# Simulations of a two-stream backward-wave oscillator with a slot-hole structure*

Shi Zong-Jun(史宗君)†, Tang Xiao-Pin(唐效频), Yang Zi-Qiang(杨梓强), Lan Feng(兰 峰), and Liang Zheng(梁 正)

*Terahertz Research Centre, School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu 610054, China*

(Received 20 March 2011; revised manuscript received 10 June 2011)

We study a two-stream backward-wave oscillator with a slot-hole structure at short millimeter waves with the help of a three-dimensional particle-in-cell simulation. In order to increase the interaction region of the electron beam, the efficiency and the output power, a slot-hole loaded rectangular waveguide structure used as the high-frequency system is proposed. Based on the mechanism of the backward-wave oscillator, a slow-wave oscillator with a frequency of 0.14 THz is designed. The simulations show that the output power and the efficiency of the oscillator can be enhanced due to the coupling between the two beams through the slot holes. The interaction efficiency is 5.18%, and the starting current density is below 5 $A \cdot cm^{-2}$ for the two beams. These attractive results indicate that, based on the two-stream backward-wave oscillator, we can get short millimeter wave sources with high power and low current density.

**Keywords:** slot-hole structure, short millimeter wave, two-stream backward-wave oscillator

**PACS:** 84.40.Fe, 07.57.Hm **DOI:** 10.1088/1674-1056/21/1/018401

## 1. Introduction

In recent years, vacuum tube radiation sources in the terahertz wave region, such as backward-wave oscillators (BWOs), travelling wave tubes and klystrons,[1,2] have attracted a great deal of interest in stimulated Cherenkov and transition radiation. For the conventional vacuum tubes, the efficiencies of high-frequency non-relativistic slow-wave devices, such as BWOs, are quite low. As a rule of thumb, the efficiency does not exceed 1% at the submillimeter wavebands.[3] Thus, efficiency enhancement of the sources has been the primary concern for a number of years. In non-relativistic slow-wave devices, the amplitude of the synchronous harmonic decreases with the increase in the distance from the structure surface, and only a thin layer of electrons moving close to the structure can efficiently interact with the high-frequency field. For short millimeter waves, the beam interacting thickness becomes thinner. To improve the properties of such types of devices, a variety of schemes have been proposed.[3−5] In those studies, because the slow-wave structure (SWS) is the key component of the vacuum electron source, obtaining a high-efficiency SWS is important for vacuum electron Cherenkov sources.[6−11]

For the surface plasmon structure,[12] an analysis presented in Ref. [13] showed that the two counter-stream electron beams not only lower the transition threshold from the spontaneous Smith–Purcell radiation to the stimulated one, but also increase the radiation intensity. Using two counter-stream electron beams can enlarge the interaction region sizes and increase the interaction efficiency, which is caused by the coupling between the two beams through the slot holes. In this paper, based on the concept of periodic hole-array structures,[12−14] a slot-hole loaded rectangular waveguide structure used as the high-frequency system of the BWO is proposed. Based on the slot-hole structure, the two-stream BWO is investigated with the help of a three-dimensional particle-in-cell (PIC) simulation.

This paper is organized as follows. Section 2 gives a description of the physical model. In Section 3 we show our PIC simulation results, and a brief conclusion is given in Section 4.

## 2. The physical model

A slot-hole loaded rectangular waveguide structure is given in Fig. 1, where $a$ and $b$ denote the width

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11075032 and 10975031).

†Corresponding author. E-mail: zongjunhao@yahoo.cn

© 2012 Chinese Physical Society and IOP Publishing Ltd

and the height of the rectangular waveguide, respectively; and $d$, $a_1$, $b_1$ and $h$ are the period, length, width and depth of the rectangular holes, respectively. In the model, the periodic slot-hole structure is located on the central plane (parallel to the $z$ axis) of the rectangular waveguide. The dispersion curves are analyzed using the HFSS code. Figure 2 shows the single-period model calculated by the HFSS.

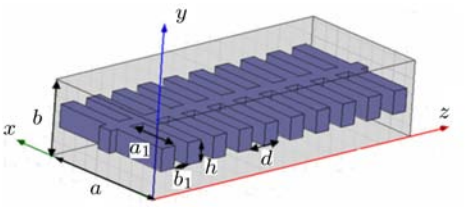



**Fig. 1.** (colour online) The structure of the slot-hole loaded rectangular waveguide.

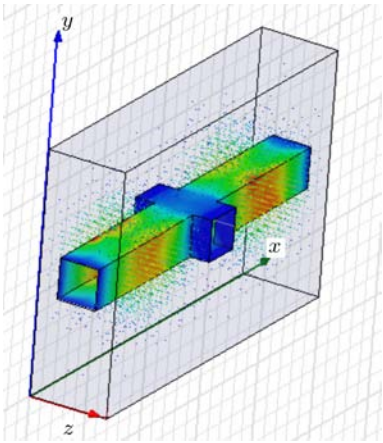



**Fig. 2.** (colour online) The HFSS single-period model.

In order to obtain a short millimeter wave source, the structural dimensions of the rectangular waveguide are assigned as follows: $a = 1.8$ mm, $b = 1.0$ mm. The dispersion curves of the fundamental mode for the structures are shown in Fig. 3. In Fig. 3(a), the dispersion curves with different periods (parameter $d$) are presented, which illustrate that the operating frequency decreases with the increase in $d$. Comparing the curves in Fig. 3(b), we find that the tops of the curves are strongly dependent on the lengths (parameter $a_1$) of the holes. The widths (parameter $b_1$) of the holes only influence the characteristics slightly, as shown in Fig. 3(c). The operating point shown in Fig. 3 is the intersection of the dispersion relation with the beam line for the 15 kV electrons. Obviously, it operates at the short millimeter waveband as the BWO. The operating mode from the view of the rectangular hole along the $y$ direction is the $TE_{y10}$. The low-frequency point of the dispersion curve is the cut-off frequency of the rectangular waveguide $TE_{10}$ mode, and the high-frequency point of the curve lies under the cut-off frequency of the rectangular hole $TE_{y10}$ mode. In this structure, the low cut-off frequency of the fundamental mode is controlled by the length of the rectangular waveguide.

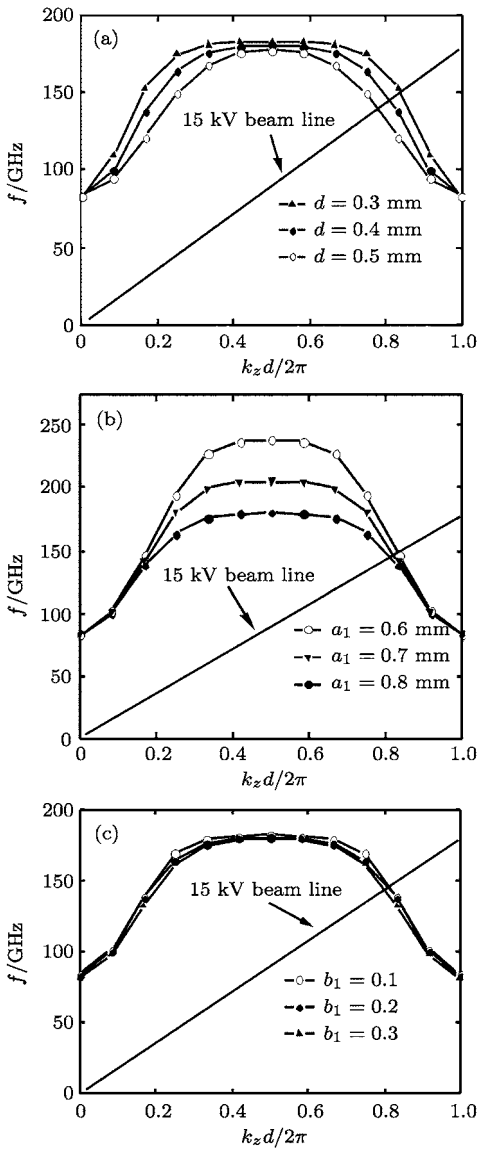



**Fig. 3.** Fundamental mode dispersion curves for the structures with (a) different periods, (b) different hole lengths and (c) different hole widths.

# 3. PIC simulations

## 3.1. Geometry and parameter simulations

The simulations are carried out using the CHIPIC code,[15] which is a finite-difference time-domain code designed to simulate plasma physics processes. The geometry used for the simulations is given in Fig. 4. It shows the $x$–$y$ and $x$–$z$ plane views of the simula-

tion geometry. The thickness of the electron beam is assigned to be $\delta_b = 0.1$ mm, and the spacing between the beam center and the slot hole is $\delta = 0.06$ mm. The beam current density with transverse dimensions of 1.6 $\times$0.1 mm is assigned to be 15 A/cm$^2$. The operating voltage and the operating current are 15 kV and 480 mA, respectively, and the number of periods is 52. The structure allows two electron beams in the interaction region. Consequently, a higher output power can be obtained for the oscillator.

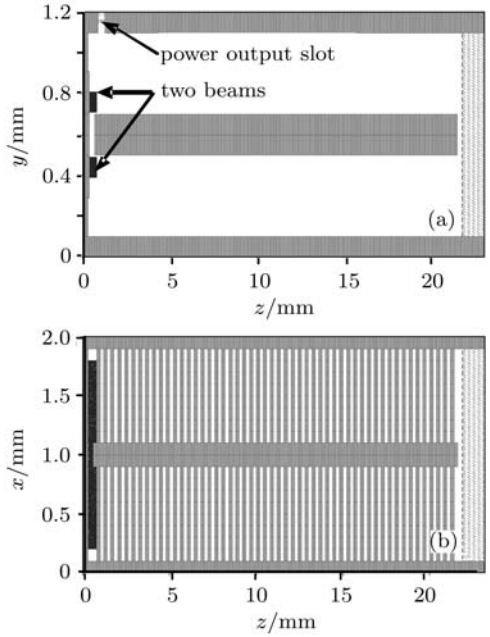



**Fig. 4.** The (a) $y$–$z$ and (b) $x$–$z$ plane views of the geometry used in the simulations.

## 3.2. Simulation results

First we carry out the simulations with two beams located at the surface of the slot-hole structure. The simulation results are as follows.

Figure 5 is the phase-space density distribution of electrons in the $x$–$z$ plane, and the bunching is evident. In order to obtain the operation frequency of the oscillator, we plot the $E_z$ field in the surface of the structure as a function of time.

Figure 6(b) is the corresponding fast Fourier transform (FFT) of Fig. 6(a). The operation frequency shown in Fig. 6(b) is 142.3 GHz, which is coincident with the frequency of the interaction point shown in Fig. 3. Figure 7 shows that the stable output power with two beams is 373 W in the time after about 1.5 ns, and the energy exchange efficiency is 5.18%. Fixing the electron energy at 15 keV, we sweep the beam current density as shown in Fig. 8. Note that the threshold current density for the two beams at 0.14 THz is below 5 A $\cdot$ cm$^{-2}$. Besides, the output power has a more rapid increase rate with the increase in current density. In addition, it is noticeable that saturation appears at a current density of 25 A $\cdot$ cm$^{-2}$. These numerical results indicate that the interaction for the structure tends to operate at a lower threshold.

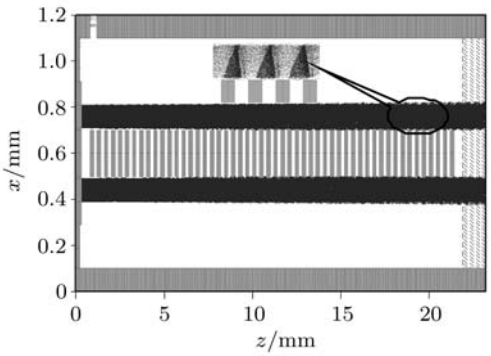



**Fig. 5.** The phase-space density distribution of electrons in the $x$–$z$ plane; bunching is evident.

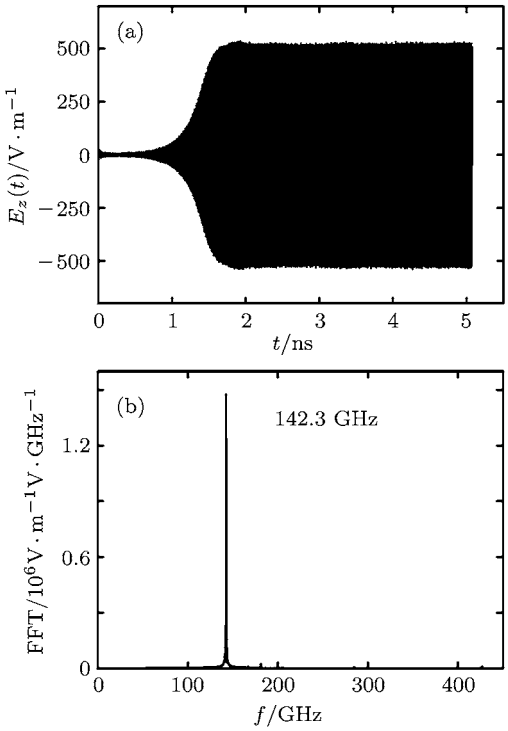



**Fig. 6.** (a) The time dependence of electric field $E_z(t)$ in the surface of the structure, and (b) the corresponding FFT of the time signal.

We also simulate the single beam located at the surface of the slot-hole structure with the same operating parameters. For the single beam, the current and current density are the same as those of the two beams, while the thickness of the electron beam is 0.2 mm.

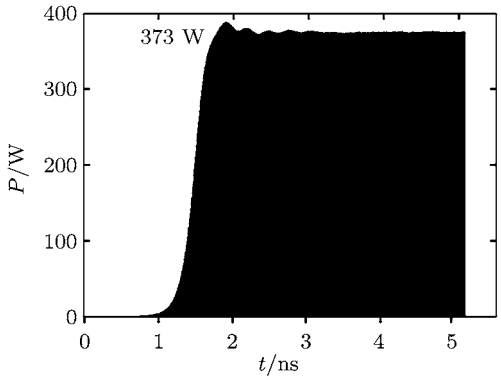



**Fig. 7.** Power evolution as a function of time for the two beams.

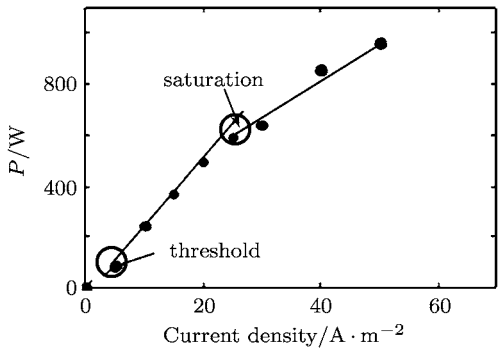



**Fig. 8.** Power evolution as a function of current density for the two beams.

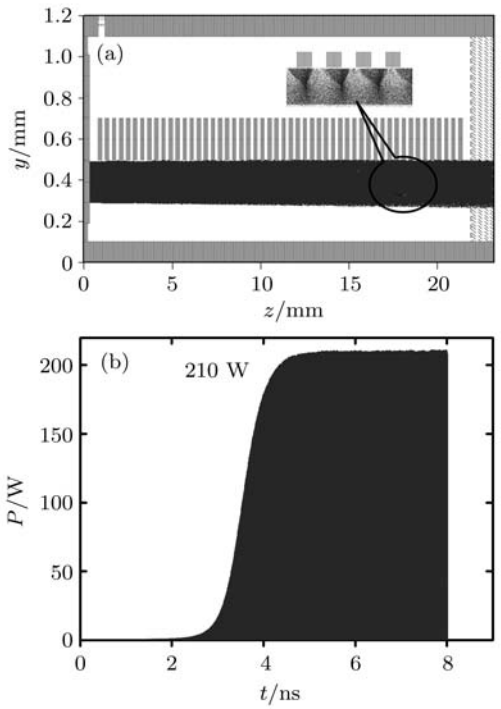



**Fig. 9.** Simulations of the single beam: (a) the phase-space density distribution of the electrons, and (b) power evolution as a function of time.

Figure 9 shows the phase-space distribution and the output power for the single beam. The stable output power is 210 W in the time after about 4.5 ns, and the efficiency is 2.92%. The results show that the output power of the single beam is less than that of the two beams. In addition, from Figs. 7 and 9(b), it is noticeable that the saturation time is increased when using the single beam. This is due to the single beam interacting with the surface mode, which decreases the effective interaction area and leads to a reduction in the beam-wave couple impedance.

### 3.3. Analyses of the simulation results

What causes the above-mentioned physical phenomenon? We assume that the fields in the holes can couple with each other to form an inner mode at the center of the structure and support a surface spatial harmonic wave, so the efficiency of such an interaction can reach an attractive value for the two electron beams. In order to demonstrate the couple process, we present a contour map of the longitudinal electric field $E_z$ in the cross section of $z = 10.3$ mm in Fig. 10. From the contour map at $t = 0.16$ ns shown in Fig. 10(a), it is clear that both sides of the holes can support the surface modes. The result in Fig. 10(b) shows that the surface modes can produce an inner mode at the center of the structure through the slot holes.

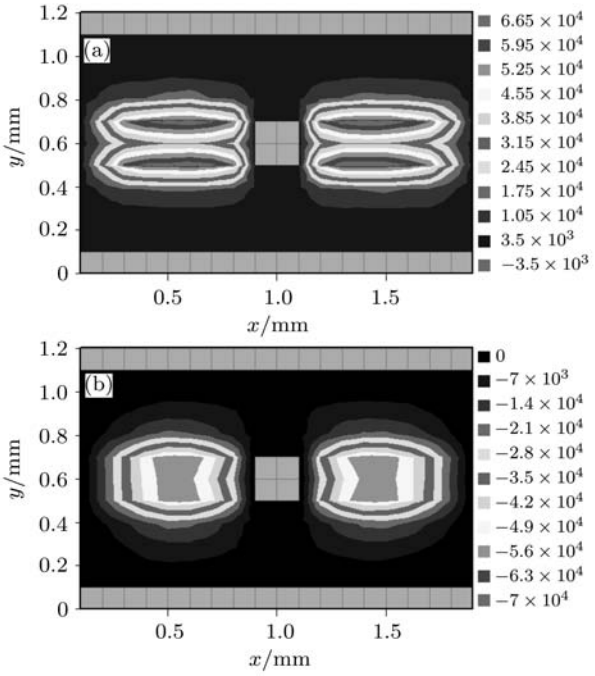



**Fig. 10.** Contour map of longitudinal electric field $E_z$ in the cross section of $z = 10.3$ mm at (a) $t = 0.16$ ns and (b) $t = 5.47$ ns.

To further analyze the interaction, we also investigate the energy and the current evolutions of the single beam and the two beams. From Figs. 11(a) and 11(b), according to the difference in the beam average energy

between the accelerating and the decelerating fields, we note that the mean energy loss due to the beam–wave interaction is about 1 keV for the two beams and about 0.6 keV for the single beam. Comparing Figs. 12(a) and 12(b), we can find that the modulated amplitude of the current evolution with the two beams is larger than that with the single beam. Through analyses of the simulation results, we find that the coupling interaction between the two beams and the surface mode in the slot holes plays a role in enhancing the output power. Besides, by using the two beams, the effective interaction space is enlarged. This is also a key factor in enhancing the output power. These attractive results indicate that, based on the two electron beams–slot holes interaction, we can obtain high-power low-current-density THz sources.

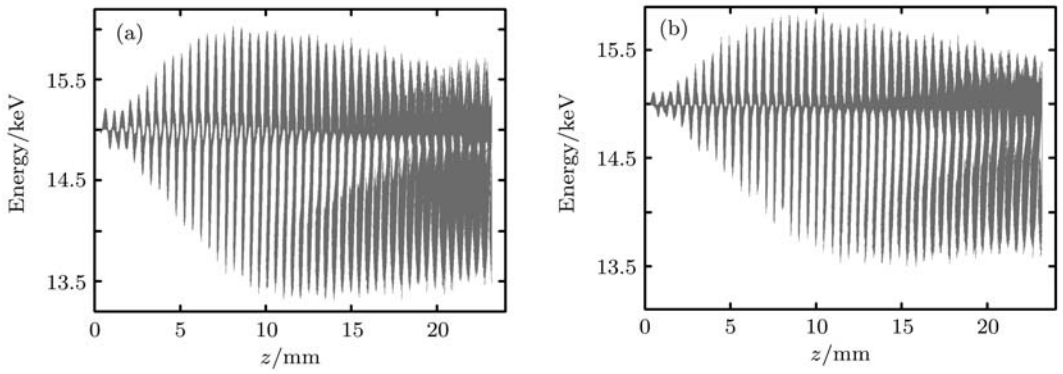



**Fig. 11.** The energy evolutions of electrons for (a) two beams and (b) a single beam.

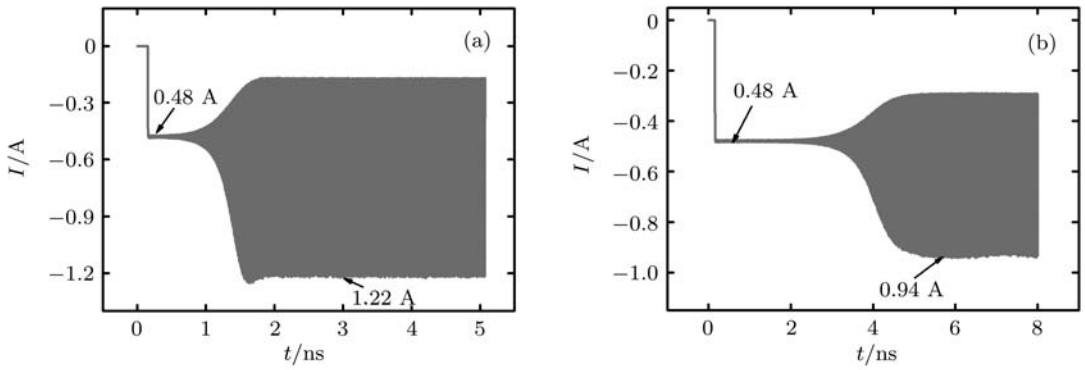



**Fig. 12.** Current evolutions as a function of time for (a) two beams and (b) a single beam.

## 4. Conclusion

In this work, we presented simulations of a two-beam BWO with a slot-hole structure at the short millimeter waveband. The PIC simulations demonstrate an attractive efficiency value for the BWO due to the coupling between the two beams. Compared with the short millimeter wave radiation sources based on the traditional oscillator, the starting current density of the interaction concerned in this paper can be reduced dramatically, and the simulations show that at 0.14 THz the starting current density is below 5 $\mathrm{A \cdot cm^{-2}}$.

## References

[1] Dobroiu A, Yamashita M, Ohshima Y N, MoritaY, Otani C and Kawase K 2004 *Appl. Opt.* **43** 5637
[2] Lewen F, Gendriesch R, Pak I, Paveliev D G, Hepp M, Schieder R and Winnewisser G 1998 *Rev. Sci. Instrum.* **69** 32
[3] Bratman V L, Dumesh B S, Fedotov A E, Makhalov P B, Movshevich B Z and Rusin F S 2010 *IEEE Trans. Plasma Sci.* **38** 1466
[4] Liu W X, Yang Z Q, Liang Z, Li D and Imaskai K 2008 *IEEE Trans. Plasma Sci.* **36** 748
[5] Liu W X, Yang Z Q, Liang Z, Li D and Imaskai K 2007 *Nucl. Inst. Methods* A **570** 171
[6] Larry R B and Shin Y M (US Patent) 60979392 [2007-10-12]
[7] Shin Y M and Larry R B 2008 *Appl. Phys. Lett.* **92** 091501
[8] Shin Y M, Larry R B and Luhmann N C 2009 *IEEE Trans.* **56** 706

[9] Shin Y M, So J K, Jang K H, Won J H, Srivastava A and Park G S 2007 *Appl. Phys. Lett.* **90** 031502

[10] Yin H R, Gong Y B, Wei Y Y, Gong H R, Yue L N, Lu Z G, Huang M Z and Wang W X 2007 *Chin. Phys.* **16** 2737

[11] Gao X, Yang Z Q, Cao W P and Jiang Y N 2011 *Chin. Phys.* B **20** 030703

[12] Ebbesen T W, Lezec H J and Ghaeml H F1998 *Nature* **391** 667

[13] Park D J, Choi S B, Ahn K J, Kim D S, Kang J H, Park Q H, Jeong M S and Ko D K 2008 *Phy. Rev.* B **77** 115451

[14] Zhang Y X, Hu M, Yan Y, Zhong R B and Liu S G 2009 *J. Phys.* D: *Appl. Phys.* **42** 045211

[15] Di J, Zhu D J and Liu SG 2005 *Electromagnetic Field Algorithm of the CHIPIC Code*