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# High power wideband terahertz traveling wave tube based on folded double ridge groove waveguide

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**Abstract**: A modified folded groove waveguide called folded double ridge groove waveguide (FDRGW) is put forward for developing broadband high-power terahertz (THz) travelling-wave tube (TWT). A new transmission waveguide which is appropriate for this new kind of SWS as input and output energy coupler is proposed. It can be found from the high frequency characteristic simulation results that the folded double ridge waveguide SWS can increase the average interaction impedance and extend its operating bandwidth. In addition, the particle-in-cell (PIC) simulation results reveal that with the beam voltage of 27.4 kV and the beam current of 0.25 A, the average output power of the new folded double ridge groove waveguide TWT can reach 65.8 W and the corresponding gain is 27.21 dB at the center frequency 340 GHz. Therefore, the folded double ridge groove waveguide TWT could be used as wide-band and high-power terahertz radiation source.

**Key words**: terahertz traveling wave tube, folded double ridge groove waveguide, high power, wideband
**PACS**: 84.40.Fe

# 曲折双脊槽波导高功率宽频带太赫兹行波管

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**摘要**:提出一种改进的曲折槽波导—曲折双脊槽波导提高太赫兹行波管的功率和带宽. 针对这种新型慢波结构设计了一种新的传输波导作为输入输出能量耦合器. 从高频特性仿真结果可以发现曲折双脊槽波导可以提高耦合阻抗并扩展带宽. 此外,粒子仿真结果表明当电子注加载27.4 kV电压和0.25 A电流时,新型曲折双脊槽波导行波管在中心频率340 GHz处输出功率能达到65.8 W同时对应增益27.21 dB. 因此,曲折双脊槽波导行波管可以用作宽带和高功率太赫兹辐射源.

**关 键 词**:太赫兹行波管;曲折双脊槽波导;高功率;宽频带

**中图分类号**:TN124 **文献标识码**:A

## Introduction

The traveling wave tube (TWT) has always played an important role for energy amplification. It also can be extensively used in radar, communications broadcasting and other electronic systems. The slow-wave structure (SWS) is the main component of the TWT and will affect performance of TWT directly. The helix and coupled cavity structure are traditional slow-wave structures. The helical SWS is mainly suitable for working below 70 GHz. The coupled cavity SWS can work at over 40 GHz and has high power-handling capability, but its bandwidth is relatively narrow[1]. Our objective is to find a new slow-wave structure that is suitable for working at high frequency with high power and wide bandwidth. The

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folded waveguide (FW) slow-wave structure was studied by waterman in 1979 and it has relatively wide bandwidth and high power characteristics compared with traditional helix and coupled cavity slow wave structure. A great deal of experimental and theoretical research on folded waveguide traveling wave tube (FWTW) have been published previously[2-6]. Several modified FWSWS are also put forward and studied for improving the performance of FWTWT.

As the working frequency increases, the dimension of the slow-wave structure becomes smaller and smaller, at the same time the surface loss is becoming more and more seriously. It must be faced that the small dimension and large surface loss would cause that the folded waveguide is not suitable for working at higher frequency band. In order to overcome the above problem, folded groove waveguide as a compact structure was studied[7-8]. The folded groove waveguide solves the problem of dimension and surface loss, besides another advantage sheet beam tunnel. Compared with circular electron beam tunnel, the sheet beam tunnel is not needed to be processed due to its nature tunnel. When the working frequency increases, the circular electron beam tunnel of folded waveguide is more and more difficult to process. The shape of the groove can be varied. We have investigated on folded rectangular groove waveguide (FRGW) and folded V-shape groove waveguide[9-10]. They have different characteristics and they are suitable for working in different bandwidth with the same dimension.

In this paper, a modified folded groove waveguide called folded double ridge groove waveguide is put forward. This structure which is fit for THz traveling-wave tubes because of its high efficiency, wideband and high power. The model of folded double ridge groove waveguide is shown in Fig. 1. This paper shows the electromagnetic characteristics and the beam-wave interaction of the folded double ridge groove waveguide by utilizing HFSS and CST Microwave studio and particles studio[11-12].

The contents of this paper is as follows. In Sect. 1, the comparison outcome for the high frequency characteristics between the folded double ridge groove waveguide SWS and folded waveguide with the same dimensions is provided. Sect. 2 presents the transmission waveguide for the folded double ridge groove waveguide SWS. Sect. 3 gives the beam-wave interaction simulation results of the folded double ridge groove waveguide. Some useful conclusions have been drawn in Sect. 4.

## 1 High frequency characteristics of the folded double ridge groove waveguide SWS

Figure 1 (a) shows the model of folded double ridge groove waveguide SWS. Figure 1 (b) shows the folded double ridge groove waveguide profile. The shape of the groove is diffident from the folded rectangular groove waveguide, folded V-shape groove waveguide and Ridge-Loaded folded rectangular groove waveguide (R-LFRGW)[13]. In Fig. 1, the parameter $s$, $p$, $d$ represent the length of the straight groove, the half of one period and the space between two metal plates, respectively. The right side view of folded double ridge groove waveguide SWS profile is shown in Fig. 2. Here, the height of the double ridge groove wide side is $a_1$, the width of the double ridge groove wide side is $b_1$, the height of the double ridge groove narrow side is $a_2$, and the width of the double ridge groove narrow side is $b_2$.

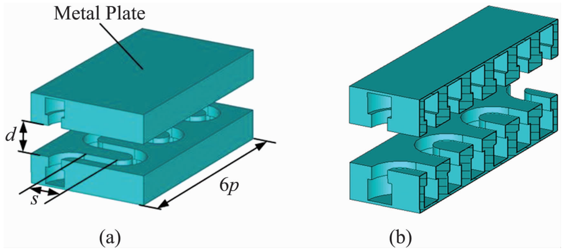


Fig. 1 (a) Model of folded double ridge groove waveguide SWS, (b) the folded double ridge groove waveguide profile
图1 (a)曲折双脊槽波导慢波结构模型,(b)曲折双脊槽波导剖面图

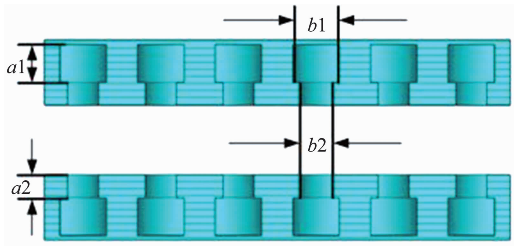


Fig. 2 Right side view of Folded double ridge groove waveguide SWS profile
图2 曲折双脊槽波导剖面右侧视图

The optimized parameters of one period of the SWS working at the THz waveband are determined by simulation of high frequency characteristics. The optimized parameters for the four structures listed in Table 1. Figure 3 presents the comparison of the normalized phase velocity of the folded double ridge groove waveguide with the folded waveguide, the folded rectangular groove waveguide, and the ridge-loaded folded rectangular groove waveguide with the same size.

**Table 1 The optimized parameters for the four structures**
**表1 四种结构的优化参量**

| Parameter/mm | $p$ | $s$ | $d$ | $b$ | $a$ | $a_1$ | $a_2$ | $b_1$ | $b_2$ | $b'$ | $C_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| FDRGW | 0.2 | 0.2 | 0.18 | – | – | 0.123 | 0.035 | 0.12 | 0.08 | – | – |
| FW | 0.2 | – | – | 0.08 | 0.496 | – | – | – | – | – | – |
| FRGW | 0.2 | 0.2 | 0.18 | 0.08 | 0.158 | – | – | – | – | – | – |
| R-LFRGW | 0.2 | 0.2 | 0.18 | 0.12 | 0.158 | – | – | – | – | 0.08 | 0.02 |

The normalized phase velocity was calculated by the HFSS Eigenmode Solver. Seen from Fig. 3, the operating frequency of the folded rectangular groove waveguide and ridge-loaded folded rectangular groove waveguide is much higher than that of the folded double ridge groove waveguide and folded waveguide with the same size. But their bandwidth is much narrower than the folded double groove waveguide and folded waveguide. The normalized phase velocity of the folded double ridge groove waveguide is higher than that of the folded waveguide, and the bandwidth of the folded double ridge groove waveguide is slightly broader than that of the folded waveguide.

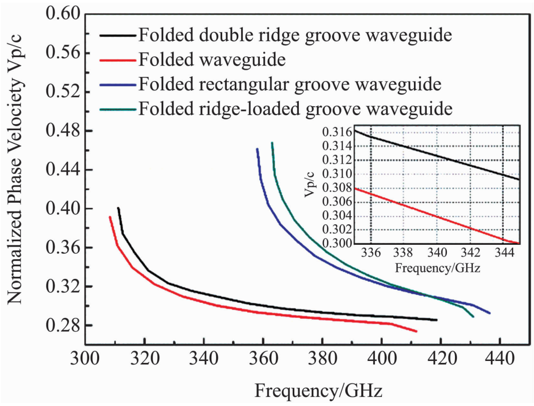


Fig. 3 Comparison of the dispersion characteristics of the four structures
图 3 四种结构的色散特性对比

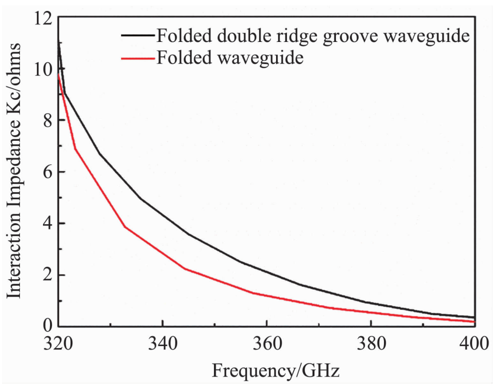


Fig. 4 comparison of the interaction impedance of the two structures
图 4 两种结构的耦合阻抗对比

The interaction impedance of folded double ridge groove waveguide and folded waveguide at the center of the beam channel was displayed in Fig. 4. It indicates that the interaction impedances of the folded double ridge groove waveguide is higher than that of the folded waveguide over the complete bandwidth, especially within 320 ~ 400 GHz. The interaction impedance of the folded waveguide is 1.7 Ω smaller than that of folded double ridge groove waveguide at 340 GHz. Figure 5 displays the loss per pitch of the folded double ridge groove waveguide and folded waveguide with the same size,

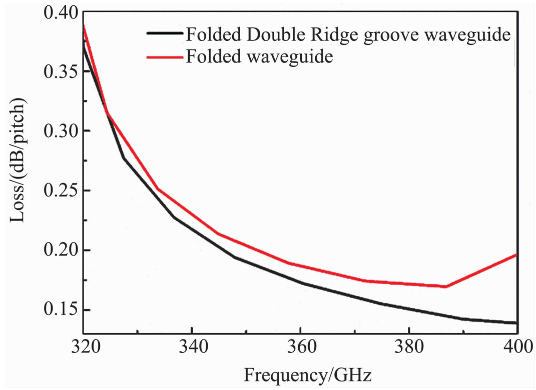


Fig. 5 Comparison of the distributed loss of the two structures
图 5 两种结构的损耗分布对比

where the background is set as loss material whose electric conductivity value is $1.43 \times 10^7$ S/m. From Fig. 5 we can see that the loss of the folded waveguide is higher than that of folded double ridge groove waveguide over the complete bandwidth, especially within 320 ~ 400 GHz.

From the analysis mentioned above, the folded double ridge groove waveguide slow wave structure is more suitable for wideband high power terahertz traveling wave tube.

## 2 The transmission waveguide for folded double ridge groove waveguide TWT

Figure 6 shows the sketch of the interaction simulation model. In the simulation process of the interaction between the electromagnetic wave and electron beam, rectangular PEC cross section is used instead of cathode emitter surface, and a new transmission waveguide is designed which is appropriate for this new kind of SWS as input/output energy coupler and the main slow wave structure was split into two sections by attenuator to suppress the self-excited oscillations. The number of input segment periods is equal to the output segment. The material of the designed attenuator is ceramics (BeO). The ceramics (BeO) is loss material and it can absorb the reflected wave in a wide range of frequencies. The material properties of the permittivity and loss tangent are set as 6.5 and 0.5 respectively in CST.

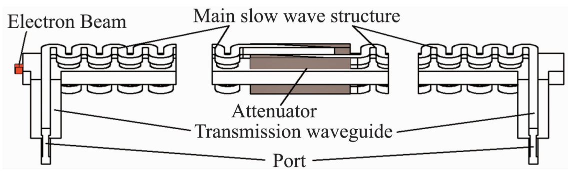


Fig. 6 Sketch of the interaction simulation model by CST
图 6 互作用 CST 仿真模型草图

The transmission waveguide of the folded double ridge groove waveguide is displayed in Fig. 7(a). The transmission waveguide consists of two parts: double groove-loaded ridge waveguide and double ridge groove

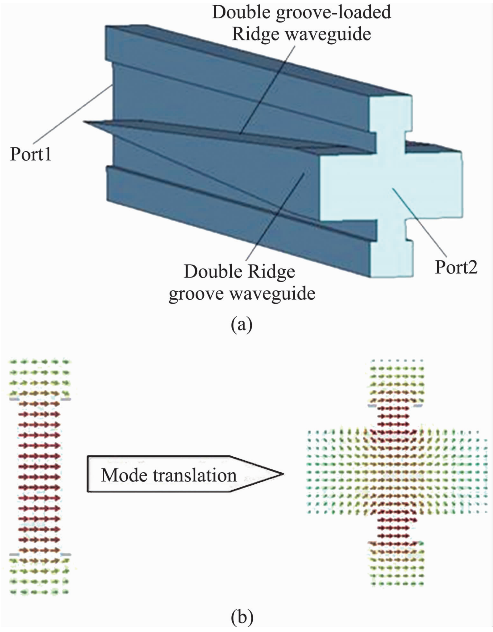


Fig. 7 (a) Transmission waveguide, (b) electric field distribution of two ports
图7 (a)传输波导,(b)两端口电场分布

waveguide. The groove of the double groove-loaded ridge waveguide gradually changes from 0 to $d$ and the process would complete the mode conversation. Both of the electric field distribution for transmission waveguide displayed in Fig. 7 (b). It can be seen from Fig. 7 (b) that the mode at port 1 is similar $TE_{10}$ mode and the mode at port 2 is similar $TE_{11}$ mode. The side view of the transmission waveguide is revealed in Fig. 8 (a). Figure 8 (b) shows the cross section of the port 2. The final parameters of the new transition waveguide are listed in Table 2.

**Table 2 Optimized parameter of transition waveguide**
**表2 传输波导优化参量**

| Parameter | Value |
|---|---|
| $L_1$/mm | 0.30 |
| $L_2$/mm | 5.00 |
| $e$/mm | 0.20 |

The VSWR of the whole folded double ridge groove waveguide system was calculated by CST microwave studio and that is shown in Fig. 9 and that is less than 1.35 in the whole frequency from 330 ~ 350 GHz. It illustrates that the reflection oscillation can be well suppressed.

## 3 Beam-wave interaction simulation

The energy exchange between electron beam and electromagnetic wave was investigated in details in this part. The cross section of the beam tunnel is $d \times s = 0.18$ mm × 0.2 mm and its packing ratio is 25% with the beam voltage of 27.4 kV and the beam current of 0.25 A. The background environment is a loss material with the conductivity of $1.43 \times 10^7$ S/m and it implies that the

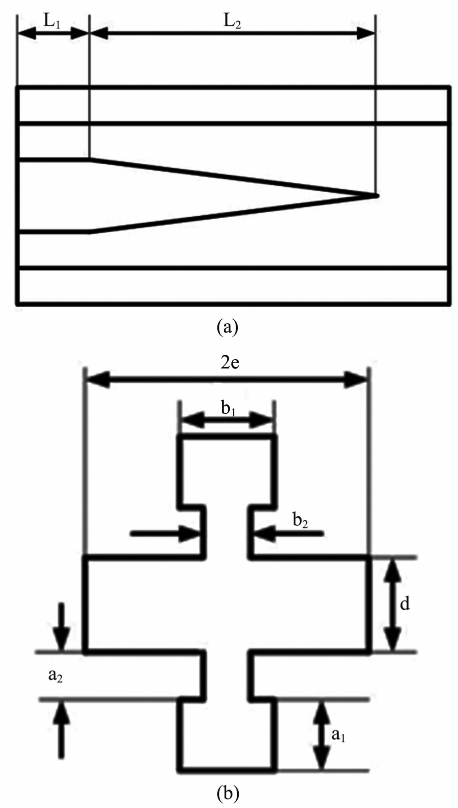


Fig. 8 Transition waveguide (a) The side view of transition waveguide, (b) the cross section of the port 2
图8 过渡波导 (a) 过渡波导侧视图,(b)端口2横截面

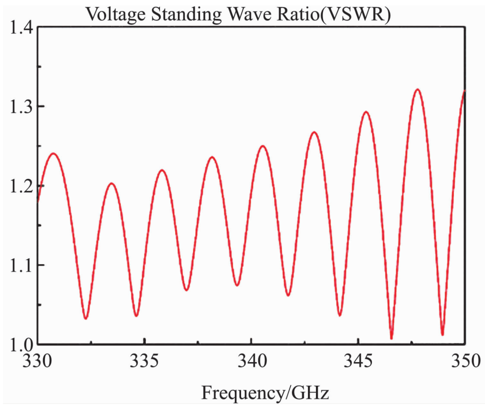


Fig. 9 VSWR of the whole folded double ridge groove waveguide system
图9 曲折双脊槽波导系统驻波

background material will dissipate part of the energy of output electromagnetic wave. A uniform magnetic field of 0.6T along the beam tunnel is set in the PIC simulation, and there is no electrons hit the folded double ridge groove waveguide structure.

CST PARTICLE STUDIO offers several sources for exciting a given structure, e. g. waveguide ports or plane waves. The sources for exciting the folded double ridge groove waveguide structure is waveguide port. The input signal scaling factor is 1 (unit: sqrt(watt)) for the folded double ridge groove waveguide, and the average power equals (1/2) * volage^2 , here the voltage is not the real voltage , its unit is sqrt(watt).

As we can see from Fig. 10 that the folded double ridge groove waveguide TWT can produce a steady output average power of 65.8W. Figure 11 displayed a wave-particle power transfer graph. Exactly as Fig. 11, the energy of most particles is decreasing and according to the law of conservation, the energy of electromagnetic field will be amplified.

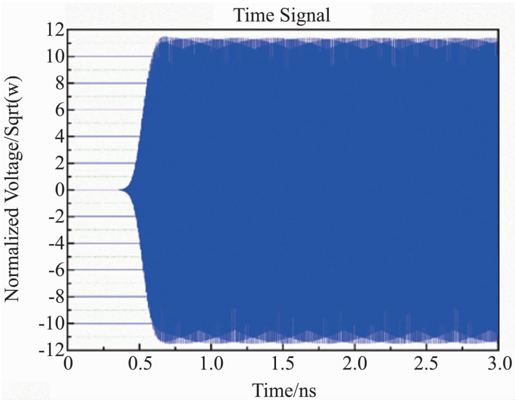


Fig. 10　Time history of the output signal at 340 GHz
图 10　频率 340 GHz 输出信号随时间变化历程

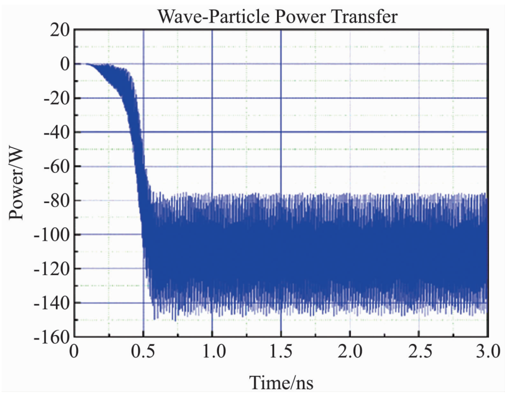


Fig. 11　Wave-particle power transfer
图 11　微波粒子功率传输

Figure 12 shows the spectrum diagram of output signals from 300 GHz to 380 GHz. We can see from Fig. 12 that the maximum value is at the center of frequency of 0.34 THz, and it is pure in the entire frequency band. It means that the fundamental model is effectively amplified and other competition modes are effectively suppressed.

Figure 13 demonstrates the picture of the average output power for the new folded double ridge groove waveguide and folded waveguide versus the frequency. The Fig. 13 shows that the average output power of the new folded double ridge groove waveguide is higher than that of folded waveguide in the whole working band-

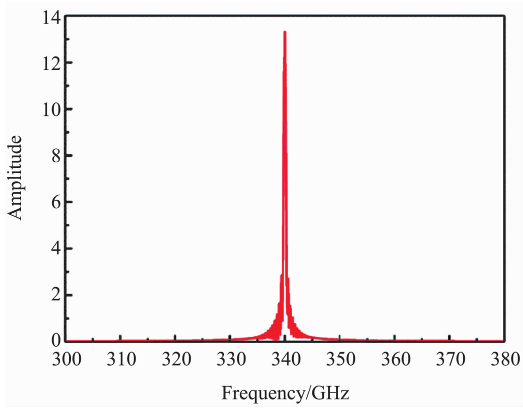


Fig. 12　Frequency spectrum of output signals
图 12　输出信号频谱

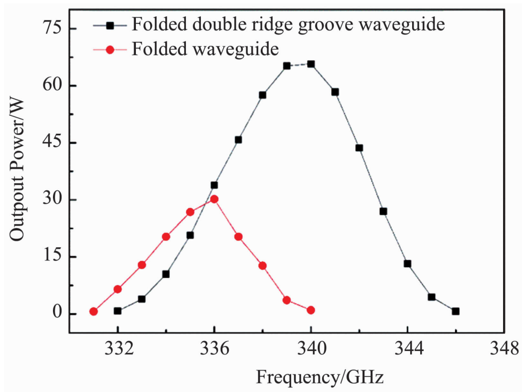


Fig. 13　Average output power versus frequency
图 13　平均输出功率随频率变化

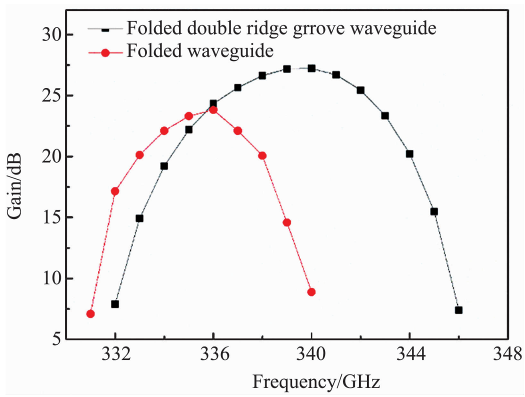


Fig. 14　The gain versus frequency
图 14　增益随频率变化

width. We can see from Fig. 13 that the average output power of the new folded double ridge groove waveguide can reach 65.8 W at the center frequency of 340 GHz. Figure 14 demonstrates the picture of the gain for this new folded double ridge groove waveguide and folded waveguide versus frequency. Figure 14 shows that the gain of the new folded double ridge groove waveguide is higher than that of folded waveguide . We can see from Fig. 14 that the maximum values of the gain is 27. 21 dB at the center of frequency 0. 34 THz. Obviously, 3 dB bandwidth ranges from 333 ~ 346 GHz. Generally, 3 dB bandwidth is useful bandwidth for TWT. Therefore, the folded double ridge groove waveguide TWT could be used as wide-band and high-power terahertz radiation source.

## 4 Conclusions

The novel folded double ridge groove waveguide TWT is presented in this paper. A new transmission waveguide which is appropriate for this new kind of SWS as input/ output energy coupler was designed. The fundamental mode is effectively amplified and other competition modes are effectively suppressed in the new SWS with the designed absorber. The energy exchange between electron beam and electromagnetic wave was investigated in details in this paper. It brings to light that the average output power of the new folded double ridge groove waveguide TWT can reach 65. 8 W and the maximum values of the gain is 27. 21 dB at the center frequency 0. 34 THz. So, the folded double ridge groove waveguide TWT has the nature characteristics of wide-band and high-power terahertz radiation source.

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