Improvement of Grating for Smith-Purcell Device

D.Li *, K. Imasaki
Institute for Laser Technology, Osaka 565-0871, Japan
X. Gao, J. Hou, Z.Yang
University of Electronic and Science Technology, Chengdu 610054, China Gun-Sik Park
Seoul National University, Seoul 151-747, Korea
* Email: dazhi_li@hotmail.com

Abstract: It is known that a grating plays a vital role in the development of a terahertz Smith-Purcell device. The transverse diffusion of optical mode in a general grating is regarded to weaken the beam-wave interaction. In this paper, a sidewall grating for the Smith-Purcell device is proposed. The optical beam can be confined between the side walls to avoid transverse diffusion, so it is possible to enhance the coupling of the optical mode with the electron beam. With the help of three-dimensional particle-in-cell simulations, it has been shown that, comparing with the general grating, the usage of a sidewall grating improves the growth rate and dramatically shortens the time for the device to reach saturation. It is also found that the sidewall grating holds the potential to reduce the start current for the operation of a Smith-Purcell device. We also simulated an ongoing experiment, and predicted the radiation characteristics and the current threshold for the device to start oscillation. This is not only an improvement of grating, but also helpful for further understanding the transverse effect of the grating optical mode.

Keywords: terahertz radiation, sidewall grating, Smith-Purcell radiation, three-dimensional simulation

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1. Introduction

In recent years, terahertz radiation sources are actively researched and developed due to a variety of applications in biophysics, medical and industrial imaging, nanostructures, and material science [1]. Electron-beam driven devices, such as backward-wave oscillators, synchrotrons, gyrotron and free-electron lasers, are promising sources of terahertz radiation. Some synchrotrons with short electron bunches, such as BESSY II in Berlin [2] and the recirculating linac at Jefferson Laboratory [3], produce broadband radiation out to about 1 THz with tens of watts average power. And conventional free-electron lasers also operate in the terahertz region at dedicated facilities, with up to hundreds of watts average power [4, 5]. However, both synchrotrons and conventional free-electron lasers require large facilities, which are expensive and not convenient to use. At present, backward-wave oscillators are compact and relatively inexpensive. At present, backward-wave oscillators are available to produce milliwatts of power from 30 to 1000 GHz [6]. The typical backward-wave oscillators run with a magnetically guided, high-current, low-energy electron beam in a compact, tightly enclosed, slow-wave structure. Actually, a tabletop Smith-Purcell device is an interesting alternative source of terahertz radiation [7, 8]. A general Smith-Purcell device operates with a low-current, medium-energy, tightly focused electron beam with no guide field. In many ways these devices are similar to backward-wave oscillators and traveling-wave tubes, but they use an open grating as the slow-wave structure.

The research on a Smith-Purcell radiation device has become very active since it is promising in the development of a high power, tunable and compact terahertz radiation source [7-10]. The wavelength of this radiation can be tuned by varying the angle of observation or the energy of the electron beam. The low-power incoherent Smith-Purcell radiation can be coherently enhanced by the electron bunching. In addition to the Smith-Purcell radiation, it is predicted that the evanescent wave can emit at the ends of the grating, with a wave length longer than that of the Smith-Purcell radiation. The super-radiant Smith-Purcell radiation has been observed experimentally at Dartmouth college [7]. The output power shows superlinear dependence on the current when the beam current is over a threshold. The super-radiant radiation is regarded as the result of electron beam bunching, induced by the strong interaction of the continuous beam with the evanescent wave propagating along the grating surface.

The Dartmouth experiment implies that the super-radiant Smith-Purcell radiation can be realized by an open grating, which is different from the conventional cavity structure [11]. The two-dimensional analysis shows that the electron beam interacts with the evanescent wave near the grating surface, and the device can operate at two different modes, traveling wave amplifier or backward wave oscillator, depending on the surface wave which is forward wave or backward wave [12-14]. The Smith-Purcell backward wave oscillator can operate without any external feedback when the beam current exceeds a threshold, hereafter we call it start current [15]. Some physical problems about the Smith-Purcell experiment are not well understood yet. The prediction of the start current based on the two-dimensional analysis is unsuccessful because the three-dimensional effect plays an important role. The analysis including the effects of transverse diffraction in the optical beam tells that the three-dimensional effects substantially reduce the gain, and the Smith-Purcell backward wave oscillator may not be possible to operate with an infinitely wide grating due to the diffusion of the optical beam [16]. Most recently, on the basis of their three-dimensional analysis, Kwang-Je Kim and Vinit Kumar predicate a very stringent requirement to the electron beam for the Smith-Purcell backward wave oscillator to operate [15].

In this paper, we improve a general grating by adding two side walls, hereafter, we call it sidewall grating. It is expected that the optical beam be confined between the two sidewalls to keep a good coupling with the electron beam during the interaction. By such a way, the requirement on the electron beam is possible to be relaxed; the growth rate could be improved and consequently the start current could be reduced. Furthermore, such a configuration adds no impact on the super-radiant Smith-Purcell emission, which emits over the grating at a certain angle relative to the direction of electron beam propagation, because there is not a top plane above the grating. The detailed characteristics of the super-radiant Smith-Purcell radiation can be found in previously published papers [14,17,18]. With the help of three-dimensional particle-in-cell simulations, we compare the general grating (without sidewall) with the sidewall grating and then show the advantages of the latter one. We also simulated an ongoing experiment to predict the star current and radiation characteristics. The growth rate determined by the simulation is in agreement with that worked out analytically.

2. Simulation description

A general grating with rectangular form is as shown in Fig. 1. The surface of the grating is assumed to consist of a perfect conductor whose grooves are parallel and uniform in the y-direction. A cylindrical electron beam is supposed to fly over the grating in the z direction. Different from the two-dimensional model, the grating is limited in the transverse direction, i.e., it has limited width. Obviously, the optical mode will diffract over the transverse edge of the grating. To avoid the diffusion of the optical mode in such a grating, we improved this structure by adding two side walls as shown in Fig. 2. The wall should be high enough over the electron beam in order to effectively confine the optical mode. Main parameters are

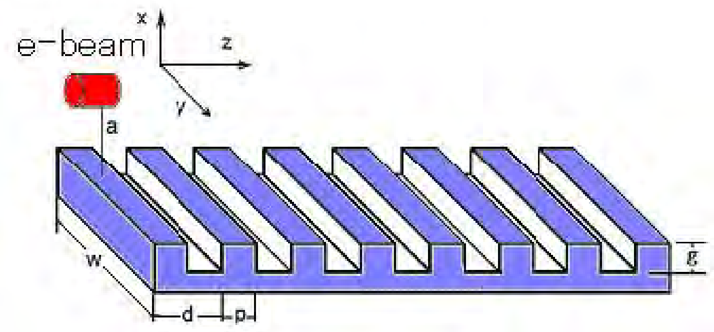

Fig.1 A general grating with rectangular form

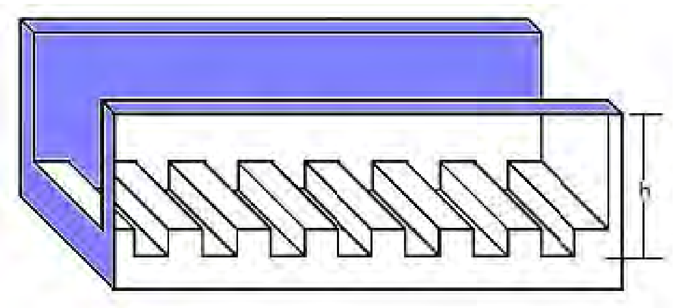

Fig.2 A sidewall grating model

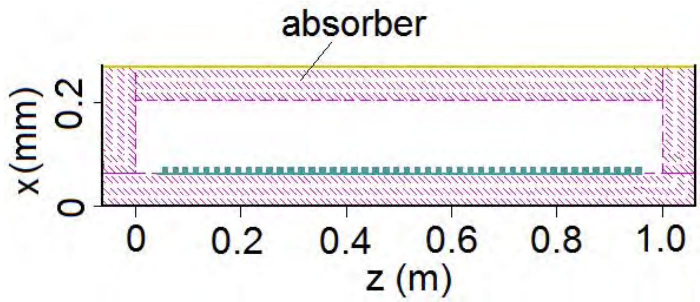

Fig.3 Simulation box built by MAGIC code

grating period	d	2 cm
ridge width	p	1 cm
groove depth	g	1 cm
period number	N	46
grating width	w	10 cm
sidewall hight	h	14 cm
beam hight	a	2 mm
beam radius	r	2.5 mm
beam energy	E	100 KeV

Table 1 Main parameters

summarized in table 1. By these parameters the electron beam interacts with the backward wave, and the device operates as a backward wave oscillator. The synchronous evanescent wave is with the frequency of 4.5 *GHz*. Details can be found in our previous work [18]. Simulations are performed by using the three-dimensional particle-in-cell code, MAGIC [19], developed by Mission Research Corporation. It is a finite-difference, time-domain code for simulating processes that involve interactions between space charge and electromagnetic fields. The grating is set in the centre of the bottom of a vacuum box bounded by an absorption region as shown in Fig. 3. A continuous beam produced from a cathode placed upstream end moves along the *z*-axis. The simulation area is divided into a mesh with a rectangular cell of very small size in the region of beam propagation and large in the rest. The simulation is performed in the gigahertz region for the convenience to run the code, and we believe the physics applies to the terahertz regime.

3. Simulation results

The observation of the super-radiant Smith-Purcell radiation requires a large simulation box to realize far-field detection, which is time consuming. To the problem of interest in this paper, the far-field detection is not necessary. The result of the beam-wave interaction is directly reflected by the evolution of the electromagnetic field of the evanescent wave, such as the longitudinal component of electric field Ez. We simulated the general grating and sidewall grating respectively and illustrate the evolution of Ez in Fig. 4. From previous investigations we know that, when certain conditions are satisfied, the electric field Ez indicates the processes from spontaneous radiation, as well as exponential growth to saturation. In Fig.4, it is shown that for the case of 0.5 *A* electron beam, the general grating device cannot reach the saturation even over 500 *ns* while the sidewall grating device saturates at about 110 *ns*; for the case of 0.6 *A* electron beam, the general grating device saturates at around 400 *ns* while the sidewall grating device saturates at 90 *ns*. Apparently, the time required to get saturation is dramatically reduced. Furthermore, by the sidewall grating the amplitude of the electric field is also improved, which means a higher output of radiation.

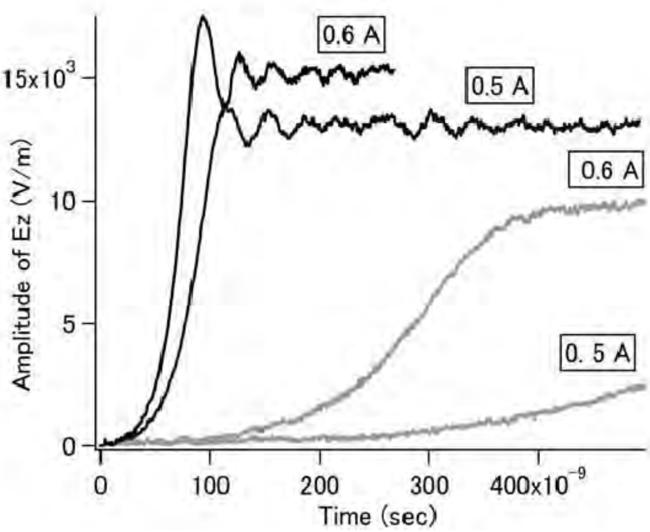

Fig.4 Evolution of amplitude of electric field Ez(gray curves for general grating and black curves for sidewall grating.)

The event that the electric field experiences the exponential growth means that the electron beam is bunched from the strong interaction with the evanescent wave. In another word, the device can oscillate. Based on this point of view, we can find the start current by gradually varying the current value and observe the evolution of the electric field as is shown in Fig. 5 and Fig.6, respectively. In Fig.5, we see that the exponential growth is not shown when the current is below 0.3 *A*, and based on this fact, we can give a crude estimate of the start current as 0.2 *A*, which is two times smaller than the general grating case 0.4 *A* as shown in Fig. 6. A much lower start current could be expected by optimizing the width between the two sidewalls.

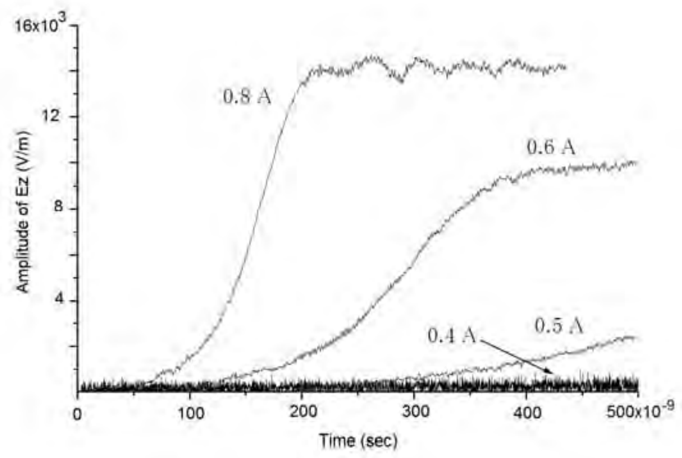

Fig.5 Evolution of amplitude of electric field Ez for general grating for various beam currents.

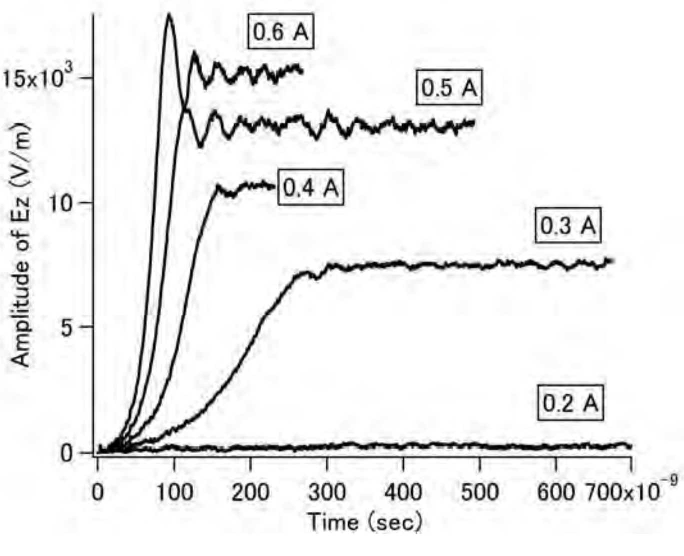

Fig.6 Evolution of amplitude of electric field Ez for sidewall grating for various beam currents.

The transverse distribution of the electric field Ez is worked out through recording the amplitude of Ez along the transverse direction. We use 0.6 *A* electron beam in this simulation and make a series of observation points with separation of 0.5 *cm* along a line of transverse direction (y-axis direction)at the centre of the longitudinal grating direction (z-axis direction). The observation line is 1 *mm* above the grating surface along the x direction, and 1 *mm* below the bottom edge of the electron beam. The simulation results are given in Fig. 7. The electric field Ez in a general grating illustrates a wide transverse profile and it extends beyond the edges of the grating (see Fig. 7), which predicts a bad coupling with the electron beam. That is the reason why a general grating device is hard to oscillate. However, The electric field Ez in a sidewall grating comes down to zero at the edges of the grating and its central amplitude is higher than that of the general grating, illustrating a confined profile, which holds the ability to enhance the beam-wave interaction and consequently relax the requirements on electron beam for Smith-Purcell device operation.

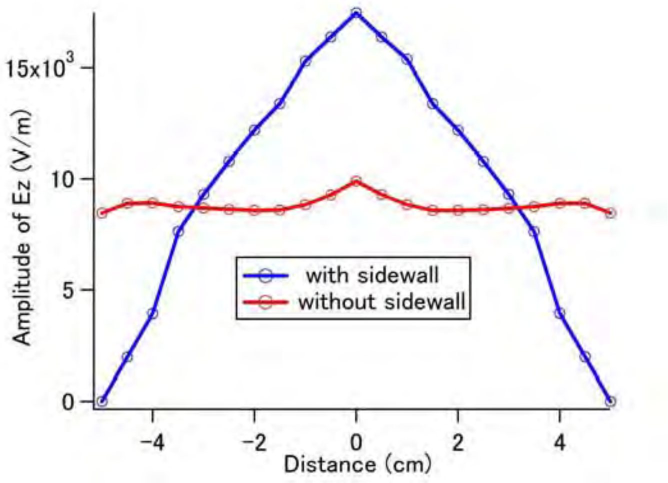

Fig. 7 Transverse profile of Ez

4. Simulations for an ongoing experiment

An ongoing experiment on sidewall grating is carried out at Vermont Photonics. Their grating model is same to that mentioned above, and we have chance to simulate a practical experiment. The main parameters used in their experiment are given in table 2. The grating and sidewall are supposed to be perfect conductor, so the surface loss is not involved in the simulation. We simulate 5 *mA*, 7 *mA* and 10 *mA* for the electron beam current, and the evolution of magnetic component is as shown in Fig. 8. It takes more time (more than 14 *ns*) for the 5 *mA* case to reach saturation than the 10 *mA* case (4 *ns*). Anyway, it illustrates the exponential increase for the 5 *mA* case, and we can deduce that the start current for this device should be lower than 5 mA, based on the reason mentioned above. From Fig.8, we can deduce the growth rate for each current value, and the results are compared with the analytical calculation carried out by Brau and his coworkers [16], as shown in Fig.9. Obviously, the simulation results are in agreement with the analytical calculations. The energy spectrum for the evanescent wave is given in Fig. 10. The peak of the evanescent wave is at 408 *GHz*, which is one of the goals to search in this experiment. As it is known, the super-radiant Smith-Purcell radiation should radiate at the harmonics of the evanescent wave because of the electron bunching [12]. Therefore, the super-radiant radiation will emit in the frequency of 816 *GHz*, at the angle of 45.3 degree from the electron beam travelling direction [12-14].

Groove depth	0.226 mm
Groove width	0.061 mm
Grating Period	0.157 mm
Grating width	0.5 mm
Beam energy	30 KeV
Sidewall height	0.6 mm

Table 2 Main parameters for simulation

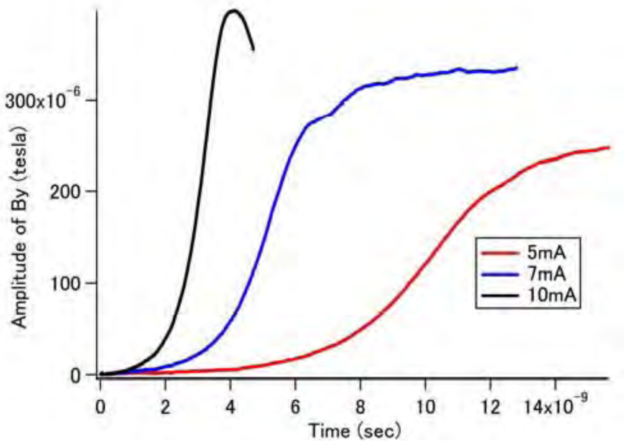

Fig. 8 Evolution of magnetic field Bz

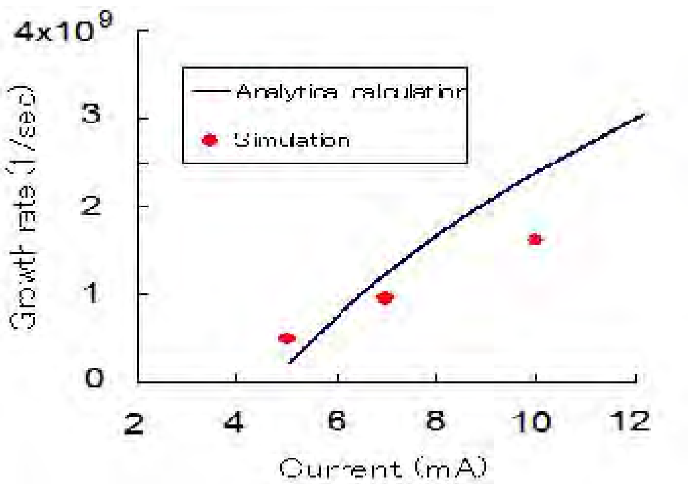

Fig.9 Growth rate

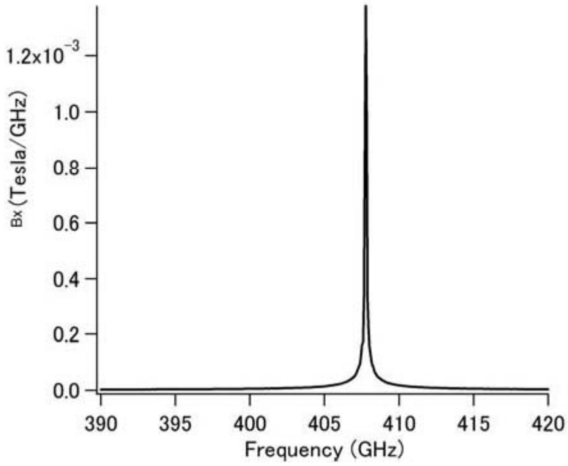

Fig. 10 Radiation of evanescent wave (case of 5A)

5. Conclusions

In order to improve the performance of Smith-Purcell device, we proposed a sidewall grating for these kinds of devices to realize effective beam-wave interaction. The Smith-Purcell backward wave oscillator based on the sidewall grating is investigated through particle-in-cell simulation. In comparison with the general grating, the sidewall grating can lower the start current, improve the output and reduce the time for device to oscillate. This research is not only an improvement of a grating, but also a great help to understand the transverse effect of a grating optical mode. Besides, we also studied an ongoing experiment concerning the sidewall grating. With the practical parameters, we performed simulations and predicted the start current, the frequency characteristics of the evanescent wave and the feature of super-radiant Smith-Purcell radiation.

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References

[1] S. P. Mickan and X.-C. Zhang, *Int. J. High Speed Electron*. Syst. 13, 601, (2003).

[2] M. Abo-Bakr, J. Feikes, K. Holldack, G. Wuestefeld, and H.-W. Huebers, *Phys. Lett*., 88, 254801, (2002).

[3] G. P. Williams, *Rev. Sci. Instrum.* 73, 1461, (2002).

[4] G. Ramian, Nucl. Instrum. *Methods Phys. Res., Sect.* A318, 225, (1992).

[5] H. Koike, M. Sobajima, V. M. Popik, M. Yokoyama, F.Oda, M. Kawai, K. Toyoda, H. Kuroda, and K. Nakai,

Nucl. Instrum. *Methods Phys. Res., Sect.* A 507, 242, (2003).

[6] A. Dobroiu, M. Yamashita, Y. Ohshima, Y. Morita, C. Otani, and K. Kawasi, *Appl. Opt*. 43, 5637, (2004).

[7] J.Urata, M. Goldstein, M. F. Kimmitt, A. Naumov, C. Platt, and J. E. Walsh, *Phys. Rev. Lett.* 80, 516, (1998).

[8] H. L. Andrews and C. A. Brau, *Phys. Rev. ST accel. Beams* 7, 070701, (2004).

[9] A. Gover, *Phys. Rev. ST accel. Beams* 8, 030701, (2005).

[10] S. E. Korbly, A. S. Kesar, J.R. Sirigiri, and R. J. Temkin, *Phys. Rev. Lett.* 94, 054803, (2005).

[11] R.P.Leavitt, D.E. Wortman and C.A. Morrison, *Appl. Phys. Lett*. 35, 363, (1979).

[12] H. L. Andrews, C. H. Boulware, C. A. Brau, and J. D. Jarvis, *Phys. Rev. ST Accel. Beams* 8, 050703, (2005).

[13] J. T. Donohue and J. Gardelle, *Phys. Rev. ST Accel. Beams* 8, 060702, (2005).

[14] D.Li, K. Imasaki, Z. Yang and Gun-Sik Park, Nucl. Instrum. *Methods Phys. Res.* A572, 948, (2007).

[15] Vinit Kumar and Kwang-Je Kim, *Phys. Rev. E*73, 026501, (2006).

[16] H. L. Andrews and C. A. Brau, *private communications*.

[17] D. Li, Z. Yang, K. Imasaki and Gun-Sik Park, *Phys. Rev. ST Accel. Beams* 9, 040701, (2006).

[18] D. Li, Z. Yang, K. Imasaki and Gun-Sik Park, *Appl. Phys. Lett.* 88, 201501, (2006).

[19] L. Ludeking, ‘‘The MAGIC User’s Manual.’’