Defence Science Journal, Vol. 71, No. 3, May 2021, pp. 320-323, DOI : 10.14429/dsj.71.16792

Design and Simulation of Extended Interaction Cavities for a Ka-band Multi-beam Klystron

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ABSTRACT

This article reports about the design approach, electromagnetic simulation and analysis results of high-frequency ladder-type input, output, and intermediate RF cavaties for Ka-band multi-beam extended interaction klystron. Several parameters of the cavity, such as quality factor, shunt impedance, etc., have been investigated by the assistance of electromagnetic software CST microwave studio.

Keywords: Cavity resonator; Multi-beam Klystron; RF cavity; Extended interaction Klystron; Ka-band, Quality factor, Shunt impedance

1. INTRODUCTION

Klystrons are vacuum-based amplifiers to amplify input microwave signals employing a DC accelerated electron beam and subsequent velocity modulation of the same. An electron beam with suitable current is obtained from a cathode and accelerated by a DC beam voltage. In the interaction region consisting of RF cavities, electrons are either accelerated or decelerated due to the influence of the RF signal. The electrons become clustered as it moves through the drift tubes. After that, the maximum beam energy is transferred to the RF field at the output cavity. Afterwards, the spent electron-beam is collected at the collector[1].

A single beam of the electron is used for beam-wave interaction in case of a conventional single-beam klystron amplifier, but in the case of multi-beam klystrons (MBK), more than one electron beam is used for the same purpose[2,3]. In general, achievable RF power and bandwidth of MBK amplifiers can be higher than traditional single-beam klystrons. Multiple electron beams propagating in the axial direction are used by the MBK amplifier to employ larger beam current for interaction with the RF fields of the resonant cavities at the interaction (RF) section. As a result, the total current of all beams is permitted to be large, but perveances of the individual beamlets are less[4]. Electron beams are moved through different tunnels to minimise their mutual influence.

Due to the attractive features like compactness, lower operating voltage, wider bandwidth, and lower focusing magnetic field requirement, Extended Interaction Klystrons (EIKs) are used in various applications such as laboratory instrumentations, airborne, and automotive radars (pulse/CW), communications, ECM (electronic countermeasures) etc.[5, 6].

Received : 05 February 2021, Revised : 22 February 2021
Accepted : 18 March 2021, Online published : 17 May 2021

In higher operating frequencies, geometrical features of the RF cavities become small, which effectively reduces the permissible individual beam currents. Therefore, to achieve desired output power, RF cavities must offer higher shunt impedance for efficient interaction between the electron beam and RF wave. This is one of the main design criticality in designing RF cavities of an MBK.

EIK cavities are multi-gap RF cavities that are popularly used for obtaining higher shunt impedances. In these cavities, shunt impedance is increased proportionately with the length of the extended interaction portion. However, proper synchronisation of the electron beam with the cavity RF field needs to be maintained for efficient beam-wave energy transfer.

This article reports the design and simulation of the RF cavities for a low voltage (3 kv) multi-beam EIK operating in the Ka-band. Starting from the analytical formulation, geometrical parameters of the cavity were obtained. Using these geometrical parameters, the same has been simulated using commercial electromagnetic simulation software.

2. DESIGN APPROACH

Ladder-type resonant cavities have been considered for the MBK because these type of circuits can be conveniently fabricated using conventional micro-fabrication techniques or three-dimensional printers. The initial dimensions of the cavity (height and width, considering no change inthe electric field along the length) have been obtained using the well-known analytical formula:

$$f_{mn} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \tag{1}$$

where f_{mn} is the resonant frequency of the TE_{mn} or TM_{mn} mode of a resonator with sides a and b. c represents the velocity of light in free space. μ_r represents relative permeability. ε_r represents relative permittivity. It may be noted that we have considered *TM* mode of operation, and there is no variation of the transverse electric field in the direction of beam propagation.

Beam-wave interaction between the electron-beam and radio frequency (RF) fields inside the cavities occurs in the gap between the two cavity walls (in case of re-entrant cavities, between the re-entrant regions). The length of this region, often termed as gap region, acts as a vital part in the synchronisation of the electron beam with the RF field and efficiency of the interaction.

Several operating modes are possible for efficient amplification of the RF signal. Among these operating modes, the 2π mode of operation has been targeted as it this operating mode is most likely to provide sufficient coupling among the RF wave and the beam for RF amplification.

The gap length (G) and pitch-length of the cavities corresponding to a beam voltage of (3 kv) and 2π mode of operation at the targeted resonant frequency of 28.5 GHz can be obtained employing the Floquet theorem for periodicity. Phase velocity v_p of the space harmonics is represented by

$$v_p = \frac{\omega}{\beta_e} \tag{2}$$

where ω is the angular frequency and β_e is the beam propagation constant. Considering the length of the pitch as p and 2π mode of operation, one may have

$$\beta_e p = 2\pi \tag{3}$$

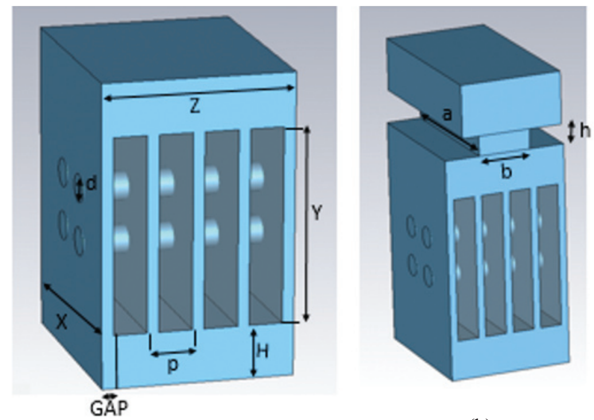
The gap length (G) may be obtained considering a gap transit angle (θ) of 1.5 radians and using the relation

$$G = \frac{\theta}{\beta_e} \tag{4}$$

With the initial dimensions of the cavity obtained from the above formulation, it has been modelled for three-dimensional electromagnetic simulations. The schematic diagram of the modelled intermediate cavity with its geometrical parameters is depicted in Fig. 1. The geometrical cavity parameters corresponding to the resonant frequency of 28.5 GHz for 2π mode of operation is given in Table 1.

Slot coupling has been used for the designed input cavity and output cavity. The cavities have been attached to standard Ka-band waveguide (WR28) via a coupling slot. The dimensions of the coupling slot have been optimised through simulation. Due to attachment of the slot and the waveguide, the resonant frequency of the input/output cavities has been changed - which has been restored back by adjusting the cavity dimensions.

It may be noted that in the complete RF section, the RF cavities will have to be stagger tuned (tuned at different frequencies - typically a few MHz apart) to achieve a broader bandwidth. Moreover, as the input and output cavities are connected to the external circuits (input RF generator and matched load respectively), they exhibit lower Q (hence broader bandwidth). Therefore, the slight difference between resonant frequencies of the intermediate RF cavities and input/output cavities will not adversely affect the functionality of the device.



(a) (b)

Figure 1. RF cavity considered for simulation: Ladder-Type Multi-beam EIK: (a) Intermediate cavity and (b) Input/output Cavity

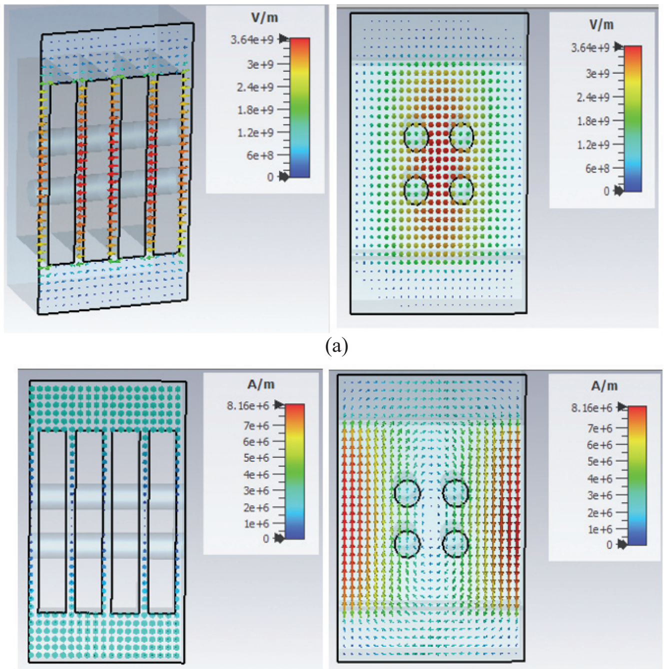
Table 1. Design parameters

Parameters	Values	
Resonant frequency	**Intermediate cavity**	**Input/output cavities**
	28.46 GHz	**28.47 GHz**
Number of beam	04	04
X	5.8 mm	5.6 mm
Y	5.5 mm	5.4 mm
Z	4.68 mm	4.68 mm
H	1.5 mm	1.5 mm
d	0.8 mm	0.8 mm
GAP	0.28 mm	0.28 mm
p	1.1 mm	1.1 mm
a	-	5.6 mm
b	-	2.0 mm
h	-	1.0 mm

3. SIMULATION RESULTS

Modal analysis of the RF cavities has been done using the eigen mode solver of the commercially available CST EM suite. The electric and magnetic field (E and M field) pattern of the operating TM mode (with resonant frequency 28.46 GHz) of the intermediate cavity is shown in Fig. 2. It may be noted that although there are other TM modes below this operating mode at 28.5 GHz, none of them exhibits 2π mode characteristics.

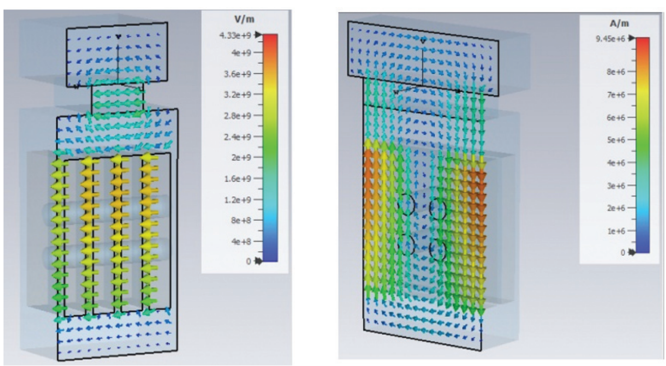
The quality factor of a particular mode of a cavity is the ratio of average energy stored to the average energy loss multiplied by the angular frequency of the mode. The quality factor of extended interaction klystron (EIK) resonant cavity with 4 numbers of beams comes out to be 744 from the simulation. Further, the shunt impedance of a particular cavity mode (usually calculated along the beam



(a)

(b)

Figure 2. Distribution of the 2π mode (views at in two cut-planes) for the intermediate cavities: (a) E-field and (b) M-field.



(a) (b)

Figure 3. Distribution of the 2π mode (views at in two cut-planes) for the input and output cavities. (a) E-field and (b) M-field.

propagation direction) is described by the proportion with the voltage developed divided by the dissipated power. Shunt impedance of the operating mode across the gaps is 0.08MΩ according to the simulation, and the estimated R/Q across the gaps is 108.

For the input and output cavities, dimensions of the coupling slot are to be optimised for proper coupling of the RF field, as well as to achieve the desired loaded Q value of the cavity. The E and M field pattern of the operating TM mode (with resonant frequency 28.47 GHz) of the input/output cavity is shown in Fig. 3.

The magnetic field plot indicates that energy inside the cavity is being magnetically coupled with the output waveguide section through the coupling slot, as desired. The amount of magnetic field coupling can be controlled by changing the coupling area, i.e. dimensions of the coupling slot.

4. CONCLUSIONS

Design of ladder-type intermediate and input/output cavities for an extended interaction multi-beam klystron operating at 28.46 GHz is presented. Cavity design parameters have been estimated using analytical formulae, and the same has been simulated using a commercial electromagnetic simulation tool. The operating mode of the cavity at 28.46 GHz has been identified from the electromagnetic field pattern, and corresponding cavity parameters like quality factor (Q), shunt impedance, and R/Q value have been estimated through simulation. The optimised RF cavity geometries are compatible with micro-fabrication/metallic 3D-printing techniques, and experimental validation of the simulation results may be attempted by fabrication of the RF section.

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