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ANALYSIS OF A COAXIAL WAVEGUIDE CORRUGATED WITH WEDGE-SHAPED RADIAL VANES OR RIDGES CONSIDERING AZIMUTHAL HARMONIC EFFECTS

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Abstract—The analysis was developed for a coaxial waveguide for two configurations — one in which the central conductor is corrugated in axial slot-wedges, with ridge-wedges between them, and the other in which the outer conductor is provided with radial metal vane-wedges. Azimuthal harmonics were considered in the structure regions, the effects of which were ignored in earlier published analyses based on the surface impedance model to replace the interface between the two structure regions by a homogeneous reactive surface. For both the structure configurations, one and the same form of the dispersion relation with proper interpretation of the symbol for the radius of the ridge/vane was obtained. The dispersion relation obtained by the present analysis was validated against that obtained by other analytical methods reported in the literature.

The shape of the dispersion characteristics is found uncontrollable by the structure parameters, and therefore the structure cannot be used for broadbanding a gyro-TWT. However, the plot of the eigenvalue versus the ratio of the outer conductor to ridge/vane radii strongly depended on the ridge/vane parameters. Thus the structure with its cross section tapered and ridge/groove parameters optimized has the potential for providing mode rarefaction in high-power, over-sized, over-moded gyrotrons.

1. INTRODUCTION

The characteristics of a waveguide would change if the guide wall had not been smooth, and this has been used to advantage in numerous microwave-engineering applications. Thus providing vanes or corrugation with waveguides has been a well-known practice to modify the characteristics of propagating or resonating structures, antennas and interaction structures for electron beam devices [1–6].

A cylindrical waveguide loaded with axially periodic annular disks or vanes is employed as a slow-wave structure in the linear electron accelerator [1]. Similarly, a waveguide is loaded with ridges to widen its bandwidth and also, if required, to reduce its overall size at lower microwave frequencies or in UHF band [2]. Corrugated horn antennas have applications as low-noise feeds of reflector antennas used in satellite communication, radio astronomy, radiometry, etc. [3–5]. In the conventional microwave tube family, azimuthally periodic cavities/vanes make the anode-cum-slow wave structure of a magnetron. Similarly, azimuthally periodic vanes projecting radially inward from the metal envelope of a helix traveling-wave tube (TWT) control the dispersion of the helix and hence widen the bandwidth of the TWT [6].

A cylindrical waveguide provided with vanes — referred to in the literature as a magnetron-like structure — however, does not provide the required dispersion control for a broadband coalescence between the beam-mode and waveguide-mode dispersion characteristics for wide bandwidths of a gyro-TWT [7, 8]. Nevertheless, such vane loading has been suggested for a gyrotron, in large-orbit configuration, operating at a higher beam harmonic with a waveguide-axis-circling hollow electron beam of a smaller radius. Such a configuration would not only relax the required background magnetic field of the gyrotron, but also call for lower electron beam energies and provide superior mode selectivity [7–10]. Furthermore, vane loading, although it does not widen the bandwidth of a gyro-TWT by controlling the waveguide dispersion, enhances the device gain. Therefore, such vane loading has been suggested to compensate for the gain of a gyro-TWT that would deteriorate in an attempt to widen the device bandwidth by tapering the waveguide cross section [10].

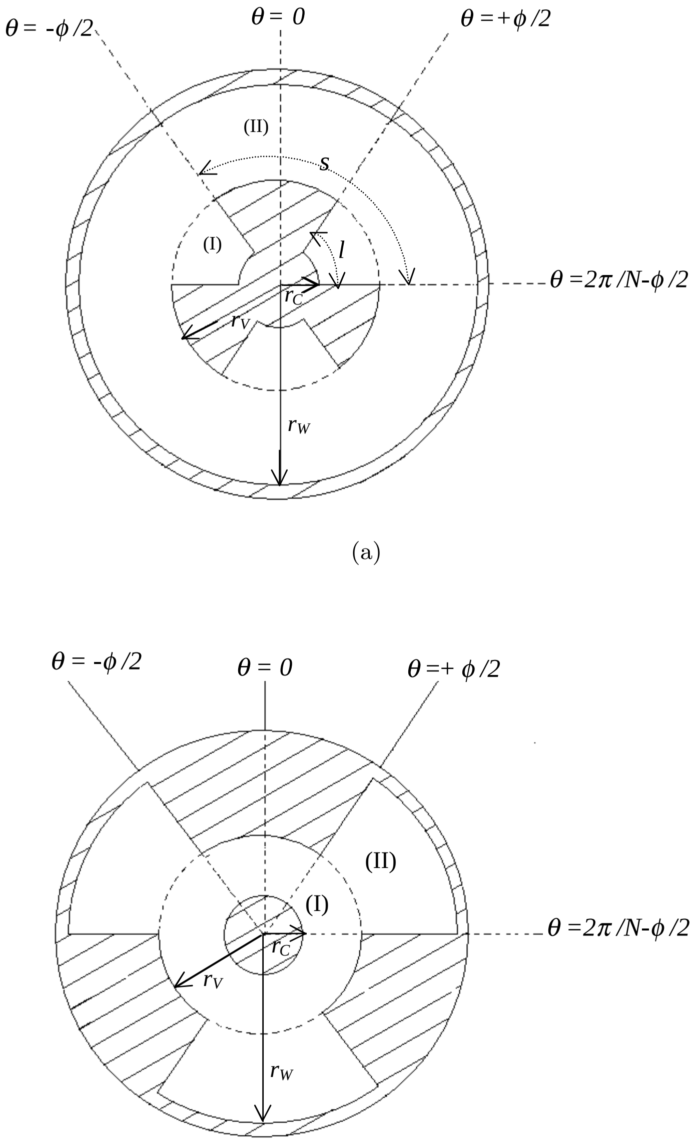
Recently, the concept of vane loading has also been extended to a coaxial cavity gyrotron in which the central conductor of the cavity is corrugated with axial slots and the structure is tapered for rarefaction of modes in the structure, which is made over-sized and hence also over-moded in order to increase the power capability of the device. Mode rarefaction in such a corrugated coaxial cavity gyrotron can be made more effective by optimizing the corrugation parameters [11–13].

We have restricted this paper to the cold (beam-absent) analysis of a vane loaded coaxial waveguide in the two configurations of the structure — one labeled as A, in which the central conductor is corrugated in axial slots with radially outward wedge-shaped metal ridges between them and the other, labeled as B, in which the outer conductor is provided with radially inward wedge-shaped metal vanes. Both the configurations have defined ridge/vane radial depth, angular width and supposedly uniform angular periodicity (Fig. 1). It will be of interest to validate the dispersion relation obtained by the present analysis against that obtained by other analytical methods reported in the literature [13].

2. ANALYSIS

Dasgupta and Saha [14], using Ritz-Galerkin technique, analyzed a quadrapule-ridged cylindrical waveguide with a coaxial insert. Chong et al. [7] analyzed the same problem, however, considering an arbitrary number of ridges or vanes; they took into account azimuthal harmonic effects though only in the vane-free region. Shrivastava [8] simplified the analysis by treating the region between vanes of the cylindrical waveguide as a fundamental-mode rectangular waveguide with the electric field being solely azimuthal. The analysis due to Singh et al. [9], also subsequently used by Agrawal et al. [10] for a gyro-TWT in a vane-loaded cylindrical waveguide, is somewhat more general in that it has azimuthal harmonics in both the vane-free and vane-occupied regions of the structure considered. The eigenvalues of the vane-loaded waveguide calculated by these analyses fairly agree to one another [9].

Furthermore, Li and Li [11], Iatrou et al. [12] and Barroso et al. [13] analyzed a coaxial waveguide with a corrugated central conductor by a simplified surface impedance model approach. In this approach, the



(b)

Figure 1. Cross section of a coaxial waveguide with ridged central conductor (configuration A) (a) and with vane-loaded outer conductor (configuration B) (b).

surface impedance is matched at the interface that radially separates the region I, containing the slots/vanes positioned at a regular angular interval, from the vane-free region II. For sufficiently large number of thin vanes/slots, the interface was considered as a homogeneous reactive surface. The azimuthal harmonics in region II, where TE modes are of more significance than TM modes in a gyrotron [15], the fields were taken as if they were for a smooth-wall coaxial waveguide [11–13].

In this section, the analysis of the vane-loaded coaxial waveguide is developed that includes the rigor of considering azimuthal harmonics in both the regions I and II into which the configurations A and B each may be divided (Fig. 1). Here, for configuration A, the region I ($r_C \le r \le r_V$) is the inter-vane free-space region within the angular bounds of $\phi/2 \le \theta \le (2\pi/N - \phi/2)$ and, for configuration B, it is the tubular free-space region within the angular bounds of $0 \le \theta \le 2\pi$. For configuration A, the region II ($r_V \le r \le r_W$) is the tubular free-space region within the angular bounds of $0 \le \theta \le 2\pi$ and, for configuration B, it is the inter-vane free-space region $\phi/2 \le \theta \le (2\pi/N - \phi/2)$. For both the configurations A and B, r_C is the radius of the central conductor (which is corrugated in configuration A) and r_W is the radius of the waveguide wall (which is provided with vanes in configuration B), r_V is the radius of the outer edge of vanes (ridges) for configuration A and that of the inner edge of vanes for configuration B. N and ϕ are respectively the number and the wedge angle of vanes/ridges, which are taken as azimuthally equispaced (Fig. 1).

2.1. Field Expressions

The effect of azimuthal harmonics due to angular periodicity of vanes may be taken into account by multiplying the usual RF dependence factor $\exp[j(\omega t - \beta z)]\exp(-jm\theta)$ for a cylindrical waveguide by the factor $\exp[-jk(2\pi/\Theta)\theta] = \exp(-jkN\theta)$. Here, ω is the signal angular frequency, β is the axial phase propagation constant, m and k are the integers, $\Theta = 2\pi/N$ is the angular periodicity of vanes, and N is the number of vanes. Therefore, considering these two factors into account, the RF quantities in the structure for both the configurations A and B will have the angular dependence $\exp[-j(m + kN)\theta] = \exp(-jv\theta)$, where $v = m+kN$ is an integer. Hence the TE-mode ($E_z = 0$) solution to the wave equation for the structure (Fig. 1) for the field quantities may be written as [1, 16]:

$$H_{z,p} = \sum_{v=-\infty}^{v=+\infty} (A_{v,p} J_v\{k_c r\} + B_{v,p} Y_v\{k_c r\}) \exp(-jv\theta) \tag{1a}$$

$$E_{r,p} = \sum_{v=-\infty}^{v=+\infty} -\left(\frac{v\omega\mu_0}{k_c^2 r}\right)(A_{v,p}J_v\{k_c r\}+B_{v,p}Y_v\{k_c r\})\exp(-jv\theta) \quad (1b)$$

$$H_{r,p} = \sum_{v=-\infty}^{v=+\infty} -\left(\frac{j\beta}{k_c}\right)(A_{v,p}J'_v\{k_c r\}+B_{v,p}Y'_v\{k_c r\})\exp(-jv\theta) \quad (1c)$$

$$E_{\theta,p} = \sum_{v=-\infty}^{v=+\infty} \left(\frac{j\omega\mu_0}{k_c}\right)(A_{v,p}J'_v\{k_c r\}+B_{v,p}Y'_v\{k_c r\})\exp(-jv\theta) \quad (1d)$$

$$H_{\theta,p} = \sum_{v=-\infty}^{v=+\infty} -\left(\frac{v\beta}{k_c^2 r}\right)(A_{v,p}J_v\{k_c r\}+B_{v,p}Y_v\{k_c r\})\exp(-jv\theta) \quad (1e)$$

in which the dependence $\exp j(\omega t - \beta z)$ is understood. Here, $p = 1$ and 2 refer to the structure regions I and II, respectively. $A_{v,p}$ and $B_{v,p}$ are the field constants. J_v and Y_v are the vth order ordinary Bessel functions of the first and second kinds, respectively. The prime indicates the differentiation of Bessel functions with respect to their argument. $k_c = (\omega_c/c)$ is the cutoff wave number, ω_c being the cutoff angular frequency.

2.2. Boundary Conditions

Mathematically, the electromagnetic boundary conditions may be written as

$$E_{\theta,1} = E_{\theta,2}\Big|_{r=r_V} \quad \text{(configurations } A \text{ and } B) \quad (2)$$

[$\phi/2 \le \theta \le 2\pi/N - \phi/2$ (configuration A); $\phi/2 \le \theta \le 2\pi/N - \phi/2$ (configuration B)]

$$E_{\theta,1} = 0\Big|_{r=r_C} \quad \text{(configurations } A \text{ and } B) \quad (3)$$

[$\phi/2 \le \theta \le 2\pi/N - \phi/2$ (configuration A); $0 \le \theta \le 2\pi$ (configuration B)]

$$E_{\theta,2} = 0\Big|_{r=r_W} \quad \text{(configurations } A \text{ and } B) \quad (4)$$

[$0 \le \theta \le 2\pi$ (configuration A); $\phi/2 \le \theta \le 2\pi/N - \phi/2$ (configuration B)]

$$H_{\theta,1} = H_{\theta,2}\Big|_{r=r_V} \quad \text{(configurations } A \text{ and } B) \quad (5)$$

[$\phi/2 \le \theta \le 2\pi/N - \phi/2$ (configuration A); $\phi/2 \le \theta \le 2\pi/N - \phi/2$ (configuration B)]

$$H_{r,1} = 0\Big|_{r=r_V} \quad \text{(configurations } A \text{ and } B) \quad (6)$$

$[-\phi/2 \leq \theta \leq \phi/2$; (configurations A and B)].

The boundary condition (2) represents the continuity of the tangential component of electric field intensity at the interface between the regions 1 and 2. The boundary conditions (3) and (4) each arises from the tangential component of electric field being zero at the conducting boundary at the inner and outer conductors, respectively. The continuity of the tangential component of magnetic field intensity at interface between regions 1 and 2 is represented by the boundary condition (5). The boundary condition (6) follows from the normal component of magnetic flux density being zero at the conducting vane-edge.

2.3. Dispersion Relation

With the help of boundary conditions (1)–(3), into which the field expression (1) is substituted, one may express the field constants $A_{v,2}$, $B_{v,1}$ and $B_{v.2}$ in terms of a single constant, namely $A_{v,1}$, as follows:

$$A_{v,2} = \left(\frac{\xi_v - \eta_v}{\xi_v - \chi_v}\right) A_{v,1} \tag{7}$$

$$B_{v,1} = -\eta_v A_{v,1} \tag{8}$$

$$B_{v,2} = -\chi_v \left(\frac{\xi_v - \eta_v}{\xi_v - \chi_v}\right) A_{v,1} \tag{9}$$

where

$$\eta_v = \frac{J_v'\{k_c r_C\}}{Y_v'\{k_c r_C\}}, \quad \chi_v = \frac{J_v'\{k_c r_W\}}{Y_v'\{k_c r_W\}}, \quad \text{and} \quad \xi_v = \frac{J_v'\{k_c r_V\}}{Y_v'\{k_c r_V\}}.$$

Now, in order to obtain the dispersion relation, one may substitute (1e) into the boundary condition (5), multiply it by $\exp(-jv'\theta)$, where $v' = m + k'N$, and integrate it between the limits $\theta = \phi/2$ and $2\pi/N - \phi/2$, where k' is an integer. We may then add the result thus obtained to the result similarly obtained by multiplying the boundary condition (6), into which (1c) is substituted, also by $\exp(-jv'\theta)$, but now integrating it between the limits $\theta = -\phi/2$ and $\phi/2$. While using the boundary conditions (5) and (6), one has to use the appropriate ranges of structure parameters of the concerned configurations A and B, as indicated following the respective boundary conditions. The procedure leads to an equation in terms of the constants $A_{v,1}$, $A_{v,2}$, $B_{v,1}$ and $B_{v,2}$, the last three of which may be expressed in terms of a single constant, namely $A_{v,1}$, with the help of

(7)–(9). The resulting equation is

$$\sum_{v=-\infty}^{v=+\infty} A_{v,1}\left[\left\{S_v - \left(\frac{\xi_v - \eta_v}{\xi_v - \chi_v}\right)T_v\right\}\int_{\phi/2}^{(2\pi/N)-\phi/2} \exp\{j(v-v')N\theta\}d\theta \right.$$

$$\left. + R_v \int_{-\phi/2}^{\phi/2} \exp\{(v-v')N\theta\}d\theta\right] = 0 \tag{10}$$

where

$$R_v = J_v'\{k_c r_V\} - \eta_v Y_v'\{k_c r_V\} \tag{11}$$
$$S_v = J_v\{k_c r_V\} - \eta_v Y_v\{k_c r_V\} \tag{12}$$
$$T_v = J_v\{k_c r_V\} - \chi_v Y_v\{k_c r_V\}. \tag{13}$$

We may divide the terms of equation (10) into two parts, one corresponding to $v = v'$ and the other to $v \neq v'$, which after evaluation of the integrals becomes

$$\alpha_v A_{v,1} + \sum_{\substack{v=-\infty \\ (v\neq v')}}^{\infty} \delta_{v,v'} A_{v,1} = 0 \tag{14}$$

where

$$\alpha_v = R_v\phi + \left\{S_v - \left(\frac{\xi_v - \eta_v}{\xi_v - \chi_v}\right)T_v\right\}(2\pi/N - \phi) \tag{15}$$

and

$$\delta_{v,v'} = \frac{2\sin\left[(v-v')\left(\frac{N\phi}{2}\right)\right]}{N(v-v')}\left[R_v - \left(S_v - \left(\frac{\xi_v - \eta_v}{\xi_v - \chi_v}\right)T_v\right)\right]. \tag{16}$$

Now, considering only the three consecutive modes of practical relevance: $v, v' = \mu - 1,\ \mu,\ \mu + 1\,(v \neq v')$ corresponding to: (i) $v' = \mu,\ v = \mu+1,\ v = \mu-1$; (ii) $v' = \mu+1,\ v = \mu,\ v = \mu-1$; and (iii) $v' = \mu-1,\ v = \mu,\ v = \mu+1$, respectively, we obtain from (14) a set of three simultaneous equations in Fourier components $A_{\mu,1}$, $A_{\mu+1,1}$ and $A_{\mu-1,1}$.

$$\begin{aligned} \alpha_\mu A_{\mu,1} + \delta_{\mu+1,\mu} A_{\mu+1,1} + \delta_{\mu-1,\mu} A_{\mu-1,1} &= 0 \\ \delta_{\mu,\mu+1} A_{\mu,1} + \alpha_{\mu+1} A_{\mu+1,1} + \delta_{\mu-1,\mu+1} A_{\mu-1,1} &= 0 \\ \delta_{\mu,\mu-1} A_{\mu,1} + \delta_{\mu+1,\mu-1} A_{\mu+1,1} + \alpha_{\mu-1} A_{\mu-1,1} &= 0. \end{aligned} \tag{17}$$

The characteristic equation of the structure is obtained as the condition for the existence of the non-trivial solutions of (17) that the determinant formed by the coefficients of the constants occurring in these equation should vanish. When the said determinant is worked out and simplified, the condition reads as

$$\alpha_\mu\alpha_{\mu+1}\alpha_{\mu-1} - \alpha_\mu\delta_{\mu-1,\mu+1}\delta_{\mu+1,\mu-1} + \delta_{\mu+1,\mu}\delta_{\mu,\mu-1}\delta_{\mu-1,\mu+1}$$
$$-\delta_{\mu+1,\mu}\delta_{\mu,\mu+1}\alpha_{\mu-1} + \delta_{\mu-1,\mu}\delta_{\mu,\mu+1}\delta_{\mu+1,\mu-1} - \delta_{\mu-1,\mu}\delta_{\mu,\mu-1}\alpha_{\mu+1} = 0. \quad (18)$$

The individual terms of (18) may be read with the help of (15) and (16). For practical situations, the first term in the left-hand side of (18) dominates over the remaining terms. For instance, in the present context, let us interpret $\mu = v(= m + kN)$ and take typically, $v = 0$ and the structure parameters as $N\phi = 2\pi/3$, $r_V/r_W = 0.5$, $r_C/r_W = 0.186$. This would make the magnitudes of the first through sixth terms as: $1.1929 \times 10^{157}, 5.0351 \times 10^{-8}, 1.21157 \times 10^{-4}, 1.4385 \times 10^3, 1.2157 \times 10^{-4}$, and 2.0139×10^{-7} respectively. Therefore, retaining only the dominating first term in the left-hand side of (18), and choosing to replace the integer μ by $v(= m + kN)$, we get

$$\alpha_v\alpha_{v+1}\alpha_{v-1} = 0. \quad (19)$$

Each of the three factors of (19) when equated to zero yields the dispersion relation for each of the three possible waves. It turns out that, out of these waves, the one that gives the solution for the desired mode is:

$$\alpha_v = 0. \quad (20)$$

With the help of (15) and which has to be read using (11)–(13), one may express the dispersion relation (20) in the following explicit form

$$\left[J'_v\{k_c r_V\} - \eta_v Y'_v\{k_c r_V\}\right]\phi + \left[J_v\{k_c r_V\} - \eta_v Y_v\{k_c r_V\}\right.$$
$$\left. - \left(\frac{\xi_v - \eta_v}{\xi_v - \chi_v}\right)\left(J_v\{k_c r_V\} - \chi_v Y_v\{k_c r_V\}\right)\right] \times (2\pi/N - \phi) = 0.$$
$$\text{(Configurations } A \text{ and } B) \quad (21)$$

In (21) one gets the one and the same form of the dispersion relation for both the configurations A and B, however, with due care in the meaning of the symbol r_V given in the beginning of the present section. Accordingly, the ridge depth in configuration A is $r_V - r_C$, while the vane depth in configuration B is $r_W - r_V$. As a special case of $\phi = 0$, and $r_V = r_W$, the dispersion relation (21) for the ridge or vane loaded coaxial waveguide (for either of the configurations A and B) passes on to that of a smooth-wall coaxial waveguide excited in $\mathrm{TE}_{v,n}$ mode:

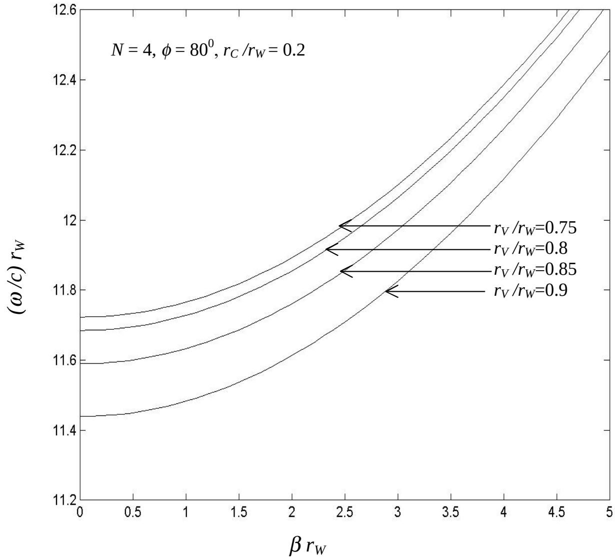
$$J'_v(k_c r_W)Y'_v(k_c r_C) - J'_v(k_c r_C)Y'_v(k_c r_W) = 0$$

which, in turn, passes in its further special case $\phi = 0$, $r_C = 0$ and $r_V = r_W$ to that of a smooth-wall cylindrical waveguide excited in $\mathrm{TE}_{v,n}$ mode: $J'_v(k_c r_W) = 0$.

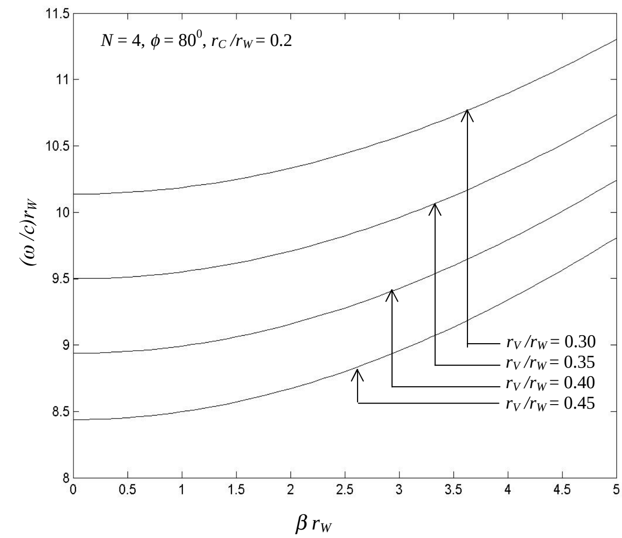
3. RESULTS AND DISCUSSION

The dispersion relation (21) may be used for plotting the ω-β dispersion characteristics of the coaxial waveguide. The shape of such plots for both the configurations A and B of the structure does not change with the ridge/vane parameters (Fig. 2). Therefore, these parameters do not have any significance in widening the bandwidth of the coalescence between the waveguide-mode and the beam-mode dispersion characteristics. Hence the ridge/vane loading does not have a role in broadbanding of a gyro-TWT. In fact, the vane parameters merely control the cutoff frequency and hence the eigenvalue of the structure. The plot of the eigenvalue versus the ratio of the outer conductor to ridge/vane radii for the various ridge/vane parameters (Figs. 3 and 4) would be significant, for instance, in the study of the effectiveness of the vane parameters in mode rarefaction in gyrotrons by cross section tapering of the structure reported in the literature [12, 13].

The results obtained by the present approach, in which the azimuthal harmonics have been considered in both the regions I and II, have been validated against those of Barroso et al. [13], the latter based on the surface impedance approach and explained in the beginning of Section 2. Barroso et al. [13], however, gave the results only for configuration A. For configuration B, the present results of the vane-loaded coaxial waveguide have been compared, though for only a special case (without a central conductor), with those of a vane-loaded cylindrical waveguide; the latter available in Singh et al. [9]. One may continue to use the present symbols for comparing the results with those of Singh et al. [9] (with reference to configuration B). However, for the sake of comparison with Barroso et al. [13] (with reference to configuration A), one finds it convenient to express the ridge parameters in terms of l, s, d and R, where l is the arc length of the slot width at the base of the slot, s is the arc length representing the periodicity of the slots/ridges at the mouth of the slots/outer edge of the ridges, d is the ridge depth and R is the ridge depth relative

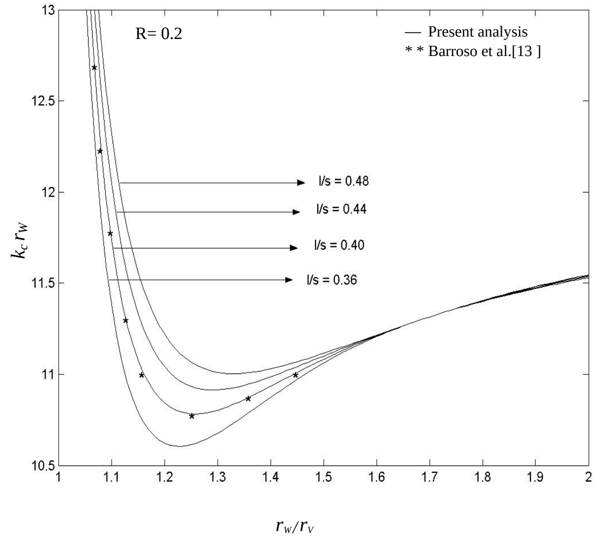


(a)



(b)

Figure 2. ω-β dispersion characteristics of a coaxial waveguide excited typically in $\mathrm{TE}_{6,2}$ mode for configurations A (a) and B (b), taking the ridge/vane dimensions as the parameters.



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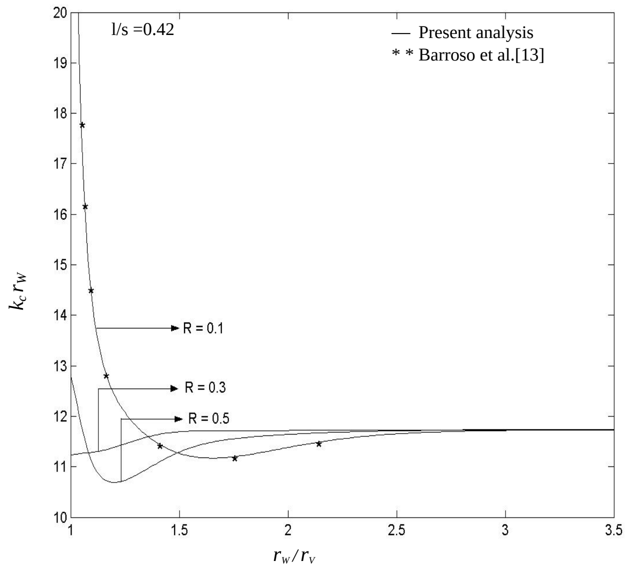

(b)

Figure 3. Variation of the eigenvalue of the typical waveguide mode $TE_{6,2}$ with the ratio of the waveguide to ridge radii for configuration A, taking the slot width relative to the ridge periodicity (a) and the ridge depth relative to the outer ridge-edge radius (b) as the parameters.

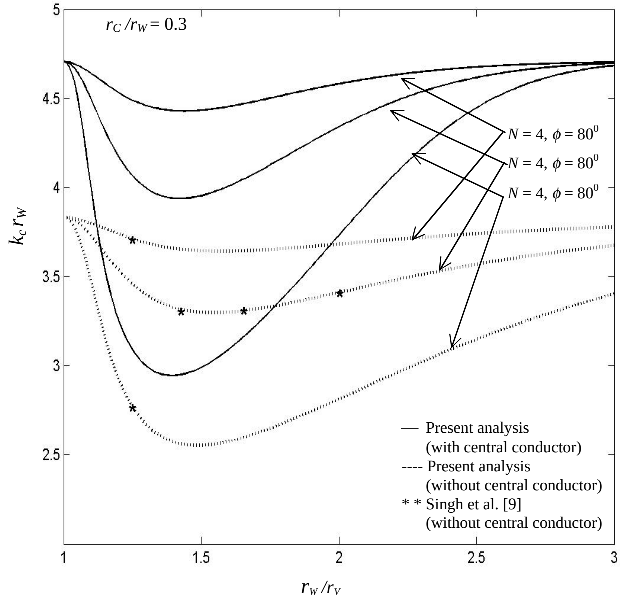

Figure 4. Variation of the eigenvalue of the typical waveguide mode $TE_{0,1}$ with the ratio of the waveguide to ridge radii for configuration B, taking the vane dimensions as the parameters.

to the outer ridge-edge radius r_V (Fig. 1(a)). From the geometry of configuration A, the ridge parameters in the present nomenclature of the present analysis are related to the ridge parameters l, s, d and R used by Barroso et al. [13] as $N\theta/2\pi = 1 - (l/s)/(1 - d/r_v)$ and $(r_V - r_C)/r_V = R$. For typical parameters, the present results are found to closely agree with both Barroso et al. [13] (Fig. 3) for configuration A and with Singh et al. [9] for configuration B, though the latter in a special case of the structure without the central conductor (Fig. 4). The plots of the eigenvalue versus the ratio of the waveguide to vane/ridge radii (Figs. 3 and 4), though they refer here to a typical mode, may be drawn for the other neighboring modes, too. The slopes of such plots for the competing modes may be controlled by the ridge/vane parameters for the purpose of mode rarefaction in over-sized high power gyrotrons [12, 13]. The details of such study are, however, kept outside the scope of the present work.

It is hoped that the dispersion relation obtained by the present analysis that takes the azimuthal harmonic effects into account should be useful in the design of a coaxial waveguide with a corrugated inner conductor or a vane-loaded outer conductor for high power gyrotrons.

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