Nonlinear Analysis of Beam-Wave Interaction for high power THz TWT Amplifier with Sheet Electron Beam

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Abstract

High power THz TWT amplifiers of frequencies between 0.1THz to 0.3THz are being investigated for their use in ultra broadband wireless communication systems, because of their high gain, high efficiency, wide bandwidth and high linearity. THz TWTs/BWOs have many other new emerging applications in medical imaging and sensing, spectroscopy, high resolution radar, etc. In-house developed small-signal model (SUNRAY-SSM) and one-dimensional large-signal model (SUNRAY-1D LSM) codes are used for linear and nonlinear beam-wave interaction analysis of a planar THz TWT with sheet electron beam. The cold circuit parameters like dispersion and impedance characteristics as simulated by CST-3D/COMSOL-3D code are used for simulating hot RF performance like output power and gain over the frequency band using SUNRAY codes. The output RF performance as simulated by SUNRAY codes are found comparable with the results as simulated by CST-3D/COMSOL-3D code over the frequency band for different THz TWTs.

Keywords: Beam-Wave Interaction Analysis, Planar RF SWS, THz High Power Amplifier, THz TWT, THz Wireless Communication.

Introduction

THz frequencies from 0.1THz to 0.3THz of the electromagnetic spectrum [1] are being explored for ultra-broadband wireless communication. The frequency band around 0.22THz (G-band) is being planned for 6G wireless communication because of relatively low atmospheric attenuation. Both solid-state amplifiers and vacuum microelectronic devices (VMEDs) are being developed for THz communications. Solid-state amplifiers are very low-power devices with power not more than 0.1W at 0.22THz frequency although they are highly linear. Vacuum microelectronic devices [2] are compatible with high output power much more than ten watts at 0.22THz frequency. Among different VMEDs, high power THz TWT (travelling wave tube) is used as an amplifier for ultra wideband communication system because of its large bandwidth >30GHz, high efficiency and high linear gain >30dB [3-6]. THz TWT is a very complex active device which has many critical components such as electron gun for beam formation, PPM focusing system for electron beam focusing, RF slow-wave structure (SWS) for supporting RF wave propagation and efficient energy extraction from the electron beam to the RF wave, RF input and output couplers with good matching with the SWS, and depressed collector for collection of spent beam with minimum energy loss.

The RF performance of a TWT primarily depends on the design of SWS (Fig.1) as it supports THz waves which get amplified by extracting energy from the electron beam under beam-wave synchronous condition. The SWS is therefore designed with high circuit impedance and wide circuit bandwidth with low circuit loss. The complete SWS for a THz TWT, has many periods (minimum 100) for 30dB gain. The SWS of a TWTA is preferably designed in 2 sections with sever or attenuation in-between for stability in tube performance against any reflections due to mismatch at terminations. Also, the structure has a phase velocity taper in the output for high electronic efficiency. RF Couplers at the input and the output ends of the SWS are designed for good matching with VSWR much less than 1.5:1 over the desired operating band.

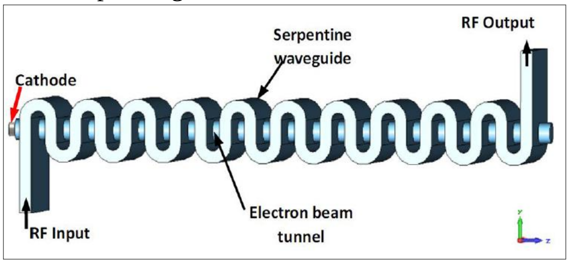

Figure 1. Schematic diagram of Slow-Wave-tructure (SWS) with electron beam and input-output couplers.

A planar RF slow-wave-structure with a sheet electron beam is chosen for a THz TWT, as shown in Fig.2. A sheet beam has much less charge density compared to cylindrical beam for same beam current because of large cross-sectional area. It therefore also requires less magnetic field for beam focussing and it has better interaction with the RF circuit field compared to a cylindrical beam of the same beam current. The sheet beam can also inherently be used with the planar RF structure. The planar RF SWS at THz frequencies is also comparatively easy to manufacture with high precsion and surface finish using microfabrication technologies. At present, design and manufacturing of a THz TWT is a cutting-edge technology and it requires rigorous efforts for optimum design and successful development of a THz TWT.

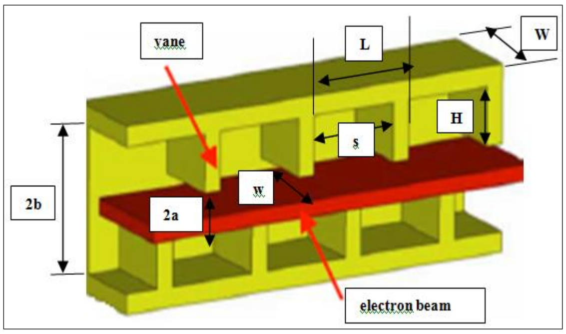

Figure 2. Staggered double-vane Slow-Wave-tructure (SWS) with rectangular sheet beam for a THz TWT.

Beam-Wave Interaction Analysis

Beam-wave interaction analysis for a planar THz TWT with sheet beam is presented. Under the beam-wave interaction analysis, the electron beam in one RF beam-wavelength is discretized into a number of equally charged particles. Each particle is tracked along the SWS by numerically solving Lorentz Force Equation in presence of RF circuit fields, ac space charge fields, and magnetic focussing field.The 3D Lorentz force equation for a particle k is given by:

$$\frac{d}{dz}\mathbf{p}_k = \frac{q_k}{v_{z,k}}[\mathbf{E}_k + \mathbf{v}_k \times \mathbf{B}_k] \quad (1)$$

Where, fields E_k and B_k are total e.m. fields acting on particle k which include RF circuit field (E^c, H^c), ac space charge field (E^{sc}, H^{sc}), dc self fields (E^{dc}, H^{dc}) and external focussing magnetic field (H^{ext}).

The RF circuit field expressions are achieved by solving Maxwell wave equations with suitable boundary conditions, and for the desired mode.

$$\left(v_{\text{ph}}^2 \nabla^2 - \frac{\partial^2}{\partial t^2}\right)\mathbf{E} = \mathbf{0}$$
$$\left(v_{\text{ph}}^2 \nabla^2 - \frac{\partial^2}{\partial t^2}\right)\mathbf{B} = \mathbf{0} \quad (2)$$
$$v_{\text{ph}} = \frac{1}{\sqrt{\mu\varepsilon}}$$

The ac space charge field is achieved by solving the Helmholtz equations:

$$\nabla^2 \vec{E} + k^2 \vec{E} = \mu \frac{\partial \vec{J}}{\partial t} + \nabla \frac{\rho}{\varepsilon}$$
$$\nabla^2 \vec{H} + k^2 \vec{H} = -\nabla \times \vec{J} \quad (3)$$

Under actual situation of beam-wave interaction along a tube, the analysis for a planar TWT with sheet beam is very complex because of electron beam movement in all three directions even it is well focussed under PPM field. 3D simulation code like CST Particle-in-Cell (CST-PIC)/COMSOL-3D code is needed for actual simulation but it is very time consuming taking many hours or even days for complete simulation over full frequency band, and also require large computer memory. Fig.3 shows COMSOL simulated electron trajectories from input to output of a TWT. Red area is strong beam bunching and blue area for least electrons. COMSOL-3D results on cold and hot RF performance of a TWT are reported comparable with CST-3D results [7-8].

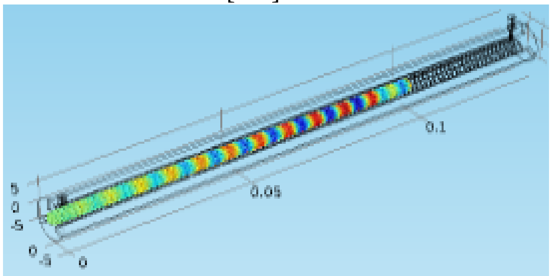

Figure 3. Electron beam trajectories at time step of 2.1ns from input to output of TWT – COMSOL computed [7].

Analytical approach for Interaction analysis

Beam-wave interaction analysis is made fast with number of simplifications for interactive use but without much loss in accuracy. Two different approaches were used for the analysis:

1. Small-signal analysis,
2. Large-signal analysis.

Under small-signal condition, the nonlinear beam-dynamic equation and the continuity equation are made linear by ignoring the second-order terms. The 4th order determinant equation is solved analytically for determining small-signal gain of the growing RF wave along TWT.
Under one-dimensional (1D) large-signal analysis, the axially confined sheet beam in one RF beam wavelength is divided in certain number of rectangular discs of equal thickness and charge. Each disc is individually tracked axially in small integration steps in presence of the RF circuit field and the ac space charge field numerically, and determines the beam bunching and net energy transfer from the bunched electron beam to the RF field at each integration plane.
Both the small-signal model and the large-signal (nonlinear) model for beam-wave interaction analysis in TWT are developed which are fast for interactive use and are fairly accurate. The propagation constant (β) and the circuit impedance as simulated by CST/ COMSOL-3D codes are used. In-house developed SUNRAY-SSM code [9] and SUNRAY-LSM code [10-12] for TWT with cylindrical beam are explored for beam-wave interaction analysis of a planar THz TWT with sheet beam under small-signal (linear) condition and large-signal (nonlinear) condition respectively.
Certain modifications are required in the present in-house developed models for TWTs to account for the change in the RF circuit field and the sheet beam. Both these models are being worked out for the analysis of a planar TWT with sheet beam, under certain assumptions.
In-house developed SUNRAY codes are used to determine RF output power and gain of a planar 0.22-THz, 100W, 30dB gain TWT with sheet beam. SUNRAY-SSM code is used for small-signal

(linear) beam-wave interaction analysis and SUNRAY-LSM code is used for large signal (nonlinear) beam-wave interaction analysis.

Simulation using SUNRAY-SSM code

SUNRAY-SSM code is used to determine small-signal gain over the frequency band for a planar THz TWT with three sheet beams, each of 70mA and voltage 21.5kV and with input data for RF and electron beam as given in [13-14]. Some assumptions are made for the sheet beam and the circuit impedance. The determined small-signal gain over the frequency band is found in reasonably good agreement with the published simulated gain using CST-3D / COMSOL-3D code over the given THz frequency band, as shown in Fig.4.

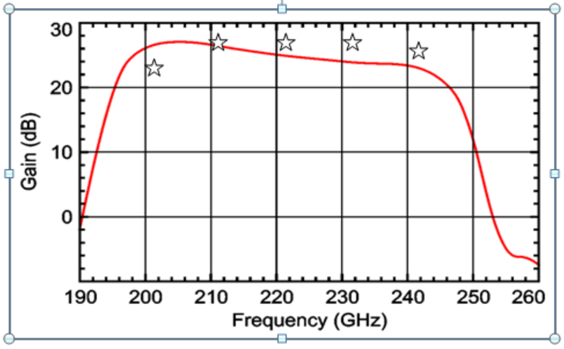

Figure 4. Small-Signal Gain versus Frequency by CST-3D/COMSOL-3D code (solid line), and star marked as determined by SUNRAY-SSM code.

Simulation using SUNRAY-LSM code

SUNRAY-LSM code for nonlinear beam-wave interaction analysis of planar TWT with sheet beam is explored to simulate the RF performance of 0.22THz, 100W TWT using 3 sheet beams as given in [13-14] with certain assumptions. Fig. 5 shows RF output power versus frequency for 0.5W drive power as determined by SUNRAY-LSM code and the published results as simulated by CST-3D/COMSOL-3D code. The results are fairly matching over the frequency band from 200GHz to 240GHz. Fig.6 compare the power profile of the growing wave as simulated by SUNRAY-LSM code with the published profile as simulated by CST-3D/COMSOL-3D code.

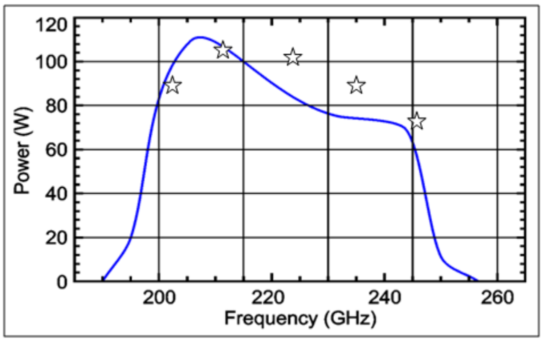

Figure 5. Output Power versus Frequency for 0.5W drive power simulated by CST/COMSOL-3D code (solid line), star marked power simulated by SUNRAY-LSM code.

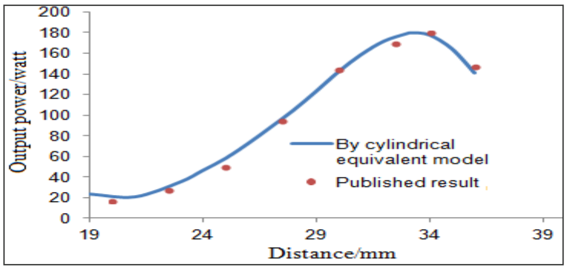

Figure 6. RF power profile along distanc, blue curve by CST/COMSOL, dot marked by SUNRAY-LSM

Simulation of 0.22THz TWT with 2 beams

SUNRAY-1D code is used for simulating RF performance of a published 150W, 0.22THz planar TWT using 2 sheet beams [15] as shown in Fig.7(a) and 7(b). It has metamaterial inspired flat SWS of high circuit impedance and high bandwidth.

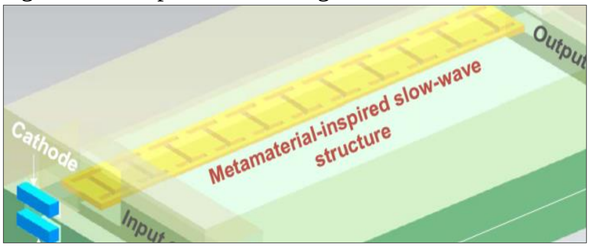

Figure 7(a). Metamaterial inspired flat SWS for a planar TWT with input and output waveguide couplers.

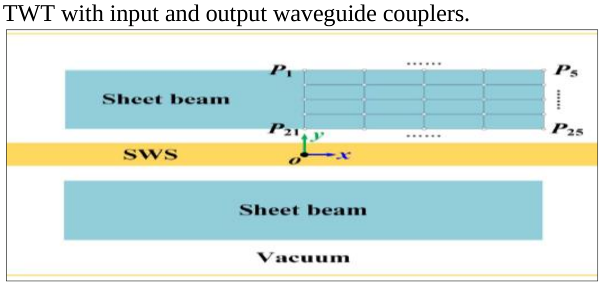

Figure 7(b). 2 parallel sheet beams up & below flat SWS

The following input beam and circuit parameters as reported for this TWT are used for simulation:
2 sheet beams each of size 0.1mm (thick) x 0.4mm (width), voltage 38.5kV & current 150mA,
Circuit length from input to output: 29.2mm,
71 periods in between input & output couplers,
Pitch of each period: 0.4mm,
Return loss at input & output terminations: -10dB,
Circuit transmission loss: 4.5dB/cm,
Propagation constant and impedance versus frequency [15] are shown in Table 1.

TABLE 1: PROPAGATION CONST. & IMPEDANCE V/S FREQUENCY FOR 0.22THZ TWT (BEAM VOLTAGE 38.5KV)

FREQUENCY (THZ)	PROPAGATION CONST. (RAD./M)	IMPD. (OHMS)
0.212	12370	9.0
0.214	12440	8.8
0.216	12568	8.6

With the present version of SUNRAY-1D code, the equivalent cylindrical beam is considered of beam radius 0.11284mm for the same cross-sectional area as that of the sheet beam of size 0.1mmx0.4mm. Also, for simulation of the above TWT with two sheet beams, as in Fig.7, the interaction analysis is done with single beam only and the input drive power is also considered half for each beam. The RF output power as simulated by SUNRAY-1D code is doubled for the TWT with two beams. Table 2 shows the RF output power versus frequency for 10mW drive power that are simulated by SUNRAY-1D code with the input data as above. The SUNRAY-1D simulated results are compared with CST simulated results [15], and found fairly good agreements for 10mW drive power.

TABLE 2: COMPARISON OF SIMULATED OUTPUT POWER VERSUS FREQUENCY BY SUNRAY CODE WITH THE PUBLISHED RESULTS

FREQUENCY (THZ)	O/P POWER (W) SUNRAY-1D	PUBL. POWER (W) [15]
0.212	96	90
0.214	166	165
0.216	154	148

Conclusions

High power THz TWT Amplifier is a cutting-edge technology, and it is being developed for 6G wireless communication and many other emerging applications. In this paper, small-signal analysis and large-signal analysis for beam-wave interaction in a planar THz TWT with sheet beam are briefly presented to determine the output RF performance. In-house developed SUNRAY-SSM code (for small-signal gain analysis) and SUNRAY-LSM code (for large signal analysis) are explored with some modifications for determination of RF performance of a THz TWT operating with single as well as multi sheet beam. The RF output power and gain response as determined by SUNRAY-SSM code and SUNRAY-LSM code are well matched with the published simulated results by the commercial 3D CST-PIC code and COMSOL 3D code. The main advantage of the in-house developed codes is their enormously fast speed for interactive application. It takes much less than 1 minute to do the simulation for a single drive power and single frequency which is at least many thousand times faster than the simulation time taken by CST-3D/COMSOL-3D code. It is therefore possible to design complete TWT with sever (for high gain) and with velocity taper (for high efficiency) interactively using SUNRAY-LSM code for desired RF performance over the given THz frequency band.

There is a need to develop AI and ML based approach for successful state-of-art design of the complex THz TWT with optimum RF performance over the desired THz frequency band. It is also important that the designed RF structure can be fabricated with high mechanical precision and high surface finish using microfabrication technique.

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