Design of a 0.22-THz 100W Microfabricated Planar Travelling-Wave Tube

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Abstract—**In-house developed analytical design tools were used to design a vacuum micro fabricated planar TWT with rectangular sheet beam of centre frequency 0.22-THz, output power 100W, gain 30dB, and bandwidth more than 20GHz. Staggered double-vane loaded rectangular waveguide slow-wave structure was used in planar TWT which was designed with cold bandwidth more than 50GHz from 195GHz to 245GHz for its operation with sheet electron beam of voltage 20kV and current 50mA. The structure was matched at the input and the output ends with the WR-3 waveguide (432μm x 864μm). Large-signal analysis code (SUNRAY-THz) was used for design of a complete SWS with input/output couplers, sever in-between circuit, and velocity taper. Very good agreements were achieved for the output power and the gain of a 0.22-THz TWT over the operating band between SUNRAY code with 3D e.m. field simulator (CST-PS).**

Keywords- THz TWT; THz amplifier; THz oscillator, Vacuum Microelectronic Devices.

I. Introduction

Compact vacuum microelectronic devices (VMDs) are being investigated for efficient high power generation and amplification of terahertz (THz) frequencies (0.1THz - 10THz) for many new and emerging applications including ultra high data rate communication, remote sensing, security, medical imaging, spectroscopy and high resolution radars [1-2]. The operation of these devices is based on the efficient interaction of the electron beam with the radiofrequency (RF) circuit field in such a manner that maximum energy from the electron beam can be transferred to the RF circuit field. Among various vacuum devices, travelling wave tubes (TWTs) are preferred for communication and radar as high power amplifiers because of their wide instantaneous bandwidth, high gain and high linearity. At THz frequencies, TWTs are very difficult to fabricate because the dimensions of the RF slow-wave structure (SWS) are just hundreds of microns. Also, because of the small size of the electron beam tunnel, the beam current density requirement is much more than 100A/cm^2. The planar SWS is preferred for a high power THz TWT because it is easier to fabricate with high precision and surface finish. MEMS technology like the UV-LIGA process is used to fabricate planar SWS within tolerance of ±5μm and surface roughness less than 10nm. The Nano-CNC technique is also being used to fabricate such structures. A rectangular/elliptical shape sheet beam is chosen for a THz TWT because it has a very low space charge field (at least 100 times less) compared to that of the equivalent cylindrical beam of the same current, voltage and charge density. The sheet beam has therefore, a high current carrying capacity providing large gain per unit length and has the requirement of a low magnetic field for focusing the electron beam.

II. Design of SWS for a 0.22-THz TWT

High efficiency, high gain 0.22-THz planar TWT, as shown in Fig.1, of output power 100W, gain 30dB and bandwidth more than 20GHz is designed using in-house developed design tools. Critical components of a planar TWT are:
(i) The electron gun assembly with flat cathode for generation of a rectangular/elliptical sheet beam;
(ii) The RF slow-wave structure (SWS) of high impedance, low loss and planar geometry for supporting and amplifying THz waves extracting kinetic energy from the sheet beam;
(iii) The input and the output couplers to feed THz signal into the circuit and coupled out amplified signal from the circuit;
(iv) The magnetic focusing circuit for confined flow of the sheet beam through the structure;
(v) The collector for collection of the spent beam efficiently with zero back streaming.

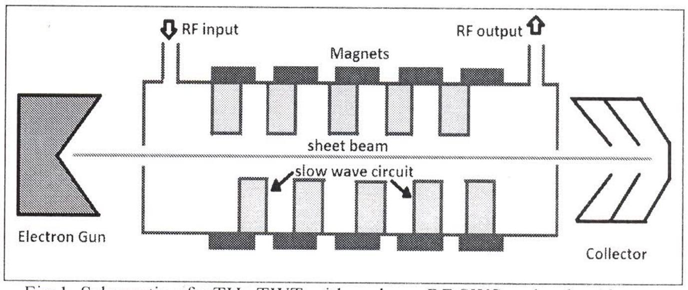

Fig.1. Schematic of a THz TWT with a planar RF SWS and a sheet beam.

Among various types of SWS as being investigated for a 0.22-THz TWT, staggered double-vane loaded rectangular waveguide slow-wave structure (SDV-SWS) [3], as shown in Fig.2, is selected for a high power planar THz TWT. It has comparatively higher impedance, broader bandwidth, less circuit loss and less higher modes. Also, SDVSWS is easier to fabricate compared to folded-wave SWS (FW-SWS) [4] for a 0.22-THz TWT with other significant advantages are:
(i) It is easier to match SDVSWS with WR-3 waveguide (425μm x 850μm) at the input and the output ends;

ii) It is convenient to introduce sever (centre loss) in between SDVSWS for stability against reflections at the terminations;
(iii) It is convenient to introduce phase velocity tapering in the SDVSWS at the output for high interaction efficiency;
(iv) The SDVSWS inherently forms rectangular beam tunnel for transporting of sheet electron beam through it.

Analytical approach is developed [5] to design parameters of the SDV-SWS (Fig. 2). The structure is designed for a 0.22-THz TWT with cold bandwidth more than 50GHz from 195GHz to 245GHz for its operation with a sheet electron beam of beam voltage 20kV and beam current 50mA.

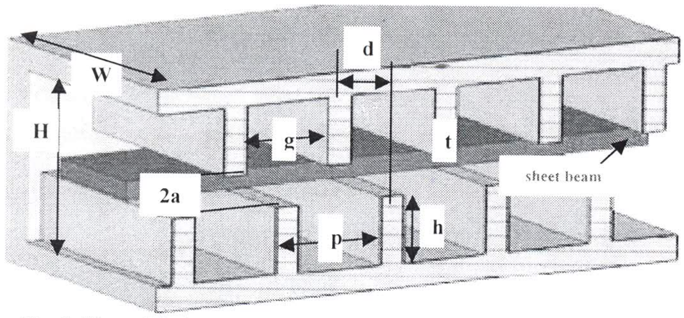

Fig. 2. Planar RF slow-wave structure for a THz TWT with sheet beam

The analytically determined parameters of the circuit are pitch (p):463μm, gap (g):139μm, vane thickness (t):324μm, beam tunnel height (2a):118μm, vane height (h):354μm, waveguide height (H) x width (W):826μm x 770μm. Vanes of rectangular shape are used and the vanes on the opposite sides are staggered by half-period to provide proper RF electric field for interaction with the electron beam leading high in teraction impedance and high gain. Comparison of the analytically determined dispersion characteristic of the structure with the values as determined by CST-MWS code is shown in Table I.

Table I: Comparison between Analytical and CST-MWS values
(βp-phase shift per pitch; f_L/ f_U lower/upper end frequency; Δf-bandwidth)

Parameter	Analytical Value	CST-MWS value
βp at 0.22THz	2.5 π	2.5551 π
f_L	194.67 GHz	194.49 GHz
f_U	245.33 GHz	245.78 GHz
Δf	50.66 GHz	51.29 GHz

III. Beam-Wave Interaction Analysis for TWT Design

SUNRAY code [6] was used to design a complete SWS with a sever in-between the circuit, a velocity taper in the output and input/output couplers for a high gain high efficiency planar 0.22-THz 100W TWT with a rectangular sheet beam. In the first approximation, the rectangular sheet beam is represented by an equivalent cylindrical beam of same cross-sectional area and the planar circuit is defined by an equivalent cylindrical tunnel for calculation of the ac space charge field. Simulated RF performance of the 0.22-THz planar TWT by the SUNRAY code is compared with the results simulated using the CST code. A reasonably good agreement between the simulated results on the gain and the output power versus frequency by the SUNRAY code with that of the CST code is found. As shown in Table-II, there is reasonably good agreement between the gain at saturation and position of saturation as simulated by the SUNRAY code and the CST-3D code, over the band of 0.20-THz to 0.24-THz. The SUNRAY code is very fast in simulation compared to the CST code, as it takes only 10-15 minutes to simulate the RF performance of a planar THz TWT over the frequency band, and therefore it can be used interactively for a tube design.

Table-II: Comparison of simulated results for 0.22-THz TWT- simulated by SUNRAY-1D code and CST code

Frequency (THz)	SUNRAY code		CST 3D code	
	Gain dB	distance mm	Gain dB	distance mm
0.20	33.1	32.0	32.6	33.0
0.22	35.6	33.9	35.5	34.0
0.24	34.0	43.2	34.2	43.0

IV. Conclusion

For meeting new and emerging applications of ultra high data rate communication, medical imaging, remote sensing, security, spectroscopy, etc., a 0.22-THz 100W planar TWT with sheet electron beam of beam voltage 20kV and beam current 50mA, is designed using in-house developed analytical design codes. The simulated results by the in-house developed codes were compared against the simulated results using the commercial available 3d e.m. field simulator (CST code). Reasonably good agreements for the dispersion characteristic, the output power and the gain over the frequency band were achieved between the two codes. The complete design of a planar RF slow-wave structure with sever (centre loss), phase-velocity taper and the input and output couplers for a high gain high efficiency 0.22-THz 100W planar THz TWT with a sheet beam of 20kV and 50mA, will be presented.

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