FLEXCOMPUTE | TIDY3D

Advanced Photonics Seminar

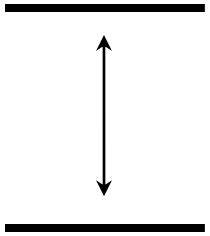
Quantum and Topological Optics in Nanophotonic Structures

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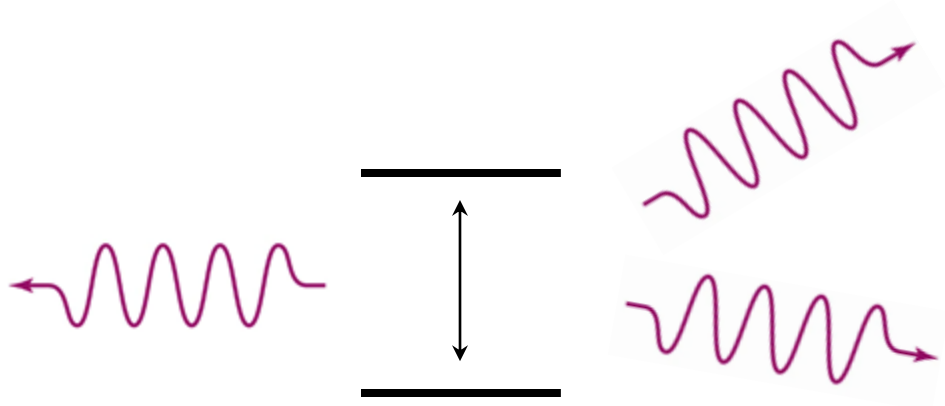
Quantum emitters

- Quantum dots, color centers / crystal lattice defects, trapped atoms / ions / molecules



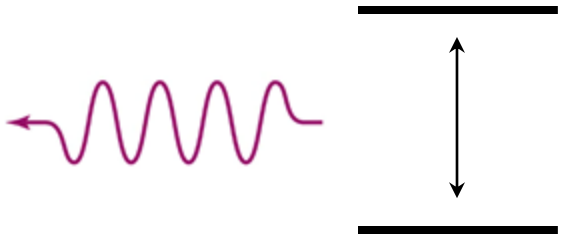
Quantum emitters

- Quantum dots, color centers / crystal lattice defects, trapped atoms / ions / molecules
- For all practical applications, we want strong coupling to the EM field



Quantum emitters

- Quantum dots, color centers / crystal lattice defects, trapped atoms / ions / molecules
- For all practical applications, we want strong coupling to the EM field
- Ideally - coupling to a single channel



Quantum emitters

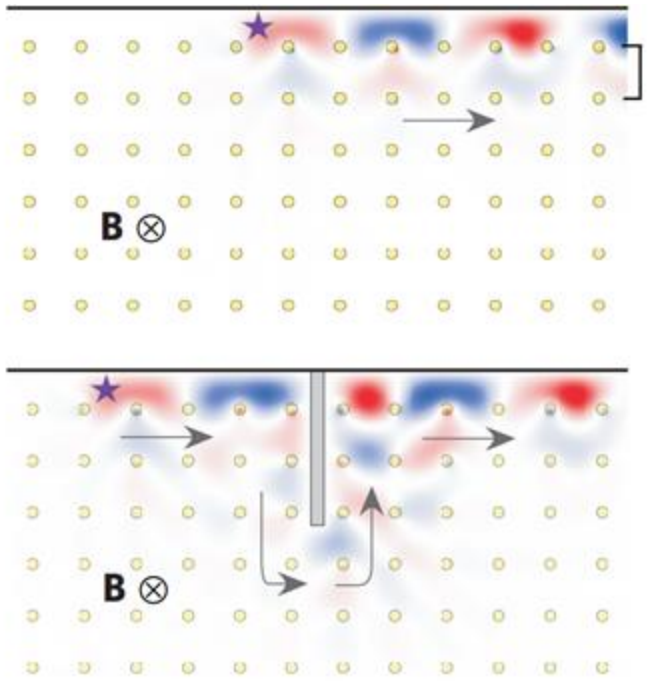
- Quantum dots, color centers / crystal lattice defects, trapped atoms / ions / molecules
- For all practical applications, we want strong coupling to the EM field
- Ideally - coupling to a single channel
- Ideally - tunable coupling between 0 and “strong”



Topological photonics

Topological photonics

- Wide range of systems to which a “topological invariant” can be associated
- In many cases there’s an associated “edge state” protected w.r.t. disorder and obstacles



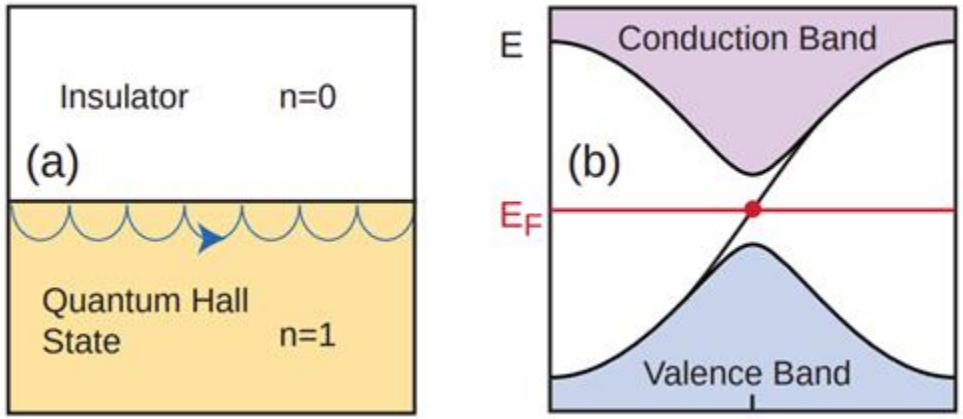
Wang, Chong, et al., Nature **461**, 772–775 (2009)

Quantum Hall and Quantum Spin Hall

M. Hasan, C. Kane, Rev. Mod. Phys. 82, 3045 (2010)

Quantum Hall and Quantum Spin Hall

Quantum hall

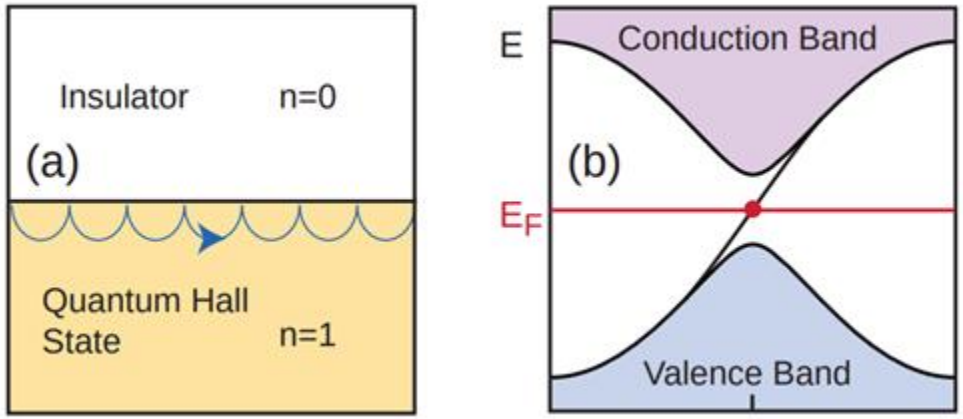


- Requires external magnetic field
- Single edge state

M. Hasan, C. Kane, Rev. Mod. Phys. 82, 3045 (2010)

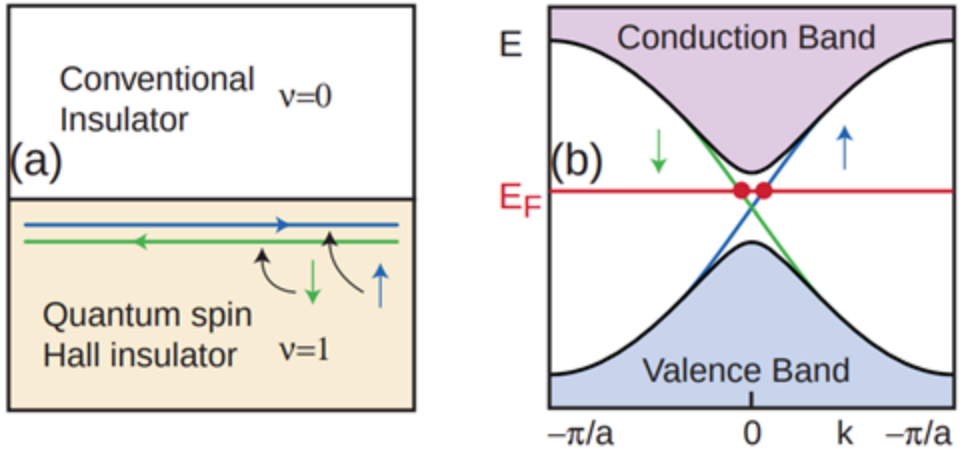
Quantum Hall and Quantum Spin Hall

Quantum hall



- Requires external magnetic field
- Single edge state

Quantum spin hall



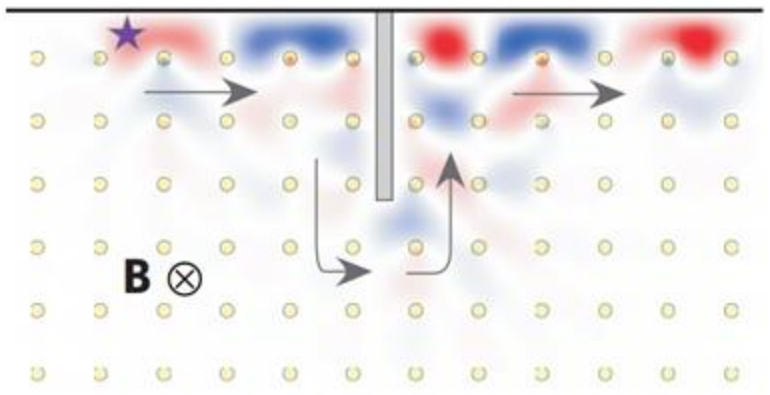
- Intrinsic due to spin-orbit interaction
- Helical edge states (spin-direction coupled)
- Protected against non-magnetic disorder

M. Hasan, C. Kane, Rev. Mod. Phys. 82, 3045 (2010)

In photonics

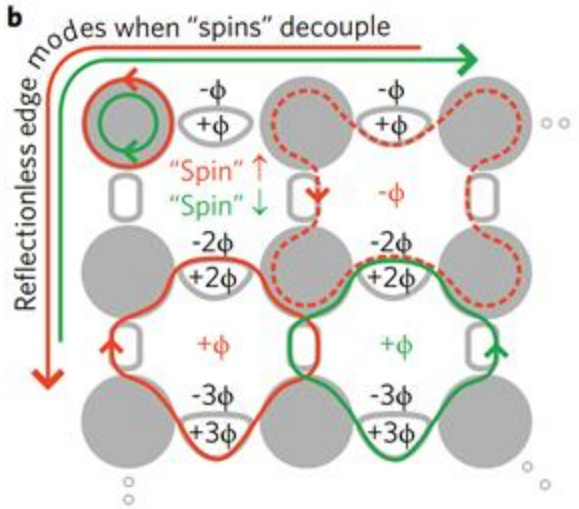
Hafezi, Demler, et al., Nature Phys. **7**, 907–912 (2011)

Quantum Hall



- Requires external magnetic field
- Single edge state
- Hard to achieve at optical frequencies and in compact devices

Quantum spin Hall



- Intrinsic due to spin-orbit interaction
- Helical edge states (spin-direction coupled)
- Not protected against (some) structural disorder

Time-reversal symmetry

Box 2 | Time reversal symmetry.

Symmetry considerations are crucial when determining the possible topological phases of a system. For example, the quantum Hall phase requires the breaking of time-reversal symmetry (T). On the other hand, in the recently discovered 2D and 3D topological insulators in electronics, T-symmetry is required to protect these topological phases characterized by $\mathbb{Z}_2$ topological invariants. For example, the 2D topological insulator, also known as the quantum spin Hall effect[98], allows the coexistence of counter-propagating spin-polarized gapless edge states. Without T-symmetry, however, these edge states can scatter into each other. The edge energy spectrum opens a gap and the insulator can continuously connect to trivial insulators, such as the vacuum. A large table of symmetry-protected topological phases have been theoretically classified[73,74]. These systems have robust interfacial states that are topologically protected only when the corresponding symmetries are present[75].

Here we point out the fundamental difference in time-reversal symmetry between electrons and photons. A photon is a neutral non-conserved non-interacting spin-1 Boson that satisfies Maxwell's equations, whereas an electron is a charged conserved interacting spin-1 Fermion that satisfies Schrödinger's equation. Similar to Schrödinger's equation, the lossless Maxwell's equations at non-zero frequencies can be written as a generalized Hermitian eigenvalue problem:

$$i\begin{pmatrix} 0 & \nabla\times \\ -\nabla\times & 0 \end{pmatrix}\begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} = \omega\begin{pmatrix} \epsilon & \chi \\ \chi^\dagger & \mu \end{pmatrix}\begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix}$$

where $\varepsilon^\dagger = \varepsilon$, $\mu^\dagger = \mu$ and χ is the bianisotropy term, where † is Hermitian conjugation.

The anti-unitary time T operator is given by:

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} K$$

which squares to unity, where K is complex conjugation (*). When $\varepsilon^* = \varepsilon$, $\mu^* = \mu$ and $\chi = -\chi^*$, the system is T-invariant. Rotating the spin by 2π is the same as applying the T operator twice (T^2). But T^2 has different eigenvalues for photons ($T^2 = +1$) and electrons ($T^2 = -1$). It is this minus sign that ensures Kramer's degeneracies for electrons at T-invariant $\mathbf{k}$ points in the Brillouin zone, thus providing the possibility of gapless connectivity for edge dispersions in the bulk gap. This fundamental distinction results in different topological classifications for photons and electrons with respect to T. For example, photons do not have the same topological phases of 2D or 3D topological insulators protected by T as for electrons.

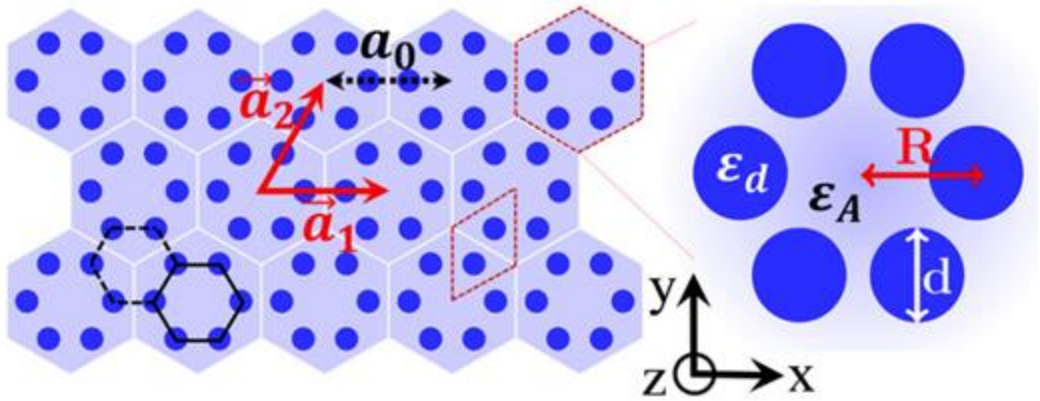
Lu, Joannopoulos and Soljačić, Nature Photonics **8** (2014)

Pseudo-spin Quantum Hall effect

PRL 114, 223901 (2015) PHYSICAL REVIEW LETTERS week ending 5 JUNE 2015

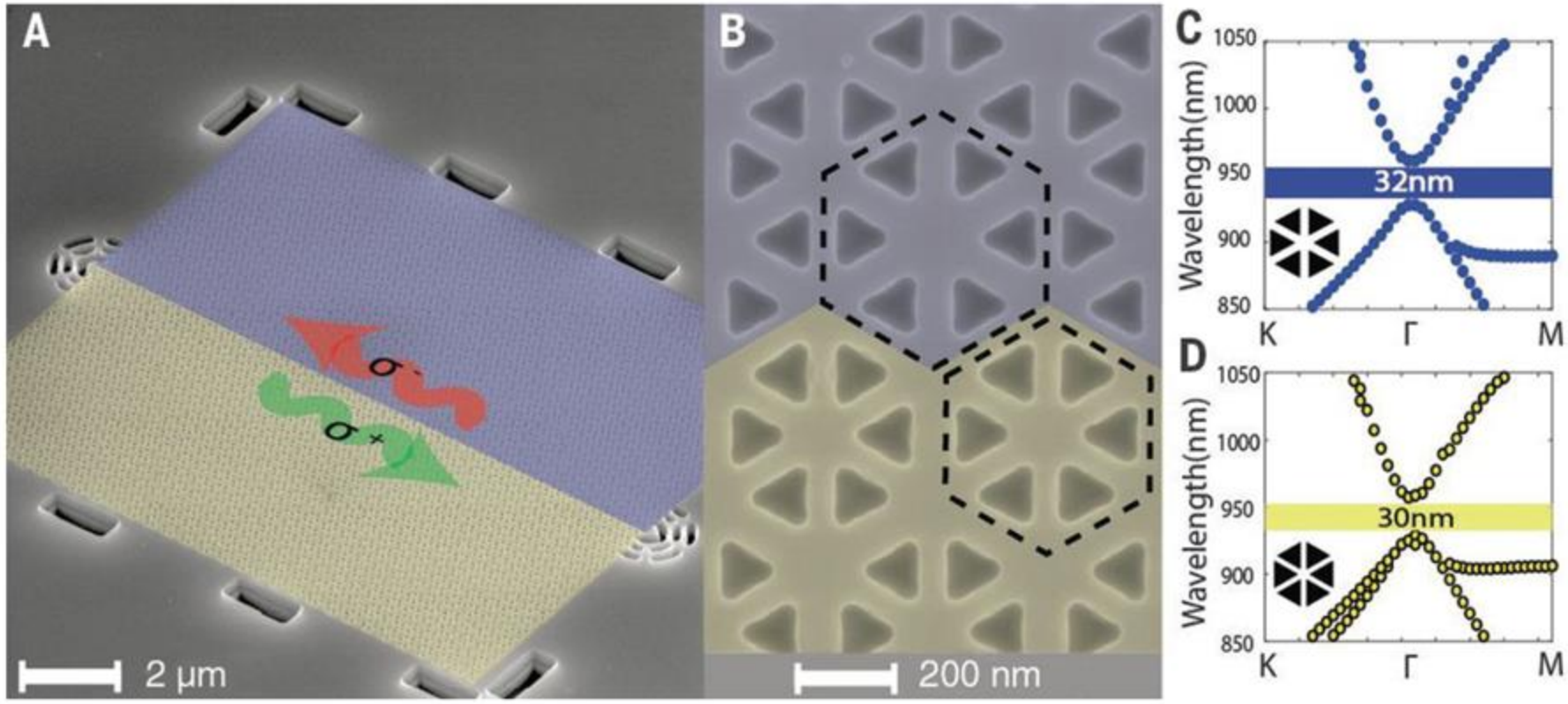
Scheme for Achieving a Topological Photonic Crystal by Using Dielectric Material

Long-Hua Wu and Xiao Hu*



Create an operator U with $U^2 = -1$ due to the **spatial** symmetry

Topological quantum interface



Barik, Karasahin, et al. Science 359.6376 (2018)

Topological quantum interface

- We can control which channel a quantum dot emits to

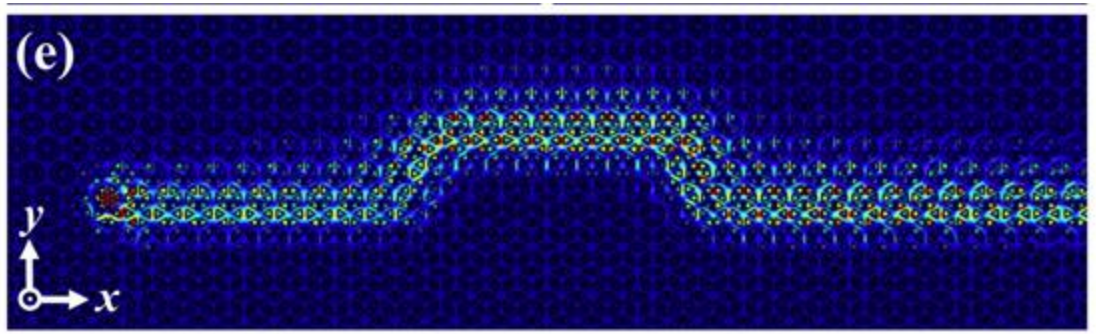


Topological quantum interface

- We can control which channel a quantum dot emits to



- Scattering protection against (some) disorder




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TECHNICAL SUPPORT

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OFFICE HOUR

One-on-one meeting
with the senior expert

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