Design and Development of an X-band Pulsed Helix TWT for Space Application

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Abstract: *A compact X-band power booster TWT was designed and developed for space applications that provides minimum of 350W of peak RF output power with 25% duty over a bandwidth of 800MHz with RF efficiency of 22% and minimum gain of 27 dB. This TWT uses an electron gun operating at a cathode voltage of 6 kV and current of 275 mA with beam filling factor of 0.5. The electron beam is focused using PPM structure with peak field of 2600G generated using Sm2Co17 magnets. The SWS comprises tungsten tape helix supported by three azimuthally, symmetrically placed T-shaped APBN support-rods inside a metallic envelope. The dimensions of SWS were derived using the in-house parametric codes and optimized using Eigen-mode solver of CST Studio to achieve the required dispersion characteristics. The beam-wave interaction analysis was carried out using the in-house 1D-codes and was optimized using 3D PIC simulations. The SWS employs positive velocity taper near the output coupler in order to enhance RF interaction efficiency and to reduce the second harmonic content. The length of the SWS is around 93 mm. A 3-stage depressed collector is used to enhance the overall efficiency of the TWT. A prototype TWT is developed and tested for performance and has achieved overall efficiency of 45% with TWT length of 250 mm and weight of 980 grams. This TWT is subjected for operational temperature cycling at* $+70^0$*C and* -20^0*C and also random vibration to verify the structural integrity and has met the requirements.*

Keywords*:* Helix TWT; Negative Dispersion; Velocity taper; Slow Wave Structure; Multipaction; Electron Gun; PPM structure; 3-stage depressed collector; waveguide coupler.

Introduction

HELIX travelling-wave tube (TWT) [1] continues to be one of the best options as the final-stage RF amplifier in medium power transmitters used for satellite-borne imaging radars wherein life, reliability and efficiency always remain critical and premium. Modern space-TWTAs also follow the gain-sharing between a short-length power-booster TWT and a solid-state power amplifier. This gain-sharing concept reduces the gain requirement of the TWT to around 25-30 dB. Similarly, the efficiency of the TWT is also a crucial factor for most of the space systems due to limitation on availability of prime power and thermal management. These requirements have pushed the research towards short length high efficiency power booster space-TWTs. In this paper, the design and development of a X-band pulsed helix TWT for application in lower-earth orbit satellite is presented.

Design aspects of the TWT

In order to meet the required gain of 25 dB (min.) and the RF efficiency of 20% (min.), the design has been carried out for a single section slow-wave structure (SWS) using one lumped loss to divide the circuit in two sub-sections (Fig. 1). The circuit uses phase velocity step tapering to improve the efficiency and to reduce the second harmonic power as shown in Fig. 1. The helical SWS primarily comprises a tungsten tape-helix supported inside a metallic barrel using azimuthally symmetrically placed three T-shaped APBN support rods [2]. The design has been carried out for cathode voltage of 6 kV and cathode current of 275 mA to achieve peak RF output power in excess of 350W over a bandwidth of 800 MHz. The first phase velocity profile (disp-1) of the SWS is chosen to be 90% of the electronic velocity (Fig. 2) and subsequent phase velocity profiles are optimised suitably through large-signal analysis in order to sustain the interaction providing the desired output power at the rated efficiency. Basic design of the SWS was carried out using in-house parametric codes and the dispersion and interaction impedance characteristics were obtained by modelling and analysing the SWS using CST Studio [3]. Backward Wave Oscillation (BWO) analysis [4] was carried out to find out the maximum allowable length of each subsection for different beam-filling factors (BFF) for the given electron optical parameters. The maximum allowable circuit length for a BFF of 0.5 was estimated to be around 40 mm. Suitable phase velocity taper was used in the output section to enhance the allowable circuit length in order to combat the onset of BWO. The design was finally optimised through particle-in-cell (PIC) simulation using CST Studio. For PIC simulations, the electron beam is launched using a circular disk and focused using a uniform magnetic field along the length of interaction region. The lumped loss is realized by introducing finite electrical conductivity over the support rod [5]. A typical CST model used for PIC simulations with lumped loss profile is shown in Fig. 3. A typical output port signal of PIC simulation is shown in Fig. 4. The predicted output power and gain of the TWT are shown in Fig. 5. The length of SWS was finalised to be around 93 mm to achieve a minimum gain of 25 dB catering the desired output power. The length of first sub-section including the loss is 47 mm and the length of the second sub-section is 43 mm with equal taper lengths.

A Pierce type single-anode beam focusing electrode (BFE) controlled electron gun was designed for operating voltage of 6 kV to provide cathode current of 275 mA. The periodic permanent focusing (PPM) system was designed with high energy density Samarium Cobalt (Sm2Co17) ring magnets. The PPM stack employed peak axial field of 2600 Gauss. A three stage depressed collector design was implemented for this TWT in order to achieve the desired efficiency. The output helix impedance is matched to a standard X-band waveguide using reactive impedance matching technique [6]. The multipaction analysis was also carried out for the output coupler to determine the threshold power margins using

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analytical approach using Woo curves [7] for coaxial transmission line and using standard ESA equations for waveguide transmission line [8] and found better than 12 dB margin by analysis.

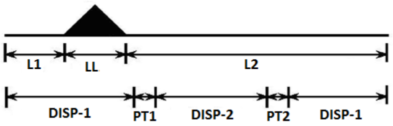

Figure 1. Interaction structure details along the length

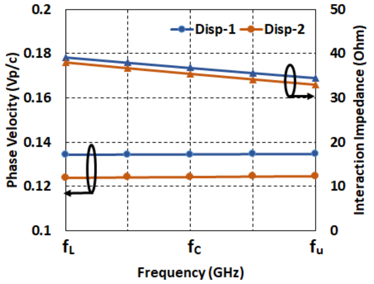

Figure 2. Phase Velocity and Interaction impedance

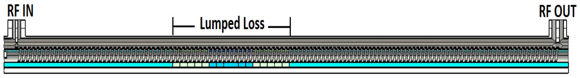

Figure 3. PIC model of TWT along with lumped loss

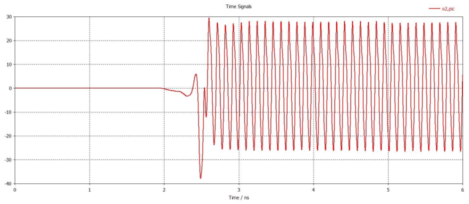

Figure 4. Typical output port signal in PIC simulation

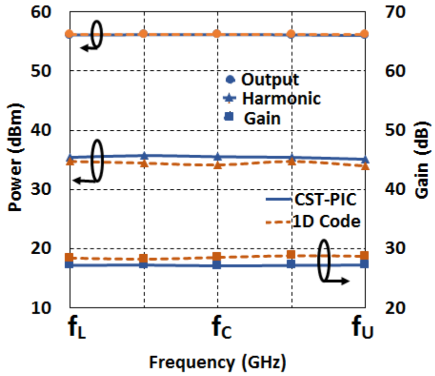

Figure 5. Performance of the TWT using 1D code and CST-PIC simulations

Development of the TWT

A prototype TWT was developed using the proposed design with SMA input connector and a waveguide output coupler as shown in Fig. 6. and characterized for the performance. The VSWR for both the input and output coupler are less than 1.6. The measured output power and gain are shown in Fig. 7. The prototype TWT could provide basic electronic efficiency of ~ 22% and second harmonics better than 20 dBc. The overall efficiency achieved is around 45% with three stage depressed collector that operates at 40%, 55%,75% of cathode voltage. The TWT was subjected to temperature cycling at high temperature (+70 ^{0}C), ambient and at low temperature (-20 ^{0}C) to measure the variation of output power and gain over the temperature and the results at extreme temperatures are presented in Fig. 7. Later the TWT was subjected to random vibration test (0.4 g^2/Hz) in all the three axes to verify the structural integrity, and the TWT passed the tests successfully.

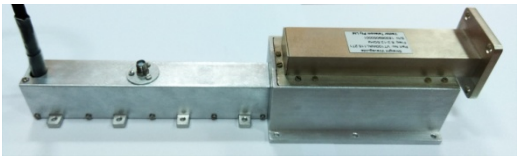

Figure 6. Developed Prototype TWT

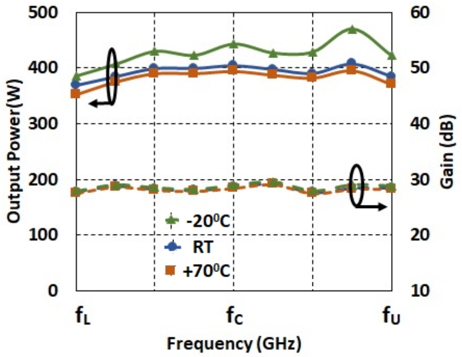

Figure 7. Output Power and Gain variation over temperature

Acknowledgements

The authors are thankful to Director, Microwave Tube Research and Development Centre (MTRDC), Bangalore, India for the kind permission to publish this work.

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