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# The Research on Backward Wave Oscillator with Wide Tunable Bandwidth and High Power

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***Abstract:*** *A continuous wave backward wave oscillator is studied in this paper. The design of the slowing wave system is completed through theoretical calculation and numerical simulation, and the slowing wave system is manufactured through precision machining. In order to improve the output power of the electron tube, a high resistance diode electron gun is used to produce a sheet electron beam with high emission current density. The test shows that the developed BWO can work in the frequency range of 250 ~ 310 GHz, and the output power is 20 mW to 42 mW.*

***Keywords:*** *backward wave oscillator (BWO), terahertz, slowing wave system, sheet electron beam.*

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## 1. Introduction

The millimeter wave and submillimeter wave technology has attracted more and more attention due to its potential applications in the radar [1], spectroscopy [2], communication engineers [3], the remote sensing field [4], and biomedical researchers [5]. In this region of the electromagnetic spectrum many special purpose sources, with combinations of strengths and weaknesses, have been developed. Vacuum electronics technology is an effective scheme to obtain high-power millimeter wave and submillimeter wave radiation sources. Numerous attempts have been made to expand the capabilities of such sources, include gyrotrons [6], free electron lasers (FELs) [7], traveling wave tubes (TWTs) [8], backward-wave oscillators (BWOs) [9], extended interaction oscillators (EIOs) [10], and extended interaction amplifiers (EIAs) [11]. BWO, which has the advantages of compact structure, small volume, light weight, working at room temperature, and high output power, has attracted more and more attention. However, the output power of BWO fluctuates greatly in the working frequency band, and even there is no signal output in some areas. This is very unfavorable to the popularization and application of the BWO. A miniaturized high-power terahertz radiation source is developed in this paper. The test results show that the developed BWO can have power output in the frequency range of 250 ~ 310 GHz.

## 2. Design of the Device

### 2.1. High Frequency System

Fig. 1 schematically shows the designed high frequency system of BWO, in which the SWS is installed into a rectangular waveguide with cross section of a×b. The planar periodic SWS supports the induced traveling electromagnetic wave interacting with the sheet electron beam. The synchronism condition of the BWO is located at the intersection point of the beam line of slope νe (the beam velocity) with the –1st order spatial harmonic among the spatial harmonic waves supported by the SWS. If the beam velocity νe is matched to the forward phase velocity νp of the wave, then the electron beam will bunch and encounter synchronously the decelerating phase of the wave's electric field Ez between each gap in the SWS, leading to a net loss of energy in the beam and a growth of the wave. The generated wave's energy travels backwards with the group velocity $v_g$, and couples into the output waveguide [9].

The synchronism condition of the BWO is set as $\varphi = k_z\ell = 1.6\pi$ for phase synchronism with the 5.5 keV electron beam. The period $\ell$ of 0.12 mm is derived from $\varphi = k_z\ell = 2\pi f_0\ell/v_e$, where $f_0$=290 GHz, and $v_e$ =0.146 c, here c is the speed of light in the free space.

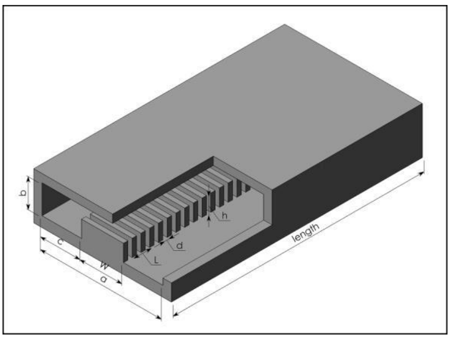


Fig. 1. Schematic of the high frequency system

There exist many harmonic waves supported by the planar SWS, it is crucial for successfully designing a BWO in the terahertz range to select the proper electromagnetic mode and avoid the mode competition. Through theoretical calculation and simulation, The $TM_{10}$ mode was used in the work, and its dispersion curves is shown in the Fig. 2 by using the geometric parameters listed in Table. 1.

Table 1. The geometric parameters

| ***High frequency system structure*** | ***Parameters*** |
|---|---|
| Width of waveguide (*a*) | 7.2 mm |
| Height of waveguide (*b*) | 1.8 mm |
| Period of grating ($\ell$) | 0.12 mm |
| Width of grating (*w*) | 2.5 mm |
| Height of slots (*h*) | 0.2 mm |
| Width of slots (*d*) | 0.06 mm |
| Length of grating (*L*) | 20 mm |

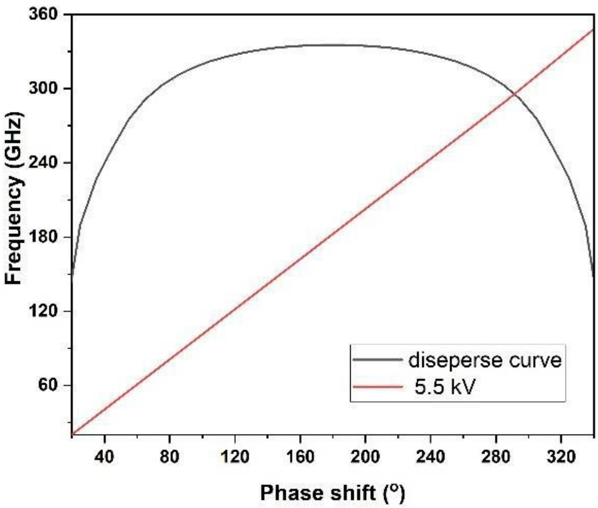


Fig. 2. Dispersion curves of the slowing wave system

## 2.2. The PIC Simulation

To validate the physical design of the BWO, its working characteristics is simulated by using a three dimensional fully electromagnetic particle-in-cell (PIC) code UNIPIC-3D [13]. The structure of SWS is made of free oxide copper. A sheet electron beam with cross section of 2.5 mm × 0.1 mm, whose acceleration voltage is 5.5 keV and beam current of 100 mA is adopted. The electron beam is just 0.01 mm above the grating, so that it can efficiently interact with the –1st spatial harmonic of backward wave. The constant magnetic field with 0.7 T can meet the requirement for beam confinement and noncollision with the grating.

The simulated results of the designed BWO are shown in Fig. 3 to Fig. 5. Fig. 3 depicts the electrons' phase space demonstrating the significant transfer of energy from the electron beam to the terahertz wave, whose working frequency is 290.63 GHz shown in Fig. 4. It is very close to that predicted by the dispersion curves given in Fig. 2. Fig. 4 also indicates that there is no noticeable other modes competition in the BWO. The power spectrum of the BWO output signal is shown in Fig. 5, which has an output power about 1.58 W.

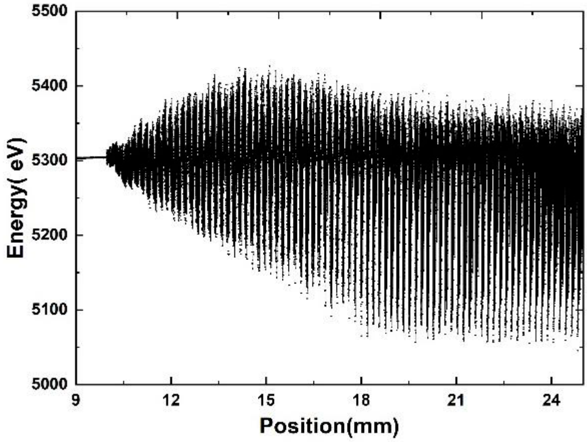


Fig. 3. The simulated phase space of electrons

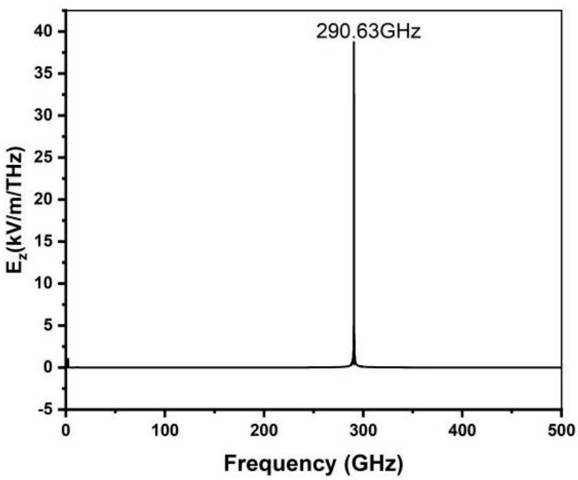


Fig. 4. The simulated output frequency of the deigned BWO

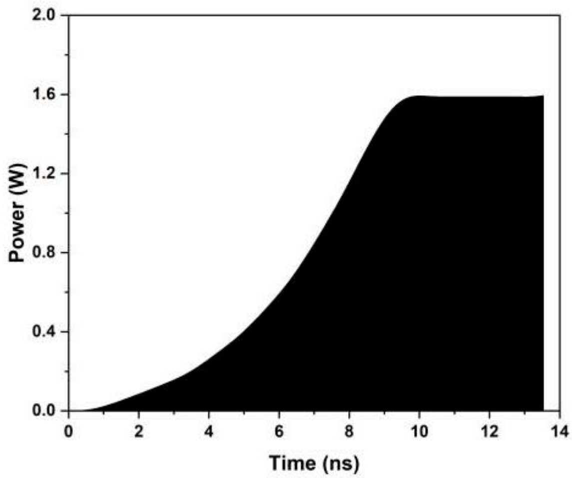


Fig. 5. The simulated output power of the device versus time

## 3. Fabricate and Test of the Device

The high precision SWS were processed by the Wire cut Electrical Discharge Machining (WEDM). Fig. 6 is the sample of SWS which was fabricated with the WEDM. Test results show that the processing error is less than 0.005 mm.

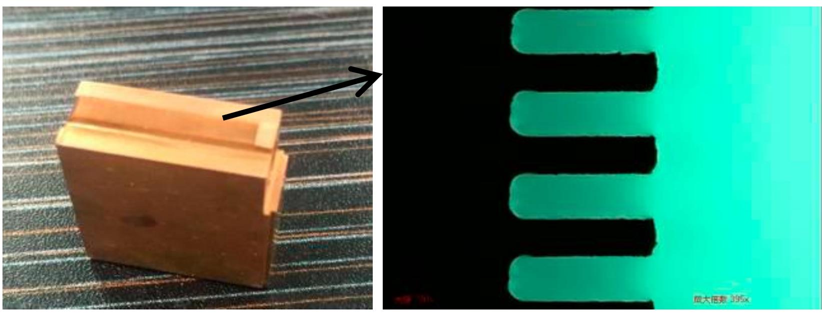

Fig. 6. The SWS fabricated with the WEDM

A high-perveance diode electron gun without compression to produce high quality sheet electron beam was used in the work. Fig. 7a is the assembled electron gun. A type of homemade barium tungsten cathode was used in the electron gun, shown in Fig. 7b. The test results show that the maximum current that the electron gun can output is 150 mA.

The BWO was assembled with electric resistance welding and argon-arc welding technology. After vacuum leak detection, the tube was continuously

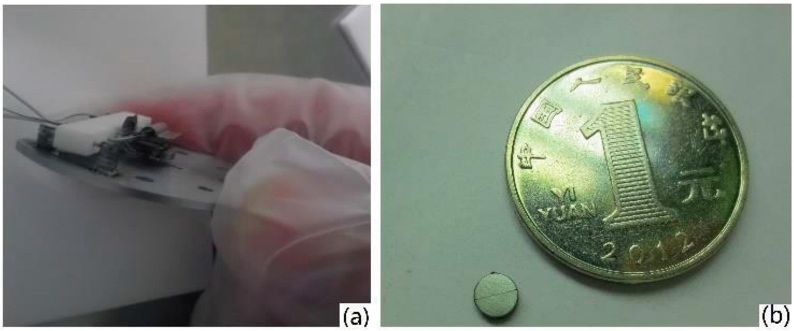

Fig. 7. (a) the electron gun, (b) the barium tungsten cathodes

evacuated to $2.0\times10^{-7}$ Pa by a turbo-molecular pump. The output characteristics of BWO are studied by using power meter and spectrum analyzer. When the electron gun current is 100 mA, the output power of the device at different frequencies is shown in Fig. 8. The frequency tuning range of the BWO is 250 GHz to 310 GHz. There is power output in the tuning frequency band, and the output power range is 22 mW to 42 mW.

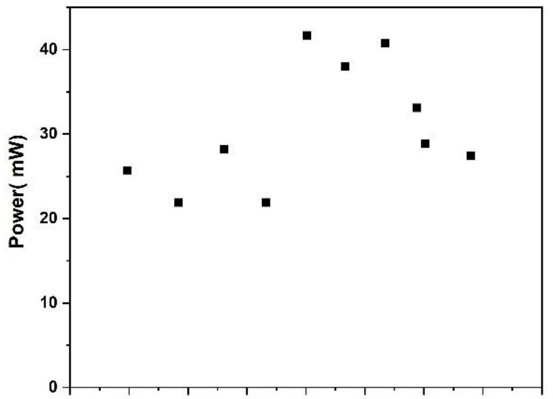

Fig. 8. The output characteristics of the BWO

## 4. Conclusion

A kind of BWO has been studied in the paper. Through theoretical analysis and computer simulation, the SWS of the BWO was designed to the planar grating structure, and the SWS was successfully fabricated with the WEDM. High quality of sheet electron beam was achieved through the high-perveance diode electron gun without compression. The BWO has been successfully assembled. In continuous wave mode, the operating frequency range of the BWO is 250 GHz to 300 GHz, and the output power is more than 22 mW.

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