Theory and Simulation of a Terahertz Single Grating Rectangular Waveguide Back-ward Wave Oscillator

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***Abstract*—A three dimensional (3-D) nonlinear analysis of the beam-wave interaction in the single-grating rectangular waveguide (SGRW) sheet-beam Back-ward Wave Oscillator (BWO) is presented, in which space-charge effects and conductivity losses are considered. The results are compared with those obtained by CST-PS code PIC simulations.**

I. INTRODUCTION

THE SGRW is a classical slow wave structure and has been used in a variety of millimeter, sub-millimeter and terahertz vacuum electron devices, such as backward wave oscillators (BWOs)[1], traveling wave tubes[2], clinitrons[3-5], etc. 1D and 2D nonlinear model had been proposed to investigate the clinitrons, in which the circuit fields were treated as cavity modes, and the fields' variation in *x*-direction was neglected[3-4]. The linear analysis can evaluate the linear growth rate and linear bandwidth properly. However, in reality, the tubes usually operate in the large signal region in order to obtain enough radiation power, and the nonlinear phenomenon during the interaction process, such as saturation and beam expansion, cannot be illustrated by the linear model. In this abstract, a 3D nonlinear field theory model is presented for the sheet beam SGRW BWO, the circuit fields are treated as travelling waves, space-charge effects and conductivity losses are considered. The methodology adopted in the well-established 3-D helix TWT code CHRISTINE 3-D [6], has been extended to our model. The Cartesian coordinate and the SI units are adopted in our model, all the electromagnetic fields except the dc space-charge fields can vary in *x*-, *y*-, and *z*-directions. The calculation results are compared with those obtained by CST-PS PIC code simulation.

Model of the SGRW BWO is shown as Fig.1, parameters for a 1.03THz SGRW SB BWO are as follows: structure period p=50μm, gap between grating d=25μm, grating height h=60μm, grating width a=240μm, beam width w=80μm, beam thickness t=20μm, beam and grating distance δ=5μm, beam tunnel height b=55μm, beam current I_0 =8mA. The material of the SGRW is set as copper with conductivity σ=2.2×107S/m. The external focusing magnetic field B^{ext} is 0.9 Tesla in *z*-direction to assure successful beam transportation. The model built in the CST-PS code PIC simulations is shown in Fig.2, the match between the SGRW and the rectangular waveguide is achieved by a coupler which is composed of a tapered section and a bended waveguide with the beam tunnel being inserted. The length of the interaction section is 132periods. In the range of 960GHz to 1100GHz, the calculated reflection coefficient S11 of the model is small (less than -15.5dB) and the signal coupled to the gun and the collector is less than -30dB.

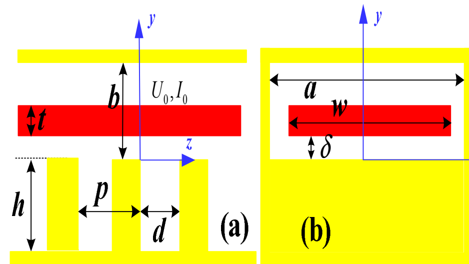

Fig.1. Model of SGRW SB interaction system. (a) axial cross section view; (b) transversal cross section view.

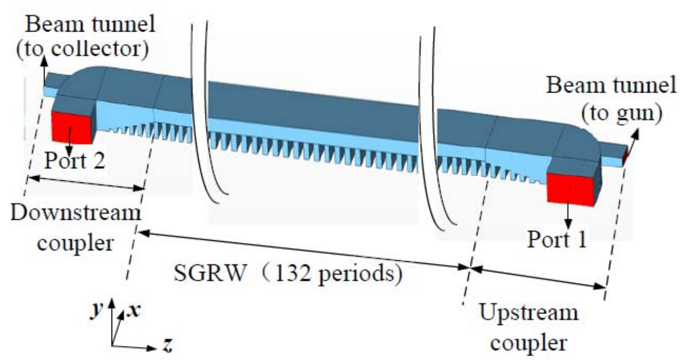

Fig.2. The model of the BWO simulated by CST.

II. RESULTS

Based on the above-mentioned parameters, the evolutions of the radiation power and representative particles' phases along the z-direction are shown in Fig. 3 and Fig. 4, respectively. The oscillation frequency is 1.03 THz and the beam voltage U0 is 12534 V. One can see that with an interaction length of 6.6 mm, radiation power of 112 mW can be reached at the entrance of the circuit. Note that the wave grows up in z-direction (Fig. 3), which is in the opposite of the beam transportation direction, while the velocity modulation of the beam and the bunching become intense gradually as z increases (Fig. 4). So the bunching is strong at the downstream end of the SWS, where RF fields are relatively weak, while the wave amplitude is great at the upstream end of the SWS, where the bunching is so not strong. Thus, the beam-wave interaction is inherently inefficient (the electron efficiency is 0.11% at 1.03 THz).

Particle preview in the CST-PS code PIC simulation for beam voltage U_0=12534V case is shown in Fig.5, one can see that accelerating electrons and retarding electrons are periodically arranged. The monitored peak power at the output port one are also shown here, the average power is 107mW. Its normalized spectrum shown here reveals the accurate operating frequency in this case is 1028GHz.

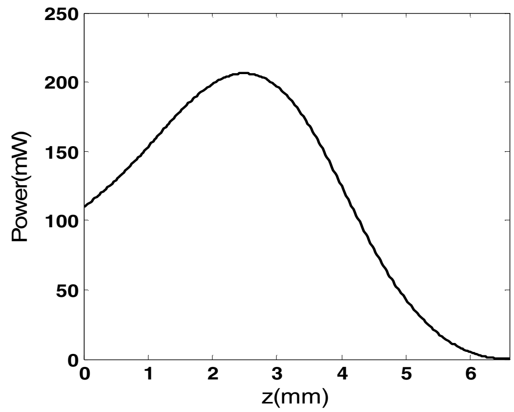

Fig.3. Evolution of the backward radiation power (f_0=1.03THz, U_0=12534V, I_0=8mA, σ =2.2×107S/m).

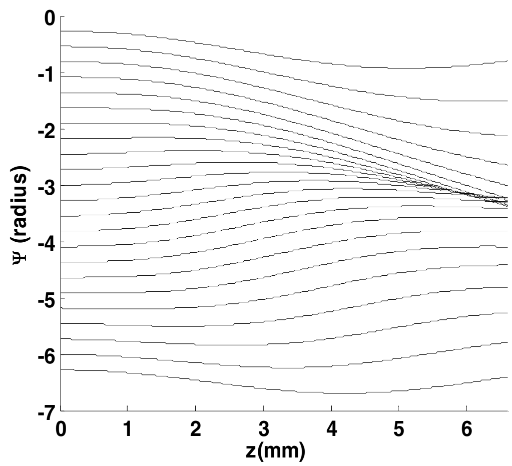

Fig.4. Evolution of the representative particles' phases (f0=1.03THz, U0=12534V, I0=8mA, σ =2.2×107S/m).

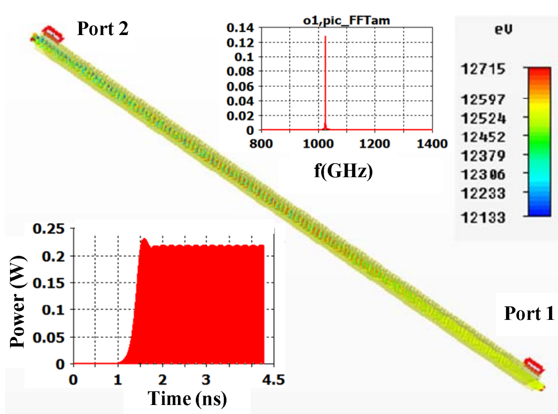

Fig.5. CST-PS PIC simulation results for beam voltage U0=12534V case.

By adjusting the beam voltage U_0 from about 9949V to 16534V while keeping other parameters fixed as the original values, the oscillation frequency can be tuned from 0.96THz up to 1.1THz. The output radiation power versus frequency is shown in Fig.6. Good consistency can be seen between the two methods, in which the CST-PS simulation results are lower than those of the theoretical model and the relative difference of both is less than 16%. Radiation power on the order of 0.1W can be reached in the operating frequency band. The numerical calculation results which ignore the space charge effects or conductivity losses are also given, one can see that the values obtained from the two methods are much higher than the 3D PIC simulation results and the discrepancies turn larger as the operating frequency goes up. So in terahertz frequency range, these two factors influence the device performance considerably and should be taken into account in order to make the model closer to practical situation.

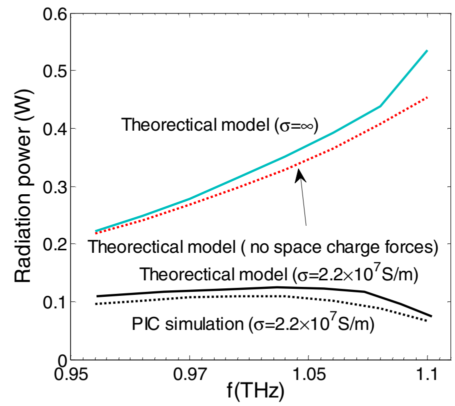

Fig.6. Radiation power versus frequency (U_0=9949~16534V, I_0=8mA).

III. Summary

Nonlinear analysis of the terahertz SGRW Cerenkov maser has been performed in this paper. For the 1.03THz BWO case, the theoretical calculation results of the radiation power are in good consistency with those obtained from the 3D particle-in-cell (PIC) simulations in the operating frequency band with the relative difference less than 16%. Radiation power of about 0.1W can be reached from 0.96THz to 1.1THz with the beam voltage adjustment from 9949V to 16534V (beam current I0=8mA, conductivity σ=2.2×107S/m, interaction length L=6.6mm).

IV. Acknowledge

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