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DESIGN AND CHARACTERIZATION OF HELIX SLOW WAVE STRUCTURE FOR KU-BAND SPACE TWT

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Abstract—A helix slow-wave structure (SWS) for a high efficiency Ku-band 140 W space TWT has been designed. Cold circuit parameters of helix SWS like propagation constant and on axis interaction impedance were determined using 3-D electromagnetic field simulators ANSOFT-HFSS and CST-MWS and validated with the experimental results. In-house developed large-signal code SUNRAY-1D was used to design the complete helix SWS in 2-section with sever and taper to achieve desired output power, gain, efficiency, and other linearity parameters such as phase shift, AM/PM factor, I/M components. Simulated RF performance of the Ku-band 140 W helix TWT was validated with the experimental results. A close agreement between the simulated and experimental results has been found.

1. INTRODUCTION

Space helix TWT is an ultra-high vacuum microwave device that is used as a high power microwave amplifier in communication satellites. Broad bandwidth, high gain, high efficiency and high linearity of a space TWT are desirable parameters for handling a large number of downlink signals in satellite communication. High efficiency of a space TWT is required because of limited power available on board satellite. High linearity is required so that the tube can be operated near saturation region in a broadband multi-carrier system in satellite [1]. To achieve the stringent requirement of space TWT in terms of power, gain, linearity, long life, due considerations have been given in the design of Electron Gun, Periodic Permanent Magnetic focusing system,

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RF Coupler and Multi-stage depressed collector assembly. A Pierce type low perveance convergent electron gun has been designed with M-type dispenser cathode with low cathode operating temperature (~ 950 degree C) at the lower heater power (~ 3.5 W) for the long life consideration. This also uses the electrically isolated beam focusing electrode (BFE) for the application of negative bias of the order of 10–15 V in order to improve the desired beam transmission (99%) in continues wave (CW) mode.

SMA type co-axial coupler for input section and TNC type with wave guide (WR-75) for output have been used for sub-quarter wave length transformer technique. The couplers have been modeled in HFSS and CST-MWS with slow wave structure with tip loss on support rods. The return loss has been obtained better than -15 dB for input and better than -20 dB for output throughout the operating band. A door knob type wave guide to co-axial adopter has been used for better heat dissipation. The RF performance of a TWT is primarily decided by the design of the helix slow wave structure. In this paper, design of helix pitch profile for a 2-section space TWT is shown in Fig. 1. The helix pitch for the input section has been selected to establish the growing wave for maximum small signal gain. Helix pitch at the start of output section has been selected with increased phase velocity to gather electron into bunches as effectively as possible for maximum normalized bunching current. Helix pitch at the end of the output section has been selected with reduced phase velocity to extract energy from the

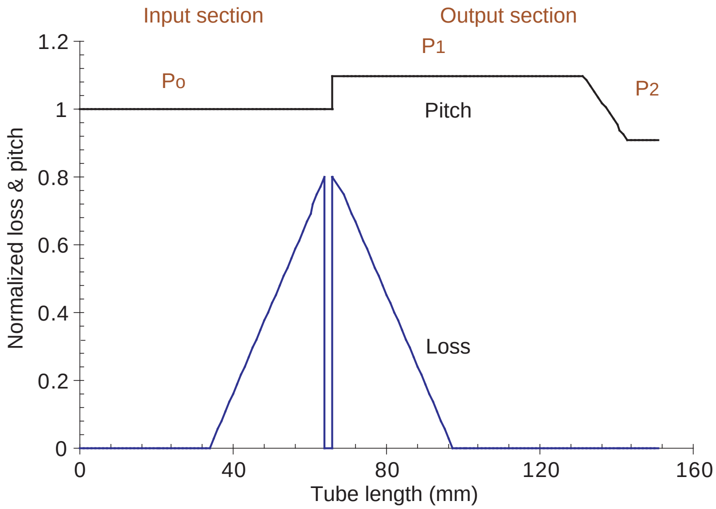

Figure 1. Normalized pitch and loss profile.

electron beam efficiently for maximum electronic efficiency [2]. This design of helix pitch profile increases electronic efficiency with high linearity and also provides well-bunched spent beam for high collector efficiency. Margin for backward wave oscillation is increased, and the non-linearity generated due to introduction of taper section at output is counteracted by the positive helix pitch. The tape width and thickness for helix SWS and size of APBN support rods have been selected for maximum possible interaction impedance at center frequency.

2. DESIGN METHODOLOGY

In this paper, design methodology of helix slow wave structure for a Ku band 140 W space TWT of operating bandwidth 10.9–11.3 GHz has been described. Three softwares have been used to design the helix SWS. Commercially available 3-D electromagnetic field simulators Ansoft HFSS [3] and CST-MWS [4] have been used to compute electrical parameters such as propagation constant (β) and impedance on axis (k) of helix SWS from its physical dimension. In-house developed 1-D large signal code, SUNRAY-1D, has been used to predict the complete RF performance of a TWT [5].

Propagation constant and impedance on axis of the helical structure have been computed using single-turn approach [6, 7]. Single turn helix assembly of Ku-band 140 W space TWT, as modeled in HFSS, has been shown in Fig. 2. Results obtained from HFSS

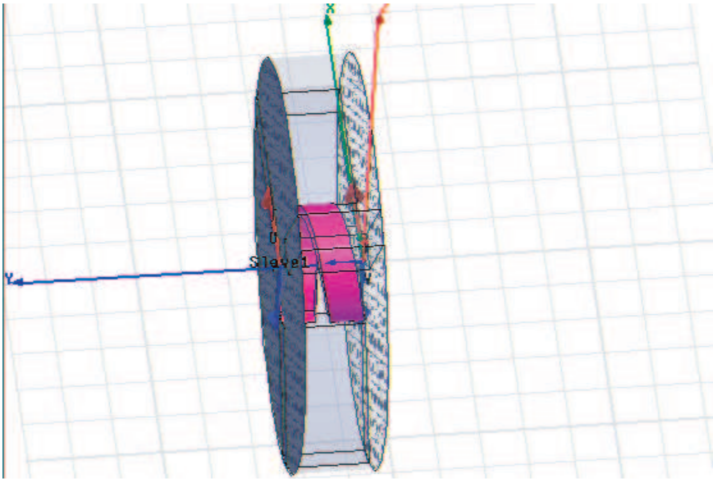

Figure 2. HFSS/CST model of helical slow wave structure.

and CST-MWS have been validated by repeated computation of β and k for different slow wave structure assemblies of different pitches. Propagation constant (β) and impedance (k) on axis of a single section with uniform pitch of helix have also been measured. Measurement accuracy has been ensured ($\approx$ $\pm 1\%$) by repeated measurement of a number of helix assemblies of different pitches. Time domain reflectrometry (TDR) technique has been used to measure the propagation constant of helix. In TDR technique a metallic short with diameter slightly less than helix inner diameter (10–15%) is inserted into helix from the other end of helix assembly with respect to coupler and is moved inside the helix by a sliding assembly. Different positions

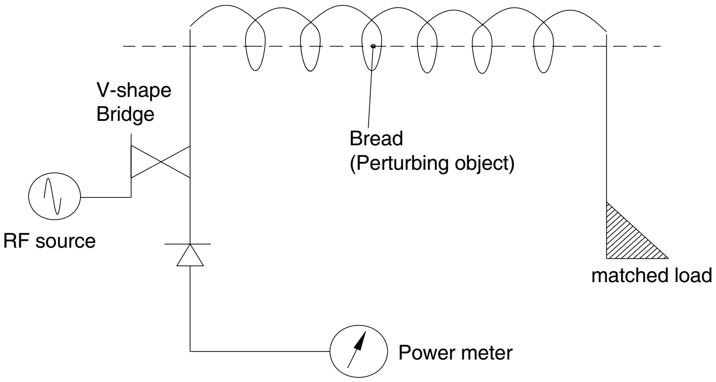

Figure 3. TDR measurement setup for helix SWS.

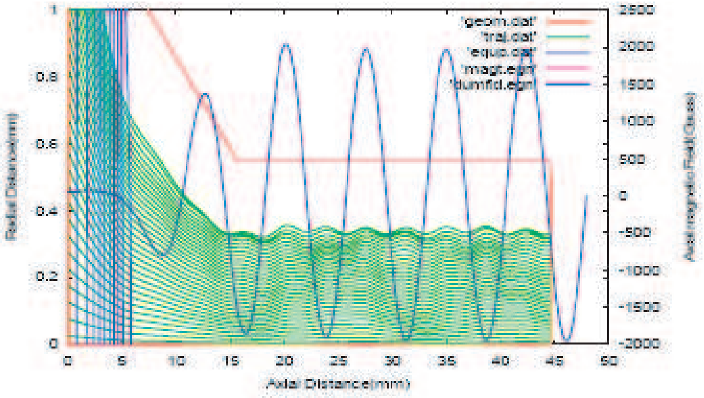

Figure 4. Simulated results of Electron Gun with PPM using EGUN code.

of short and corresponding propagation time of RF from coupler to the short position were measured respectively by sliding assembly and by VNA in TDR mode. By measuring the time and shorting position, phase velocity and corresponding propagation constants are calculated. Fig. 3 shows the TDR measurement setup. In this measurement, the accuracy is ensured ($\approx 3\%$) for helix assembly of different pitches by a number of measurements. Fig. 4 shows the simulated results of electron gun using EGUN code. Fig. 5 and Fig. 6 show the comparison between the computed values from the HFSS and CST codes and the measured results respectively for the propagation constant and

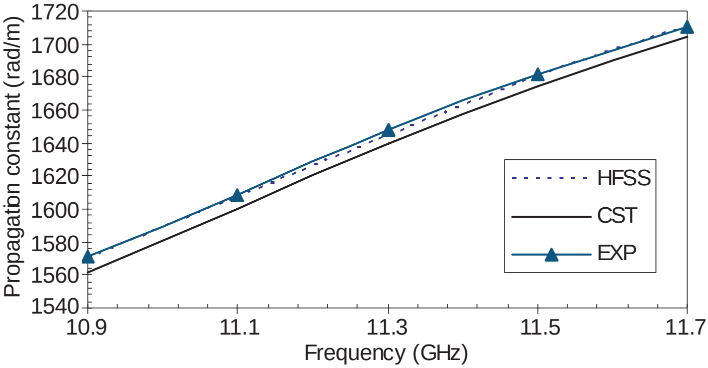

Figure 5. Comparison of experimental and simulated propagation constant vs frequency.

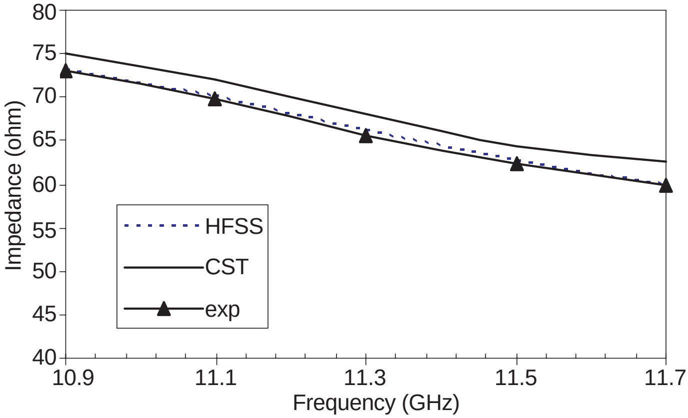

Figure 6. Comparison of experimental and simulated Impedance vs propagation constant.

impedance on axis. The size and shape of tungsten tape for helix SWS, APBN support rods and barrel inner diameter have been optimized for optimum interaction impedance, phase velocity variation $< 5\%$ and optimum heat dissipation in the operating band 10.9–11.7 GHz.

SUNRAY-1D code [8] has been used to determine both the loss and helix pitch profiles, as shown in Fig. 1, to achieve the desired RF performance of the Ku-band 140 W TWT, such as output power, gain, efficiency, phase shift, IM products. SUNRAY-1D code is a large signal one-dimensional multi-carrier code. In this code Lagrangian formulation is used for beam wave interaction. It is a disc model, and electron beam is considered as a cylinder with radius equal to average beam radius. Beam of one RF wavelength is divided into a number of discs of uniform charge and thickness. Movement of each disc under RF circuit field and space charge field is tracked in small steps. Each signal is characterized by propagation constant $\Gamma(=\alpha+j\beta)$, where α is attenuation constant; β is axial propagation constant; and K is interaction impedance. Multi-signal effects including higher order harmonics and (I/M) components were simulated by defining base frequency that is the greatest common factor of all signal frequencies. All signals are considered as higher order harmonics of base frequency. The nth harmonic components at any plane are calculated by using (1) and (2) of the RF beam current and circuit voltage respectively [9]:

$$\begin{aligned} i_n(z) &= \left(\frac{2}{T_o}\right)\int\limits_{t-T_o}^{t} i_n(z,t)\exp(-jn\omega_o t)dt \qquad (1)\\ V_n(z) &= C_{1n}\exp(-\Gamma_{no}z)+C_{2n}\exp(\Gamma_{no}z)\\ &\quad -\left(\frac{K_n}{2}\right)\exp(-\Gamma_{no}z)\int\exp(\Gamma_{no}z)\left(\frac{\partial i_n}{\partial z}\right)dz\\ &\quad +\left(\frac{K_n}{2}\right)\exp(\Gamma_{no}z)\int\exp(-\Gamma_{no}z)\left(\frac{\partial i_n}{\partial z}\right)dz \qquad (2)\end{aligned}$$

$i_n(z,t)$ is RF beam current for a disc at plane z. Time t, ω_o is base frequency, and T_o is one RF period. The first and second terms of (2) are solution of homogeneous equation, and the third and fourth terms represent forward and backward induced voltages respectively.

Helix SWS has been designed as follows [10]:

i) Input electron beam power was determined from output power (140 W) and an estimated electronic efficiency (25%). This beam power was converted into beam voltage and beam current by choosing the perveance of electron gun (0.2 µp).

ii) The helix mean radius (a) has been determined from $\beta_e a \approx 1$ (for high efficiency), where $\beta_e = \omega u_o$ where ω is the signal frequency, and u_o is the electron beam velocity.

iii) SUNRAY-1D has been 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 ($I_1/I_{o\,\max}$) and maximum electronic efficiency ($\eta_{\max}$).

Figures 7, 8, and 9 show respectively the small-signal gain (dB) versus propagation constant (radian/m), bunching current (I_1/I_o) versus propagation constant, and the electronic efficiency (%) versus propagation constant, for a uniform one-section tube. Impedance has been adjusted at different propagation constants as per the Pierce interaction impedance formula. From these three plots,

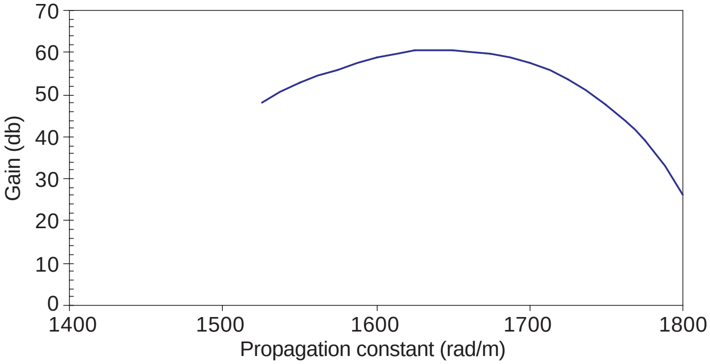

Figure 7. Small signal gain versus propagation constant.

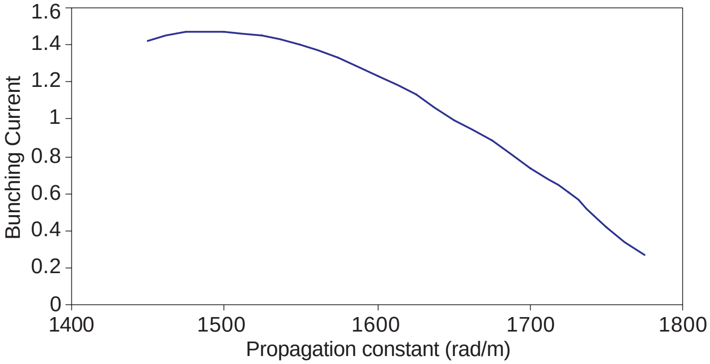

Figure 8. Normalized bunching current versus propagation constant.

helix pitches (p_o, p_1, p_2), corresponding to the propagation constants for growing wave section, bunching section and power extraction (taper) section, are determined using the 3D electromagnetic simulator codes. Different section lengths for helix pitch profile and loss profile have been optimized using SUNRAY-1D code to achieve the desired RF performance. For simulation, loss of helix has been taken as 80 dB/meter, and circuit has been severed between input section of pitch p_o and section of pitch p_1. Linearly increasing attenuators at each side of sever has been used, and total loss is 60 dB [11].

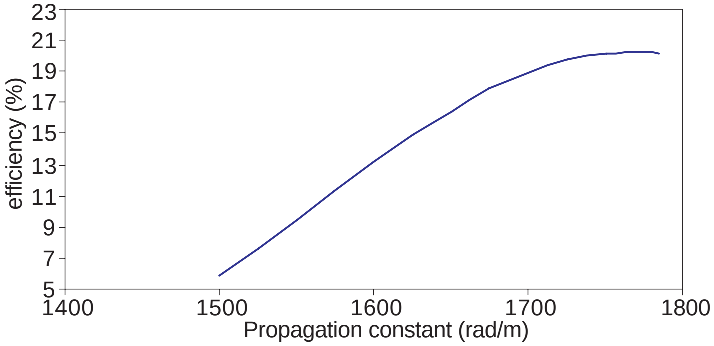

Figure 9. Electronic efficiency versus propagation constant.

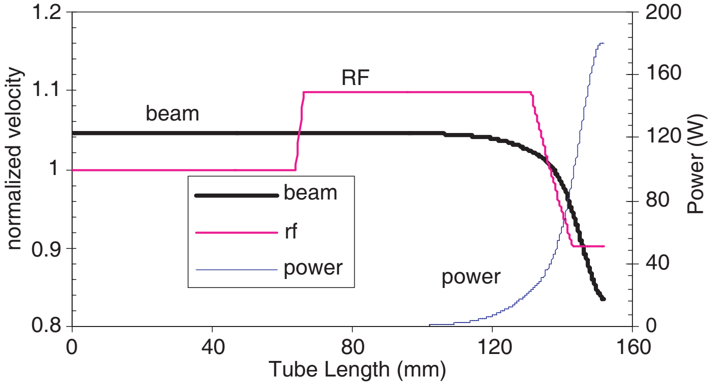

Figure 10. RF phase velocity, power profile, rms beam velocity vs tube length.

3. RF PERFORMANCE

A two-section 140 W Ku-band helix space TWT whose specifications are given in Table 1 has been designed by the design procedure

Table 1. Specification of ku-band 140 W space TWT.

Parameters	Unit	Values
Frequency band	GHz	10.9–11.7
Power	Watts	140
Gain	dB	50
Efficiency	%	> 50
Phase	Degree	< 45
2nd harmonic	dBc	< -15

Table 2. Specification of helix SWS for ku-band 140 W space TWT.

Parameters	Value (mm)
Pitch (P_o, P_1, P_2)	0.54, 0.57, 0.495
Tape thickness	0.175
Tape width	0.375
Helix radius	0.56
Barrel radius	2.3

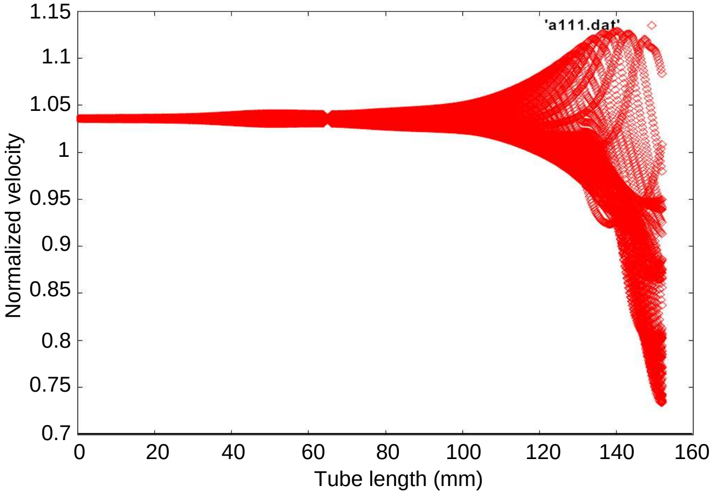

Figure 11. RMS beam velocity vs tube length.

mentioned in the previous section. Table 2 shows the dimensional details of helix. The helix SWS has been designed with the propagation constant of first section equal to the propagation constant corresponding to maximum small signal gain. The second section consists of an increased phase velocity section (propagation constant corresponded to maximum bunching current) followed by a uniform negative tapering section. RF performance of the complete design tube has been simulated using SUNRAY-1D code [12]. In this simulation, −15 dB return loss from input and output coupler and severing section

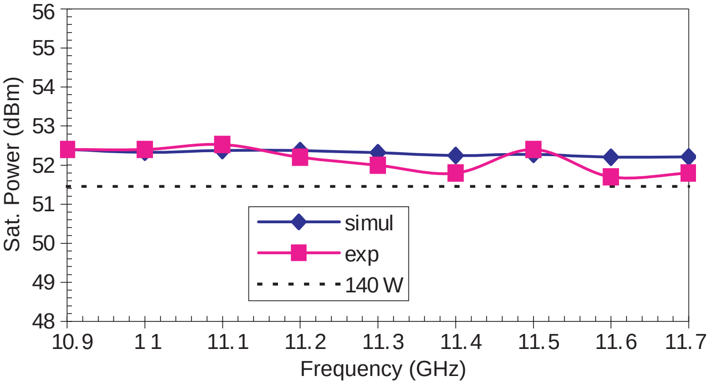

Figure 12. Comparison of experimental and simulated saturated output power vs frequency.

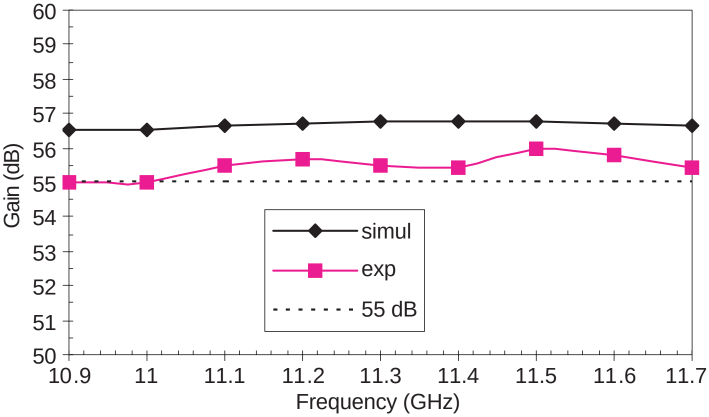

Figure 13. Comparison of experimental and simulated saturated gain vs frequency.

have been assumed. Fig. 10 shows simulated results for the variation of RF phase velocity, power profile, rms beam velocity vs tube length for the Ku-band 140 W TWT. Fig. 11 shows the normalized axial velocity of the representative electrons over the total tube length. Figs. 12 and 13 show the comparison between experimental and simulated results respectively for the saturated output power and gain at operating voltage of 5.9 kV and beam current 95 mA with beam transmission $> 97\%$ in CW operation.

4. CONCLUSION

A methodology for the design of helix slow wave structure for a Ku-band 140 W space TWT has been described. Two commercially available software codes Ansoft HFSS, CST MWS as well as an in-house developed large-signal code SUNRAY-1D have been used for the design. The accuracy of helix SWS design has been confirmed against various experimental data.

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