Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2018, 5(11): 852-857

Research Article ISSN: 2394 - 658X

Design of a 10 kW W-band Sheet Beam Extended Interaction Klystron

Anurag Srivastava

Microwave Tube Research and Development Center, DRDO, Bangalore, India-560013
anurag@mtrdc.drdo.in

ABSTRACT

The extended-interaction klystron (EIK) is a very promising compact vacuum electronic device for generating kilowatts of power at millimeter-wave frequencies. In this paper, systematically the design of a W-band sheet beam EIK was performed using eigen-mode solver, transient solver, and particle-in-cell (PIC) solver of CST MWS. Initially, a five-gap single cavity was designed for fundamental 2π-mode operation at 94 GHz using eigen-mode analysis. Thereafter transient analysis has been performed to find out whether there is any problem with respect to mode competition since sheet beam EIK device is prone for mode-competition and oscillation. It was found that the return-loss of five gap single cavity with input and output couplers was -28 dB. Later, 3-D PIC simulations were carried-out for a three-cavity EIK structure at 19.5 kV and 3 A. A saturated output power of 10.5 kW has been achieved at 94 GHz with a gain of 30 dB, an electronic efficient of 18%, and a 3-dB bandwidth of 0.7 GHz.

Key words: Cavity, extended-interaction klystron (EIK), mode-competition, particle-in-cell (PIC), sheet electron beam

---

INTRODUCTION

The gain and bandwidth of any klystron amplifier are basically decided by the characteristic impedance of the cavities. The characteristic impedance of a cavity is determined by the ratio of the shunt impedance 'R_{sh}' to the quality-factor 'Q_{total}' value. In conventional klystrons, this 'R_{sh}/ Q_{total}' value is reduced by narrow RF gaps between re-entrant cavities. Hence, Chodorow et al. [1] has reported the concept of using cylindrical beam extended interaction klystron incorporating multiple RF-gaps in the single cavity for obtaining comparably higher 'R_{sh}/ Q_{total}' value, that provides higher gain and/or bandwidth. Sheet beam and multi-beam EIK devices give better interaction impedance as compared to the cylindrical beam circuit, hence one can get higher power at the same beam voltage [2, 3]. Nguyen et al. [2] has reported the design concept of a millimeter-wave sheet beam extended-interaction klystron (SBEIK). The SBEIK is promising at upper-end millimeter wave (75 GHz to 300 GHz) technology because of its high output power and high gain at low operating voltage. 94 GHz frequency is chosen because at this window frequency atmospheric attenuation is comparatively lower [4], and kilowatts of power are required for many applications like long-range object tracking and high data rate communication [5, 6]. At W-band and higher frequencies, multi-gap EIKs are the preferable choice as they give higher power handling capacity with less complex design and suitable for microfabrication/ micromachining techniques. Pasour et al. [7] have reported a state-of-the-art design and experimental results of a W-band SBEIK deliver a peak power of 7.5 kV, a gain ~ 28 dB, and a 3-dB bandwidth around 200 MHz The benefit of SBEIK is that it offers a combined advantage in terms of output power, bandwidth, gain and efficiency within a shorter length interaction circuit length. However, such sheet beam EIK also have serious problems with mode competition due to closely spaced modes [8].

In this paper, the practical design of a W-band multi-gap sheet beam EIK amplifier and the method to overcome mode-competition and unwanted oscillation are presented. In section 2, the electrical design of the multi-gap single cavity is presented. Section 3 presents the estimation of SBEIK device RF properties, like output power, gain, bandwidth, and electronic efficiency using particle-in-cell simulations. Section 4 gives the conclusion.

DESIGN OF EIK CAVITY

The cross-sectional view of a W-band three-cavity extended interaction klystron (EIK) is shown in Figure 1. It consists of a high energy sheet electron beam that passes through the rectangular beam-tunnel, multi-gap three cavity circuit for the interaction of coherent RF-field with sheet beam, input coupler for injecting the RF-signal, output coupler for extracting the amplified signal, and an intermediate cavity terminated with the load.
The preliminary design specification is shown in Table 1.

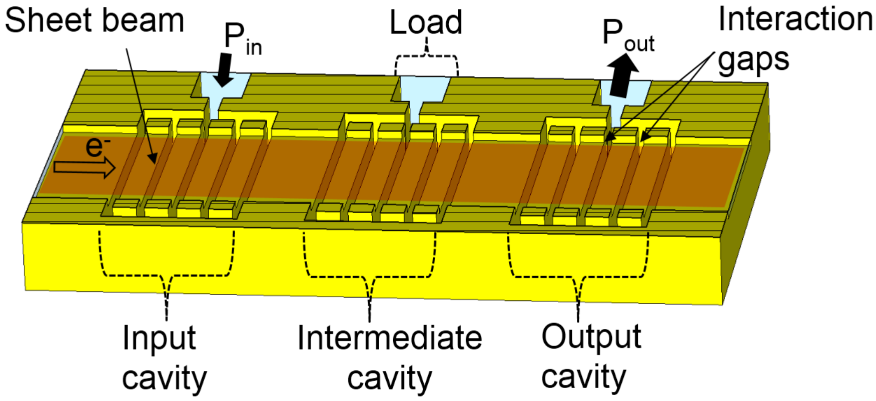

Fig. 1 Schematic of the three-cavity sheet beam EIK

Table -1 Design specifications of the W-band sheet beam EIK

Center frequency f_0 (GHz)	94
Beam voltage V_b (kV)	19.5
Beam current I_b (A)	3
3-dB Instantaneous bandwidth (GHz)	0.7
Minimum output power P_{out} (kW)	10
Minimum saturated gain, G (dB)	28
Minimum electronic efficiency	16

Design Parameters

The schematic of the simulation vacuum model of a five-gap cavity is shown in Figure 2(a-c), and table 1 contains its normalized design dimensions. Here, *'L'* is the cavity length, *'W'* is the cavity width, and *'H'* is the cavity height. A five-gap cavity is chosen due to the strong coupling between top and bottom cavities. Initially, the SBEIK cavity parameters were synthesized using an analytical approach. The design is made such that the cut-off frequency is away from the operating frequency by a factor of 1.6. The cavity cut-off frequency is decided by the cavity height. The cross-section of the rectangular sheet beam tunnel is '*TW* x *TH'*. Since the beam-tunnel area is chosen by considering a sheet beam filling factor of ~ 60 %, *'TH'* value is dependent on sheet beam height. The sheet beam height to width ratio is chosen as 1:12 by considering the $E\times B$ velocity shear effect [9]. Here, the beam height value is almost λ/10.
The distance between the intermediate gaps was decided based on the beam velocity and the phase-shift for obtaining the maximum output power. The pitch *'p'* is determined by the phase relation $\beta_e p < n\pi$, where $\beta_e=2\pi/\lambda_e$. Here, 'β_e' is the electron beam phase-constant, '*n*' is the mode-number, and 'λ_e' is the beam-wavelength. Relativistic equation $\gamma m_0c^2 = m_0c^2 + eV$ is implemented for estimating the beam velocity. Here, '*V*' is beam voltage, and 'γ' is the relativistic-factor.

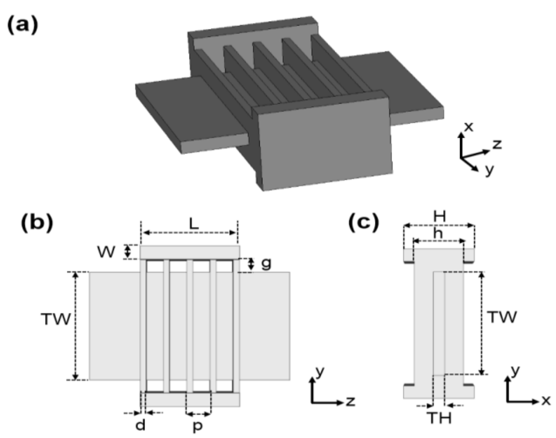

Fig. 2 Simulated vacuum model of five-gap SBEIK cavity: (a) 3D view, (b) top view, and (c) front view.

Table -1 Design parameters of SBEIK cavity

Normalized parameter (mm)	TW	TH	BW	BH	p	d	g	H	h
	1.41	0.13	1.25	0.08	0.2	0.06	0.16	0.8	0.55

Eigenmode and Impedance Characteristics

The single cavity incorporated with five-gap is optimized using the 'eigenmode solver' of CST MWS -studio [10]. The eigenmode analysis is carried out by applying proper boundary conditions for calculating the electric field component along the beam propagation direction. The E-field plot shows that the desired operating 2π-mode falls at 94 GHz [Figure 3(a)]. Figure 3(b) shows the axial electric field plot along A-A' and B-B' axis. The five peaks seen in figure corresponds to the electric field intensity at the five-gaps of the cavity providing an efficient beam-wave interaction.

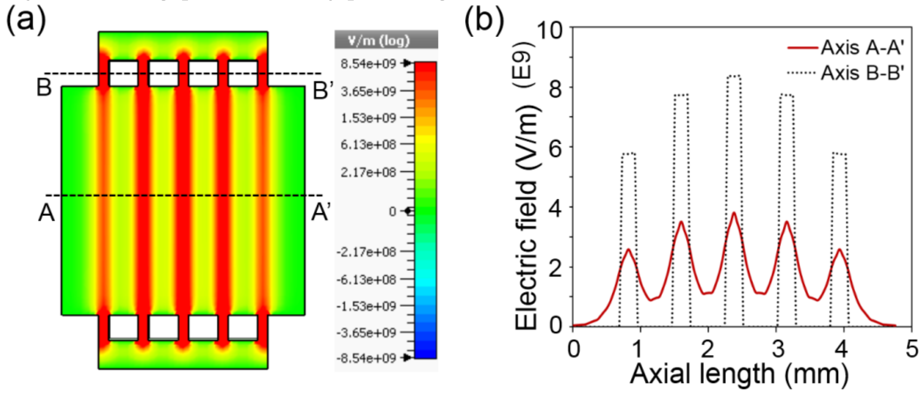

Fig. 3 Eigenmode simulation of the for five-gap cavity: (a) 2π-mode at 94 GHz, and (b) axial E_z-field distribution for the same mode

While carrying at the cavity design, the gap design is very critical. It should be large enough to withstand voltage breakdown, but small enough to improve the coupling there by increasing efficiency. A rough thumb rule is that the maximum electric field on the walls of the cavity should not be more than about 300 kV/cm at the operating frequency. Since, the beam voltage (19.5 kV) is distributed in a five-gap cavity, each gap should withstand a voltage of ~ 4 kV. The computed electric field intensity 58.73 kV/cm is in the safe range, as the cavity length is of ~ 3.32 mm.

The characteristic impedance of a cavity is given by $R_{sh}/Q_{total} = \left(\int_{-\infty}^{\infty} |E_z| dz\right)^2 / 2\omega W_s$, where '$\omega$' and '$W_s$' are the angular frequency and stored energy, respectively. Table 2 shows the simulated characteristic impedance values for 2π-mode and adjacent modes. The EIK cavity operated at 94 GHz for the TM_{11} mode gives an impedance value of 89.8 Ω. The higher 'R_{sh}/Q_{total}' value of the cavity leads to high gain and/or bandwidth of the EIK.

Table -2 Simulated eigenmodes at 2π mode and adjacent modes for EIK Cavity

Frequency (GHz)	$\mathbf{Q_{total}}$	$\mathbf{R_{sh}/Q_{total}}$ **(Ω)**
94 GHz (TM_{11})	803	89.8
97 GHz (TM_{21})	835	7.9×10^{-17}
99 GHz (TM_{31})	906	1.19 10^{-17}

Return-Loss Analysis

The return-loss of the cavity is improved by optimizing the coupler design using the 'transient solver' of CST-MWS [10]. The Figure 4(a) shows the simulation model which consists of the five-gap cavity with input coupler. The effective conductivity of 2.25×10^7 s/m for oxygen-free high thermal conductivity (OFHC) copper is assigned as cavity material in the simulation model [11]. The return-loss value is observed to be better than -26 dB at the desired resonant frequency of 94 GHz [Figure 4(a)]. The three resonance peaks at 94 GHz, 97.8 GHz, and 99 GHz correspond to the TM_{11}, TM_{21}, and TM_{31} mode, respectively [Figure 4(b)].

Mode competition is one of a serious problem faced by a sheet beam EIK, but this can be overcome by a proper designing of the cavity. Figure 4 (a) illustrates the next higher order mode resonance (TM_{21}) was observed almost of 3.7 GHz far from the fundamental mode resonance (TM_{11}). Hence, with considering the maximum ~ 1 GHz bandwidth of EIK, this cavity design is completely safe from the mode-competition.

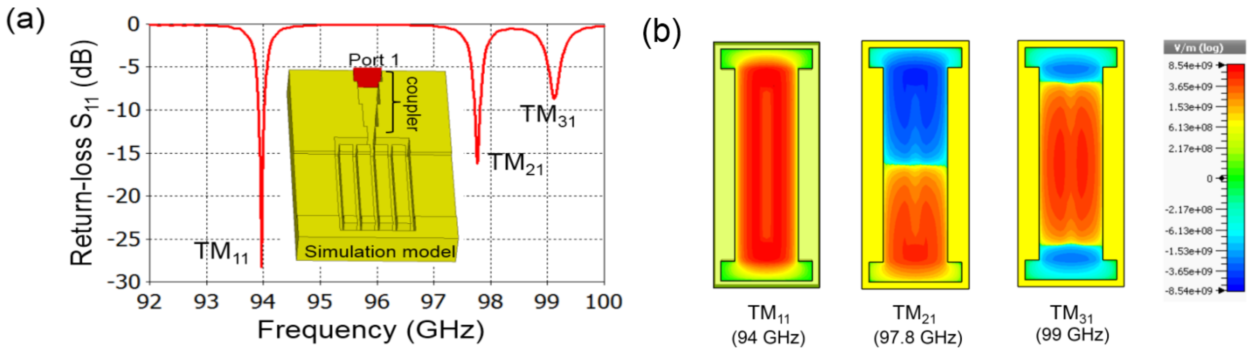

Fig. 4 (a) Simulated return-loss values for SBEIK cavity, and (b) electric-field pattern for the TM_{11}, TM_{21}, and TM_{31} modes at specific frequencies.

PARTICLE-IN-CELL SIMULATIONS FOR THREE CAVITY EIK

The non-linear interaction between the bunched electron beam and RF-wave in the multi-gap cavities has been examined by CST particle-in-cell (PIC) 3-D simulation code [10]. The three cavity simulation model is chosen for obtaining the device output power, saturated gain, and bandwidth [Figure 5(a)]. Here, the first cavity works as 'Buncher cavity' and the third cavity works as 'Catcher cavity'. The intermediate cavity is terminated with the proper load of SiC (ε_r = 10 and tanδ = 0.3, at 10 GHz) to avoid for generating oscillation [12]. In the simulation, at 19.5 kV and 3 A, a sheet beam with a cross-section of 4 mm x 0.25 mm is launched in a rectangular beam-tunnel of 4.5 mm x 0.4 mm and a uniform magnetic field of 8 kG is applied for transporting the beam through the rectangular beam-tunnel [13]. Figure 5(a) shows the simulated result of the sheet electron beam bunching profile. Figure 5(b) shows the input signal *'i1'* and output signal *'o3'* as a function of the simulation time at WR10 port 1 and WR10 Port 3, respectively. At 94 GHz, the drive signal of 3.16 V gets amplified to 103 V, corresponding an output power (=voltage amplitude^2) of almost 10.6 kW, a gain of 30 dB, and an electronic efficiency of ~ 18 %.

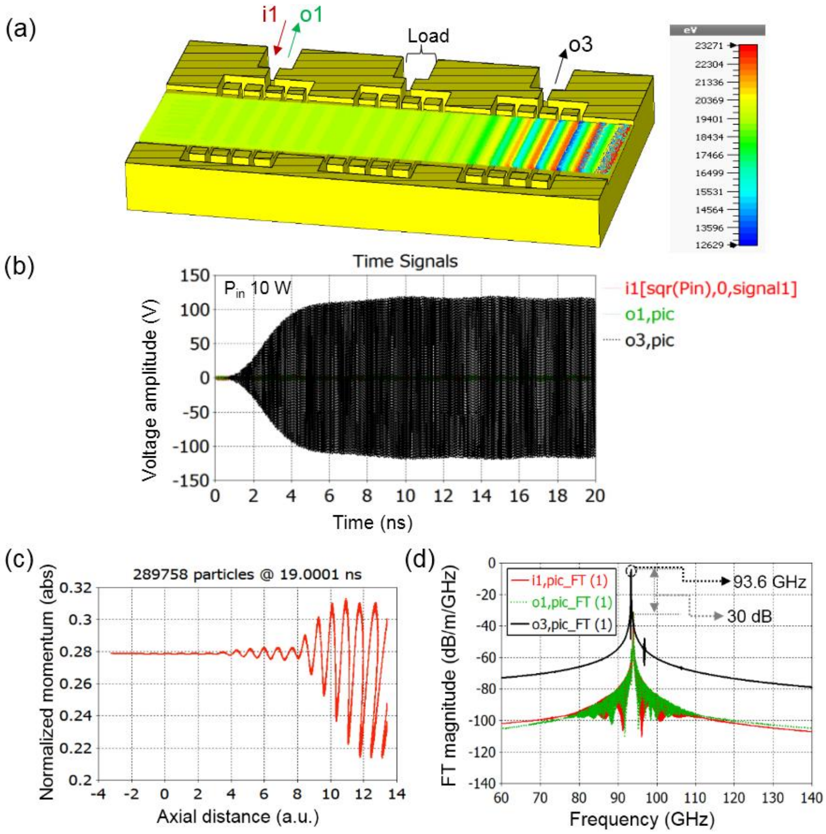

Fig. 5 PIC simulation of a three-cavity SBEIK: (a) snapshot of bunched sheet beam electron beam, (b) generated 'o1' and 'o3' electric field signals for injected signal 'i1' at 94 GHz, (c) snapshot of the normalized electron momentum plot @ 19 ns, and (d) FT magnitude vs. frequency plot at 19.5 kV and 3A

Figure 5(c) shows the beam velocity modulation along the axial distance at 19 ns for a total circuit length of ~ 14 mm. It clearly illustrates that most of the electrons are in the decelerated state in the second and third cavities. Figure 5(d) shows the gain growth of around 30 dB at 93.6 GHz. The magnitude of the received signal at port 1 *'o1'* is almost 40 dB less

than the magnitude of the received forward signal at port 3 *'o3'*. The figure demonstrates that the simulated three-cavity SBEIK structure is free from oscillation and mode-competition.
Figure 6(a) illustrates the output power and saturated gain curves as a function of drive input power at beam voltage of 19.5 kV and the frequency of 94 GHz. The EIK can be produced a maximum output power of 70.25 dBm for input power of 40 dBm. It also demonstrates that output power drive linearly increases with respect to input power. The numerical analyses confirm an instantaneous 3-dB bandwidth of almost 0.7 GHz for the SBEIK [Figure 6(b)].

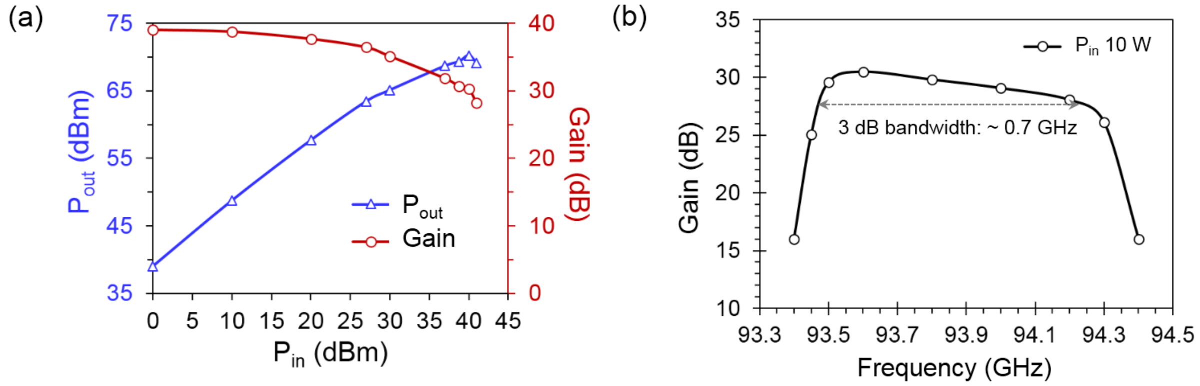

Fig. 6 Numerical analyses for three-cavity SBEIK: (a) Output power and gain vs. input power, and (b) Gain vs. frequency for fixed input power at 10 W

CONCLUSION

The characteristics of the three-cavity circuit have been analysed for a W-band high power sheet beam EIK. The five gap single cavity design at fundamental resonant 2π-mode provides a uniform electric-field distribution and a characteristic impedance of 89.8 Ω at 94 GHz. The transient-analysis has confirmed that this cavity design is safe from mode-competition. The PIC simulations for three cavities EIK structure at 19.5 kV and 3 A demonstrate that it can stably produce an output power of 10.6 kW, a gain of 30 dB, an efficiency of ~ 18%, and 3-dB minimum bandwidth of 0.7 GHz. The results prove that the device has potential to generate the kilowatts of power at lower voltage and compact interaction circuit, which fulfilling the device need at W-band for long-range tracking and high-data-rate communication applications.

ACKNOWLEDGEMENT

The author would like to thank Dr Latha Christie, Associate Director, MTRDC for the many useful comments on the manuscript.

REFERENCES

[1]. M Chodorow, TWessel-Berg, A high-efficiency klystron with distributed interaction, *IRE Trans. on Electron Devices*, **1960**, 8(1), 44-55.
[2]. KT Nguyen, D Pershing, EL Wright, J Pasour, et al., Sheet beam 90 GHz and 220 GHz extended-interacion klystron designs, Pr*ocedings of IEEE 8th International Vacuum Electronic Confeence*, May 15-17, Kitakyushu, Japan, **2007**.
[3]. S Lu, C Zhang, S Wang, Y Wang, Stability analysis of a planar milti-beam circuit for W-band high power extended-interaction klystron, *IEEE Trans. on Electron Devices*, **2015**, 62(9), 3042-3048.
[4]. A Srivastava, Microfabricated Terahertz Vacuum Electron Devices: Technology, Capabilities and Performance Overview, *European Journal of Advances in Engg. & Tech.*, **2015**, 2(8), 54-64.
[5]. A Roitman, D Berry, S Brain, State-of-the-art W-band extended inercation klystron for the cloudsat program,*IEEE Trans. on Electron Devices*,**2005**, 52(5), 895-898.
[6]. SS Dhillon, MS Vitiello, EH Linfield, et al., The 2017 terahertz science and technology roadmap, *J. Phys D Appl. Phys.*, **2017**, 50, 043001–043001.
[7]. J Pasour, W Edward, et al., Demonstration of a multikilowatt, solenoidally focused sheet beam amplifier at 94 GHz, *IEEE Trans. on Electron Devices*, **2014**, 61(6), 1630-1636.
[8]. C Shuyuan, C Ruan, et al., Particle-in-cell simulation and optimization of multigap extended output cavity for a W-band Sheet beam EIK, *IEEE Trans. on plasma science*,**2014**, 42(1), 91-98.
[9]. KT Nguyen, JH Pasour, et al., Intense sheet electron beam transport in a uniform solenoidal magnetic field, *IEEE Trans. on Electron Devices*, **2009**, 56 (5), 744-752.
[10]. http://www.cst.com.
[11]. A Srivastava, L Christie, Design of a high gain and high efficiency W-band folded waveguide TWT using phase-velocity taper, *J. of Electromagnetic Waves and Applications (Taylor & Francis)*, **2018**, 32(10),1316-1327.
[12]. AJ Theiss, Measuring return-loss resonances to estimate RF wall loss in MM-wave coupledcavity circuits, *IEEE Trans. on Electron Devices*, **2009**, 56(5), 981–985.

[13]. Y Zheng, D Gamzina, B Popovic, NC Luhmann Jr, Electron beam transport system for 263-GHz sheet beam TWT, *IEEE Trans on Electron Devices*, **2016**, 63 (11), 4466-4472.

Check List

1.	**All the reference has been cited with large brackets - YES**
2.	**DOCX File [word file] is ready- YES**
3.	**Duly filled and signed scan copy of Copyright form is ready-YES**
4.	**All the figures and tables are numbered and have caption-YES**
5.	**Figures, tables and equations are given in Editable form-YES** **[If figures are not in editable form, please send high resolution figure]**