Investigation of a wideband folded double-ridged waveguide slow-wave system*

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The folded double-ridged waveguide structure is presented and its properties used for wide-band traveling-wave tube are investigated. Expressions of dispersion characteristics, normalized phase velocity and interaction impedance of this structure are derived and numerically calculated. The calculated results using our theory agree well with those obtained by using the 3D electromagnetic simulation software HFSS. Influences of the ridge-loaded area and broad-wall dimensions on the high frequency characteristics of the novel slow-wave structure are discussed. It is shown that the folded double-ridged waveguide structure has a much wider relative passband than the folded waveguide slow-wave structure and a relative passband of 67% could be obtained, indicating that this structure can operate in broad-band frequency ranges of beam–wave interaction. The small signal gain property is investigated for ensuring the improvement of bandwidth. Meanwhile, with comparable dispersion characteristics, the transverse section dimension of this novel structure is much smaller than that of conventional one, which indicates an available way to reduce the weight of traveling-wave tube.

Keywords: millimeter wave traveling-wave tube, slow-wave structure, folded waveguide, high-frequency characteristics

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1. Introduction

The traveling wave tube (TWT) is one of the most important devices used for energy at microwave frequencies. It is widely used in communications, radar transmitters and electronic countermeasures.[1−3] As a component of beam–wave interaction of a TWT for exciting microwave energy, the slow-wave circuit directly influences the properties of TWT. A helix and a coupled-cavity are most commonly used in TWT as slow-wave structures. The helix TWT[4,5] has a very wide bandwidth, producing radiation power up to hundreds of watts in the frequency range of 1–40 GHz with more than one Octave bandwidth. A helix space TWT working at 60 GHz with 25 W output power is also reported by Kornfeld *et al.*[6] However, its low capacity for thermal dissipation limits the power delivered by the tube as the operating frequency approaches the millimeter wave frequency range. The thermal dissipation capability of the coupled-cavity TWT is clearly better than that of the helix TWT; but its operation bandwidth is considerably narrower than that of the helix TWT.

A new slow-wave structure (SWS) possessing broader bandwidth and higher power capacity is the constant goal for which the microwave tube workers make their great efforts. The folded waveguide slow-wave structure (FWSWS) is one of this kind and was studied by Waterman in 1979.[7] It has advantages over others due to its moderate bandwidth ($> 10\%$) and high power-handling capability at higher frequencies, with the additional advantages of simple coupling and robust structure. Also, its compatibility with planar fabrication by micro-electro-mechanical systems (MEMS) technologies draws attention to develop a miniaturized radiation sources in millimeter and submillimeter wave regimes.[8−10] A number of experimental and theoretical studies on electric field plane (E-plane) bent folded waveguide traveling wave tube (FWTWT) have been published previously.[7−14] Magnetic field plane (H-plane) bent folded waveguide and its modified structure are used in the gyrotron TWT amplifier as a beam–wave interaction system.[15,16] Several modified FWSWS are proposed

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and investigated for improving the performance of FWTWT. The ridged-loaded FWSWS is studied for enhancing the beam–wave interaction and the linear theory of this structure is developed for analysing the gain property.[17] Another modified structure E-bent folded double-ridged waveguide is also investigated with the emphasis on the beam–wave interaction: the linear theory is built[18] and the particle-in-cell simulation of the nonlinear interaction is carried out.[19] However, the characteristics of the wave propagating along this modified FWSWS, which provide the theoretical basis for designing this SWS for wideband traveling-wave tubes, have not been found in the literature.

In this paper, the E-bent folded double-ridged waveguide structure is studied for wideband application and the slow-wave characteristics including dispersion characteristics, normalized phase velocity $v_{\rm p}/c$ (where c is the light speed in vacuum) and interaction impedance of this structure are investigated. In Section 2, the equations of dispersion characteristics, normalized phase velocity and interaction impedance are derived. In Section 3, the expressions of high-frequency characteristics obtained by using the present theory are numerically calculated and compared with those of HFSS. Meanwhile, the influences of ridge-load area and broad-wall dimensions on slow-wave characteristics are investigated. A brief summary is given in Section 4.

2. Theory of folded double-ridged waveguide slow-wave system

The folded double-ridged waveguide SWS is formed by bending a double-ridged rectangular waveguide in E-plane so that the orientation of the $\rm TE_{10}$ electric field changes, as illustrated in Fig. 1(a). A schematic of the folded double-ridged waveguide SWS is also shown in Fig. 1(b), where the Cartesian coordinates (x, y, z) are employed. It is assumed that the lowest transverse-electric (TE) mode, $\rm TE_{10}$, propagates along the folded path z' shown by a dashed line. An axially focused electron beam passes through the circular beam tunnel hole in the broad wall of the rectangular waveguide. The beam–wave interaction in the folded double-ridged waveguide occurs when the beam phase velocity is synchronized with the effectively slowed-down wave phase velocity.

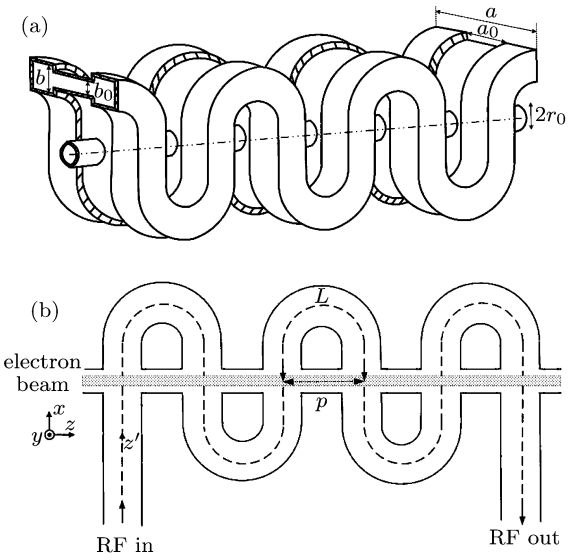


Fig. 1. (a) Configuration of a folded double-ridged waveguide SWS. a and b are the outer dimensions of the guide, a_0 is the width of ridge-loaded area, b_0 is the height of ridge-loaded area and $2r_0$ is the beam hole diameter. (b) Illustrative sketch of a folded double-ridged waveguide SWS and circuit sketch comparing L and p, the wave and beam pathlengths, respectively, between beam-crossing.

2.1. Dispersion characteristics

In the folded double-ridged waveguide SWS, the phase velocity $v_{{\rm ph},z'}$ of the wave propagates along the serpentine path z' can be written as

$$v_{{\rm ph},z'} = \frac{\omega}{\beta_{\rm wg}}, \tag{1}$$

where ω is the angular frequency of the wave (rad/s); $\beta_{\rm wg} = \sqrt{k^2 - k_{\rm c}^2}$ represents the phase constant along the serpentine waveguide; k is the phase constant in free space; $k_{\rm c} = \omega_{\rm c}/c$ is cut-off phase constant; the cut-off frequency ω of the $\rm TE_{10}$ is given by the lowest root of the following equations:[20−22]

$$\tan(k_{\rm c}a_0/2) - \frac{b_0}{b}\cot\left(k_{\rm c}\frac{a-a_0}{2}\right) + \frac{b_0}{b}\frac{2}{\pi}k_{\rm c}b\ln\left[\csc\left(\frac{\pi b}{2b_0}\right)\right] = 0. \tag{2}$$

In a beam reference frame, the transverse electromagnetic waveguide mode is effectively slowed down. The effective phase velocity and phase constant along the beam axis can be written as

$$v_{\rm ph} = \left(\frac{p}{L}\right)v_{{\rm ph},z'}, \tag{3}$$

$$\beta = \left(\frac{L}{p}\right)\beta_{\rm wg}, \tag{4}$$

where p is one period measured along the beam tunnel and L is the path length for the wave between beam-crossings, as shown in Fig. 1(b). In the standpoint of

electron beam, it experiences a 180 degree phase shift of electric field in every pitch. The phase constant of the n-th space harmonics in this SWS is given by

$$\beta_n = \frac{kL}{p}\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2} + \frac{(2n+1)\pi}{p}, \quad n = 0, \pm 1, \pm 2, \ldots. \tag{5}$$

As we know, for wide-band amplification in a traveling-wave tube, the electromagnetic wave and the beam must maintain synchronisation in a broad-band frequency range, which means that the axial component of the phase velocity of the wave in the slow-wave structure must approximate to the electron beam velocity. The variation of the phase velocity with frequency is a very important consideration in the design of a TWT and will decide its bandwidth. The normalized phase velocity of the n-th space harmonics in this SWS is written as

$$v_{pn}/c = \left[\frac{L}{p}\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2} + \frac{(2n+1)\pi}{p}\right]^{-1}. \tag{6}$$

2.2. Interaction impedance

The beam–wave interaction impedance is another important parameter in a TWT. It is a measure of the interaction between an RF wave and an electron beam. In the folded double-ridged waveguide SWS, the electron beam sees the transverse-magnetic (TM) mode when it enters the beam holes. Therefore, it is the transverse component of the electric field E_{zn} that interacts with the electron beam. According to Pierce's theory,[23] the interaction impedance of n-th space harmonic is defined as

$$K_{cn} = \frac{E_{zn}E_{zn}^*}{2\beta_n^2 P_w}, \tag{7}$$

where E_{zn} is the transverse component of the electric field of the n-th space harmonic at the position of the electronic beam and E_{zn}^* is its conjugate.

The field distribution of the TE_{10} mode in a double-ridged waveguide is given by[24]

$$E_z = e^{i(\omega t - \beta_{\omega g} z)} \begin{cases} E_0 \cos(k_c |y|), & 0 < |y| < \dfrac{a_0}{2}, \\ \dfrac{E_0 b_0}{b} \dfrac{\cos\left(k_c \dfrac{a_0}{2}\right) \sin\left(k_c \dfrac{a}{2} |y|\right)}{\sin\left(k_c \dfrac{a-a_0}{2}\right)}, & \dfrac{a_0}{2} < |y| < \dfrac{a}{2}, \end{cases} \tag{8}$$

$$H_x = -\frac{i}{\mu\omega}\frac{\partial E_z}{\partial y}, \tag{9}$$

$$H_y = \frac{1}{\mu\omega}\beta_{\omega g} E_z, \tag{10}$$

where μ is the permittivity. The effects of the fringing fields are taken into account in the dispersion relation by including the susceptance term in Eq. (2). Because the beam–wave interaction area is not close to the fringing fields, we can use the approximate fields in Eqs. (8)–(10) to calculate the beam–wave interaction impedance. In the region $(0 < |y| < a_0/2)$ where the electronic beam exists, one obtains the following according to Eq. (8)

$$E_{zn}E_{zn}^* = E_0^2\left(\frac{a_0}{p}\right)^2\left[\sin\left(\beta_n\frac{a_0}{2}\right)\Big/\left(\beta_n\frac{a_0}{2}\right)\right]^2. \tag{11}$$

P_w is the total power flow through the whole circuit and the power in each region can be derived from the Poynting flux $P = \frac{1}{2}\,\mathrm{Re}\int \boldsymbol{E}\times\boldsymbol{H}^*\cdot \mathrm{d}\boldsymbol{S}$ using Eqs. (8)–(10)

$$P_w = P_1 + P_2 = \frac{\beta_{wg}E_0^2}{2\mu\omega}(A_1 + A_2), \tag{12}$$

where P_1 is the power flows in region $(0 < |y| < a_0/2)$; P_2 is the power flows in region $(a_0/2 < |y| < a/2)$. A_1 and A_2 are written as

$$A_1 = \frac{b_0}{2}\left[a_0 + \frac{\sin(a_0 k_c)}{k_c}\right], \tag{13}$$

$$A_2 = \frac{b_0^2}{b}\left[\frac{\cos\left(k_c\dfrac{a_0}{2}\right)}{\sin\left(k_c\dfrac{a-a_0}{2}\right)}\right]^2 \times\left[\frac{a-a_0}{2} + \frac{\sin\left(k_c a\dfrac{a-a_0}{2}\right)}{k_c a}\right]. \tag{14}$$

Based on the definition of interaction impedance (7) but accounting for waveguide cutoff effects,[9] an analytic estimate for the beam–wave interaction impedance of the n-th space harmonic in folded double-ridged SWS can be obtained as follows:

$$K_{cn} = \frac{\mu\omega\,(a_0/p)^2\,(\sin(\beta_n a_0/2)/(\beta_n a_0/2))^2}{\beta_{wg}\beta_n^2(A_1+A_2)I_0^2(k_c r_0)}, \tag{15}$$

where I_0 is a modified Bessel function, r_0 is the beam tunnel radius.

In order to verify the merit of this folded double-ridged waveguide SWS, the small signal gain is also investigated by the formulation given by Pierce[25]

$$G = -9.54 + 47.3CN, \tag{16}$$

where $C = (K_{cn}I_0/4V_0)^{1/3}$ is the gain parameter, $N = (\beta L_z/2\pi)$ is the normalized interaction length, L_z is the interaction length, I_0 and V_0 are the beam current and voltage. It should be noted that the linear gain calculated here is on the basis of the simple equivalent circuit model of beam–wave interaction in the TWT. For analysing the gain property more specifically, the method based on the rigid field theory is recommended in Ref. [17].

3. Numerical results and discussion

The expressions of dispersion characteristics, normalized phase velocity and the interaction impedance obtained in the previous section are easy to solve numerically. Figures 2(a), 2(b) and 2(c) show the dispersion characteristics, normalized phase velocity and the interaction impedance of a folded double-ridged waveguide SWS, respectively, where the normalized frequency is written as ka and the phase shift is normalized by dividing 2π. The parameters of the slow-wave circuit are (unit: mm): $a = 1.8$, $b = 0.4$, $p = 0.6$, $L = 1.74$, $r_0 = 0.18$, $a_0 = 0.9$, $b_0 = 0.3$. For comparison, we also simulated this novel structure using a three-dimensional EM simulation software HFSS.[1)] The continuous curve represents the calculated results obtained numerically, and the circular points indicate the results obtained by means of HFSS. It is very clear that HFSS simulation data agree well with the numerical calculation data from the present theory, which support the theory.

Figure 3(a) shows the effect of ridge-loaded area width a_0 on the dispersion characteristics of the novel FWSWS. It is observed that as a_0/a changes from 0 to 1.0, the relative passband $\Delta_{\rm band}$ decreases for $a_0 < 0.5a$ while increases for $a_0 > 0.5a$, where $\Delta_{\rm band} = (f_{\rm H} - f_{\rm L})/[(f_{\rm H} + f_{\rm L})/2]$. Especially as a_0/a is 0.5, the relative passband of structure C is 42.25% (2.8–4.3). Figures 3(b) and 3(c) show the influence of a_0 on the normalized phase velocity and interaction impedance of the folded double-ridged waveguide SWS, respectively. An interesting phenomenon can be seen from Fig. 3(b) that as the width a_0 increases, the normalized phase velocity decreases for $a_0 < 0.5a$; however, the phase velocity changes reversely for $a_0 > 0.5a$. It is mainly because the cut-off frequency of double-ridged rectangular waveguide changes in the same way and is the lowest when the width a_0 is equal to 0.5a. The influence of the width a_0 on interaction impedance is the same.

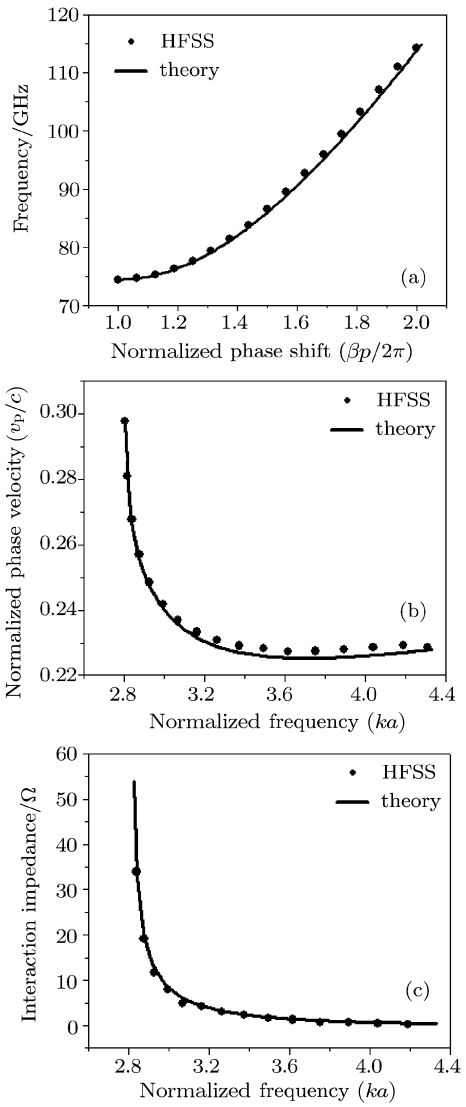


Fig. 2. (a) Dispersion characteristics of a folded double-ridged waveguide SWS, (b) normalized phase velocity of a folded double-ridged waveguide SWS, (c) interaction impedance of a folded double-ridged waveguide SWS.

As shown in Fig. 3(c), the broader the operating bandwidth is, the lower the interaction impedance of the fundamental harmonic is. It should be acceptable

[1)] High frequency structure simulator user's reference Anosft Co, 2001

in view of the physics conception.

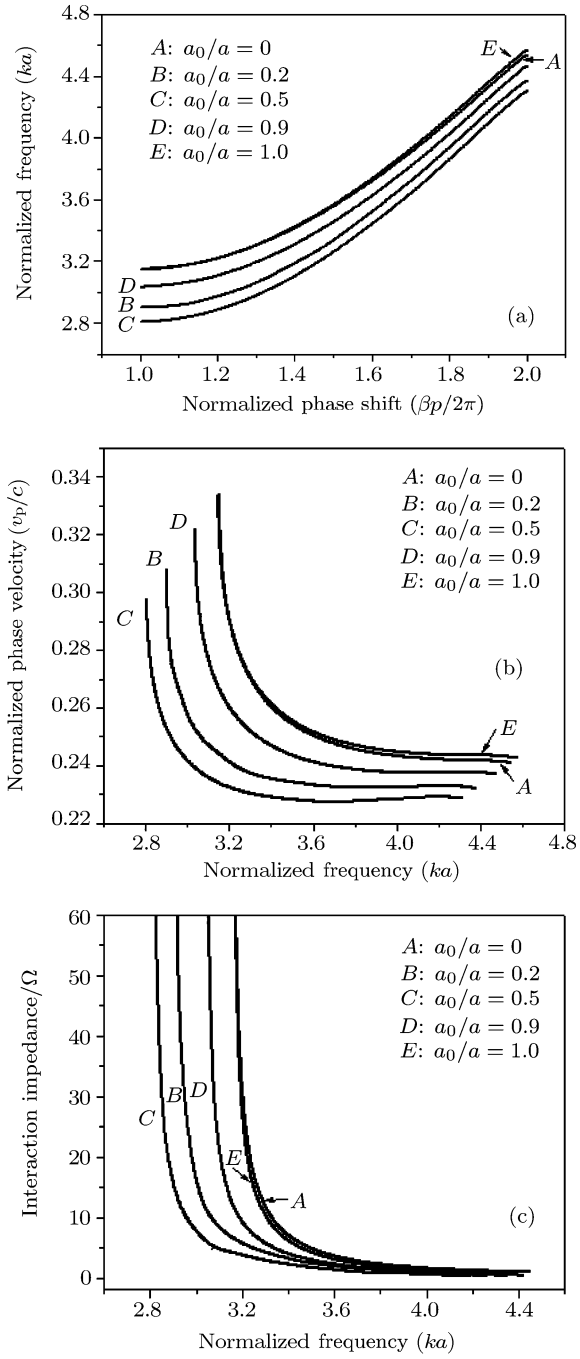


Fig. 3. (a) Effect of a_0/a on the dispersion characteristics, (b) effect of a_0/a on the normalized phase velocity, (c) effect of a_0/a on the interaction impedance. Calculating parameters: $a/b = 4.5$, $p/b = 1.5$, $L/b = 4.35$, $r_0/b = 0.45$ $b_0/b = 0.75$.

Figures 4(a), 4(b) and 4(c) show the effects of the ridge-loaded area height b_0 on the high frequency characteristics of the novel slow-wave structure, respectively.

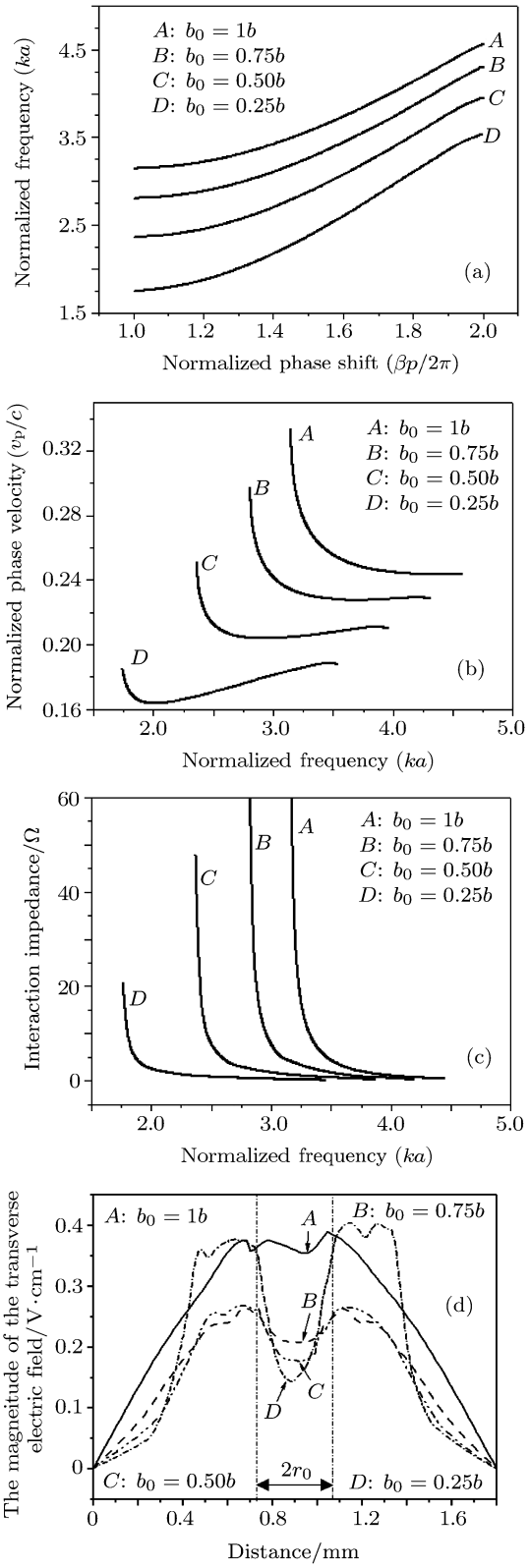


Fig. 4. (a) Effect of b_0/b on the normalized phase velocity, (b) effect of b_0/b on the normalized phase velocity, (c) effect of b_0/b on the interaction impedance, (d) effect of b_0/b on the transverse electric field across the guide by HFSS. Calculating parameters: $a/b = 4.5$, $p/b = 1.5$, $L/b = 4.35$, $r_0/b = 0.45$, $a_0/b = 2.25$.

As shown in Fig. 4(a), the relative passband $\Delta_{\rm band}$ increases obviously as b_0 decreases: the $\Delta_{\rm band}$ of structure A is relatively narrow, only 37.09 % (3.14–4.57), while the $\Delta_{\rm band}$ of structure D is 67 % (1.74–3.53). Therefore, it is concluded from the comparison that the folded double-ridged waveguide SWS has much wider relative passband than the conventional one.

It is indicated from Fig. 4(b) that, as the height b_0 decreases, forcing the gap between the waveguide of ridge-loaded section to be smaller, the normalized phase velocity decreases and the dispersion curves become flatter. Therefore, the frequency range of beam–wave synchronization extends as the height b_0 decreases. Also the negative dispersion can be attained by selecting a smaller ridge height. So, there exists an optimum b_0 that may correspond to fairly dispersion-free characteristics. One may expect this structure to operate in broad-band frequency ranges of beam—wave interaction.

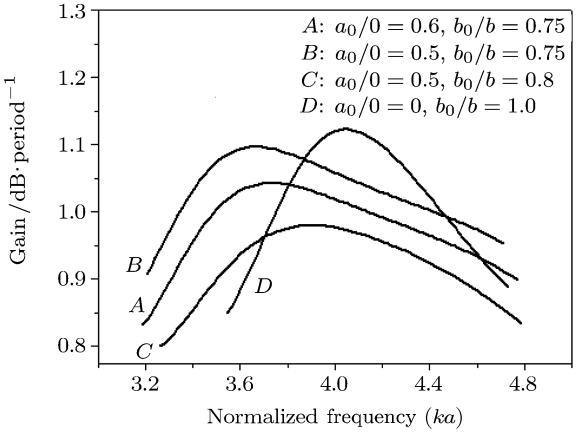


Fig. 5. Comparison of small-signal gains for different combinations of ridge dimensions. Calculating parameters: $a/b = 4.5$, $p/b = 1.5$, $L/b = 4.35$, $r_0/b = 0.45$.

Meanwhile, the interaction impedance decreases as the height b_0 decreases, as shown in Fig. 4(c). This is because the tunnel diameter becomes relatively larger while the gap between the rectangular waveguides of ridge-loaded section decreases, which makes it is easier for microwave power to leak out from the guide into the tunnels. The variation of the transverse electric field across the rectangular guide is obtained by HFSS and shown in Fig. 4(d), where the dot-dashed lines show the position of the electronic beam tunnel. As we can see, with the decrease of b_0, the magnitude of electric field at the position of beam tunnel is reduced, which means that the strength of the interaction is effectively reduced as the ridge height decreases.

Since the SWS operating bandwidth depends on the coalescence of the SWS dispersion with beam-mode dispersion, the Pierce's small-signal gain is investigated for ensuring the improvement of bandwidth. Figure 5 shows a comparison of gains for different combinations of ridge-loaded area width and height with a beam voltage of 15 kV and a beam current of 0.1 A. With suitable ridge dimensions, the folded double-ridged waveguide SWS can provide a broader bandwidth for operation.

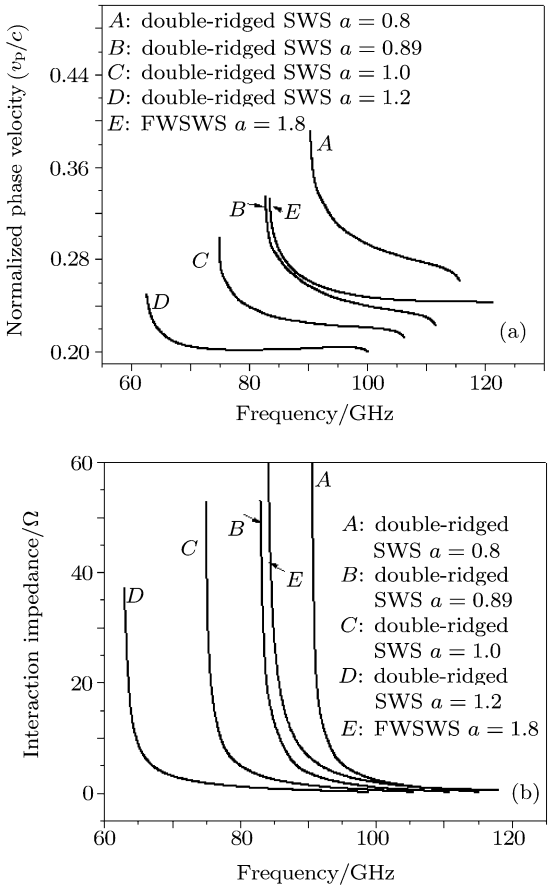


Fig. 6. (a) Effect of a on the normalized phase velocity, (b) effect of a on the interaction impedance. Calculating parameters: $p/b = 1.5$, $L/b = 4.35$, $r_0/b = 0.45$, $a_0 = a/2$, $b_0/b = 0.5$.

The effect of broad-wall dimension on the normalized phase velocity and interaction impedance is investigated, as shown in Figs. 6(a) and 6(b). It is obvious from Fig. 6(a) that as the broad-wall dimension $a$decreases, the cutoff frequency increases and so is the normalized phase velocity. Meanwhile, the curves B and E in Figs. 6(a) and 6(b) imply that the normalized phase velocity of folded double-ridged SWS is

comparable to that of FWSWS, while the interaction impedance is less than that of FWSWS.

However, the broad-wall dimension of the folded double-ridged SWS is less than half of that of the FWSWS, which means that the former has much smaller transverse section dimension. As we know, periodic magnetic systems are usually employed to focus electron beam and the inner radius of pole shoe may decrease equally as the transverse section dimension of slow-wave structure decreases. Therefore, the size and weight of the magnetic system of a folded double-ridged TWT can be reduced apparently, which indicates an available way to lower the weight of TWT.

4. Conclusion

In this paper, a folded double-ridged waveguide SWS has been investigated for wide-band TWT application. The expressions of dispersion characteristics, normalized phase velocity and interaction impedance are derived and numerically calculated. The influences of ridge-loaded area and broad-wall dimensions on high frequency characteristics are investigated. The numerical results reveal that compared with FWSWS, the folded double-ridged waveguide SWS has a wider relative passband, a lower normalized phase velocity and a flatter dispersion curve, whereas the interaction impedance reduces. Meanwhile, with comparable dispersion characteristics, the broad-wall dimension of folded double-ridged SWS is much smaller than that of FWSWS, which implies an possible way to reduce the weight of magnetic systems and TWT. With the additional advantage of being easy of fabrication based on MEMS technologies, the folded double-ridged waveguide structure holds promise for application in compact TWTs.

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