

Bulk and surface electromagnetic response of metallic metamaterials to convection electrons

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The electromagnetic response of three-dimensional metallic metamaterials with isotropic effective index of refraction to fast-moving electrons is studied by numerical simulations. The considered metamaterials can support Cerenkov radiation [P. A. Cherenkov, Dokl. Akad. Nauk SSSR 2, 451 (1934)], and their effective dielectric behavior is confirmed by the detailed angular dependence of the generated radiation cone on the kinetic energy of electrons. Moreover, in addition to the predicted bulk modes, surface electromagnetic excitation is observed in a specific type of metamaterials and its dispersion is sensitive to the thickness of the subwavelength rods. © 2011 American Institute of Physics. [doi:10.1063/1.3625952]

Unless accelerated, the evanescent electromagnetic (EM) waves of a fast-moving charged particle are not radiatively coupled to the farfield except when its velocity exceeds the phase velocity of EM waves in the medium or it encounters optical inhomogeneity. The former is the famous Cerenkov radiation¹ and the latter is known for transition² or diffraction radiation³ depending on the type of optical inhomogeneity. These radiation mechanisms have found their established applications in the generation of intense EM waves⁴ or diagnosis of fast-moving particles.⁵

However, with the advent of photonic crystals⁶ and metamaterials,⁷ there have been fundamental changes in manipulating the flow of light, which has also triggered studies predominantly on Cerenkov radiation in such media with unconventional optical properties. One of the striking examples of unusual Cerenkov radiation is found in a metamaterial showing a negative effective refractive index,⁸ where Cerenkov radiation is emitted backward.^{9,10} Moreover, it has been shown that even the threshold energy limitation of Cerenkov radiation can be lifted off by introducing one-dimensional (1D) metallic metamaterials consisting of cut-through slits in perfect conducting films,^{11–13} where the threshold-free generation relies on the effective anisotropic dielectric response of the considered metamaterials.¹³

Recently, it has been shown that the generalization of the subwavelength slits in the 1D metallic metamaterials into three-dimensional (3D) ones can lead to isotropic dielectric response with the geometrically determined index.¹⁴ This suggests their possible contributions to the generation of Cerenkov radiation including the alleviation of the threshold limitation. In this letter, we consider these generalized metallic metamaterials with isotropic dielectric response as possible Cerenkov media and identify the bulk effective

dielectric response of the considered metamaterials via measuring the angles of radiation cones. We also manifest the existence of surface EM waves in addition to the bulk EM waves in such metamaterials.

In order to study the interaction between the metamaterials and the beam of convection electrons, a particle-in-cell (PIC) code¹⁵ has been used. As shown in Fig. 1(a), the metamaterials were modeled in the PIC code as three-dimensional (3D) periodic structures with unit cells consisting of a perfect conducting cube, Fig. 1(b) (type I), or perfect conducting plates and rods, Fig. 1(c) (type II). The type I structure is the direct 3D generalization of the 1D metallic metamaterials, but it has a strong diamagnetic response leading to the reduction of the effective index. However, this diamagnetic response can be suppressed by transforming the cubes into plates and rods as shown in Fig. 1(c).¹⁴

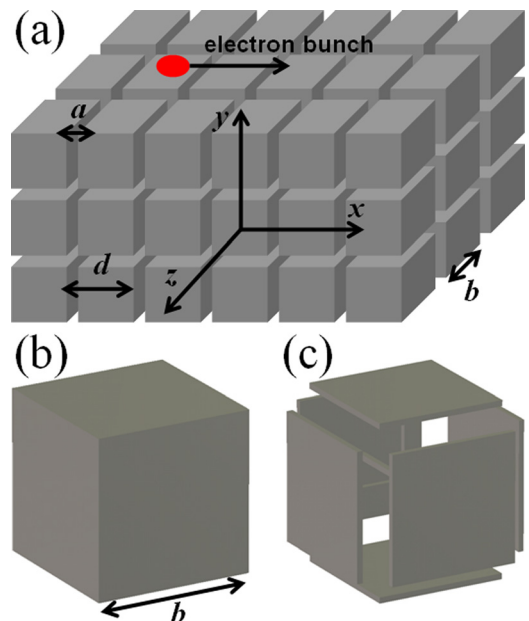


FIG. 1. (Color online) (a) Schematic model of the considered metamaterials with convection electrons. Unit cell structures for (b) type I and (c) type II metamaterials.

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These metamaterials were assigned the common filling ratio of the slit, $d/a = d/(d-b) = 4$. For the assigned filling ratio, the refractive indexes of metamaterials of types I and II are found to be 1.32 and 1.54, respectively, which were retrieved from the transmission and reflection coefficients for structures with a thickness of $10d$.¹⁴ Then, a Gaussian electron bunch was modeled to pass above the grating with a pulse width of $\sigma/d = 1/2$ to guarantee coherent radiation from the electron bunch in the considered frequency range, below the normalized frequency, $\pi c/d$.

The kinetic energy of the electron bunch was varied to verify the well-known dependence of Cerenkov radiation on particle's velocity such as the angle of radiation cone and the velocity threshold found in normal isotropic dielectric medium. The energy variation was made around the threshold energies, 271.9 and 161.0 keV, for dielectric media with $n = 1.32$ and 1.54, respectively. As the electron bunch travels near the top surface of the structure, it encounters subwavelength slits, which leads to the diffractive coupling of its evanescent waves into propagating slit modes.¹³ The overall propagation of the diffractively coupled waves at each slit would be governed by the effective dielectric properties of the medium. Thus, for a particle's velocity larger than the phase velocity of the effectively dielectric medium, coherently propagating EM waves can be observed.

As expected, the considered metamaterials support Cerenkov radiation when the kinetic energy of the particles exceeds the threshold energies for the considered effective media. Fig. 2(a) shows the typical contour plot of the generated H_z field for the metamaterial type I at 360 keV, which exhibits Cerenkov radiation cone with its radiation angle of

19.2°. The radiation angles were measured at various kinetic energies for the metamaterials of types I and II by taking the contour plots of z-component of magnetic field, H_z , where the threshold characteristic is clearly observed for both types of metamaterials as depicted in Fig. 2(b). To further validate the effective medium description of the metamaterials, the measured radiation angles from the metamaterials type I (filled circles) and type II (hollow circles) were also compared with the calculated ones for their effective dielectric media with $n = 1.32$ (solid line) and 1.54 (dashed line) as shown in Fig. 2(b). As can be seen in this figure, these metamaterials are precisely described as effective dielectric media with those values of refractive index.

However, for type II structure, the driving electron bunch accompanies strong surface waves behind it in addition to the predicted bulk modes as shown in Fig. 3(a), which shows the contour plot of H_z field for type II structure with the rod thickness of $t = d/40$ at 300 keV. The frequency of the excited surface waves can be obtained by taking the Fourier transform of the time signal of H_z field measured slightly above the structure, which shows a peak at the frequency of 0.167 as shown in Fig. 3(b). By measuring the phase variation in the x -direction, the dispersion of the excited surface waves can be obtained. As shown in Fig. 3(c), the surface EM resonance (hollow circle) is located in the lowest band gap (shaded) and has a phase velocity synchronism with 300

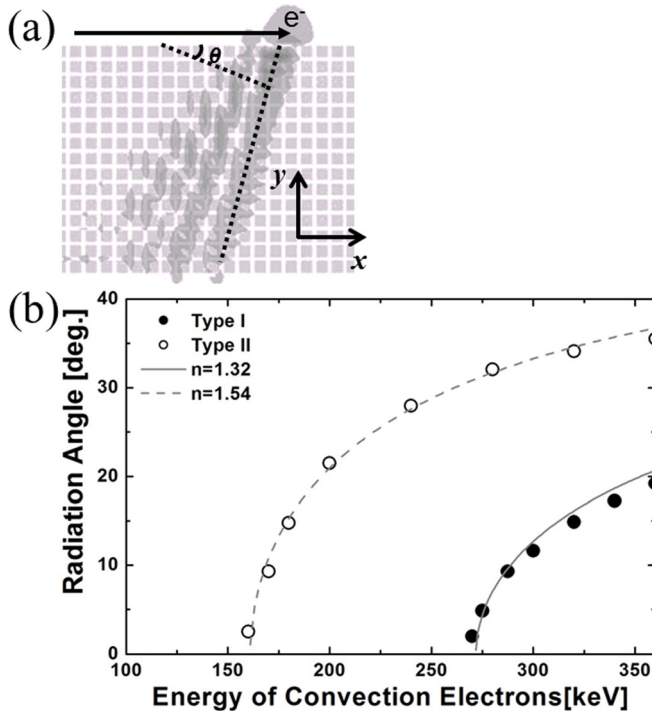


FIG. 2. (Color online) (a) Contour plot of the H_z field distribution is shown for 3D metamaterial type I at 360 keV of beam energy. (b) Simulated radiation angles for metamaterial type I (filled circles) and type II (hollow circles) are compared with the calculated angles for isotropic dielectric index of $n = 1.32$ (gray solid curve) and 1.54 (gray dashed curve), respectively.

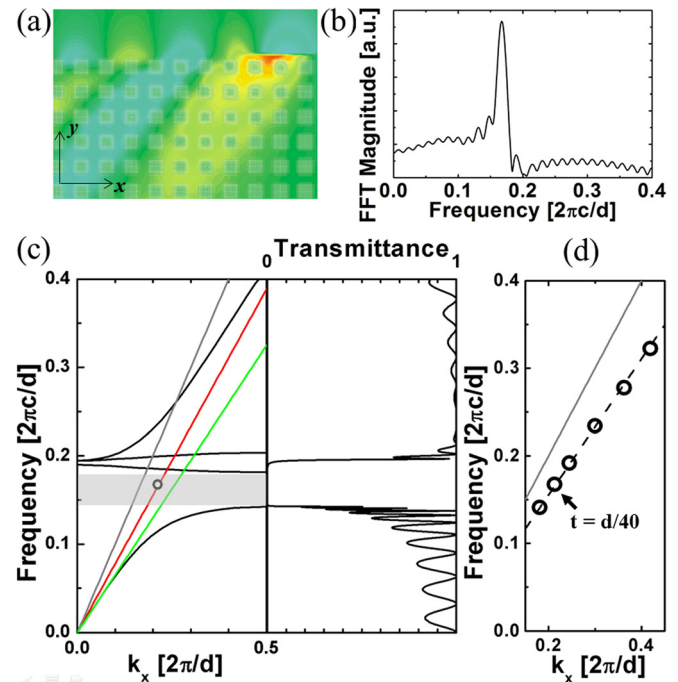


FIG. 3. (Color online) (a) Contour plot of the H_z field distribution is shown for the metamaterial of type II with the filling ratio, $d/a = 4$, and rod thickness of $d/40$ at 300 keV of beam energy. The red and blue colors indicate positive and negative amplitudes, respectively. (b) Frequency spectrum of the generated H_z field measured slightly above the structure. (c) Dispersion and transmittance plots for the metamaterial of type II with the filling ratio, $d/a = 4$, and rod thicknesses of $d/40$. The gray, green, and red lines refer to the light lines in free space and the medium with $n = 1.54$ and 300 keV beam line, respectively. The excited surface bound state (hollow circle) is located in the lowest band gap (shaded). (d) Dispersion plot of the excited surface waves (hollow circle) while varying the rod thickness from $d/40$ to $d/5$ is plotted together with 300 keV beam line (dashed line) and light line (solid line).

keV beam line below the light line (gray solid line). Thus, this mode cannot radiate neither into the metamaterials nor the free space.

This unexpected surface EM mode exhibits sensitive dependence on the thickness of subwavelength rods, t . With the kinetic energy of the fast-moving electrons being fixed at 300 keV, the frequency of the excited surface EM mode is increased as the thickness of rods is increased from $d/400$ to $d/5$ as shown in Fig. 3(d). The phase velocity synchronism between the surface EM mode and 300 keV electron beam is maintained during this increase of the mode frequency, which clearly shows that the waves are excited via the fast-moving electrons.

In conclusion, we have shown that the two types of metallic metamaterials support Cerenkov radiation with the presence of fast-moving electrons, which originates from the diffractive coupling at each slit opening. From the relationship between the angles of Cerenkov radiation cone and the beam energy, both types of metamaterials are confirmed to behave effectively as isotropic dielectric media according to the predicted refractive indexes. In addition to the predicted bulk dielectric response, surface plasmonic response is observed in one type of the considered metamaterials. This unexpected surface EM response together with the bulk positive dielectric response would broaden the applicability of this type of metamaterials.

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