Design and Characterization of X-Band Sheet Beam Klystron Cavity

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Abstract. Sheet Beam Klystron (SBK) is a device employing rectangular/elliptical cross section beam. The barbell cavity for SBK has been designed providing uniform flat electric field profile across the width of the cavity. The loop coupling arrangement has also been designed using CST Microwave studio software tool and optimized for maximum return loss. The designed barbell cavity has been re-optimized after the insertion of the loop coupling to provide flat electric field profile across the width of the cavity. The cavity has also been fabricated and initial characterization has been carried out. The simulated results and the experimental results matches closely.

1. Introduction
Attaining high power at higher frequency regimes is still an active area of research in microwave tubes. The major limitation is that the device size scales down as wavelength. So devices which overcome these shortcomings using various techniques are been continuously studied. Sheet Beam Klystron (SBK) is one such device which is expected to give good results in both high and low frequency regimes which employs a rectangular cross section beam instead of circular. It is similar to arranging several cylindrical beams in linear fashion. Thus for the given beam voltage and beam current density since beam area is increased, the beam current is increased proportional to the beam width. Thus higher power is achieved at reduced input voltage. This futuristic device has wide range of applications like directed energy weapons, linear accelerators and muon accelerators [1-3]. Despite many advantage, there are several critical issues in this device such as high aspect ratio sheet electron beam generation and need for design with high transmission efficiency. Also because of diocotron effect the breakdown of the beam might occur [4,5]. Also the drift tube can propagate all the TE modes and hence there is a serious problem of feedback and oscillations. Due to the large lateral dimension of the beam SBK requires large drift tubes and overmoded cavities. R/Q of the cavity is also much less than that of the conventional Klystron [6]. Major objectives in the cavity design of sheet beam tubes are a flat field across the whole beam width, a large (unloaded) shunt impedance and reduction of transit time effect [7].

2. Concept of the barbell cavity
Due to the usage of high aspect sheet beam, the cavity used for such a beam should be specially designed to provide uniform field across the overall width of the beam. The barbell cavity is one such cavity to provide the desired uniform flat field profile. The barbell cavity comprises of three sections. The centre one is a simple rectangular waveguide operated closed to cut off with a quarter wave
section on either side of the waveguide as shown in figure 1. As the central waveguide is operated close to the cut off, the group velocity of the wave is nearly zero which maintains the electric field profile to be uniform along the overall width of the cavity. To terminate the open waveguide, the quarter wave sections are used. The quarter wave section transforms the short at the wall to open at the waveguide ends [8].

Fig. 1. Barbell cavity showing the middle waveguide section and the two quarter wave section along with the drift tubes

The height of the quarter wave sections are greater than that of the middle waveguide section but has the same length as the waveguide section. The width of the quarter wave sections are not exactly \( \lambda/4 \). The greater the height difference the greater is the width required to get the flat field profile.

3. Design of the X-band SBK cavity

The operating frequency is chosen in the X-Band at 11.4 GHz. As we know the middle section has to be near cut off. So

\[
\lambda = \frac{c}{f} = \frac{3 \times 10^8}{11.4 \times 10^9} = 26.32 \text{ mm}
\]

For a wave to propagate in a wave the broader dimension 'h' should be,

\[
h \geq \frac{\lambda}{2}
\]

Hence for 11.4 GHz, \( h \geq 13.16 \)

for the waveguide to operate close to cut off the broader dimension ‘a’ is chosen as 14 mm. In this way we have \( h = 14 \) mm.

The width of the waveguide depends on the beam width along with the needed clearance. The length of the middle section is equivalent to the gap in the conventional re-entrant cavity. So the length depends on the wavelength of the RF to be amplified. To get better coupling coefficient we need the length in which the beam is exposed to the RF field should be less than \( \lambda/2 \). The cavity length 'l' has been chosen accordingly.

The design of the quarter wave sections are done by using CST MWS [9]. The length of the quarter wave section should be same as that of the middle waveguide section length ‘l’. Since the middle section height \( h = 14 \) mm, the quarter wave section height should be greater than 14mm. As already mentioned the higher the height of the quarter wave section larger is the width needed to get the flat field. The height and width of the quarter wave sections has also been optimized with the 3D simulation tool as shown in figure 2.
The parameter ‘sidewid’ represents the width of the side quarter wave section. Thus for a width of 11 mm the desired uniform field profile has been achieved.

4. Design of loop coupling for the X-Band barbell cavity

The major parameters of the loop coupling are:
- Outer diameter (OD) of the inner conductor forming the loop
- Inner diameter (ID) of the outer conductor radius
- The radius of the loop
- The length projection of the inner conductor into the cavity before forming the loop

They are given in the following figure 3.

![Coupling loop](image)

Fig. 3. Coupling loop

All the loop dimensions are optimized for the best return loss at the operating frequency using CST MWS. The final optimized dimensions are given in table 1.

| Table 1. Optimized loop parameters |
|------------------------------------|
| Loop conductor radius              | 0.62 mm |
| Loop radius                        | 2 mm    |
| Loop inner length                  | 2.5 mm  |
| Dielectric used                    | Teflon  |
| Dielectric constant                | 2.08    |
| ID of the outer conductor          | 4.13 mm |
5. Electric field profile across the cavity

The next step is to insert the loop in the cavity designed. So the cavity is redesign with the loop. Then the eigenmode analysis of the cavity is carried out and the field profile across the cavity width is found to be no longer uniform. The field profile in the presence and absence of the loop is given in figure 4. So it is first necessary to recover the distorted field profile.

![Field profile across the cavity width with and without the loop](image)

By slightly altering the width of the quarter wave section in which the loop is placed, the flat uniform electric field profile can be regained back. After many iterations in the CST MWS, the final dimensions of the barbell cavity including the loop and losses of the dielectric in the loop is given in the table 2

| Parameters                        | Dimensions |
|-----------------------------------|------------|
| Beam height                       | 6 mm       |
| Beam width                        | 95 mm      |
| Cavity height                     | 14 mm      |
| Cavity length                     | 10 mm      |
| Left quarter wave section height  | 16.5 mm    |
| Right quarter wave section height | 16.5 mm    |
| Left quarter wave section length  | 10 mm      |
| Right quarter wave section length | 10 mm      |
| Left quarter wave section width   | 11.54 mm   |
| Right quarter wave section width  | 11.5 mm    |
6. Fabrication of the designed cavity

The central barbell structure is fabricated and is shown in the figure 5(a).

![Fig. 5(a). Fabricated barbell structure](image1)

The fabricated drift tubes along with the barbell structure is shown in the figure 5(b).

![Fig. 5(b). Fabricated Barbell cavity with drift tubes on either sides](image2)

7. Characterization of the fabricated barbell cavity

The cavity is excited using the copper antenna and is inserted through one of the drift tubes. The experimental set up is shown in the figure 6. The probe is inserted in a hole offset from the centre. This is to excite all the modes in the given frequency range. The depth of insertion also affects the resonant frequencies of the cavity mode. The lighter the insertion better is the accuracy of the observed results. The deeper the insertion the modes will appear prominently but the frequency of the corresponding modes will be shifted. This is due to the fact that the exciting probe acts also as a perturbing antenna which affects the field pattern considerably.

![Fig. 6. Experimental setup for characterization of the Barbell cavity](image3)
The Vector Network Analyzer is used for characterization of the barbell cavity. The measured and simulated results are tabulated in table 3.

**Table 3.** The measured and simulated results

| MODE NO | CST MWS simulated results (GHz) | Experimentally measured results (GHz) |
|---------|---------------------------------|--------------------------------------|
| 1       | 11.4257                         | 11.4250                              |
| 2       | 11.4853                         | 11.47                                |
| 3       | 11.712                          | 11.7388                              |
| 4       | 12.1412                         | 12.128                               |
| 5       | 12.684                          | 12.685                               |
| 6       | 13.3503                         | 13.351                               |
| 7       | 14.1738                         | 14.1738                              |

To identify the modes one more copper wire as perturbing object has been used, and is inserted in various holes of the cavity one by one. If the wire is at the field maximum of the excited mode, then there will be severe disturbance or change in the corresponding resonant frequency. But if the wire is at the field minimum, the change or shift in the resonant frequency of the corresponding mode is very less.

8. **Conclusion and future work**

The barbell cavity for SBK has been designed and fabricated. The initial experimental verification of the modes inside the cavity was done and the results quite matches with the simulation. The future work includes the insertion of the loop followed by experimentally measuring the R/Q of the cavity along the overall width of the cavity.

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