Nonlocal Limit of Cherenkov Radiation in Hyperbolic Metamaterials

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Abstract

A charged particle travelling faster than the phase velocity of light in a substance can emit Cherenkov radiation (CR). This phenomenon was experimentally discovered by Cherenkov in 1934 [1] and theoretically explained by Framk and Tamm's work in 1937 [2]. However, CR in conventional isotropic crystals requires the particle velocity beyond a threshold so called Cherenkov threshold (i.e. *c*/*n*). Due to finite refractive index *n* of the nature material, the Cherenkov threshold is high up to hundreds of keV, limiting the applications of Cherenkov devices (e.g. Cherenkov detectors or Cherenkov emitters).

A recent work revealed that CR in the hyperbolic metamaterials (HMMs) may offer the possibility to 'remove' the Cherenkov threshold [3], suggested by effective medium theory (EMT). While this theory is ubiquitous in the deep subwavelength range, it leads us to specious conclusions in some special situations. Especially, when optical modes involve much larger wavevectors compared with those in bulk media, metamaterials exhibit strong spatial dispersion. This regime, also called non-local regime, gives a more accurate description of the material dielectric response. How the nonlocal effects modify behaviors of CR such as the Cherenkov threshold still remains elusive.

In this work, we explored the nonlocal effects on the CR in the HMM, shown as Fig. 1(**a**). We prove the existence of Cherenkov threshold in realistic multilayer structure, as suggested in Fig. 1(**b**) and (**c**). On the one hand, the finite thicknesses introduces a cut-off on the maximum achievable wavevector $\mathbf{k}_y^{cf}$ (seeing Fig. 1(**d**)-(**f**)), inducing none-zero Cherenkov threshold. On the other hand, as geometric features approach to the Thomas-Fermi screening length λ_F, the charge screening effect inside the metal sets an ultimate bound on the minimum Cherenkov threshold as $\boldsymbol{v_{th}} = \boldsymbol{\beta} = \sqrt{\frac{3}{5}}\boldsymbol{v_F}$, where v_F is Fermi-velocity (seeing Fig. 1(**g**)).

Images

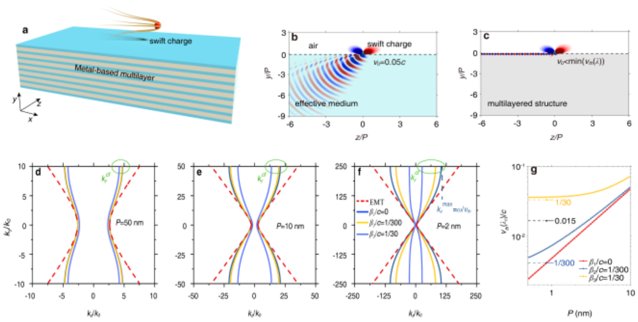

Fig. 1. (**a**) Structural schematic. A swift electron moves with a velocity of $\bar{v} = \hat{z}v_0$ and its trajectory parallel to the interfaces of a multilayer periodic structure. The unit cell of the periodic structure is composed by an Ag slab and a SiO_2 slab, with the thickness of d_1 and d_2 respectively; the pitch of unit cell is $P = d_1 + d_2$ ($P \leq 50$ nm), which is much smaller than the interested wavelength λ in free space ($\lambda \in [0.1\ 10]$ μm). For all cases, we set $d_1/P = 0.4$. (**b-c**) Field distribution of Cherenkov radiation in the time domain. The realistic multilayer structure in (**a**) is adopted for (**c**), while it is replaced by an effective homogeneous hyperbolic material for (**b**). Here $P = 25$ nm, and $v_0 = 0.05c$. (**d**)-(**f**) is the dispersion relation of the hyperbolic metamaterial in effective medium approximation, and realistic structure with different level of nonlocal charge screening effect. Here the period is varied from 50 nm to 2 nm. (**g**) The determined Cherenkov threshold at the wavelength $\lambda_0 = 1\ \mu m$, in realistic structure with different level of nonlocal charge screening effect.

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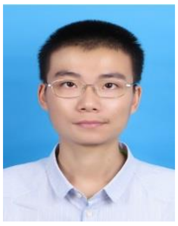
Recent Publications

Hu, H.; Zhang, J. L.; Maier, S. A.; Luo, Y., Enhancing Third-Harmonic Generation with Spatial Nonlocality. *ACS Photonics* 2018, *5* (2), 592-598.



Biography

Hu Hao received his Bachelor of Engineering in Zhejiang University, China, in 2016. He is currently a PhD student at the Photonics Centre of Excellence OPTIMUS, Nanyang Technological University, Singapore. Hao does research in Electrical and Electronic Engineering. His research interests are quantum and nonlocal plasmonics, Cherenkov radiation and metamaterials.

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