Research of sine waveguide slow-wave structure for a 220-GHz backward wave oscillator*

Xu Xiong(许 雄), Wei Yan-Yu(魏彦玉)†, Shen Fei(沈 飞), Huang Min-Zhi(黄民智), Tang Tao(唐 涛), Duan Zhao-Yun(段兆云), and Gong Yu-Bin(宫玉彬)

National Key Laboratory of Science and Technology on Vacuum Electronics, University of Electronic Science and Technology of China, Chengdu 610054, *China*

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A watt-class backward wave oscillator is proposed, using the concise sine waveguide slow-wave structure combined with a pencil electron beam to operate at 220 GHz. Firstly, the dispersion curve of the sine waveguide is calculated, then, the oscillation frequency and operating voltage of the device are predicted and the circuit transmission loss is calculated. Finally, the particle-in-cell simulation method is used to forecast its radiation performance. The results show that this novel backward wave oscillator can produce over 1-W continuous wave power output in a frequency range from 210 GHz to 230 GHz. Therefore, it will be considered as a very promising high-power millimeter-wave to terahertz-wave radiation source.

Keywords: backward wave oscillator, sine waveguide, slow-wave structure, terahertz

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1. Introduction

A high power millimeter wave or terahertz wave radiation source is attractive due to its many applications, such as imaging, diagnostic systems, radar, high-data-rate telecommunication and space applications.[1−16] A backward wave oscillator (BWO), based on the conventional vacuum electronic principle, is also one of the most important high-power signal generators.[9,17−19] The BWO, as a wideband electronically tunable device, possesses compact dimensions and mW-class output power, especially at a frequency range of 100 GHz–1 THz. Therefore, it has attracted intensive investigation. Despite this it is still far from the requirements of a watt-class or higher output power device. The high power terahertz wave radiation source is critical to investigate the new nonlinear phenomena and the dynamic properties of materials.[1]

The main problems arise from high circuit radio frequency (RF) transmission loss and strong reflection in the current devices. These problems severely prevent power enhancement. The most important reason for this is that the cross sections of many of the current structures are not uniform. Then, it becomes more difficult to design a good input or output coupling component as the operating frequency increases up to the shorter millimeter wave or terahertz regime. Therefore, the transmission characteristics of the high frequency circuit will be not good enough for use in applications. Now, we have a feasible solution to this problem. Sine waveguide slow-wave structure has been proposed for a 220-GHz traveling wave tube (TWT). The benefits of this structure include low propagation loss and low reflection, as well as its easy fabrication.[20] It possesses a very concise coupling component to achieve good RF transmission characteristics. It also supports strong beam-wave interaction. Therefore, it can be considered to serve as an RF structure for a high power millimeter wave or terahertz wave BWO.

In this paper, a group of reasonable structure dimensions is designed to operate around 220 GHz. The BWO radiation performance will then be forecast by using the particle-in-cell (PIC) method. Then, we can predict what capability it will have when the sine

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†Corresponding author. E-mail: yywei@uestc.edu.cn

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waveguide is used to design a BWO.

2. Slow wave circuit design

Commonly, considering the entire system dimension, the operating voltage is assumed to be below 30 kV. In view of this design consideration and the high-aspect-ratio microfabrication process, a group of dimensions about sine waveguide slow-wave structure as shown in Fig. 1(a), are given as follows:

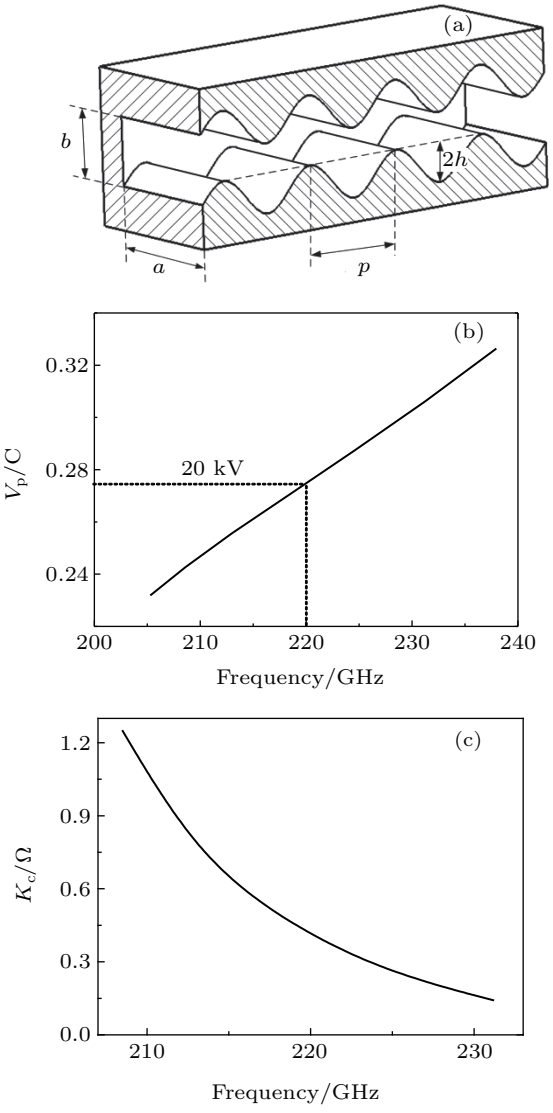


Fig. 1. Dimension parameters (a) and slow wave characteristics of sine waveguide: dispersion characteristics about the first negative spatial harmonics (b), and interaction impedance defined on the central axis of the beam tunnel (c).

wide side length $a = 0.74$ mm; narrow side length $b = 0.52$ mm; oscillating period $p = 0.32$ mm; oscillating amplitude $h = 0.2$ mm. The dispersion characteristics about the first negative spatial harmonics and the interaction impedance defined on the central axis of the beam tunnel are shown in Figs. 1(b) and 1(c). Both curves are calculated by the Eigenmode Solver from Ansoft HFSS with master and slave boundary conditions.[21,22] From Fig. 1(b), we can see that by tuning the beam line around 20 kV, the operating frequency range can be tuned from 210 GHz to 230 GHz.

3. Circuit radio frequency transmission loss calculation

As mentioned in the introduction, the circuit transmission loss becomes nearly the most important factor when a millimeter wave or terahertz wave electron device is designed. In this paper, the circuit transmission loss is calculated using the model shown in Fig. 2(a), at frequencies ranging from 210 GHz to 230 GHz. This model consists of two rectangular waveguides, two transitions and one sine waveguide slow wave structure.[20] The material of the model is set as high conductivity copper with a conductivity of 5.8×10^7 S/m. Due to the modern high manufacturing level such as X-LIGA, UV-LIGA or DRIE, the copper surface roughness is four or five times smaller than the skin depth in the above operating frequency range.[23,24] So, it is neglected in the following simulation. However, this method will not make the simulation results unreasonable, and it has been extensively adopted.[19,20,25,26] Here, the S-parameters of the model are calculated by the Transient Solver in CST Microwave Studio.[27] The calculation results are shown in Fig. 2(b). Over the entire frequency range, sine waveguide shows good electromagnetic propagation characteristics. Also, we can obtain the circuit transmission loss as shown in Fig. 2(c), by formula

$$\text{Loss}\,(\text{dB/mm}) = \frac{|S_{21}|}{L_{\text{total}}}, \tag{1}$$

where L_{total} is the total length of the circuit. Here, the sine waveguide slow-wave structure has 60 periods, so the total length equals 23.68 mm.

One can see that the total circuit transmission loss is low. Therefore, the sine waveguide is very suitable for operating in the millimeter wave or terahertz frequency band.

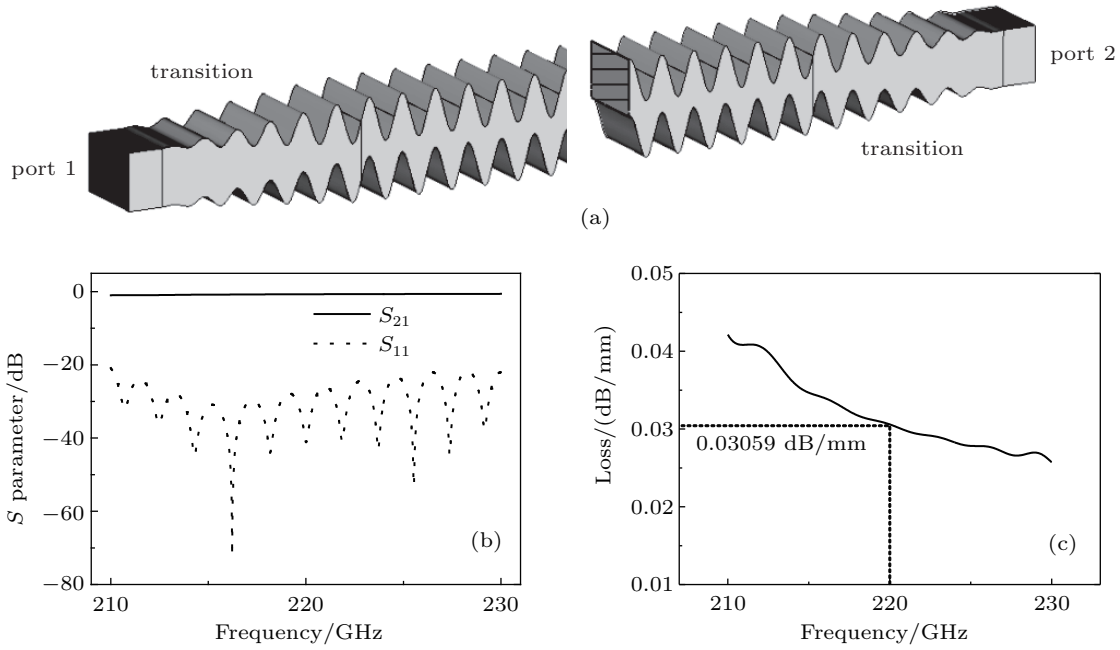


Fig. 2. Electromagnetic propagation characteristics of the slow-wave circuit. Panel (a) shows the circuit transmission loss calculation model, panel (b) indicates the S-parameters of the circuit transmission loss model, and panel (c) displays the circuit loss versus frequency.

4. Device performance prediction

In order to predict the BWO performance, the particle-in-cell method is used to calculate the output power and oscillation frequency. In the simulation, a pencil electron beam with a radius of 35 μm is adopted in the middle of the beam tunnel but not a sheet electron beam. Because the pencil beam technology is more mature than the sheet beam technology, the BWO does not need a current as large as that in TWT. Here, the beam current is set to be 10 mA, so the pencil beam mentioned above can support the current. The current density is about 259 A/cm^2. A uniform longitudinal focusing magnetic field of 0.5 T is used to guide the pencil electron beam. Subsequently, the PIC code in the CST Particle Studio is used to execute the simulation.[28] The simulation is carried out on a computer with a CPU frequency of 2.66 GHz. For example, an operating voltage of 20 kV takes about 79 h to stabilize the self-consistent oscillation processes. Figure 3 shows a cross section of the model where one can see that the pencil beam is focused well in the beam tunnel.

Also, we can obtain a signal generation at port 1 but not port 2. This is an obvious characteristic of a BWO. Figure 4 just shows the monitored signal at port 1.

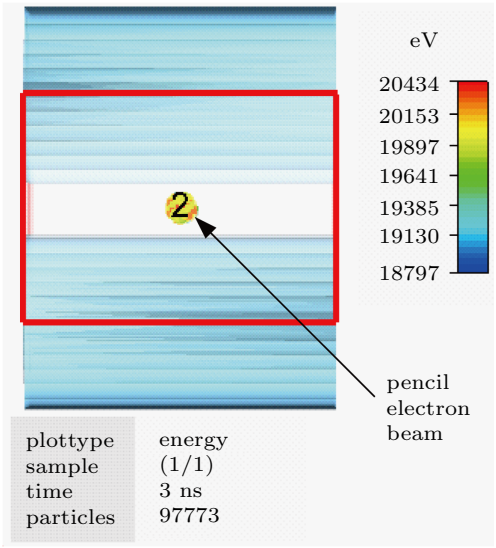


Fig. 3. (colour online) The cross section of the model about electron beam transmission.

One can see that the signal takes about 20 ns to become stable, and the output peak power is up to 5 W. The continuous wave (CW) power is half the peak power. Therefore, the corresponding interaction efficiency is over 1.25%. Its spectrum is illustrated in Fig. 4(b). From the spectrum it follows that the oscillation frequency is 217.2 GHz but not 220 GHz. This is a common phenomenon. One reason may be that a small beam velocity slows down when electrons go away from the emitter, due to a beam potential

depression near the emitter.[16] The potential depression is caused by a virtual cathode, formed by electron accumulation. So the practical beam velocity is a bit lower than the one set. Thus a signal with lower frequency will be synchronized to produce stable oscillation. The other reason is that in the beam wave interaction, there are two space charge waves propagating on the electron beam. One is a fast space-charge wave; the other is a slow space-charge wave. Actually, the backward wave interacts mainly with the slow space-charge wave. So the oscillation frequency is determined by the phase velocity of the slow space-charge wave. In one-dimensional space-charge wave theory,[29] the phase velocity of the slow space-charge wave is calculated by the following formula:

$$v_{\mathrm{p}}^{(\mathrm{s})} = \frac{v_{\mathrm{e}}}{1 + \omega_{\mathrm{p}}/\omega}, \tag{2}$$

where v_{e} is the electron beam velocity, ω_{p} is the plasma angular frequency, and ω is the signal angular frequency. Obviously, the v_{p} is lower than v_{e}. Therefore, the actual oscillation frequency is lower than the predicted design frequency.

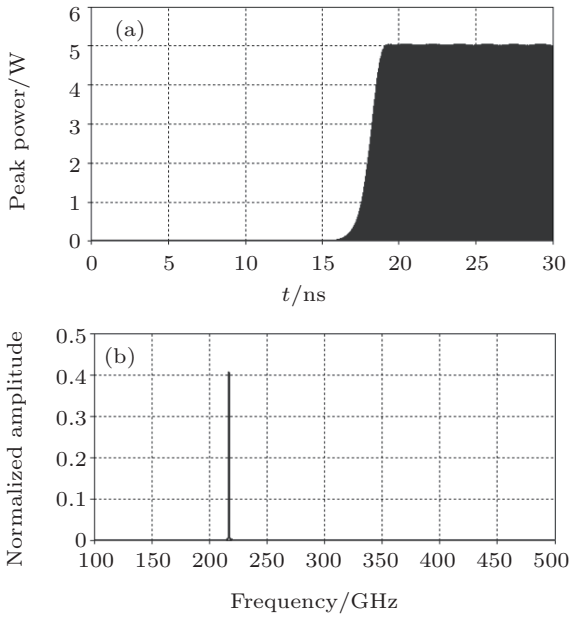


Fig. 4. Monitored signal at port 1. Panel (a) shows the variation of output peak power with time, and panel (b) indicates the spectrum of the output signal.

Subsequently, by changing the operating voltage from 17 kV to 26 kV, the power output performance of the BWO can be predicted as shown in Fig. 5. It shows that this BWO can produce more than 1-W CW power output in a frequency range from 210 GHz to 230 GHz. It is also predicted that the CW power produced at 220-GHz central frequency is over 2 W. Therefore, we can say that the BWO based on the above sine waveguide slow-wave structure can be used to generate high-power electromagnetic radiation at the millimeter wavelength or in a terahertz frequency band.

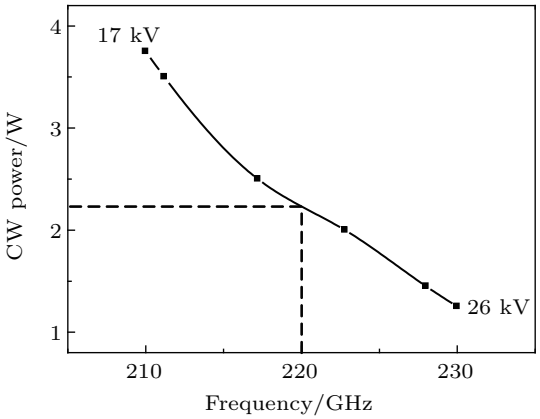


Fig. 5. BWO power output versus frequency.

5. Conclusion

In this paper, the sine waveguide can be considered as a promising slow-wave structure for a high-power millimeter wave or terahertz wave backward wave oscillator. The investigation results show that the sine waveguide backward wave oscillator can produce a watt-class output power ranging from 210 GHz to 230 GHz with a tuning operating voltage in a range from 17 kV to 26 kV and a pencil beam current of 10 mA. Therefore, this sine waveguide BWO will become a very promising watt-class millimeter wave or terahertz wave radiation source for future applications.

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