On a tunable free-electron Terahertz radiation source

Hu Min, Liu Weihao, Zhang Yaxin, Zhang Ping, Liu Shenggang
Terahertz research center,
University of Electronic Science and Technology of China,
Chengdu, China, 610054

***Abstract*—We propose a tunable free-electron terahertz diffraction radiation source making use of the special kind mechanism of diffraction radiation excited by electron beam coupling with the guided modes in a periodic structure [1,2]. The detailed theoretical investigation and digital simulation confirm the characteristics of the source. The terahertz diffraction radiation sources working around 1THz are proposed. Several promising ways of enhancing the radiation power and efficiency are also presented. Specially, the coherent diffraction radiation excited by pre-bunched electron beam is discussed theoretically and numerically. This mechanism of diffraction radiation may open a good opportunity to the vacuum electronic and bring attractive prospects to develop compact and tunable radiation sources in THz and higher frequency regime.**

I. Introduction And Background

Due to the potential applications, Terahertz (THz) science and technology becomes one of the significant and prospective fields in the science and technology. However, till now it is still an urgent problem to develop a portable and miniature terahertz source for practical applications. For terahertz frequency regime lies between the region of traditional photonics and electronics, there are two typical ways to generate the terahertz waves: methods of photonics and electronics.

The probable way may be to utilize the diffraction radiation excited by electron beam in the periodic structure [1,2]. In the past years, diffraction radiation of the electron beam as the millimeter and terahertz radiation sources have been studied extensively and lots of goods results have been made.

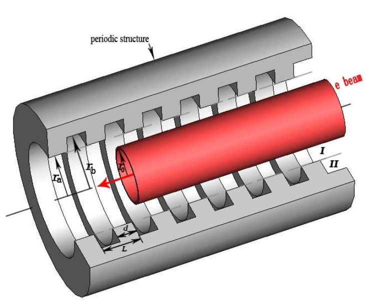

Figure 1 Schemes of THz diffraction radiation source

II. Theoretical analysis

Without sacrifice of the generality, the annular electron beam (shown in Fig.1) with radius of r_0 is used to excite the THz wave radiation. By the use of Maxwell equations and boundary conditions, the dispersion equation with the electron beam excitation can be found:

$$\frac{d}{L}\sum_{n}\frac{k_0}{k_{rn}}\frac{d_n I_1(k_{rn}r_a)-e_n K_1(k_{rn}r_a)}{d_n I_0(k_{rn}r_a)+e_n K_0(k_{rn}r_a)}\sin c^2\left(\frac{k_{zn}d}{2}\right)=\frac{J_1(k_0r_a)N_0(k_0r_b)-J_0(k_0r_b)N_1(k_0r_a)}{J_0(k_0r_a)N_0(k_0r_b)-J_0(k_0r_b)N_0(k_0r_a)}$$

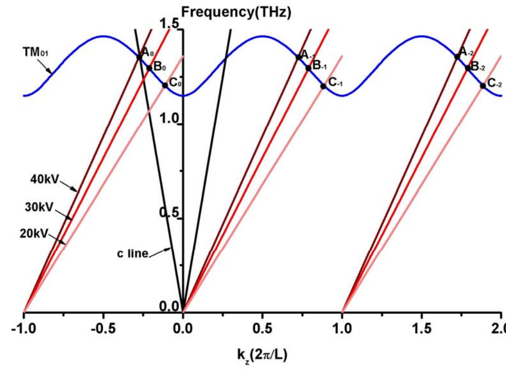

Figure 2 Dispersion curves with different beam energy

III. Enhancement of radiation power and efficiency

In order to get higher power and efficiency, the parameters of this concerned kind of the source should be optimized. The first way is to adjust the electron beam injection location in the periodic structure. The radiation intensity is related to the beam location. It means that the radiation intensity excited by the electron beam closed to periodic structure edge will be much higher (more than 100 times) than that by the center injection beam.

The second way is to increase the beam current density. The radiation intensity is proportional to the square of the beam current. The efficiency will increase linearly with beam current theoretically.

The third way is to adjust the position of the working points on the dispersion curve. According to Bloch-Flouquet's theorem, the amplitudes of different wave space harmonics are different. The amplitudes decrease with the increase of harmonic order (n). To obtain the higher radiation energy, the coupling points (intersection of the electron beam's fundamental wave with the guided modes) should be chosen properly. In this paper, we adjust the coupling point to the first negative harmonics as shown by green lines in Fig. 3(a). The comparison of the radiation efficiency under these two conditions is indicated in

Fig. 3(b), which shows that the efficiency can be improved en times higher than the former case.

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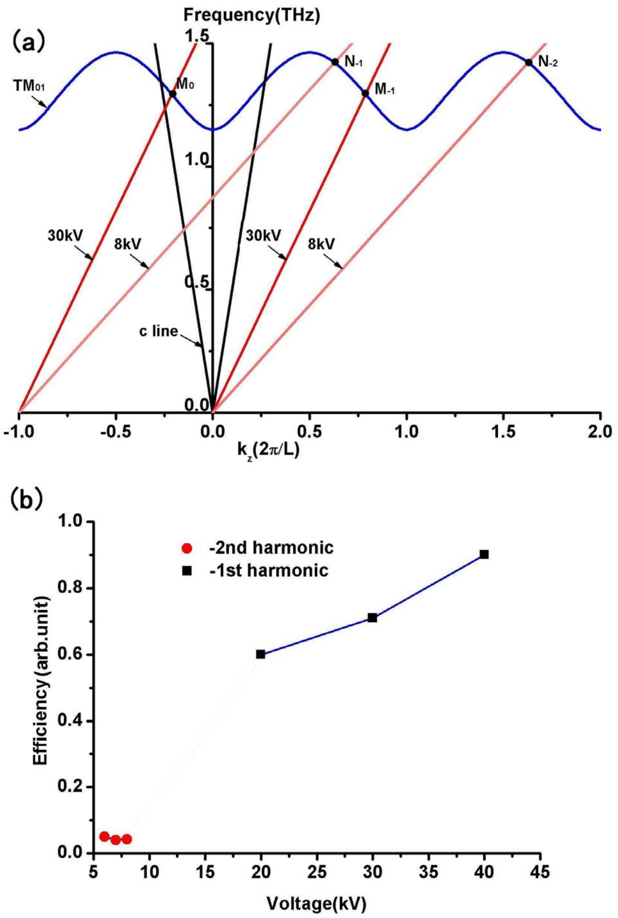

Figure 3 (a) location of coupling points on the dispersion curve by electron beam with different voltages; (b) radiation efficiency of -1st and -2nd harmonic excitation

Finally, the depressed collector can be used technologically to recover the energy of electron beam. By means of using the depressed collector, the efficiency of this kind of diffraction radiation sources can be improved up to 20%.

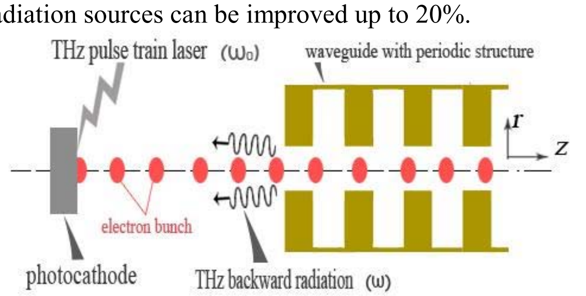

Figure 4 Coherent radiation excited by pre-bunched beam

The proposed way to enhance the radiation efficiency is using a train of electron bunches to make the radiation coherent. It is reasonable since the pre-bunched electron beam with terahertz modulation frequency has been achieved by a photocathode prompted by THz pulse train laser [3].

It seems that the coherence conditions of this kind source are similar with Smith-Purcell radiation. Due to the special kind mechanism, there are differences between the coherence of Smith-Purcell effect and this source. In Smith-Purcell effects, the frequencies of diffraction radiation are angular dependent. But in this source, the mechanism is the coupling of diffraction radiation wave and the periodic structure mode. That means the frequencies of diffraction radiation waves should match the working points in the Brillioun diagram as shown in Fig.2 to obtain the maximum output power. Fig.5 shows the relation between the diffraction radiation intensity and the various bunching frequencies. It proves that the diffraction radiation intensity can be maximumly obtained only when the bunching frequency match the work point in the dispersion curve. This should be the extra coherence condition for this kind of diffraction radiation source.

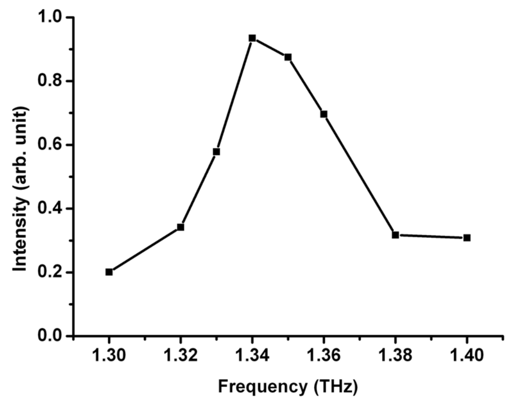

Figure 5 The simulated diffraction radiation power vs. the bunching frequency

As our above analysis, the mechanism of this source is the coupling of the diffraction radiation waves with the periodic structure mode, but the output waves are incoherent. We will show that to utilize the train of bunches the output power and efficiency may be greatly enhanced. Radiation from a single bunches or from train of bunches have been extensive investigated for the case of Cherenkov radiation, transition radiation and Smith-Purcell radiation.

Simulation results show that by using of train of pre-modulated bunches the power of the diffraction radiation can reach the level of hundreds of million watts and the efficiency of 0.1% at the frequency of 1THz.

Summering the above exploration, the results obtained in this paper confirm the unique distinguished characteristics of the mechanism of the special kind of diffraction radiation in a waveguide with periodic structure, and show that this mechanism is of great significance in physics and optics, especially for THz science and technology.

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