High-Efficiency K-Band Space Traveling-Wave Tube Amplifier for Near-Earth High Data Rate Communications

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Abstract — The RF performance of a new K-Band helix conduction cooled traveling-wave tube amplifier (TWTA), is presented in this paper. A total of three such units were manufactured, tested and delivered. The first unit is currently flying onboard NASA's Lunar Reconnaissance Orbiter (LRO) spacecraft and has flawlessly completed over 2000 orbits around the Moon. The second unit is a proto-flight model. The third unit will fly onboard NASA's International Space Station (ISS) as a very compact and lightweight transmitter package for the Communications, Navigation and Networking Reconfigurable Testbed (CoNNeCT), which is scheduled for launch in 2011. These TWTAs were characterized over the frequencies 25.5 to 25.8 GHz. The saturated RF output power is >40 W and the saturated RF gain is >46 dB. The saturated AM-to-PM conversion is 3.5°/dB and the small signal gain ripple is 0.46 dB peak-to-peak. The overall efficiency of the TWTA, including that of the electronic power conditioner (EPC) is as high as 45%.

Index Terms — Amplifiers, microwave power amplifiers, traveling-wave tubes (TWTs), satellite communication, transmitters.

I. INTRODUCTION

The Lunar Reconnaissance Orbiter (LRO) is the first mission in NASA's Vision for Space Exploration, a plan to return to the Moon and then to travel to Mars and beyond. The LRO objectives are to find safe landing sites, locate potential resources, characterize the radiation environment, and demonstrate new technology [1]. NASA desires to transmit to Earth the planetary science data and video images of the Moon from the LRO at much higher data rates than the Apollo missions. The higher data rate requires higher power microwave amplifier. The amplifier has to have high efficiency since the DC power onboard the LRO is limited. In addition, the amplifier has to have very high reliability since the LRO operates in a harsh environment with high radiation and extreme temperatures, which extends over two years.

Vacuum electronics based devices for space applications such as helix traveling wave tube amplifiers (TWTAs) have demonstrated high on-orbit reliability at microwave frequencies [2]. In addition, TWTAs can deliver much higher RF output power with higher efficiency at K-Band/Ka-Band frequencies than MMIC based solid-state power amplifiers (SSPAs) [3, 4].

In this paper, we present the RF performance characteristics of a new K-Band helix conduction cooled space traveling-wave tube amplifier (TWTA). A total of three such units were manufactured and are fully compliant with the required specifications. The first unit is currently flying onboard the NASA's Lunar Reconnaissance Orbiter (LRO) spacecraft. A photograph of the fully packaged LRO TWT and electronic power conditioner (EPC) is shown in Fig. 1. The second unit was set aside as a proto-flight model and subjected to higher degree of mechanical shock and vibrations to evaluate the performance margins. The plan is to fly this unit as a spare on a future mission. The third unit will fly onboard NASA's International Space Station (ISS) as a very compact and lightweight transmitter package for the Communications, Navigation and Networking Reconfigurable Testbed (CoNNeCT), which is scheduled for launch in 2011. The CoNNeCT will investigate reprogrammable radio technology for use during space missions. This investigation will advance a common, software defined radio (SDR) architecture standard for future use on long duration space exploration missions. In addition, CoNNeCT will demonstrate communications from the ISS to the Tracking and Data Relay Satellite (TDRS) constellation at K-Band frequencies [5]. The above three amplifiers were manufactured by L-3 Communications Electron Technologies Inc., (ETI) under a contract from NASA Glenn Research Center (GRC).

Fig. 1. Photograph of the LRO 40-W K-Band traveling-wave tube in a conduction cooled package attached by an umbilical power cord to an electronic power conditioner located in the background. The TWT input/output waveguide ports are WR-34.

II. Traveling-Wave Tube Amplifier Design and Modeling

Modern electromagnetic simulation/optimization software tools enabled the first pass design success. These software tools include the U.S. Naval Research Laboratory's CHRISTINE 3-D Code for high efficiency slow-wave interaction circuit and MICHELLE 3-D Code for multi-stage depressed collector design [6-8]. In addition, thermal modeling/simulation tools enabled the design of an efficient conduction cooled package [9], which enhanced the power handling capability of TWT. Furthermore, advances in materials technology resulted in lightweight, temperature stable, high BH product samarium cobalt permanent magnets, which enabled focusing the electron beam. Moreover, advances in tungsten/osmium cathode technology resulted in cathode lifetimes exceeding 20 years in space [10].

The baseline design for the LRO TWT was the model 999HA Ka-Band TWT [9], which made use of WR-28 waveguide-based input and output couplers. NASA recommended replacing the WR-28 waveguide couplers by larger WR-34 waveguide couplers in the LRO TWT. The advantages are: first, it eliminated the need for a tapered transition from WR-28 to WR-34 waveguide, reducing the overall height of the packaged TWT. Second, it resulted in thicker and larger diameter quartz windows for the vacuum seals inside the TWT, which provided additional strength to withstand mechanical shocks and vibrations and thus enhanced reliability. The proto-flight model TWT test results clearly demonstrated that this was the case. Third, the WR-34 waveguide operates across the frequency range of 22 to 33 GHz, which includes the frequency bands of interest for NASA's near-Earth communications. Thus with a minor design change in the helical slow wave circuit, the LRO TWT design can be optimized to meet future near-Earth NASA mission requirements without the need for re-qualification. The WR-34 waveguide lowered the total attenuation of the signal in the waveguide run between the TWT output and the antenna, which enhanced system efficiency.

III. Requirements for the Lunar Reconnaissance Orbiter Traveling-Wave Tube Amplifier

A brief set of requirements for the LRO TWT and EPC are presented in Tables I and II.

TABLE I
EPC Specifications

Parameter	NASA Specifications
Voltage	7 kV
Mass	1300 gm
Size	20(L) x 7(W) x 11(H) cm

TABLE II
TWT Specifications

Parameter	NASA Specifications
Frequency Band	25.5 to 25.8 GHz
Output Power, CW	40 W min
Saturated Gain	46 dB min
Gain Flatness (peak-to-peak)	0.5 dB max
Phase (peak-to-peak)	8 deg max
AM-to-PM	4.5 deg/dB max
VSWR	2.0:1 max
Overall Efficiency	44 percent min
Overdrive	+6 dB
Mass	1500 gm
Size	37(L) x 9(W) x 9(H) cm
Input/Output Ports	WR-34 waveguide
Operating Life/Mission Life	14/26 months
Environment	Lunar orbit

IV. Lunar Reconnaissance Orbiter Traveling-Wave Tube Amplifier and Performance Characteristics

The TWT has a four-stage collector circuit for high efficiency. The collector circuit requires high voltages, which are provided by a standalone 7-kV EPC, which is attached by an umbilical power cord to the TWT. The EPC is designed to operate from an unregulated spacecraft bus voltage in the range of 21.25 to 35 V. The EPC has also a telemetry interface to the spacecraft bus, which provides the ON/OFF state of the TWTA as well as the anode voltage, helix current and the RF output power. The construction of the EPC is explained in [9]. The TWTA was characterized over the frequencies 25.5 to 25.8 GHz reserved for NASA's near-Earth communications. The measured data reported here are at a nominal spacecraft bus voltage of 31 V and ambient temperature of 25 °C.

A. RF Output Power and Phase Shift

The measured relative RF output power and phase shift as a function of the input drive level is presented in Fig. 2. These measurements were carried out at the center frequency of 25.65 GHz. The output power at saturation is 46.22 dB or 41.88 W, which exceeds the requirements of 40 W. The phase shift through the amplifier, as the input drive is increased from small signal to saturation drive, is about 30°. The saturated gain compression is 6.09 dB and the saturated AM-to-PM conversion is 3.5°/dB.

B. Saturated RF Gain

The measured saturated RF gain as a function of the operating frequency range is presented in Fig. 3. The saturated RF gain is about 49.25 dB across the operating frequency range and exceeds the requirements of 46 dB.

C. Saturated RF Output Power

The measured saturated RF output power as a function of the operating frequency range is presented in Fig. 4. The saturated RF output is about 46.25 dB or 42.17 W across the frequency range and exceeds the end of life (EOL) requirements of 40 W.
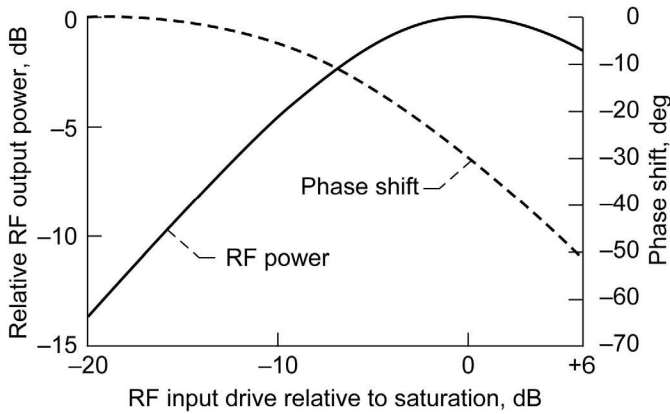
Fig. 2. Measured relative RF output power and phase shift as a function of the RF input drive relative to saturation at the center frequency of 25.65 GHz.
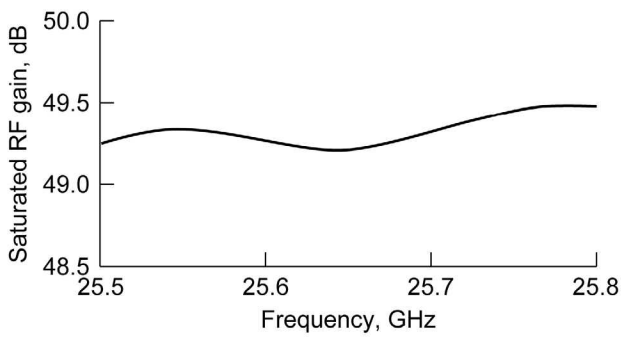

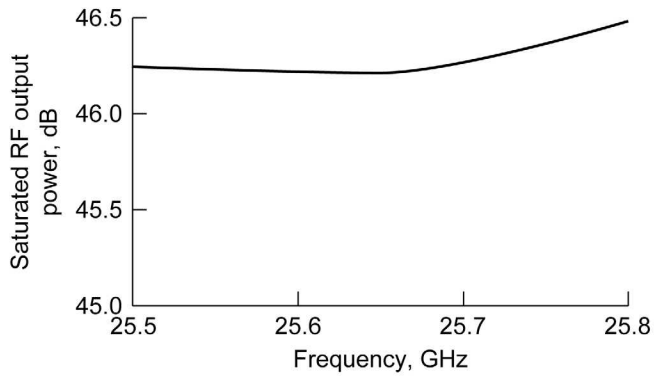Fig. 3. Measured saturated RF gain as a function of frequency.

Fig. 4. Measured saturated RF output power as a function of frequency.

D. Overall Efficiency

The efficiency of the TWT alone is 55.2%. However, when the efficiencies of the TWT and the EPC are combined, the overall efficiency of the TWTA is about 45%. The measured overall efficiency as a function of the operating frequency range is presented in Fig. 5. The overall efficiency exceeds the requirements of 44%.
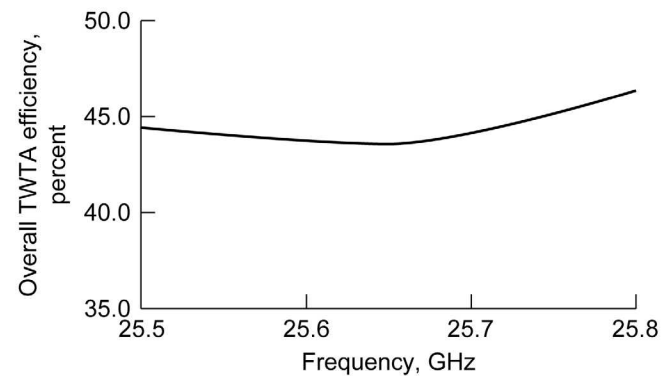

Fig. 5. Measured overall TWTA efficiency as a function of frequency.
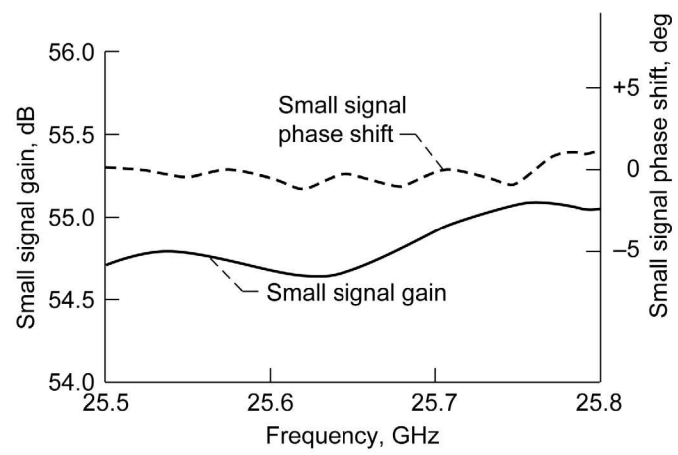

Fig. 6. Measured small signal gain and phase shift as a function of frequency.

E. Noise Figure and Second Harmonic Level

The measurements made at the center frequency of 25.65 GHz show that the noise figure is 29.97 dB and the second harmonic level is 23.52 dB below the fundamental.

F. Small Signal Gain and Phase Shift

The measured small signal gain and residual phase shift as a function of the operating frequency range is presented in Fig. 6. The small signal gain ripple is 0.46 dB peak-to-peak, which is within the requirements. The residual peak-to-peak small signal phase after subtracting the linear phase component corresponding to a group delay of 3.798 nS is 2.02°, which is also within the requirements.

G. Input/Output VSWR

Figures 7(a) and (b) present the measured input/output return loss as a function of frequency. These results indicate that the input/output VSWR is in the range of 1.4 to 1.7, over the operating frequency range of 25.5 to 25.8 GHz, which is within the requirements.
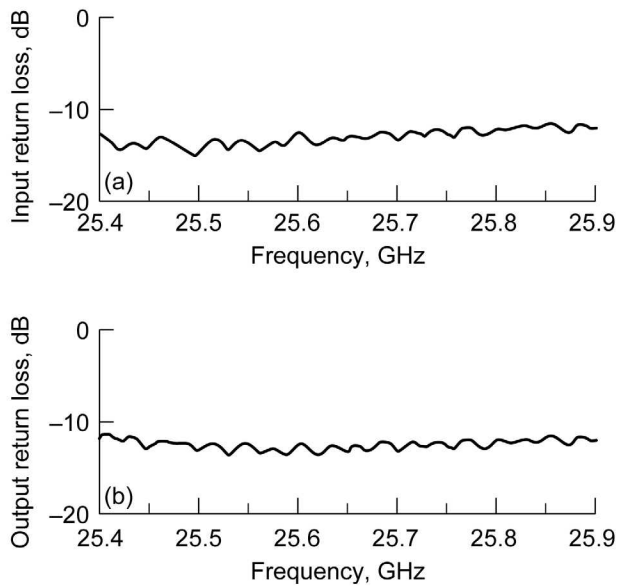
Fig. 7. Measured return loss as a function of frequency. (a) Input port (b) Output port.

H. Data Rate

The LRO downlink data rate that this TWTA enables is on the order of 100 Mbps. The modulation is OQPSK. The total volume of data received on Earth per day is on the order of 450 Gb. Compared with the previous Apollo missions to the Moon, the new technology offers several orders of magnitude improvement in data rates and volume.

I. EMI/EMC

The input filter in the EPC was designed, manufactured and implemented within the physical limitations of the EPC package. This filter did not adequately suppress the conducted emissions from the EPC to the bus. Hence, in order to meet the LRO requirements an external LC filter, which effectively reduced the nonconformance to zero, was designed, manufactured and inserted between the EPC and the bus.

V. Conclusions And Discussions

The performance parameters of a state-of-the-art compact lightweight K-Band TWTA for NASA's LRO and the CoNNeCT are presented. The saturated RF output power exceeds 40 W and saturated RF gain exceeds 46 dB. The saturated AM-to-PM conversion is 3.5°/dB and the small signal gain ripple is 0.46 dB peak-to-peak. The overall efficiency including that of the EPC is as high as 45%. The LRO downlink data rate that this TWTA enables is as high as 100 Mbps, which is several orders of magnitude higher than the Apollo mission. The mass and size of the TWT and the EPC are fully compliant with the specifications presented in Tables I and II.

The TWTA onboard the LRO spacecraft has flawlessly completed over 2000 orbits around the Moon since its launch in June 2009. An independent judging panel and the editors of the R&D Magazine recognized the TWTA as one of the 100 most technologically significant products introduced in the past year and awarded it the 2009 R&D 100 Award. In addition, the LRO was chosen as #3 on Time's 50 Best Inventions of 2008. Furthermore, the December 2009 issue of Popular Science has named the LRO as one of the 100 Best Innovations of the year.

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