Analysis of a coupled-cavity slow wave structure for a TWT

M K Alaria & V Srivastava
Microwave Tubes Area, Central Electronics Engineering Research Institute, Pilani 333 031, Rajasthan, India
Email: mukesh_pilani@yahoo.co.in & vs@ceeri.res.in

Received 20 November 2006; revised 28 June 2007; accepted 14 February 2008

This paper describes an approach of designing a coupled-cavity slow wave structure (CC-SWS) for a high power traveling wave tube (TWT) using HFSS code, which is a 3-D high frequency electromagnetic simulator. The criteria of deciding the initial design parameters of a cavity are first discussed. Method of computing the dispersion and impedance characteristics of the CC-SWS has been discussed. Analysis was carried out for single and double-slot CC-SWS with coupling slots. Mesh size was optimized for speed and maximum accuracy. The CPU time on Pentium-4, 2.66 GHz system with 1 GB RAM was less then 25 min for three or four cavities. Results of HFSS are matched with the experimental results for a C-band coupled cavity SWS and also compared with the results of analytical method.

Keywords: Dispersion, Coupled-cavity slow-wave structures (CC-SWS), Traveling wave tube, Staggered structure, Coupling slots

PACS No.: 84.40.De

1 Introduction

Coupled-cavity TWT is a high power microwave amplifier. Its peak output power varies from tens of kW to thousands of kW and average power goes up to few tens of kW. Gain up to 70 dB and overall efficiency up to 60% can be achieved. It is available up to 100 GHz. The CC-TWTs is widely used in radar systems. A CC-TWT consists of electron gun, coupled-cavity slow wave structure, periodic-permanent magnet focusing system, input and output couplers and collector\(^1\). The coupled-cavity slow wave structure is a stack of circular cavities, which are coupled to each other through their common wall. The SWS plays a crucial role by synchronizing the phase velocity of the rf circuit field with the electron beam passing through the circuit. This causes the electron beam to interact with the rf field for efficient energy transfer from the electron beam to the field causing its amplification.

The CC-SWS is mainly characterized by its dispersion (variation of phase velocity with frequency) and its interaction impedance, the first determine the tube bandwidth while the second is related to tube gain. There are different types of CC-SWS (Coupled-cavity slow-wave structures) depending on the type of coupling. In CC-SWS, cavities are coupled to each other through either single or double slots, which are shown in Fig. 1. In a single-slot CC-SWS, there is one coupling slot in each common wall, and the slots of the coupling plates are staggered at 180 deg to each other for wider bandwidth. In a double-slot CC-SWS, there are two slots at 180 deg in each coupling plate, which are staggered to the slots of the adjacent plates by 90 deg. Presently a double-slot staggered structure is being used. This type of CC-SWS is also called space harmonic SWS\(^2\). This structure is widely used in CC-TWTs.

2 Analytical approach

There are nine design parameters of a cavity of CC-SWS, in which the slots are taken of kidney shape: cavity period \((L)\), cavity height \((H)\), gap length \((G)\), beam hole diameter \((a)\), ferrule diameter\((C)\), cavity diameter \((R)\), slot angle \((\alpha)\), slot width \((r_s)\), and slot position \((R_s)\). One has to decide these design parameters\(^3\) for 70 kW output power at center frequency of 5.6 GHz and efficiency 20%. For this case, input dc power needed is 360 kVA. The beam perrveance is selected less than 1.5 \(\mu\)p for long-life cathode. This needs to set operating beam voltage of 36 kV and beam current 10 A.

After deciding the beam voltage, the cavity period \((L)\) is decided on the principal of maintain synchronism between the electron beam and the rf field. This requires \((BL)\) nearly equal to 1.5\(\pi\) at the center frequency for wide band operation. Therefore,
\( L = 1.5 \pi /\beta \), where \( \beta = \omega /u_0 \) is the axial propagation constant, \( \omega \) the angular frequency and \( u_0 = \sqrt{(2e/m)V_0} \) the axial beam velocity. Therefore \( L = 13 \text{ mm} \). Cavity height \( (H) \) is to be selected as large as possible for high gain, but the wall thickness should be sufficient to avoid any magnetic saturation. Wall thickness in this case is taken nearly 4 mm. Therefore \( H = 9.7 \text{ mm} \). The gap length \( (g) \) is selected for maximum interaction impedance. A narrow gap cavity has higher interaction impedance\(^4\). The ratio \( (g/L) \) is chosen nearly 0.30, therefore \( g = 4.0 \text{ mm} \). Beam radius \( (b) \) is determined by the frequency of operation, the normalized beam radius \( (\beta b) \) is selected in the range of 0.6-1.0, to ensure high gain and efficiency. Therefore \( b = 3.0 \text{ mm} \). The beam filling factor \( (b/a) = 0.7 \), this calculates the value of beam hole diameter \( (a) \). The ferrule radius \( (C) \) decides the concentration of electric field at the interaction gap. It is decided from the thermal dissipation against beam interception. Ferrules are made of copper with \( (c/a) \) chosen nearly 1.1 at the nose and 1.2 at the base, with minimum thickness of 0.5 mm. This helps to set the value of \( C \).

The cavity radius \( (R) \) affects resonant frequency of \( \text{TM}_{01} \) mode of the cavity, which is the upper cutoff frequency of the slow wave circuit, the cavity radius \( (R) \) is chosen nearly equal to the cavity period \( (L) \) for high-Q of the cavity.

The slot length related to slot angle can be treated as equivalent width \( (a) \) of a rectangular wave-guide with cutoff wavelength = \( 2a \) for he \( \text{TE}_{10} \) mode\(^5\). A single coupling slot is taken and slot angle \( (a) \) is chosen as 72 deg, slot position \( (R_s) = 0.5 \) \((R + c)\) and slot width \( (w) \), which is twice of slot radius \( = (R - c) \).

The optimized design parameters for CC-SWS with single coupling slot are given in Table 1.

### 3 Computational approach

The above parameters are used to the analysis of coupled cavity SWS in the Ansoft HFSS. The dispersion and impedance characteristics of coupled cavity SWS has been obtained using Ansoft HFSS\(^6\) with the help of different boundary conditions. In HFSS, Eigen mode solution is selected to calculate the Eigen modes, a set of three or four cavities has been used to find out the dispersion characteristics and Q-value of coupled-cavity SWS. Quality factor \( Q \) is a measure of energy lost in the structure. The eigen mode solver finds the resonant frequencies of the structure and the fields of those resonant frequencies. The eigen mode solver can find the eigen modes of lossy as well as loss-less structure and can calculate the unloaded \( Q \) of a cavity. The coupled cavity SWS is terminated at its ends with electric and magnetic walls to determine sets of eigen modes. Each eigen mode corresponds to a frequency for standing wave with an integral number of half wave lengths (phase shift of \( \pi \)). The HFSS model of double-slot staggered structure has been used in simulation shown in Fig. 2.

A set of three cavities coupled with double-slots was used in the present work. In first step the structure is modeled using electric wall (perfect electric - perfect electric) boundaries at both ends. This gives three eigen mode frequencies corresponding to the following phase shift per cavity\(^7\).

(i) \( \pi + \pi/3 = 4 \pi/3 \)

(ii) \( \pi + 2\pi/3 = 5 \pi/3 \)

(iii) \( \pi + 3\pi/3 = 2 \pi \)

In the next step the structures is modeled using one end electric and other end magnetic. This condition gives the three eigen mode frequencies corresponding to the following phase shift per cavity:
Fig. 2—HFSS model of double-slot staggered structure

(i) \( \pi + (\pi/2)^{\times\frac{1}{3}} = \frac{7\pi}{6} \)
(ii) \( \pi + (\frac{3\pi}{2})^{\times\frac{1}{3}} = \frac{3\pi}{2} \)
(iii) \( \pi + (\frac{5\pi}{2})^{\times\frac{1}{3}} = \frac{11\pi}{6} \)

Tables 2 and 3 present simulated results for double-slot staggered structure (slot angle 72°) of CC-SWS. Figure 3 shows the experimental set-up for dispersion and impedance characteristics.

### 4 Results and discussion

The dispersion and impedance characteristics were obtained by the six resonant frequencies to \( \pi, 1.2\pi, 1.4\pi, 1.6\pi, 1.8\pi \) and \( 2\pi \) phase shifts. In HFSS, directly calculate the interaction impedance. Figures 4 and 5

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Frequency, GHz</th>
<th>Q-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.20</td>
<td>4557</td>
</tr>
<tr>
<td>2</td>
<td>5.55</td>
<td>5291</td>
</tr>
<tr>
<td>3</td>
<td>6.08</td>
<td>7180</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Frequency, GHz</th>
<th>Q-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.15</td>
<td>4429</td>
</tr>
<tr>
<td>2</td>
<td>5.41</td>
<td>4861</td>
</tr>
<tr>
<td>3</td>
<td>5.85</td>
<td>6147</td>
</tr>
<tr>
<td>4</td>
<td>6.22</td>
<td>7881</td>
</tr>
</tbody>
</table>

Fig. 3—The experimental set-up for dispersion and impedance characteristics
show comparison of dispersion and impedance characteristics obtained by HFSS, analytical and experimental results. Figure 6 shows the dispersion curve for different type of structure, and Fig. 7 shows the Dispersion curve for multi-cavity SWS. Figure 8 shows the electric field pattern for TM01 mode.

Acknowledgements
The authors are thankful to the Director, CEERI, Pilani, Dr S N Joshi and Dr R S Raju, Project leader (CC-TWT), Electron Tubes Area, for their support and guidance and to all other project team members for their support.

References
2 Akhtar M Jaleel & Srivastava V, Analysis of a coupled-cavity slow wave structure for a high power TWT, IETE Tech Rev (India), 16 (1999) 255.
6 Ansoft HFSS v-9.0, 3D Electromagnetic simulator, Ansoft Corporation, Pittsburgh.