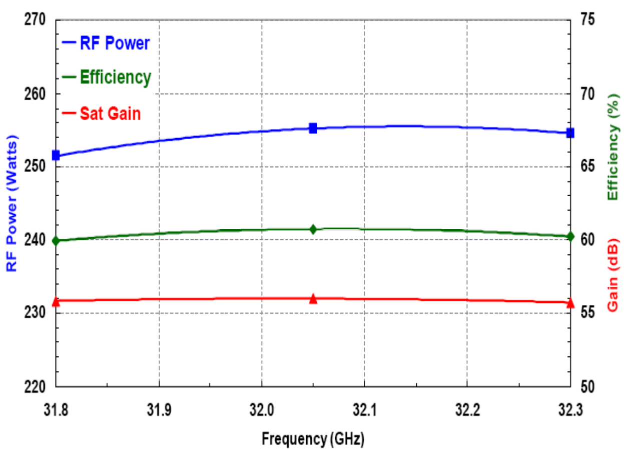

Fig. 2. Measured performance of Model 999HA space TWT over design bandwidth.

V. Electronic Power Conditioners (EPC)

The model 2300HE 7-kV electronic power conditioner (EPC) is mated with the 40-Watt K-Band TWT and the model 1693HC 14-kV EPC is mated with the 180-Watt Ka-Band TWT to form two new TWT amplifiers. These EPCs are also manufactured by L-3 Communications ETI. These EPCs are highly reliable and efficient (90%). They can operate from either regulated or unregulated space-craft bus voltages. The mass and dimensions of the TWT and the EPC are summarized in Table IV.

Table IV
Mass and Dimensions of TWT and EPC

Device Type	Mass (gm)	Dimensions (cm) L x W x H
9835H K-Band TWT	1500	35.1 x 8.9 x 8
2300HE 7-kV EPC	1300	19.8 x 6.7 x 10.2
999HA Ka-Band TWT	1600	36.6 x 8.9 x 7.1
1693 HC 14-kV EPC	4300	33.8 x 12.2 x 13.7

VI. Conclusions and Discussions

The performance parameters of a K-Band TWT for NASA's near-Earth and a Ka-Band TWT for deep space communications are presented. These results are state-of-the art and provide unprecedented performance. Prior to this development, the highest CW RF power produced by a space TWT at Ka-Band and flown in space is the Model 910H TWT manufactured by L-3 ETI for the Cassini-Huygens Mission with 10 Watts, 41 % overall efficiency, and mass of 750 gm. The figure-of-merit (FOM) is defined as the ratio of the RF power output to the mass (W/kg), which for this TWT is about 13. In contrast, the Ka-Band Model 999HA traveling wave tube presented in this paper has a FOM of 133, which is an improvement by a factor of ten over the previous generation TWTs.

Acknowledgments

The authors greatly appreciate the excellent support we received from Neal R. Robbins, Daniel R. Dibb, Dr. W.L. Menninger, Dr. Xiaoling Zhai, Robert Benson, James Burdette, David E. Lewis, and Paul C. Spitsen at L-3 Communications, Electron Technologies Inc.

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