SMITH-PURCELL FREE-ELECTRON LASER WITH SIDEWALL GRATING*

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Abstract

A sidewall grating for the Smith-Purcell free-electron laser is proposed to enhance the coupling of the optical mode with the electron beam and consequently relax the stringent requirements to 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 free-electron. The simulations for a practical experiment are also reported.

INTRODUTION

Recently, the research on a Smith-Purcell (SP) free-electron laser became very active since it is promising in the development of a high power, tunable and compact terahertz radiation source [1-7]. The Dartmouth experiment implies that the super-radiant SP radiation can be realized by an open grating [1], which is different from the conventional cavity structure [8]. 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 (TWA) or backward wave oscillator (BWO), depending on the surface wave is forward wave or backward wave [9-11]. The Smith-Purcell BWO can operate without any external feedback when the beam current exceeds a threshold value, hereafter we call it start current [12]. 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 BWO may not be possible to operate with an infinitely wide grating due to the diffusion of the optical beam [13]. 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 BWO to operate [12].

In this paper, a sidewall grating is proposed to enhance the coupling of the optical beam with the electron beam. 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. 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. 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 SP emission can be found in published papers [14,15]. 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. At last, we simulate an ongoing experiment to predict the start current and so on..

GENERAL SIMULATION

Simulations are performed by using the three-dimensional MAGIC [16], a code for simulating processes involving interactions between space charge and electromagnetic fields.

General Model

The simulation models for the general grating and sidewall grating are shown in Fig. 1 (a) and (b),

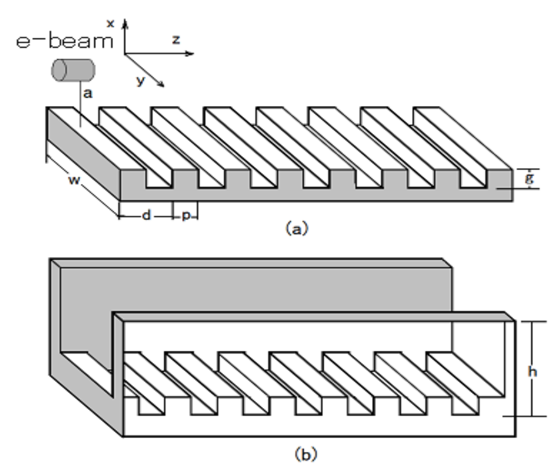

Figure 1: Schematic of grating model. (a) general grating (b) sidewall grating

respectively. A cylindrical electron beam is supposed to fly over the grating. Main parameters are summarized in table 1. By these parameters the device operates as a backward wave oscillator and the synchronous evanescent wave is with the frequency of 4.5 GHz. Details can be found in our previous work [17]. The grating, assumed to be a perfect conductor, is set in the center of the bottom of a vacuum box bounded by an absorption region. A continuous beam produced from a cathode moves in the *z*-axis. The simulation area is divided into a mesh with a rectangular cell of very small size in the region of beam

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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.

Table 1: Main Parameters

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

Output and Start Current

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, as is shown in Fig. 2. When certain

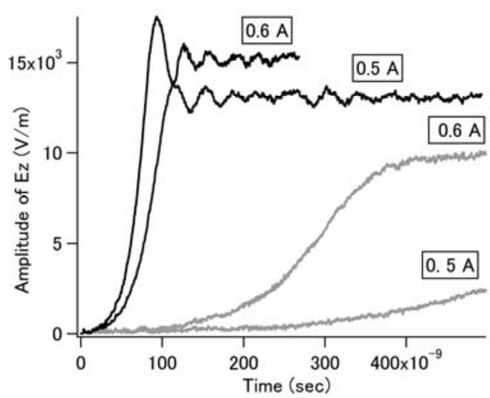

Fig. 2 Evolution of amplitude of electric field Ez (gray curves for general grating and black curves for sidewall grating).

conditions are satisfied, the electric field Ez indicates the processes from spontaneous radiation, exponential growth to saturation. In Fig. 2, the comparisons for the general and sidewall gratings are given. 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.

The event that the electric field experiences the exponential growth means the device can oscillate. Based on this point of view we can find the start current of the sidewall grating device by gradually varying the current value and observe the evolution of the electric field as is shown in Fig. 3. From these simulation results in this figure 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 [18]. A much lower start current could be expected by optimizing the width between the two sidewalls.

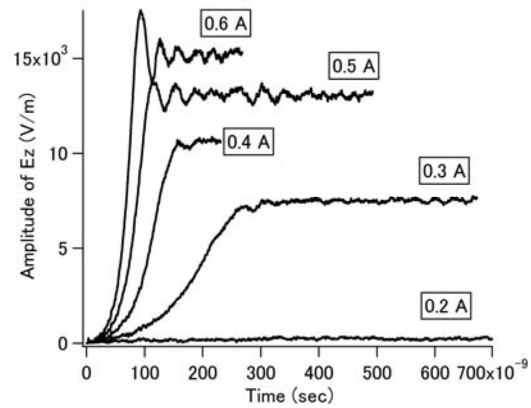

Figure 3: Evolution of amplitude of electric field Ez for sidewall grating for various beam currents.

Transverse Profile

The transverse distribution of the electric field Ez is worked out through recording the amplitude of Ez along the transverse direction. The simulation models are same as is shown in Fig.1.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 (x-axis direction)at the center of the longitudinal grating direction (z-axis direction). The observation line is 1 mm above the grating surface along the y direction, and 1 mm below the bottom edge of the electron beam. The simulation results are given in Fig. 4. The electric field Ez in a general grating illustrates a wide transverse profile and it extends beyond the edges of the grating (see Fig. 4), which predicts a bad coupling with the electron beam.

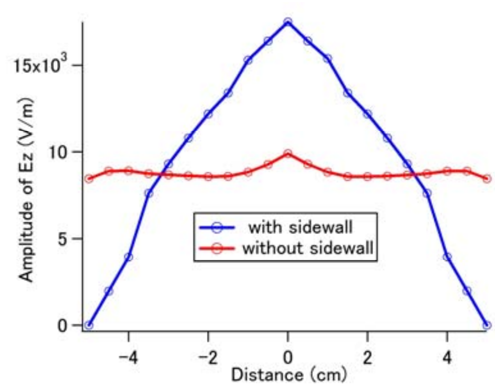

Figure 4: Transverse profile of Ez.

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 free-electron laser operation.

SIMULATION FOR AN 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 10 mA and 5 mA for the electron beam current, and the evolution of magnetic component is as shown in Fig. 5. 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. The energy spectrum for the evanescent wave is given in Fig. 6. Obviously, the radiation of the evanescent wave is at 408 GHz, which has been observed at their experiment.

Table 2: MainParameters for Simulation

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

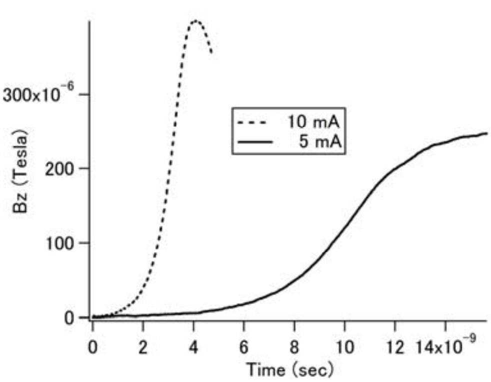

Figure 5: Evolution of magnetic field Bz.

CONCLUSION

We investigate a sidewall grating for the Smith-Purcell free-electron laser with the help of particle-in-cell simulation. Comparing with the general gating, the sidewall grating shows the advantages in output power, start current and the required time for saturation.

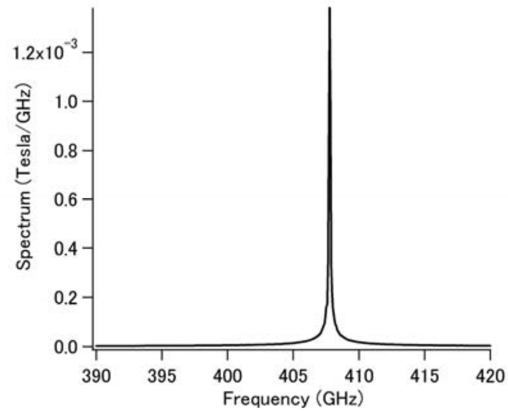

Figure 6: Radiation of evanescent wave (case of 5mA).

REFERENCES

[1] J.Urata, M. Goldstein, M. F. Kimmitt, A. Naumov, C. Platt, and J. E. Walsh, Phys. Rev. Lett. **80**, 516 (1998).
[2] H. L. Andrews and C. A. Brau, Phys. Rev. ST accel. Beams **7**, 070701 (2004).
[3] A. Gover, Phys. Rev. ST accel. Beams **8**, 030701 (2005).
[4] S. E. Korbly, A. S. Kesar, J.R. Sirigiri, and R. J. Temkin, Phys. Rev. Lett. **94**, 054803 (2005).
[5] Vinit Kumar* and Kwang-Je Kim, Phys. Rev. **E73**, 026501 (2006).
[6] J. T. Donohue and J. Gardelle, Phys. Rev. ST Accel. Beams **8**, 060702 (2005).
[7] Amit S. Kesar, Phys. Rev. ST Accel. Beams **8**, 072801 (2005).
[8] R.P.Leavitt, D.E. Wortman and C.A. Morrison, Appl. Phys. Lett. **35**, 363 (1979).
[9] H. L. Andrews, C. H. Boulware, C. A. Brau, and J. D. Jarvis, Phys. Rev. ST Accel. Beams **8**, 050703 (2005).
[10] J. T. Donohue and J. Gardelle, Phys. Rev. ST Accel. Beams 9, 060701 (2006).
[11] D.Li, K. Imasaki, Z. Yang and Gun-Sik Park, Nucl. Instrum. Methods Phys. Res. **A572**, 948 (2007).
[12] Kwang-Je Kim and Vinit Kumar, Phys. Rev. ST Accel. Beams **10**, 080702 (2007).
[13] C. A. Brau, private communication.
[14] H. L. Andrews, C. H. Boulware, C. A. Brau, and J. D. Jarvis, Phys. Rev. ST Accel. Beams **8**, 110702 (2005).
[15] D. Li, Z. Yang, K. Imasaki and Gun-Sik Park, Phys. Rev. ST Accel. Beams 9, 040701 (2006).
[16] L. Ludeking, ''The MAGIC User's Manual.''
[17] D. Li, Z. Yang, K. Imasaki and Gun-Sik Park, Appl. Phys. Lett. **88**, 201501 (2006).
[18] D. Li, Z. Yang, K. Imasaki and Gun-Sik Park, Jpn. J. Appl. Phys. **46**, 601 (2007).