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Travelling-Wave Tubes for Space Application: Present and Future

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Abstract

Traveling wave tube amplifiers (TWTAs) and solid-state power amplifiers (SSPAs) are the two main RF amplifiers for onboard communications satellites. In fact, TWTAs are the first successful RF power amplifier technology for communication systems since the birth of space age and covers ~ 60% global market among vacuum tubes for various applications. Both uplinked and downlink signals experience substantial losses and hence must be suitably amplified. However, demand for high power, high frequency, wideband, high efficiency and with the advancements technology such as linearization, miniaturization, weight reduction, etc. makes TWTAs superior compare to SSPAs and also in the family of vacuum microwave devices and resulting TWTAs as the best choice and no other amplifiers can give similar performance. With advancement of state-of-the-art TWTs for space communication, for instance, wideband, high power, gain efficiency, reliability, light weight etc make realization of space TWT more and more complex and challenging. However, many of the older version of TWTs have been replaced by its counterpart, SSPA, in L, S, C and X bands where both power and bandwidth requirements were limited. In present generation of TWTs, C, X, Ku and Ka band TWTs are being used with wideband width and much higher performances where SSPAs cannot rival. In addition to that, with the agility of wideband, high frequency, much higher performance in a single device for next generation realization of space TWTs in above band including W band and so on becoming a challenge to designers. This paper, presents the state-of-the-art space TWTs for present and future communication satellites.

1. Introduction

The TWT is a vacuum electron device that consists of an electron gun, a slow wave structure (SWS), a magnetic focusing system, RF input and output couplers, and a collector (Fig. 1). The electron gun of a TWT with a suitable conditioned power, emits electron beam — focused through a magnetic focusing system and thrown into interaction structure for amplification in the interaction structure —the slow-wave structure (SWS), after exchange power through couplers finally gets collected in collector. For long life and reliable applications, a simple helix SWS and a M-type disperser cathode have extensively been used. The former one provides the greatest dispersion control and widest operating bandwidth and the latter one provides high bean currents and capable of surviving and functioning under several severe qualification conditions over 15-20 years. However, new methods for cathode fabrication to replace M-type cathode with a micro-fabricated silicon substrate with enhanced electric field features is a challenge for both designers and developers. Approximately 70% of the total consumed power by a TWT is converted into RF energy, and the remaining 30% is converted to waste heat and dumped in the collector. Hence, one need to primarily focuses for improving TWT efficiency by recovering waste heat.

In general, TWTs are uniquely identified in terms of their saturated power level — threshold for output power for saturated input level. Hence, TWTAs are often operate at an RF output 'back off' from saturation or else conversion of consumed power into desired RF power decreases which increases waste heat in the collector. However, if the TWT is operated at saturation and or higher input drive level, intermodulation distortion (IMD) causes interference generating unwanted frequencies and, hence, must both be carefully engineered to minimize power consumption and IMD. TWTs yield higher data rates and greater bandwidth than their alternatives because these devices are generally capable of providing high power at high frequencies with better efficiency and can operate at higher temperatures for 15–20 years.

Due to modern-day state-of-art design concepts and technological innovations TWTs have undergone several evolutions and significant progress has been made over the past decade. Present satellites are prone to use flexible TWTs —voltage adjustable TWTs. These types of TWTs redistribute available power through a telecomm and to modify anode voltage, which changes the output power and life of the TWT due to conservation of power. Variation of anode voltage yields a different cathode current producing different TWT gain and output power. Moreover, modern-day TWT technology has experienced substantial advancements with design changes focusing on increasing RF power output, efficiency, and packaging compactness. Space-qualified TWTs in all frequency bands between L-band and Ka-band. These TWTs have efficiencies of up to 72% and power ranges from as low as 20W (in C-band, X-band, and Ka-band) to as high as 300W. TWTA efficiencies are currently in the mid to upper 60%, which is the combined efficiency of the EPC (~94%) and TWT (~72%), respectively. In terms of mass and size, the TWT mass ranges from 0.76 to 3.2 kg, and the size ranges from280 × 75 × 65 mm for K-band to 700 × 160 × 160mm.

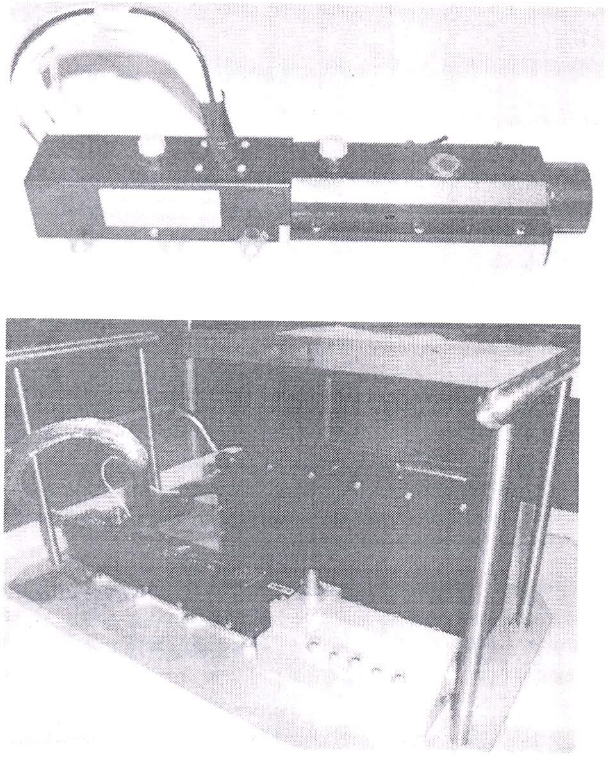

Figure 1. High efficiency TWTs, developed at CSIR-CEERI

2. Future traveling wave tube amplifiers technology:

As discussed, TWT technologies have had significant improvements over the past decades, but it is not about future game-changing advancement for the TWT. Meanwhile, TWT designers and developers are continuously working to refine TWT with respect to frequency, bandwidth, power, gain, efficiency, weight and size reduction, reliable life enhancement, cost reduction, etc. One potential advancement or future change for the TWT is the increased use of Mini-TWTs. Mini-TWTs are a shorter, lighter, and lower-power version of the traditional TWT but are not able to reach as high of RF output power. Mini-TWTs are considered advantageous as they can provide a 5:1 reduction in size and weight as well as a 50% improvement in efficiency. Mini-TWTs also serve as the basis of microwave power modules, which are compact units that consist of a solid-state RF power amplifier and a mini-TWT integrated with power and control circuits.

Thus, realization of present and future TWTs demand state of art design concepts, technological innovations with exploration of newer smart materials for state-of-the-art performance with reduction in size and weight. Advance modelling such as, linking large signal, existing 3-D electromagnetic and particle-in-cell codes to form a single modeling and simulation environment through development of software architecture through end-to-end modeling for analysis, synthesis, and optimization that lead to first pass design success. Development of simulation environment and access compatibility with current engineering techniques and advanced manufacturing technologies and demonstration in vacuum electron devices, namely, helix TWT. Innovative manufacturing techniques identification and establishment with newer and smart materials and manufacturing precision appropriate for mm-wave devices and their demonstration such that these techniques can produce a sample part that matches the dimensions of the CAD model. Measure relevant mm-wave performance related properties including surface roughness conductivity and thermal and high vacuum compatibility of one or more sample parts produced using the advanced manufacturing technique.

State of the art manufacturing techniques for interaction structure and other mm-wave tube components. Innovative research must give output in new applications of emerging technologies, such as Selective Laser Sintering (SLS), 3-D printing technology to manufacture the structure as a whole, and advanced manufacturing techniques which would be able to manufacture precession components directly from CAD with appropriate materials without losing any precision and alignment, etc. Also, care must be taken for cost effective TWTs and or current vacuum electron devices. Further, innovative SWSs for efficient beam-wave interaction over wide bandwidth for high average power handling capacity with significantly low loss coupling system.

However, life of a TWT depends on life of cathode which deteriorates with time for continuous emission of electrons, and hence, researchers also need to address low-temperature < 800 °C cathodes which can provide high current density and long-life at lower temperature. Also, interaction structure plays the key role in device performance and hence, one may need to design and adopt low loss, interaction structure. Moreover, thermal management of the interaction structure restricts the average power handling capability which further aggravated with the increase in frequency where transverse dimension of the structure decreases. Thus, one may need to choose thermally efficient, smart and advance materials for the interaction structure which may possibly enhance transverse dimensions of the structure at higher frequency. Thus, researchers need to address newer and smart materials properties and their processes to address cathode challenges including experimental verification to ensure cathode performance before putting into TWT. In addition to that research needs to extend for state-of-the art design concepts and technologies for efficient collection of electron beam for efficiency enhancement of the device as much as 100% by recovering spent beam energy in collector. New, smart and light weight materials have to be explored for suppression of secondary electron emission from collector, efficient heat dissipation, weight reduction, etc.