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Numerical design of a 100 W, 38 dB gain, W-band multi-section serpentine waveguide vacuum electronic TWT

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ABSTRACT

The serpentine waveguide circuit is a robust beam-wave interaction circuit for W-band TWTs. Here presented the electromagnetic properties and design methodology for W-band multi-section SWG traveling wave tube. Cold-test (in absence of electron beam) numerical design performed theoretically and further optimized/validated with standard simulation code to predict the dispersion, interaction impedance, ohmic-loss and small-signal gain. Numerical simulation for the quarter wave transformer couplers with SWG circuit geometry shown the return-loss less than −20 dB for the 5% frequency band. Later, in systematic manner, hot-test (in presence of electron beam) numerical design performed for multi-section TWT by using standard particle-in-cell 3-D simulation code. The three section, 60 periods SWG TWT predicted peak radiation power 130 W at target frequency 94 GHz, 39.5 dB saturated gain, 5.3% instantaneous 3-dB frequency bandwidth, and 6.5% electronic efficiency.

1. Introduction and background

The electromagnetic spectrum of W-band (75–110 GHz) to THz (10^{12} Hz) frequencies shows many promising defence and civilian applications especially in the area of indoor/outdoor high-data-rate secure wireless communications and sensing (concealed threat detection/contraband imaging) [1–5]. Modern communication beyond 50 GBits/s transmitters require high power and wide-band devices. In the W-band frequency spectrum, near 94 GHz frequency, atmospheric attenuation is less than 1 dB/km with almost constant bandwidth more than 15% [4], which makes this natural atmospheric low-loss attenuation window suitable for discussed applications.

Hence, presently in mm-wave region, high power vacuum electronic devices like traveling wave tubes (TWTs) [1,2] and solid-state devices (SSDs) based on GaN, GaAs [6,7] have been employed as major transmission devices for wireless communication links. When high power density is needed for high power generation at W-band and above frequencies, TWTs show merit over SSDs in terms of managing and removing waste heat from device which result high breakdown limits [1]. But, in other hand, it requires ultra-high vacuum packaging challenge and high beam voltage requirement. The dimensions of a vacuum electronic device scale with operating frequency. Therefore, circuit feature dimensions become micron scale size and desire surface roughness becomes order of a few hundred nanometers at W-band [2]. Therefore, for predicting the practical circuit and TWT design, firstly it requires methodical theoretical approach followed by precise in-depth electromagnetic simulations. Finally, realization of circuit is possible by novel micro/nano EDM milling machining or microfabrication like UV-LIGA/ DRIE techniques [2,8–10].

There is enormous demand of W-band TWTs for high data rate secure communication and imaging radar systems [1]. The silent features of W-band practical tubes reported by leading companies/agencies like Thales, L3-EDD, BVERI, and Teraphysics were listed in Table 1. Serpentine waveguide (SWG) circuit is one of the most promising circuits at W-band frequencies. The elliptical conformal transformation approach was reported for dispersive properties estimation in terms of phase-velocity and impedance estimation for serpentine circuit [16]. The single section and two-section folded waveguide W-band TWT designs were predicted gain nearly 24 dB and 30 dB, respectively [17,14].

Now, in this paper aiming for the TWT's gain almost 38 dB with saturated peak power more than 100 W, multi-section (3-section) TWT amplifier has been designed. As multi-section TWT design is very much prone to generate undesired oscillations in the vacuum tube. Hence, precise numerical design by 3-D electromagnetic simulation plays an important role in the design and estimation of dispersive properties as well as RF-properties of high power and high gain vacuum electronic multi-section TWT. Nowadays advancement in 3-D Particle-in-cell (PIC) numerical simulation codes provide a complete information about electron beam and wave

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Table 1
Parameters of some of the practical W-band TWTs.

S. No.	Company/ Agency	Frequency (GHz)	Type of Slow-Wave Structure	Min Peak Power (W)	Gain (dB)	V_b (kV)	I_b (mA)	Target application	Reference paper
1.	Thales	94 ± 0.5	Metallic delay line	150	40	22	180	Airborne military radar	Werner Gerum, et al., [11]
2.	L-3 EDD	90.6	Folded waveguide	200	30	21	324	Airborne radar	Alan J Thesis, et al., [12]
3.	L-3 EDD	94	Serpentine waveguide	100	38	20.5	220	High resolution imaging radar	Richard Kowalczyk, et al., [13]
4.	BVERI	94	Folded waveguide	100	33	21.7	171	High resolution imaging radar	Jinjun Feng, et al., [14]
5.	Teraphysics Corp.	94	Helix	25		9.7	13.5	5 G wireless backhaul	James A Dayton, at al., [15]

interactions which is helpful to precisely estimate the device RF-performance. Therefore, theoretical basis for synthesis of cold-design main parameters like dispersion, interaction impedance and circuit ohmic-loss for FWG, and RF-parameters estimation for TWT such as power, gain, bandwidth and efficiency are very much useful for getting the optimum complete design of W-band TWT. In this paper, in-depth design of a W-band SWG vacuum electronic TWT presented by using analytical theory and further validated/optimized with advanced 3-D numerical simulation code in order to investigate the beam & wave dynamics in multi-section TWT. Initially, in Section 2, cold-test (in absence of electron beam) numerical design accomplished to determine the dispersive properties of the SWG TWT. In Section 3, hot-test simulations (in the presence of an electron beam) performed to predict the operating characteristics of TWT such as saturated peak RF output power, gain, bandwidth, and efficiency. Finally, concluding remakes listed in Section 4.

2. Cold-test numerical design

The vacuum electronic SWG TWT design target parameters are shown in Table 2.

2.1. Design parameters of interaction circuit

Fig. 1(a) shows a schematic half-cut view of SWG interaction circuit metal model with presence of cylindrical electron beam proportion towards x-direction. The half-cut view one period model with labeled dimensions shown in Fig. 1(b).

Here, 'a' and 'b' are inside width and height of the rectangular waveguide, respectively. The p (= 2 b) is a pitch which corresponds to a half period of the structure; L (= h + πp/2) is the RF waveguide per pitch path length; R (= p/2) is the half mean radius; h (= 1.1 p) is the vertical segment of the SWG; and $2r_T$ is the diameter of the beam-tunnel. The value of 'a' has chosen f/f_c value ~1.14 for aiming to get higher interaction impedance. Here, f_c is the cut-off frequency for SWG. The value of 'p' was found by matching the wave velocity (v_p) with beam velocity (v_e) in the axial direction. The circuit was aimed to design at 1.5π phase-shift ϕ (= β_m p) for obtaining the maximum bandwidth. Here, β_m is the phase-constant along the curvilinear SWG axis, and for beam-wave velocity modulation matching condition which can be defined as $2\pi f_0/v_e$. Here, f_0 is the center frequency and v_e is the velocity of the electron. Further, $v_e = \beta c = 0.272$ c for beam voltage (V_b) 20 kV. Here, 'β' relates with relativistic energy factor 'γ' like as: $\gamma = 1 + eV_b/m_ec^2 = (1-\beta^2)^{-1/2}$; e and m_e represent the charge and rest mass of electron, respectively. Here, notation 'c' for velocity of light. Therefore, calculated 'p' value for 20 kV beam voltage is ~0.65 mm. Mainly, RF-propagation characteristics for a serpentine waveguide circuit (SWGC) can be completely described by using three circuit parameters: phase velocity, interaction impedance, and ohmic-loss. Therefore, theoretical basis for synthesis of these parameters are very useful for getting the optimum cold-test (in absence of electron beam) design of W-band TWT.

Table 2
Design goal for W-band SWG TWT.

Center frequency f_0 (GHz)	94
Minimum 3-dB bandwidth (GHz)	±1
Beam voltage V_b (kV)	20
Beam current I_b (A)	0.1
Minimum gain G (dB)	38
Minimum peak output power P_{out} (W)	100

2.2. Dispersion (ω-β_m) characteristics

The dispersion simply expressed by Eq. (1) for the shown SWG model in Fig. 1.

$$\omega^2 = \omega_c^2 + \beta_m^2 c^2 \tag{1}$$

Here, ω is the angular frequency and c is velocity of the light. TE_{10} angular cut-off frequency can be defined as $\omega_c = \pi c/a$ for a waveguide of width 'a'. The phase-constant of the space harmonics in the periodic E-plan bend folded waveguide has defined as $\beta_m = \beta_{x,m} + (2m+1)\pi/L$, where phase-constant along the beam-axis is $\beta_{x,m} = (L/p)\beta_{wg}$, phase constant along the serpentine waveguide is $\beta_{wg}(=2\pi/\lambda_g)$, and m is the space harmonic number. For electron beam reference frame, in the serpentine waveguide the transverse electromagnetic wave is effectively slow down its phase velocity by $(p/L)v_{p,wg}$, where $v_{p,wg} = \omega/\beta_m = \omega/(\Phi/p)$ is a phase velocity along the SWG, p is the one pitch measured along the beam-tunnel, L is length measured along the one pitch SWG, and β_m is waveguide's effective axial wave number. Here, SWG circuit is E-plan folded waveguide [Fig. 1], hence π – term added in the phase constant expression for the m^{th} space harmonic geometric phase reversal which reverse the orientation of the RF electric field. However, for the beam-wave interaction at gap to gap opening points into the SWG circuit, phase-shift ϕ along the beam propagation direction defined by Eq. (2).

$$\phi = \beta_{x,m}L + (2m+1)\pi \tag{2}$$

Then, from Eq. (1) and (2), one can get Eq. (3) the dispersion relation for the SWG circuit in the frequency normalized form.

$$f/f_c = \sqrt{1 + (a/L)^2[(\phi/\pi) - (2m+1)]^2} \tag{3}$$

Here, m = 0, ±1, ±2. . .. denotes the spatial harmonics due to interact periodic nature of the circuit.

The beam-wave interaction in the SWG occurs when beam phase velocity is synchronized with the effectively slowed-down wave phase velocity, resultantly satisfying both the waveguide mode given by Eq. (3) and a beam dispersion line given by Eq. (4).