Imaging topological edge states in silicon photonics

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Topological features—global properties not discernible locally—emerge in systems ranging from liquid crystals to magnets to fractional quantum Hall systems. A deeper understanding of the role of topology in physics has led to a new class of matter—topologically ordered systems. The best known examples are quantum Hall effects, where insensitivity to local properties manifests itself as conductance through edge states that is insensitive to defects and disorder. Current research into engineering topological order primarily focuses on analogies to quantum Hall systems, where the required magnetic field is synthesized in non-magnetic systems. Here, we realize synthetic magnetic fields for photons at room temperature, using linear silicon photonics. We observe, for the first time, topological edge states of light in a two-dimensional system and show their robustness against intrinsic and introduced disorder. Our experiment demonstrates the feasibility of using photonics to realize topological order in both non-interacting and many-body regimes.

Charged particles in two-dimensional structures with a magnetic field exhibit a remarkable range of macroscopic quantum phenomena, including integer and fractional quantum Hall effects and quantum spin Hall effects, and the emergence of particles with fractional statistics (so-called anyons) is predicted theoretically. Despite great success in electronic systems, advances in experimental efforts have been hampered by stringent experimental requirements such as purity. Recently, neutral ultracold gases have been studied both theoretically and experimentally for the observation of these effects. Ultracold atomic systems are advantageous because they provide tools for the in situ control of most parameters describing quantum Hall systems. However, a strong effective magnetic field remains elusive. In contrast, photons, which avoid many of these experimental difficulties, provide a new avenue for the investigation of quantum Hall physics at room temperature. Arrays of coupled optical resonators provide a toolbox, in the context of quantum simulation, to engineer several classes of Hamiltonians and allow the direct observation of the wavefunction. Furthermore, such photonic systems might find applications in optical devices such as filters, switches and delay lines by exploiting topological robustness. Here, we report the first implementation of a magnetic-like Hamiltonian in a two-dimensional photonic system and present the direct observation of robust edge states—the hallmark of topological order.

Many proposals for implementing magnetic-like Hamiltonians in photonic systems require an external field such as a large magnetic field or strain or harmonic modulation or optomechanically induced non-reciprocity. However, it has been shown that using an external field is not necessary. Instead, by using either a polarization scheme, differential optical paths or bi-anisotropic metamaterials, one can achieve a magnetic-like Hamiltonian in direct analogy to a spin–orbit interaction in electronic systems. Topological states of light have also been explored in one-dimensional photonic systems. Moreover, such systems could have direct applications in silicon photonics. Specifically, we implement a synthetic gauge potential using an induced pseudo-spin–orbit interaction where a time-reversed pair of resonator modes (clockwise and anticlockwise circulation) acts as a pseudo-spin. Owing to the large size of the resonators (several tens of micrometres), such photonic implementation of a magnetic-like Hamiltonian allows the direct observation of the wavefunction via optical imaging. We made three primary experimental observations: (1) light propagates along the system edges where the boundaries are defined as either the magnetic domains or the physical edges; (2) the light propagation profile of the edge states remains unchanged over a broad band, a signature of robustness against intrinsic disorder; (3) edge-state propagation is robust against introduced disorder—indeed, transport is not impeded even in the absence of a resonator on the edge.

Experimental implementation

We fabricated a two-dimensional array of coupled optical-ring resonators in which the design of the waveguides in the array allowed us to simulate a magnetic field for photons using silicon-on-insulator (SOI) technology. High-Q ring resonators (Q > 1 × 10⁶) were fabricated on a SOI wafer with a 220-nm-thick layer of silicon on top of a 2-μm-thick buried oxide (BOX) layer that isolated the optical mode and prevented it from leaking to the substrate. The cross-section of the waveguides, which forms the link and site resonators, was designed to measure 510 nm × 220 nm to ensure single-mode propagation of the transverse electric (TE) light (the electric field in the slab plane) at the telecom wavelength (≈1.55 μm). The typical air gaps for evanescent coupling between the site resonators and the probing waveguides and link resonators were chosen to be 180 nm and 200 nm, respectively. The 90° bending radius of the rounded rectangles was chosen to be 6 μm to keep the bending loss negligibly small. The fabrication of silicon chips was performed through ePIXfab, by the Leti-CEA and IMEC facilities. The masks were made using deep-ultraviolet 193 nm photolithography and were etched in two steps (70 nm/220 nm) for gratings and waveguides, respectively. The process was followed by thermal oxidation (10 nm) to reduce the surface roughness. In our experimental set-up, grating couplers were used for input and output coupling to the device. Light scattered from the resonators was spatially imaged using a ×25 microscope.
objective and an InGaAs infrared camera (640 × 512 pixel grid with a 25 μm pitch; Fig. 1c). Such a set-up allowed us to measure the relative amount of light scattered from each site26. Transmission through the device was measured using an optical vector analyser (Luna Technologies OVA 5000).

To describe the essence of the scheme, we considered a single plaquette of our lattice, which consisted of four site resonators and four link resonators in the form of rounded rectangles (Fig. 1a). The link and site resonators were coupled to one another through directional couplers, so photons circulating in one direction in the site resonators only coupled with each other and with photons circulating in the opposite direction in the link resonators. The effective length of the link resonators was chosen to be larger than that of the site resonators by 2\( \eta \), so that the links and sites were resonant at different frequencies. Consequently, a photon resonant with the site resonators spent substantially more time in the sites than in the links. We associate the clockwise photons in site resonators with the up-component of a pseudo-spin. By virtue of time-reversal symmetry, the pseudo-spin-down component (anticlockwise photons in the site resonators) is degenerate with the pseudo-spin-up component. For the moment, we focus on the spin-up component. Depending on the positioning of the links, the photon acquires a different phase hopping forwards than backwards. In particular, the hopping process between sites 1 and 2 in Fig. 1a is described by

\[
\hat{a}_i^\dagger \hat{a}_j e^{-i\phi_{ij}} + \hat{a}_j^\dagger \hat{a}_i e^{i\phi_{ij}}, \quad \text{where } \hat{a}_i \text{ is the creation operator of a photon at site } i.
\]

The phase arises from an offset of the link waveguides from the symmetric point (defined as equal amounts of additional length above and below the directional coupler). Specifically, the additional phase is given by the optical length \( \phi_{ij} = 4\pi n \eta x_{ij} / \lambda \), where \( n \) is the index of refraction, \( x_{ij} \) is the position shift of the link resonator, and \( \lambda \) is the wavelength of the light. Note that the additional length \( \eta \) and position shifts away from the symmetric point are designed to keep the lengths of the directional couplers, the geometry of their coupling regions, and their coupling efficiencies invariant (Fig. 1a). Thus, the overall Hamiltonian describing photon hopping in the plaquette can be written as

\[
-H = \hat{H}_{\text{inter}} + \hat{H}_{\text{intr}} + \hat{H}_{\text{eff}} + h.c.
\]

where \( H \) is the tunnelling rate and the photon going anticlockwise around the plaquette acquires a 2\( \pi \alpha \) phase (where \( \alpha = 2\pi (x_{14} - x_{12}) / \lambda \)) and h.c. is the Hermitian conjugate. If the phase per plaquette is uniform over a region, the photonic dynamics are equivalent to those of charged particles in a uniform perpendicular magnetic field27. Such a system is predicted to exhibit edge states at the boundaries of that region27,28. In a photonic system, such edge states can be excited by driving the system in specific frequency bands.

To verify that the expected edge physics arises entirely from our synthetic gauge field, we first designed a phase slip between 10 × 4 stripes, as shown in Fig. 1b. This results in magnetic domains that are entirely due to passive, and controlled, interference effects. The resulting edge states of the system then follow along the edge of the magnetic domains induced by this phase slip (Fig. 1b), rather than the physical edge of the system (Supplementary Section S2). The effective uniform magnetic field in the stripe is given by \( \alpha \approx 0.15 \). The dispersion of the system is shown in Fig. 2a, where the edge-state bands are shown between magnetic bulk bands. The field is coupled to the two-dimensional ring resonators using a bent waveguide at the two bottom corners (Fig. 1b). Depending on the pumping direction, the two different pseudo-spin components can be excited, for example, coupling light into the system at port 1 (2), pumps the system in the spin-up (spin-down) component.

Results

As a demonstration of the scheme we measured the transmission spectrum of the two-dimensional system through various ports and compared it with our simulation (Fig. 2). We first characterized the different system parameters using simpler devices including a notch filter (single resonator coupled to a waveguide) and an add/drop filter (single resonator coupled to two waveguides) fabricated on the same chip to allow for calibration and characterization of the waveguides and resonators (Supplementary Section S2). We estimated the probing waveguide–resonator coupling rate (\( \kappa_{\text{ex}} \approx 15 \) GHz), the intrinsic loss (\( \kappa_{\text{in}} \approx 1 \) GHz) and the tunnelling rate between site resonators (\( J \approx 16 \) GHz), with all measurements within 2 nm of the centre wavelength of 1,539 nm. Given these parameters, we simulated a 10 × 10 lattice using the transfer matrix formalism (Supplementary Section S2) (Fig. 2a). We also considered a random onsite impurity shift of the resonance frequency with a standard deviation of 0.8\%. In a lossless system, the transmission spectrum for the spin-down (\( T_{\text{down}} \)) and spin-up (\( T_{\text{up}} \)) should be identical, although they may take different paths. However, the presence of loss breaks this symmetry. We observed a qualitative agreement between simulation and experiment (Fig. 2b,c).
A crucial point that allows us to implement the magnetic Hamiltonian in our photonic system is the weakness of backscattering. In principle, backscattering in the waveguide and resonators can flip the pseudo-spin and destroy the desired behaviour. To address this, we used directional couplers to reduce the effect of backscattering in the coupling regions. However, the surface roughness of the waveguides still leads to some backscattering, which can accumulate in our large two-dimensional system. The pseudo-spin can therefore flip from up to down (that is, clockwise to anticlockwise) and leave the system by the opposite channel (for example, when the system is pumped with pseudo-spin up from port 1, the flipped spin exits the system at port 4). We confirm that the level of backscattering, as characterized by $T_{14}$ in Fig. 2b,c, is small, as predicted previously.

To demonstrate the presence of edge states in our system we imaged the propagation of light in various devices. We started with a system with magnetic domains (Fig. 1b). In the presence of a magnetic field, one expects edge states to appear when the system is pumped at certain frequencies. According to the dispersion simulation (Fig. 2a), we expect the absence of bulk states and the presence of edge states to occur in the frequency interval $\omega/J = 2.5 \pm 0.5$. Figure 2d shows such an edge state starting at the input, routing around the $10 \times 4$ stripe edge and leaving the system at the output. In the experiment we observe a similar behaviour (Fig. 2e). Note that, compared to the simulation, the edge state in the experiment undergoes higher loss and attenuates more rapidly before reaching the other side of the two-dimensional system. The remarkable feature of such edge states is that they route around the boundary that is defined by our synthetic magnetic field, rather the physical edge of our system. When the system is pumped at a different frequency, bulk states are excited that do not have a particular shape (Fig. 2f,g). States propagating in the bulk are more susceptible to the frequency mismatch of the resonators, so one should not expect the spatial profile to match the numerical simulation. More importantly, the edge-state profile does not significantly change over a band broader than 5 GHz. We attribute this remarkable difference to the topological protection of the edge states.

**Figure 2 | Edge states around a magnetic domain.** a, Simulated dispersion of the system. $k \Lambda$ is the relative phase between two adjacent resonators on the edge, and $\omega$ is the relative detuning of frequency with respect to the band centre, in units of tunnelling rate. Red circles represent the dispersion of our system and black dots the simulation of a longer system ($10 \times 400$), to better distinguish the bulk band from the edge band. b, Simulated transmission of a $10 \times 10$ lattice. $T_i$ is the transmittance between ports $i$ and $j$, as shown in Fig. 1b. $T_{ij}$ measures the backscattered light. Simulation parameters are estimated from the experiment. c, Measured transmission spectrum. d, Simulated scattered light from a two-dimensional array of coupled resonators when the system is pumped at the edge state band. e, Image of the edge state. The system is pumped at the frequencies corresponding to the edge state band. f,g, Images of bulk states. The state is pumped at frequencies in the bulk state band.
We next imaged the edge state for a system designed without a phase slip; that is, the magnetic field was uniform over the entire system. Figure 2 shows light propagation along the short (Fig. 3a,c) and long (Fig. 3b,d) edges. Light was launched in a specific frequency band $\nu/\nu_J = 1.7 \pm 0.6$ ($-1.7 \pm 0.6$), corresponding to the short (long) edge excitation. The physical transverse width of the edge state was about one to two resonators, as observed both in experiment and simulation. The width is slightly greater in the experiment than in the numerical simulation due to the presence of intrinsic disorder in the fabrication, which was ignored in the

**Figure 3 | Edge state propagation in a homogeneous magnetic field (8 x 8 array).** a-d. Light enters from one corner and exits from the other. The experiment shows that, depending on input frequency, the light takes the short edge (a) or the long edge (b). The experimental results (ab) are in good agreement with the simulation results (cd). The simulation parameters are $(k_{ex}, k_{in}, J) = (31, 0.57, 26)$ GHz, which are extracted from experimental measurement of simpler devices. e. SEM image of the system.

**Figure 4 | Edge state protection against a defect.** a. SEM image showing that a resonator has been intentionally removed from the array. b,c. Topological protection is observed in the experiment (b) as light propagating along the edge routes around the defect, in agreement with simulation (c). Parameters for the simulation are as in Fig. 3.
simulation. Owing to the topological robustness of the system, in the long edge band the light takes two sharp corners (Fig. 2b–d) and leaves the system at the output port. Again, similar to the previous case, we observe that the edge-state profile is robust over a band (10 GHz) broader than the bulk states (0.2 GHz) due to topological protection of the edge states. Note that if the system were isolated (that is, in the absence of input/output ports), the edge states could circulate around the entire system. Once the system is coupled to input/output ports, depending on the excitation frequency either the short or long edge acquires higher coupling and the resonators exhibit higher light scattering.

Finally, to confirm that the edge state is robust against an introduced disorder, we fabricated a 10 × 10 array with a missing resonator on one of the edges (Fig. 3a). As a result of topological robustness, it was expected that the edge state would bypass the impurity and the transmission would not be impeded. Launching light at the short edge band (over 15 GHz), we observed that the light entered at the bottom row from the left input corner, routed tightly around the disorder—in this extreme case, an entirely missing resonator—and travelled to the output port without entering into the bulk (Fig. 4b), in good agreement with simulation (Fig. 4c). For the simulation we used parameters independently measured using single-ring devices. The residual presence of light at the missing resonator location in Fig. 4b is due to background noise.

Conclusion
We have demonstrated the presence of robust edge states in an engineered two-dimensional photonic system. The SOI technology allowed us to measure both transport properties and the spatial wavefunction of such states. This platform opens the door to studying different types of magnetic fields and topological orders with photons in the non-interacting regime, due to resonant enhancement. Moreover, intriguing avenues can be seen for exploring many-body physics by integrating strong nonlinearity, for example, mediated by quantum dots or Rydberg atomic ensembles.

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Author contributions
M.H. conceived the experiment. M.H., J.F. and J.M.T. designed the chips. M.H., S.M. and J.F. carried out the experiment and analysed the data. M.H. and J.M.T. wrote the manuscript. All authors contributed considerably.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.H.

Competing financial interests
The authors declare no competing financial interests.
CORRIGENDUM

Ultrafast fibre lasers
Martin E. Fermann & Ingmar Hartl

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In the version of this Review Article originally published online and in print, the label for the horizontal axis in Fig. 3 should read “Wavelength (μm)” and not “Wavelength (nm)”. This has now been corrected in both the HTML and PDF versions of the Review Article.

CORRIGENDUM

Recent advances in fibre lasers for nonlinear microscopy
C. Xu & F. W. Wise

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In the version of this Review Article originally published online and in print, no competing financial interests were declared. However, the authors wish to acknowledge relevant patents. The competing financial interests statement in the HTML and PDF versions of the Review Article has been modified to that shown below:

F. W. Wise is a named inventor on US patent US 8,416,817 B2 (publication date 04.09.2008, filing date 18.09.2007) and Chinese patent number 200780042670.8, which are related to the dissipative-soliton laser described in this Review Article. European patent application number 7873804.4 has been filed on the same subject. Wise has also submitted a patent application relating to picosecond-pulse sources for coherent anti-Stokes Raman microscopy (international patent PCT/US/2012/058817 (publication date 11.04.2013, filing date 04.10.2011).

ERRATUM

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In the version of this Review Article originally published online and in print, the DOI was incorrectly specified as 10.1038/nphoton.2013.270. The correct DOI is 10.1038/nphoton.2013.280. This has now been corrected in both the HTML and PDF versions of the Review Article.