Surface Polariton Cherenkov Light Radiation Source

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A physical phenomenon has been found: in a structure of nanometal film with dielectric-medium loading, the surface polaritons excited by a uniformly moving electron bunch can be transformed into Cherenkov radiation with intensity enhancement in the medium. Based on this mechanism, the surface polariton Cherenkov light radiation source is presented and explored in the Letter. The results show that surface polariton Cherenkov light radiation source can generate radiation, from visible light to the ultraviolet frequency regime and the radiation power density can reach or even exceed 10^8 W/cm^2 depending on the beam energy and current density. It is a tunable and miniature light radiation source promising to be integrated on a chip and built into a light radiation source array.

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Recently, intense investigation has demonstrated that the combination of electronics, photonics, and nanotechnology is a promising method to generate radiation, ranging from terahertz to visible light [1–7]. Among these studies, Refs. [1–3] concentrate on a waveguide with a nanoscale periodic structure excited by uniformly moving electron beams, while Refs. [4,5] concern the Cherenkov radiation excited by an electron beam and optical pulse, respectively. In addition, the state-of-the-art development of electron accelerators shows that up to attosecond short pulse electron beams with very good beam quality can be obtained [8], and the wake-field Cherenkov radiation may dramatically enhance the output power [4]. Moreover, advances in nanotechnology enables us to manufacture components and periodic structures of very small size.

The past years have seen the development of different types of Cherenkov radiation, such as Cherenkov radiation in photonic crystals, metameterial, etc., [4,5,9,10]. In this study, we found that, in a structure of nanometal film with dielectric-medium loading, surface polaritons (SPs) excited by a uniformly moving electron bunch can be transformed into Cherenkov radiation. Based on this phenomenon, the SP Cherenkov light radiation source (SPCLS) is presented and explored in this Letter for the generation of radiation, ranging from visible light to the ultraviolet regime. Two kinds of structures, planar and circular cylindrical, with silver film are proposed. Detailed theoretical analyses, numerical calculations, and computer simulations are carried out, and their results agree well with each other.

Surface polaritons are electromagnetic surface waves propagating along the metal-air or metal-dielectric interface, and can be excited by moving electrons [9,11–14]. The planar structure of SPCLS, shown in Fig. 1(a), is a nanometal (Ag) film of thickness d embedded on a dielectric medium. In the case of a structure without a dielectric medium, the electron bunch uniformly moving along the metal film surface excites the SPs in both sides of the metal film, as shown in Fig. 1(b). However, in Fig. 1(a), if the Cherenkov radiation condition $\sqrt{\varepsilon_d}\beta > 1$ is fulfilled in the medium (here ε_d is the permittivity of the dielectric medium, and β is the ratio of the beam velocity to the speed of light c in vacuum), the excited SPs are transformed into Cherenkov radiation, as shown in Fig. 1(c).

Now we deal with the mechanism of SPCLS with the planar structure. In order to study the frequency response, all physical quantities are in the frequency domain. Making use of the Maxwell equations, we get a nonhomogeneous Helmholtz equation for electromagnetic fields induced by the electron bunch. Then, solving the nonhomogeneous Helmholtz equation by means of the Wronskian approach, we obtain the electromagnetic fields for each region shown in Fig. 1(a). Matching the boundary conditions, we get the dispersion equation of the SPs [Eq. (1)] and the Cherenkov radiation power in the medium [Eq. (2)] as follows [15]:

$$\frac{(\varepsilon_m k_1 - k_2)}{(j\varepsilon_m k_3 - \varepsilon_d k_2)} e^{-k_2 d} = \frac{(\varepsilon_m k_1 + k_2)}{(j\varepsilon_m k_3 + \varepsilon_d k_2)} e^{k_2 d} \quad (1)$$

$$P = \frac{8\pi q^2}{c} \times \mathrm{Re}\left\{\left[\frac{k_2 k_0^2 \varepsilon_d^{3/4} \varepsilon_m e^{k_2 d} e^{-k_c^i (y_0 - d)}/k_c^i}{(j\varepsilon_m k_3 + \varepsilon_d k_2)(k_2 - \varepsilon_m k_1) + (j\varepsilon_m k_3 - \varepsilon_d k_2)(\varepsilon_m k_1 + k_2) e^{2k_2 d}}\right]^2\right\}, \quad (2)$$

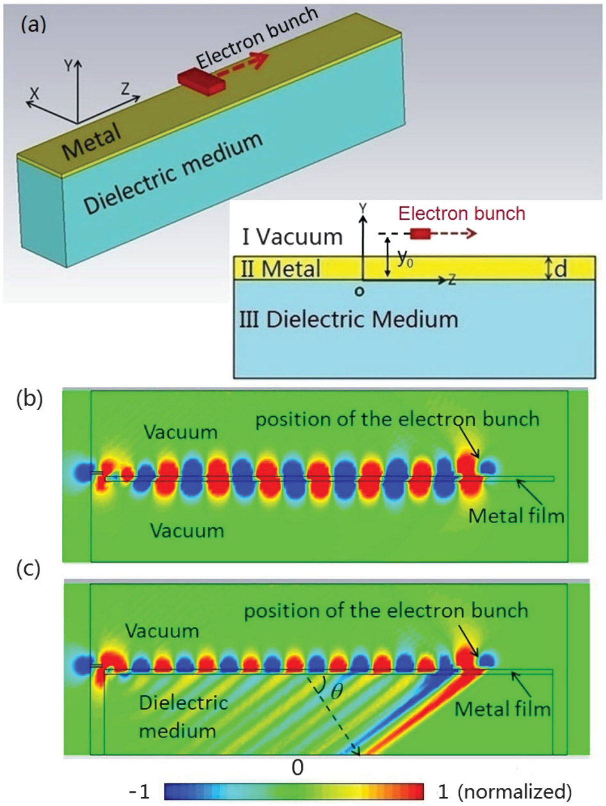

FIG. 1 (color). (a) A schematic of the planar structure SPCLS. Region I is a vacuum, region II is a metal film, and region III is dielectric medium. (b) Simulation results of the contour map of electrical field E_z excited by an electron bunch of $d = 20$ nm thick silver film without dielectric-medium loading. (c) A contour map of electrical field E_z excited by an electron bunch in the planar structure SPCLS ($\varepsilon_d = 9$). The angle of the Cherenkov cone is θ.

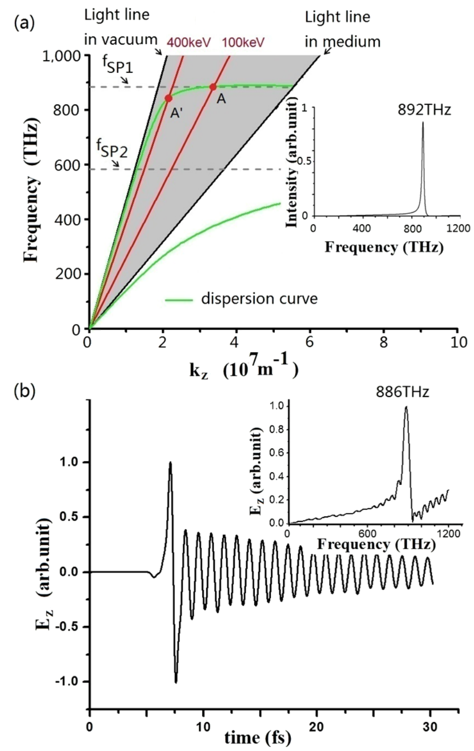

FIG. 2 (color online). (a) Dispersion curves of $d = 20$ nm thick Ag film covering the dielectric medium ($\varepsilon_d = 9$). The intersection is A or A' for electron beam lines with energy of 100 or 400 keV. f_{SP1} and f_{SP2} are the surface plasmon frequencies at the vacuum-metal and metal-dielectric interfaces, respectively. The inset of Fig. 2(a) shows the calculated power spectrum. (b) Field E_z of the simulation and its Fourier spectrum.

where $k_0 = \omega/c$, $k_1 = \sqrt{k_z^2 - k_0^2}$, $k_2 = \sqrt{k_z^2 - k_0^2\varepsilon_m}$, $k_3 = \sqrt{k_0^2\varepsilon_d - k_z^2}$, $k_c = jk_c^i = \sqrt{k_0^2 - (\omega/u_0)^2}$, k_z is the wave vector in z direction, u_0 is the electron bunch velocity, q and y_0 are the charge quantity and the position of the electron bunch, respectively, and ε_m is the dielectric function of the metal. The modified Drude model based on the Sommerfeld theory of metal is adopted [16–19]: $\varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 - i\gamma\omega}$. For Ag, $\omega_p = 1.39 \times 10^{16}$ rad/s, $\gamma = 3.2 \times 10^{13}$ Hz, and $\varepsilon_\infty = 5.3$.

The dispersion curves based on a numerical calculation of Eq. (1) are shown in Fig. 2(a), where the parameters are $d = 20$ nm and $\varepsilon_d = 9$. The SPs can be transformed into Cherenkov radiation in the shaded part shown in Fig. 2(a). It can be seen that there are two SP modes, only one of which can be excited. It shows that the frequency is determined by the intersection of the beam line with the SP dispersion curve; this point satisfies both the Cherenkov radiation condition and the SP dispersion relation. Consequently, all such points are available for the transformation of SPs into Cherenkov radiation. In the region between the vacuum light line and the medium light line, wave-phase velocity is lower than the speed of light and higher than that in the medium. This is exactly what is required for Cherenkov radiation, and therefore is the working region of SPCLS. The frequency can be tuned by adjusting the beam energy.

A computer simulation is implemented for 100 keV. The radiation field E_z and its Fourier spectrum are shown in Fig. 2(b). The peak frequency is 886 THz, which agrees well with the numerical calculation. The influence of metal film thickness has also been studied, and the results show that $d = 20$ nm is the best value [15].

Even more interesting is the cylindrical structure shown in Fig. 3, a dielectric rod covered by thin metal film. In this structure, SPCLS can generate not just one- but two-color light radiation. The dispersion equation of circular cylindrical structure is

$$\frac{\varepsilon_m k_1 K_0(k_1 r_b) I_1(k_2 r_b) + k_2 K_1(k_1 r_b) I_0(k_2 r_b)}{\varepsilon_m k_1 K_0(k_1 r_b) K_1(k_2 r_b) - k_2 K_1(k_1 r_b) K_0(k_2 r_b)} = \frac{\varepsilon_m k_3 J_0(k_3 r_a) I_1(k_2 r_a) - \varepsilon_d k_2 J_1(k_3 r_a) I_0(k_2 r_a)}{\varepsilon_m k_3 J_0(k_3 r_a) K_1(k_2 r_a) + \varepsilon_d k_2 J_1(k_3 r_a) K_0(k_2 r_a)}, \quad (3)$$

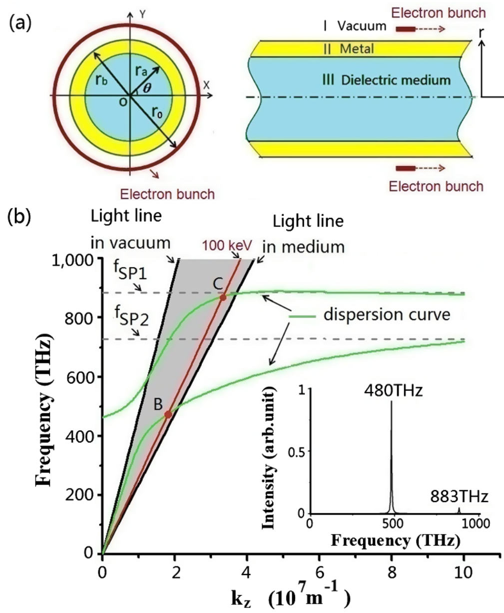

FIG. 3 (color online). (a) A schematic of the circular cylindrical structure SPCLS. The radius of the dielectric medium is r_a, the silver film is in the region of $r_a \leq r \leq r_b$, and the radius of the hollow electron bunch is r_0. (b) Dispersion curves and beam lines in SPCLS. The dielectric cylindrical rod is covered by silver film. The green lines are the dispersion curves for the structure $r_a = 100$ nm, $r_b = 120$ nm, and $\varepsilon_d = 4$. The intersection points are B and C with beam energy of 100 keV. The inset is the calculated power spectrum, and the peak frequency of Cherenkov radiation is 480 THz.

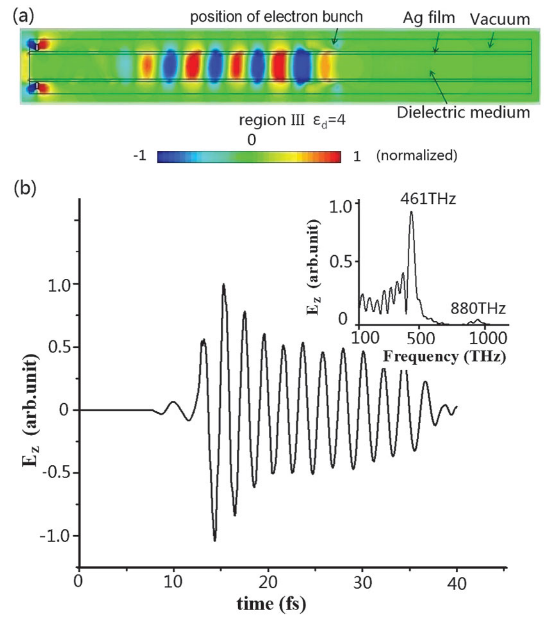

FIG. 4 (color). (a) A contour map of E_z. (b) Simulation results of E_z and its Fourier spectrum; the peak frequency is 461 THz.

and the output power of SPCLS can be found as

$$P_z = \frac{u_0 k_z^2 \varepsilon_d r_a^2}{8k_3^2} \mathrm{Re}\{[J_1^2(k_3 r_a) - J_0(k_3 r_a) J_2(k_3 r_a)](B_4)^2\}, \tag{4}$$

where

$$B_4 = \frac{2\pi^2 k_0 q k_2 H_0^{(1)}(k_c r_0)[\chi I_0(k_2 r_a) - K_0(k_2 r_a)] M_3}{c k_c J_0(k_3 r_a)[-k_2 K_1(k_1 r_b) M_1 - \varepsilon_m k_1 K_0(k_1 r_b) M_2]}$$

$$M_1 = \chi I_0(k_2 r_b) - K_0(k_2 r_b)$$

$$M_2 = \chi I_1(k_2 r_b) + K_1(k_2 r_b)$$

$$M_3 = k_c K_1(k_1 r_b) J_0(k_c r_b) - k_1 K_0(k_1 r_b) J_1(k_c r_b)$$

$$\chi = \frac{\varepsilon_d k_2 J_1(k_3 r_a) K_0(k_2 r_a) + \varepsilon_m k_3 J_0(k_3 r_a) K_1(k_2 r_a)}{\varepsilon_d k_2 J_1(k_3 r_a) I_0(k_2 r_a) - \varepsilon_m k_3 J_0(k_3 r_a) I_1(k_2 r_a)}.$$

In Eqs. (2) and (4), $k_z = \frac{\omega}{u_0}$. $J_n(x)$ is the first kind of Bessel function, $H_n^{(1)}(x)$ is the Hankel function, and $I_n(x)$ and $K_n(x)$ are modified Bessel functions. The parameters and calculated dispersion curves are shown in Fig. 3(b). In the cylindrical structure, the electron beam line intersects with dispersion curves at two points of the two modes, unlike in the planar structure. This means these two SP modes can be transformed into Cherenkov radiation with the same Cherenkov cone. The spectrum of the output power, calculated by Eq. (4), is shown in the inset of Fig. 3(b). There are two frequencies, 480 and 883 THz, corresponding to the intersection points B and C, respectively.

Computer simulation for the scheme in Fig. 3 is carried out for a 100-keV hollow electron bunch. The radiation frequency of the dominant mode is 461 THz, which agrees well with the numerical calculation. The frequency of the second mode is 880 THz. These two SP modes are transformed into Cherenkov radiation, but the intensity of the second mode is very small. Figure 4 shows that the fields are concentrated in the center of the structure.

Figure 5 shows that the two SP modes in the visible-light frequencies can be transformed into Cherenkov radiation by changing the parameters of the cylindrical structure and that the radiation field intensities are comparable. The frequencies obtained by computer simulation are 384 and 739 THz, which agree with the theoretical calculation of 390 and 756 THz, respectively. Figure 5(c) shows that the high-frequency mode is asymmetric but the low-frequency mode is symmetric.

Now we evaluate the radiation power density of the SPCLS. Both computer simulation results and numerical calculation show that, where the charge quantity in an electron bunch is 3.2×10^{-15} Coulomb, the power density can reach 10^8 W/cm^2. The SPCLS can also operate at lower beam energy, for example, 35–40 keV.

So far only Ag has been used; actually, Au and Al also can be used in SPCLS. For Au, radiation frequency should be lower and the operation frequency region should be narrower to avoid quantum transition, and for Al radiation frequency can be higher and the working-frequency region can be broader [20–23].

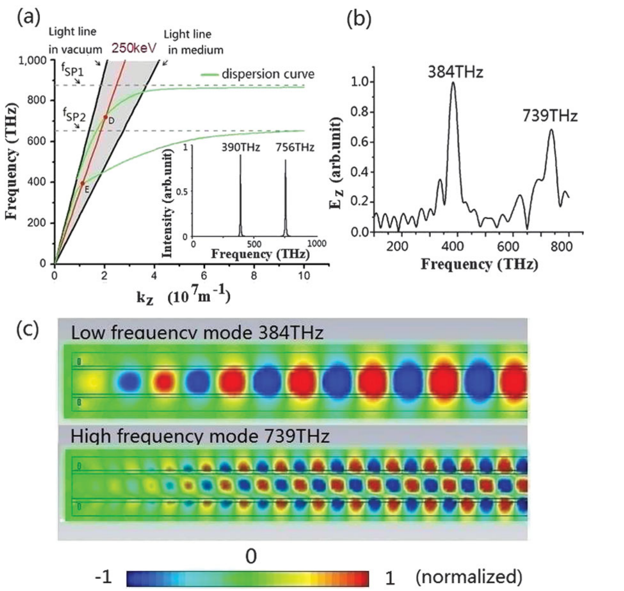

FIG. 5 (color). (a) Numerical calculation results. The green dispersion curves describe the structure $r_a = 100$ nm, $r_b = 130$ nm, and $\varepsilon_d = 6$. The intersection points D and E correspond to a beam energy of 250 keV. The inset is the calculated power spectrum. (b) The Fourier spectrum of E_z by computer simulation. (c) A contour map of E_z for low- and high-frequency modes.

Our results show that the mechanism of SPCLS is essentially different from that of all other kinds of Cherenkov radiation [9,10,24–27]. In ordinary cases, Cherenkov radiation is a broad and continuous spectrum radiation, and the maximum radiation frequency depends on the highest response frequency of the medium [10,24]. For Cherenkov radiation in a waveguide filled with a dielectric medium, radiation frequency is determined by the wave band of the waveguide [25,26]. If an electron beam is incidental to a metal film, the excited Cherenkov radiation might be accompanied by transition radiation [9].

As for SPCLS, the uniformly moving electron bunch does not excite Cherenkov radiation in the metal film directly. Instead, it excites the SPs first, and then the SPs are transformed into Cherenkov radiation with intensity enhancement in the dielectric medium on which the metal film, as an active medium, is embedded. Therefore, the velocity of the moving electron bunch is required not to be higher than but just equal to the phase velocity of the SPs. And the working frequency of radiation is determined by the intersection of the beam line with the SP dispersion curve, which means the SPs in the SPCLS serve as a *tunable frequency filter*.

Recent advances in optical materials and their optical properties provide interesting opportunities for SPCLS. For example, MgO-TiO_2, porous silicon, ZnSe, SiC, and $Bi_4Ge_3O_{12}$ have excellent optical properties. Most of them can work in the spectrum, from visible light to ultraviolet, and are good dielectric media for SPCLS [15].

To summarize, we have found a physical phenomenon: SPs excited by a uniformly moving electron bunch in a metal film with dielectric-medium loading can be transformed into Cherenkov radiation with enhanced intensity. SPCLS is presented and explored in the Letter based on this mechanism. The results obtained show that SPCLS has the following unique characteristics: it can generate radiation in the spectrum, from visible light to the ultraviolet regime; it is a broad band tunable light radiation source; for the cylindrical structure, it may generate a two-color light with the same Cherenkov cone; its power density is high, up to 10^8 W/cm^2 or even higher, depending on beam energy and current density; it is of micro- or nanoscale size, so it can be integrated on a chip and built into a light radiation array. Therefore, this tunable and miniature light radiation source could provide great opportunities and challenges to modern physics and optics.

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[15] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.109.153902 for Appendix A (theoretical analysis), Appendix B (influence of film thickness), and Appendix C (recent advances in optical materials and an example of SPCLS with a $Bi_4Ge_3O_{12}$ dielectric medium).

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