Enhancement of Non-linear Effects in Traveling Wave Tubes (TWTs) for Space Applications

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Abstract:

Traveling wave tubes (TWTs) are high-power microwave amplifiers based on vacuum electronic technology. They are widely used as high-power RF amplifiers in the transponders of communication satellites. More than 60 TWTs of different frequency bands, e.g., C-band (3.6-4.3GHz), Ku-band (10.9-11.75GHz), and Ka-band (20.6-21.3GHz) are used in a normal-size communication satellite. Due to overcrowding of C-Band frequencies the satellite communication systems migrated to Ku-band and Ka-band frequencies. The design and development of space TWT require special considerations in order to achieve broad bandwidth, high flexibility, high efficiency, high linearity, and long life. High linearity with phase shift less than 30 degrees and high efficiency of more than 60% of a space TWT are highly desirable requirements for communication. Non-linearity of a space TWT is specified by the noise-power ratio (NPR), carrier-to-intermodulation level (C/3IM), 1 dB compression point, and multi-signal intercept points. The Large Signal Model (LSM-1D and 2.5D) is a specialized program for the analysis of non-linear beam-wave interaction in TWTs. SUNRAY is a simplified and improved large-signal code for helix TWTs that takes into account both the loss and circuit variation along a tube and the inherent backward wave and reflection due to mismatch at the input and output coupler. CST-PS is another code for 3D electromagnetic analysis and design of TWTs in the high-frequency range. The results for the gain and the output power over the operating band given by these two codes were found to be comparable but the SUNRAY code is faster in comparison to the CST code. It takes less than a minute to simulate the RF performance of a typical high-frequency TWT at a single frequency. In this paper, the design and development of a space TWT for improved linearity and high efficiency will be presented with a detailed description of the proposed tools for modeling and analysis of TWTs.

Keywords:

Communication, Efficiency, High linearity, RF amplifiers, Traveling wave tubes

Introduction:

Space Traveling wave tubes (TWTs) are expected to have high linearity, high efficiency, low intermodulation distortion, and high power outputs. Linearity improvement of high-power and high-frequency TWTs. Higher linearity permits using more minimal and more affordable power supplies. High-efficiency TWTs can work more reliably and have a longer life cycle due to reduced collector loading. While the high-power outputs and wide gain-band widths make TWTs undeniably appropriate for these purposes. The nonlinearity of TWTs results in amplitude, phase, and spectral distortion. Nonlinear distortion products appear as harmonics and for multi-carrier operation also as intermodulation products, at the output of the amplifier in this way limiting the usable bandwidth of the amplifier and degrading fundamental efficiency.

Helix-TWT is a broadband moderate power amplifier used in telecommunication and space applications. TWTs for space communications basically require long life, high efficiency, high reliability along with the least possible size and weight. The SWS has a significant role in deciding the above stringent requirement of space TWTs. SWS of helical type is usually used in satellite communication applications due to its low dispersion characteristic. Short-length Traveling wave tubes (TWTs) are used in a microwave power module to provide gain at a high power level. Here helical SWS for Ku-band 140W short length TWT has been designed in a single section to provide gain around 25dB with electronic efficiency of more than 26% over the frequency band of 10.9GHz- 11.7GHz.

Design and Approach:

The significant components of a space TWT are as follows:

- Electron gun
- Helix slow-wave structure (SWS)
- Integral-pole-piece (IPP) barrel assembly
- Samarium-cobalt periodic permanent magnets (PPM)
- Input and output RF couplers
- Beam refocusing section (BRS)
- Multi-stage depressed collector (MDC) along with the base plate and isotropic fin-type radiator.

Electron gun (Pierce type low perveance convergent) is designed with M-type dispenser cathode with low cathode operating temperature (950 °C) at the lower heater power (3.5W) for the long life consideration which uses the electrically isolated BFE (beam focusing electrode) for the application of negative bias of the order of 10 to 15 V to improve the required beam transmission (99%) in CW (continues wave) mode. SMA type co-axial coupler for input section and TNC type with waveguide (WR-75) for output are used for sub-quarter wave length transformer technique. The couplers are customized in CST-MW and HFSS with slow wave structure (SWS) with tip loss on support rods. The return loss is acquired better than −15 dB for input and better than −20 dB for output throughout the operating band. A door knob type waveguide to co-axial adopter is used for better heat dissipation.

Three software packages SUNRAY 1D, HFSS and CST MW are used for design of different components of the helix TWT [1, 2] for meeting the requirements of the space TWT. Electrical parameters such as propagation constant (β) and impedance on axis (κ) of helix SWS from its physical dimension are computed by 3-D electromagnetic field simulators Ansoft HFSS [3] and CST-MWS [4]. SUNRAY-1D code is a large signal one-dimensional multi-carrier code which is used to predict the complete RF performance of a TWT [5]. Propagation constant (β) and impedance on axis (κ) of the helical structure are computed using single-turn approach [6, 7]. SUNRAY-1D is used to find out both the loss and helix pitch profiles to achieve the desired efficiency, output power, phase shift, gain, intermodulation (IM) products TWT.[8, 9].

Helix SWS (slow wave structure) is designed as follows [10]:

- Input electron beam power is determined from output power (140W) and an estimated electronic efficiency (>26%). This beam power is converted into beam voltage and beam current by choosing the perveance of electron gun (0.224 µm).
- The helix mean radius (α) is determined from $\beta_e\alpha = \omega\mu_0 \approx 1$, Where ω-signal frequency, and μ_0- electron beam velocity.
- SUNRAY-1D is used to determine three values of phase propagation constant of uniform single section helix corresponding to maximum small signal gain (G_{max}), maximum normalized fundamental component of RF beam current (I_1/I_{omax}) and maximum electronic efficiency (η_{max}).

Helix pitches (Po, P1, and P2), corresponding to the propagation constants for growing wave section, bunching section, and power extraction section, are determined using the 3D electromagnetic simulator codes, and section lengths for helix pitch profile and loss profile to achieve the desired RF performance are optimized using SUNRAY-1D code. Centre loss is 60dB and Ckt. loss is 2dB/inch. RF performance of the complete design tube is simulated using SUNRAY-1D code [11].

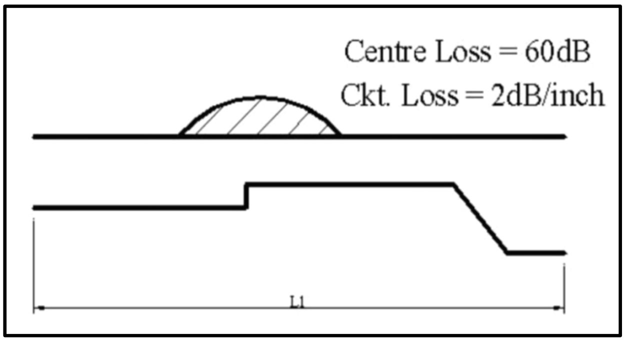

Fig.1 Pitch profile and loss profile for helix TWT design

Table 1: Parameters for design radio frequency (RF) section for helix TWT

Parameter	**Value**
Operating Frequency	10.9-11.7GHz
Power	>140W
Bandwidth	0.8GHz
Beam Voltage	5.8KV
Beam Current	95mA
Beam radius	0.34mm
Beam filling factor	0.50
Tunnel radius	1.124mm
Barrel inner radius	3.5mm
Helix inner radius	1.1mm
Helix tape thickness	0.15mm
Helix tape Width	0.30mm

Support rod Type	T-shape APBN
Pitch profile(mm)	0.54, 0.57, 0.50
Perveance	0.224µm
Pierce gain	0.0834
Output power(dBm)	52.614
Saturated gain(dB)	25.835
Efficiency of TWT (%)	26.422
Gain flatness	0.8dB/GHz
Phase shift	< 45deg
AM/PM	< 3deg/dB

Results and Discussion:

The simulated radio frequency (RF) output power and gain at saturation is obtained for the operating band of 10.9 to 11.7GHz. The design of Ku-band helix TWT delivers output power above 140W with gain 25.835 dB and electronic efficiency more than 26.422% is achieved. The AM/PM conversion factor at saturation and at different input drives below saturation is smaller than 3deg/dB. Phase shifts at different frequencies from saturation to 20dB below saturation are under 40degrees.

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