Optimization Of Corrugated Coaxial Cavity Parameters For Mode Rarefaction In A Gyrotron

Kalpana Singh[(1)], P. K. Jain[(2)], and B. N. Basu[(3)]
[(1)] Department of Physics, Banaras Hindu University, Varanasi-221005, India. kalpanasingh@myself.com
[(2)] Centre of Research in Microwave Tubes, Department of Electronics Engineering, Institute of Technology, Banaras Hindu University, Varanasi-221 005, India. pkjain@bhu.ac.in
[(3)] As (2) above, but Email: bnbasu@bhu.ac.in

ABSTRACT

The analysis of a coaxial waveguide resonator with its central conductor corrugated with wedge-shaped slots, considering space harmonic effects due to slot periodicity, was used to study the problem of mode competition in a gyrotron. A more positive slope of the plot of the eigenvalue versus the ratio of the waveguide wall to outer slot radii (coaxial parameter) for the desired mode, typically, $TE_{8,4}$ as compared to the corresponding slopes for the competing modes formed a basis for the study of mode separation. Considering the aspect of mode separation on the basis of the relative slopes of the eigenvalue plot and that of mode degeneracy, a tradeoff was made to select the slot depth at a value intermediate between the values corresponding to the narrow and deeper slots. For the slot depth parameter so selected, one may find the coaxial parameter, around which to taper the structure cross section, for mode separation on the basis of relative slopes of the eigenvalue plot, avoiding, at the same time, the region of the mode degeneracy. The analysis excludes the limitation of closely spaced slots in earlier analyses based on the surface impedance model. The interpretation of results for mode separation of nearby modes with reference to the typical mode $TE_{8,4}$ chosen is extendible to higher modes as well.

INTRODUCTION

In the development of high power, high frequency gyrotrons, two major constraints are the thermal loading of the wall of the waveguide resonator and the potential depression inhibiting the transport of large electron beam currents [1]-[4]. In order to evade the problem of thermal loading, large interaction cavities are suggested that would keep ohmic wall losses within acceptable limit ~2-3 kW/cm^2 that can be managed by usual cooling techniques. However, as the resonator size increases, the spectrum of eigenfrequencies becomes densely populated, leading to the possibility of multi-mode interaction and the associated problems like instability of gyrotron interaction and deterioration of the coherence and directivity of radiation, which would also lead to a decrease in the gyrotron efficiency [5]. Adjusting the location of the electron beam to experience the maximum RF field of the desired mode makes one select the mode of interest out of the competing modes excited in oversized cavities. The method of such mode selection is however not adequate for gyrotrons scaled to megawatt powers at high frequencies to meet the electron cyclotron resonance heating requirements for high-magnetic field plasma configurations such as the International Thermonuclear Experimental Reactor (ITER) [6], where the spectrum of eigenmodes becomes so dense that it is necessary to employ still more precise methods of mode selection.

The introduction of a coaxial metal insert in a circular waveguide resonator reduces the potential depression caused by the presence of the electron beam. The enhanced current transport capability of a gyrotron using a coaxial waveguide increases the electron beam power available in the device for conversion to microwaves [7]. Furthermore, the problem of selecting the desired mode amongst the competing nearby modes has been addressed in a coaxial cavity interaction structure by tapering the structure cross section [7]-[9]. For such a structure, if the plot of the eigenvalue versus outer-to-inner radii of the coaxial waveguide has a more positive slope for the desired mode than for the competing modes, then the desired mode would move closer to the cutoff frequency and thus have a lower group velocity than the competing modes. This would reduce the energy velocity of the desired mode and hence increase its diffractive quality factor as compared to the competing modes. Consequently, this would also increase the total quality factor and in turn reduce the start oscillation current of the desired mode for the gyrotron as compared to that of the competing modes.

Iatrou *et al.* [8] and Barroso *et al.* [9] analyzed a coaxial waveguide in the surface impedance model valid for closely spaced slots, in which they derived the dispersion relation of the structure by matching the average wave impedances of the slot and slot-free regions at the interface between these regions. Hence they showed that providing azimuthally periodic corrugation or slots in the axial direction on the coaxial insert would increase the effectiveness of tapering the cross section of the structure in reducing the problem of mode competition in a gyrotron [8], [9]. In the present analysis, we have considered wedge-shaped slots and taken into account the effects of the azimuthal harmonics due to the angular periodicity of slots and made no assumptions of closely spaced slots, unlike in the analyses using the surface impedance model.

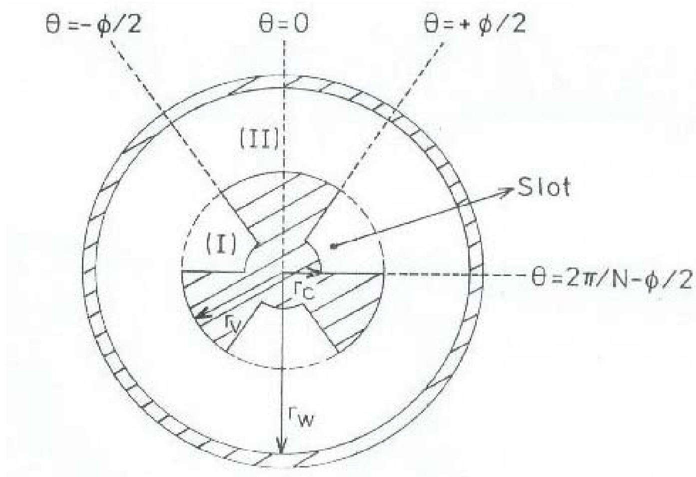


Fig. 1 Cross section of a coaxial waveguide corrugated with wedge-shaped slots on its central conductor.

ANALYSIS

The structure is divided into two regions — (i) the free-space wedge-shaped slot region: $\phi/2 \le \theta \le 2\pi/N - \phi/2$; $r_C \le r \le r_V$, labeled as region *I*, and (ii) the tubular free-space region outside the slots: $0 \le \theta \le 2\pi$; $r_V \le r \le r_W$, labeled as region *II*, where r_C is the inner edge radius of the slot on the central conductor, r_V is the outer edge radius of the slot, and r_W is the waveguide wall radius. N is the number of slots and ϕ is the uniform angular separation between consecutive wedge-shaped slots (Fig. 1).

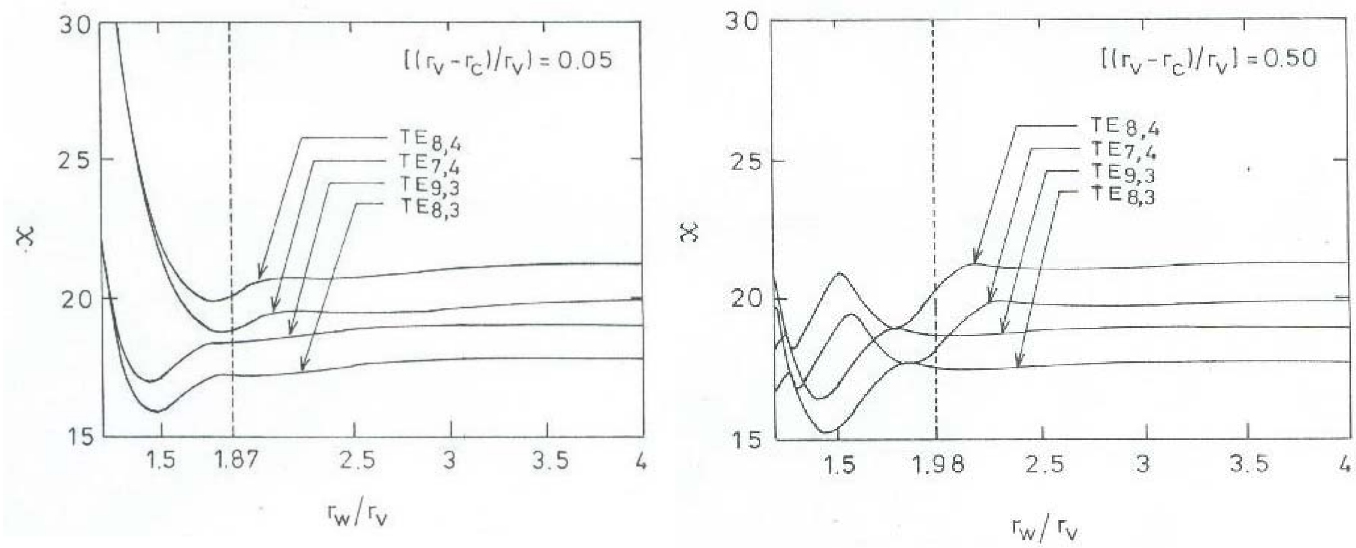
Taking the effect of azimuthal harmonics due to the angular periodicity of slots and following the method given in Kalpana *et al.* [10], the dispersion relation of the structure is as follows

$$\left[J'_\nu\{k_c r_V\} - \eta_\nu Y'_\nu\{k_c r_V\}\right]\phi + \left[J_\nu\{k_c r_V\} - \eta_\nu Y_\nu\{k_c r_V\} - \left(\frac{\xi_\nu - \eta_\nu}{\xi_\nu - \chi_\nu}\right)\left(J_\nu\{k_c r_V\} - \chi_\nu Y_\nu\{k_c r_V\}\right)\right](2\pi/N - \phi) = 0 \quad (1)$$

where $\eta_\nu = \dfrac{J'_\nu\{k_c r_C\}}{Y'_\nu\{k_c r_C\}}$, $\chi_\nu = \dfrac{J'_\nu\{k_c r_W\}}{Y'_\nu\{k_c r_W\}}$, and $\xi_\nu = \dfrac{J'_\nu\{k_c r_V\}}{Y'_\nu\{k_c r_V\}}$. J_ν and Y_ν are the ν^{th} order ordinary Bessel functions of the first and second kinds, respectively. The prime indicates the derivative of Bessel functions with respect to their argument. $k_c (= \omega_{cut}/c)$ is the cutoff wave number, ω_{cut} being the angular cutoff frequency of the waveguide.

RESULT AND DISCUSSIONS

One may find the eigenvalue $\chi (= k_C r_W)$, with the help of the dispersion relation (1) of the slotted coaxial waveguide, and plot it against the ratio of the waveguide wall to outer slot radii $(= r_W / r_V)$, henceforth referred to as the 'coaxial parameter' for the various modes of interest (Fig. 1). We analyze, considering angular harmonic effects, the behavior of the



(a) (b)

Fig. 2 Eigenvalue $\chi(=k_C r_W)$ versus coaxial parameter r_W / r_V characteristics of a coaxial waveguide with its coaxial insert with shallow slots, typically, of depth parameters (a) $(r_V - r_C)/r_V = 0.05$, and (b) $(r_V - r_C)/r_V = 0.05$, for nearby modes $TE_{8,4}$, $TE_{7,4}$, $TE_{9,3}$, and $TE_{8,3}$, taking $N = 8$ and $\phi = 2\pi/9$. The vertical line on the plot indicates the value of the coaxial parameter r_W / r_V that would correspond to the mode of interest $TE_{8,4}$ enjoying a higher value of positive slope than the neighboring competing modes, around which to taper the structure cross section.

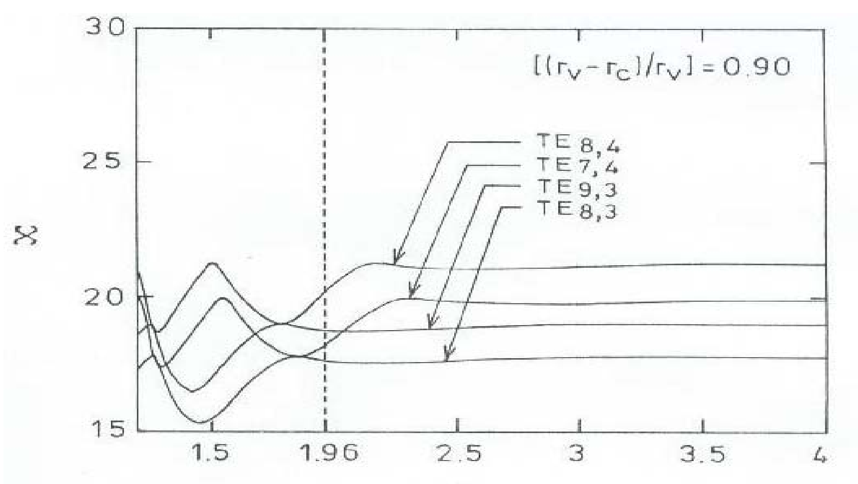


Fig. 3 Eigenvalue $\chi(=k_c r_W)$ versus coaxial parameter r_W / r_V characteristics of a slotted coaxial waveguide, for relatively deep slots, typically, of depth parameters $(r_V - r_C)/r_V = 0.90$, for nearby modes $TE_{8,4}$, $TE_{7,4}$, $TE_{9,3}$, and $TE_{8,3}$, taking $N = 8$ and $\phi = 2\pi/9$. The vertical line on the plot has the same significance as in Fig. 2.

structure with reference to four modes, namely $TE_{8,4}$, $TE_{7,4}$, $TE_{9,3}$ and $TE_{8,3}$ which are intermediate between the modes (Figs. 2 and 3). We earlier found that the eigenvalue (χ) versus coaxial parameter (r_W / r_V) plots, for a typical mode $TE_{6,2}$, very closely agreed [10] with Barroso *et al*. [9].

In the presence of corrugation, the plot of the eigenvalue versus coaxial parameter, in general, exhibits more than one eigenvalue minimum (Figs. 2 and 3). The appearance of more than one minimum is more distinguished for deeper slots, as can be seen from Figs. 3 [$(r_V - r_C)/r_V = 0.9$] in comparison to shallow slots as can be seen from Fig. 2 (a) [$(r_V - r_C)/r_V = 0.05$]. Also, the separation between consecutive minima on the scale of the coaxial parameter r_W / r_V decreases with the increase of the slot depth for both the shallow and deep slots (Figs. 2 and 3). Further, for deeper slots [$(r_V - r_C)/r_V = 0.9$] the modes degenerate at some regions of the coaxial parameter [Figs. 2(b) and 3].

For a structure, one can find an optimum coaxial parameter (to be interpreted as $r_W / r_V = r_W / r_C$) where the desired mode would have a more positive slope of the eigenvalue versus coaxial parameter plot than the competing modes, and thus around this optimum coaxial parameter one may choose to taper the structure cross section for the desired mode separation. However, it can be seen by comparing Figs. [2] with Fig. [3], with the increase of the slot depth, though the mode separation found on the basis of relative slopes of modes becomes more effective, the optimum coaxial parameter becomes closer to the region of mode degeneracy. This would call for a tradeoff between shallow slots [typically, $(r_V - r_C)/r_V = 0.05$] [Fig. 2 (a)] and deeper slots [typically, $(r_V - r_C)/r_V = 0.5, 0.9$] [Figs. 2(b) and 3] so that one would be prompted to choose an intermediate value of the slot depth. Subsequently, for this value of the slot depth, one may select the coaxial parameter r_W / r_V , where to taper the structure cross section, at a value that would provide reasonable amounts of both (i) mode separation on the basis of relative slopes of eigenvalue plot and (ii) coaxial parameter separation from the region of mode degeneracy.

Thus it is hoped that the method of interpretation of the slope of the eigenvalue versus coaxial parameter characteristics for mode rarefaction suggested would be helpful in designing coaxial cavities for high power gyrotrons. The analysis is however valid for wedge-shaped slots that have angular geometrical symmetry and is not applicable to the slots of geometry deviating from angular symmetry such as rectangular slots.

REFERENCES

[1] V. Gaponov-Grekhov and V. L. Granatstein, *Applications of High-Power Microwaves*, New York: Artech House, Inc., 1994.

[2] R. J. Barker, and Edl. Schamloglu, *High-Power Microwave Sources and Technologies*, New York: IEEE Press, 2001.

[3] O. Dumbrajs and G. I. Zaginaylov, “Ohmic losses in coaxial gyrotron cavities with corrugated insert,” *IEEE Trans*. *Plasma Sci*., vol. 32, pp. 861-866, 2004.

[4] K. E. Kreischer, R. J. Temkin, H. R. Fetterman, and W. J. Mulligan, “Multimode oscillation and mode competition in high-frequency gyrotrons,” *IEEE Trans*. *Microwave Theory Tech*., vol. 32, pp. 481-490, 1984.

[5] M. I. Airilla, O. Dumdrajs, P. Kall, and B. Piosczyk, “Influence of reflections on the operation of the 2 MW, CW 170 GHz coaxial cavity gyrotron for ITER,” *Nucl*. *Fusion*, vol. 43, pp. 1454-1457, 2003.

[6] M. Makowski, “ECRF systems for ITER,” *IEEE Trans. Plasma Sci.*, vol. 24, pp. 1023-1032, 1996.

[7] G. S. Nusinovich, M. E. Read, O. Dumbrajs, and K. E. Kreischer, “Theory of gyrotrons with coaxial resonators,” *IEEE Trans. Electron devices*, vol. 41, pp. 433-438, 1994.

[8] T. Iatrou, S. Kern, and A. B. Pavelyev, “Coaxial cavities with corrugated inner conductor for gyrotrons,” *IEEE Trans. Microwave Theory Tech*., vol. 44, pp. 56-64, 1996.

[9] J. J. Barroso, R. A. Corrêa, and P. J. de Castro, “Gyrotron coaxial cylindrical resonators with corrugated inner conductor: Theory and experiment,” *IEEE Trans. Microwave Theory Tech*., vol. 46, pp. 1221-1230, 1998.

[10] K. Singh, P. K. Jain, and B. N. Basu, “Analysis of a coaxial waveguide corrugated with wedge-shaped radial vanes considering azimuthal harmonic effects,” *Progress in Electromagnetic Research*, vol. 47, pp. 297-312, 2004.