

Observation of Radiation-Loss-Based Non-Hermitian Point Gap in Photonic Crystals

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A non-Hermitian point gap (NHPG) is a unique phenomenon in non-Hermitian systems and induces a non-Hermitian skin effect (NHSE). In photonic crystals, NHPG and NHSE have previously been explored mainly through material loss, where the typically low Q factors make direct observation of complex frequencies challenging. Here, we demonstrate the direct experimental observation of an NHPG by using a radiation-loss-based non-Hermitian photonic crystal. Radiation loss can be engineered through structural design, enabling control of the imaginary part of the complex frequency and allowing relatively high Q factors. This approach is compatible with widely used absorption-free silicon-slab photonic crystals. We developed a measurement system that can measure photonic bands along arbitrary lines in k space. Our measurements showed complex-frequency loops of the NHPG in photonic crystals, and the reversal of non-Hermitian topology through the flip of the loop rotation in a complex plane. These results establish radiation-loss engineering as a practical route to directly measuring and controlling complex photonic band structures and bulk point-gap topology in nanophotonic systems without gain media or nonreciprocity.

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In conventional condensed matter and quantum physics, most studies have concentrated on systems governed by Hermitian Hamiltonians due to the requirement of observable (real) eigenvalues. On the other hand, there has been growing interest in non-Hermitian systems whose Hamiltonians do not conserve energy. More recently, extensive work has focused on non-Hermitian systems that possess parity-time ($\mathcal{PT}$) symmetry [1,2]. $\mathcal{PT}$ -symmetric systems can exhibit real eigenvalues despite being non-Hermitian and give rise to characteristic singularities called exceptional points. These theoretical advances have recently been introduced into photonics, leading to emergence of non-Hermitian photonics and a variety of counter-intuitive photonic effects [3–15]. Because photonic systems allow the straightforward implementation of complex potentials via optical gain and loss, they provide an ideal platform for exploring and harnessing non-Hermitian physics. In addition to material gain or loss, radiation loss can also be used to implement a loss mechanism in

photonic systems, which realizes non-Hermitian photonic systems including an exceptional ring [16,17] and a bulk Fermi arc [18].

The non-Hermitian point gap (NHPG) is a hallmark phenomenon of systems described by non-Hermitian Hamiltonians [19–22]. A point gap is a type of energy gap unique to non-Hermitian spectra, in which complex eigenvalues wind around but avoid a specific point in the complex energy plane [22]. The presence or absence of NHPGs plays a crucial role in the symmetry-based classification of the system and underlies topological properties unique to non-Hermitian systems [23]. The loop structure in complex-frequency space forming the NHPG possesses chirality associated with its rotation direction and is characterized by a topological winding number [22,24]. This topological chirality governs the boundary at which skin modes accumulate under the non-Hermitian skin effect (NHSE). The NHSE emerges in systems with a NHPG, where bulk eigenstates under periodic boundary conditions are transformed into skin modes localized at a boundary when open boundary conditions are applied [19]. This indicates that both the bulk spectra and eigenmodes depend sensitively on boundary conditions unlike in Hermitian systems.

Experimental observations of NHPGs and NHSEs have been reported in several systems including optical fiber systems [25], coupled waveguides [26], phononic crystals [27], electrical circuit lattices [28], and mechanical systems

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[29]. The NHSE has typically been identified by spatially mapping the amplitude of excited modes to reveal their localization. In contrast, direct observation of an NHPG is more challenging, since it requires retrieving the complex eigenvalues of the system. So far, although optical NHPGs have been experimentally demonstrated in synthetic dimensions [30,31], NHPGs have not been observed in real space such as photonic crystals. Extraction of complex frequencies from experiments generally requires resonances with relatively high Q factors. However, in nanophotonic systems with material loss [32], the Q factor is usually much lower, which has prevented the observation of NHPGs in photonic crystals.

In this Letter, we observed an NHPG in a conventional silicon photonic crystal by using radiation-loss-induced non-Hermiticity. Because radiation loss can be engineered through the structural design of the system, it enables the realization of non-Hermitian photonic systems with higher Q factors than those relying on material loss. Most previous observations of NHPGs have employed nonreciprocal systems. In contrast, our reciprocal platform eliminates the need for additional mechanisms such as external magnetic fields or nonlinearities. We developed a photonic band measurement system that can take the band diagrams along arbitrary lines in Fourier space. By applying temporal coupled-mode theory (TCMT) to the measured spectra, we extracted the complex eigenvalues of the system. Comparison with band simulations confirms that our method enables the direct observation of complex photonic bands and NHPGs. Our experiments demonstrate the first observation of an optical NHPG in a nanophotonic platform. Because our system is reciprocal and does not require optical nonlinearity or gain media, but relies only on a simple two-dimensional structure, our results provide a robust approach for investigating complex bands, which is a fundamental hallmark of non-Hermitian systems.

We consider the NHPGs in a 2D reciprocal system [33–35]. In the 2D reciprocal systems, an NHPG can arise when the system exhibits both loss (or gain) and anisotropy [33]. Here, the “2D reciprocal system” refers to a system characterized by the in-plane Bloch wavevector (k_x, k_y) and Lorentz reciprocity $[\omega(+k_x, +k_y) = \omega(-k_x, -k_y)]$, irrespective of the microscopic origin of non-Hermiticity (material loss or radiation loss). In this system, a mode propagating upward with finite k_y experiences different losses for left- and right-going components ($\pm k_x$). This situation is analogous to the nonreciprocal Hatano-Nelson model [36]. The Hatano-Nelson model is a tight binding model with asymmetric hopping $t_{\pm} = t_0 \exp(\pm g)$, where g is the factor of asymmetry. Its complex eigenvalues E can be written as $E = 2t_0 \cos(k + ig)$, where k is the wave number. From this equation, one finds that the complex eigenvalues of the Hatano-Nelson model trace out an ellipse in the complex-frequency plane as k varies, which constitutes the NHPG. In reciprocal 2D systems,

$\omega(+k_x, +k_y)$ and $\omega(-k_x, +k_y)$ are generally not equal in the presence of anisotropy. Moreover, if the system has loss, the imaginary parts satisfy $\text{Im}[\omega(+k_x, +k_y)] \neq \text{Im}[\omega(-k_x, +k_y)]$, leading to asymmetric propagation in the $+x$ and $-x$ directions. In this sense, k_y in a 2D reciprocal system plays a role similar to the nonreciprocal parameter g in the Hatano-Nelson model. Consequently, reversing the sign of k_y (i.e., the propagation direction along y) flips the winding direction of the complex energy loop. Here, we emphasize that the NHPGs in 2D reciprocal systems can be observed only if the system has not only loss but also anisotropy. The anisotropic loss gives rise to an imaginary gauge potential that is proportional to k_y [33].

The discussion above provides a general theory on the reciprocal NHPGs in 2D momentum space. We apply this general framework to a photonic-crystal slab where non-Hermiticity is introduced by out-of-plane radiation leakage. Because we employ radiation loss to achieve the NHPG, conventional photonic crystals made of lossless materials such as Si can be used [37]. Figure 1(a) is the structure of the square-lattice photonic crystal, whose unit cell contains a right-isosceles air hole in a Si slab. The lattice constant and triangle side are a and d , respectively. Numerical simulations in this study are performed by the commercial solver (COMSOL) using a finite element method and we consider TE modes, whose electric field lies in the plane of the photonic crystal, only. If we use a 2D model and treat the slab as infinitely thick, no radiation channels exist, and the calculated bands (eigenfrequency) are real, which means the system is Hermitian and its bands form lines in a complex frequency plot. In contrast, 3D simulations can model the photonic crystal slab structures with a finite thickness. An out-of-plane radiation channel is included in the 3D model, which means the system can be non-Hermitian and the complex eigenfrequencies are allowed [37].

Here, we focus on the second TE band of the square-lattice photonic crystal because the TE band is the lowest band above the light line in slab-type photonic crystals although TM bands can support the NHPG [34]. When the unit cell possesses C_{4v} symmetry, this TE band supports a symmetry-protected bound state in the continuum (BIC) at the Γ point, resulting in relatively low radiation loss (high Q factor) in the vicinity of the Γ point. In our structure, by changing the air holes into triangles as shown in Fig. 1(a), we break the C_2 symmetry while preserving inversion symmetry along the $\pm 45^\circ$ directions. This symmetry reduction induces strong anisotropy in the radiation loss as discussed later. Figure 1(b) shows the simulated photonic bands. Because of the anisotropy of the unit cell, the band structure can be asymmetric if $k_y \neq 0$ as presented in the red curve. Because the system becomes non-Hermitian due to radiation loss, the eigenfrequencies acquire finite imaginary parts as shown in Fig. 1(c). Regardless of the value of k_y , when the real part lies below the light line, the

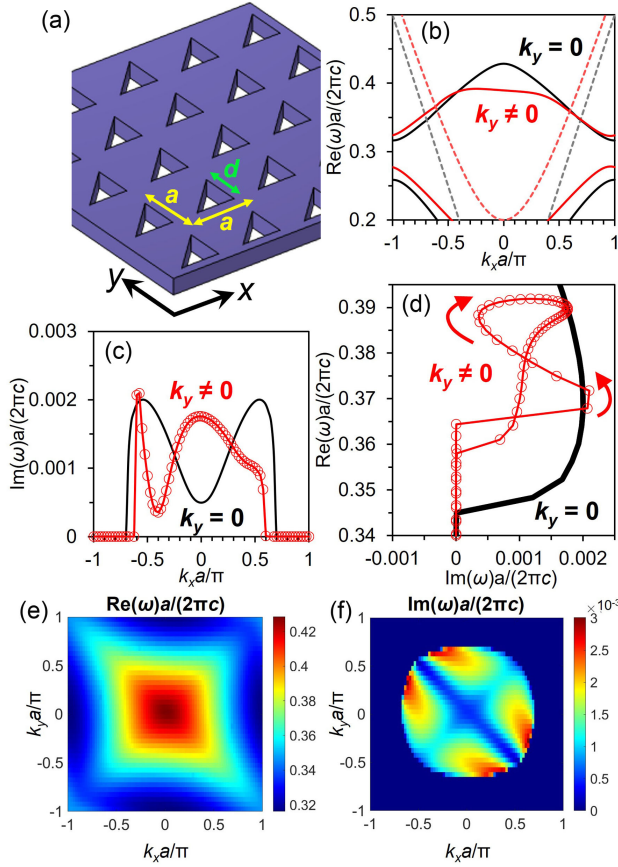


FIG. 1. (a) Structure of Si photonic crystal slab with an anisotropic unit cell. The period of the photonic crystal is a . The d and thickness of the slab are $0.6a$ and $0.25a$, respectively. (b) Real and (c) imaginary parts of simulated complex frequency bands (only the second TE bands are plotted). The dashed lines in (b) indicate the light lines for $k_y = 0$ and 0.4 . (d) Complex frequency plot of complex eigenfrequencies. Black and red markers correspond to $k_y a/\pi = 0$ and 0.4 , respectively. Isofrequency plots of (e) real and (f) imaginary parts of simulated eigenfrequencies. The structure is floating in the air and refractive index of Si slab is set to 3.48.

radiation loss vanishes and the imaginary part becomes zero. When $k_y \neq 0$, the imaginary part becomes clearly asymmetric, serving as the origin of the NHPG. When we plot the complex frequencies in the complex plane, a trajectory of the complex band becomes a line for $k_y = 0$ because reciprocity enforces identical eigenvalues at $\pm k_x$ [the black line in Fig. 1(d)]. On the other hand, at finite k_y , an NHPG can open because $\pm k_x$ acquire different imaginary parts [the red line in Fig. 1(d)], which is radiation-induced NHPG. When crossing the light line, radiation loss vanishes and the loop suddenly collapses into a straight line. For $k_y = 0$, the band lies below the light line at $\text{Re}(\omega a/2\pi c) \approx 0.345$, resulting in zero imaginary part. Similarly, at $k_y = 0.4$, the band falls below the light line at $\text{Re}(\omega a/2\pi c) \approx 0.36$ and 0.365 , where the imaginary part becomes exactly zero. If an objective lens with numerical

aperture (NA) = 1 were used in the experiment, all bands above the light line could in principle be observed. However, the NA of practical lenses is generally limited, and, as shown later, only the higher-frequency portion of the complex loop in Fig. 1(d) is accessible in our experimental measurements. Additional data of complex band structures and loop plots for other k_y cases are presented in S1 in Supplemental Material [38]. We also confirmed the presence of the NHSE associated with these NHPGs in simulations, and found the intriguing phenomenon that skin modes and extended modes coexist within the same band due to the light-line cutoff (see S2 in Supplemental Material [38]).

To show the anisotropy in the complex eigenfrequencies more clearly, we plot the real and imaginary parts of the simulated isofrequency contours in Figs. 1(e) and 1(f), respectively. Reflecting the structural anisotropy, the isofrequency contours exhibit anisotropy in both their real and imaginary components. In Fig. 1(f), a region with a small imaginary part appears along the -45° direction. When the air hole in the unit cell is square, this band has an at- Γ symmetry-protected BIC. Breaking the symmetry from a square to a triangular hole, at- Γ BIC changes to a quasi-BIC (q-BIC) and a low-imaginary-part region extending along the -45° direction is formed. This anisotropic imaginary part leads to the formation of a large NHPG (see S6 in Supplemental Material [38]). The dark-blue regions in Fig. 1(f) correspond to wave vectors for which the band lies below the light line, resulting in purely real eigenfrequencies with zero imaginary part. Q factors of the second TE band are on the order of 10^2 across the entire momentum-space range, and exceed 10^3 at certain wave numbers [see Fig. S13(c)]. Such high- Q resonances are generally difficult to achieve in material-loss-based systems, where resonance peaks (or dips) in the spectra can become too broad and shallow to reliably extract the linewidth. The relatively high Q factors provide a practical advantage of radiation-loss-based NHPGs for experimental observation.

For experiments, we fabricated the Si photonic crystal slab and measured its photonic bands. To prepare the device, we use a silicon-on-insulator wafer with a 150 nm-thick Si device layer on a BOX SiO_2 layer with 3 μm thickness. The triangular hole patterns with $a = 600$ nm and $d = 360$ nm were defined by electron-beam lithography. Finally, the triangular periodic pattern is transferred into the silicon layer using dry etching. The patterned area in each device is $300 \mu\text{m} \times 300 \mu\text{m}$. A typical scanning electron microscope (SEM) image is presented in Fig. 2(a).

To observe photonic bands, we used a homemade setup of Fourier-plane imaging spectroscopy [40,41]. The schematic of the setup is shown in Fig. 2(b). Fourier-plane imaging spectroscopy is a method that directly measures the momentum-space information of photonic bands by imaging the Fourier plane formed by the objective lens with two relay lenses. By placing a camera at the detection

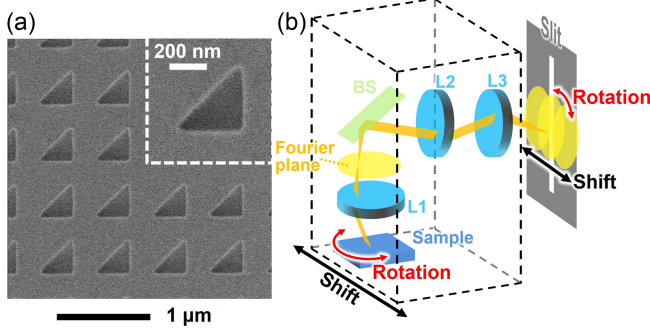


FIG. 2. (a) SEM image of the fabricated Si photonic crystal slab. (b) Schematic of the setup used to measure photonic bands along arbitrary lines in k space. The optical system can be translated relative to the slit of the imaging spectrometer to access different momentum-space cuts.

position, isofrequency surfaces can be obtained, whereas using an imaging spectrometer allows the measurement of photonic band diagrams [40]. An important improvement in our homemade setup compared with conventional setups [40] is that the entire optical setup can be translated parallel to the slit of the imaging spectrometer, as illustrated in

Fig. 2(b). (For details of our setup, see S3 in Supplemental Material [38].) By combining this translation with rotation of the sample, our method enables band measurements along arbitrary lines in the Fourier plane. Using this setup, we can measure the photonic band diagrams at finite k_y , which are required to observe the NHPG in photonic crystals. Fitting each measured band at a given k_y with TCMT [42] enables us to retrieve the complex resonance frequencies (For details, see S4 in Supplemental Material [38]).

Figures 3(a) and 3(b) are the measured isofrequency surfaces for the incidence of y - and x polarization, respectively. We used a bandpass filter with a center wavelength of 1500 nm and a bandwidth of 10 nm. The dark features represent the excitation of the TE-like band and clearly reveal the expected anisotropic isofrequency surface. The isofrequency surface measured at a different wavelength (1480 nm) is presented in S5 of the Supplemental Material [38]. The dashed lines mark the positions in momentum space corresponding to the later.

Figures 3(c)–3(e) show measured photonic bands for $k_y = 0.00k_0$, $+0.382k_0$, and $-0.382k_0$, respectively. The horizontal axis of these figures, k_x/k_0 , corresponds to $\text{NA} = \sin \theta_{\text{in}}$ (θ_{in} is an incident angle). Namely, k_0 denotes

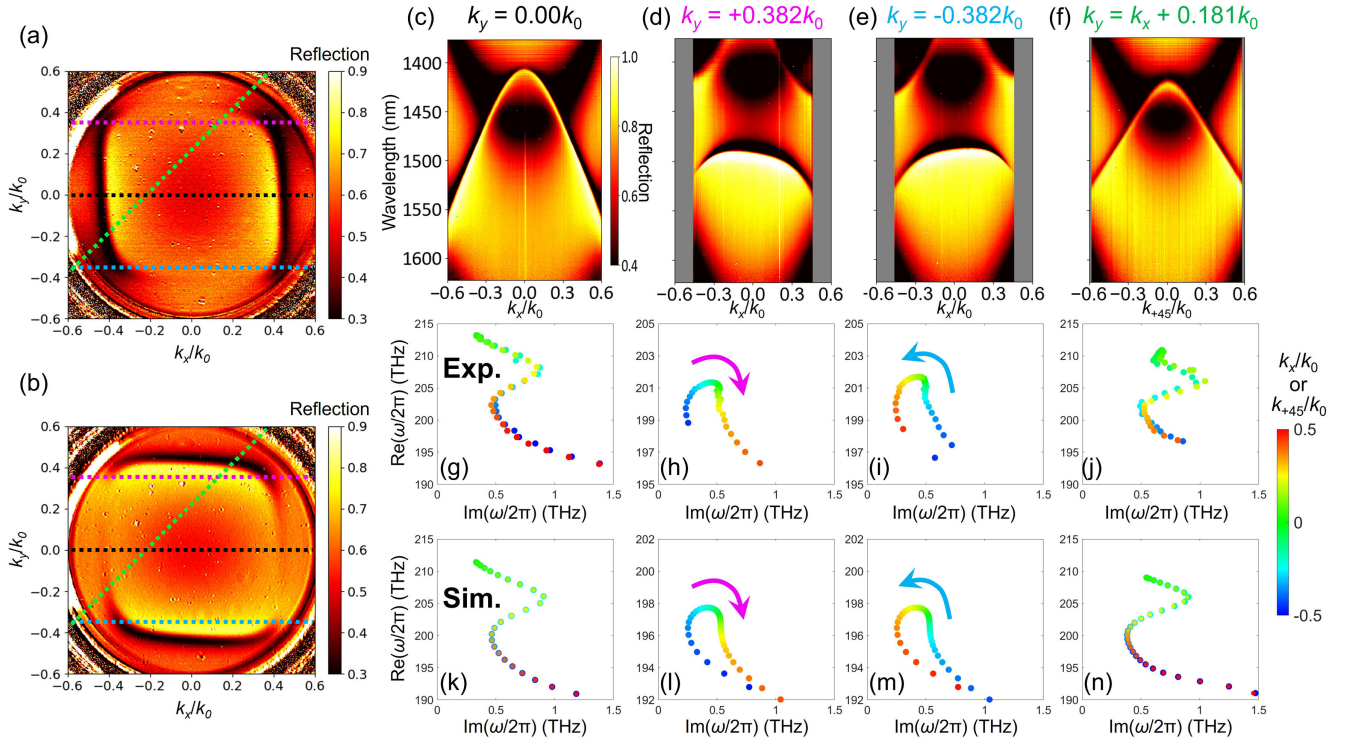


FIG. 3. (a), (b) Measured isofrequency surface at 1500 nm under y - and x -polarized incidence, respectively. (c)–(f) Measured photonic bands for $k_y/k_0 = 0$, $k_y/k_0 = +0.0382$, $k_y/k_0 = -0.0382$, and $k_y = k_x + 0.181k_0$. Incident polarization was set to y polarization for (c) and (f), and x polarization for (d) and (e). Since the NA is constant for all wavelengths, the horizontal axes are normalized by the wave number k_0 for each wavelength. The horizontal axis in (f) corresponds to the direction along the yellow-green line in (a). (g)–(j) Retrieved complex eigenfrequencies obtained from the measured bands (c)–(f). (k)–(n) Simulated complex eigenfrequencies corresponding to (g)–(j). In the simulations, k_0 is fixed to 1.5 μm . For visual clarity, the markers for positive k_x are drawn with reduced size in (k) and (n).

the free-space wavenumber corresponding to each wavelength in the spectrum. To efficiently excite the TE-like mode, we use y -polarized incidence at $k_y = 0$ (i.e., s polarized). However, as k_y becomes finite, y -polarized incidence approaches p polarization, reducing the coupling efficiency to the TE-like mode. Therefore, for finite k_y , we instead employ x -polarized incidence to efficiently excite the TE-like mode (see S5 in Supplemental Material [38]). We can see clear resonances of the TE-like bands with an upward-convex dispersion. When $k_y = 0$ [Fig. 3(c)], the band is symmetric, while asymmetric bands are observed for the finite k_y [Figs. 3(d) and 3(e)]. This asymmetry of the bands is the origin of the NHPG in the complex frequency plane.

Complex eigenfrequencies retrieved by TCMT are shown in Figs. 3(g)–3(i). The colors of the data points indicate corresponding k_x values. Representative fitting data are shown in Fig. S5 in the Supplemental Material [38]. Figures 3(h) and 3(i) present the complex eigenfrequencies for positive and negative k_y , respectively. The opening of the NHPG is clearly observed when $|k_y| \neq 0$, while the trajectory for $k_y = 0$ is just a line. The rotation direction of the loop is flipped when the sign of k_y is reversed as shown in Figs. 3(h) and 3(i). In a 2D reciprocal system, the point-gap topology is inverted simply by reversing k_y [33,34]. By rotating the sample by 45° , we can measure the band dispersion along a line tilted by 45° in momentum space. By rotating the optical system, we measure the band diagrams along the line $k_y = k_x + 0.181k_0$, as shown in Fig. 3(f). The horizontal axis of this figure, k_{+45}/k_0 , is along the light green line in Figs. 3(a) and 3(b). In this case, the photonic band appears symmetric and no NHPG appears [Fig. 3(j)]. This is because the structure is symmetric with respect to the -45° direction, eliminating the anisotropy along this line.

Since we used the objective lens with $\text{NA} = 0.6$, the accessible range of k_x is $\pm 0.6k_0$ for $k_y = 0.00k_0$. As shown in Figs. 3(a) and 3(b), the accessible range of k_x becomes narrower as $|k_y|$ increases ($\pm 0.463k_0$ for $k_y = 0.382k_0$). When this k_x range is converted into the k_x normalized by a [the horizontal axis of Fig. 1(b)], it becomes $k_x = \pm 0.6k_0 \sim \pm 0.48\pi/a$. The experimentally accessible k_x range can be extended by using an objective lens with a larger NA. For example, immersion-type objectives allow measurements in wavevector regions beyond the $\text{NA} = 1$ limit [43]. In addition, higher-order bands can be observed over a wider k_x -range because a large portion of these bands lies above the light line. Furthermore, introducing a weak modulation with a period twice a [44] enables band folding, providing access to an even broader portion of the band.

Figures 3(k)–3(n) show the simulated eigenfrequencies corresponding to Figs. 3(g)–3(j), respectively. The simulated eigenfrequencies are directly obtained from eigenfrequency simulations using COMSOL, not from the TCMT fitting of

simulated spectra. The simulated complex eigenfrequencies show good agreement with the experiments. The figure that quantitatively compares the experiments and simulations is shown in Fig. S6 in Supplemental Material [38]. These results indicate our method can directly obtain complex eigenfrequencies of photonic bands and reveal our observation is direct evidence of NHPGs in photonic crystals. We experimentally varied k_y from $-0.385k_0$ to $0.385k_0$ and the results agree well with the simulations for every value of k_y (see S5 in Supplemental Material [38]).

In addition to supporting high resonance Q factors, radiation-loss-based NHPGs also provide the advantage of generating larger complex loops. To quantitatively evaluate the size of the complex loop, we define a figure of merit (FOM) that characterizes the size of the complex-frequency loop (see Sec. S7 for details). We find that the radiation-loss-based design achieves an FOM approximately one order of magnitude larger than that attainable with material loss, corresponding to a much larger complex-frequency loop. This enhancement arises because radiation loss can be made strongly asymmetric between $\pm k_x$ through symmetry breaking. In contrast, material loss affects the entire mode and makes it difficult to produce large asymmetry in the imaginary part. These results highlight a key advantage of radiation-loss-induced NHPGs.

In conclusion, we have directly observed an NHPG generated by anisotropic radiation loss in a Si photonic crystal. The photonic band measurements and TCMT analysis yielded clear opening of the NHPG in complex eigenfrequencies. Moreover, we demonstrated the reversal of loop orientation when the sign of k_y is flipped experimentally. Our experiments demonstrated the NHPG in real-space photonic systems. Our 2D reciprocal system, which operates without optical nonlinearity or gain media, provides a versatile platform for investigating complex bands featuring non-Hermiticity. Moreover, since BICs and quasi-BICs can be controlled through the symmetry of the system [45], appropriate structural design may provide an efficient means of creating large NHPGs.

Our observation of NHPGs in a reciprocal photonic crystal provides a basis for investigating the associated NHSE. A characteristic feature of two-dimensional reciprocal systems is that they can support propagating skin modes. We have theoretically shown that such modes can form circulating states carrying orbital angular momentum [46], with potential applications in compact optical-vortex sources and routing devices for integrated photonic circuits. On the other hand, excitation and observation of the skin modes in a purely lossy platform such as the present radiation-loss-based system remain nontrivial [33,47]. The NHSE has not yet been experimentally observed in photonic crystals, and its realization remains an important subject for future work. Optical gain may compensate for propagation attenuation caused by radiation loss and facilitate the excitation and observation of skin modes. For example, replacing the silicon

slab with III–V semiconductor materials could provide optical gain in a photonic-crystal platform, thereby compensating the loss bias inherent to the present radiation-loss-based system [48,49]. Recent theoretical studies have also shown that appropriately designed excitation schemes, including complex-frequency excitation, can reveal the stationary response associated with the NHSE even in passive systems [33,50].

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Data availability—The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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