Non-Hermitian Skin Effect in Silicon Photonic Crystals

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Recent theoretical work has established that non-Hermiticity (i.e., dissipation) can have a profound impact on the band structure of periodic wave systems and their related topological properties [1]. In fact, the energy eigenvalues and eigenfunctions of finite-size non-Hermitian systems can be markedly different from the predictions of Bloch theory based on periodic boundary conditions. Most remarkably, a macroscopic number of modes in these systems can become localized near a boundary – a phenomenon known as the non-Hermitian skin effect (NHSE). At the same time, the conventional bulk-boundary correspondence (one of the cornerstones of topological band theory) can also break down in the presence of non-Hermiticity.

In photonic micro- and nanostructures, sources of dissipation naturally exist, and can be accurately engineered, in the form of radiative scattering losses and material absorption or gain. As a result, these structures provide an ideally well-suited platform to investigate novel non-Hermitian topological phenomena, and possibly exploit them to enable useful functionalities. A particularly interesting platform in this context is photonic crystal (PhC) slabs, because of their high design flexibility and technological significance for multiple device applications in optoelectronics and integrated optics. So far, the emergence of the NHSE and related breakdown of Bloch band theory in PhCs has only been described in a few theoretical studies focused on purely two-dimensional structures with ad-hoc (and unrealistically large) values of the imaginary part of the refractive index [2, 3].

Here, we investigate PhC slabs consisting of rectangular arrays of triangular Si nanoparticles on a planar SiO_2 substrate, designed to support leaky modes (i.e., guided resonances that can couple to external radiation) at wavelengths within the Si absorption band. Using finite-element and finite-difference-time-domain simulations with realistic wavelength-dependent optical constants, we compute the dispersion and field distribution of these modes in several structures of different lattice constants. Evidence of the NHSE is provided by the observation of modes strongly confined at the edges of finite-size samples, combined with nonzero values of a topological invariant of the energy eigenvalues under periodic boundary conditions (their winding number in the complex energy plane).

The results of this study provide three key conclusions with important fundamental and practical implications. First, the NHSE can indeed be established in realistic PhC slabs, as long as the unit cells have sufficiently reduced in-plane symmetry. Second, the resulting skin modes display a distinctive chiral behavior, i.e., modes confined at opposite edges propagate along opposite directions, and therefore can be selectively excited with free-space radiation by controlling its direction of propagation. Third, the NHSE in Si PhC slabs persists even at photon energies below the Si band gap, where the imaginary part of the refractive index is negligibly small, so that dissipation is entirely due to radiation losses. Altogether, these conclusions suggest

that novel non-Hermitian effects could be uncovered in practical semiconductor PhC structures, and used to engineer their spectral, angular, and spatial response for different applications such as modulators, lasers, and even passive devices.

[1] E. J. Bergholtz, J. C. Budich, and F. K. Kunst, “Exceptional topology of non-Hermitian systems,” *Rev. Mod. Phys.* **93**, 015005 (2021).

[2] J. Zhong, K. Wang, Y. Park, V. Asadchy, C. C. Wojcik, A. Dutt, and S. Fan, “Nontrivial point-gap topology and non-Hermitian skin effect in photonic crystals,” *Phys. Rev. B* **104**, 125416 (2021).

[3] K. Zhang, Z. Yang, and C. Fang, “Universal non-Hermitian skin effect in two and higher dimensions,” *Nat. Commun.* **13**, 2496 (2022).