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ABSTRACT

Interfacial Cherenkov radiation originates from the interaction of charged particles with sequential interfaces inside photonic crystals and is crucial to many applications, ranging from particle detectors and lasers to electron microscopy and spectroscopy, since it can create directional light emission at arbitrary spectra. However, the interfacial Cherenkov radiation suffers from chromatic issues and is featured with frequency-sensitive radiation angles due to the intrinsic structural dispersion of photonic crystals. Counterintuitively, here we reveal a universal mechanism to create the broadband achromatic interfacial Cherenkov radiation from photonic crystals. Our mechanism exploits the anomalous Maxwell-Garnett theory beyond the long-wavelength limit via the Brewster effect and introduces it for the first time into the context of Cherenkov radiation. Specifically, we present photonic crystal designs that mimic homogeneous achromatic media in terms of their interfacial Cherenkov radiation, emitted precisely at the Brewster angle. We find the radiation peak angle could be frequency-insensitive, even over the entire visible spectrum.

INTRODUCTION

Cherenkov radiation offers a compelling effect to create directional light emission at arbitrary spectral regimes.[1–3] This effect thus finds exotic uses in both basic science and practical applications in various realms, ranging from cosmology,[4,5] high-energy physics,[6–9] nanophotonics,[10–14] plasmonics,[15–17] and materials science,[18,19] to imaging,[20–23] photodynamic therapy[24,25] and vacuum electronics.[26,27] However, since the conventional Cherenkov radiation is a *bulk effect*, originating from the interaction of moving charged particles with bulk materials, its emergence requires particle velocities faster than the so-called Cherenkov threshold, namely, the phase velocity of light in the host bulk material. As a result, all these applications of bulk Cherenkov radiation are strictly limited by the particle velocity and the material property. As a typical example, the particle detector based on bulk Cherenkov radiation generally requires the usage of specific materials with their refractive index very close to unity, which are often restricted to silicon aerogels or large gas chambers, for the identification of high-energy particles in the giga-electron-volt (GeV) range.[28]

To tackle this issue, Refs. 7 and 29 recently revealed a brand-new way to create the effective Cherenkov radiation by exploiting the *interface effect*, namely, the interaction of moving charged particles with sequential interfaces inside photonic crystals, rather than the bulk effect. This way, the interfacial Cherenkov radiation from photonic crystals fundamentally overcomes the velocity and material limitations for conventional bulk Cherenkov radiation and holds great promise for the development of many enticing on-chip photonic devices.[30–33] One promising application of interfacial Cherenkov radiation is the design of integrated light sources[34–37] at previously hard-to-reach frequencies via low-velocity charged particles. This is because the interfacial Cherenkov radiation is intrinsically threshold-free and can be excited by ultralow-energy charged particles with their kinetic energy down to several electron-volts (eV).[29] Another potential application of interfacial Cherenkov radiation is the development of miniaturized Cherenkov detectors with enhanced sensitivity by using regular dielectrics, without resorting to index-near-unity materials. This is enabled by the unique feature that the interfacial Cherenkov radiation is capable of controlling the sensitivity of its radiation angle to the particle velocity on demand through merely the structural design of photonic crystals.[7]

To facilitate the practical implementation of these enticing applications, it is necessary to further keep the exotic performance of interfacial Cherenkov radiation (e.g., the radiation angle) invariant to the frequency over a prescribed bandwidth. However, the interfacial Cherenkov radiation from photonic crystals is inherently chromatic. That is, its radiation angle is rather sensitive to the working frequency. This chromatic feature of interfacial Cherenkov radiation is mainly caused by the structural dispersion of photonic crystals.[38–41] This structural dispersion would persist even when the constituent materials of photonic crystals are achromatic.

Consequently, even though photonic crystals provide a versatile platform to control light–matter interactions, their structural dispersion would generally degrade the performance of directional light emission over a predefined frequency range. Current strategies to bypass the chromatic issue of photonic crystals rely heavily on numerical optimization approaches,[42–45] such as inverse design.[46–51] For example, one may mitigate the chromatic aberration of light propagation through photonic crystal fibers by carefully tailoring the structural parameters. Due to the lack of general physical insights, the extension of these numerical optimization approaches to mitigate the chromatic issue of charged particle radiation from photonic crystals is not straightforward, and indeed, this problem has remained. Altogether, despite the extensive research into both charged particle radiation[52–65] and photonic crystals,[66–76] no solution has been found to date to eliminate or at least reduce the chromatic response of charged particle radiation from photonic crystals.

Here, we reveal a feasible route to create the *achromatic* interfacial Cherenkov radiation from photonic crystals via the usage of the Brewster effect. Counterintuitively, we find that the spatially inhomogeneous photonic crystal could act like a spatially homogeneous achromatic medium (e.g., across the visible regime) for interfacial Cherenkov radiation emitted at the Brewster angle, through the judicious design of particle velocity. The underlying mechanism is essentially rooted in the anomalous Maxwell-Garnett theory, which could remain valid for photonic crystals beyond the long-wavelength limit by exploiting the Brewster effect. As background, the Maxwell-Garnett theory, dating back to the pioneering work of James Clerk Maxwell-Garnett in 1904, offers a powerful yet simple framework to describe the inhomogeneous structure as an effective homogeneous structure.[77–83] Despite its extensive research over the past century and wide applications in diverse realms, ranging from photonics, acoustics, and thermodynamics to materials science,[84–88] the Maxwell-Garnett theory has never been connected to charged particle radiation from photonic crystals. We find that the connection between Maxwell-Garnett theory and charged particle radiation from photonic crystals can significantly reduce the overall complexity in the analysis, calculation, and design of achromatic interfacial Cherenkov radiation.

RESULTS

We begin with the conceptual illustration of achromatic interfacial Cherenkov radiation from photonic crystals as shown in Fig. 1. For brevity, we consider a swift electron moving with a velocity $\bar{v} = \hat{z}v$ and traveling perpendicularly through a one-dimensional photonic crystal, which is composed of two achromatic dielectrics. The constituent dielectric X has a relative permittivity $\varepsilon_{r,X}$ and a thickness d_X, where $X = 1$ or 2. Under this scenario, the emitted light is purely p-polarized. According to the Bloch theory, the dispersion for p-polarized light inside the designed photonic crystal[89,90] is obtained as

$$\cos(k_z d) - \left[\cos(k_{z,1}d_1)\cos(k_{z,2}d_2) - \frac{1}{2}\left(\frac{\tilde{\eta}_1}{\tilde{\eta}_2} + \frac{\tilde{\eta}_2}{\tilde{\eta}_1}\right) \times \sin(k_{z,1}d_1)\sin(k_{z,2}d_2)\right] = 0, \quad (1)$$

where $\bar{k} = \hat{\perp}k_\perp + \hat{z}k_z$ is the wavevector of Bloch eigenmodes inside the photonic crystal, $\hat{\perp}$ is the basis vector perpendicular to $\hat{z}$, $d = d_1 + d_2$, $k_{z,X} = \sqrt{\frac{\omega^2}{c^2}\varepsilon_{r,X} - k_\perp^2}$, ω is the angular frequency, c is the speed of light in vacuum, and $\tilde{\eta}_X = \frac{k_{z,X}}{\omega\varepsilon_0\varepsilon_{r,X}}$ corresponds to the impedance of dielectric X under the oblique incidence of light.

Upon close inspection, Eq. (1) can be significantly reduced if $\tilde{\eta}_1 = \tilde{\eta}_2$, namely, if the impedance-matching condition is fulfilled, under which we have $k_\perp = k_{\perp,B}$ and

$$k_{\perp,B} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{r,1}\varepsilon_{r,2}}{\varepsilon_{r,1} + \varepsilon_{r,2}}}. \quad (2)$$

Essentially, this impedance-matching condition is related to the Brewster effect at the interface between dielectrics 1 and 2,[63,78,91–96] since the reflection coefficient at this dielectric interface is $R_{1,2} = \frac{\tilde{\eta}_1 - \tilde{\eta}_2}{\tilde{\eta}_1 + \tilde{\eta}_2} = 0$, if $\tilde{\eta}_1 = \tilde{\eta}_2$.

We now apply the impedance-matching condition into Eq. (1). To be specific, if $\tilde{\eta}_1 = \tilde{\eta}_2$, we have $\frac{1}{2}\left(\frac{\tilde{\eta}_1}{\tilde{\eta}_2} + \frac{\tilde{\eta}_2}{\tilde{\eta}_1}\right) = 1$, and Eq. (1) is reduced to $\cos(k_{z,B}d) = \cos(k_{z,1}d_1 + k_{z,2}d_2)$. This way, one simple solution to Eq. (1) is $k_{z,B}d = k_{z,1}d_1 + k_{z,2}d_2$. By further expressing $k_{z,X}$ with $k_{\perp,B}$, this solution can be transformed to

$$\frac{k_{\perp,B}^2}{\varepsilon_{\text{eff},z}} + \frac{k_{z,B}^2}{\varepsilon_{\text{eff},\perp}} = \frac{\omega^2}{c^2}, \quad (3)$$

$$\varepsilon_{\text{eff},\perp} = \frac{\varepsilon_{r,1}d_1 + \varepsilon_{r,2}d_2}{d_1 + d_2}, \quad (4)$$

$$\varepsilon_{\text{eff},z} = \frac{\varepsilon_{r,1}\varepsilon_{r,2}(d_1 + d_2)}{\varepsilon_{r,1}d_2 + \varepsilon_{r,2}d_1}, \quad (5)$$

where both $\varepsilon_{\text{eff},\perp}$ and $\varepsilon_{\text{eff},z}$ are frequency-independent. Equations (3)–(5) indicate that the spatially inhomogeneous photonic crystal is equivalent to a spatially homogeneous achromatic uniaxial medium with an effective relative permittivity, $\bar{\bar{\varepsilon}}_r = \text{diag}[\varepsilon_{\text{eff},\perp}, \varepsilon_{\text{eff},\perp}, \varepsilon_{\text{eff},z}]$. That is, the anomalous Maxwell-Garnett theory for photonic crystals, as governed by Eqs. (3)–(5), would be valid beyond the long-wavelength limit via the Brewster effect. Despite this anomalous Maxwell-Garnett theory being reported in 1988,[78] its connection to charged particle radiation has never been explored before.

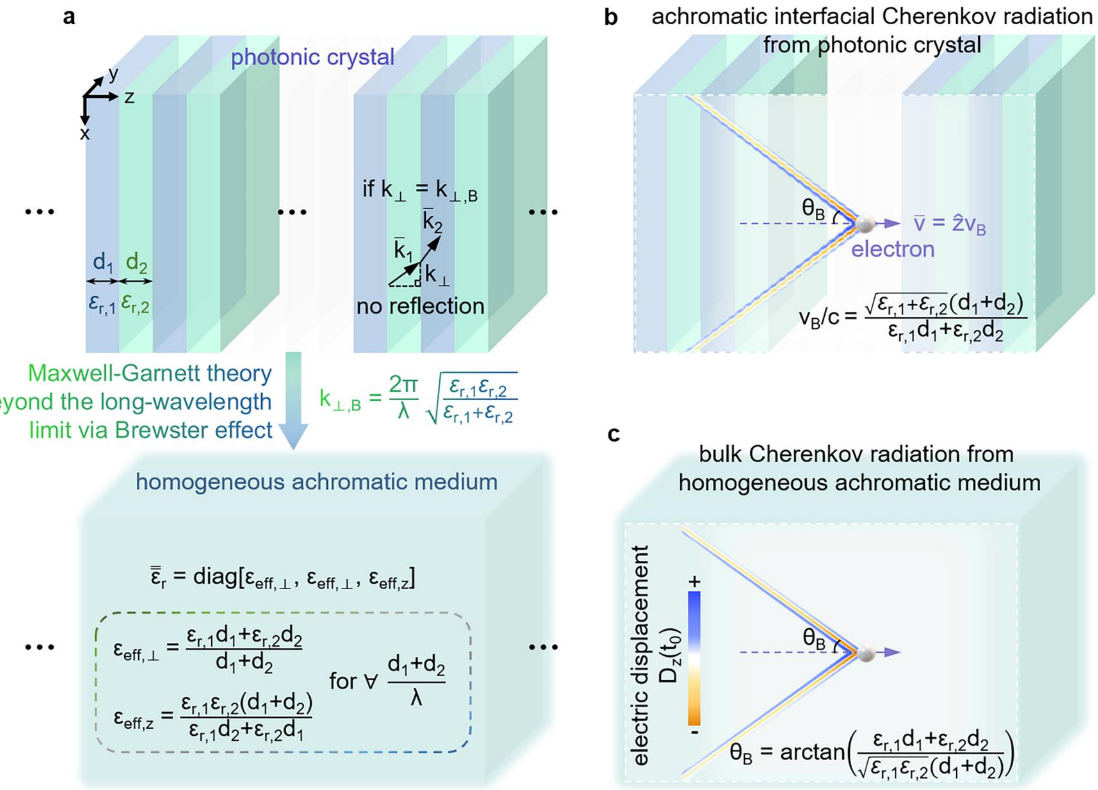

FIG. 1. Conceptual illustration of achromatic interfacial Cherenkov radiation from infinite-thickness photonic crystals. (a) Maxwell-Garnett theory beyond the long-wavelength limit via Brewster effect. The photonic crystal is composed of two achromatic dielectrics. The constituent dielectric X has a thickness d_X and a relative permittivity $\varepsilon_{r,X}$, where $X = 1$ or 2. The light inside dielectric X has a wavevector $\bar{k}_X = \hat{\perp} k_\perp + \hat{z} k_{z,X}$, where $\hat{\perp}$ is the basis vector perpendicular to $\hat{z}$. Under the incidence of light at the Brewster angle (i.e., $k_\perp = k_{\perp,\mathrm{B}}$), there is no reflection at the dielectric interface, where $k_{\perp,\mathrm{B}} = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_{r,1}\varepsilon_{r,2}}{\varepsilon_{r,1}+\varepsilon_{r,2}}}$. Under this scenario, the photonic crystal is equivalent to an achromatic medium with an effective relative permittivity $\bar{\bar{\varepsilon}}_r = \mathrm{diag}[\varepsilon_{\mathrm{eff},\perp}, \varepsilon_{\mathrm{eff},\perp}, \varepsilon_{\mathrm{eff},z}]$, where $\varepsilon_{\mathrm{eff},\perp} = \frac{\varepsilon_{r,1}d_1+\varepsilon_{r,2}d_2}{d_1+d_2}$ and $\varepsilon_{\mathrm{eff},z} = \frac{\varepsilon_{r,1}\varepsilon_{r,2}(d_1+d_2)}{\varepsilon_{r,1}d_2+\varepsilon_{r,2}d_1}$. (b) and (c) Field distribution of the electric displacement $D_z(t_0) = \int d\omega D_z(\omega)e^{-i\omega t_0}$, which is induced by a swift electron moving with a velocity $\bar{v} = \hat{z}v$ inside the photonic crystal or the effective achromatic medium. In (b) and (c), $v = v_\mathrm{B}$ is set to ensure the emergence of achromatic interfacial Cherenkov radiation at the Brewster angle θ_B, where $v_\mathrm{B}/c = \frac{\sqrt{\varepsilon_{r,1}+\varepsilon_{r,2}}(d_1+d_2)}{\varepsilon_{r,1}d_1+\varepsilon_{r,2}d_2}$ and $\theta_\mathrm{B} = \arctan\left(\frac{\omega/v_\mathrm{B}}{k_{\perp,\mathrm{B}}}\right) = \arctan\left(\frac{\varepsilon_{r,1}d_1+\varepsilon_{r,2}d_2}{\sqrt{\varepsilon_{r,1}\varepsilon_{r,2}}(d_1+d_2)}\right)$. For illustration, here we set $\varepsilon_{r,1} = 5$, $\varepsilon_{r,2} = 2.4$, $d_1 = 150$ nm, and $d_2 = 150$ nm.

On the contrary, all Bloch eigenmodes induced by the swift electron initially have a z-component wavevector of $k_z = \omega/v$, according to the phase-matching condition along the electron moving direction (i.e., z direction). In order to create light emission at the Brewster angle θ_B inside the photonic crystal [Fig. 1(b)] or the effective uniaxial medium [Fig. 1(c)], $k_z = k_{z,B}$ is further required, namely, $\omega/v = k_{z,\mathrm{B}}$, where $\theta_\mathrm{B} = \arctan(k_{z,\mathrm{B}}/k_{\perp,\mathrm{B}})$. By substituting the condition of $k_{z,\mathrm{B}} = \omega/v$ into Eq. (3), we have the following:

$$\frac{k_{\perp,\mathrm{B}}^2}{\varepsilon_{\mathrm{eff},z}} + \frac{(\omega/v)^2}{\varepsilon_{\mathrm{eff},\perp}} = \frac{\omega^2}{c^2}. \tag{6}$$

From Eq. (6), the critical electron velocity that enables the emergence of achromatic interfacial Cherenkov radiation from photonic crystals [Fig. 1(b)] is obtained as $v = v_\mathrm{B}$, where

$$v_\mathrm{B}/c = \frac{\sqrt{\varepsilon_{r,1}+\varepsilon_{r,2}}(d_1+d_2)}{\varepsilon_{r,1}d_1+\varepsilon_{r,2}d_2}. \tag{7}$$

In practice, the photonic crystal always has finite thickness and is surrounded by the substrate and the superstrate, as schematically shown in Fig. 2(a). For illustration, we consider that both the substrate and the superstrate are composed of the same material, with a relative permittivity $\varepsilon_{r,\mathrm{out}}$. In order to extract the excited interfacial Cherenkov radiation from the surrounding material, one necessary condition is to fulfill $|\bar{k}_\mathrm{out}| \geq k_{\perp,\mathrm{B}}$, namely, $\sqrt{\varepsilon_{r,\mathrm{out}}} > k_{\perp,\mathrm{B}}/(2\pi/\lambda)$, so that the total reflection at the interface between the photonic crystal and the surrounding material can be avoided, where $|\bar{k}_\mathrm{out}| = (2\pi/\lambda)\sqrt{\varepsilon_{r,\mathrm{out}}}$ is the wavevector of light in the surrounding material and $\lambda = 2\pi c/\omega$ is the wavelength of light. Since regular lossless dielectrics have a relative permittivity larger than 2,[95–97] we generally have $k_{\perp,\mathrm{B}}/(2\pi/\lambda) = \sqrt{\frac{\varepsilon_{r,1}\varepsilon_{r,2}}{\varepsilon_{r,1}+\varepsilon_{r,2}}} > 1$, such as $k_{\perp,\mathrm{B}}/(2\pi/\lambda) = 1.27$, if $\varepsilon_{r,1} = 5$ and $\varepsilon_{r,2} = 2.4$ are used in Fig. 2. This way, the non-vacuum surrounding material with $\sqrt{\varepsilon_{r,\mathrm{out}}} > 1$ (e.g., $\varepsilon_{r,\mathrm{out}} = 1.8$ used in Fig. 2) is needed in order to safely extract

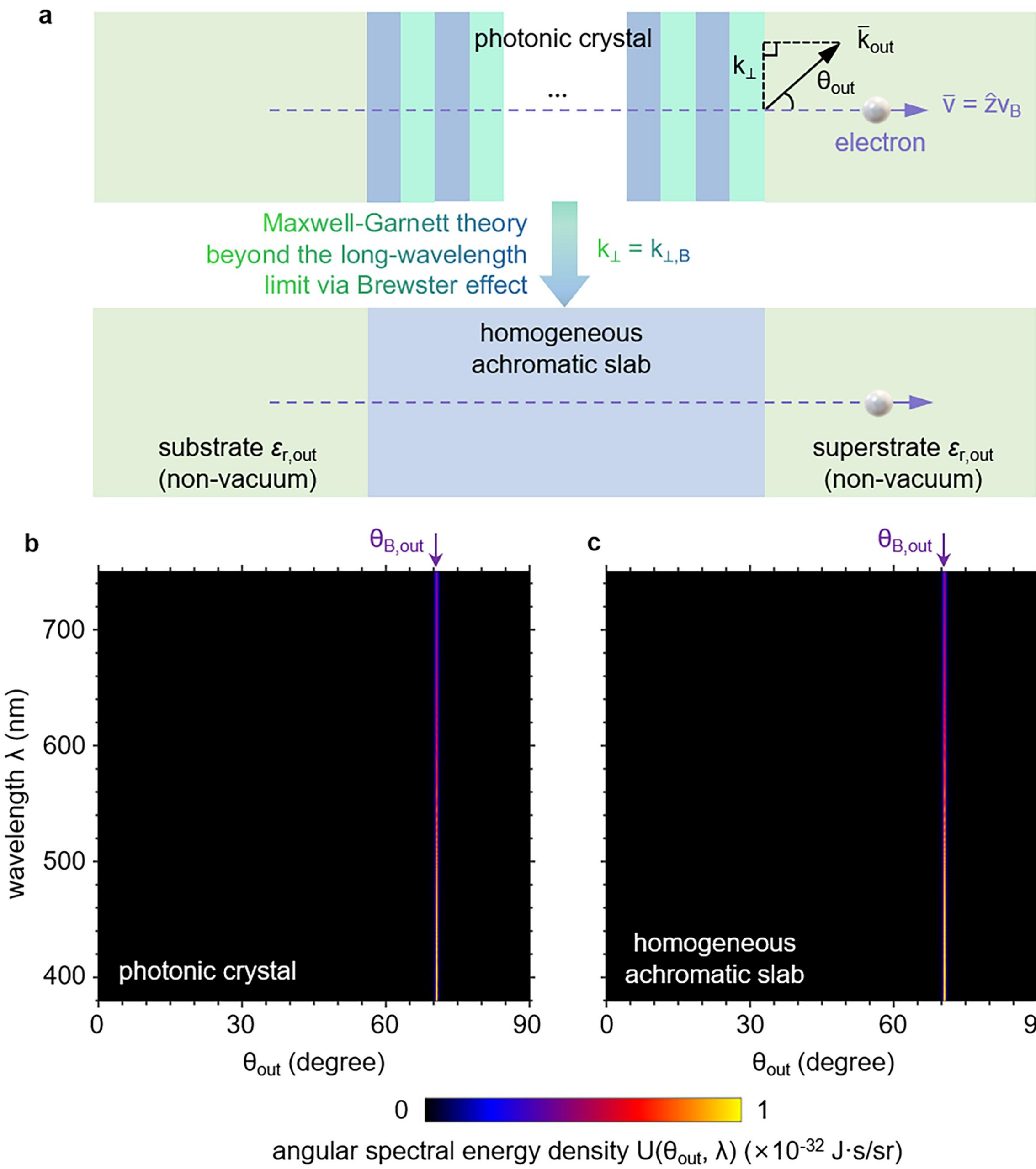

FIG. 2. Achromatic interfacial Cherenkov radiation from finite-thickness photonic crystals with non-vacuum surroundings. (a) Structural schematic. The photonic crystal and its homogenized counterpart are surrounded by the non-vacuum substrate and superstrate, both of which have a relative permittivity $\varepsilon_{r,out}$. For illustration, $\varepsilon_{r,out} = 1.8$ is used, and the photonic crystal consists of 400 unit-cells. The other setup is the same as that in Fig. 1. (b) and (c) Angular spectral energy density $U(\theta_{out}, \lambda)$ of forward light emission into the superstrate, where θ_{out} is the angle between the wavevector $\bar{k}_{out} = \hat{\perp}k_\perp + \hat{z}k_{z,out}$ of light in the superstrate and the electron velocity $\bar{v}$. The radiation peak angle $\theta_{peak}(\lambda)$ of interfacial Cherenkov radiation shows up at the Brewster angle $\theta_{B,out}$, namely, $\theta_{peak}(\lambda) = \max(U(\theta_{out}, \lambda), \theta_{out}) \equiv \theta_{B,out}$, irrespective of the working wavelength λ, where $\theta_{B,out} = \arcsin\left(\frac{k_{\perp,B}}{|\bar{k}_{out}|}\right) = \arcsin\left(\sqrt{\frac{\varepsilon_{r,1}\varepsilon_{r,2}}{(\varepsilon_{r,1}+\varepsilon_{r,2})\varepsilon_{r,out}}}\right)$ according to the Brewster effect.

the achromatic interfacial Cherenkov radiation at the Brewster angle into the surrounding material.

Under this scenario, the angular spectral energy density $U(\theta_{out}, \lambda)$ (Refs. 98–100) of the forward light emission into the superstrate is studied in Figs. 2(b) and 2(c), where θ_{out} is the angle between $\bar{k}_{out}$ and the electron velocity $\bar{v}$. When $v = v_B = 0.735c$ in Fig. 2(b), the radiation peak angle $\theta_{peak}(\lambda) = \max(U(\theta_{out}, \lambda), \theta_{out})$ always shows up at a fixed angle $\theta_{B,out}$, namely, $\theta_{peak}(\lambda) \equiv \theta_{B,out}$,

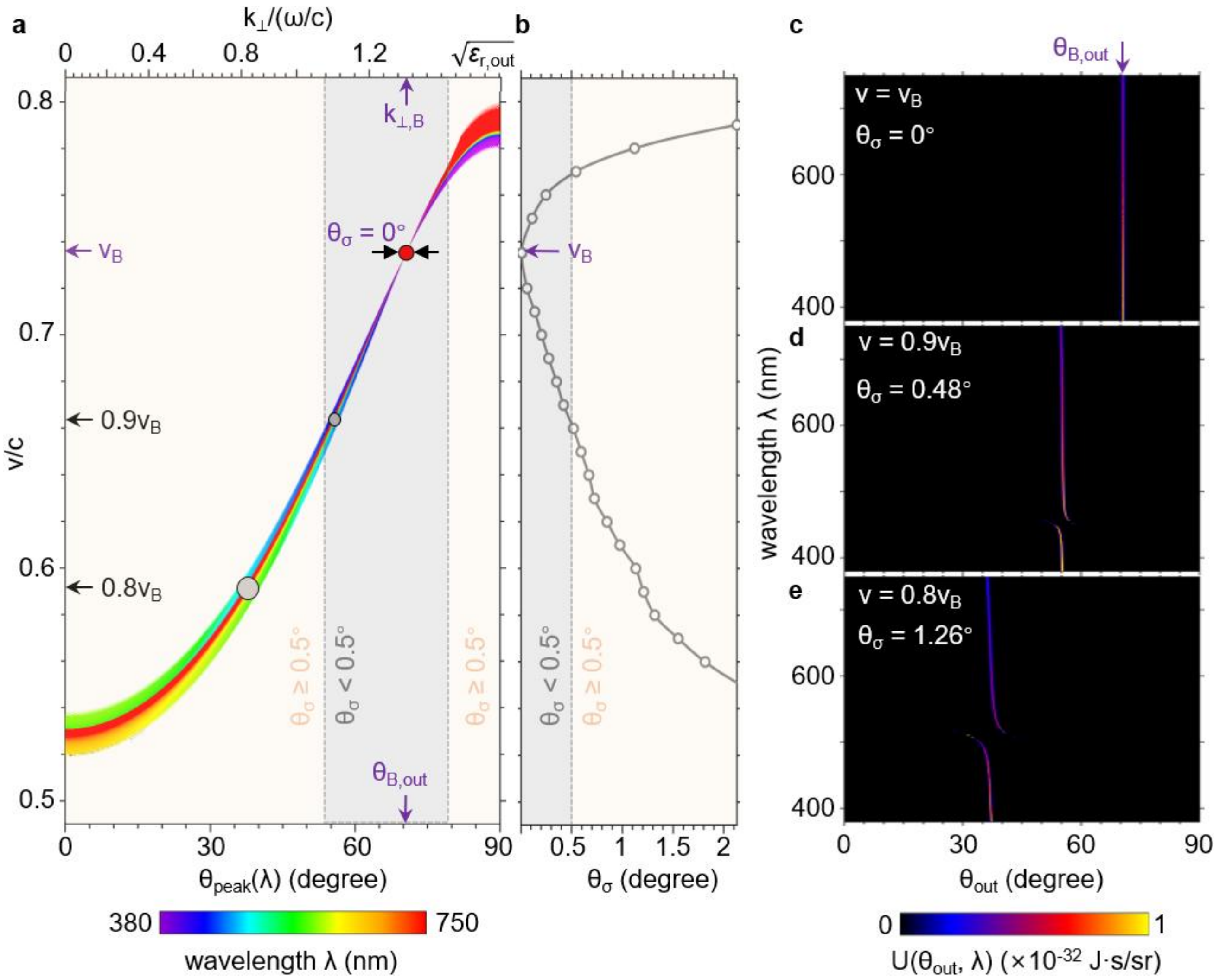

FIG. 3. Angular spread of the interfacial Cherenkov radiation from finite-thickness photonic crystals with non-vacuum surroundings. The structural setup here is the same as that in Fig. 2(a). (a) Dependence of the radiation peak angle $\theta_{peak}(\lambda)$ on the electron velocity v for various working wavelengths within the visible spectrum. The standard deviation of $\theta_{peak}(\lambda)$ throughout the visible light spectrum, namely, θ_σ, is used to quantitatively characterize the angular spread of interfacial Cherenkov radiation. (b) Dependence of the angular spread θ_σ on the electron velocity v. We have $\theta_\sigma = 0^\circ$ if $v = v_B$, where $v_B/c = 0.735$ in (a) and (b). For clarity, we argue that the achromatic interfacial Cherenkov radiation appears if $\theta_\sigma < 0.5^\circ$, e.g., in the gray regime with $v/c \in (0.661, 0.768)$, highlighted in (a) and (b). (c)–(e) Angular spectral energy density $U(\theta_{out}, \lambda)$ of forward light emission for various electron velocities.

irrespective of the working wavelength of light. This fixed angle is theoretically obtained as $\theta_{B,out} = \arcsin\left(\frac{k_{\perp,B}}{|\bar{k}_{out}|}\right) = \arcsin\left(\sqrt{\frac{\varepsilon_{r,1}\varepsilon_{r,2}}{(\varepsilon_{r,1}+\varepsilon_{r,2})\varepsilon_{r,out}}}\right) = 70.6^\circ$ in Fig. 2(b), according to the phase-matching condition and the Brewster effect. Moreover, this exotic achromatic feature of interfacial Cherenkov radiation from photonic crystals in Fig. 2(b) is the same as that of bulk Cherenkov radiation from the effective achromatic uniaxial medium in Fig. 2(c).

Figure 3 further investigates the angular spread of interfacial Cherenkov radiation from finite-thickness photonic crystals with non-vacuum surroundings. Without loss of generality, the standard deviation of the radiation peak angle $\theta_{peak}(\lambda)$ throughout the whole visible spectrum, namely, θ_σ, is used to quantitatively characterize the chromatic feature (e.g., the angular spread) of interfacial Cherenkov radiation from photonic crystals in Figs. 3(a) and 3(b). When the electron velocity v is equal to the critical velocity v_B, namely, $v = v_B = 0.735c$ in Fig. 3(c), we have $\theta_{peak}(\lambda) \equiv \theta_{B,out}$ and $\theta_\sigma = 0^\circ$ throughout the visible spectrum in Figs. 3(a) and 3(b). When the electron velocity slightly deviates from the critical velocity [e.g., $v = 0.9v_B$ in Fig. 3(d)], the angular spread θ_σ is quite small and relatively insensitive to the variation of electron velocity in Figs. 3(a) and 3(b). To be specific, we have $\theta_\sigma < 0.5^\circ$, if $v/c \in (0.661, 0.768)$ in Fig. 3(b). When the electron velocity further deviates from the critical velocity [e.g., $v = 0.8v_B$ in Fig. 3(e)], the angular spread θ_σ would increase rapidly and become sensitive to the variation of electron velocity in Figs. 3(a) and 3(b).

For conceptual demonstration, below we define that the achromatic interfacial Cherenkov radiation appears within a prescribed wavelength regime if $\theta_\sigma < 0.5^\circ$. The robustness of achromatic interfacial Cherenkov radiation with respect to the electron velocity in Fig. 3 is essentially related to the robustness of the anomalous Maxwell-Garnett theory with respect to the impedance-matching condition $\tilde{\eta}_1 = \tilde{\eta}_2$. To be specific, if the impedances of two constituent dielectrics have $\tilde{\eta}_1 \approx \tilde{\eta}_2$, instead of $\tilde{\eta}_1 = \tilde{\eta}_2$, we have the factor $\frac{1}{2}\left(\frac{\tilde{\eta}_1}{\tilde{\eta}_2} + \frac{\tilde{\eta}_2}{\tilde{\eta}_1}\right) \approx 1$ in Eq. (1), which can still be approximately reorganized into Eqs. (3)–(5). On this basis, the dependence of the peak angle of interfacial Cherenkov radiation on the electron velocity, as governed by the anomalous Maxwell-Garnett theory, can remain valid if the impedance-matching condition is approximately fulfilled or if $v \approx v_B$ (see also the supplementary material for more details).

We now proceed to discuss the possibility of achieving achromatic interfacial Cherenkov radiation from finite-thickness photonic crystals with vacuum surrounding in Figs. 4(a)–4(c). This issue is of practical importance, since the detection of interfacial Cherenkov radiation in vacuum surroundings would generally be much more convenient than that in non-vacuum surroundings. However, when the electron velocity is equal to the critical velocity, the achromatic interfacial Cherenkov radiation emitted at the Brewster angle inside the photonic crystal with $\theta_\sigma = 0^\circ$ has $k_\perp = k_{\perp,B} > 2\pi/\lambda$ and cannot couple into the vacuum surrounding due to the total reflection at the interface between the photonic crystal and vacuum. As a result, the forward light emission into the vacuum superstrate will not contain the signal of achromatic interfacial Cherenkov radiation and is of poor directionality and intensity in Fig. 4(b). On the contrary, when the electron velocity is smaller than the critical velocity and judiciously designed, the achromatic interfacial Cherenkov radiation emitted at the non-Brewster angle with $\theta_\sigma < 0.5^\circ$ can have $k_\perp < 2\pi/\lambda < k_{\perp,B}$; see Fig. 3(a) for example. This indicates an enticing scheme to get rid of the total reflection at the interface between the photonic crystal and the vacuum and to safely extract the achromatic interfacial Cherenkov radiation into the vacuum surrounding. For example, when $\varepsilon_{r,1} = 2.18$ [e.g., SiO_2

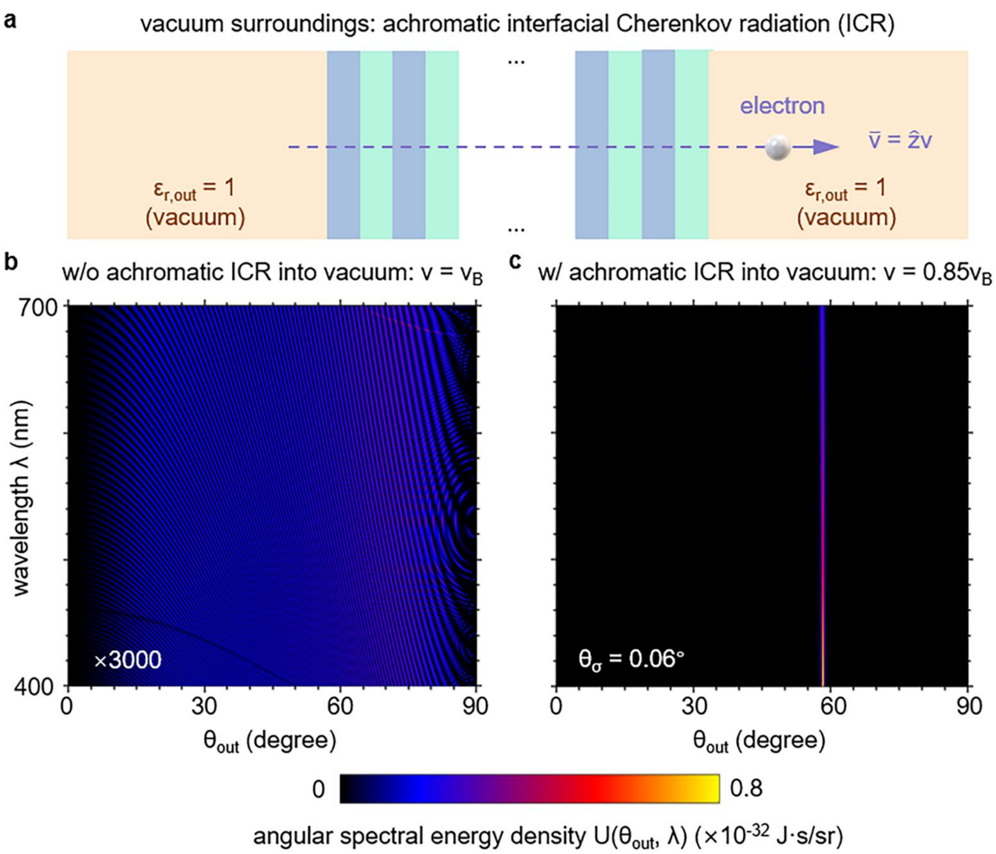

FIG. 4. Achromatic interfacial Cherenkov radiation from finite-thickness photonic crystals with vacuum surroundings. (a) Structural schematic. Both the substrate and superstrate are vacuum. For illustration, here we set $\varepsilon_{r,1} = 2.18$ [e.g., SiO_2 (Ref. 101)] and $\varepsilon_{r,2} = 2.56$ [e.g., LaF_3 (Ref. 102)]. The other structural setup is the same as that in Fig. 2. (b) and (c) Angular spectral energy density $U(\theta_{out}, \lambda)$ of forward light emission for different electron velocities. If $v = v_B$ in (b), due to the total internal reflection at the interface between vacuum and the photonic crystal, the achromatic interfacial Cherenkov radiation created inside the photonic crystal with $k_\perp = k_{\perp,B} > 2\pi/\lambda$ cannot couple into vacuum, where $k_{\perp,B}/(2\pi/\lambda) = \sqrt{\frac{\varepsilon_{r,1}\varepsilon_{r,2}}{\varepsilon_{r,1}+\varepsilon_{r,2}}} = 1.09$ and $v_B/c = 0.919$. If $v \neq v_B$ (e.g., $v = 0.85v_B$) in (c), the achromatic interfacial Cherenkov radiation created inside the photonic crystal with $k_\perp < 2\pi/\lambda < k_{\perp,B}$ [e.g., $k_\perp/(2\pi/\lambda) = 0.85$ in (c)] can couple into vacuum.

(Ref. 101)], $\varepsilon_{r,2} = 2.56$ [e.g., LaF_3 (Ref. 102)], and $v = 0.85v_B$ in Fig. 4(c), the achromatic interfacial Cherenkov radiation with $\theta_\sigma = 0.06^\circ$ shows up in the vacuum superstrate.

DISCUSSION

In conclusion, we have unveiled the enticing possibility of creating achromatic interfacial Cherenkov radiation from photonic crystals via the Brewster effect. According to the anomalous Maxwell-Garnett theory beyond the long-wavelength limit, we have found that the photonic crystal is essentially equivalent to a homogeneous achromatic medium for achromatic interfacial Cherenkov radiation emitted at the Brewster angle. This finding indicates a brand-new paradigm to deal with the chromatic issues in complex photonic systems and should be of fundamental importance to facilitate the development of charged particle-driven achromatic optical devices (e.g., miniaturized achromatic photonic Cherenkov detectors for the identification of high-energy particles with improved sensitivity), which are crucial to many practical applications, including communications, on-chip information processing, biomedical sensing, chemical detection, and imaging. This finding also indicates rich unexplored physics still exists in the realm of light–particle–matter interactions and might stimulate continuous explorations of achromatic light emission and scattering (including charged particle radiation) from more sophisticated but exotic optical systems,[103–105] such as random media and spatiotemporal media. Particularly, whether we can realize the achromatic charged particle radiation with high directionality from random media (e.g., via the extension of the anomalous Maxwell-Garnett theory to random media) remains elusive and is certainly worthy of further in-depth investigation.

SUPPLEMENTARY MATERIAL

See the supplementary material for the three sections, including derivation of interfacial Cherenkov radiation from photonic crystals, derivation of conventional bulk Cherenkov radiation from the effective homogeneous achromatic uniaxial slab, and more discussion on achromatic interfacial Cherenkov radiation from photonic crystals.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Xiangfeng Xi and Zheng Gong contributed equally to this paper.

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DATA AVAILABILITY

The data that support the findings of this study are available within the article and its supplementary material.

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