The Smith-Purcell Radiation in the Grating-well Structure

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Abstract: *The emergence of the fine micro-nano structure has advanced the development of traditional radiation. The periodical micro-nano structure can not only regulate the electromagnetic wave, but also have the potential to improve the intensity and directionality of radiation from moving electrons. We introduce the diaphragms in the grating structure to control the Smith-Purcell radiation intensity and directionality. Smith-Purcell can be seen as the radiation from the surface current, which is induced by the moving electrons. The simulation with the theory analysis shows that the diaphragms can not only enhance the intensity of the surface current, but also adjust the distribution of it. The changes of the radiation from the fine micro-nano structure demonstrated a more powerful way to control the radiation, and it is of significance in developing electron beam driven THz radiation source.*

Keywords: Smith-Purcell radiation; grating-well structure; surface current

Introduction

The mechanism based on the electron-beam driven devices is a promising way in the development of high power THz radiation devices. It is necessary to study on the radiation from the moving electrons, and this is also an innovation headspring for exploring high power THz sources. Recently, with the development of micro-nano fabrication technology, it is possible to fabricate finer micro-nano structures, so there are more and more studies on the radiation from the micro-nano structures excited by the electrons.

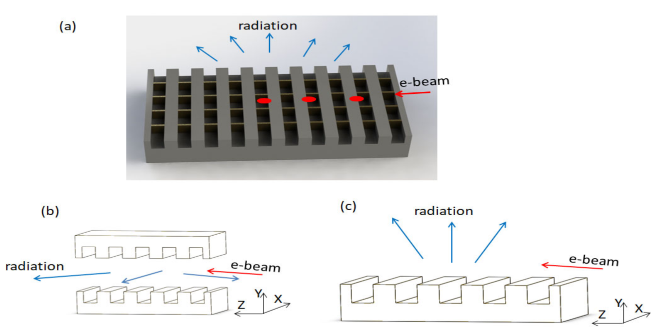

Figure 1. (a) The schematic of grating-well structure. (b) bi-grating structure. (c) grating structure.

Here, we will show the micro-nano technology bring welcome changes to the Smith-Purcell (SP) radiation in THz radiation source researches [1-3]. In order to improve the efficiency of the radiation and control the radiation direction, the micro diaphragms are placed periodically in the metal grating grooves, as shown in Fig. 1(a).

The idea is based on a structural synthesis of two designs. In the conventional grating structure, the electron passes above the grating along Z direction, and the radiation is mainly perpendicular to the grating surface, while in the two symmetric gratings, the radiation is resonated in the direction perpendicular to the grating surface, then the radiation direction will become is parallel to the grating surface. Combined with these two kinds of structures, we can think about the structure of Fig. 1(b) rotating by 90º and placing it on the structure of Fig. 1(c) to form the structural prototype of Fig. 1(a). So, it is more natural to add diaphragms in grating groove to realize this idea, especially the development of micro-nano processing technology, such as 3D printing technology, which also makes it possible to process this fine structure. Here, we note that this kind structure can be seen as grating wells, which forms by grating grooves and the diaphragms.

More Surface Currents Enhance Radiation

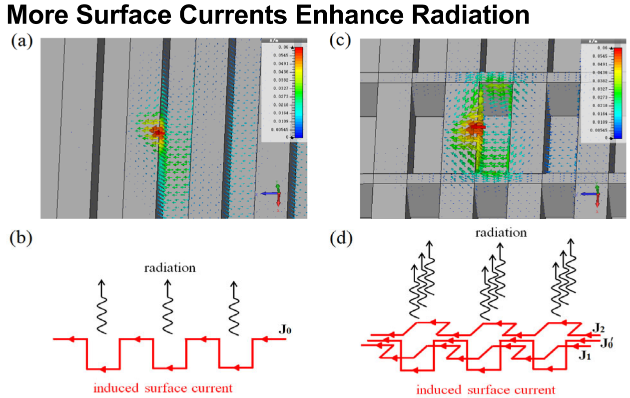

Figure 2. The simulation result of surface current in grating structure (a), and it with period L give rise to radiation (b). The simulation result of surface currents in grating-well structure (c), and the surface current J_0, J_1 and J_1 are have the same period L, which controbutied to radiation (d).

As an electron skims over the surface of a metal grating it induces an image charge on the grating surface which keeps pace with it. Variation in the surface causes this induced current to accelerate [1, 2]. From Jackson [2], the energy radiated in the far field per unit frequency unit solid angle due to a current density J_{total} is

$$W = \frac{\partial^2 I}{\partial\omega\partial\Omega} = \frac{\omega^2}{4\pi^2 c^3}\left|\int dt \int d^3x\, \hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathbf{J}_{total}(\mathbf{r},t)\, e^{j(\omega t - \mathbf{k}\cdot\mathbf{r})}\right|^2 \quad (1)$$

The Schematics of the induced surface current are shown in Fig. 2. For the conventional grating structure, the induced surface current is labeled J_0, which is on the grating surface. For the grating-well metasurface structure, the induced surface currents are labeled by J_0', J_1 and J_2, and the space periods of J_0', J_1 and J_2 are the same, so the radiations of the J_0', J_1 and J_2 have the same radiation frequency band, and they will couple together depending on the space distribution of surface currents, and then enhance the radiation [4].

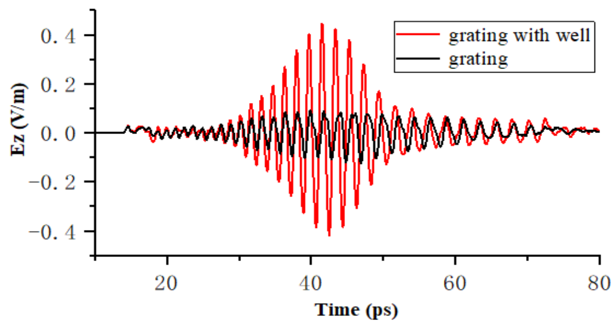

Figure 3. The E_z field in time domain for grating-well and grating structure.

So, loading diaphragm is a way to adjust the induced current distribution, it will make the induced current stronger and its distribution more concentrated, shown in Fig.2(a) and 2(c) [4,5].

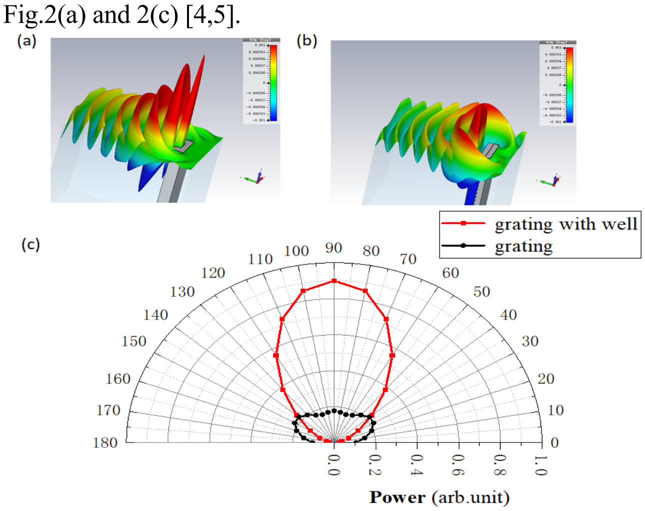

Figure 4. The transient E_z field distribution in the cross section for the grating-well structure (a) and grating structure (b). (c) The comparison of the radiation intensity.

In the simulation, a single electron bunch with energy 40keV is used to drive the grating and grating-well structure. We set up a probe at the distance 20 times the periods above the grating to obtain the SP radiation field. The probe can obtain the time domain waveform and spectrum of SP. From the comparison of time domain waveforms, the radiation field is obviously increased, and the maximum difference of time domain waveform is nearly 3 times, shown as Fig.3.

In the cross section perpendicular to the direction of the electron motion, we set up a series of observation points. For grating structure, with no diaphragm, the radiation directivity in the XY plane is not obvious, however in grating-well structure, radiation directivity is very obvious. When the Angle is φ is small, the field strength of grating-well structure is slightly greater than the grating. With the angle φ is increasing, the fields in the grating well structure began to increase rapidly, when the Angle φ reaches 90°, the fields are strongest, this means the field becomes focusing at the top of the grating, as shown in Fig.4.

Conclusion

In summary, we have presented the changes of SP radiation due to the emergence of the fine micro-nano structure. The periodical micro-nano diaphragms in grating structure have the potential to improve the intensity and directionality of radiation from moving electrons. This idea exhibits the improvement in radiation efficiency and directionality, and it opens potential applications of fine micro-nano structure in high power electron-driven THz radiation source, especially for a tabletop THz SP free electron laser.

Acknowledgements

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References

1. S. J. Smith and E. M. Purcell, "Visible light from localized surface charges moving across a grating," Phys. Rev.92(4), 1069, 1953.
2. J. H. Brownell, J. Walsh, and G. Doucas, "Erratum: spontaneous smith-purcell radiation described through induced surface currents," Phys. Rev. E, 57(1), 1075-1080, Jan. 1998.
3. P. Zhang, M. Hu, R. Zhong, X. Cheng, S. Gong, et al., "A tunable terahertz radiation source based on a surface wave transformed into Cherenkov radiation in a subwavelength array," J. Phys. D: Appl. Phys. 49,145302, Mar. 2016.
4. P. Zhang, L. Wang, Y. Zhang, A. Aimidula, and M. Tang, "Intensive vertical orientation Smith–Purcell radiation from the 2D well-array metasurface," Optics Express, 27(4), 3952, Feb. 2019.
5. P. Zhang, Y. Zhang, and M. Tang, "Enhanced THz Smith-Purcell radiation based on the grating grooves with holes array," Optics Express, 25(10), 10901, May. 2017.