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TERAHERTZ SMITH-PURCELL RADIATION FROM THE HIGH-HARMONIC COMPONENT OF MODULATED ELECTRON BEAM FROM DIELECTRIC STRUCTURE*

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Abstract

In this paper, a new radiation scheme, which adopts the high order harmonic of modulated electron beam from dielectric loaded waveguide to excite the Smith-Purcell terahertz (THz) radiation, is proposed and investigated by numerical simulations. The results show that the radiation with frequency close to 1.0 THz is generated, while, the fundamental bunching frequency of electron beam is 0.28 THz. Thus, this scheme offer a new method to get the higher frequency THz radiation.

INTRODUCTION

Recently, Terahertz (THz) radiation has been applied in many areas including biomedicine [1], THz imaging [2], THz communication [3], etc. However, the lack of the radiation source has still been an urgent problem. For filling this "THz gap", accelerator, laser, and vacuum electronics devices have made lots of efforts [4-6]. The electron accelerator based THz radiation can provide above megawatt (MW) within THz range, while, it also requires the large equipment. The compact sources, such as quantum cascade laser and back-wave oscillator (BWO), are limited by the strict requirement for the temperature and the tiny size, respectively.

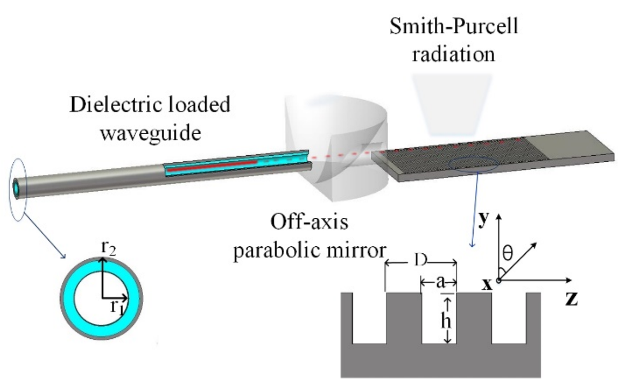

Figure 1: Radiation scheme.

Smith-Purcell radiation, which is excited when the electron moving above a grating without crossing it, was revealed by Smith and Purcell in 1953 [7]. Its frequency f strongly depends on the angle of the radiation emission θ, which can be described as:

$$\lambda_n = \frac{c}{f} = \frac{D}{n}\left(\frac{1}{\beta} - sin\theta\right), \quad n = 1, 2, \ldots\ldots \tag{1}$$

Where c is velocity of the light in vacuum, λ_n is the wave length of the radiation, D is the period length of grating, h and a is the depth and width of the slot respectively, which are shown in Fig. 1.

The radiation power from a bunched electron beam with the bunching factor with b(f) can be expressed as [8]:

$$P = N_e P_0[1 + (N_e - 1)\, b^2(f)]. \tag{2}$$

$$b(f) = \frac{1}{N_e} \left| \sum_{i=1}^{N_e} e^{-j2\pi f t_i} \right|$$

Note that N_e is the electron number, P_0 is the radiation power from single electron, t is the time distribution of electron beam.

In order to raise the radiation power, we can increase the bunching factor b (f) by techniques of shaping electron beam [9]. The wakefield-based bunching in the dielectric loaded waveguide (DLW), which is formed by a hollow cylindrical dielectric tube coated on the outer surface with metal, is one of the most attraction methods to get the bunched electron beam [10, 11]. And the electron beam in DLW will be bunched in the frequency which satisfied with the dispersion equation [12],

$$\frac{I_1(\sqrt{k_z^2-k^2}\, r_1)}{I_0(\sqrt{k_z^2-k^2}\, r_1)} = \frac{\varepsilon_r \sqrt{k_z^2-k^2}\,[J_0(B)Y_1(A)-Y_0(B)J_1(A)]}{\sqrt{\varepsilon_r k_z^2-k^2}\,[J_0(B)Y_0(A)-Y_0(B)J_0(A)]}. \tag{3}$$

Where $A = \sqrt{\varepsilon_r k^2 - k_z^2}\, r_1$, $B = \sqrt{\varepsilon_r k^2 - k_z^2}\, r_2$, $k = \frac{2\pi f}{c}$ and k_z are the total wave number in the vacuum region and longitudinal wave number respectively, ε_r is the relative permittivity of the dielectric material, $J_m(x)$ and $Y_m(x)$ are Bessel functions of the first and second kinds of order m, and $I_m(x)$ is the modified Bessel function of the first kind of order m.

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In this paper, the proposed radiation scheme is shown in Fig. 1. The electron beam is modulated by the wakefield in DLW with transverse size of r_1, r_2. The direction of radiation from the DLW is changed by an off-axis parabolic mirror, while, the electron pass through the hole of the mirror and move above the grating to generate Smith-Purcell radiation. By selecting the suitable radiation emission angle above the grating, we can obtain the higher frequency radiation from the high-harmonic component of the modulated electron beam.

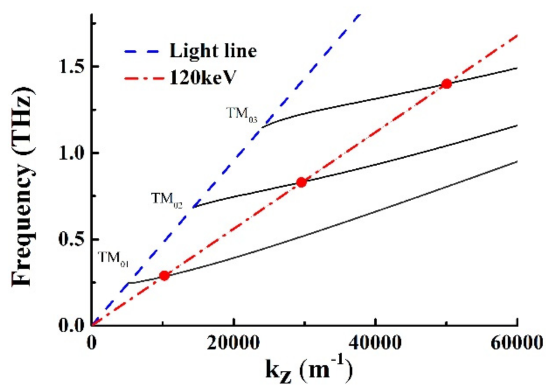

Figure 2: Dispersion curve of the first three modes (black lines) and beam lines.

SIMULATION

We numerically simulate the proposed the radiation scheme by applying the 3D electromagnetic particle-in-cell (PIC) code CST [13]. The electron beam with energy of 120 keV and beam current of 5A is injected into the DLW with r_1= 0.25 mm, r_2= 0.35 mm and ε_r= 9.8 (material: alumina). The length of the DLW is set as 27 mm. After optimization, the grating parameters are set as: D = 0.2 mm, h= 0.1 mm, a= 0.1 mm. The material of grating is perfect conductor. Fig. 2 shows the dispersion curves of the first three order modes and electron beam line, and the frequencies of the first three order modes are 0.282, 0.832 and 1.40 THz, respectively.

The simulation results of the electron beam in DLW are given in Fig. 3. Subplot (a) is the time evolution and frequency spectrum of the electron field (E_Z component). It shows that the wakefield in DLW will reach saturation after 3.2 ns, and the radiation with frequency of 0.28 THz is obtained, which will serve as the field to modulate the electron beam. The subplot (b) shows the phase space of the electron beam in DLW, which directly present the energy modulation of the electron. Subplot (c) is the bunch factor of the electron beam from the export port and the Smith-Purcell radiation emission angel in different frequency according to the Eq. (1). We can see that the second mode and third mode of the electron are within the radiation emission range, however, the bunching factor of these two modes are small compared with the fundamental mode.

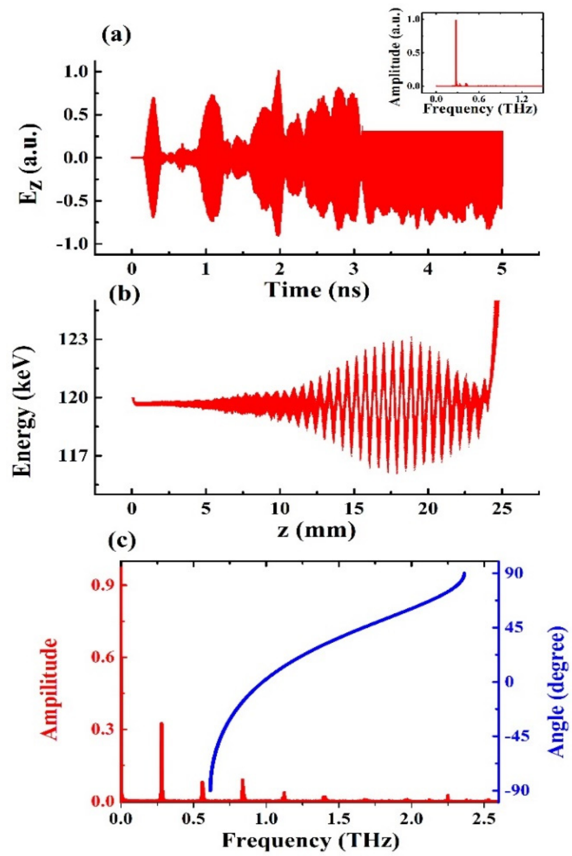

Figure 3: (a) Simulation results of the time evolution of the E_z field and its frequency spectrum inside the DLW. (b) The map of the phase space of the electron in DLW. (c) The bunching factor of the modulated electron beam and the radiation emission angel above grating in different frequency.

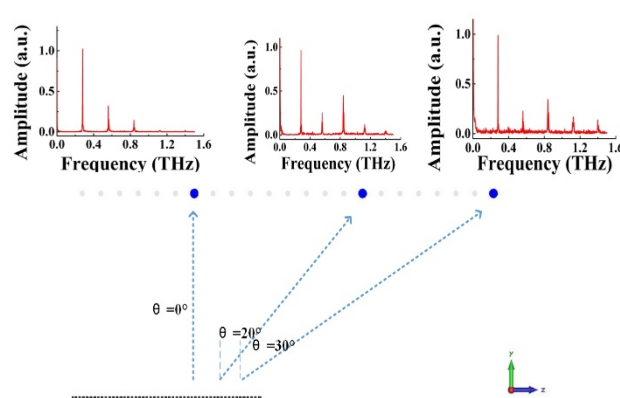

Figure 4: The frequency spectrum of the field B_x for the emission angle $\theta = 0, 20°, 30°$.

Figure 4 shows the frequency spectrum of the B_x field in three different radiation emission angel. For the case of the $\theta = 20°$, it is easy to see that the second mode with frequency of 0.838 THz is enhanced compared with the case

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of $\theta = 0°$, while, the third mode so small that the radiation with frequency of 1.4 THz is still not obvious for the case of the $\theta = 30°$. Due to the reflection of the grating edge and big bunching factor, the radiation with frequency of 0.282 THz is strong for three cases.

CONCLUSION

In summary, a radiation scheme using the high-order harmonic component of the modulated electron beam from dielectric loaded waveguide is proposed and investigated. It offers a promising way to generate the radiation with frequency close to 1 THz.

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