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The study of synchronization in the periodic nonuniform folded waveguide*

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The periodic nonuniform folded waveguides are special structures, the physical dimension of which is between the periodic folded waveguide and the tapering period folded waveguide. Therefore, the synchronization between the microwave and the electron beam can be maintained in the whole interaction process and the periods are not tapered. In comparison with the tapering period folded waveguide, the theoretical analysis and the technological requirements for this structure are more convenient. In order to study this structure, the space harmonics are analysed, the conditions to make the m-th space harmonic synchronizing with the electron beam in the whole interaction process are present, and the dispersion curve and the coupling impedance curve are obtained by the simulation software HFSS.

Keywords: folded waveguide, nonuniform, synchronization, physical dimension
PACC: 7870G, 1220, 8760F

1. Introduction

In order to amplify the microwave in the slow wave structure of a travelling wave tube, the microwave should synchronize with the electron beam so that the kinetic energy of the electron beam can be transferred to the energy of the microwave. In this process of the beam-wave interaction, electrons continuously lose their kinetic energy. Therefore, their velocities continuously decrease. And the loss of the kinetic energy of the electron beam would cause the non-synchronization. This is an important reason for the limitation of the efficiency of the slow wave structure. There are two ways to improve the efficiency of wave-beam interaction. We can increase the velocity of the electron beam or decrease the phase velocity of the microwave at an appropriate time when the non-synchronization of the microwave and the electron beam appears. Actually, the electron beam can synchronize with the microwave in the whole process, if the physical dimension of the slow wave structure can be correspondingly varied with the change of the velocity of the electron beam. This can obviously improve the efficiency of the wave-beam interaction. Many researchers put emphasis on it.[1−9] However, theoretical analysis of the tapering period slow-wave structure is difficult and the fabrication of this structure is inconvenient. The periodic nonuniform folded waveguide is similar to the periodic folded waveguide, but the periods in the former structure are constant. This is helpful to the theoretical analysis of this structure, and the technological requirements can be reduced. Finally, the studies of the periodic nonuniform folded waveguide are useful to the researches of the tapering period folded waveguide.

The folded waveguide circuit has a series of advantages over other slow wave structures, such as low-cost fabrication, high strength, simple input and output circuits, and high-power handing capability with a moderate bandwidth in the millimetre frequency range.[10−12] Therefore, the folded waveguide travelling wave tube is an appropriate device that may achieve millimetre wave amplification with higher power and wider bandwidth in combination.

The study on periodic nonuniform folded waveguide is presented in this paper. This structure not only can keep many advantages of the folded waveguide, but also can make the microwave moves synchronously with the electron beam in the whole interaction process. The regularity of the physical dimension in this structure is obtained by the theoretical derivation, and the dispersion curve and the coupling impedance curve in this structure are obtained by using a simulation software.

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2. Theoretical analysis

A schematic drawing of a folded waveguide is depicted in Fig.1, where Q is the number of periods, L is the period length, and $p = L + 2h$ is the length along the waveguide for one period. It is assumed that this structure is a no-loss structure, and the TE_{10} mode is propagating in this structure. In addition, in a straight waveguide, the TE_{10} mode does not have a longitudinal electric field. But in a folded waveguide, because of the bend in the waveguide, the transverse electric field of the TE_{10} mode has the same direction as the velocity of the electron beam. So we can assume that the electric field that is seen by the electron beam is as follows:

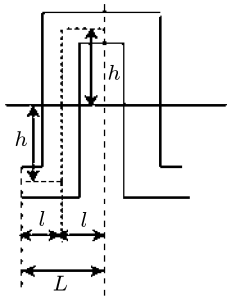


Fig.1. Folded waveguide.

$$E_z = \begin{cases} E_0 \mathrm{e}^{\mathrm{j}\beta_0 z} & \left(n+\frac{1}{2}\right)L - \frac{b}{2} < z < \left(n+\frac{1}{2}\right)L + \frac{b}{2}, \\ 0 & \left(n+\frac{1}{2}\right)L + \frac{b}{2} < z < \left[(n+1)+\frac{1}{2}\right]L - \frac{b}{2}. \end{cases} \quad n = 0, 1, 2, ..., Q \tag{1}$$

Using Fourier series, we define the space harmonic in this structure as:

$$\begin{cases} E_z = \sum\limits_{n=-\infty}^{+\infty} E(\beta_n)\mathrm{e}^{-\mathrm{j}\beta_n z}, \\ E(\beta_n) = \dfrac{1}{L}\displaystyle\int_0^L E_0 \mathrm{e}^{\mathrm{j}\frac{2n\pi}{L}z}\mathrm{d}z, \end{cases} \tag{2}$$

where $\beta_n = \beta_0 + 2n\pi/L$.

We assume that the period of the periodic nonuniform folded waveguide is not changed, but the length along the waveguide for each period is varied. And again assume that a no loss is in this structure and that there is propagating TE_{10} mode as the regular folded waveguide. A schematic drawing of a periodic nonuniform folded waveguide is depicted in Fig.2.

In Fig.2, Q is the number of periods, L is the period length, and $p_q = L + h_q + h_{q+1}$, where q=1, 2, ..., Q, and $h_1 = h_2$, p_q is the length along the waveguide of the qth period. Because the period of the periodic nonuniform folded waveguide is not varied, the space harmonic of this structure can be expressed by Fourier series. So the expression of the space harmonic of this structure is the same as Eq.(2).

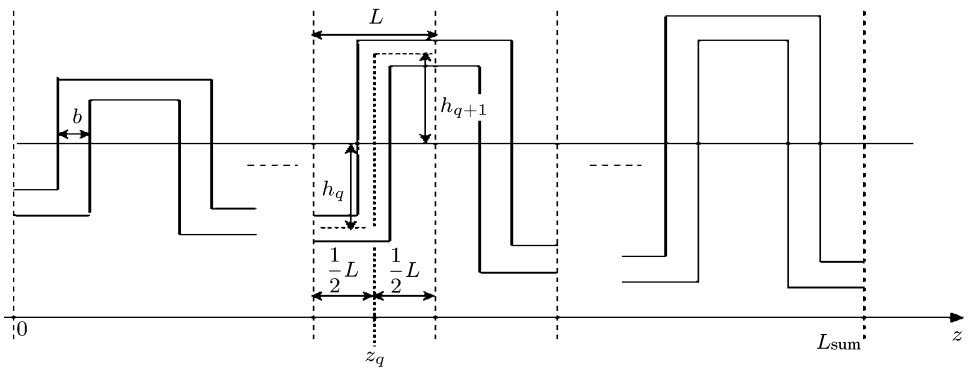


Fig.2. Periodic nonuniform folded waveguide.

Because the direction of the electric field changes one time at each period in the periodic nonuniform folded waveguide, it can be expressed as

$$\beta_0 L = \beta_{\rm wg} p_q + \pi, \tag{3}$$

$$\beta_n = \frac{p_q}{L}\beta_{\rm wg} + \frac{(2n+1)\pi}{L}, \tag{4}$$

where $\beta_{\rm wg}$ is the phase constant of the microwave propagating along the waveguide.

The cut off wavelength of the $\rm TE_{10}$ mode in the straight waveguide is $2a$, thus we can obtain

$$\beta_{\rm wg} = \frac{2\pi f}{c}\sqrt{1-\left(\frac{c}{2af}\right)^2}, \tag{5}$$

where a is the wide side of the cross section of the waveguide, c is the velocity of the light.

According to Eqs.(3) (4) and (5), it is found that the same space harmonic for the same frequency may have the different phase constant in each period. So one can design a periodic nonuniform folded waveguide which contains a space harmonic with a phase velocity, and the change of this phase velocity is the same as that of electron beam in the whole process of the wave-beam interaction.

Assuming that the mth space harmonic synchronizing with the electron beam in the first period in a periodic nonuniform folded waveguide, one can obtain

$$\frac{2\pi f}{v_0} = \frac{2\pi p_1}{L}\sqrt{\frac{f^2}{c^2}-\frac{1}{4a^2}} + \frac{(2m+1)\pi}{L}. \tag{6}$$

And then, one can assume that the change of the velocity of the electron beam in a periodic nonuniform folded waveguide is such that the velocity of the electron beam does not change in a period but has certain variance between different periods. And the velocity at the initial point of each period is $A(q)v_0$, where $A(q)$ with q=1, 2, ..., Q is the coefficient of the change of the velocity of the electron beam, v_0 is the initial velocity of the electron beam when the beam enters the slow wave. Because the velocity of the electron beam decreases with the increase of the period number q, the relationship $1 > A(q) > A(q+1) > 0$ is obvious.

The phase velocity of the mth space harmonic in the qth period can be expressed as

$$\frac{2\pi f}{v_{pm,q}} = \frac{2\pi p_q}{L}\sqrt{\frac{f^2}{c^2}-\frac{1}{4a^2}} + \frac{(2m+1)\pi}{L}, \tag{7}$$

where $v_{pm,q}$ is the phase velocity of the mth space harmonic in the qth period.

According to Eqs.(4) (5) and (7), one can obtain

$$v_{pm,q} = \frac{1}{\dfrac{p_q - p_1}{fL}\sqrt{\dfrac{f^2}{c^2}-\dfrac{1}{4a^2}} + \dfrac{1}{v_0}}. \tag{8}$$

Thus, if p_q satisfies the following condition

$$p_q = \frac{\dfrac{fL}{v_0}\left[\dfrac{1}{A(q)}-1\right]}{\sqrt{\dfrac{f^2}{c^2}-\dfrac{1}{4a^2}}} + p_1, \tag{9}$$

then, $v_{pm,q} = A(q)v_0$. It means that the phase velocity of the mth space harmonic in every period is equal to the velocity of the electron beam. So one can conclude that if the physical dimension of a periodic nonuniform folded waveguide satisfies the condition (9), there exists in this structure an mth space harmonic synchronizing with the electron beam in the whole interaction process.

3. Software simulation

The practical periodic nonuniform folded waveguide structures have been simulated by using HFSS, and the result is used to compare with that of calculation. The physical dimensions of a periodic nonuniform folded waveguide are that the period number is Q=8, the wide side of the cross section of the waveguide is a=2 mm, the narrow side of the cross section of the waveguide is b=0.3 mm, the channel radius of the beam is r=0.1 mm, the period is L=0.5 mm, the length along the waveguide of the first period is p_1=1.4 mm. In order to verify the conclusion, we consider a simple situation. Assuming that the velocity of the electron beam decreases linearly in the whole interaction process, the velocity of the electron beam at each period can be expressed as $A(q) = 1-0.005(q-1)$, and the initial velocity of the electron beam is v_0=6.37×10^7 m/s. The frequency of the microwave which synchronizes with the electron beam is f=90.9 GHz. So the physical dimension of this periodic nonuniform folded waveguide can be obtained by using Eq.(9). In addition, it is assumed that the fundamental wave of the microwave with the frequency f=90.9 GHz synchronizes with the electron beam in the first period.

The physical dimension of this periodic nonuniform folded waveguide is given in Table 1, where q is the period number, p is the length of one period along the waveguide. It is found that the length along

the waveguide for each period increases with increasing period number. In physics, the increase of the length of a period along the waveguide would decrease the phase velocity of the microwave. As a result, the microwave can move synchronously with the electron beam in the whole interaction process.

Table 1. The "period".

q	p/mm
1	1.4
2	1.4209
3	1.4421
4	1.4635
5	1.4851
6	1.5069
7	1.5289
8	1.5512

The model used to simulate by using HFSS is shown in Fig.3. In Fig.4(a), the curves calculated by using HFSS are the dispersion curves for the eight periods in this periodic nonuniform folded waveguide. It is found that the phase velocity of the microwave decreases with increasing period number. In Fig.4(b), the simulation value is the phase velocity of the fundamental wave with f=90.9 GHz calculated by using HFSS in each period and the theoretical value is the velocity of the electron beam calculated according to $A(q) = 1 - 0.005(q - 1)$ in each period. It is found that the phase velocity of this space harmonic is almost the same as the velocity of the electron beam in each period. It proves that, if the physical dimension of a periodic nonuniform folded waveguide satisfies condition (9), a space harmonic in this structure will synchronize with the electron beam in the whole interaction process.

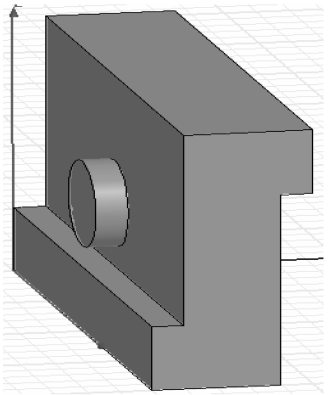


Fig.3. A period of the periodic nonuniform folded waveguide.

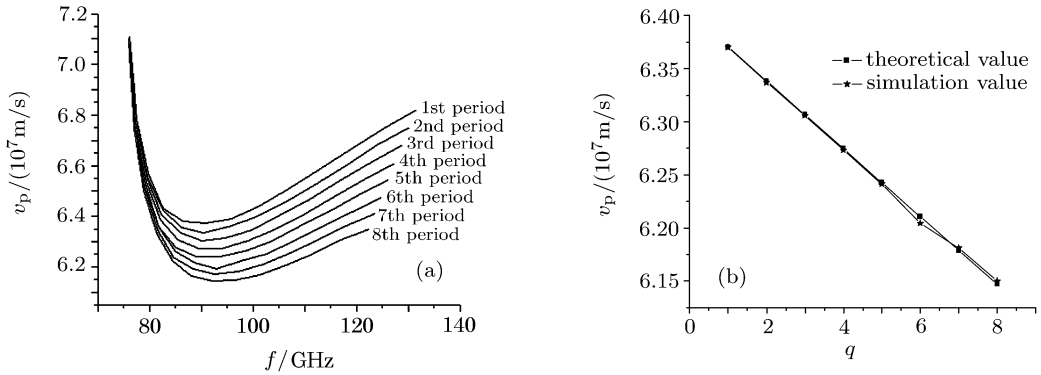


Fig.4. (a) Dispersion curve. (b) Phase velocity for each period.

In Fig.5, the curves calculated by using HFSS are the coupling impedance curves for the eight periods in this periodic nonuniform folded waveguide. It is found that the coupling impedances in each period are almost the same. This means that the variation of the physical dimensions of this structure does not affect the coupling impedance. So the efficiency of the slow wave structure may be improved, if a space harmonic synchronizes with the electron beam during the whole interaction process in this structure.

Above all, one can draw a conclusion that if the physical dimension of a periodic nonuniform folded waveguide satisfies condition (9), the efficiency of the wave-beam interaction can be enhanced.

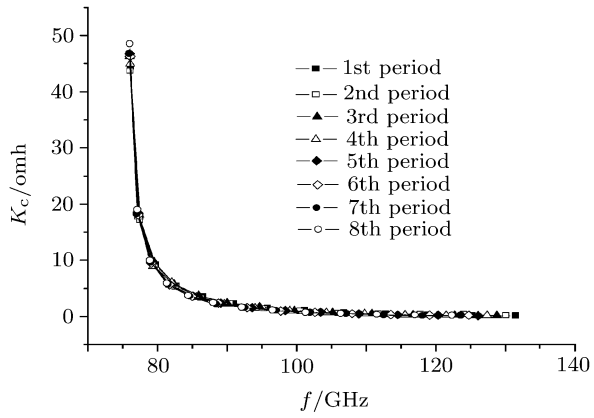


Fig.5. Coupling impedance curve.

4. Conclusion

The periodic nonuniform folded waveguide has been formed by varying the physical dimensions of the folded waveguide. This structure not only can keep many advantages of the folded waveguide, but also can make the microwave synchronize with the electron beam in the whole interaction process. It is a good way to enhance the efficiency of the wave-beam interaction; and moreover, it is more convenient than the tapering period folded waveguide. The conditions to make the mth space harmonic synchronize with the electron beam in the periodic nonuniform folded waveguide have been studied in this paper, and this conclusion is verified by the software simulation. The above results may be useful to the future studies.

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