Design and study of slow wave structure of the THz folded waveguide TWT over 60W

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Abstract. In this paper, the equivalent circuit method is used to analyze the dispersion characteristics of the folded waveguide and calculate the coupling impedance. The influence of the surface roughness and conductivity of the waveguide on the loss of the high frequency circuit is considered. In order to improve the efficiency of the beam wave interaction, the two kinds of slow wave structures of the folded waveguide TWT are designed by using the variable period technology. The three-dimensional electromagnetic software Microwave Tube Simulation Software (MTSS) is used to simulate the beam wave interaction of TWT. After optimization, the output power of both structures is over 60W, the electronic efficiency is more than 5.5% and the gain is greater than 32dB in the 211GHz-221GHz frequency range.

1. Introduction

Terahertz wave belongs to electromagnetic wave. Its frequency spectrum is between millimeter wave and infrared light. The frequency range is 100 GHz to 10 THz and the wavelength range is 3-30um. Terahertz wave occupies a special position in the electromagnetic spectrum, which is in the transition area from electronics to photonics. It has special properties that microwave and infrared radiation do not have, such as low photon energy, narrow pulse width, strong penetrability, wide frequency band and strong anti-interference ability[1][2][3]. It shows great advantages in the fields of radar, detection and communication. However, one of the most important problems in the development of Terahertz Science and technology is how to obtain a stable and reliable terahertz radiation source with low cost, high frequency, broadband, high power and high efficiency. In the terahertz band, the folded waveguide TWT has the advantages of large power capacity, good thermal stability, wide working band, easy processing, etc., and is recognized as a potential terahertz source[4]. Efficiency is an important work index of TWT. At present, one of the effective ways to increase the efficiency of TWT is to improve the beam wave interaction efficiency by designing a reasonable high frequency structure. In order to solve the question of the decrease of the interaction impedance and the increase of the high frequency loss of the beam wave interaction which lead to the decrease of the electron efficiency, in this paper, the idea of the variable period is proposed. The saturated output power and electronic efficiency of the designed variable period structure are much higher than those of uniform periodic structure, which meet the system index requirements.
2. Analysis of cold characteristics
Before the calculation of beam wave interaction, the high frequency characteristics and loss characteristics of folded waveguide should be analyzed. In order to finish beam wave interaction, first of all, the synchronization of electron beam and electromagnetic wave speed should be satisfied, which can be determined by the dispersion characteristics of the relationship between the phase speed and frequency of electromagnetic wave. Secondly, the longitudinal component of the electric field at the high frequency structure interaction gap should be strong enough, which can be characterized by the interaction impedance[5]. The loss determines the performance of the slow wave circuit and is also one of the important parameters of the slow wave structure[6]. The folded waveguide structure is shown in Figure 1. a is the wide edge, b is the narrow edge, h is the straight waveguide height, \( p \) is the half cycle axial length, and \( r_c \) is the electron beam channel radius.

2.1 Analysis of dispersion characteristics
The equivalent circuit method can be used to study the dispersion characteristics of folded waveguide high frequency circuits. Each part of the folded waveguide is equivalent to an independent transmission unit, so that the cascade transmission matrix and the single period FWG transmission matrix are equal, and the dispersion characteristics of the waveguide can be solved[7]. The folded waveguide is divided into four parts: A is the curved part of the waveguide, B is the connecting part of the straight waveguide and the curved waveguide, which can be represented by an equivalent reactance \( X_1 \)[8]. C is the straight waveguide part, which can be regarded as a uniform transmission line with a length of \( l \) and a characteristic impedance of \( Z_1 \). \( D_e \) is the electron beam channel. The equivalent circuit diagram of folded waveguide is shown in Figure 2. The corresponding relationship of parameters of each part is as follows[9]:

\[
\eta_0 = \frac{2b \eta_0}{a} \left[ 1 - \left( \frac{\lambda_c}{\lambda_0} \right)^2 \right]^{\frac{1}{2}} \tag{1}
\]

\[
\frac{Z_0}{Z_i} = \frac{1}{12} \left( \frac{b}{R} \right)^2 \left[ \frac{1}{2} - 1 - \left( \frac{2a}{\lambda_0} \right)^2 \right] \tag{2}
\]

\[
\frac{X_1}{Z_i} = \frac{32}{\pi} \left( \frac{2a}{\lambda_0} \right)^2 \left( \frac{b}{R} \right)^3 \sum_{n=1}^{\infty} \frac{1}{n} \left[ 1 - \left( \frac{2b}{n \lambda_0} \right)^2 \right]^{\frac{3}{2}} \tag{3}
\]

\( \eta_0 \) is the characteristic impedance of free space, \( R \) is the center radius of curved waveguide, \( \lambda \) is the wavelength of free space, \( \lambda_c \) is the cut-off wavelength, is the guided wave wavelength of straight
waveguide. The relationship between the guided wave length $\lambda_g'$ in curved section and the guided wave length $\lambda_g$ in straight section is as follows:

$$\lambda_g' = \lambda_g \left[1 - \frac{1}{12} \left(\frac{b}{R}\right)^2 \left(-\frac{1}{2} + \frac{1}{5} \left(\frac{2\pi b}{\lambda_g}\right)^2 + \cdots \right)\right]$$

(4)

When considering that there is an electron beam hole in the folded waveguide, assuming that the transverse wave is not directly coupled through the electron beam hole, and that the electron beam is regarded as a parallel reactance $X_2$ in the center of the straight waveguide, the reactance $X_2$ can be expressed as follows[10]:

$$\frac{X_2}{Z_1} = \frac{k_0 b}{8\pi^2} \left(\frac{a}{b}\right)^2 \left(\frac{2r_1}{a}\right)^3$$

(5)

The transmission matrix corresponding to each part of the folded waveguide is as follows:

$$A = \begin{bmatrix} \cos(k_1 l_i) & jZ_0 \sin(k_1 d_i / 2) \\ j \sin(k_1 d_i / 2) / Z_0 & \cos(k_1 d_i / 2) \end{bmatrix}$$

(6)

$$B = \begin{bmatrix} 1 & -jX_1 \\ 0 & 1 \end{bmatrix}$$

(7)

$$C = \begin{bmatrix} \cos(k_1 l_i / 2) & jZ_0 \sin(k_1 d_i / 2) \\ j \sin(k_1 d_i / 2) / Z_0 & \cos(k_1 d_i / 2) \end{bmatrix}$$

(8)

$$D = \begin{bmatrix} 1 & -jX_2 \\ 0 & 1 \end{bmatrix}$$

(9)

In the formula, $k_0$ and $k_1$ are the phase constants in the curved waveguide and the straight waveguide respectively, so the equivalent transmission matrix of the folded waveguide as the transmission line is:

$$F = \begin{bmatrix} \cos(\theta) & jZ_0 \sin(\theta) \\ jY \sin(\theta) & \cos(\theta) \end{bmatrix} = [A] [B] [C] [D] [I] [B] [A]$$

(10)

$\theta$ is the phase shift of one interaction period $p$, $Z$ and $Y$ are respectively the impedance and admittance of the circuit. We bring the corresponding matrix expression of each part into $F$, and the dispersion characteristic curve as shown in Figure 3 can be obtained.

2.2 Analysis of interaction impedance

By using the formula of axial electric field component and the power calculation method of $TE_{10}$ mode in rectangular waveguide, the coupling impedance of nth spatial harmonic can be obtained:
\[ K_n = \eta \left( 1 - \frac{\omega_1^2}{\omega_0^2} \right)^{1/2} \left( \frac{1}{\beta_n} \frac{\sin(\beta_n b/2)}{a} \right)^2 \] \tag{11}

\( \eta \) is the inherent impedance of the medium. When considering the electron beam channel in practice, the modified coupling impedance is \[ K_{n,\text{axis}} = K_n \left( \frac{1}{I_0^2} (K_w r_j) \right) \] \tag{12}

In the formula, \( \beta_n \) is the phase constant of the nth spatial harmonic, \( K_n = \beta_n^2 - k^2 \), \( k \) is the spatial phase constant, \( n \) is the order of the harmonic, \( I_0 \) is the zero order distorted Bessel function. After theoretical calculation, the initial parameters of folded waveguides are obtained. The width \( a \) is 0.85mm, the narrow \( b \) is 0.12mm, the height of the straight waveguide \( h \) is 0.27mm, the period of the waveguide \( p \) is 0.23mm, and the radius of the electron beam channel \( r_j \) is 0.1mm. The interaction impedance curve is calculated as shown in figure 4.

![Interaction impedance curve](image)

**Figure 4.** Interaction impedance curve.

### 2.3 Analysis of circuit attenuation

Loss is one of the important parameters of slow wave structure. In practice, the distributed loss of the circuit must be considered. With the increase of frequency, skin depth decreases and the loss increases. In fact, the machined waveguide surface is rough. When the surface roughness is close to or even greater than the skin depth, the loss caused by the surface roughness also needs to be considered, and the conductivity of the conductor needs to be corrected\[12\]:

\[ \sigma = \frac{\sigma}{K_w} = \frac{\sigma}{\left[ 1 + \exp \left( -\frac{\delta}{2h} \right) \right]^2} \] \tag{13}

\( K_w \) is the modified coefficient, \( \sigma \) is the conductivity of the material under ideal condition, \( \sigma' \) is the modified equivalent conductivity, \( \delta \) is the skin depth of the waveguide, \( h \) is the roughness of the inner wall of the waveguide, \( \mu \) is the permeability of the material, and \( \omega \) is the angular frequency.

Figure 5(a) shows the relationship between skin depth and frequency. It can be seen that the skin depth decreases gradually when the frequency increases. Figure 5(b) shows the modified conductivity under different skin depths. It can be seen that when the surface roughness is determined, the modified conductivity decreases gradually with the increase of working frequency, and the conductor loss increases. When the working frequency is determined, the corrected conductivity decreases with the increase of surface roughness, but the value of \( K_w \) increases, and the conductor loss in the waveguide increases.
When selecting the surface roughness of materials in modeling calculation, the general principle is that the surface roughness value and skin depth are comparable. The material selected in this paper is copper. After considering the actual processing conditions and working frequency band, the modified conductivity of materials is calculated to be 1.48e7 S/m.

The main mode of folded waveguide is TE10 mode. If the mode propagates along the zigzag path without any change in the folded waveguide, the loss of folded waveguide slow wave structure can be calculated by the attenuation coefficient of rectangular waveguide, which is[13]:

$$\alpha = \frac{R_s}{377b}\sqrt{1 - \left(\frac{f_a}{f}\right)^2}\left[1 + \frac{2b}{a}\left(\frac{f_a}{f}\right)^2\right]$$  \hspace{1cm} (14)

$R_s$ is the corrected surface impedance of the conductor.

It can be seen from Figure 6(a) that when the working frequency band is determined, the attenuation coefficient increases with the increase of the surface roughness of the conductor, resulting in the greater the conductor loss. Figure 7(b) is the comparison diagram of theoretical calculation, HFSS simulation and MTSS simulation of single high-frequency structure loss. It can be seen that the attenuation coefficient calculated in MTSS is larger, because various losses are considered in MTSS calculation, which is closer to the actual situation.
3. Design of high efficiency folded waveguide slow wave system
The purpose of this section is to improve the saturated output power and maximum electronic efficiency of TWT. The method of variable period is used in the optimal design of folded waveguide slow wave structure. Its main purpose is to reduce the percentage of electrons in acceleration field or increase the percentage of electrons in deceleration field.

3.1 Design of dynamic variable period FWG
Figure 7 shows the dynamic variable period FWG with a total length of 42.6mm. The specific length of each part and the corresponding half cycle length $P$ are as follows: $L_1 / L_{total} = 0.594$, $p = p_0 = 0.23mm$, $L_2 / L_{total} = 0.27$, $p_1 / p_0 = 1.043$, $L_4 / L_{total} = 0.0155$, $L_5 / L_{total} = 0.023$, $p_2 / p_0 = 0.87$ and $L_1 + L_2 + L_3 + L_4 + L_5 = 1$.

The function of L1 part is to make the high frequency signal modulate the electron beam, let the electron beam carry the high frequency signal with the same frequency, and establish the growth wave. It can provide the electron beam with good clustering, and make good preparation for the subsequent beam wave interaction. The function of L2 part is to correct the phase shift of subsequent interaction by properly increasing the value of half period $p$, so as to increase the phase velocity of electromagnetic wave and weaken the electron beam bunching state whose speed is in acceleration state after being modulated from the input section. After releasing part of energy, the bunching current will increase, which will make the beam wave interaction stronger and improve the saturation output power and maximum electronic efficiency. In this section, the maximum period of the gradient section is $p_1$ and the minimum period is $p_2$. The relationship between the two can be expressed as $p_1 - \Delta p_1 * n_1 - \Delta p_2 * n_2 = p_2$, where $\Delta p_1 * n_1$ represents dynamic gradient section L3, the unit gradient is $\Delta p_1 = 0.001mm$, $n_1$ represents the unit gradient quantity, $\Delta p_2 * n_2$ represents dynamic gradient section L4, the unit gradient quantity is $\Delta p_2 = 0.1mm$ and $n_2$ represents the unit gradient quantity.

In this paper, sever and attenuator are used to suppress the reflection of high-frequency signal. The length of the sever is 2mm, the attenuator is loaded on both sides of sever and trapezoidal input-output mode is used. The total length is 20 interaction periods, the gradient ratio is 0.5 and the maximum attenuation is 3000dB / m.

![Figure 7. The dynamic variable period FWG.](image)

3.2 Design of periodic stepping FWG
Figure 8 shows the periodic stepping FWG with a total length of 44.5mm. The specific length of each part and the corresponding half cycle length $p$ are as follows: $L_1 / L_{total} = 0.568$, $p_0 = 0.23mm$, $L_4 / L_{total} = 0.258$, $p_1 / p_0 = 1.043$, $L_4 / L_{total} = 0.025$, $p_2 / p_0 = 0.956$, $L_1 + L_2 + L_3 + L_4 = 1$. The design of truncation and attenuator is the same as Section 2.2.
In this section, MTSS is used to calculate the high efficiency structure and uniform periodic structure. The working parameters of TWT in terahertz band are as follows: the cold electron beam is assumed to have a voltage of 13.6kV, the beam current is 0.08A, the filling ratio of the beam is set as 0.5, the magnetic field type is periodic magnetic field, the peak value is 9600 GS, the period length of magnetic field is 2.6mm, its initial phase is 90 degrees. After calculation, the performance index of the folded waveguide TWT as shown in Table 1 is obtained. (Take 217GHz as an example)

| Performance Index       | Uniform period FWG Value | Periodic stepping FWG Value | Dynamic variable FWG Value |
|-------------------------|---------------------------|-----------------------------|-----------------------------|
| Saturated output power(W) | 35.37                     | 66.73                       | 66.74                       |
| Maximum electron efficiency (%) | 3.25                     | 6.13                        | 6.13                        |
| Saturated gain(dB)       | 33.44                     | 35.69                       | 35.23                       |

The total interaction length(42.6mm) of the folded waveguide slow wave structure designed by the variable period technology is shorter than that of the uniform periodic folded waveguide structure(44.1mm). From Table 1, it can be seen that in the working frequency of 217GHz, compared with the uniform periodic structure, the saturated output power of the periodic stepping structure and the dynamic variable period structure increases from 35.37W to 66.73W and 66.74W respectively, the maximum electron efficiency raises from 3.25% to 6.13%, and the saturated gain improves from 33.44 dB to 35.69 dB and 35.23 dB, respectively.
Adjusting the input power of each working frequency point can make it reach the saturation output power and the maximum electronic efficiency at the end of the output section. Figure 9(b) shows the comparison of the saturated output power of the three structures, and figure 9(a) shows the comparison of the maximum electron efficiency. The saturated output power of the dynamic variable structure is more than 60W in the 211GHz-221 GHz frequency range, the maximum electron efficiency is greater than 6% in the 215 GHz-219 GHz frequency range, and the saturated output power of the periodic stepping structure is over 60W in the 211GHz-223 GHz frequency range, and the maximum electron efficiency is greater 6% in the 216GHz-221 GHz frequency range. Figure 10, Figure 11 and Figure 12 shows the comparison of the axial velocity distribution of electrons at 220GHz, whose axial velocity represents the energy carried by the electron beam. It can be seen that with the beam wave interaction, the speed of electrons gradually decreases slowly, and the speed of most electrons at the end of the output section decrease sharply, and the electrons release a lot of energy.

In figure11 and figure12 the percentage of electrons in the deceleration field and the decrease degree of electron velocity are higher than that in figure10, so that the saturated output power and maximum electron efficiency of the two kinds of variable period folded waveguide TWT are greatly improved compared with that of the uniform period folded waveguide TWT. According to variable period structure is that the unit gradient of waveguide in the output section first slowly decreases and then gradually increases, so that the waveguide period first slowly decreases and then rapidly decreases, and the electromagnetic wave velocity first slowly decreases and then rapidly decreases. It is reasonable to make it keep the speed of the electromagnetic wave in sync with the speed of the electron.
5. Conclusion

In this paper, the high frequency characteristics and loss characteristics of waveguide structure are analyzed. According to the actual situation, the surface roughness and equivalent conductivity of waveguide model are set, and two kinds of high-efficiency folded waveguide slow wave structures are designed by using the variable period technology. The output power of both structures is more than 60W in the 211GHz-221GHz frequency range, the electron efficiency is over 5.5%. Compared with the uniform period structure at 217GHz, the saturated output power the two structures is increased by 88.6% and the maximum electronic efficiency is increased by 88.6%. It shows that the structure designed in this paper is reasonable and correct, which provides a method for the actual processing and making model in the future.

References

[1] Lei Hongwen, Wang Hu, Yang Xu, Duan Chongdi. (2017) Analysis and Progress of Terahertz Techniques Applied in Space Science[J].Space Electronic Technology,2:1-7.
[2] Li Dasheng, Deng Chuqiang, Liu Zhenhua, Sun Jun,J in Lin.(2015)Research Progress of THz Imaging Radar System[J].Journal of Microwaves,31(6):82-87.
[3] Zhao Guozhong, Shen Yanchun, Liu Ying. (2015)Application of terahertz technology in military and security field[J].Journal of Electronic Measurement and Instrumentation,29(8):1097-1101.
[4] Zheng Ruilin, Chen Xuyuan. (2009)Parametric simulation and optimization of cold-test properties for a 220 GHz broadband folded wave guide traveling-wave tube[J].J Infrared Milli Terahz Waves,30:945-958.
[5] Cheng Zhaohua. (2006)Research on transmission characteristics of folded waveguide in THz device[D]. Chengdu, China: University of Electronic Science and Technology of China.
[6] Fan Xiaonian, Wu Xianping. (2000) The Study on the Loss characteristics of Helical Slow Wave Structure[J]. Vacuum Electronics, 3:1-9.

[7] Li Ke, Liu Wenxin, Wang Yong, et al. (2013) Accurate equivalent circuit analysis of dispersion characteristics of THz two-beam folded waveguide[C]// The Proceedings of the 19th Annual Conference of the Institute of Vacuum Electronics of the Chinese Society of Electronics. Huangshan, Anhui, China: [s.n.], 285-288.

[8] BOOSKE J H, CONVERSE M C, GALLAGHER D A, et al. (2005) Parametric modeling of folded waveguide circuits for millimeter-wave traveling wave tubes[J]. IEEE Transactions on Plasma Science, 52(5): 685-694.

[9] MARCUVITZ N. (1986) Waveguide handbook[M]. Stevenage, UK: Peregrinus.

[10] Collings R E. (1991) Field Theory of Guided Waves. Institute of Electrical and Electronics Engineers, New York, 521.

[11] J.K. So, Y.M. Skin, K.H. Jang, et al. (2006) Experimental Investigation of Micro-fabricated Folded Waveguide Backward Wave Oscillator for Submillimeter Application. IRMMW-THz, 315.

[12] Pang Hexi. (2008) Research on the Effect of Inner Surface Roughness of Waveguides on Performance of Electromagnetic Waves[D]. Xi’an, China: Xidian University.

[13] Yang Wenyuan, Dong Zhiwei, Dong Ye, et al. (2014) Linear analysis on the folded waveguide tube in the terahertz band. High Power Laser and Particle Beams, 26: 083104.