COAXIAL RESONATOR FOR HIGH-POWER, MILLIMETER-WAVE GYROTRONS

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Abstract

To provide the required mode selectivity for a megawatt 280 GHz gyrotron, a coaxial resonator operating in a high order TE mode is considered. Mode discrimination is achieved both by exploring the differences in the transverse structures of the competing modes and investigating a suitable geometry for the coaxial insert. In the resonator studied here, the frequency separation between the design mode $TE_{26,10,1}$ and its nearest competing mode $TE_{20,12,1}$ is about 0.6% and the ratio of the corresponding Q factors is as high as 6.5. Unlike the coaxial resonator, in the hollow cavity without the inner conductor the fundamental spectrum of eigenfrequencies is more dense, and all TE modes within the frequency interval 271–288 GHz have approximately the same Q factor.

1. Introduction

Current gyrotron research is a very active field and is being driven by the requirements of microwave sources with output power capabilities up to 1 MW at 280 GHz for controlled thermonuclear fusion research[1]. One major constraint in the design of megawatt gyrotrons[2] is the average ohmic heating density of the resonator walls. Because of this technical restriction, it is necessary to operate in a very high order mode to maintain accepted values for the ohmic loss ($\leq 4\,\mathrm{kW/cm^2}$) while keeping the output power of the millimeter-wave gyrotron at the megawatt level. However, as the resonator cross section gets larger, the spectrum of eigenfrequencies becomes densely populated which leads to the possibility of exciting parasitic. modes.

In this paper, we examine some possibilities of rarefying the spectrum of eigenfrequencies in a coaxial resonator designed to operate in the $TE_{26,10}$ mode at 280 GHz. Mode discrimination is obtained both by investigating appropriate geometries for the coaxial insert and exploring the differences between the design mode and the parasitic ones with regard to their transverse structures.

2. Normal modes of the cylindrical coaxial resonator

We shall assume that the resonator consists of weakly irregular coaxial cylinders. Hence, in the single mode approximation the longitudinal distribution of the electric field satisfies the equation

$$\frac{d^2V(z)}{dz^2} + k^2_{\parallel,s}(z)V(z) = 0\,, \tag{1}$$

where

$$k^2_{\parallel,s} = \omega^2/c^2 - k^2_{\perp,mp}\,,$$

with s denoting the set of indices (m,p,q); ω is the frequency of the field and $k_{\perp,mp}$ designates the transverse wave number. Solutions to eq. (1) subject to appropriate radiation conditions at the cavity ends[4]

$$(dV/dz \mp ik_{\parallel}V)\Big|_{z_{out}}^{z_{in}} = 0\,, \tag{2}$$

determine the eigenfrequencies of the resonator. Such eigenfrequencies are close to the cutoff frequencies $\omega_c = ck_{\perp,mp} = c\chi_{mp}/R_w(z)$, where $R_w(z)$ denotes the radius of the outer cylinder and χ_{mp} should be determined from the transcendental equation

$$J'_m(\chi_{mp})N'_m(\chi_{mp}/C) - J'_m(\chi_{mp}/C)N'_m(\chi_{mp}) = 0. \tag{3}$$

The parameter C is defined as the ratio of the outer to inner radii of the coaxial cylinders; J'_m and N'_m are the derivatives of Bessel and Neumann functions of order m.

3. Design of a 280 GHz, $TE_{26,10}$ gyrotron coaxial resonator

Before treating the electrodynamic selection for the $TE_{26,10}$ mode, it is very informative to discuss the equivalence relationship between the coaxial and hollow resonators in such a manner that a given normal mode should have the same eigenfrequency and Q factor in both resonators [3]. The interest in the concept of equivalent hollow resonator stems from its usefulness in providing a qualitative explanation of how the geometry of the coaxial cylinders modifies the selective properties of the resonator. These properties are characterized by the relative differences between the natural frequencies of the operating mode and the nearest parasitic modes and by the ratio of the Q factors associated with these modes.

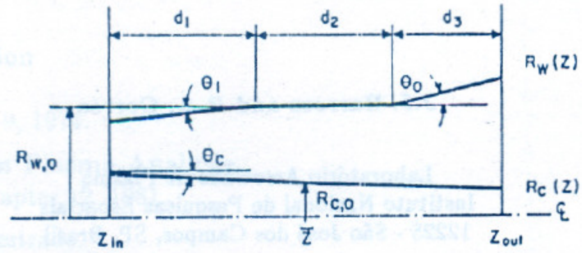

Fig. 1 - Schematic diagram of the coaxial resonator geometry.

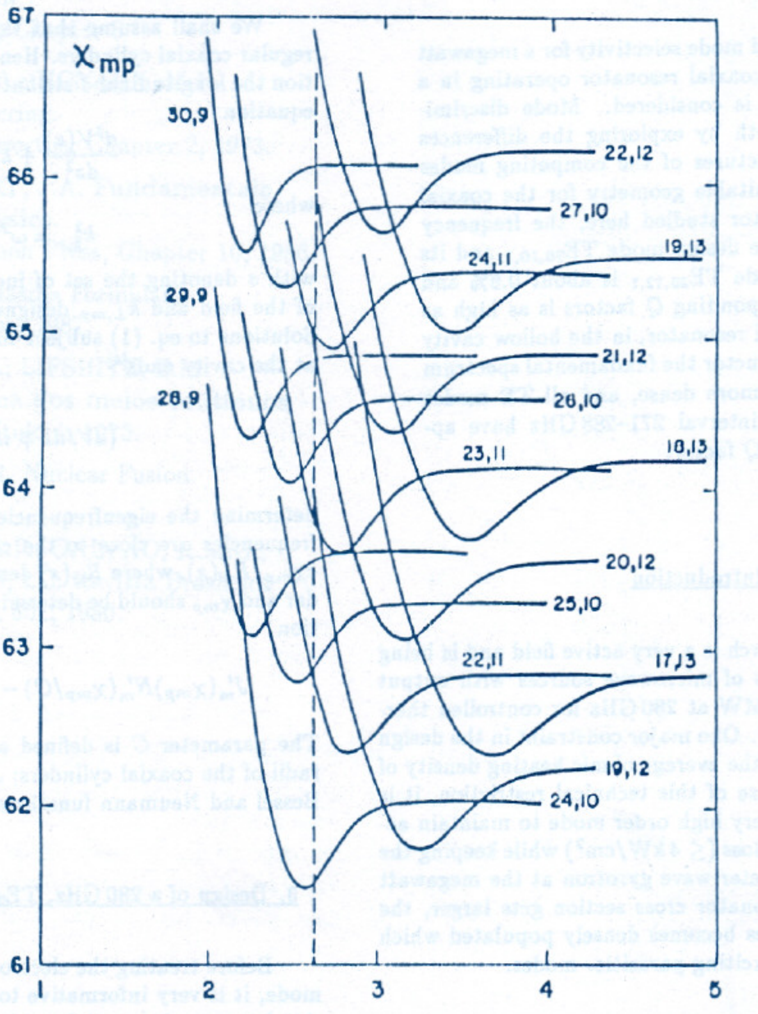

Fig. 2 - Curves $\chi_{mp}(C)$ for some high-order TE modes in coaxial resonators. The dashed line indicates the design parameter $C = 2.62$ for the operating mode $TE_{28,10}$.

In the present study, the coaxial cylinders are considered to have linearly varying radii (Fig. 1), which leads to the following expression for the longitudinal profile of the equivalent hollow resonator:

$$R_{eq}(d_1 \leq z - z_{in} \leq d_1 + d_2) = R_{w,o} + (z - \bar{z}) \frac{\bar{C}^2}{\chi} \left(\frac{d\chi}{dC} \right) \Big|_{\bar{C}} \tan \theta_c . \tag{5}$$

For instance, if the derivative d_χ/dC at $C = \bar{C}$ is negative and the inner taper narrows to the output ($\theta_c < 0$), then the mid-section of the equivalent hollow resonator will be a linearly uptapered waveguide, i.e., $Q(\bar{C}) < Q_0$ where $Q(\bar{C})$ denotes the diffraction Q factor of a given mode in the coaxial resonator and Q_0 is the Q factor of this mode in the hollow resonator without the conical insert.

To verify the properties of the coaxial resonator, eq. (1) subject to radiation conditions (2) was solved numerically. The complex eigenfrequency is represented by $\omega = \omega_R + i\omega_I = \omega_R(1 + i2/Q)$ and the root $\chi_{mp}(C)$ of eq. (3) is computed for each integration step. The geometrical parameters of the outer cylinder are $d_1 = 1.000\,\text{cm}$, $d_2 = 0.300\,\text{cm}$, $d_3 = 0.500\,\text{cm}$, $R_{w,o} = 1.100\,\text{cm}$, $\theta_1 = 1°$, and $\theta_3 = 3°$. One can use Fig. 2 to estimate suitable values of the quantity $\bar{C}$ and taper angle θ_c for the electrodynamic selection in favor of the $TE_{26,10}$ mode. After a careful analysis, the design values $\bar{C} = 2.62$ and $\theta_c = -2°$ have been selected. As can be seen in Fig. 2, this allows the eigenfrequencies f of all $p = 10$ modes to decrease relative to those for the original state in the hollow resonator, while the associated Q factors become higher than Q_0. For higher order $p \geq 11$ modes, in addition to a noticeable increase in f, the associated Q factors are significantly lowered since the line $C = 2.62$ intersects the $\chi = \chi(C)$ curves on the branch of negative derivative $d\chi/dC$. Finally, for $p \leq 9$ modes both the values of f and Q are roughly unchanged. In particular, even though the eigenfrequencies of the $TE_{26,10}$ and $TE_{20,12}$ modes get closer (Fig. 3), the respective Q factors turn out to be widely different, i.e., $Q_{26,10}/Q_{20,12} \simeq 6.5$. This illustrates the effectiveness of such a method of radial selection.

4 - Conclusion

It has been demonstrated that the coaxial open cylindrical resonator provides an effective radial mode selection in highly overmoded millimeter-wave gyrotron cavities. In the 280 GHz resonator studied here, the frequency separation between the design mode $TE_{26,10,1}$ and its nearest competing mode $TE_{20,12,1}$ is about 0.6%, and the ratio of the corresponding Q factors $Q_{26,10}/Q_{20,12}$ is as high as 6.5.

In the hollow resonator, by contrast with the coaxial one, the frequency separation between the $TE_{26,10,1}$ mode and the closest parasitic mode $TE_{29,0,1}$ is 0.4%, and the ratio of the respective Q factors approaches unity. This is explained as the dependence of the Q factors of these modes upon their transverse field structures expresses itself only in terms of the roots χ_{mp}, since $d\chi_{mp}/dC \to 0$ as $C \to \infty$. Therefore, in the dense spectrum of eigenfrequencies in a hollow cavity all the fundamental TE modes have approximately the same Q factor.

On the other hand, in the coaxial resonator we explore the relation $\chi_{mp} = \chi_{mp}(C)$ by taking advantage of the distinguishing characteristics of the transverse structures of the modes under consideration. Even for a particular value of C for which the frequency separation between adjacent modes is too narrow, the respective derivatives $d\chi/dC$ can be markedly different, and also, as a consequence, the corresponding Q factors.

References

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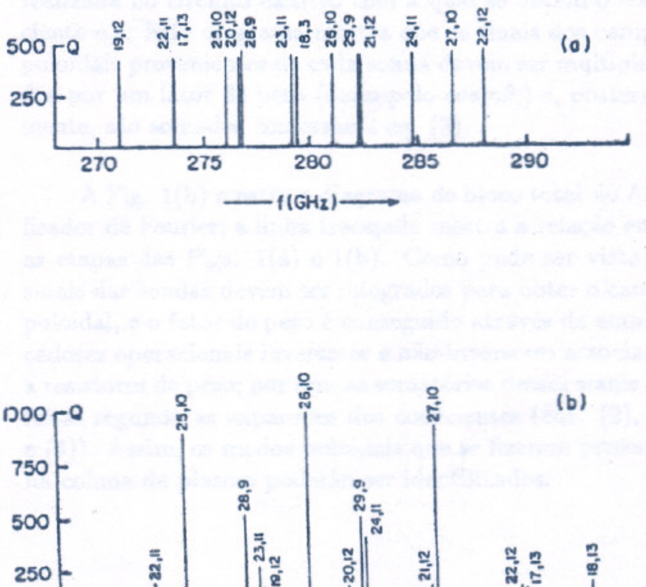

Fig. 3 - Fundamental spectrum for TE modes in the (a) hollow and (b) coaxial resonators.