Eigenwave Analysis and Simulation of Disc Loaded Interaction Structure for Wideband Gyro-TWT Amplifier

R. K. Singh and P. K. Jain

Abstract—In the present paper, disc loaded interaction structure for potential application in wideband Gyro-TWT amplifier has been analyzed, taking all the space and modal harmonics into consideration, for the eigenwave solutions. The analysis has been restricted to azimuthally symmetric $TE_{0,n}$ mode. Dispersion characteristics have been plotted by varying the structure parameters and have been validated against HFSS simulation results. The variation of eigenvalue with respect to different structure parameters has also been presented. It has been observed that disc periodicity plays very important role for wideband operation of disc-loaded Gyro-TWT.

Keywords—Broadbanding, Disc-loaded interaction structure, Eigenvalue, Gyro-TWT, HFSS.

I. INTRODUCTION

GYRO traveling wave tube (gyro-TWT) takes advantage of the cyclotron maser instability to produce coherent electromagnetic (EM) radiation from electrons gyrating in an external magnetic field and interacting with fast traveling waves in a cylindrical smooth waveguide structure. In such a device, employing cylindrical smooth waveguide structure, RF wave propagates with a phase velocity greater than that of speed of light. Such type of interaction structures used in gyro-TWTs are not capable of providing fairly wide bandwidths due to rapid increase in the group velocity with frequency, at or near the cut-off frequency of the waveguide, which causes a narrow band coalescence between the beam-mode line and the waveguide-mode dispersion hyperbola [1-2]. The device bandwidth can be maximized by suitably choosing the beam and magnetic field parameters [3-6]. 3-dB bandwidths of approximately 10% are not difficult to obtain even if the conventional smooth-wall cylindrical waveguide interaction structures are used in the device. However, still wider bandwidths are not achievable from the device, using conventional waveguides.

In order to achieve wideband performance of a gyro-TWT, one has to realise the grazing intersection between the beam-mode and waveguide-mode $\omega - \beta$ dispersion characteristics over a wide range of frequencies. Several techniques can be adopted for broadbanding a gyro-TWT. Some of these techniques are i) taper the cross section of the waveguide and synchronously profile the magnetic flux density, ii) load the wall of a non-tapered waveguide either by dielectric lining its wall or by placing a dielectric rod at the axis of the guide, iii) a two-section dielectric loading [7-11].

Simultaneously tapering both the cross section of the waveguide and the background magnetic field is a simple technique of broadbanding a gyro-TWT. This technique predicted large bandwidths though at the cost of gain [12-15]. This is due to different smaller length portions of the interaction length of different cross sections become effective for different operating frequency ranges over the amplification band of the device. For a gyro-TWT using a rectangular waveguide interaction structure, the taper profile and the corresponding gain-frequency response was studied by [8]. For the device using a cylindrical waveguide, it was presented by [16] that the optimum taper can be chosen for a flat gain-frequency response.

Another method of wide-banding the device is to go for dispersion shaping the interaction structure by proper loading techniques that would reduce the variation of the group velocity near the cut-off frequency of the waveguide. Various loading techniques have been reported like dielectric loading [17-19], helix loading [20-24] and disc loading [24-26]. However, while the method of dielectric loading entails the risk of charging of the dielectric and heating the dielectric if it is lossy, the problem of mode competition needs to be seriously addressed in helix loading. On the other hand, a circular waveguide loaded with axially periodic annular metal discs i.e. disc-loaded circular waveguide, which has been studied in the slow-wave regime for a conventional TWT for high gains [27-28], though not for wide bandwidths, and which is more well known for its application in the linear accelerator, has also shown potential as a fast-wave structure for wideband gyro-TWTs. In disc loading we find an easy method of controlling the dispersion characteristics of the interaction structure by the geometry of the discs and by the axial periodicity of the discs.

By the introduction of slow-wave structure like circular discs at regular intervals in a cylindrical smooth-wall

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waveguide structure, the phase and group velocities of RF waves can be controlled independently as per requirements. In addition to low frequency cut-off due to circular smooth waveguide, the periodic loading of circular discs introduces a high frequency cut-off. Thus a circular waveguide loaded with circular discs at regular intervals enjoys many of the characteristics of a band pass filter. Axial periodic loading or corrugation of a smooth-wall circular waveguide modifies its hyperbolic dispersion characteristics by breaking it into numbers of transmission pass-and stop-bands, which also associates the dispersion shaping to obtain the wideband coalescence between beam-mode line and waveguide-mode hyperbola for a broadband gyro-TWT performance. For instance, the RF phase velocity of a circular waveguide changes due to the loading of the waveguide by axially periodic annular discs projecting radially inward from the waveguide-wall depending upon the mode and depth of corrugation. Adjusting the disc parameters can control the dispersion characteristics of a disc-loaded circular waveguide in the fast-wave regime. Hence, such a structure has been considered as a potentially wideband structure for wideband gyro-TWTs.

Periodic structures were analyzed in the past by various approaches and models, such as the equivalent circuit approach [2], [29-30], the surface impedance or surface admittance model [31-32], the variational technique [33-34], the transfer matrix and half-cell formulations [35], the Galerkin's method [36-37], the coupled integral equation approach [38-39], the scattering matrix formalism [40], and the field and mode matching techniques [41-43]. Out of all these methods, it is found that the field matching techniques are simple to explore the RF interaction structures for wideband gyro-TWTs. Choe and Uhm [43], found it worth trying out the simple field matching technique to study the behaviour of a disc-loaded waveguide with respect to its dispersion characteristics and hence predict the optimum structure parameters for wideband coalescence between the beam-mode and waveguide-mode dispersion characteristics of the device. The same approach is also made in the present work, however, with due care to include the rigour of considering the effect of higher order modal harmonics. The computer execution time for obtaining convergent solution has also been reduced to a great extent.

Organization of the present paper is as follows. In Section II, the field expressions for a disc-loaded structure have been presented. These field expressions substituted into the relevant boundary conditions results in dispersion relation of the structure. Results have been presented in Section III along with a brief discussion of the results. Finally, the work is concluded along with some suggestions in Section IV.

II. DISC LOADED STRUCTURE ANALYSIS

A. Field Expressions

For the analysis, the disc-loaded circular waveguide is divided into two free-space regions (Fig. 1) — the disc-free region, labelled as region-I, and the disc-occupied region, labelled as region-II. In the structure, region I occupies $0 \leq r < r_D$ and $0 < z < L$, while region II occupies $r_D \leq r < r_W$ and $0 < z < L - T$, where r_D is the disc-hole radius, r_W is the waveguide-wall radius, L is the axial periodicity of discs and T is the disc thickness.
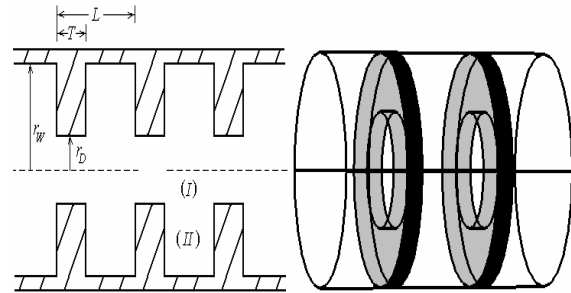

Fig.1 Schematic of a circular waveguide loaded with annular metal discs showing the structure regions (I and II) and disc parameters.

The wave equations for the axial components of magnetic (H_z) and electric (E_z) field intensities are:

$$\nabla^2 H_z - \mu_0 \varepsilon_0 \frac{\partial^2 H_z}{\partial t^2} = 0 \tag{1}$$

$$\nabla^2 E_z - \mu_0 \varepsilon_0 \frac{\partial^2 E_z}{\partial t^2} = 0 . \tag{2}$$

Further, the analysis here is restricted only to the excitation of the interaction structure in the TE mode ($E_z = 0$), and not to the TM mode ($H_z = 0$), in view of the potential application of the structure in a gyro-TWT. This is because the gyro-TWT operates at the grazing intersection between the beam-mode and waveguide-mode dispersion characteristics corresponding to the RF wave group velocity equalling the beam axial velocity, where the TM-mode growth rate is found to vanish [19, 44].

Solution of the wave equation (1), with reference to a structure that enjoys a cylindrical symmetry, for the axial field components, comprised of all the space harmonics, in the cylindrical system of co-ordinates (r, θ, z), choosing to consider a non-azimuthally varying or azimuthally symmetric mode ($\partial/\partial\theta = 0$), results in:

$$
\begin{aligned}
H_z^I &= \sum_{n=-\infty}^{+\infty} H_{z,n}^I \\
&= \sum_{n=-\infty}^{+\infty} [A_n^I J_0\{\gamma_n^I r\} + B_n^I Y_0\{\gamma_n^I r\}] \exp j(\omega t - \beta_n^I z)
\end{aligned} \tag{3}
$$

where, $\gamma_n^I = (k^2 - \beta_n^{I\,2})^{1/2}$ is the radial propagation constant, $k \,(= \omega(\mu_0\varepsilon_0)^{1/2})$ being the free space propagation constant, β_n^I being the axial phase propagation constant. Here, n represents the order of the space harmonic arising from the structure periodicity. A_n^I and B_n^I are the field constants. J_0

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and Y_0 are the zero[th] order Bessel functions of the first and second kinds, respectively.

It may be noted that, with reference to region-I, the field constant B_n^I occurring in (3) has to be put equal to zero in order to prevent the field from blowing up to infinity, since the function $Y_0\{\gamma_n^I r\} \to -\infty$ as $r \to 0$. Thus,

$$H_z^I = \sum_{n=-\infty}^{+\infty} H_{z,n}^I = \sum_{n=-\infty}^{+\infty} A_n^I J_0\{\gamma_n^I r\} \exp j(\omega t - \beta_n^I z) \qquad (4)$$

As the behaviour of a periodic structure obeys Floquet's theorem [48], one can easily obtain,

$$\beta_n = \beta_0 + \frac{2n\pi}{L} \quad (\text{n} = 0, \pm 1, \pm 2, \pm 3 \ldots) \qquad (5)$$

where β_0 is fundamental axial phase propagation constant.

The field components in disc-free region can be obtained with the help of Maxwell's equations [2], for our case, as:

$$E_z^I = 0 \qquad (6)$$

$$E_\theta^I = \sum_{n=-\infty}^{+\infty} E_{\theta,n}^I = j\omega\mu_0 \sum_{n=-\infty}^{+\infty} \frac{1}{\gamma_n^I} A_n^I J_0'\{\gamma_n^I r\} \exp j(\omega t - \beta_n^I z) \quad (7)$$

$$E_r^I = 0 \qquad (8)$$

$$H_r^I = \sum_{n=-\infty}^{+\infty} H_{r,n}^I = -j \sum_{n=-\infty}^{+\infty} \frac{\beta_n^I}{\gamma_n^I} A_n^I J_0'\{\gamma_n^I r\} \exp j(\omega t - \beta_n^I z) \quad (9)$$

$$H_\theta^I = 0 \qquad (10)$$

where $J_0'\{\gamma_n^I r\}$ represents first derivative of Bessel function of first kind with respect to its argument.

The region-II of the disc-loaded waveguide (the region between two consecutive discs, separated by an axial distance $(L-T)$) supports stationary waves due to reflection at discs. Considering the fields in disc-occupied region-II to be comprised of all the stationary-wave modal harmonics, one can write, the solution of wave equation (1) as:

$$H_z^{II} = \sum_{m=1}^{+\infty} H_{z,m}^{II}$$
$$= \sum_{m=1}^{+\infty} [A_m^{II} J_0\{\gamma_m^{II} r\} + B_m^{II} Y_0\{\gamma_m^{II} r\}] \exp j(\omega t - \beta_m^{II} z) \qquad (11)$$

where $\gamma_m^{II} = (k^2 - \beta_m^{II\,2})^{1/2}$ is the radial propagation constant in disc-occupied region, β_m^{II} being the axial phase propagation constant in disc-occupied region-II. Here, m is the stationary-wave modal number. A_m^{II} and B_m^{II} are the field constants.

Considering the stationary waves due to reflection at discs one may express β_m^{II} in terms of the structure dimensions as,

$$\beta_m^{II} = \frac{m\pi}{L-T} \quad (m=1, 2, 3, \ldots\ldots) \qquad (12)$$

Since there exists the forward-wave component and the backward-wave component in region-II, caused by reflections from disc surface, one may write (11) as,

$$H_z^{II} = \sum_{m=1}^{\infty} H_{z,m}^{II} = \sum_{m=1}^{\infty} A_m^{II} Z_0\{\gamma_m^{II} r\} \exp(j\omega t) \sin(\beta_m^{II} z) \qquad (13)$$

where

$$Z_o\{\gamma_m^{II} r\} = J_o\{\gamma_m^{II} r\} Y_0'\{\gamma_m^{II} r_W\} - J_0'\{\gamma_m^{II} r_W\} Y_o\{\gamma_m^{II} r\} \qquad (14)$$

in which $Y_0'\{\gamma_n^I r_W\}$ represents first derivative of Bessel function of second kind with respect to its argument

Again, the field quantities in disc-occupied region-II can be expressed, using Maxwell's equation, as,

$$E_z^{II} = 0 \qquad (15)$$

$$E_\theta^{II} = \sum_{m=1}^{\infty} E_{\theta,m}^{II}$$
$$= j\omega\mu_0 \sum_{m=1}^{\infty} \frac{1}{\gamma_m^{II}} A_m^{II} Z_0'\{\gamma_m^{II} r\} \exp(j\omega t) \sin(\beta_m^{II} z) \qquad (16)$$

$$H_\theta^{II} = 0 \qquad (17)$$

$$E_r^{II} = 0 \qquad (18)$$

$$H_r^{II} = -\frac{j\beta_m^{II}}{\gamma_m^{II}} \sum_{m=1}^{\infty} A_m^{II} Z_o'\{\gamma_m^{II} r\} \exp(j\omega t) \sin(\beta_m^{II} z) \qquad (19)$$

where $Z_0'\{\gamma_m^{II} r\}$ is obtained by taking the first derivative of the function (14) with respect to its argument.

Further, it is implied that (3) and (11) are essentially the fast-wave solutions, since the structure is intended to be used in a gyro-TWT that operates in the fast-wave regime. In other words, one has to take γ_n^I and γ_m^{II} as a real quantity in (3) and (11) under this fast-wave assumption ($k > \beta_n^I$; $k > \beta_m^{II}$) made.

B. Boundary Conditions

The continuity of the tangential components of electric and magnetic field intensities at the interface, $r = r_D$, between the free-space disc-free region-I and disc-occupied free-space region-II as well as the vanishing of the tangential component of electric field intensity at the metal inner circumferential edge of the discs, $r = r_D$, may be specified by the following electromagnetic boundary conditions:

$$E_\theta^I = \begin{cases} E_\theta^{II} & 0 < z < (L-T) \\ & \\ 0 & (L-T) \le z \le L \end{cases} \quad (r = r_D) \qquad (20)$$

$$H_z^I = H_z^{II} \quad 0 < z < (L-T) \quad (r = r_D) \qquad (21)$$

Similarly, the electromagnetic boundary condition stating that the tangential component of electric field intensity vanishes at the metal wall of the waveguide, at $r = r_W$, may be put as:

$$E_\theta^{II} = 0 \quad (0 \le z < \infty; \quad r = r_W) \qquad (22)$$

C. Dispersion Relation

The approach for finding the dispersion relation is as follows. Making use of boundary condition (21), multiplying it by $\sin(\beta_m^{II} z)$ and then integrating it between $z = 0$ and $L - T$ results in a relation between the field constants A_m^{II} and A_n^I, as

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$$A_m^{II} = \sum_{n=-\infty}^{\infty} A_n^I X_{nm} \qquad (23)$$

where,

$$X_{nm} = \frac{2}{(L-T)} \frac{\beta_m^{II} \left(1 - (-1)^m \exp[-j\beta_n^I (L-T)]\right)}{[(\beta_m^{II})^2 - (\beta_n^I)^2]} \frac{J_0\{\gamma_n^I r_D\}}{Z_0\{\gamma_m^{II} r_D\}}$$

Another series expression for A_m^{II} can be obtained, by making use of boundary condition (20) and integrating from $z = 0$ to L, as

$$A_m^{II} = \sum_{n=-\infty}^{\infty} A_n^I \Re_{nm} \qquad (24)$$

where

$$\Re_{nm} = \frac{\left[\beta_m^{II} - \exp(-j\beta_0^I L)\left(\beta_m^{II} \cos(\beta_m^{II} L) + j\beta_n^I \sin(\beta_m^{II} L)\right)\right]}{[(\beta_m^{II})^2 - (\beta_n^I)^2]}$$
$$\times \frac{2}{(L-T)} \frac{\gamma_m^{II}}{\gamma_n^I} \frac{J_0'\{\gamma_n^I r_D\}}{Z_0'\{\gamma_m^{II} r_D\}}$$

Equating right hand sides of (23) and (24), one obtains

$$\sum_{n=-\infty}^{\infty} A_n^I (X_{nm} - \Re_{nm}) = 0 \qquad (25)$$

One can form a series equation each for each value of m considered in (25). Thus, m number of simultaneous series equations in the field constants A_n^I ($-\infty < n < \infty$) can be formed. Taking a finite number, say κ, of stationary-wave modes in order to find converging solutions: $m = 1, 2, 3, ..., \kappa$ and the same number of space-harmonic modes: $n = 0, \pm 1, \pm 2, ..., \pm(\kappa-1)/2$, where κ (≥ 1) is a natural number, one may form κ number of simultaneous equations in the constants $A_0^I, A_{\pm 1}^I, A_{\pm 2}^I, ..., A_{\pm(\kappa-1)/2}^I$. Hence, one may find the dispersion relation as the condition for the existence of a non-trivial solution of these simultaneous equations, in the form of a determinant of order $\kappa \times \kappa$ put equal to zero, as follows:

$$\det\left|(X_{nm} - \Re_{nm})\right| = 0, \qquad -\frac{\kappa-1}{2} < n < +\frac{\kappa-1}{2}, \ 1 \leq m < \kappa),$$

That results in,

$$\det\left|\mathfrak{I}_{nm} J_0\{\gamma_n^I r_D\} Z_0'\{\gamma_m^{II} r_D\} - Z_0\{\gamma_m^{II} r_D\} J_0'\{\gamma_n^I r_D\}\right| = 0$$
$$\left(-\frac{\kappa-1}{2} < n < +\frac{\kappa-1}{2}, \ 1 \leq m < \kappa\right), \qquad (26)$$

where,

$$\mathfrak{I}_{nm} = \frac{\gamma_n^I \beta_m^{II} \left(1 - (-1)^m \exp[-j\beta_n^I (L-T)]\right)}{\gamma_m^{II} \left[\beta_m^{II} - \exp(-j\beta_0^I L) \left(\beta_m^{II} \cos(\beta_m^{II} L) + j\beta_n^I \sin(\beta_m^{II} L)\right)\right]}$$

III. RESULTS AND DISCUSSION

In the previous section, the analysis of the disc-loaded waveguide, taking all the space and modal harmonics into consideration, has been carried out. The analytical expression for studying the dispersion characteristics of the device has been developed (26). It is of interest to study the effect of

parameter variation on these characteristics. These characteristics have been examined by making use of the in-built subroutine *fsolve* of MATLAB and have been validated against simulation results obtained from High Frequency Structure Simulator (HFSS). Analytical and simulation results thus obtained have been found in very close agreement.
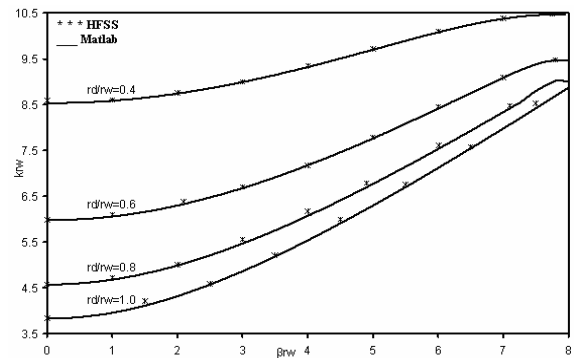

Fig. 2 Dispersion characteristic for a disc loaded waveguide operating in TE$_{01}$ mode having dimensions $L/r_W = 0.4$ and $T/r_W = 0.1$, taking disc-hole radius as the parameter (solid curve), and validation against HFSS (shown by asterisks).
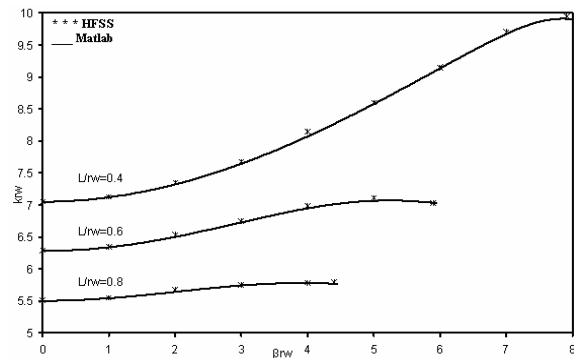

Fig. 3 Dispersion characteristic for a disc loaded waveguide operating in TE$_{01}$ mode having dimensions $r_D/r_W = 0.5$ and $T/r_W = 0.1$, taking disc-periodicity as the parameter (solid curve), and validation against HFSS (shown by asterisks).
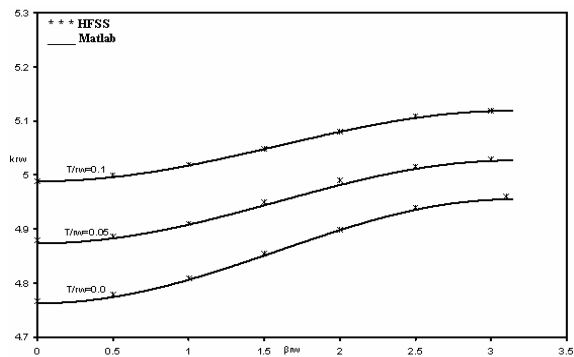

Fig. 4 Dispersion characteristic for a disc loaded waveguide operating in TE$_{01}$ mode having dimensions $r_D/r_W = 0.5$ and $L/r_W = 1.0$, taking disc-thickness as the parameter (solid curve), and validation against HFSS (shown by asterisks).

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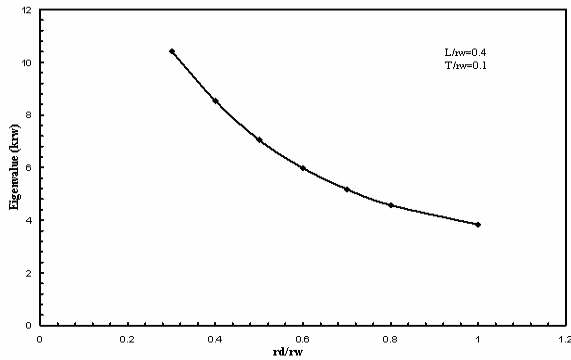Vol:2, No:5, 2008

Fig. 5 Variation of eigenvalue with respect to variation in disc-hole radius relative to waveguide wall radius.
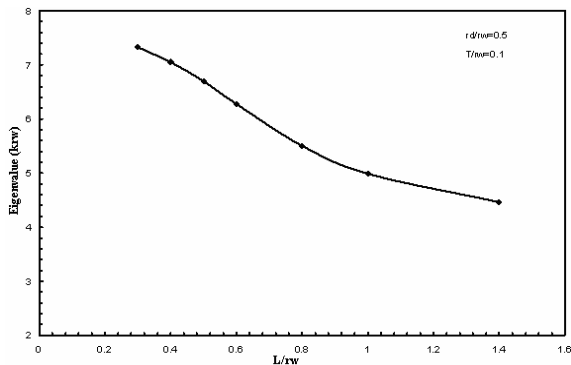

Fig. 6 Variation of eigenvalue with respect to variation in disc-periodicity relative to waveguide wall radius.
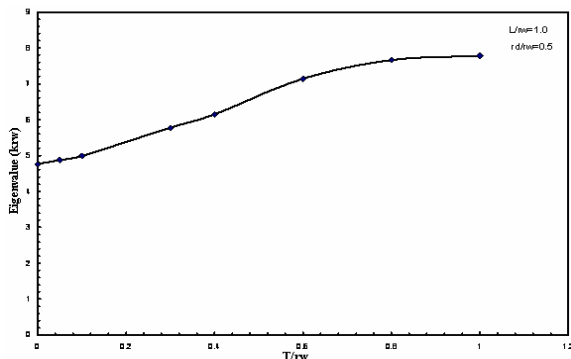

Fig. 7 Variation of eigenvalue with respect to variation in disc-thickness relative to waveguide wall radius.

The effect of parameter variation on the dispersion characteristics of disc-loaded waveguide, excited in TE_{01} mode, is shown in Fig. (2-4). The effect on the bandwidth of the device can be observed by the study of dispersion characteristics of the device for different parameters. Fig. (2) shows the normalized dispersion characteristics of the disc-loaded waveguide, taking the disc-hole radius r_D/r_W as parameter. It is found that, while the lower-edge frequency of the passband increases by a large value, the upper-edge frequency of the pass band comparatively increases by a lower value, with the decrease of the disc-hole radius relative to waveguide-wall radius, r_D/r_W. However, for the upper limiting case $r_D/r_W = 1$, the dispersion characteristics pass on

to those for a smooth-wall circular waveguide. Fig. (3) shows the normalized dispersion characteristics of the disc-loaded waveguide, taking the disc-periodicity L/r_W as the parameter. From the figure it is observed that the lower and upper-edge frequencies of the pass band each increase with the decrease of the structure periodicity relative to waveguide-wall radius L/r_W. Fig (4) shows the normalized dispersion characteristics of the disc-loaded waveguide, taking the disc-thickness T/r_W as the parameter. This characteristic reveals that disc-thickness plays an important role in parameter optimization for broadening the device bandwidth. The variation of eigenvalue with respect to r_D/r_W, L/r_W and T/r_W have been shown in Figs. (5-7).

IV. Conclusion

From the above discussion it can be concluded that the shape of the dispersion characteristics depends on both the disc-hole radius and the structure periodicity, being more sensitive to the latter. So, one has to optimize the structure parameters for widening the coalescence bandwidth preferably near the waveguide cut-off, where the axial phase propagation constant of the structure tends to zero that would in turn make the Doppler shift rather small. Thus, the disc-hole radius may be decreased and the structure periodicity increased for widening the device bandwidth. Hence, the structure dimensions should be optimally selected for higher bandwidths and gains.

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