EXPERIMENTAL INVESTIGATION ON GEOMETRICAL EFFECTS IN GYROTRON COAXIAL RESONATORS

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Abstract

A study of the selective properties of gyrotron coaxial resonators on accounting of geometrical effects has been conducted and compared to cold-test measurements on TE modes over the frequency range 11 to 14 GHz. On the basis of a geometrical design criterion for resonance of the normal modes, it has been demonstrated that the spectral mode density associated with a purpose-built test coaxial cavity is significantly lower than that for the empty cavity without the coaxial insert.

Introduction

Open coaxial cylindrical resonators have found important applications in high power, high frequency gyrotrons where highly selective oversized resonators were required. The main characteristics of the coaxial cavity is strong dependence of the inner conductor geometry on the mode spectrum density. In this way, due to the spectral rearrangement occurred by the presence of a coaxial insert, it is possible both to isolate the desired operating mode from its closest competitors and to reduce the number of resonant modes over a given frequency range. Thus, some possibilities for achieving single-mode gyrotron operating are explored. For example, a high power (3 MW), high frequency (140 GHz) gyrotron [1] operating in the $TE_{21,13}$ mode is under construction for electron cyclotron heating of large scale tokamaks such as the ITER. That gyrotron uses a coaxial cavity with a straight cylindrical inner rod. In this paper we investigate the electrodynamical properties of cylindrical coaxial cavity using conical and partially conical central rod. For a specially designed cavity, we demonstrate that the mode spectrum for TE modes in the range 11 to 14 GHz is significantly less dense than that of the hollow cavity (without coaxial insert).

Mode Selection from Geometrical Effects

We shall consider the open coaxial cavity type as depicted in Fig. 1. The inner conductor is a conical rod whereas the outer cylinder consists of a weakly irregular waveguide with a regular cylindrical mid-section joined to two linear tapers. The down taper is extended far enough to ensure cutoff of the working mode while the up taper couples the quasi-stationary field in the main resonant mid-section to an outgoing travelling wave.

The effects of the inner conductor geometry upon the cavity selective properties can be explained by considering an equivalent empty resonator [2], so that a given normal mode has the same resonant frequency and diffractive Q-factor in both resonators. In this context, a coaxial resonator turns out to be equivalent to an empty one with a longitudinal profile:

$$b_{cq}(z) = b(z) - (b(z) - \bar{C}a(z))\frac{C}{\chi}\frac{d\chi}{dC}\bigg|_{\bar{C}} \qquad (1)$$

where $\bar{C}$ denotes the average value of C over the interval $0 \leq z \leq d_1 + d_2$ (Fig. 1). The parameter $C = b/a$ is defined as the ratio of the external radius to the internal one; χ denotes the p-th nontrivial root of the Bessel-Neumann combination [2,3] $J'_m(\chi_{mp})N'_m(\chi_{mp}/C) - J'_m(\chi_{mp}/C)N'_m(\chi_{mp}) = 0$.

Hence, if the derivative $d\chi/dC$ is negative at $C = \bar{C}$ and $\theta_c > 0$, the input section of the equivalent empty resonator is a truncated cone narrowing to the cavity output provided the following relation

$$\frac{\bar{C}|T|}{1-T} > \frac{tan\theta_i}{tan\theta_C} \quad (2)$$

holds, where $T \equiv (C/\chi)(d\chi/d_C)|_{\bar{C}}$. As a result, modes satisfying relation (2) do not suffer a total reflection on the left side of the main resonant mid section, and, in consequence, cannot resonate. Using the resonance condition (2) a coaxial cavity with $\bar{C} = 3.2$, – in which the geometric parameters $\theta_i = 0.8^o$, $\theta_o = 3.0^o$, $d_1 = d_2 = 10.50$ cm, $d_3 = 15.75$ cm, and $b_0 = 3.36$ cm define the outer waveguide whereas $a_i = 0.68$ cm and $\theta_c = 1.0^o$ specify the conical inner rod –, gives the set of curves shown in Fig. 2. We conclude that the circularly symmetric modes (TE_{01}, TE_{02}, and TE_{03}) in addition to the volume mode $TE_{1,3}$ are all suppressed, as relation (2) does apply to such modes. Note in Fig. 3(a), however, that the mid-section of the equivalent empty resonator for the $TE_{2,3}$ mode is a truncated cone that narrows to the output section. This yields an exceedingly high diffractive Q_D factor ($> 1.0 \times 10^6$) for the fundamental $TE_{2,3,1}$ mode, with calculations indicating intolerably high Q_D factors ($> 1.0 \times 10^5$) for higher axial order modes $TE_{2,3,q}$ with $q \geq 2$. To circumvent such a drawback posed by the fully-conical inner rod, it is sufficient to consider a cylindrical coaxial insert with a constant radius along the output and mid sections, but keeping a conical shape in the input section. On adopting this geometry for the inner rod, where $\theta_c = 1.0^o$, $a(0) = 0.68$ cm, and $a(z \geq d_1) = 0.87$ cm such that $\bar{C} = 3.2$, we can now see in Fig. 3(b) that the mid-section for the equivalent empty resonator is a uniform circular cylinder with radius $b_o = 3.63$ cm. This gives for the $TE_{2,3,1}$ mode a diffractive Q factor $Q_D = 2140$ nearly equal to that in the empty cavity. In addition, as displayed in Fig. 2, the circularly symmetric modes as well as the volume $TE_{1,3}$ mode remain still suppressed in this new cavity configuration with $\bar{C} = 3.2$ central insert partially conical.

Experimental Investigation

The experimental characterization of coaxial cavities was achieved using a HP8510B network analyzer along with a HP83040A synthesized source. TE modes in the coaxial resonator were excited by means of a standard WR-90 rectangular waveguide feeding a small coupling hole drilled through the center of the resonator mid-section [3]. A pyramidal horn antenna connected to a detector was used as a receiving device to collect the power reradiated by the resonator. The Q-factor measured is the loaded $Q_L = Q_D Q_\Omega/(Q_D + Q_\Omega)$ (where Q_D is the diffractive Q and Q_Ω is the ohmic Q) as determined directly from frequency readings at the half-power points on the detected spectrum. The cavity external structure is a single electroformed copper piece for which an electrical resistivity of $\sigma_b = 3.8 \times 10^7$ S/m has been assumed, whereas the inner rod is made from aluminum ($\sigma_a = 2.5 \times 10^7$ S/m).

To verify the findings anticipated by theory, resonant frequency and Q_L-factor measurements were performed in the frequency range 11 to 14 GHz. Experimental results are presented in Tab. 1 for conical and partially conical inserts, which confirms the $TE_{1,3}$ - and $TE_{0,2}$ - mode suppression in both cases. In fact, if the $TE_{0,2}$ and $TE_{1,3}$ modes were present, their corresponding eigenfrequencies would be around 12.1 GHz and 12.5 GHz. However, after scanning the 11-14 GHz frequency range no such modes were detected. The observed resonant frequencies are in excellent agreement with those predicted by theory. Nevertheless, measured values of Q_L are typically 10% below the calculated ones for most of the cases.

Fig. 4 shows the resonant curves for the fundamental mode $TE_{2,3,1}$ (f_1) and the higher order modes $TE_{2,3,q}$ with $q = 2, 3$ (f_2 and f_3). Thus we can confirm the extremely high Q-loaded values (several thousands) for these modes. The resonant curve at left in Fig. 5 corresponds to the $TE_{8,1}$ mode that isn't completely tuned with the electric probe.

Fig. 5 shows the mode spectra observed for both the empty and coaxial cavities using a partially conical insert over the frequency range 9 to 17 GHz. We can note the absence of the azimuthal symmetric modes and the $TE_{1,3}$ mode – that have been suppressed as a result of the inner rod action.

Table 1. Measured and calculated values of resonant frequencies and Q_L factors for fundamental TE modes in the coaxial resonators

	conical rod				partially conical rod			
	calculated		measured		calculated		measured	
mode TE_{mp}	f [GHz]	Q_L	f [GHz]	Q_L	f [GHz]	Q_L	f [GHz]	Q_L
3,2	10.9444	111	10.9273	108 ± 05	10.9197	990	10.9067	1002 ± 30
7,1	12.1838	1237	12.1635	1262 ± 60	12.18334	1324	12.1666	1207 ± 40
4,2	12.9729	149	12.9258	158 ± 10	12.9534	1467	12.9364	1409 ± 60
8,1	13.6989	1577	13.6740	1469 ± 20	13.6984	1656	13.6771	1308 ± 25
2,3	13.7937	16000	13.7943	∞	14.2226	2502	14.2068	1688 ± 50

Conclusion

A study of gyrotron open coaxial resonators was conducted theoretically and experimentally giving emphasis to the geometrical effects generated by influence of the inner conductor on the cavity selective properties. Based on a geometrical criterion for resonance condition of normal modes, it was demonstrated that some modes can be effectively suppressed with the presence of a coaxial insert with suitable shape and dimensions. For experimental verification, measurements of resonant frequency and loaded Q were achieved over the frequency range 11 to 14 GHz. These measurements confirm the suppression of modes $TE_{0,2}$ and $TE_{1,3}$. Hence, the $TE_{7,1}$ mode remains virtually isolated from its closest competitors by a frequency shift on about 1.0 GHz.

References

[1] M.E. Read, G.S. Nusinovich, O.Dumbrajs, H.Q. Dinh, D. Opie, G. Bird, K. Kreischer, and M. Blank, *Proc. 18th Int. Conf. Infrared Millimeter Waves*, Colchester, England, vol. SPIE 2104, p. 521-522, 1994.

[2] J.J. Barroso and R.A. Correa, *Int. J. Infrared mmWaves*, vol. **12**(7), p. 717, 1991.

[3] P.J. Castro, J.J. Barroso, and R.A. Correa, *Int. J. Infrared Millimeter Waves*, vol. **13**(1), p. 91-104, 1992.

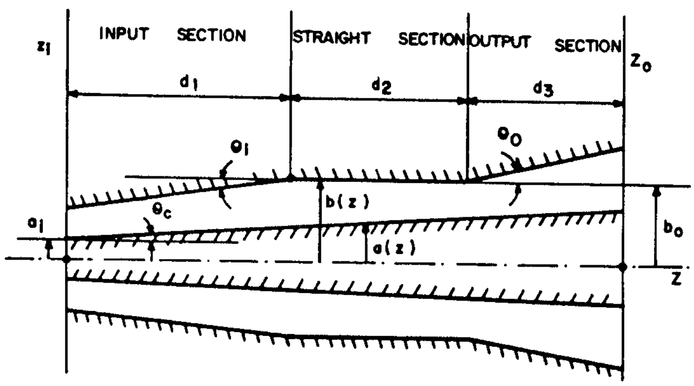

Fig. 1. Schematic diagram of the coaxial resonator along with geometric parameters

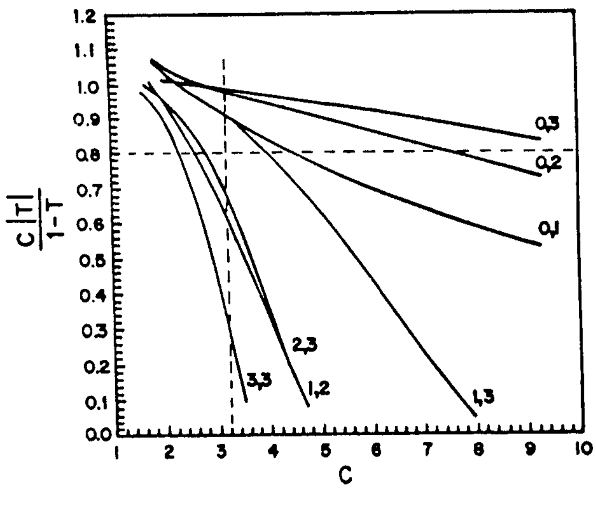

Fig. 2. $C|T|/(1-T)$ as function of parameter C where $T \equiv (C/\chi)(d\chi/dC)$

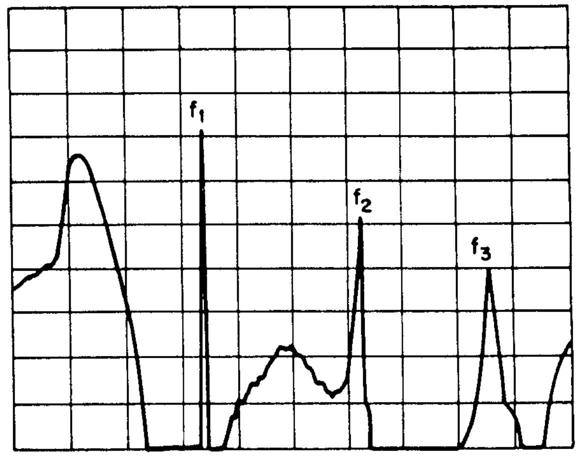

Fig. 4. Resonant curves corresponding to the $TE_{2,3,q}$ modes (q=1,2,3)

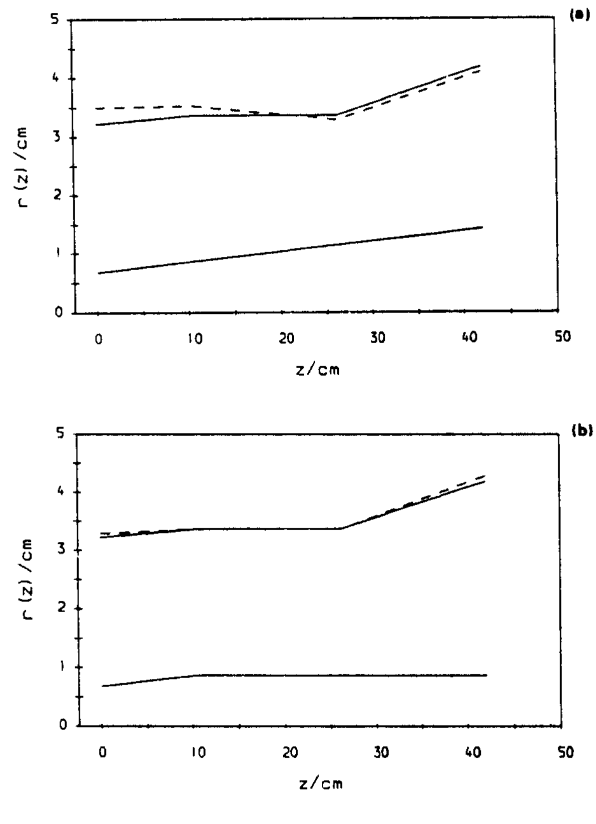

Fig. 3. Longitudinal profiles for the coaxial (solid line) and equivalent empty (dashed line) resonators for $TE_{2,3}$ mode with (a) fully-conical and (b) partially-conical inner rods

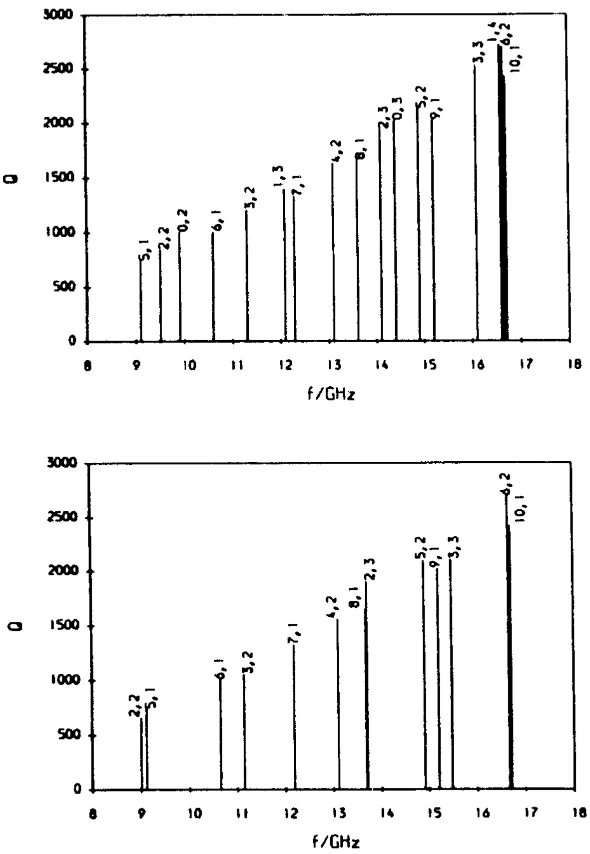

Fig. 5. Mode spectrum corresponding to the (a) empty cavity and (b) the coaxial cavity with the partially-conical rod