Analysis of Terahertz Smith-Purcell Radiation Generated from Tapered Grating by PIC Simulation

Wenxin Liu, Zhao Chao and Yong Wang
Key Laboratory of High Power Microwave Sources and Technologies, Chinese Academy Science, Beijing,100190, China
Institute of Electronics, Chinese Academy Science, Beijing,100190, China

Abstract- **A novel method for generating Terahertz (THz) Smith-Purcell (SP) radiation from a tapered gating is presented in this paper. For analyzing the characteristics of this kind of grating, the three-dimensional (3D) particle-in-cell simulations are employed, the time of start oscillator, saturated power, the electric field near the tapered grating are analyzed with the help of three-dimensional PIC simulation. On the other hand, the radiation power generated from the tapered grating and normal one is compared. The results of PIC simulations show that the radiation power can be remarkably enhanced and the time of start oscillation can be reduced by the tapered grating.**

I. INTRODUCTION

As we all know, SP radiation is emitted when an electron passes near the surface of a periodic metallic grating [1]. The radiation wavelength λ observed at the angle θ measured from a direction of surface grating is deter-mined by

$$\lambda = \frac{D}{|n|}\left(\frac{1}{\beta} - \cos\theta\right), \qquad (1)$$

where D is the grating period, βc the electron velocity, c the speed of light, and the integer n the spectral order. In recent years, there is a substantial interest in the super-radiant SP radiation, since it is a promising alternative in the development of THz sources [2-4]. The THz sources, a currently active research area, are importance of in a variety of applications to nanostructures, medical and industrial imaging, and material science[5,6]. In order to improve the performance of such kind of device, it is necessary to find an efficient mechanism for the beam-wave interaction. Many methods and theories have been studied. The THz Smith-Purcell radiation is enhanced by making use of two-stream instability, Kim et al use the prebunched beam for the improvements of THz radiation, Li[7] et al use the grating with a sidewall to confine with the electron beam for the improvement of Smith-Purcell Radiation, etc. As far as we know, many methods about improvement the THz radiation characteristics are in terms of electron beam.

In present work, a tapered grating for generating THz Smith-Purcell radiation is presented. The radiation characteristics are analyzed with the help of 3D PIC simulation, on the other hand, the saturated power, the saturated time and electric field are studied. The results of PIC simulations show that the radiation power can be remarkably enhanced and the saturated time can be reduced by the tapered grating.

The organization of present work is organized as follows: the descriptions of PIC simulation are depicted in section 2, the results and discussions are in the section 3, and some conclusions are presented in Section 4.

II. PIC SIMULATION

2.1 Descriptions of Simulation Geometry

The basic simulation geometry is shown in Fig. 1. A grating with rectangular form is set at the center of the bottom of simulation box and a Cartesian coordinate system is adopted with the origin at the center of the grating. The surface of the grating is assumed to consist of a perfect conductor whose grooves are parallel and uniform in the *z*-direction. For the x-directions, the depth of groove is identified called normal grating, shown in Fig. 2. For the improvement of Smith-Purcell radiation, a tapered grating is adopted. The depth of grating is from shallow to deep, which is called tapered grating, shown in fig.3, the depth of grating taper is 0.01mm in present work.

The beam-wave interaction and radiation propagation occur in the vacuum area, which is enclosed by a special region (called *free-space* in CHIPIC[8] language), where the incident electromagnetic waves and electrons can be absorbed. The whole simulation area is divided into a mesh with rectangular cells of small size in the region of beam propagation and grating, and large size in the rest of the region.

The code uses the finite-difference time-domain (FDTD) method [8] to solve Maxwell's equations for the electro-magnetic fields and the motion of charged particles is found by numerically integrating the relativistic Lorentz force equations. The continuity equation is solved, yielding current and charge densities needed for a consistent solution. Various sorts of boundary conditions may be enforced and the properties of the materials forming the boundaries may be specified.

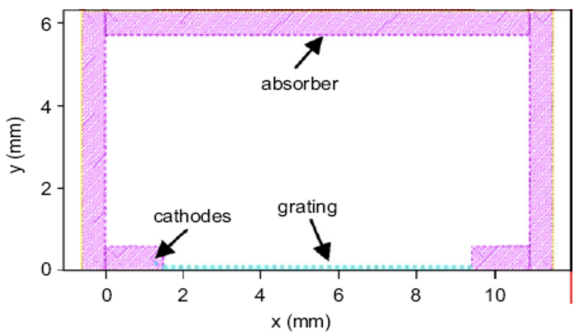


Fig. 1 Simulation Geometry

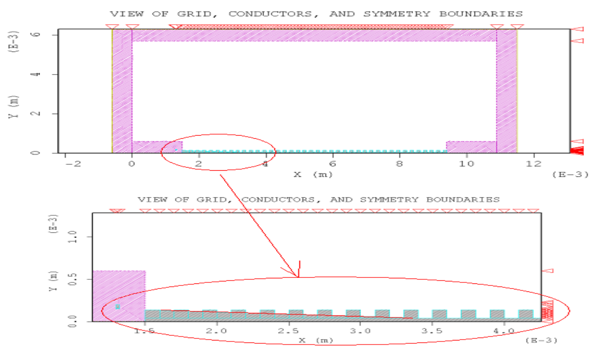


Fig.2 Tapered Grating

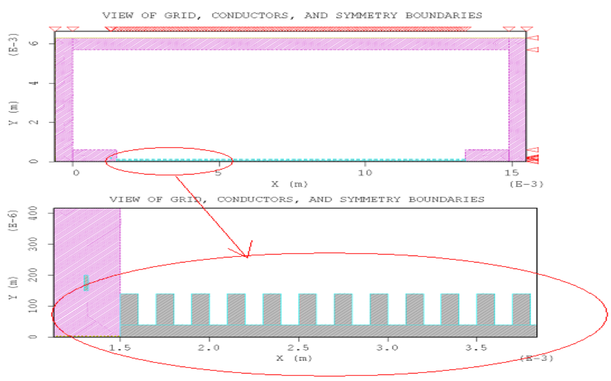


Fig.3 Normal Grating

2.2 Description of Simulation Parameters

The main parameters of the grating and electron beams are summarized in Table 1. The periodic of grating is 0.2mm, the width and depth of groove are equal to 0.1mm. Since it is a two-dimensional simulation, it assumes that all fields and currents are independent of the *z*-direction. The current and voltage of electron beam system is 1000A per meter and 40kV, respectively. We point out the choice of such a large value of current to speed up the long computations, and note that the current value mentioned in this paper represents the current per meter in the *z*-direction. The external magnetic field with 2 Tesla is used in order to ensure stable beam propagation above the grating. As to the diagnostics, CHIPIC allows us to observe a variety of physical quantities such as electro-magnetic fields as functions of time and space, power outflow, and electron phase-space trajectories, etc. We can set the relevant detectors anywhere in the simulation area.

Table I

MAIN PARAMETER FOR SIMULATIONS

Parameters	**Single beam**
Grating Period	D=0.2mm
Groove width	d=0.1mm
Groove depth	h=0.1mm
Depth taper	Ht=0.01mm
Beam voltage	V=40.0kV
Beam current	I=1000A/m
Beam thickness	2b=0.04mm
Beam-grating distance	R=0.04mm
Guiding magnetic	Bx=2T

III. RESULTS OF PIC SIMULATION

Recently, Li and coworkers [2,7], Donohue and Gardelle[9] have addressed the superradiant SP radiation with the help of 2D or 3D PIC simulations. They studied the evanescent wave, electron beam bunching and radiation gain, the loss of grating, etc. Shin[10] reported that evanescent tunneling transmission of effective surface plasmon polaritons between two counterstreaming beams noticeably increased the SP radiation. Here, we focus on the enhancement of terahertz SP radiation by the tapered grating.

3.1 Dispersion Characteristics

According to refs.11, the dispersion curves along with the beam line for 40kV are given in Fig.4. The solid line is theoretically calculated and the square dots are obtained from the PIC simulations. From the Fig.4, the dispersion curve of simulation is kept in agreement with the theoretical calculation. The frequency of operating point (solid dot) is about 391.5GHz, it shows the SP operates at backward wave.

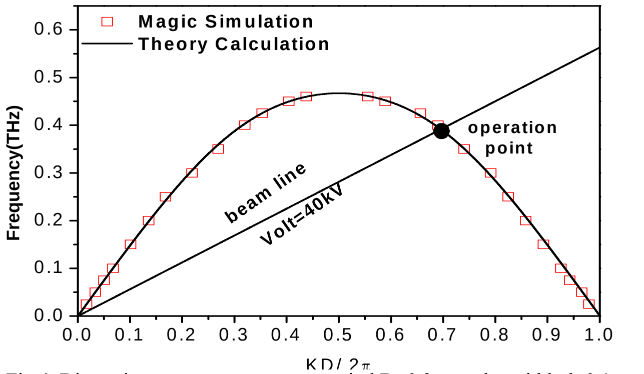
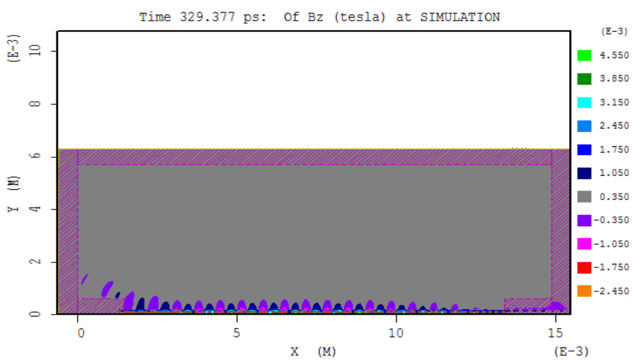
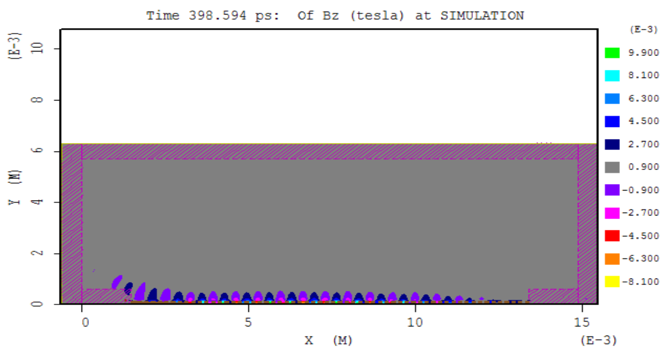


Fig.4. Dispersion curves, parameters: period D=0.2mm, slot width d=0.1mm and groove depth h=0.1mm.

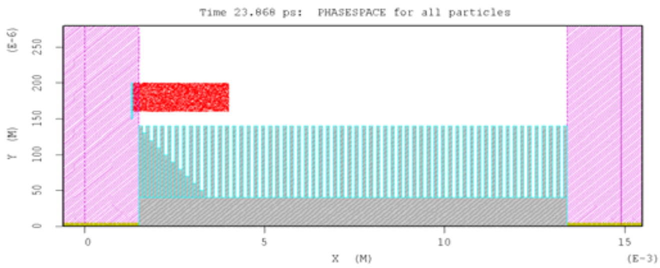


(1) t=329.377ps

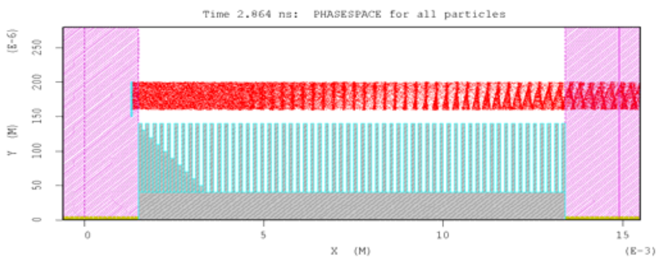


(2) t=398.594ps

Fig.5 The Bz magnetic field



(1)t=23.868ps



(2)t=2.864ns

Fig. 6 Bunching beam in phasespace at different time

3.2 Radiation Characteristics of Tapered Grating

To know the radiation characteristics of tapered grating, the radiation magnetic field Bz and bunched beam are studied with the help of 3D PIC simulations.

Figure 5 is the z-direction of magnetic field (Bz) distribution. Fig.5(1) is Bz field at the moment of 329.377ps, and Fig.5(2) is that of 398.594ps. From the amplitude of Bz, we can find that the amplitude of Bz is increased at the negative x-direction. This shows that the THz SP device operates at the backward wave. This result is consistent with that dispersion curve.

Figure 6 is the bunching beam at the different time at the THz SP tapered device. From the electron beam bunching beam in the phase-space, the electron beam can be bunched by the beam runs a distance, which is the least length of grating, otherwise, the electron beam will not be bunched. On the other hand, the distance between the bunched beam is equal to grating period. It shows the electron beam is bunched due to the periodical magnetic and electric field near the grating.

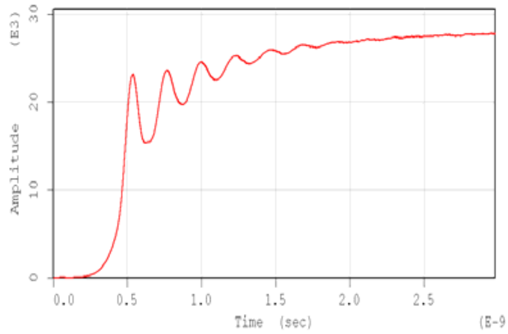


Fig.7 Output Power

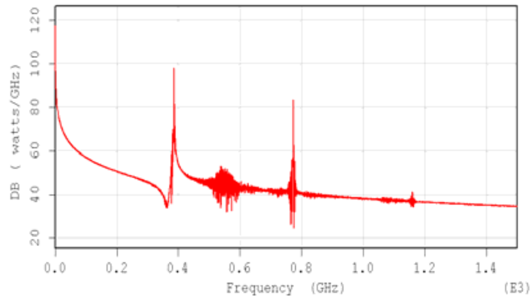


Fig.8 Frequency of output Power

3.3 Radiation Power

The radiation power of THz SP radiation generating from the tapered grating is shown in Fig.7. This figure shows the time of start oscillator is about 0.55ns, and it reaches the saturated power is about 2.5ns, the amplitude is about 28kW.

The frequency of radiation signal is shown in Fig.8, which is obtained by the DB scale of fig.7, and the operating frequency is about 0.38THz. The operation frequency is lower than the theoretical calculation because of space charge and finite boundary condition during the PIC simulation, however, this case in the theoretical calculation is not considered.

On the other hand, the comparisons of radiation power generated from the tapered grating with normal grating are shown in Fig.9.From this figure, the time of start oscillator is shorter than the normal grating, the former time is about 0.55ns, and the latter time is about 0.8ns. Moreover, the saturated time of tapered grating is shorter than that of normal grating, the former is about 2.5ns and the latter time is about 3.0ns, the radiation power of tapered grating is about 28kW, and that of normal grating is about 22kW. The enhancement of radiation power, shorten saturated time and time for start oscillation are because of the tapered grating, which leads to the increasing impedance.

Moreover, to know the enhancement of radiation power for tapered grating, the longitudinal electric field is analyzed by the PIC simulation, the results are shown in fig.10. The longitudinal electric field is stronger than that of normal grating , which can result to the stronger bunching beam in the tapered grating system, leading to the enhancement of radiation power. The saturated time can be shortened by the stronger electric field.

IV. EXPERIMENT SETUP FOR TERAHERTZ RADIATION

The electron beam can be produced by the RF photocathode driven by femosecond laser system, and the experimental setups for THz Smith-Purcell are shown in Fig.11. The charge of bunching can be tested by intergration current transformer.

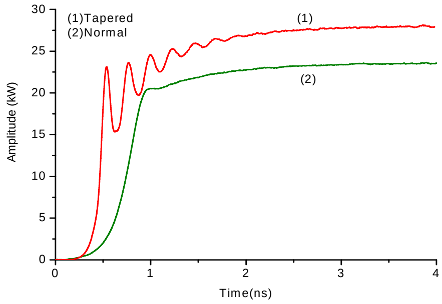


Fig.9 Comparisons of Radiation Power

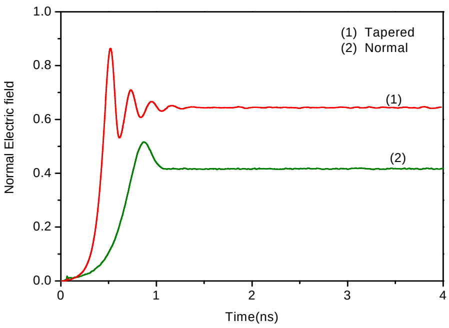
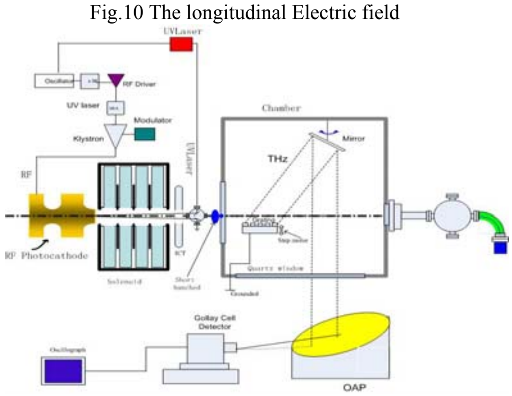


Fig.10 The longitudinal Electric field



(a)

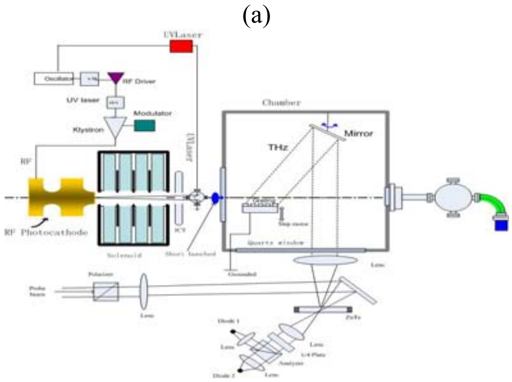


Fig.11. The experimental setup: (a) power measurement (b)frequency measurement;

When the THz wave escapes from the vacuum chamber, its frequency can be measured by the improved Martin-Purplett interferometer, shown in Fig. 11(a). And the intensity of THz CTR can be detected by Gollay cell detector combinations with off-axis parabolic mirrors, shown in Fig. 11(b).

V. CONCLUSIONS

THz SP radiation producing from a tapered grating is presented in this paper, and the radiation characteristics are investigated with the help of 3D PIC simulations, moreover, the experiment setup of THz SP radiation is displayed. The enhancement of radiation power, the shorten time of start oscillation and saturated time are observed through the PIC simulations. On the other hand, the longitudinal electric field because of the tapered grating, which leads to the increase of coupling impedance, is observed in this work. The results of PIC simulation show that the radiation characteristics can be improved by the using of a tapered grating, which has some unique prospects in the THz radiation power.

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