Analysis of a Tapered Disc-Loaded Waveguide for a Wideband Gyro-TWT

Vishal Kesari, P. K. Jain, *Senior Member, IEEE*, and B. N. Basu

***Abstract*—The solution of the dispersion relation of a disc-loaded circular waveguide for the propagation constant, obtained by the cold (beam-absent) field analysis, was fed back into the small-signal gain equation of a gyro-traveling wave tube (TWT) to assess the technique of tapering the structure cross section for widening the bandwidth of the device, a technique that is known to broadband the device in a smooth-wall waveguide, usually at the cost of the device gain. The disc-to-disc distance of a nontapered disc-loaded circular waveguide, reportedly the most effective structure parameter for widening the bandwidth of a gyro-TWT, becomes an insignificant parameter for tapering the structure for wide bandwidths of a gyro-TWT, while simultaneous tapering of the waveguide-wall and disc-hole radii led to wide bandwidths at reasonably large gains.**

***Index Terms*—Disc-loaded waveguide, gyrotron amplifier, periodic electromagnetic structure, wideband millimeter-wave amplifier.**

I. Introduction

THE APPLICATIONS of periodic structures as electromagnetic filters [1]–[3], phase shifters [3], [4], polarizers [3], [4], corrugated antennas [3], [4], antenna feeds [2], [4], mode converters [5], etc., are well known in the community of microwave engineers. In the family of vacuum electron devices, periodic structures are used as the slow-wave interaction structures for linear accelerators [1], [6] and conventional microwave tubes such as the traveling-wave tube (TWT), magnetron, crossed-field amplifier, and extended interaction oscillator, as well as for nonconventional high power microwave (HPM) sources driven by relativistic electron beam, for instance, the backward-wave oscillator, radiation diffraction generator (orotron), multiwave Cèrenkov generator, multiwave diffraction generator, magnetically insulated line oscillator (MILO), etc., [6]–[9], and also as nonconventional interaction structures for fast-wave devices like the vane-loaded gyrotron, disc-loaded gyro-TWT, etc., [9]–[13].

In a fast-wave device like the gyrotron, gyro-klystron, and gyro-TWT, a beam of electrons is made periodic in helical trajectory to interact with electromagnetic waves supported usually by a non-periodic interaction structure such as a conventional smooth-wall circular waveguide [9]. However, in order to realize a low-energy, large-orbit, high beam harmonic and mode-selective gyrotron oscillator, use has been made of an "azimuthally" periodic, magnetron-like interaction structure consisting of a circular waveguide resonator provided with metal vanes projecting radially inwards from the waveguide-wall [10]. Also, an "axially" periodic interaction structure consisting of a circular waveguide loaded with annular metal discs has proved its potential for widening the bandwidth of a gyro-TWT by controlling the dispersion of the waveguide that would widen the bandwidth of coalescence between the beam-mode and waveguide-mode dispersion characteristics for the desired wideband beam-wave interaction [11]–[13]. In fact, for the purpose of widening the coalescence bandwidth of a gyro-TWT, loading the waveguide by metal discs is preferred to dielectric lining the waveguide-wall that entails the risk of dielectric charging and associated heating [14]. An alternative method of widening the bandwidth of a gyro-TWT, which, however, is associated with a reduction in the device gain, is to taper the cross section of the interaction waveguide and synchronously profile the magnetic field in the structure [10], [15]–[18]. This motivates the authors of this paper to study the advantages of both disc loading the waveguide and tapering the waveguide cross section. It is expected that the presence of the discs would enhance the amplitude of the available radio frequency (RF) electric field for interaction with the electron beam and hence the interaction impedance of the structure [19] which in turn would enhance the device gain thereby compensating for the gain reduction due to tapering of the waveguide cross section. The different schemes of tapering the structure parameters (Section II-A), the analytical approach to obtaining the cold (beam-absent) dispersion relation (Section II-B) of the structure and the gain equation (Section II-C), in which the solution of the cold dispersion relation for the phase propagation constant is to be substituted, and the magnetic field and beam parameter profiles (Section II-D) compatible with tapered structure parameters to maintain synchronism between the RF wave and cyclotron frequencies are presented. Hence, the device performances with respect to the gain, bandwidth, and midband frequency using different tapering schemes and their combination in widening the bandwidth of a disc-loaded gyro-TWT at an appreciable gain are studied (Section III), and major conclusions drawn (Section IV).

II. Analytical Approach

The approach that is followed to appreciate the effects of tapering the structure parameters (Section II-A) on the gain-frequency response of a disc-loaded gyro-TWT is to substitute the axial propagation constant from the solution of the cold (beam-absent) dispersion relation of a disc-loaded waveguide [13] (Section II-B) into the gyro-TWT gain equation, the latter

Manuscript received November 4, 2005; revised March 7, 2006. The work of V. Kesari was supported by the Centre of Advanced Study, Department of Electronics Engineering, Banaras Hindu University.

The authors are with the Centre of Research in Microwave Tubes, Department of Electronics Engineering, Institute of Technology, Banaras Hindu University, Varanasi-221 005, India (e-mail: vishal_kesari@rediffmail.com; pkjain_crmt@sify.com).

Digital Object Identifier 10.1109/TPS.2006.875767

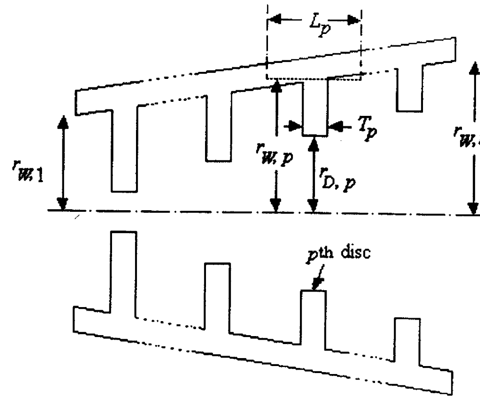

Fig. 1. Disc-loaded circular waveguide with tapered waveguide-wall and disc-hole radii showing the pth $(1 \le p \le n_D)$ disc parameters, as well as the wall radii at the entrance and exit of the structure.

obtained by interpreting the hot (beam-present) dispersion relation of the device [10], [13] (Section II-C), taking care to profile the magnetic field and beam parameters synchronous with the chosen scheme of tapering the structure parameters (Section II-D).

A. Tapering Schemes

For the sake of simplicity of analysis, the continuous tapering of the structure parameters over the entire length of the interaction structure is approximated by the variation of the structure parameters in n_D number of steps, it being implied that within a particular step the four structure parameters, namely, the waveguide-wall radius r_W, the disc-to-disc distance L, the disc-hole radius r_D, and the disc thickness T are each uniform. Considering the step-to-step variation of the structure parameters as linear, the parameters of the $p\text{th}(1 \le p \le n_D)$ step may be defined, as per the following tapering schemes, labelled as 1, 2, 3, and 4, respectively:

$$\left.\begin{aligned} r_{W,p} &= r_{W,1} + (r_{W,n_D} - r_{W,1}) \\ &\quad \times (p-1)/(n_D-1) \qquad \text{(Scheme 1)} \quad \text{(a)} \\ L_p &= L_1 + (L_{n_D} - L_1) \\ &\quad \times (p-1)/(n_D-1) \qquad \text{(Scheme 2)} \quad \text{(b)} \\ r_{D,p} &= r_{D,1} + (r_{D,n_D} - r_{D,1}) \\ &\quad \times (p-1)/(n_D-1) \qquad \text{(Scheme 3)} \quad \text{(c)} \\ T_p &= T_1 + (T_{n_D} - T_1) \\ &\quad \times (p-1)/(n_D-1) \qquad \text{(Scheme 4)} \quad \text{(d)} \end{aligned}\right\} \quad (1)$$

where the subscript $p(1 \le p \le n_D)$ with the structure parameters r_W, L, r_D, and T refers to the pth step of the parameter, the pth disc being positioned at the middle of the pth step. Here, $p = 1$ and $p = n_D$ would then refer to the start and the end steps, respectively (Fig. 1). In each of these schemes, one out of the four structure parameters is tapered in steps, the remaining three parameters being kept constant. The total interaction length l, say, of the structure may in general be expressed as $l = \sum_{p=1}^{p=n_D} L_p$, for all the four tapering schemes 1–4, defined according to (1a) to (1d), respectively. However, for each of the three tapering schemes 1, 3, and 4 [in none of which the disc-to-disc distance L is tapered according to (1b)], or for the combination thereof, the interaction length would be $l = n_D L_p$ (in view of the relation $L_1 = L_2 = \ldots = L_p = \ldots = L_{n_D} = L$). In fact, it would be of interest to explore the combination of the tapering schemes 1 and 3 for widening the bandwidth of a gyro-TWT at a relatively large gain (Section III).

B. Cold (Beam-Absent) Dispersion Relation of a Conventional, Nontapered Disc-Loaded Waveguide or That of a Particular Step of a Tapered Disc-Loaded Waveguide

Several authors reported the analysis of a disc-loaded waveguide in the literature. For instance, in order to study transverse magnetic (TM) modes, Hahn [20] used the modal field matching technique and Clarricoats and Olver [5] used the surface impedance model. Amari *et al.* [21] used the coupled-integral-equation technique to study transverse electric (TE) modes in a disc-loaded waveguide. Further, while Amari *et al.* [3] used the coupled-integral-equation technique, Esteban and Rebollar [22] used the modal expansion technique and Hahn *et al.* [23] the transfer matrix and half-cell formulations to study hybrid TE and TM modes. Keeping the potential application of broadbanding a gyro-TWT in mind, Choe and Uhm [11] used the field matching technique to analyze a disc-loaded circular waveguide in the fast-wave regime. They included the effects of the lowest order standing wave mode in the disc-occupied region and the fundamental traveling wave mode in the disc-free region. They, however, excluded the effects of finite disc thickness. Kesari *et al.* [12], [13] extended the analysis of Choe and Uhm [11] considering higher order standing and traveling wave modes in the disc-occupied and disc-free regions, respectively, by first ignoring [12] and then considering [13] the effects of finite disc thickness.

Since the structure parameters are uniform over a given step, the cold dispersion relation of a conventional, nontapered disc-loaded circular waveguide continues to be valid for the pth step of the structure, that may therefore be written, for azimuthally symmetric TE modes, as [13]

$$\det\left|M_{nm} J_0\left(\gamma_n^I r_{D,p}\right) Z_0'\left(\gamma_m^{II} r_{D,p}\right) - Z_0\left(\gamma_m^{II} r_{D,p}\right) J_0'\left(\gamma_n^I r_{D,p}\right)\right| = 0 \quad (2)$$

where (see the equation at the bottom of the page) J_0 and Y_0 are the zeroth-order Bessel functions of the first and second kinds, respectively. The prime with a function represents the derivative of the function with respect to its argument. $\gamma_n^I (= [k^2 - (\beta_n^I)^2]^{1/2})$ and $\gamma_m^{II} (= [k^2 - (\beta_m^{II})^2]^{1/2})$ are the radial

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

$$Z_0\left(\gamma_m^{II} r\right) = \left(Y_0'\left(\gamma_m^{II} r_{W,p}\right) J_0\left(\gamma_m^{II} r\right) - J_0'\left(\gamma_m^{II} r_{W,p}\right) Y_0\left(\gamma_m^{II} r\right)\right) / Y_0'\left(\gamma_m^{II} r_{W,p}\right)$$

propagation constants in terms of the axial phase propagation constants β_n^I and β_m^{II}, respectively, where the superscripts I and II refer to the disc-free and disc-occupied regions, respectively, k being the free-space propagation constant. Referring to the pth step of tapering, one may express β_n^I as $\beta_n^I = \beta_0^I + 2\pi n/L_p$ ($n = 0, \pm 1, \pm 2, \ldots . \pm \infty$), according to Floquet's theorem, in the disc-free, free-space region supporting traveling waves. Similarly, one may express β_m^{II} as $\beta_m^{II} = m\pi/(L_p - T_p)$ ($m = 1, 2, 3, \ldots . \infty$) in the free-space region of the groove between discs of axial length $L_p - T_p$ supporting standing waves of integral multiple of half guide wavelengths [11]–[14].

Obviously, the dispersion relation (2) may be interpreted for a nontapered disc-loaded waveguide, taking $r_{W,p} = r_W$, $L_p = L$, $r_{D,p} = r_D$, and $T_p = T$, since it is implied that, within a step, the structure is characterized by uniform parameters.

C. Small-Signal Gain Equation

Adding the gain contributions G_p ($1 \leq p \leq n_D$) from all the steps of the step-tapered gyro-TWT, the small-signal equation for the gain G in decibel of the device may be interpreted from the hot (beam-present) dispersion relation of the device, and expressed in a form similar to that for a conventional TWT as follows [10], [13]:

$$G = \sum_{p=1}^{p=n_D} G_p = \sum_{p=1}^{p=n_D} (A_p + B_p C_p N_p) \tag{3}$$

where

$$\left.\begin{aligned} A_p &= -20\log_{10}\left|(1-\delta_2/\delta_1)(1-\delta_3/\delta_1)\right| \\ B_p &= 40\pi(\log_{10} e)x_1 \cong 54.6x_1 \\ C_p &= (K_p I_0/4V_0)^{1/3} \\ N_p &= \left(\beta_0^I/2\pi\right) L_p \end{aligned}\right\} \tag{4}$$

where δ_1, δ_2, and δ_3 are the solutions of the hot cubic dispersion relation $\delta(\delta + jb)^2 = j$ corresponding to the three forward waves of the device, in which $b(= (\omega - \beta_0^I v_{z,p} - s\omega_c/\gamma)/(\beta_0^I v_{z,p} C_p))$ measures the departure of the Doppler-shifted frequency $\omega - \beta_0^I v_{z,p}$ from the resonance with a harmonic of the relativistic electron cyclotron frequency $s\omega_c/\gamma$, s being the beam-harmonic mode number, ω_c the nonrelativistic cyclotron angular frequency. $v_{z,p}(= c[(\gamma^2-1)/(1+\alpha_0^2)]^{1/2}/\gamma)$ is the axial velocity of electrons, $\alpha_0(= v_{t,p}/v_{z,p})$ is the beam pitch factor, $v_{t,p}$ being the transverse velocity of electrons. γ $(= 1 + |e|V_0/m_{e0}c^2)$ is the relativistic mass factor, V_0 being the beam voltage, e is the electronic charge, m_{e0} is the rest mass of an electron, and c is the velocity of light in free-space. x_1 is the real part, supposedly positive, of δ_1, corresponding to a growing wave. N_p is the interaction length L_p of the pth step measured in terms of guide wavelengths $2\pi/\beta_0^I$. K_p is the interaction impedance of the pth step of the gyro-TWT, which is given by [10] and [13], see (5) shown at the bottom of the page, where $r_{H,p}$ and $r_{L,p}$ are the hollow-beam radius and the Larmor radius in the pth step, respectively.

D. Magnetic Field and Beam Profiles

The magnetic field parameters and the beam parameters depending thereupon need to be profiled in the stepped structure so as to maintain the condition of electron cyclotron resonance throughout the steps of the structure. Further, this has to be done such that the background magnetic flux density $B_{0,p}$ in the structure maintains a constant ratio with the corresponding grazing point magnetic flux density $B_{g,p}(= (m_{e0}\gamma\omega_{cut,p}/(|e|s))(1 - v_{t,p}^2/c^2)^{1/2})$, and, at the same time, the combined beam and magnetic field parameters $r_{L,p}B_{0,p}^{1/2}$, $r_{H,p}B_{0,p}^{1/2}$, and $v_{t,p}B_{0,p}^{-1/2}$ individually maintain a constant value [10], throughout the structure $(1 \leq p \leq n_D)$, in order to obey the adiabatic beam-flow condition [24], the conservation of magnetic flux [18], and the conservation of electron magnetic moment [18], respectively.

III. Results and Discussion

Since within a step the structure is characterized by uniform parameters, one may interpret the gain equation of a gyro-TWT in a tapered disc-loaded waveguide for the corresponding equation for the device in a nontapered disc-loaded waveguide as well, as discussed preceding (3). The results so obtained for the nontapered structure pass on to those published in [13]. The gain of a nontapered disc-loaded gyro-TWT depends on the structure parameters, namely, the waveguide-wall radius r_W, the disc-to-disc distance L, the disc-hole radius r_D, and the disc thickness T (Fig. 2). Thus, the device gain in the nontapered structure increases without appreciable change in the midband frequency, as r_W is increased, all other structure parameters remaining constant [Fig. 2(a)]. Similarly, all other structure parameters remaining unchanged, as L is increased and correspondingly n_D decreased to keep the interaction length l more or less the same, the device gain increases and bandwidth decreases though not appreciably with a slight decrease of the midband frequency [Fig. 2(b)]. As r_D is increased, keeping all other structure parameters constant, the device bandwidth decreases with noticeable increase in both the device gain and midband frequency [Fig. 2(c)]. The increase of T, though it hardly affects the device gain, causes a decrease in the bandwidth as well as an increase in the midband frequency, however not so significantly [Fig. 2(d)]. Obviously, the foregoing control of the structure parameters r_W, L, r_D, and T over the device gain, bandwidth and midband frequency would also be reflected on the device performance if the disc-loaded waveguide were tapered according to schemes 1–4, as per (1a)–(1d), respectively [Fig. 2(a)–(d)]. Therefore, the parameter r_W as per scheme 1 controls the device gain more appreciably than the parameters L

$$K_p = \frac{(\mu_0/\varepsilon_0)^{1/2}(v_{t,p}/c)^2\left(\gamma_0^I r_{W,p}\right)^2\left(1+\alpha_0^2\right) J_s^2\left(\gamma_0^I r_{H,p}\right) J_s'^2\left(\gamma_0^I r_{L,p}\right)}{\pi J_0^2\left(\gamma_0^I r_{W,p}\right)(v_{z,p}/c)\left(\beta_0^I r_{W,p}\right)^4} \tag{5}$$

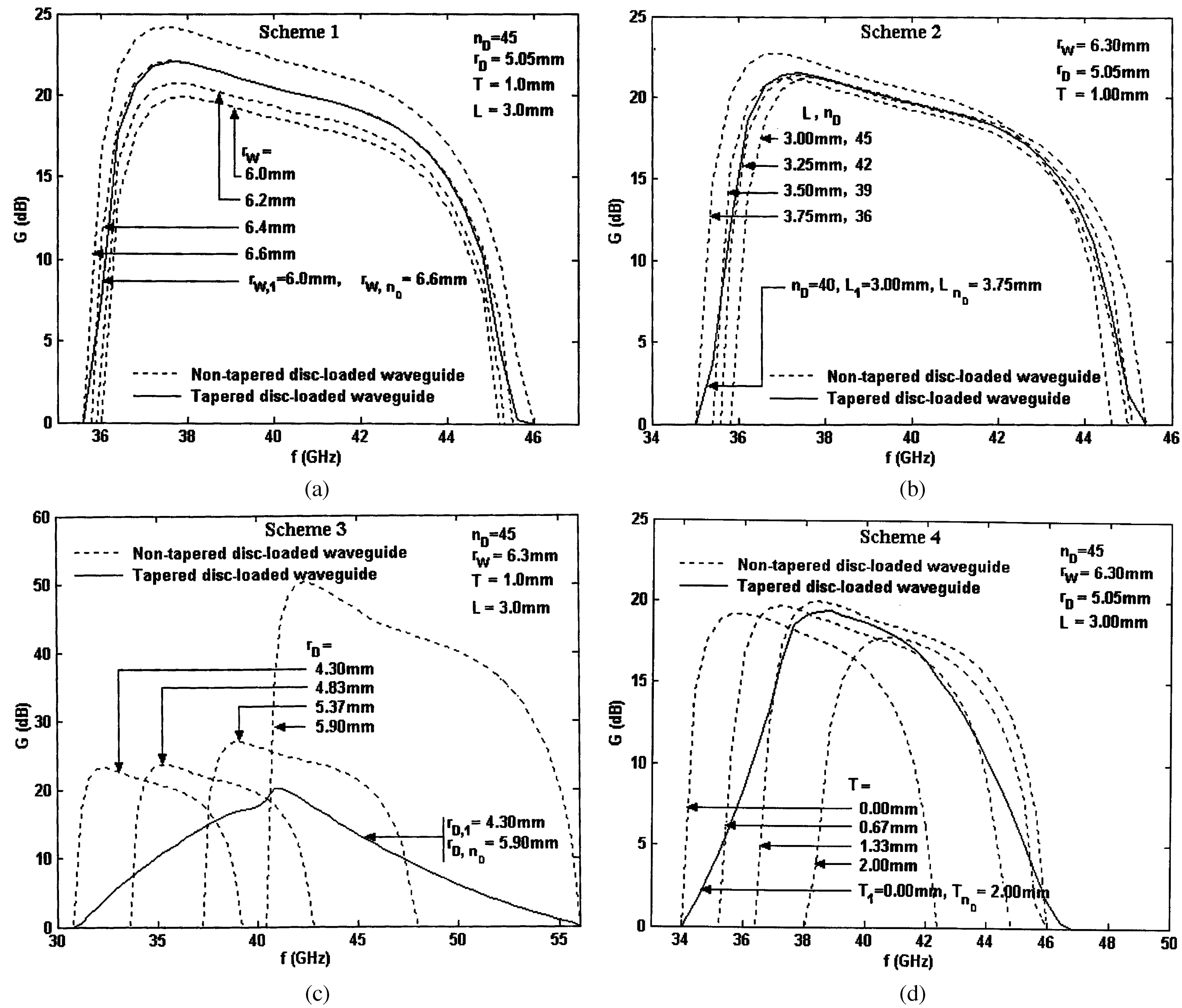

Fig. 2. Gain frequency response of a gyro-TWT in a disc-loaded waveguide tapered with respect to the structure parameters (a) waveguide-wall radius, (b) disc-to-disc distance, (c) disc-hole radius, and (d) disc thickness (schemes 1–4) together with the response when these parameters are, respectively, taken as the parameters in a nontapered device. Typically, the waveguide length and mode are taken as $l \sim 135$ mm and TE_{01}, respectively; the beam parameters as $I_0 = 9.0$ A, $V_0 = 100$ kV, and $\alpha_0 = 0.5$, and the magnetic field parameters corresponding to $r_{H,1} = 3.5$ mm, $r_{L,1}/r_{W,1} = 0.1$ at the start of taper and $B_{0,p}/B_{g,p} = 1.0$ $(1 \leq p \leq n_D)$ through out taper, which all representing the same corresponding quantities for the nontapered device.

and T as per schemes 2 and 4, respectively, without significant effect on the bandwidth and midband frequency [Fig. 2(b) and (d)]. However, the parameter r_D, which has been found to control the device performances with respect to the gain, bandwidth, and midband frequency to an appreciable extent, as mentioned above for the device in a nontapered structure, significantly influences these performances of the device in the tapered structure, too, as per scheme 3 [Fig. 2(c)]. Thus, the tapering of the parameter r_D, according to scheme 3, spreads the amplification band over a relatively wide frequency range, however, at the cost of the device gain obtainable in a nontapered structure of a relatively larger value of r_D [Fig. 2(c)]. This prompts the authors to combine the tapering schemes 1 and 3, that is, the taper the parameter r_W as per scheme 1 for the purpose of enhancing the device gain [Fig. 2(a)] that would deteriorate if the parameter r_D were tapered with a view to spreading the frequency range of amplification over a wide band as per scheme 3 [Fig. 2(c)].

The 3-dB bandwidth of a tapered disc-loaded waveguide (schemes 1 and 3 combined) would increase, typically by 60%, and the gain would decrease, typically by 6%, over the corresponding quantities for a tapered smooth-wall waveguide, had the latter followed the tapering profile of the wall radius of the disc-loaded waveguide (Fig. 3, Table I). Correspondingly, both these quantities, namely 3-dB bandwidth and gain of a tapered disc-loaded waveguide (schemes 1 and 3 combined) would increase, typically by 5% and 23%, respectively, over those of a tapered smooth-wall waveguide, if the latter had followed the tapering profile of the disc-hole radius of the disc-loaded waveguide (Fig. 3, Table I).

Thus, the disc-to-disc distance of in a disc-loaded circular waveguide of nontapered structure cross section, which is

TABLE I
COMPARISON OF TAPERED SMOOTH-WALL AND DISC-LOADED WAVEGUIDES WITH RESPECT TO THE GAIN AND BANDWIDTH OF A GYRO-TWT, TAKING THE BEAM AND MAGNETIC FIELD PARAMETERS WITH REFERENCE TO FIG. 2 AND THE STRUCTURE PARAMETERS WITH REFERENCE TO FIG. 3

Interaction Structure	Gain	3-dB bandwidth	Mid-band frequency
Disc-loaded waveguide tapered with respect to the waveguide-wall radius and the disc-hole radius (schemes 1 and 3 combined)	16.5 dB	8.0 GHz	~ 42 GHz
Tapered smooth-wall (disc-free) waveguide following the tapering profile of the disc-hole radius of the disc-loaded waveguide	13.4 dB	7.6 GHz	~ 42 GHz
Tapered smooth-wall (disc-free) waveguide following the tapering profile of the wall radius of the disc-loaded waveguide	17.6 dB	5.0 GHz	~ 34 GHz

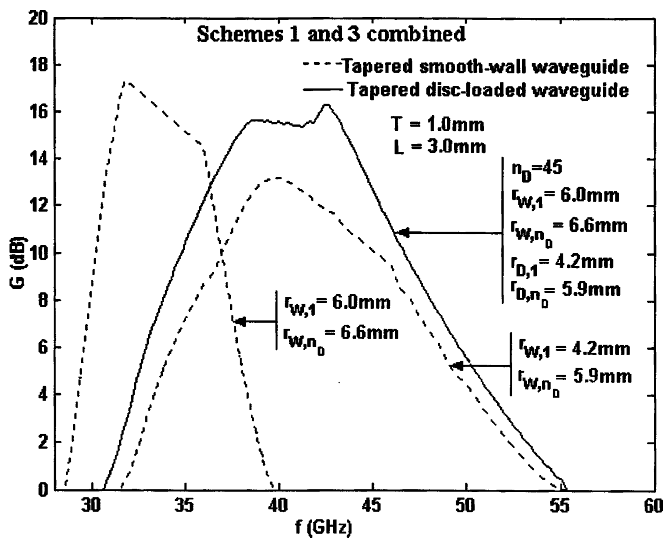

Fig. 3. Gain-frequency response of a gyro-TWT in a disc-loaded waveguide tapered with respect to the waveguide-wall radius and the disc-hole radius, according to schemes 1 and 3 combined (solid curve), compared with that in a smooth-wall waveguide (broken curve). Waveguide length and mode, as well as the beam and magnetic field parameters are the same as in Fig. 2.

reported in the literature [12], [13] to be the most effective optimizing structure parameter for widening the bandwidth of a gyro-TWT, becomes an insignificant parameter as far as tapering the structure (scheme 2) for wide device bandwidths is concerned, while simultaneous tapering of the waveguide-wall and disc-hole radii (schemes 1 and 3 combined) leads to wide bandwidths at reasonably large gains of a gyro-TWT in a tapered disc-loaded waveguide.

In obtaining the results presented here, care has been taken to taper the magnetic field synchronously with the tapered structure cross section, while choosing the beam parameters such that they obey the adiabatic beam-flow condition as well as the conservations of magnetic flux and that of electron magnetic moment (Section II-D). However, it is assumed that the electron beam is essentially monoenergetic with no velocity spread, an effect that would reduce the device efficiency, unless the operating point corresponds to a lower value of the axial phase propagation constant, towards the waveguide cutoff and away the from the grazing-point intersection or coalescence between the beam-mode and waveguide-mode dispersion characteristics, corresponding to a decrease in the device bandwidth. Therefore, future scope of the work should include the effect of beam velocity spread anticipating that by tapering the magnetic field, electrons on the high end of the energy distribution tail undergo less interaction than they would if the magnetic field were constant, thus leading to larger spreads at the end of the interaction structure.

IV. CONCLUSION

The wall radius of a smooth-wall circular waveguide interaction structure of a gyro-TWT can be tapered for wideband device performance however at the cost of the device gain. The present analysis shows that a disc-loaded circular waveguide interaction structure, which is known to widen the bandwidth of a gyro-TWT with its structure parameters optimized, if tapered simultaneously with respect to the waveguide-wall radius and the disc-hole radius, can lead not only to a further widening of bandwidth but also to a higher gain as compared to a smooth-wall waveguide with its wall radius tapered.

ACKNOWLEDGMENT

The authors would like to sincerely thank the reviewers for fruitful suggestions.

REFERENCES

[1] E. L. Chu and W. W. Hansen, "The theory of disc-loaded waveguides," *J. Appl. Phys.*, vol. 18, pp. 996–1008, Nov. 1947.
[2] J. Uher, J. Bornemann, and U. Rosenberg, *Waveguides Components for Antenna Feed Systems, Theory and CAD*. Norwood, MA: Artech, 1993.
[3] S. Amari, R. Vahldieck, J. Bornemann, and P. Leuchtmann, "Spectrum of corrugated and periodically loaded waveguides from classical matrix eigenvalues," *IEEE Trans. Microw. Theory Tech.*, vol. 48, no. 3, pp. 453–460, Mar. 2000.
[4] P. J. B. Clarricoats and A. D. Olver, *Corrugated Horns for Microwave Antennas*. London, U.K.: Peter Peregrinus, 1984.
[5] M. K. Thumm and W. Kasparek, "Passive high-power microwave components," *IEEE Trans. Plasma Sci.*, vol. 30, no. 3, pp. 755–786, Jun. 2002.
[6] R. F. Soohoo, *Microwave Electronics*. Reading, MA: Addison-Wesley, 1971.
[7] H. Guo, Y. Carmel, W. R. Lou, L. Chen, J. Rodgers, D. K. Abe, A. Bromborsky, W. Destler, and V. L. Granatstein, "A novel highly accurate synthetic technique for determination of the dispersive characteristics in periodic slow wave circuits," *IEEE Trans. Microw. Theory Tech.*, vol. 40, no. 11, pp. 2086–2094, Nov. 1992.
[8] S. Banna, J. A. Nation, L. Schächter, and P. Wang, "The interaction of symmetric and asymmetric modes in a high-power traveling-wave amplifier," *IEEE Trans. Plasma Sci.*, vol. 28, no. 3, pp. 798–811, Jun. 2000.

[9] J. Benford and J. Swegle, *High-Power Microwaves*. Boston, MA: Artech, 1992.
[10] M. Agrawal, G. Singh, P. K. Jain, and B. N. Basu, "Analysis of a tapered vane loaded broad-band gyro-TWT," *IEEE Trans. Plasma Sci.*, vol. 29, no. 3, pp. 439–444, Jun. 2001.
[11] J. Y. Choe and H. S. Uhm, "Theory of gyrotron amplifiers in disc or helix-loaded waveguides," *Int. J. Electron.*, vol. 53, no. 6, pp. 729–741, Sep. 1982.
[12] V. Kesari, P. K. Jain, and B. N. Basu, "Analytical approaches to a disc loaded cylindrical waveguide for potential application in wideband gyro-TWTs," *IEEE Trans. Plasma Sci.*, vol. 32, no. 5, pp. 2144–2151, Oct. 2004.
[13] ——, "Analysis of a circular waveguide loaded with thick annular metal discs for wideband gyro-TWTs," *IEEE Trans. Plasma Sci.*, vol. 33, no. 4, pp. 1358–1365, Aug. 2005.
[14] ——, "Modeling of axially periodic circular waveguide with combined dielectric and metal loading," *J. Phys. D, Appl. Phys.*, vol. 38, pp. 3523–3529, Sep. 2005.
[15] S. Ahn, "Gain and bandwidth of a gyrotron amplifier with tapered rectangular waveguide," *Int. J. Electron.*, vol. 53, no. 5, pp. 673–679, May 1982.
[16] G. S. Park, S. Y. Park, R. H. Kyser, C. M. Armstrong, A. K. Ganguly, and R. K. Parker, "Broadband operation of a Ka-band tapered gyro-traveling-wave amplifier," *IEEE Trans. Plasma Sci.*, vol. 22, no. 5, pp. 536–543, Oct. 1994.
[17] G. S. Park, J. J. Choi, S. Y. Park, C. M. Armstrong, A. K. Ganguly, R. H. Kyser, and R. K. Parker, "Gain broadening of two-stage gyrotron traveling wave tube amplifier," *Phys. Rev. Lett.*, vol. 74, no. 12, pp. 2399–2402, Mar. 1995.
[18] K. R. Chu, Y. Y. Lau, L. R. Barnett, and V. L. Granatstein, "Theory of a wideband distributed gyrotron traveling wave amplifier," *IEEE Trans. Electron Dev.*, vol. 28, no. 4, pp. 866–871, Apr. 1981.
[19] V. Kesari, P. K. Jain, and B. N. Basu, "Analysis of a disc-loaded circular waveguide for interaction impedance of a gyrotron amplifier," *Int. J. Infrared Millim. Waves*, vol. 26, pp. 1093–1110, Aug. 2005.
[20] H. Hahn, "On the analysis of periodic waveguide discontinuities by modal field matching," *Int. J. Electron. Commun., AEU*, vol. 32, no. 2, pp. 81–85, Feb. 1978.
[21] S. Amari, R. Vahldieck, and J. Bornemann, "Analysis of propagation in periodically loaded circular waveguides," *IEE Proc. Microw. Antennas Propag.*, vol. 146, no. 1, pp. 50–54, Feb. 1999.
[22] J. Esteban and J. M. Rebollar, "Characterization of corrugated waveguides by modal analysis," *IEEE Trans. Microw. Theory Tech.*, vol. 39, no. 6, pp. 937–943, Jun. 1991.
[23] H. Hahn, C. I. Goldstein, and W. Bauer, "On the theory of iris-loaded waveguides," *Int. J. Electron. Commun.*, vol. 30, no. 7, pp. 297–302, Jul./Aug. 1976.
[24] J. M. Baird and W. Lawson, "Magnetron injection gun (MIG) design for gyrotron applications," *Int. J. Electron.*, vol. 61, no. 6, pp. 953–967, Dec. 1986.

Vishal Kesari was born in Mughalsarai (Uttar Pradesh), India, in 1978. He received the M.Sc degree in physics from Purvanchal University, Jaunpur, India, in 2001. He is currently working toward the Ph.D. degree in the Department of Electronics Engineering, the Institute of Technology, Banaras Hindu University, Varanasi, India, in the area of microwave tubes, as Senior Research Fellow under CAS (UGC) program.

His research interest includes periodically loaded circular waveguides for slow- and fast-wave vacuum electron devices.

P. K. Jain (SM'05) received the B.Tech degree in electronics engineering, and the M.Tech. and Ph.D. degrees in microwave engineering, all from Banaras Hindu University (BHU), Varanasi, India, in 1979, 1981, and 1988, respectively.

In 1981, he joined the Centre of Research in Microwave Tubes, Department of Electronics Engineering, Institute of Technology, BHU, as Lecturer, and is currently a Professor. He was Principal Investigator of the project Studies on slow- and fast-wave interaction structures for beam–wave interaction in TWTs, sponsored by Ministry of Defence. The areas of his current research and publication include CAD/CAM, modeling and simulation of microwave tubes and their subassemblies, including broadbanding of helix traveling-wave tubes (TWTs); cyclotron resonance measure devices including gyrotrons and gyro-TWTs and their performance improvement.

Dr. Jain is a Fellow of the Institution of Electronics and Telecommunication Engineers (India).

B. N. Basu received the B.Tech., M.Tech., and Ph.D. degrees from the Institute of Radiophysics and Electronics, Calcutta University, Calcutta, India, in 1966 and 1976, respectively.

He was a Professor and Coordinator at the Centre of Research in Microwave Tubes, Electronics Engineering Department, Banaras Hindu University (BHU), Varanasi, India. He was associated with Central Electronics Engineering Research Institute (CEERI), Pilani, Council of Scientific and Industrial Research (CSIR), India as Distinguished Visiting Scientist of CSIR. He was the partner with University of Lancaster (UoL), U.K. and CEERI under Academic Link and Interchange Scheme (ALIS) between CSIR and British Council and worked at UoL. Also, he was with Seoul National University, Seoul, Korea, as Visiting Scientist. His areas of current research and publications include helix-TWTs, gyrotrons and gyro-TWTs. He has authored or coauthored around 100 research papers in peer-reviewed journals and authored a book entitled *Electromagnetic Theory and Applications in Beam-Wave Electronics* (World Scientific: Singapore, 1996).

Dr. Basu is Member of the Technical Committee on Vacuum Electron Devices of IEEE Electron Devices Society. He is Fellow and recipient of S. V. C. Aiya Memorial Award for outstanding contributions in motivating research, of Institution of Electronics and Telecommunication Engineers, India.