Coherent terahertz radiation from Fabry–Pérot resonances via a special Smith-Purcell effect

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(Received 20 September 2018)

Abstract: A physical mechanism of multicolor coherent terahertz radiation is presented. We have found that, in a transmission metallic grating with deep enough slits, the multi-modes Fabry–Pérot resonances in the slit cavity can be efficiently excited by an electron beam moving atop the grating, and then transformed into radiation via a special Smith-Purcell effect. The radiation is coherent and highly directional, which is essentially different from the ordinary Smith-Purcell radiation. The radiation power density is an order of magnitude higher. The radiation frequency can be tuned by adjusting the grating parameters and beam energy. Based on this mechanism, the coherent, tunable, intense, and miniature terahertz radiation sources can be developed.

Keywords: Terahertz radiation, Fabry–Pérot resonances, Smith-Purcell effect

doi: 10.11906/TST.026-032.2019.03.03

Introduction

Since its first observation in 1953 [1], SPR, by electrons passing over a periodic structure, has attracted tremendous interest for its great applications in radiation generation, beam acceleration and nondestructive diagnostics of electron beams [2-5]. Its dispersion relation is

$$\lambda = -\frac{L}{n}\left(\frac{1}{\beta} - \cos\theta\right) \quad (1)$$

where λ is the wavelength of the radiation, n is the order of the radiation, L is the grating period, β is the ratio of the electron velocity to the speed of light, and θ is the observation angle (shown in Fig. 1(a)). Van den Berg firstly utilized a diffraction model to accurately explain the mechanism of SPR [6-8]. The evanescent wave generated by a moving electron beam and the diffracted fields are expanded in terms of independent modes of the metallic grating system and the boundary condition are matched at the surface.

Coherent radiation can be generated by SP effect with pre-modulated electron bunches (generated previously by the accelerator or by the beam–wave interaction on the periodic surface), which is generally called the Smith–Purcell free electron laser (SP-FEL) [9–11]. SP-FEL has been extensively studied for its potential in generating radiation that cannot be easily obtained by other methods, especially for terahertz (THz) wave generation [9, 10]. In SP-FEL, the SPR is coherent in some specific directions due to the SPR frequency is harmonic of bunching frequency. The radiation power density is remarkably increased since it is proportional to the square of the bunch number. Recent works demonstrated that coherent terahertz (THz) SPR can also be generated from SPP resonance mode in a structure of graphene deposited on a dielectric grating [12-14]. This mechanism provides a promising way to develop room-temperature, miniature, tunable, coherent, and high-powered THz radiation sources covering the whole THz regime. The desired THz radiation can be generated mainly depending on the remarkable properties of graphene SPPs, such as extremely high confinement, low Ohmic loss, and more importantly wide tunability in the THz to mid-infrared regimes by adjusting the gate voltage or chemical doping [15-19].

In this paper we uncover a new kind of SPR multicolor coherent radiation from the multi-modes Fabry–Pérot (FP) resonances in a metallic grating with deep enough slits excited by an electron beam moving atop the grating surface. The results show that the mechanism of coherent SPR presented here is essentially different from the theoretical models mentioned above. The radiation frequency is not only satisfied with the dispersion relation of SPR, but also the FP resonance condition. The generation of coherent SPR does not need a pre-bunched electron beam, which is the primary challenge for SP-FEL. Besides, the radiation intensity is much higher than the ordinary SPR. The radiation frequency can be tuned by adjusting the grating parameters and beam energy. Therefore, the results presented here could provide an exciting potential for developing the coherent, tunable, intense, and miniature terahertz radiation sources covering the whole THz frequency regime.

The metallic grating has period L, thickness h, and slits width w, as shown in Fig. 1(a). An electron beam moves parallel at a constant velocity v_0 in the x direction above the grating surface by a distance z_0. In the THz frequency regime, the gratings are treated as perfectly conductor. The theoretical analysis and numerical calculation are based on the method proposed in [14]. The dash-dotted lines in Fig. 1(b) show the radiation spectra of the ordinary SPR from a thin grating. The radiation is incoherent and with broad angular distribution. However, when the grating silts increase deeply enough, the radiation characteristics are essentially changed. The radiation spectra (solid lines) shown in Fig. 1(b) indicate the generation of coherent THz radiation. There are two radiation peaks marked by points A and B, and the radiation frequencies are 4.64 *THz* and 9.34 *THz*, respectively. For the radiation in the upper half-space, the radiation intensity is enhanced by 4.4 and 29 *times* compared to that of the ordinary SPR at the resonance frequencies. The physical origin of the large enhancement is that the intensity of fields of FP resonances excited by the electron beam is an order of magnitude higher than that of the evanescent wave.

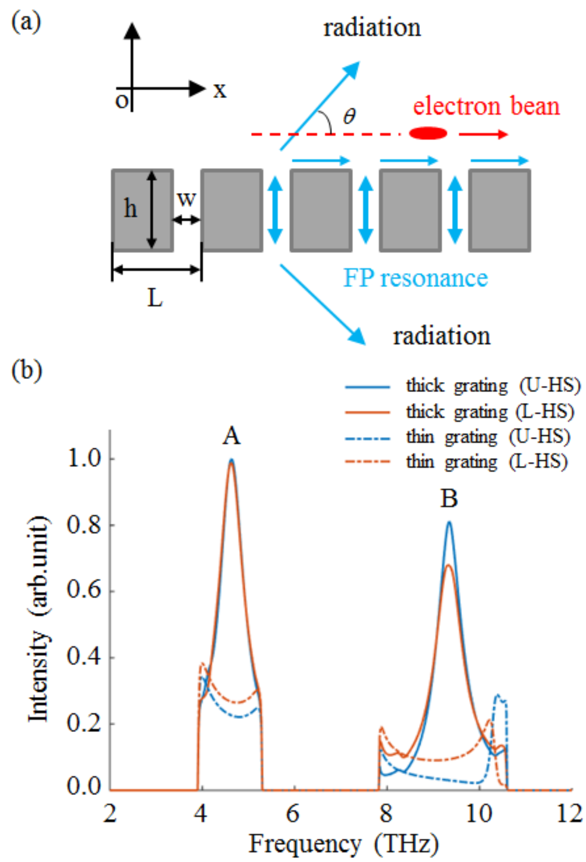

fig. 1 (a) Schematic of the coherent THz radiation from a thick metallic grating, θ indicates the radiation direction. (b) Fourier spectra of radiation intensity from thick (h=30 μm) and thin (h=3 μm) metallic gratings (the other geometric size is L=10 μm, w=1 μm). The beam velocity is 0.15 c. U-HS (L-HS) means the radiation towards to upper (lower) half-space.

To uncover the physical mechanism of the coherent SPR presented here, we calculate the distribution of magnetic field intensity of radiation at points A and B, as shown in Fig. 2. The strong resonances phenomenon is observed in the grating slits. The wavelengths of radiation satisfy the FP resonance equation (2). The mode order is characterized by m in the FP relation.

For $m \neq 0$, $m-1$ nodes could be observed in the field distribution along the slits. The mode at points A and B are corresponding to the first and second orders of FP resonance modes. Thus, we can conclude that the coherent SPR is transformed from the FP resonance modes. The radiation angles are 78 degree and 75 degree, obeying the dispersion equation (1) of SPR.

$$\lambda = \frac{2h}{m} \qquad (2)$$

Where m is an integer.

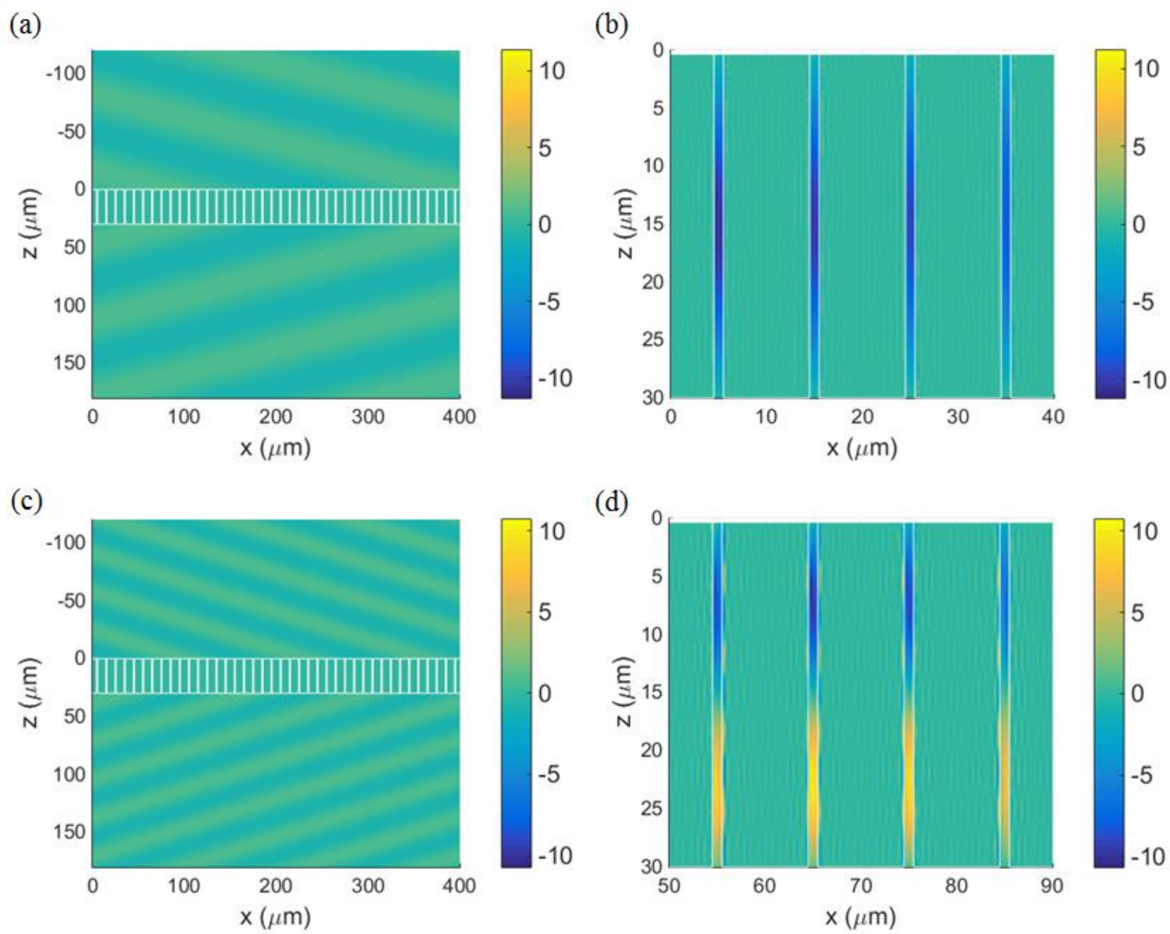

fig. 2 The contour maps of magnetic field intensity H_y in the X-Z plane of the structure for points A and B, respectively. (b), (d) indicate the fields in the grating slits.

The dispersion curves of FP resonance of the grating structure also confirm our above analysis, as shown in Fig. 3. The beam lines with the velocity 0.15 *c* intersect with the dispersion curves of first and second FP resonance at points A and B. These intersection points are located in the diffraction radiation zone, thus, the excited FP resonances can be transformed into radiation. We also note that the FP modes are with no dispersion for a certain thickness, thus, the radiation frequencies are fixed when tuning the beam energy. However, the radiation angle can vary from 0 degree to 180 degree by adjusting the beam energy. This unique feature of high directional and tunable radiation angle may make the proposed structure useful in directional coupling and THz switch.

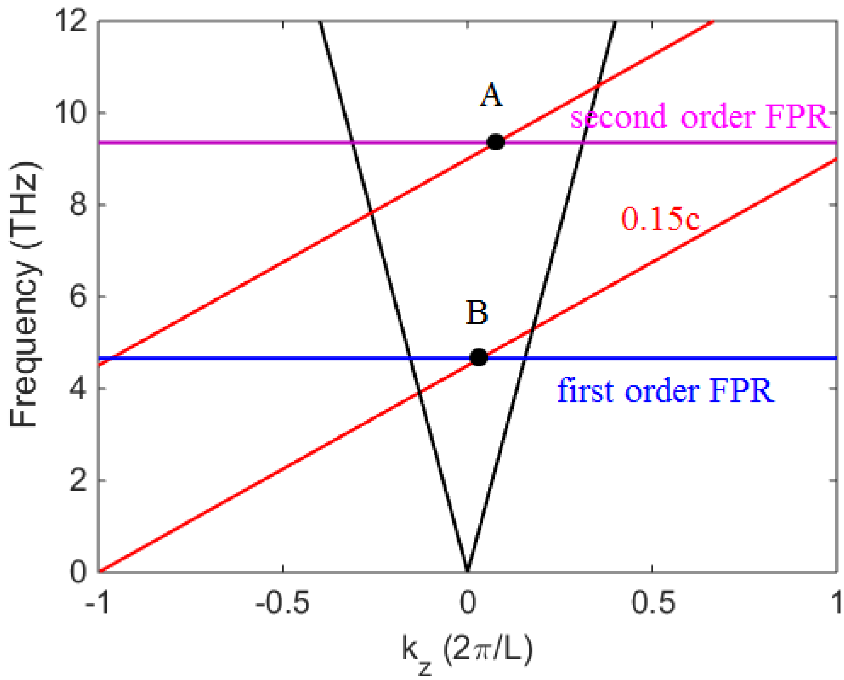

fig. 3 The dispersion curves of first and second orders of Fabry–Pérot resonances (FPR), the beam line with velocity 0.15 *c* intersects with the dispersion curves at points A and B, respectively.

According to equation (2), the wavelengths of FP resonances are proportional to the grating height with a linear relation, thus, the radiation frequencies can be tuned by adjusting the grating height. Fig. 4 shows the dependence of radiation characteristics of the first and second orders of FP resonance modes on the grating height. The beam energy is adjusted with the variation of grating height to grantee the intersection point between beam line and dispersion curves locating in the radiation region. Fig. 4 (a) indicates that the radiation frequencies of both first and second FP modes decrease with the increasing thickness, obeying the FP resonance equation (2). As the height of the grating increases, the radiation intensity of both first and second FP modes decreases, as shown in Fig. 4 (b). We also notice that the radiation intensity of first order FP mode is larger than that of second order. This may contribute to the radiation of first order FP mode transformed from the first negative space harmonic, while, that of second order FP mode transformed from the second negative space harmonic.

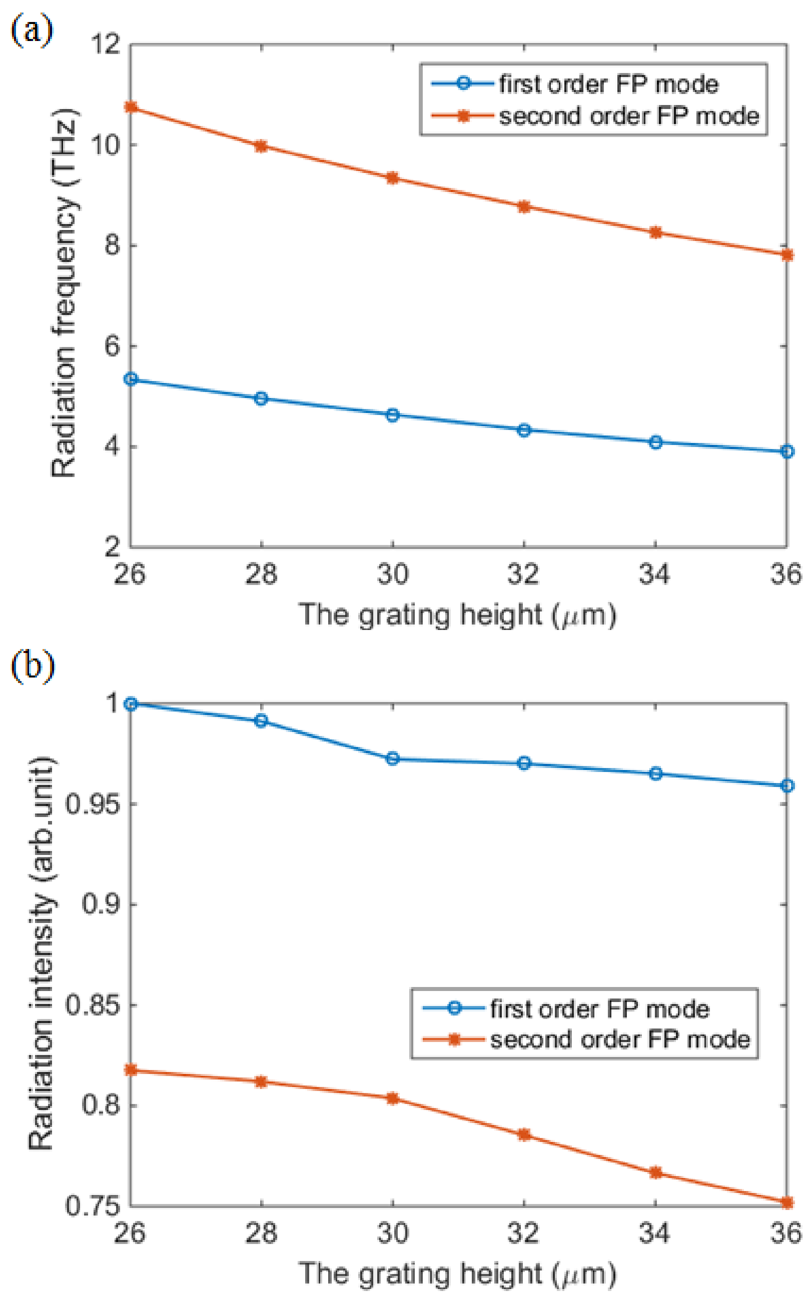

fig. 4. The radiation frequencies (a) and intensity (b) of first and second orders of FP modes vs. the grating height.

In summary, we have demonstrated a physical mechanism of multicolor coherent terahertz generation. In this mechanism, the multi-modes Fabry–Pérot resonances can be efficiently excited by an electron beam moving atop a transmission metallic grating with deep enough slits, and then be transformed into radiation via a special Smith-Purcell effect. The radiation is coherent and highly directional, which is essentially different from that of the ordinary Smith-Purcell radiation. The radiation power density is enhanced over an order of magnitude than the ordinary Smith-Purcell radiation. The radiation frequency can be tuned by adjusting the grating parameters and beam energy. Therefore, our finding presented here may provide promising opportunities for developing the coherent, tunable, intense, and miniature terahertz radiation sources.

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