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Designer Surface Plasmons Enable Terahertz Cherenkov Radiation

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(*Invited*)

Abstract—Cherenkov radiation (CR) is a promising method to generate high-power terahertz (THz) electromagnetic (EM) waves, which are highly desired in numerous practical applications. For the purpose of economy energy, naturally occurred materials with flat surface (e.g., graphene), which can support highly-confined surface-plasmon-polariton (SPP) modes, have been proposed to construct high-efficiency terahertz CR source; however, these emerging materials cannot be easily fabricated nor flexibly designed. Here, we propose a designer-SPP metamaterial scheme to pursue terahertz CR. The metamaterial is a structure-decorated metal surface, which is compatible with planar fabrication and can support SPP-like EM modes in terahertz frequencies, also named as designer SPP. Due to the structure dependence of designer SPP, its dispersions can be flexibly designed by changing the structure geometries as well as choosing proper dielectric medias. Numerical results clearly demonstrated this scheme. Our proposal may promise future high-efficiency and intense THz source with design flexibilities.

1. INTRODUCTION

Terahertz (THz) electromagnetic (EM) radiation, referred to frequencies from 0.1 to 30 THz, has attracted extensive interests because of its promising applications in nondestructive detection, homeland security, and high-speed wireless communication [1–5]. So far, various THz generation approaches [2, 6] have been proposed; however, low power output is still the bottleneck in achieving these applications. Inspired by high-power microwave and light generation from free electron beams, many efforts have recently been devoted to exploring by using free electron beams [7, 8]. Cherenkov radiation [9, 10], emitted from electrons when their velocity surpasses the phase velocity of EM waves, is a typical mechanism exploited for high-power EM wave generation, such as in well-developed microwave vacuum electronic devices [8]. In such devices, the key component is the slow-wave structure which can slow down the phase velocity of EM waves. Two typical slow-wave structures are folded waveguides [11, 12] and dielectric-lined waveguides [13–15], both of which have been successfully demonstrated for radiation generation below 1 THz. However, these structures have not been pushed to higher frequencies with unsacrificed power level, because smaller electron passages limited by device sizes permit smaller driving currents.

Surface plasmon polaritons (SPP), a type of surface EM modes existing on the interfaces between conductive and dielectric materials, offers possibility to construct novel slow-wave structures at higher frequencies [16]. In 2012, Liu et al. proposed that a metal nanofilm loaded with dielectric can be utilized for Cherenkov light generation [17]. Simultaneously, a fishnet metamaterial structure was proposed to

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achieve reversed optical CR, due to its effective negative refractive index [18]. Later, a threshold-free Cherenkov source was demonstrated with multilayer metal-dielectric structure in visible frequencies [19]. These designs are compact and highly efficient, but cannot be directly transferred to THz frequencies, since plasmon resonances of metal are in optical frequencies. Carbon nanotubes were proposed to avoid the loss of metal in optical frequency [20]. Given the above, some groups proposed to replace metal nanofilms with graphene [21–25] or Dirac semimetals [26], whose plasmon frequencies are in THz region. However, these materials are very challenging to fabricate and incompatible with mass manufacturing.

In 2004, Pendry et al. disclosed that holy-structured metal films can support SPP-like surface EM modes in THz region, when the structure period is in deep subwavelength region [27]. This type of mode, also named as designer surface plasmon polaritons (DSPP) [28–31], has driven many passive applications such as beam collimators [32, 33], conformal waveguides [34], and topological waveguides [35]. Recently, extensive interest has also been attracted to its interaction with electron bunches for active applications. When a bunch of electrons parallelly fly over holy-structured metal surfaces (or various transformed structures), high-power coherent DSPP can be excited according to the Cherenkov condition [36–38], which is fundamentally different from that of Smith-Purcell radiation originating from zone folding [39–42]. The generated Cherenkov DSPP can only propagate along the metal surface, but has not been coupled out of the surface to form radiations.

Here, we propose a dielectric-loaded metamaterial layer to interact with electron bunches (as shown in Fig. 1), which can efficiently generate coherent Cherenkov radiation (CR). The underlying physics is that a bunch of electrons parallelly fly over the metamaterial layer are composed of a holy-decorated metal film and can excite Cherenkov DSPP propagating along the metamaterial surface. The Cherenkov DSPP can further be transformed to CR by the loaded dielectrics. We also show that this DSPP-based CR can be tuned by switching electron velocity, and controlled by flexibly designing metamaterial geometries.

2. DSPP PROPERTIES

We first illustrate the configuration as shown in Fig. 1, where the metamaterial structure is periodic in both y and z directions, but with finite thickness in x direction. A typical unit cell is shown in the inset of Fig. 2(a), where the periodicity and thickness are d and h, respectively. The skeleton material is metal, and the square hole with size a is filled up with dielectrics of refractive index n_h.

To display the EM properties of the freestanding metamaterial layer, we simulate it with CST Microwave Studio. Because metal loss is negligible in terahertz frequency, metal can be approximated

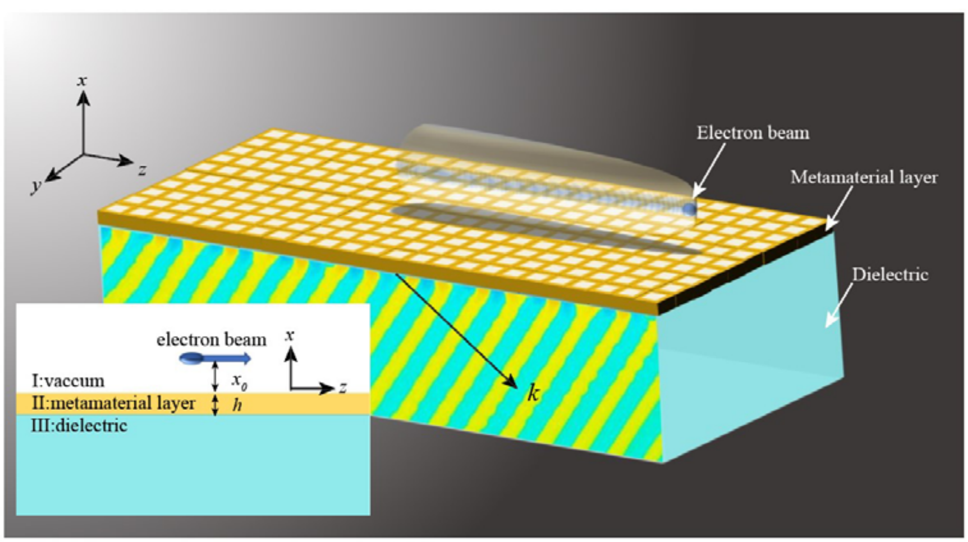

Figure 1. The schematic of the metamaterial-dielectric structure. The inset shows x-z cross section. Region I, II, III are vacuum, metamaterial layer, and dielectric medium respectively.

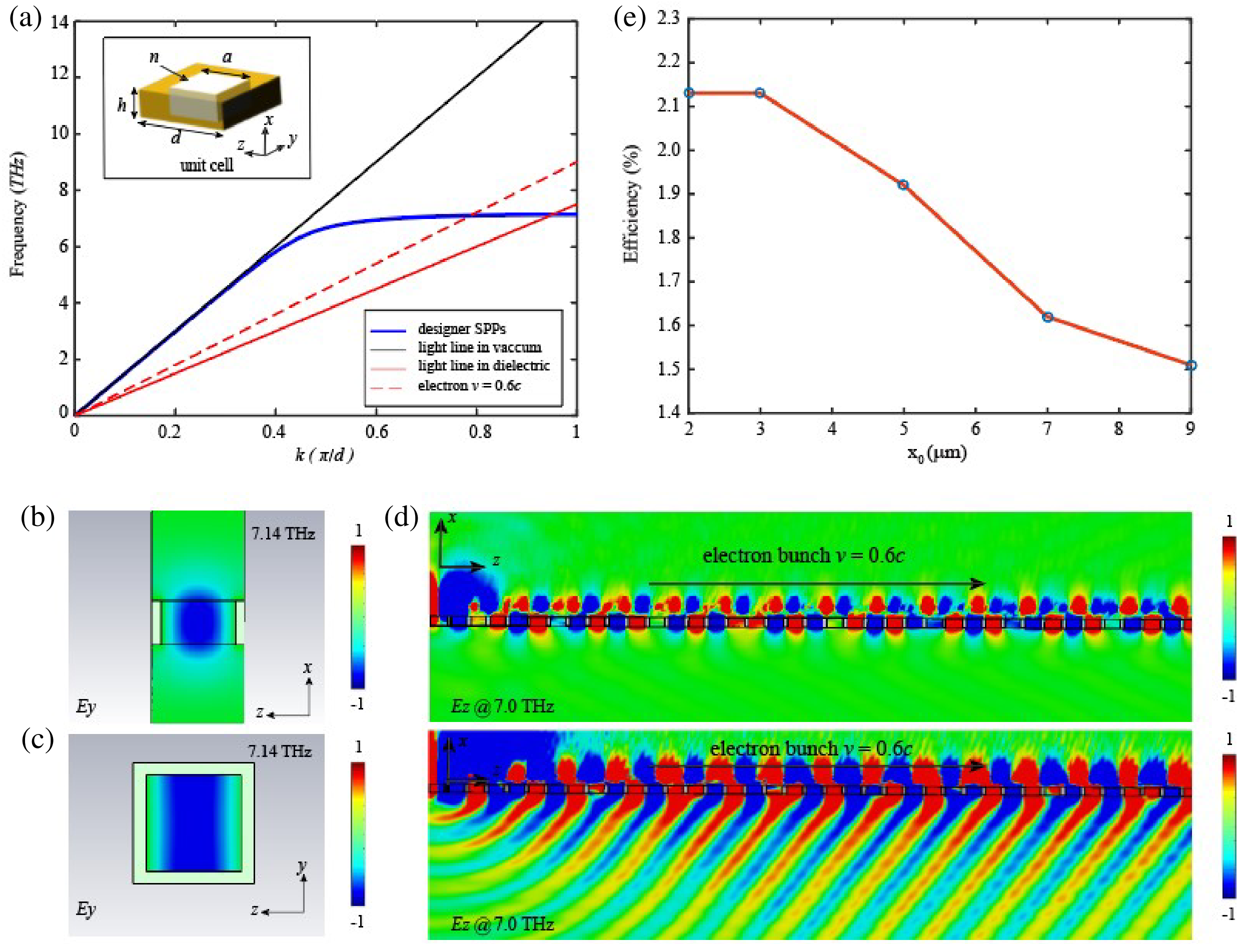

Figure 2. (a) Dispersion curve of the designer surface plasmon polariton (DSPP). The simulated unit cell is illustrated in the inset with parameters $d = 10\,\mu\text{m}$, $a = 0.8d$, $h = 0.5d$, $n = 3$. (b)–(c) Ey component of the simulated eigenmode in the xz and yz cross sections respectively. (d) The excited field by a bunch of electrons with velocity $v = 0.6c$. Without and with dielectric medium for top and bottom panels respectively. (e) The excitation efficiency depending on the distance between electron beams and the metamaterial layer x_0.

as a perfect electric conductor. Taking a typical unit cell with $d = 10\,\mu\text{m}$, $a = 0.8d$, $h = 0.5d$, $n_h = 3$ as an example, its dispersion is shown in Fig. 2(a), which resembles the SPP dispersion in optics and lies outside of the light cone. The horizontal wave vector of the DSPP is larger than that of the light, which indicates that the mode is evanescent in the vertical direction. According to the simulated field pattern as shown in Fig. 2(b), the eigenmode is evanescent along x direction, which is consistent with the dispersion analysis. Furthermore, Fig. 2(c) shows that the E_y pattern in the hole waveguide is the fundamental mode. Consequently, the waves in x direction has to be evanescent in the whole dispersion band which is below the cutoff frequency of the fundamental mode.

3. TUNABLE CHERENKOV RADIATION

Then, we shoot a bunch of electrons with velocity $v = 0.6c$ skimming over the freestanding metamaterial layer, and c is the velocity of light. In the upper panel of Fig. 2(d), the E_z field in xz plane exhibits that the excited DSPP at 7.0 THz are strongly confined on the surface of the metamaterial layer, which cannot radiate into the ambient. We further investigate the excitation-efficiency dependence on the flying height of electrons x_0. The excitation efficiency reaches 2.13% when x_0 is set as 3 µm, as shown in Fig. 2(e). Increasing x_0 leads to a decrease in excitation efficiency because the evanescent field of DSPP decays away from the metamaterial surface. In contrast, by loading the metamaterial with a dielectric media, the excited DSPP at the same frequency is coupled into the dielectric where CR cone occurs, as shown in the lower panel of Fig. 2(d). The charge quantity in electron bunches is 1.6×10^{-18} Coulomb, and the power density can reach 160 W/m^2. In order to understand the underlying physics of CR, we decompose the process into two steps. Firstly, DSPP is efficiently excited under the Cherenkov condition ($\nu \geq \omega/k_{\mathrm{DSPP}}$), then, the loaded dielectric transforms the excited DSPP to CR. In the lower region of the metamaterial layer, the vertical component of DSPP wavevector can be expressed as $k_x = \sqrt{n^2 k_0^2 - k_{\mathrm{DSPP}}^2}$. For the freestanding case where the lower region is vacuum ($n = 1$), k_x is imaginary thus the waves being evanescent in x direction, due to the larger DSPP wavevector k_{DSPP} than that of light k_0. For the dielectric-loaded case ($n = 2$), k_x becomes real thus DSPP being transformed into CR, because of the increased wavevector of light in the dielectric nk_0.

Interestingly, the frequency of CR can be tuned by switching the velocity of electron bunches. We still utilize the same structure as above, while employ electron bunches with different velocities ($v = 0.6c$, $v = 0.8c$, $v = 0.9c$). The three beam lines intersect with DSPP dispersion at points A, B, C, whose frequencies decrease as the electron velocities increase. The amplitude spectra of DSPP CR (shown in Fig. 3(b)) are numerically obtained, whose central frequencies agree well with the intersection points in

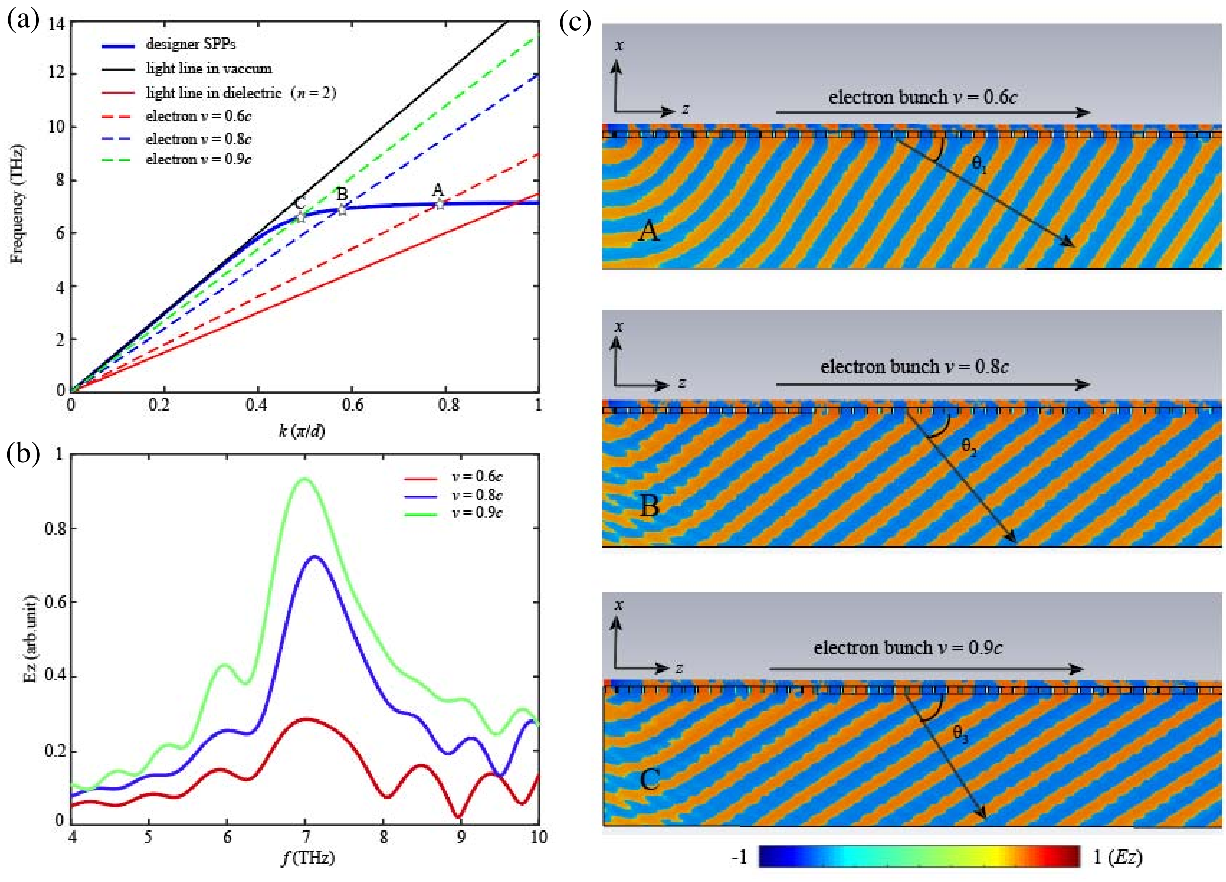

Figure 3. Tunable DSPP-Cherenkov radiation. (a) The dispersion curves of DSPP, light lines in vacuum and dielectric, and beam lines with different velocity ($v = 0.6c$, $0.8c$, $0.9c$). (b) The amplitude spectra of DSPP Cherenkov radiations. (c) The simulated field patterns corresponding to the three stars marks respectively in (a).

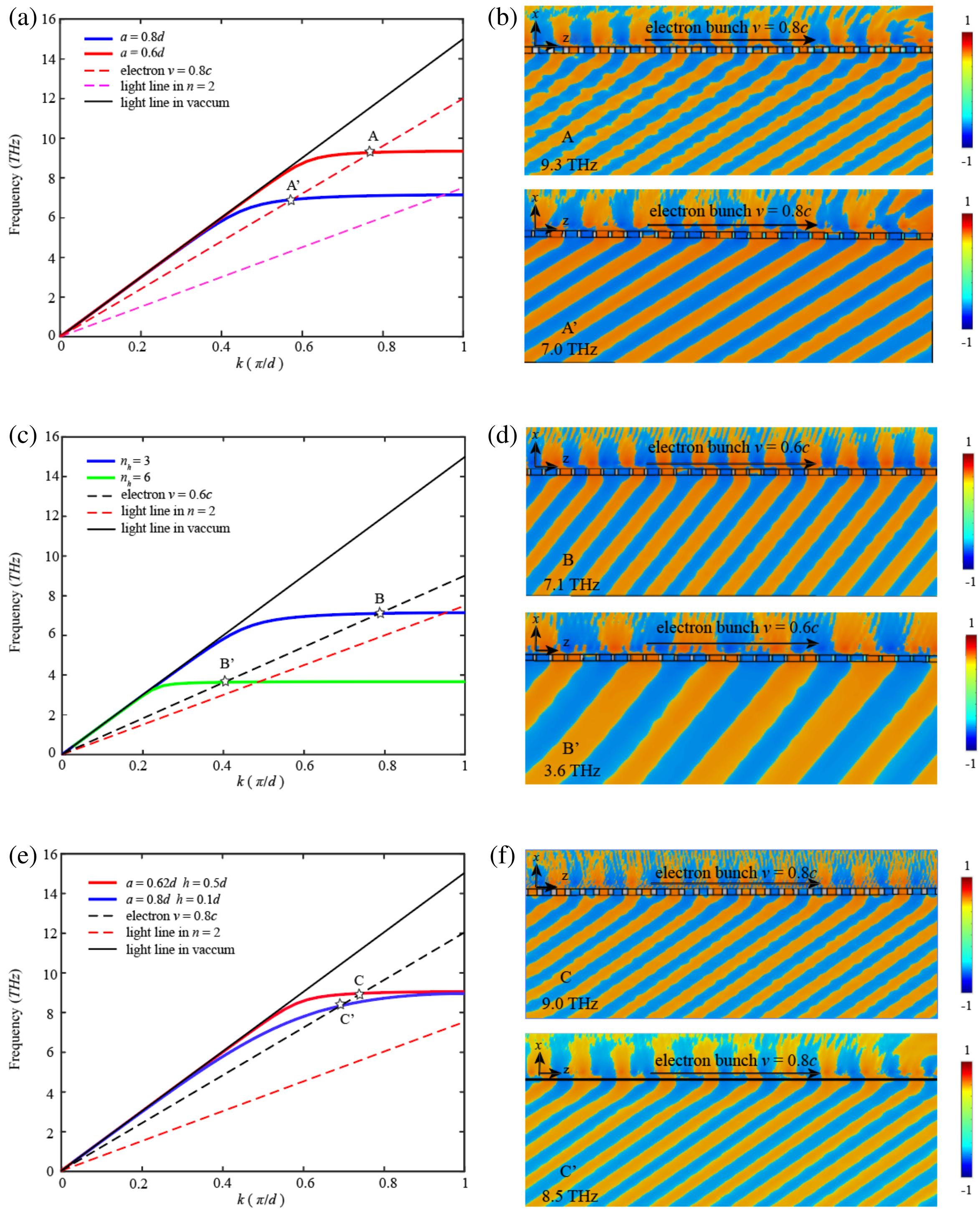

Figure 4. Flexible design of DSPP-Cherenkov radiation. (a) Filling ratio dependence of DSPP dispersion dependence of DSPP dispersion. (b) The simulated E_z in x-z plane at 9.3 THz for $a = 0.6d$ (top), and 7.0 THz for $a = 0.8d$ (bottom). (c) Material-in-hole dependence of DSPP dispersion. (d) The simulated E_z in x-z plane at 7.1 THz for $n_h = 3$ (top), and 3.6 THz for $n_h = 6$ (bottom). (e) The gradient of the group velocity dependence of DSPP dispersion. (f) The simulated E_z in x-z plane at 9.0 THz for $a = 0.62d$, $h = 0.5d$ (top), and 8.5 THz for $a = 0.8d$, $h = 0.1d$ (bottom).

dispersions. In Fig. 3(c), radiations are clearly observed in the dielectric regions at three intersection frequencies depending on different electron velocities. Additionally, the three cases show the radiation cones, whose angles are 31.0°, 51.4°, 56.5° corresponding to velocities $v = 0.6c$, $0.8c$, $0.9c$, respectively. The velocity-dependent cones can be understood with the Cherenkov-cone formula [43]:

$$\cos\theta = \frac{k_z}{k_d} = \frac{c}{nv} \tag{1}$$

where k_d is the wave vector in the dielectric medium in region III, and n is the refractive index of the dielectric medium. The theoretical angles are 33.2°, 51.0°, 56.1° for velocities $v = 0.6c$, $0.8c$, $0.9c$, respectively, which further confirms the simulation results.

4. FLEXIBLE DESIGN OF DSPP-CHERENKOV RADIATION

Beside changing electron velocities, the intersection frequency, which determines the CR spectra, can also be designed by altering DSPP dispersions. It can be easily found that a DSPP dispersion shows two features including the asymptotic frequency and the gradient of the group velocity. Firstly, we manipulate the asymptotic frequency by changing the properties of the holes, because the asymptotic frequency of the DSPP dispersion is dependent on the cutoff frequency of the holes waveguide [28]. According to the expression of cutoff frequency of holes ($f = c/2n_h a$), increasing holes size a from $0.6d$ to $0.8d$ leads to the decrease of asymptotic frequency, thus a fall of intersection frequency, as shown in Fig. 4(a). We further show the field patterns in Fig. 4(b) at the two intersection frequencies A and A′ in Fig. 4(a). The change of CR wavelengths is clearly observed, indicating the change of intersection frequencies. Moreover, increasing the refractive index n_h of the in-hole materials from 3 to 6, the asymptotic frequency drops dramatically as shown in Fig. 4(c). It offers great possibility to generate THz radiation in lower frequency. Secondly, we manipulate the gradient of the group velocity by choosing proper holes geometries as shown in Fig. 4(e). A larger gradient leads to a higher intersection frequency, which is further verified by the simulated field patterns shown in Fig. 4(f).

5. CONCLUSION

In summary, we propose a DSPP metamaterial scheme to pursue high power terahertz radiation by using CR mechanism. The frequency of THz radiation can be tuned by changing the electron velocity and manipulated by altering the structure parameters. Our proposal is promising to be demonstrated experimentally, and further push forward various practical applications of THz radiations.

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