Optical Isolation with Nonlinear Topological Photonics

Xin Zhou, You Wang, Daniel Leykam and Yidong Chong

Nanyang Technological University, Singapore

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What is Optical Isolation

Optical isolators are devices that allow light to pass in one direction (e.g., along a waveguide), while blocking transmission in the other direction, thus acting as the analogues of diodes in electronic circuits

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

Figure 1: A schematic picture of optical isolator.

Why we need it

- In modern fibre communication networks it is an essential device to prevent interference between different parts of the networks.
- Nowadays people become more and more interested in large-scale on-chip optical networks, so optical isolation on-chip size is becoming increasingly important.

How to Achieve Optical Isolation

Lorenz Reciprocity

For linear, static and non-magnetic material,

$$\nabla \cdot (E^{'} \times H^{''} - E^{''} \times H^{'}) = j\omega(E^{''}\epsilon E^{'} - E^{'}\epsilon E^{''} - H^{''}\mu H^{'} + H^{'}\mu H^{''}) = 0 \quad (1)$$

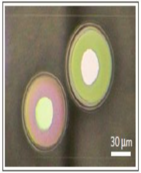
Here, $(E^{'}, H^{'})$ and $(E^{''}, H^{''})$ are two sets of excitation.

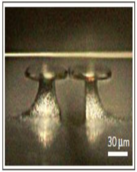
Magneto-Optical Effect

For magneto-optical material so ϵ and μ are non-symmetric tensor.

Optical Nonlinear Material

For nonlinear material,ϵ and μ depend on E and H





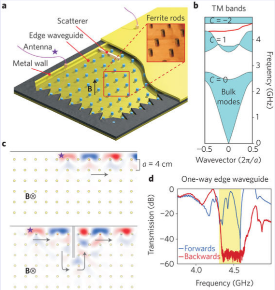
Spacial-temporal Modulation

For ϵ and μ depend on time, the derivation is not valid, so does Lorentz Reciprocity.

Topological Photonics

Realizing Topological State in Photonic System

Photonic Crystal | Photonic Waveguide | Ring Resonator



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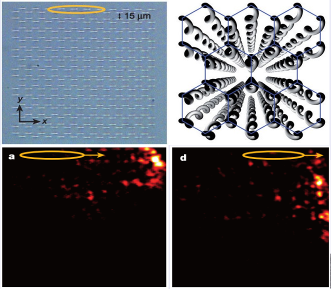

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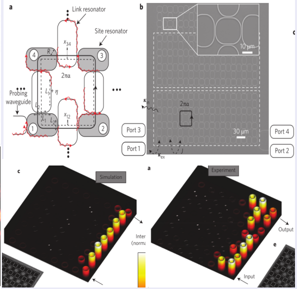
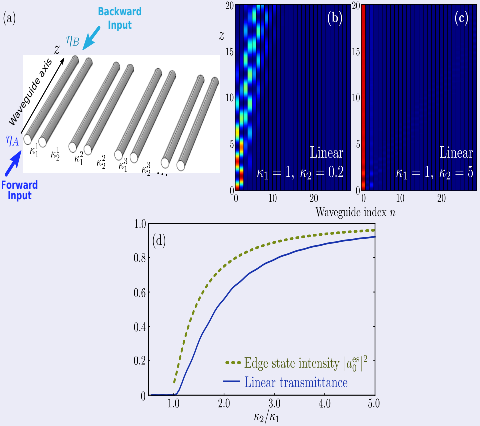


Nature Photon. 7, 1001–1005 (2013).

Key Feature of Topological Edge State

- Propagate along the edge without scattering into the bulk
- Unidirectional without backscattering
- Robust even in the presence of impurities

Nonlinear 1D Su–Schrieffer–Heeger (SSH) model



Using coupled-mode theory:

$$i\frac{da_n}{dz} = \kappa_1^n b_n + \kappa_2^{n-1} b_{n-1} \quad (2)$$

$$i\frac{db_n}{dz} = \kappa_1^n a_n + \kappa_2^{n-1} a_{n+1} \quad (3)$$

- Topological transition at $\kappa_1 = \kappa_2$
- Edge state with zero eigenvalue appear when $\kappa_1 < \kappa_2$

Transmittance

$$T = \frac{|a_0(Z)|^2}{I}, I = |a_0(0)|^2 \quad (4)$$

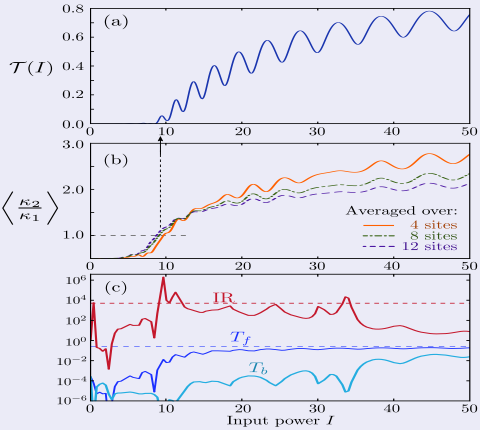
I is input power and Z is pre-defined propagation distance.

Nonlinear 1D Su–Schrieffer–Heeger (SSH) model

Nonlinear coupling

$$\kappa_2^n(z) = \kappa_0 + \alpha(|a_{n+1}(z)|^2| + b_n(z)|^2) \qquad (5)$$

$\kappa_1 = 1$, $\kappa_0 = 0.5$, $\alpha = 1$, Z=20



Forward transmittance:

$$T_f = \eta_A^2 \eta_B^2 T(\eta_A^2 I) \qquad (6)$$

Backward transmittance:

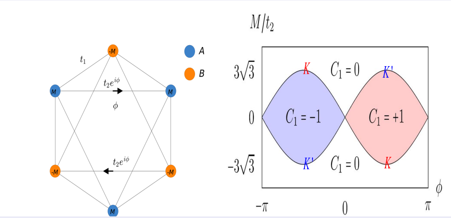
$$T_b = \eta_A^2 \eta_B^2 T(\eta_B^2 I) \qquad (7)$$

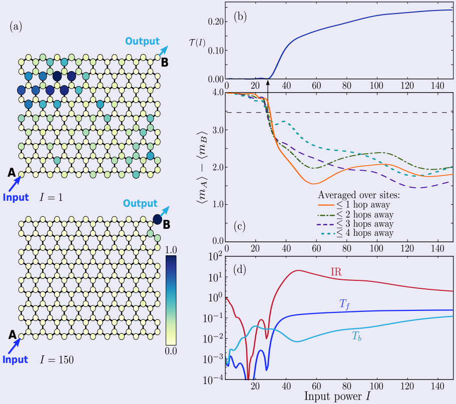
Isolation Ratio:

$$IR = \frac{T_f}{T_b} \qquad (8)$$

1. T(I) increase significantly when $< \frac{\kappa_2}{\kappa_1} >$ crosses 1
2. $< \frac{\kappa_2}{\kappa_1} >= 1$ indicates topological trnasition for underline linear lattice
3. T_b is pretty smaller comparing to T_f in a broad range of I

Nonlinear 2D Haldane Model





Nonlinear on-site potential

$$m_A^\mu = \frac{m_0}{1+|a_\mu|^2}, \; m_B^\mu = \frac{-m_0}{1+|b_\mu|^2}$$

$$t_1 = 1, \; t_2 = \frac{1}{3}, \; \phi = \frac{\pi}{2}, \; m_0 = 2$$

For fixed t_1, t_2, ϕ, topological phase transition happens at

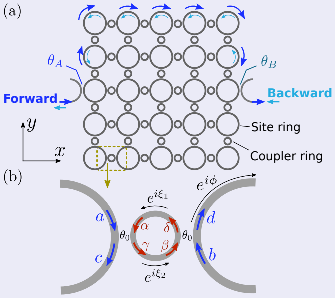
$$m_A - m_B = |6\sqrt{3} t_2 \sin\phi|$$

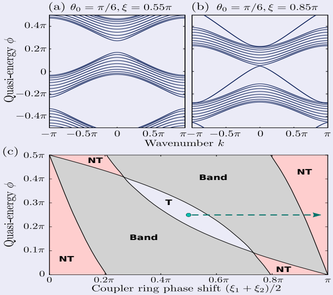
$$Z = 19.2, \; \eta_A = \eta_B = 1.0$$

1. T(I) increase significantly when $< m_A > - < m_B >$ crosses $2\sqrt{3}$
2. $< m_A > - < m_B > = 2\sqrt{3}$ indicates topological trnasition for underline linear lattice
3. T_b is pretty smaller comparing to T_f in a broad range of I.

Topological Optical Isolation

Nonlinear Coupled Ring Lattices





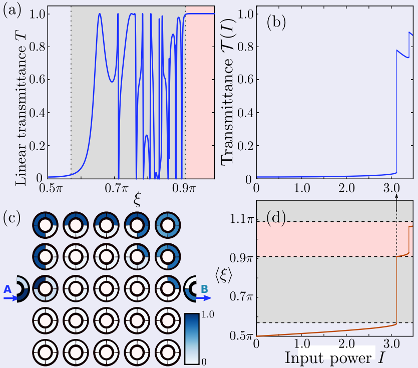
$$\begin{bmatrix} c \\ \gamma \end{bmatrix} = S_c(\theta_0) \begin{bmatrix} a \\ \alpha \end{bmatrix}, \begin{bmatrix} d \\ \delta \end{bmatrix} = S_c(\theta_0) \begin{bmatrix} b \\ \beta \end{bmatrix}, S_c(\theta_0) = \begin{bmatrix} \sin(\theta_0) & i\cos(\theta_0) \\ i\cos(\theta_0) & \sin(\theta_0) \end{bmatrix} \quad (9)$$

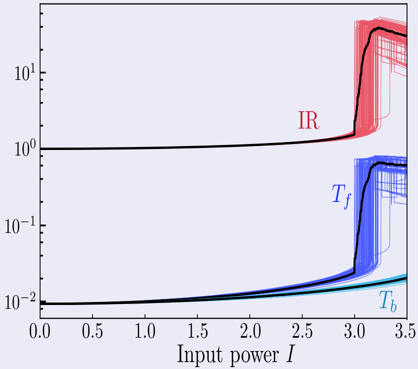
$$\alpha = e^{i\xi_1}\delta, \beta = e^{i\xi_2}\gamma \quad (10)$$

Nonlinear Coupled Ring Lattices

Introduce Kerr-like nonlinearity to phase shift on each arm

$$\xi = \xi_0 + \kappa I \tag{11}$$



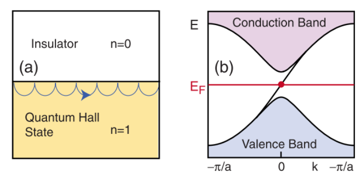


Conclusion

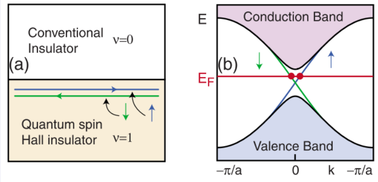
Topological Photonics

Discover of Topological State

Insulating in the bulk while conducting in the surface without backscattering even in the presence of impurities.



(a) Quantum Hall Effect. Time reversal symmetry is broken. Hasan and Kane, RMP, 2010



(b) Quantum Spin Hall Effect. Time reversal symmetry is preserved. Hasan and Kane, RMP, 2010