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Manipulating photonics synthetic dimension based on optical orbital angular momentum

Zhengwei Zhou
（周正威）

Univ. of Sci. & Technol. of China,
Hefei, Anhui, China

NSFC

CHINESE ACADEMY OF SCIENCES

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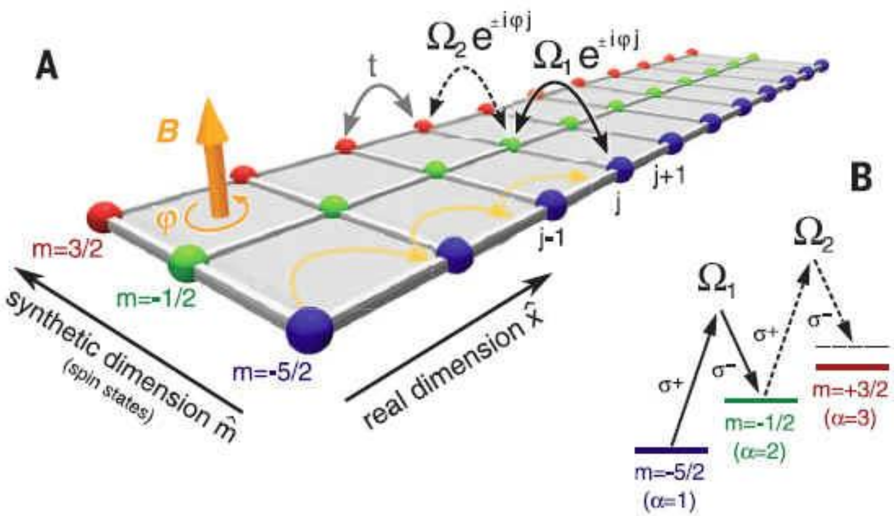
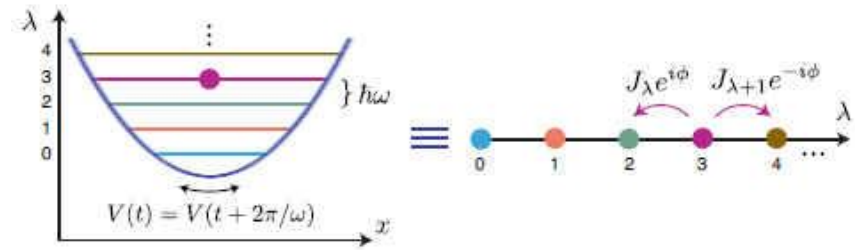
Outline

- Background on synthetic dimensions
- Simulation for topological physics based on degenerate cavities
- All-optical devices based on degenerate cavities
- Summary

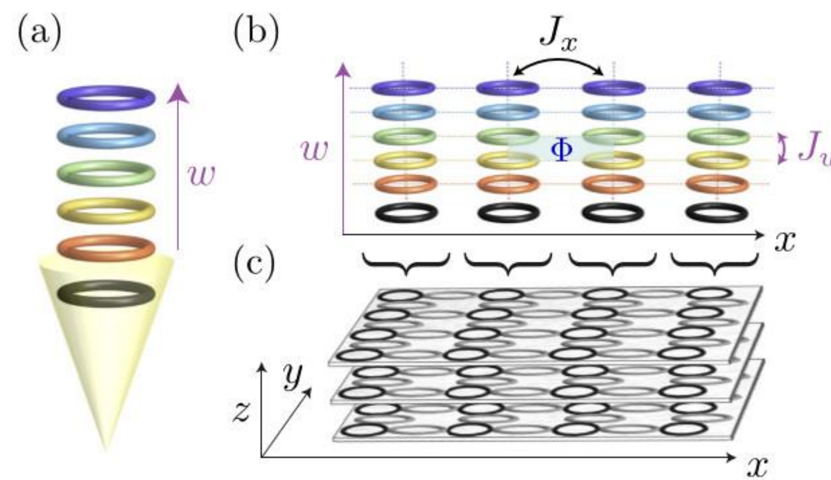
Quantum simulation by utilizing synthetic dimensions





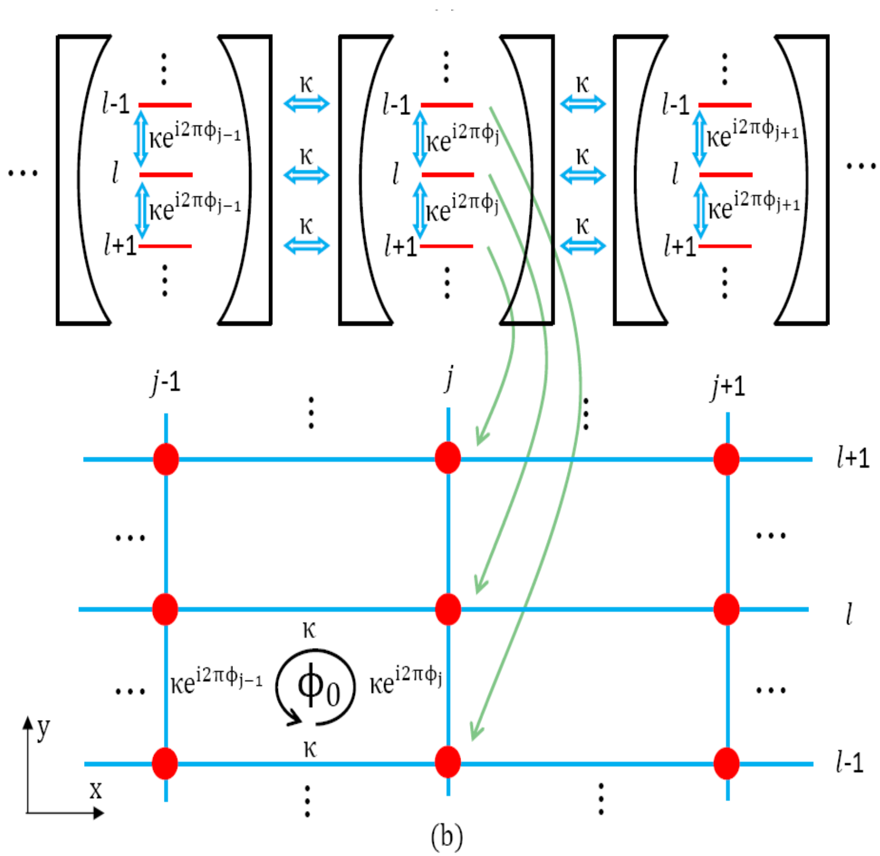
Phys. Rev. A 95, 023607 (2017)

PRL 108, 133001 (2012);
PRL 112, 043001 (2014);
Science 349, 1510 (2015);
Science 349, 1514 (2015).



Phys. Rev. A 93, 043827 (2016)

Quantum simulation by utilizing synthetic dimensions



Advantages:
a large amount of optical modes; manipulating optical modes via linear optical elements

Drawback:
inducing nonliear interactions between optical modes are quite difficult.

Nature Communications 6:7704 (2015)

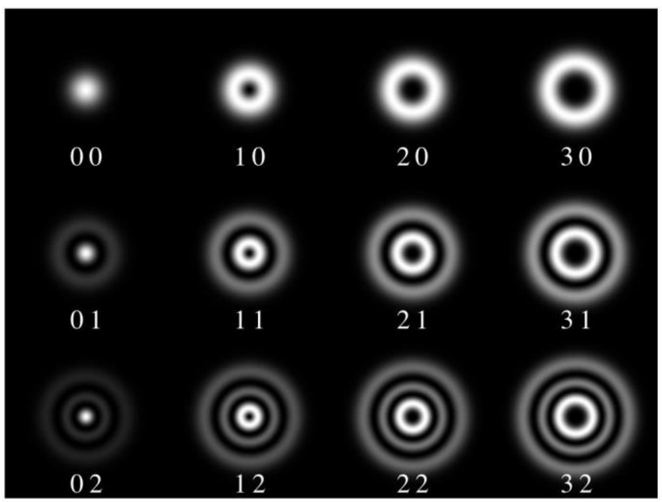
Orbital angular momentum

LG Mode :

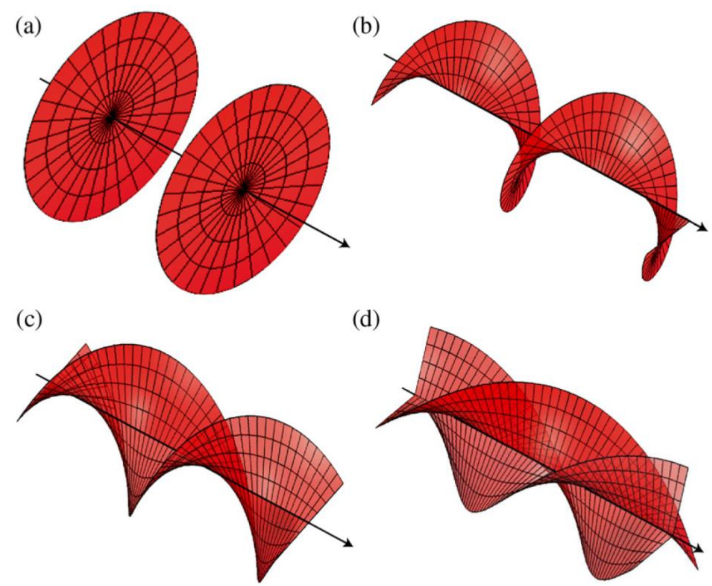
$$E_{p,l}(r,\varphi) = E_0 \frac{W_0}{W(z)} \left(\frac{r\sqrt{2}}{W(z)}\right)^{|l|} \mathcal{L}_p^{|l|}\left(\frac{2r^2}{W(z)^2}\right) \times \exp\left(\frac{-r^2}{W(z)^2}\right) \exp\left(\frac{-ikr^2}{2R(z)}\right) \times \exp\left[i(2p+|l|+1)\zeta(z)\right] e^{il\varphi},$$

***l* :** azimuthal mode index

***p*:** radial mode index



(l p)

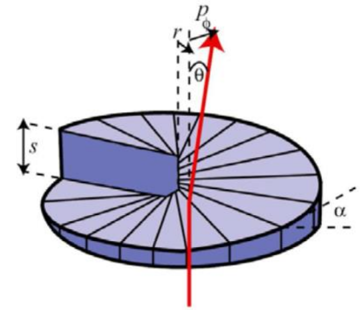


Helical phase fronts for (a) $\ell = 0$, (b) $\ell = 1$, (c) $\ell = 2$, and (d) $\ell = 3$.

Phase fronts for helical beams

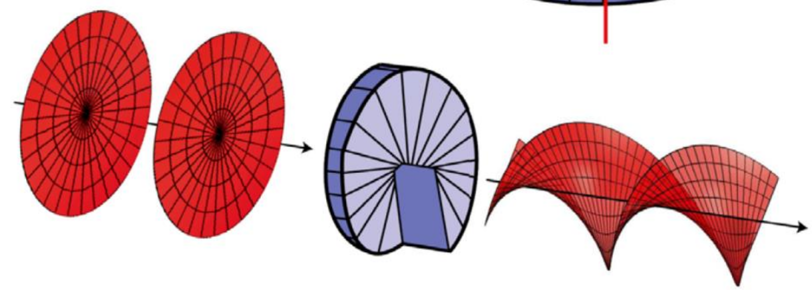
OAM generation:

Spatial light modulator (SLM)



Step index: M

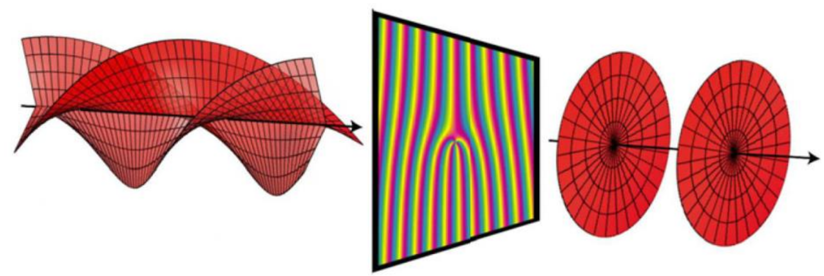
$l \rightarrow l + M$

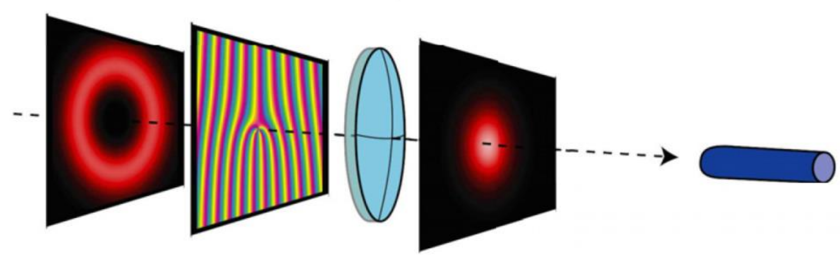


OAM detection:

SLM &

Single mode fiber





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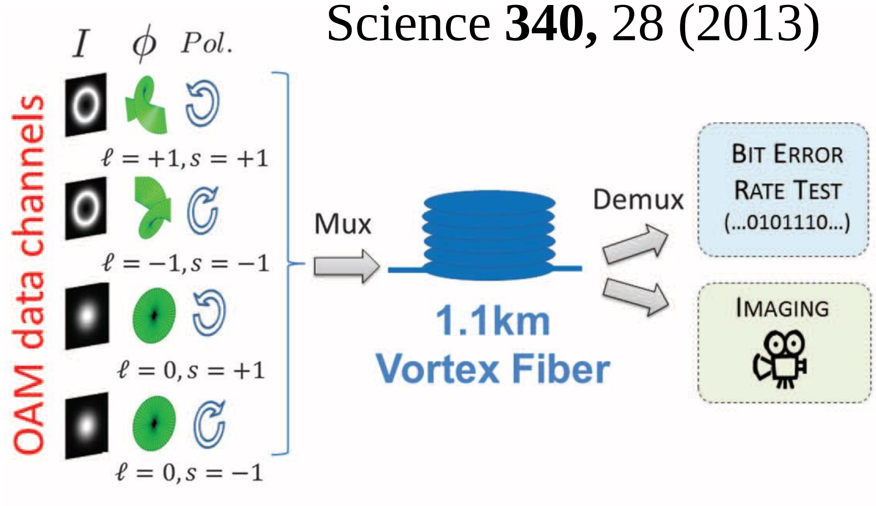
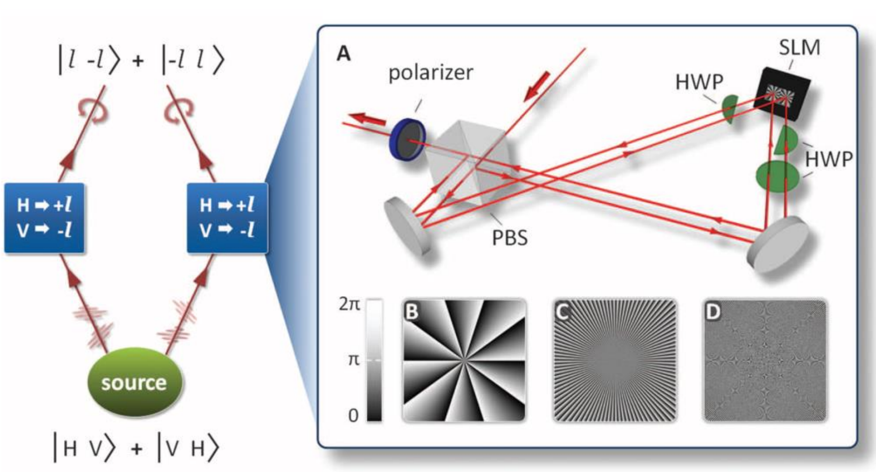
Orbital angular momentum

Science **340,** 28 (2013)



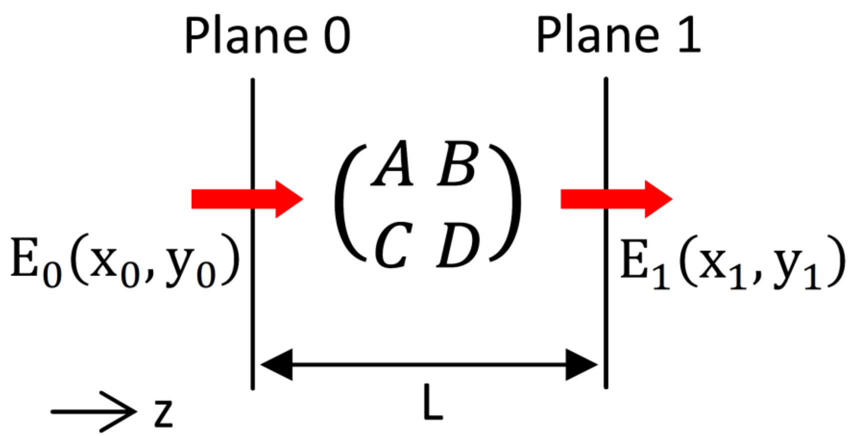
High capacity communication



High dimensional quantum entanglement

Science **338,** 2 (2012)

Degenerate cavity



Degenerate condition:
Unit ray matrix

$$A = D = 1; B = C = 0$$

$$E_1(x_1, y_1) = \iint G(x_1, y_1; x_0, y_0) E_0(x_0, y_0)$$

G: depends on ray matrix [A,B;C,D]
G=Delta function: Unit ray matrix

Resonance condition: $kL_0 - (2p + l + 1)\arccos\frac{A + D}{2} = 2n\pi$

Applied optics, 8(1):189 (1969); Nature Communications 6:7704 (2015)

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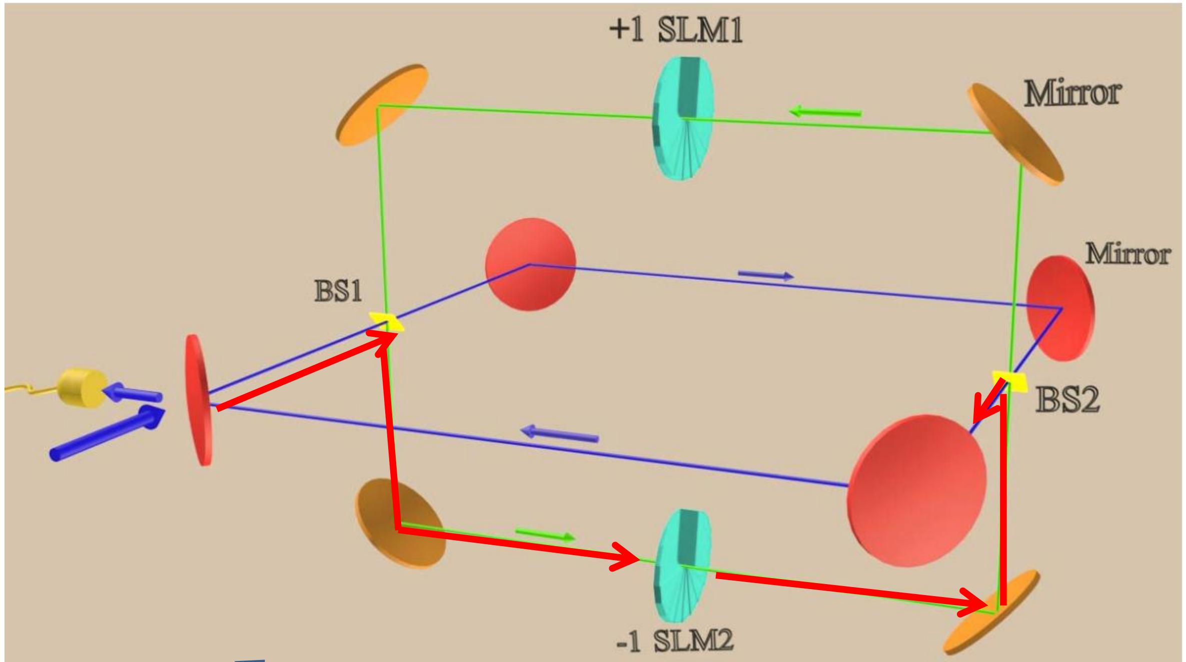
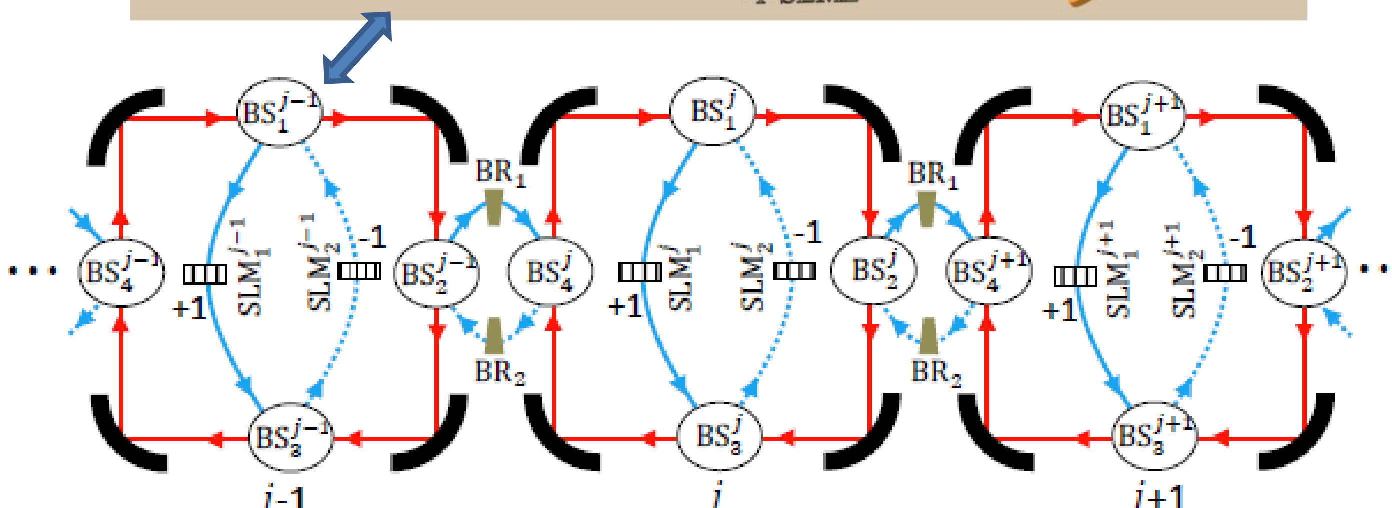
Simulating photonic lattices





X-W Luo, X. Zhou, C. F. Li, J. S. Xu, G. C. Guo, Z. W. Zhou, Nat. Commun. 6, 7704 (2015)

Abelian gauge field

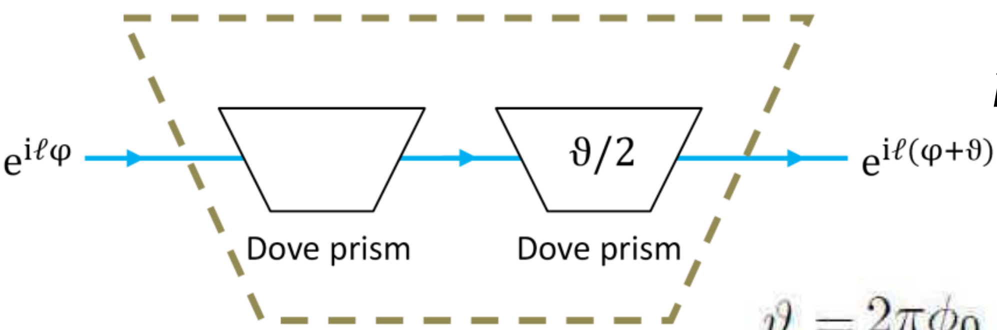
$$\mathcal{H}_2 = -\kappa \sum_{j,l} \left(a^\dagger_{j,l+1} a_{j,l} + a^\dagger_{j,l} a_{j,l+1} + e^{-i2\pi l \phi_0} a^\dagger_{j+1,l} a_{j,l} + e^{i2\pi l \phi_0} a^\dagger_{j,l} a_{j+1,l} \right)$$

- Tunnelling phase in x direction

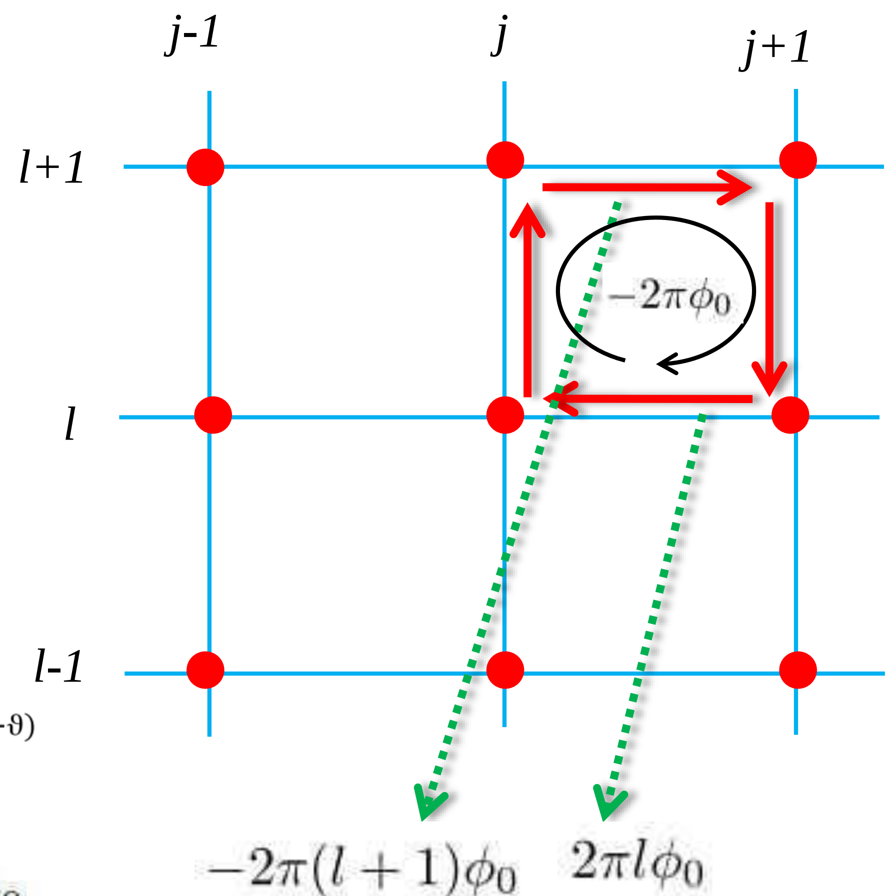
$$\phi_x = 2\pi l \phi_0$$

- Tunnelling phase in y direction

$$\phi_y = 0$$



$$\vartheta = 2\pi\phi_0$$

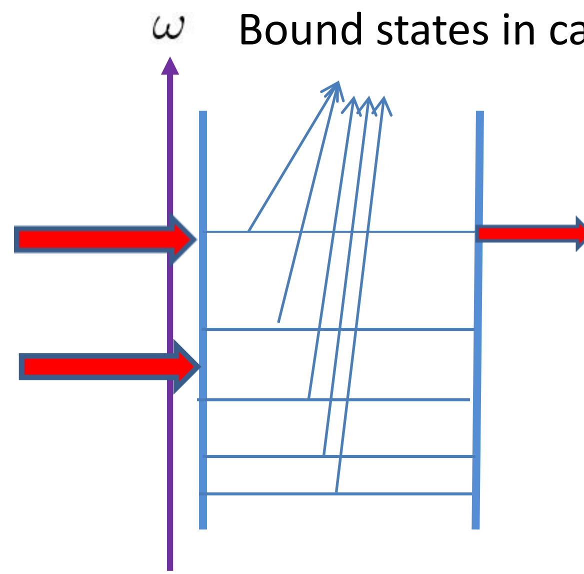


Detection

- Input-output relation

$$d_{out,n'}(\omega) = \sum_n \left\{ \delta_{n'n} - i \left[\sqrt{\Gamma} \frac{1}{\omega - \mathcal{H}_{SYS} + i\Gamma/2} \sqrt{\Gamma} \right]_{n'n} \right\} d_{in,n}(\omega),$$

Bound states in cavity



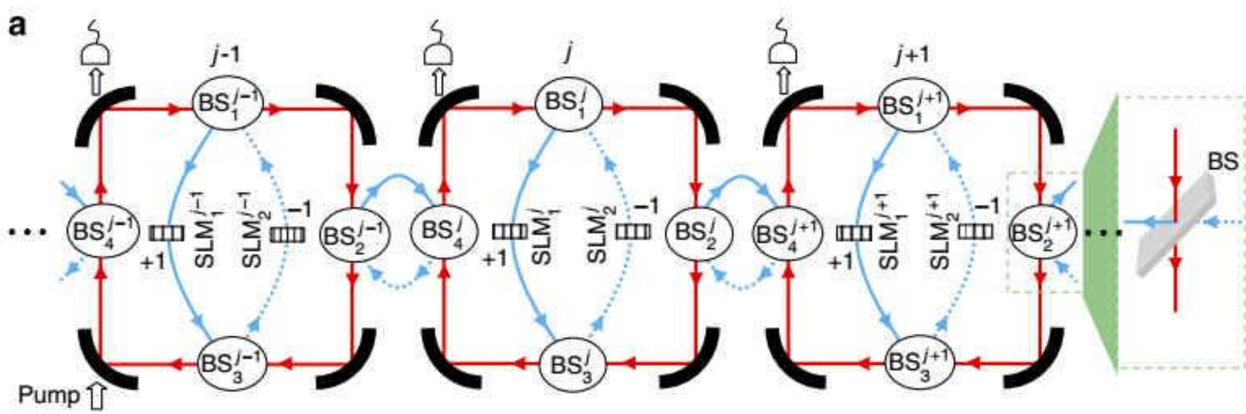
$$\Gamma = \mathrm{diag}\{\gamma_1, \gamma_2, \ldots, \gamma_n\}$$

$$T_n^{n'} = -i \langle n' | \frac{\gamma}{\omega - \mathcal{H}_{SYS} + i\gamma/2} | n \rangle,$$

transmission spectroscopy

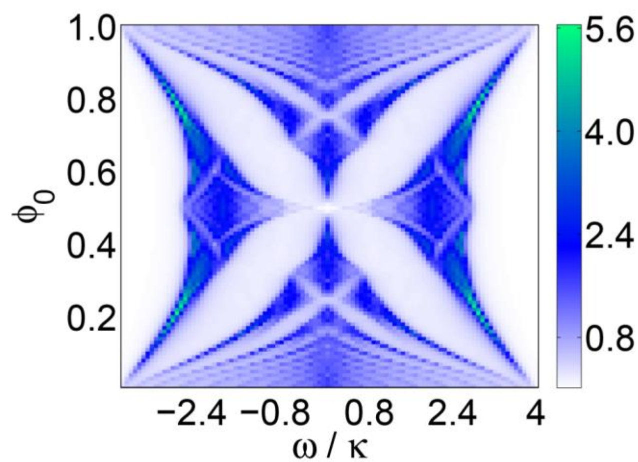
$$\mathcal{H}_1 = -\kappa \sum_{j,l} \left(e^{i2\pi\phi_j} \hat{a}^\dagger_{j,l+1} \hat{a}_{j,l} + \hat{a}^\dagger_{j+1,l} \hat{a}_{j,l} + \text{h.c.} \right)$$

$$T^{j_o,l_o}_{j_i,l_i}(\omega) = -i\gamma \left\langle j_o, l_o \left| \frac{1}{\omega - H + i\gamma/2} \right| j_i, l_i, \right\rangle$$



$$\mathcal{T}_{j_i,l_i}(\omega) = \sum_{j_o,l_o} |T^{j_o,l_o}_{j_i,l_i}(\omega)|^2$$

$$\sum_{j_i=0}^{N-1} \mathcal{T}_{j_i,0}$$



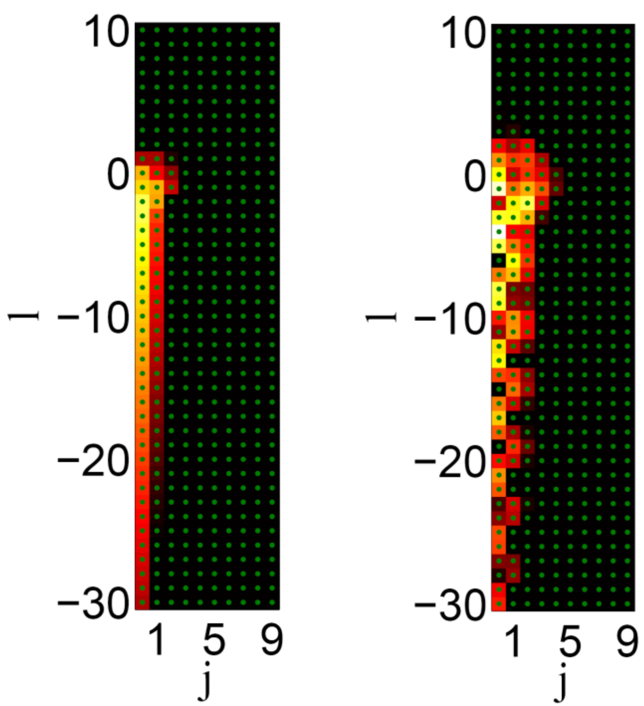
Detecting topological invariants

- Simulation of edge-state transport

$$\phi_0 = 1/6 \qquad \mathcal{T}_{0,0}^{j,l} \equiv |T_{0,0}^{j,l}|^2$$

$$\mathcal{H}_1 = -\kappa \sum_{j,l} \left(e^{i2\pi\phi_j} \hat{a}_{j,l+1}^{\dagger} \hat{a}_{j,l} + \hat{a}_{j+1,l}^{\dagger} \hat{a}_{j,l} + \text{h.c.} \right)$$

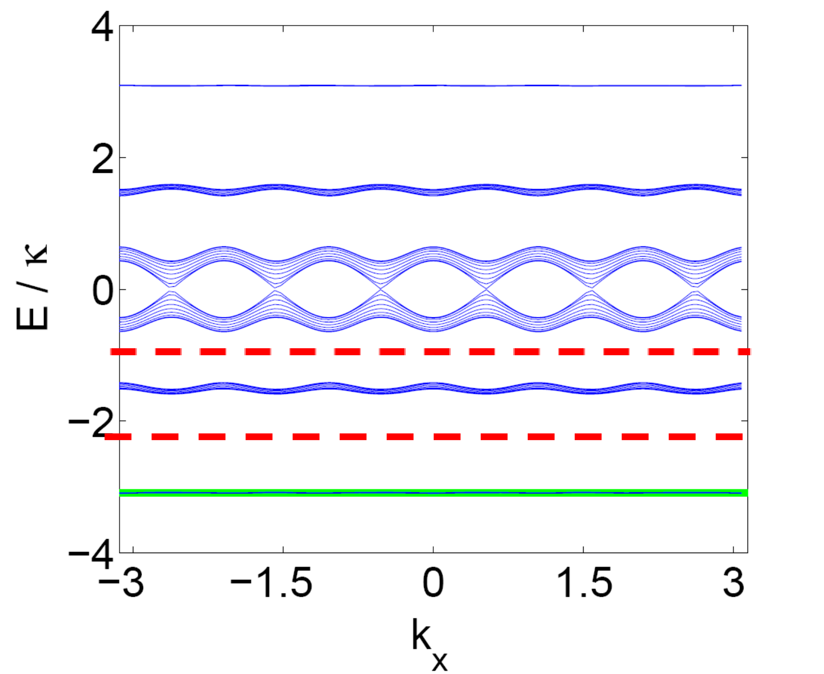
  - unidirectionality & robustness



$\omega = -2.2\kappa \qquad \omega = -1.0\kappa$

- Energy band

$\phi_0 = 1/6$

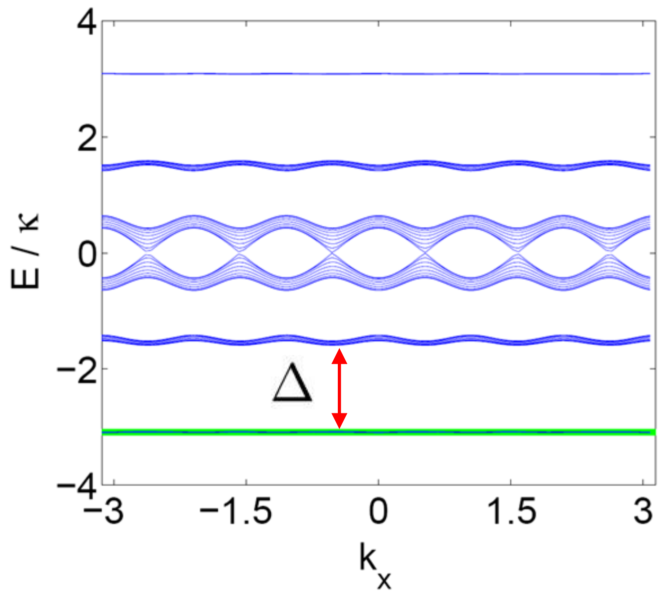


Measuring Chern number

$$T(k_x, k_y, l_q) = F\left[T_{0,0}^{j,ql+l_q}\right]$$

$$T(k_x, k_y, l_q) \propto u_{l_q}^m(k_x, k_y)\frac{i\gamma}{\omega - E_m(k_x, k_y) + i\gamma}u_0^m(k_x, k_y)^*$$

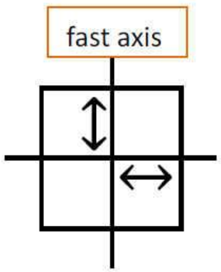
$$\omega - E_m(k_x, k_y) \ll \gamma \ll \Delta.$$

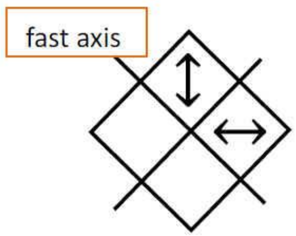


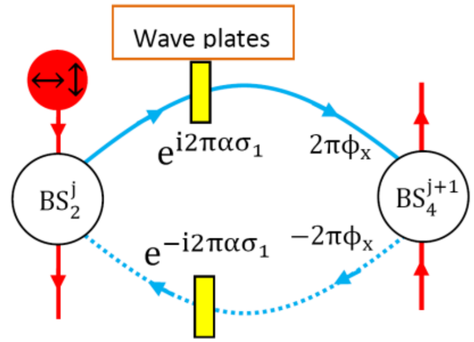
$$T(k_x, k_y, l_q) \propto u_{l_q}^m(k_x, k_y)u_0^m(k_x, k_y)^*$$

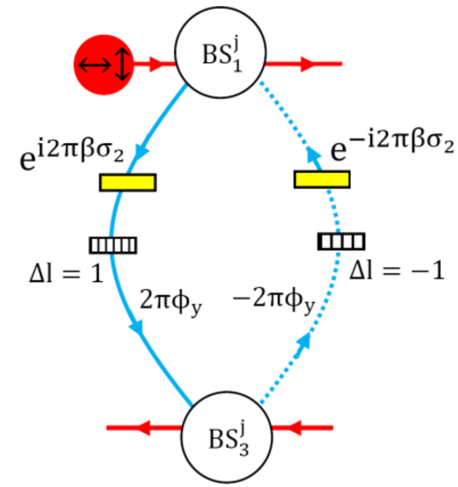
$$C = \frac{1}{2\pi i}\int\int dk_x dk_y (\langle\frac{\partial u^m}{\partial k_x}|\frac{\partial u^m}{\partial k_y}\rangle - \langle\frac{\partial u^m}{\partial k_y}|\frac{\partial u^m}{\partial k_x}\rangle)$$

NonAbelian gauge field









$$\begin{pmatrix} |\leftrightarrow\rangle \\ |\updownarrow\rangle \end{pmatrix} \Rightarrow e^{i2\pi\phi\sigma_z} \begin{pmatrix} |\leftrightarrow\rangle \\ |\updownarrow\rangle \end{pmatrix} \qquad e^{i2\pi\phi\sigma_x}$$

$$\mathcal{H}_2 = -\kappa \sum_{j,l} \left(\hat{\mathbf{a}}^{\dagger}_{j,l+1} e^{i2\pi\hat{\theta}_y} \hat{\mathbf{a}}_{j,l} + \hat{\mathbf{a}}^{\dagger}_{j+1,l} e^{i2\pi\hat{\theta}_x} \hat{\mathbf{a}}_{j,l} + \mathrm{h.c.} \right)$$
$$+ \sum_{j,l} \lambda_j \hat{\mathbf{a}}^{\dagger}_{j,l} \hat{\mathbf{a}}_{j,l},$$

$$\hat{\theta}_x = \phi_x + \alpha\sigma_1, \hat{\theta}_y = \phi_y + \beta\sigma_2,$$

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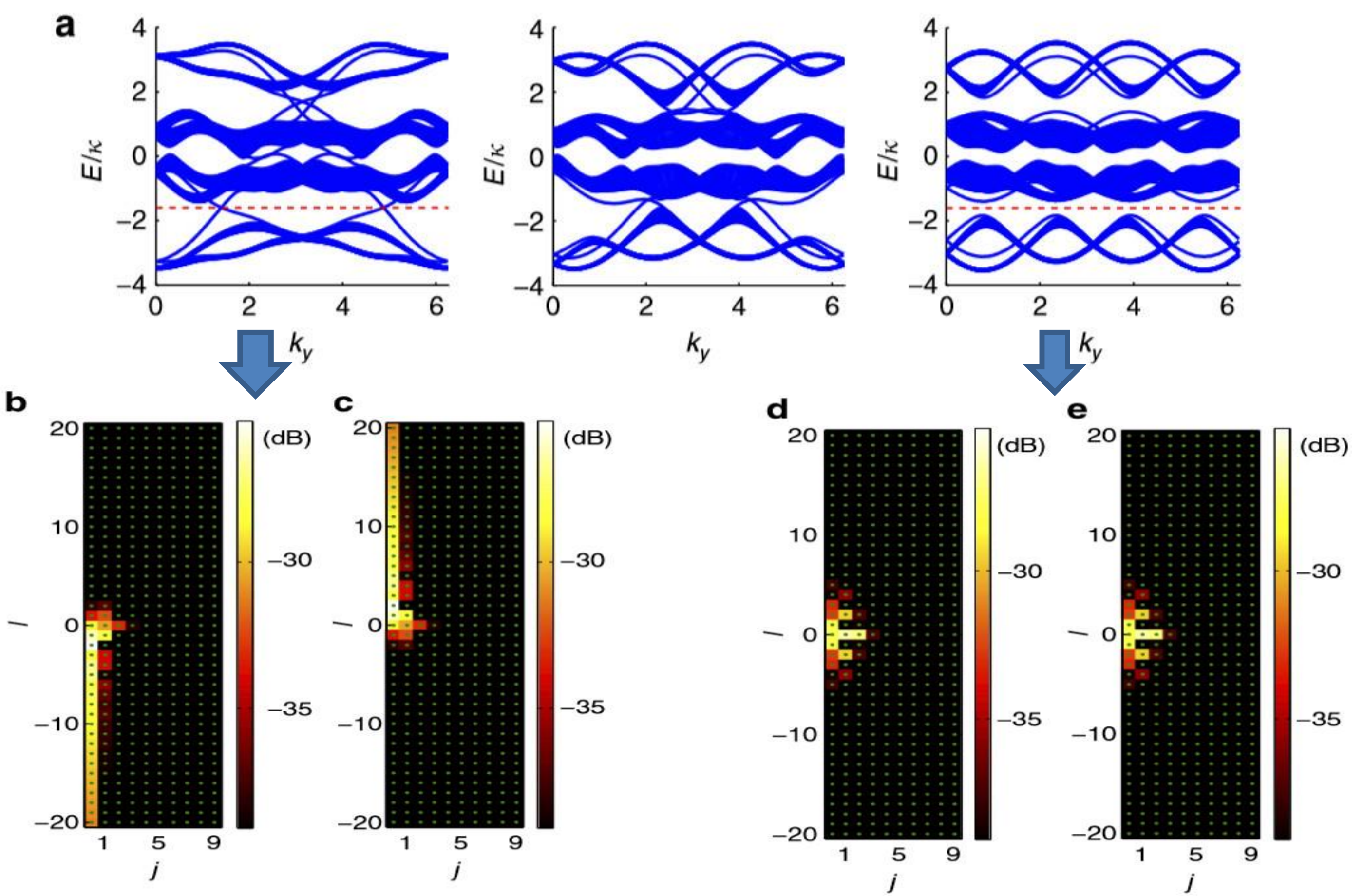
Simulating Topological QPT

$$\mathcal{H}_4 = -\kappa \sum_{j,l} \left(\hat{\mathbf{a}}^\dagger_{j,l+1} e^{i\left(\frac{\pi}{2}j+\beta_0\right)\sigma_z} \hat{\mathbf{a}}_{j,l} + \hat{\mathbf{a}}^\dagger_{j+1,l} i\sigma_x \hat{\mathbf{a}}_{j,l} + \mathrm{h.c.} \right) + \sum_{j,l} \lambda_0 \cdot [\mathrm{mod}(j,4) - 1.5] \hat{\mathbf{a}}^\dagger_{j,l} \hat{\mathbf{a}}_{j,l},$$

$\lambda_0 = 0.6\kappa$

$\beta_0 = 0$ $\beta_0 = 0.075$ $\beta_0 = 0.125$



1D topological model:

Su-Schrieer-Heeger (SSH) model
(Phys. Rev. B 22, 2099 (1980))

1D-spinless p-wave paired superconductor
(Physics-Uspekhi 44, 131 (2001))

In principle, it is enough for single degenerate optical cavity to simulate topological feature of photonic modes.

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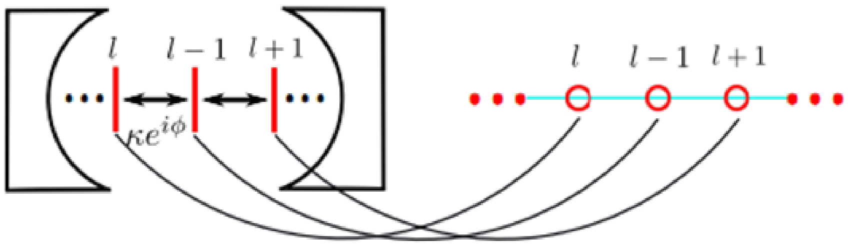
Soft boundary

X. F. Zhou, X. W. Luo, S. Wang, G. C. Guo, X. Zhou, H. Pu, Z. W. Zhou, PRL, 118, 083603(2017)



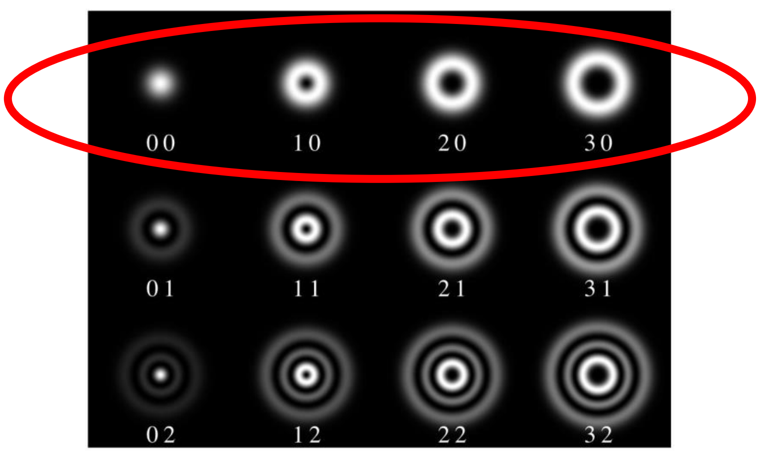
$$\mathcal{H} = -\kappa \sum_l \left(e^{i\phi}\hat{a}_{l+1}^{\dagger}\hat{a}_l + h.c.\right)$$

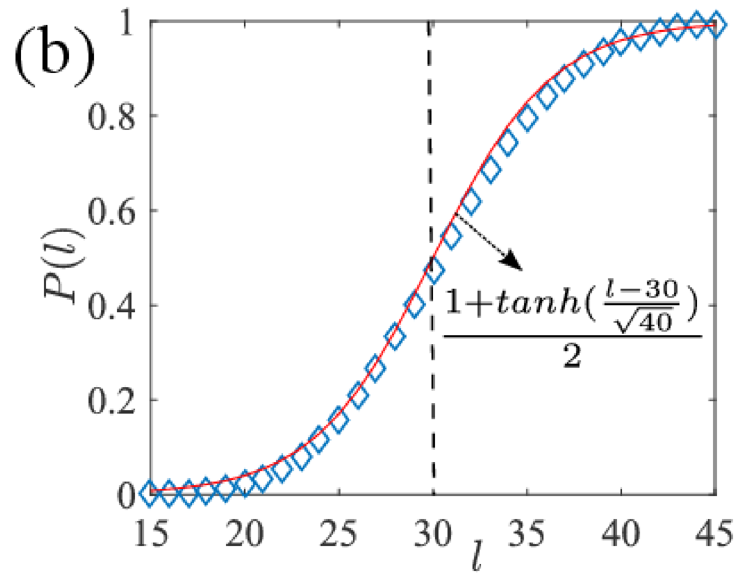
$$P(l) = \int_{\sqrt{L/2}}^{\infty} dr r |E_l^0|^2$$

$$r = \sqrt{l/2}.$$

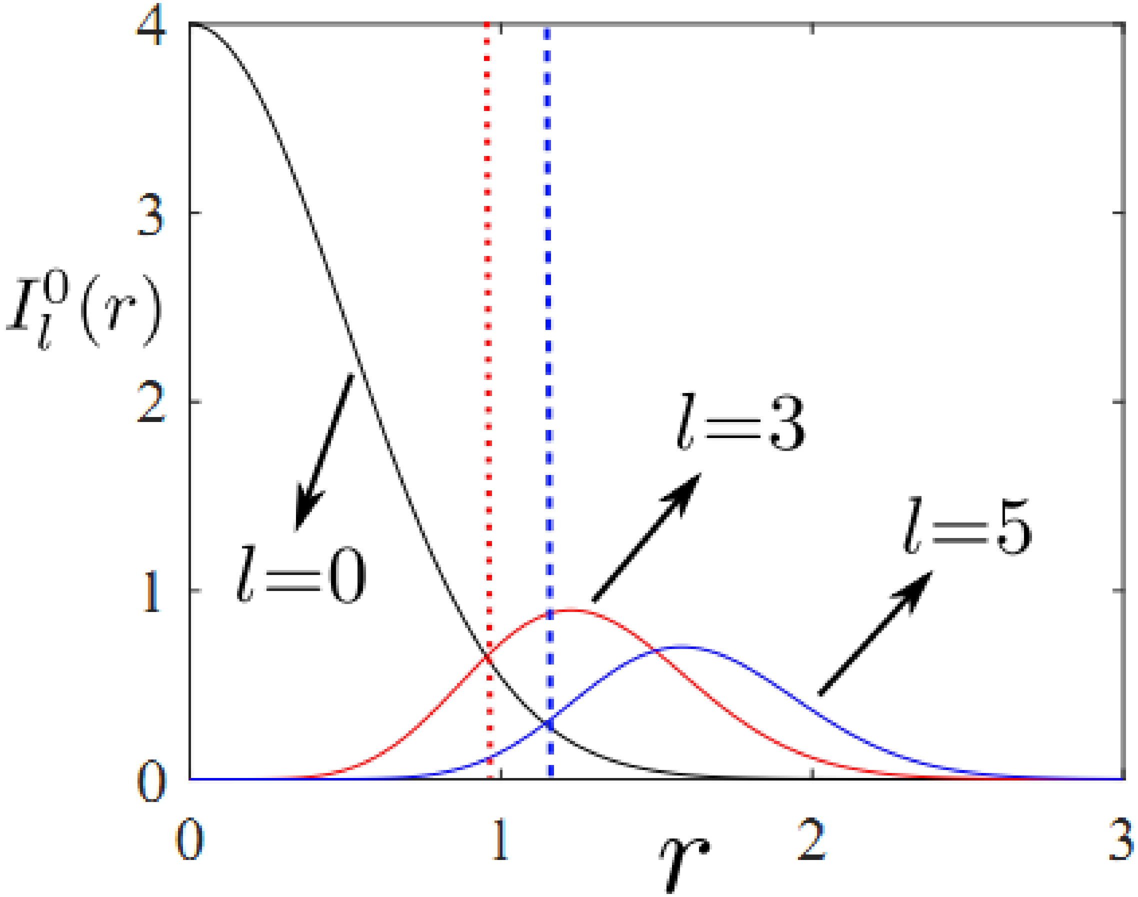
***l* :** azimuthal mode index

***p*:** radial mode index



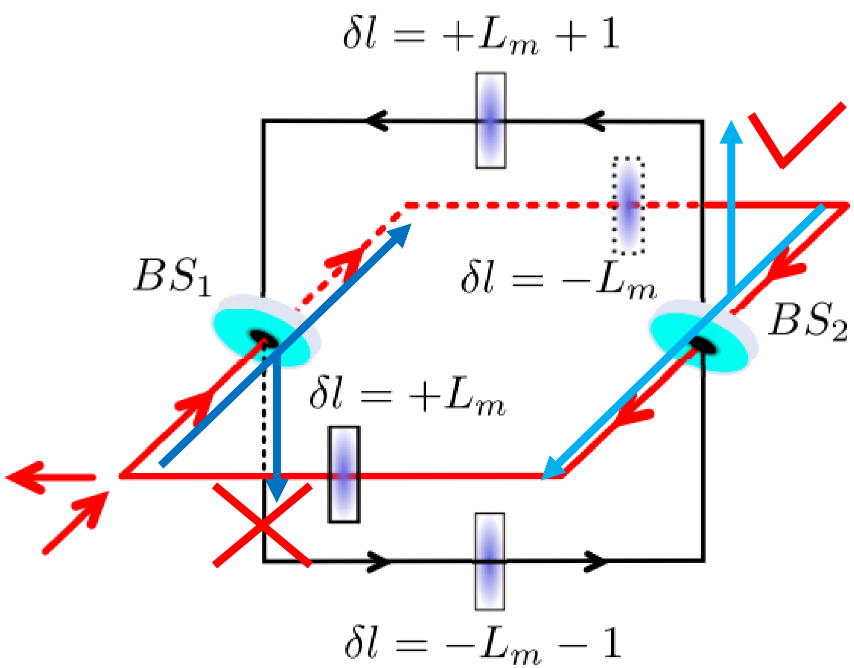


Intensity distribution of LG modes



$$\int dr\, r\, I_0^0 I_n^0 \sim e^{-n}$$

Boundary construction using composite mode

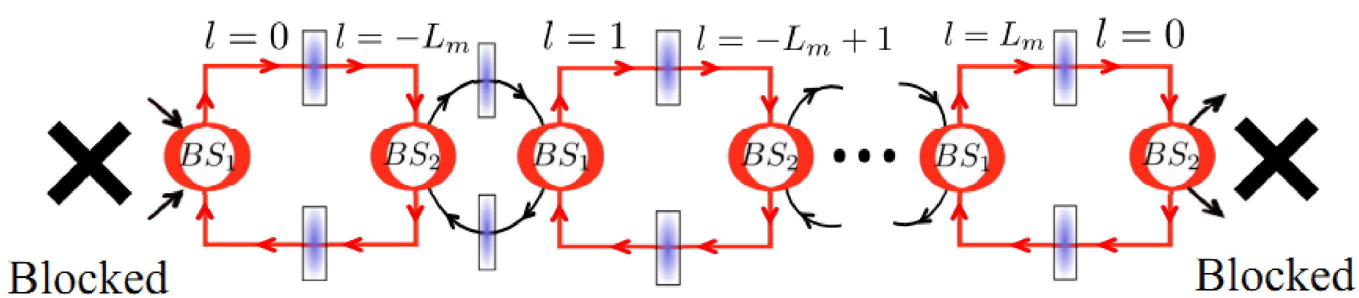


composite mode

$$[\,l, -L_m + l\,]$$

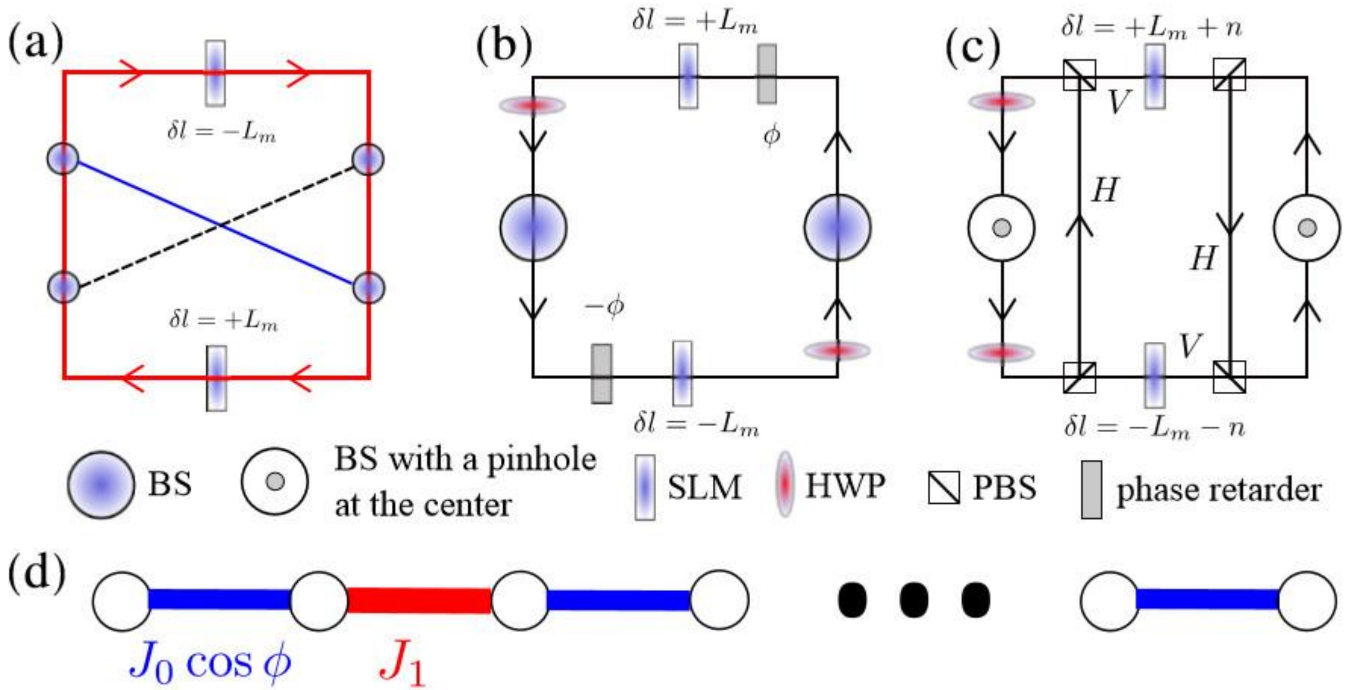
$$[0, -L_m] \rightarrow [1, -L_m + 1]$$

$$[0, -L_m] \cancel{\leftrightarrow} [-1, -L_m - 1]$$



Sharp boundary!

Example: SSH model inside single cavity



$$a_{2l} \to E^p_{l,H} \text{ and } a_{2l+1} \to E^p_{l,V}$$

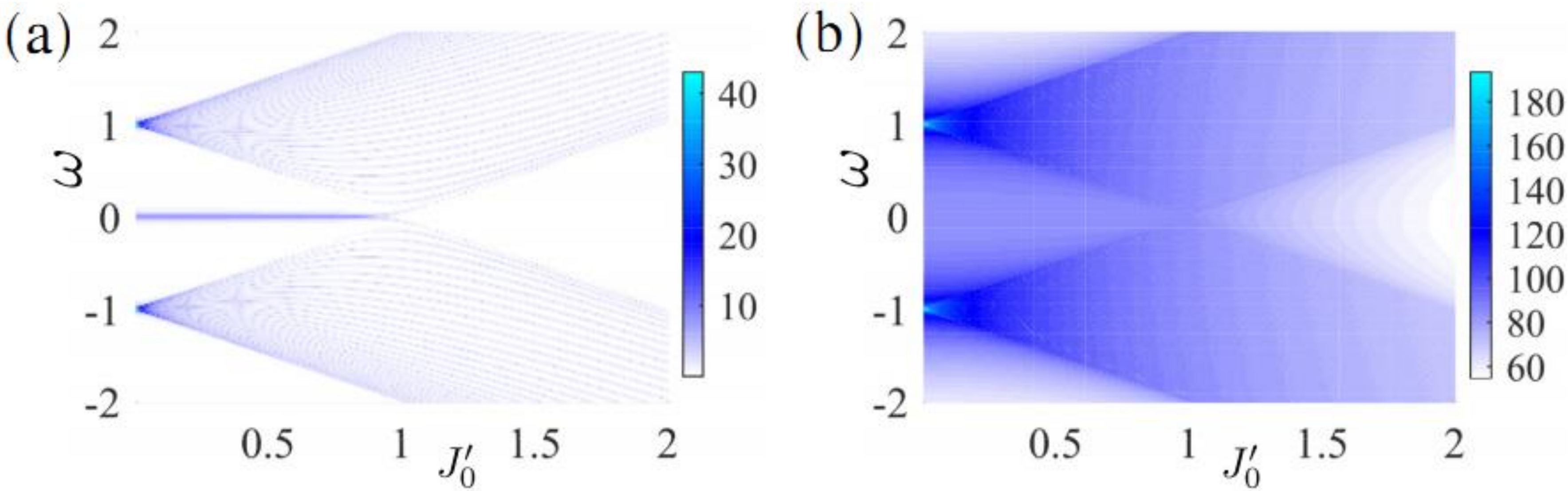
$$H = \sum_{l=0}^{L_m} \left[J_0 \cos(\phi) a^\dagger_{2l} a_{2l+1} + J_1 a^\dagger_{2l+1} a_{2l+2} + h.c.\right], (2)$$

$J_0' \equiv J_0 \cos\phi$ $\quad N = \int \frac{dk}{2\pi} \frac{d\phi_k}{dk} = 1$ only when $J_0' < J_1$

Example: SSH model inside single cavity

$$\partial_t a_j = -i[a_j, H(t)] - \frac{\gamma_j}{2} a_j - \sqrt{\gamma_j} a_{in,j}$$

$$\tau(\omega) = \sum_{j,j'} |T_{jj'}|^2 \qquad T_{jj'} = -i\langle j|[\omega - H + i\gamma_j/2]^{-1}|j'\rangle.$$



$$J_1 = 1 \text{ and } L_m = 59$$

$$\gamma_j = 0.05(e^{-j/\sqrt{30}} + e^{-|j-L_m|/\sqrt{30}})$$

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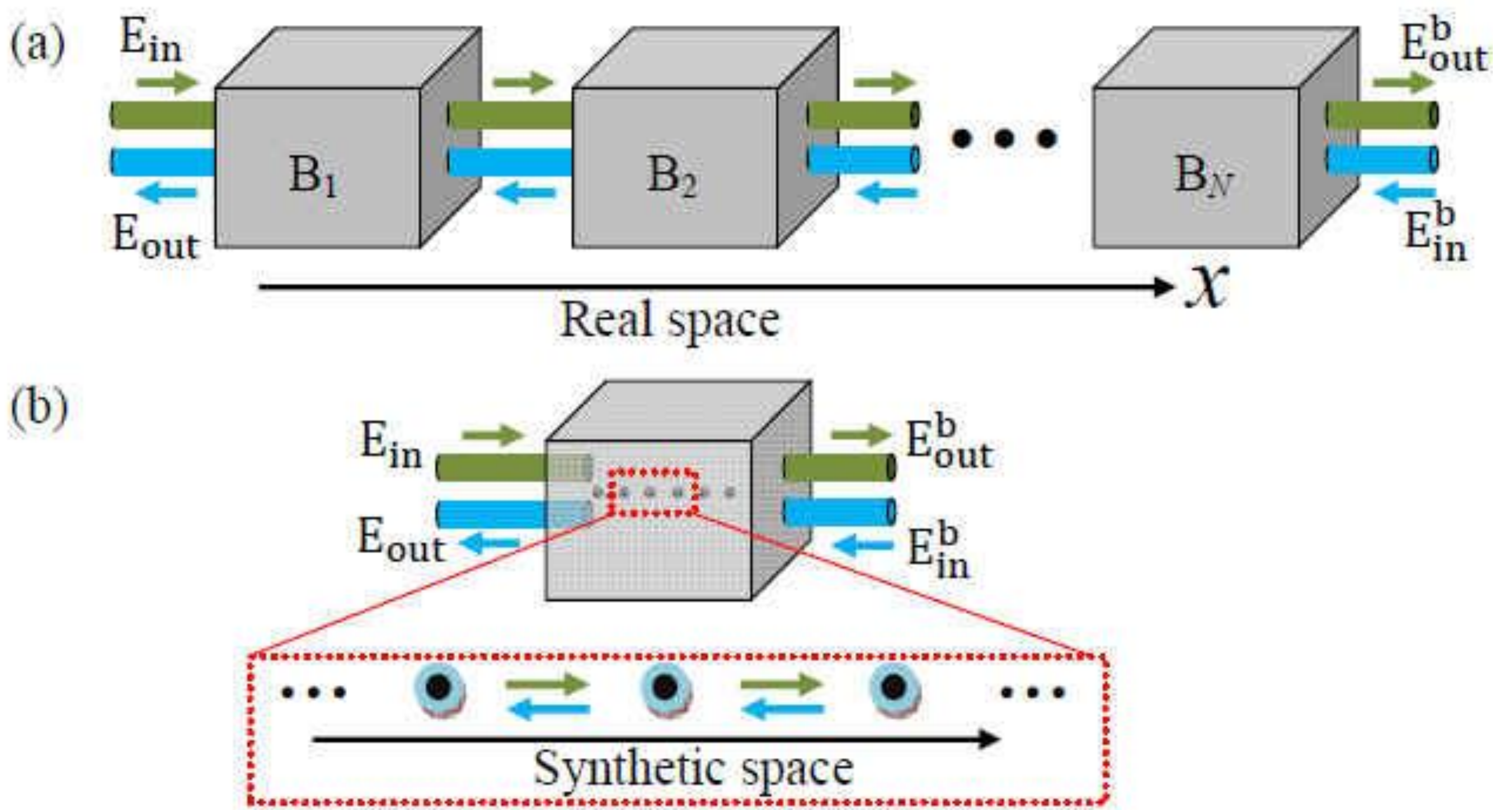
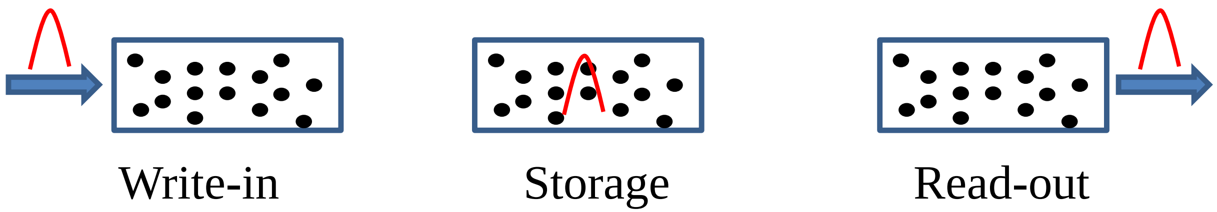


X. W. Luo, X. Zhou, J. S. Xu, C. F. Li, G. C. Guo, C. Zhang, Z. W. Zhou, Nat. Commun. 8, 16097 (2017).

Quantum memory

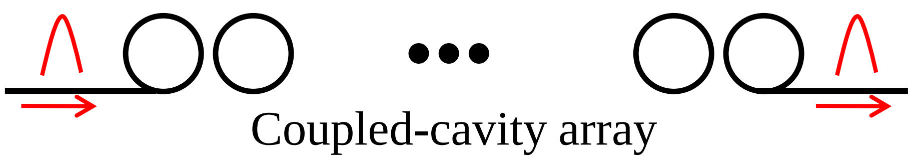
Atomic ensemble



Optical pulse → Collective atomic excitation

Shortcoming: photon ↔ Atomic ensemble

Optical waveguide

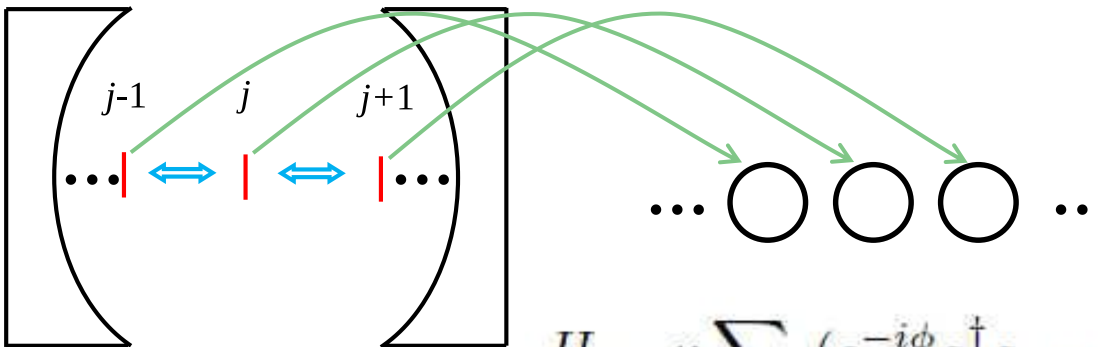


Refractive index modulation ↔ Controlled delay

Shortcoming: fabricating large numbers of identical optical cavities or homogeneously tuning the index of optical materials

Quantum memory

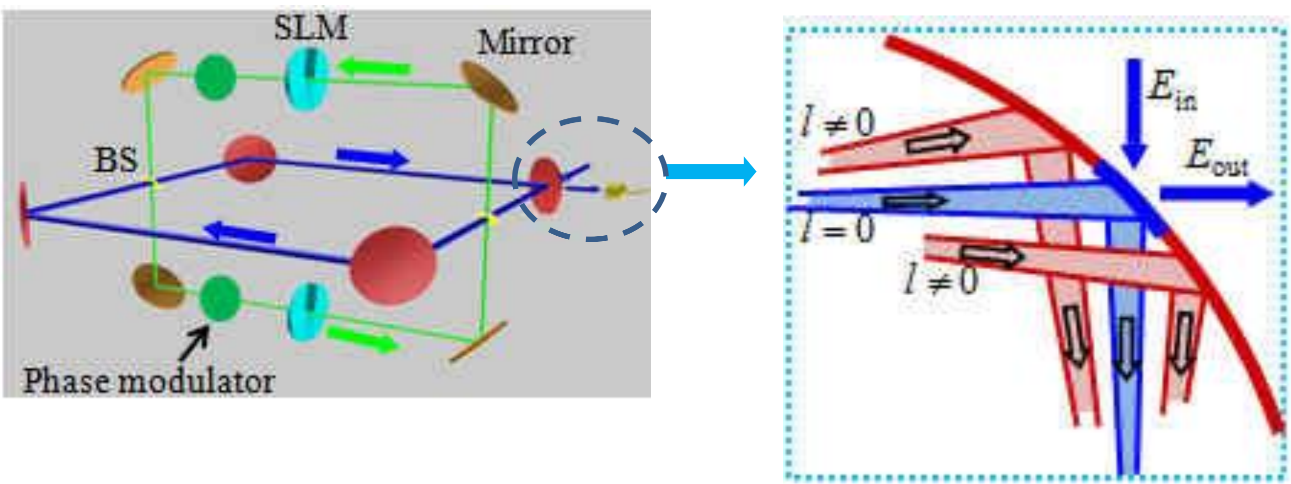
Degenerate cavity



Site index: *j*
Step index: *M*
OAM index: *l=j*M*

$$H = \kappa \sum_j (e^{-i\phi} a_j^\dagger a_{j+1} + h.c.) + \omega_0 \sum_j a_j^\dagger a_j$$

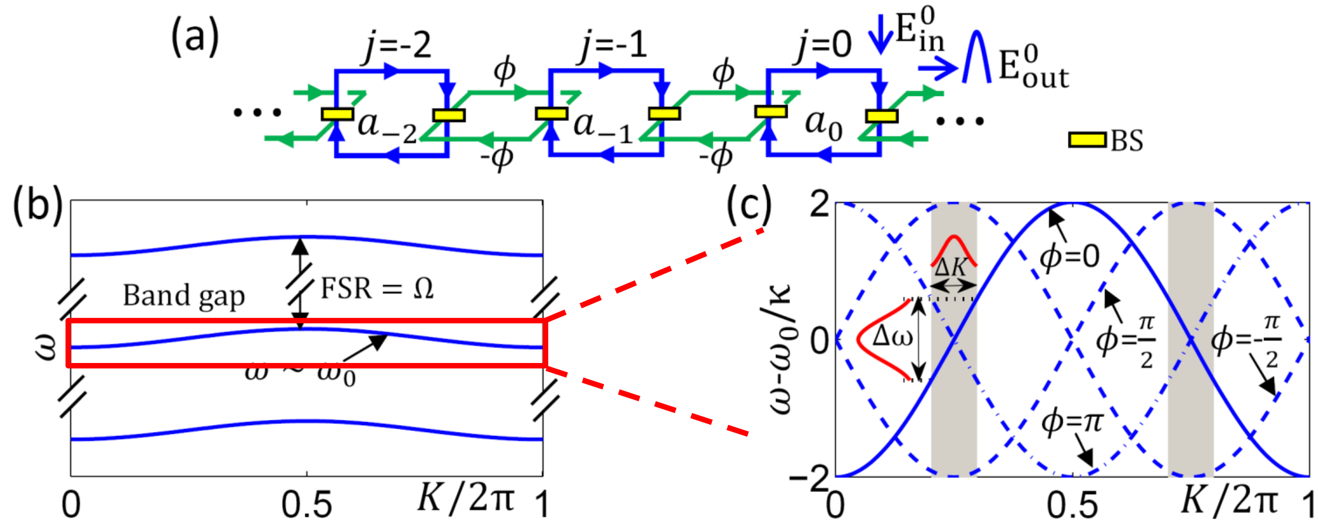
Optical design



Input/output:
Pinhole couples
l = 0 mode in/out

X. W. Luo, X. Zhou, J. S. Xu, C. F. Li, G. C. Guo, C. Zhang, Z. W. Zhou, Nat. Commun. 8:16097 (2017)

Effective circuit & band structure



Phase imbalance ϕ , Electro-optical modulator

Spectrum engineering → propagation control

$$\omega = \omega_0 - 2\kappa\cos(K-\phi)$$

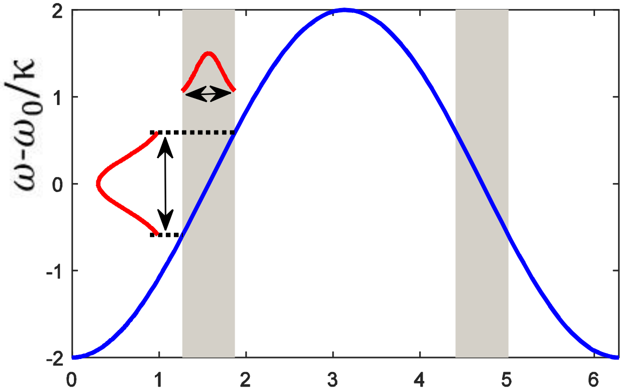
$$v_g = 2\kappa\sin(K-\phi)$$

Phase modulation speed:
Slow compared with gap

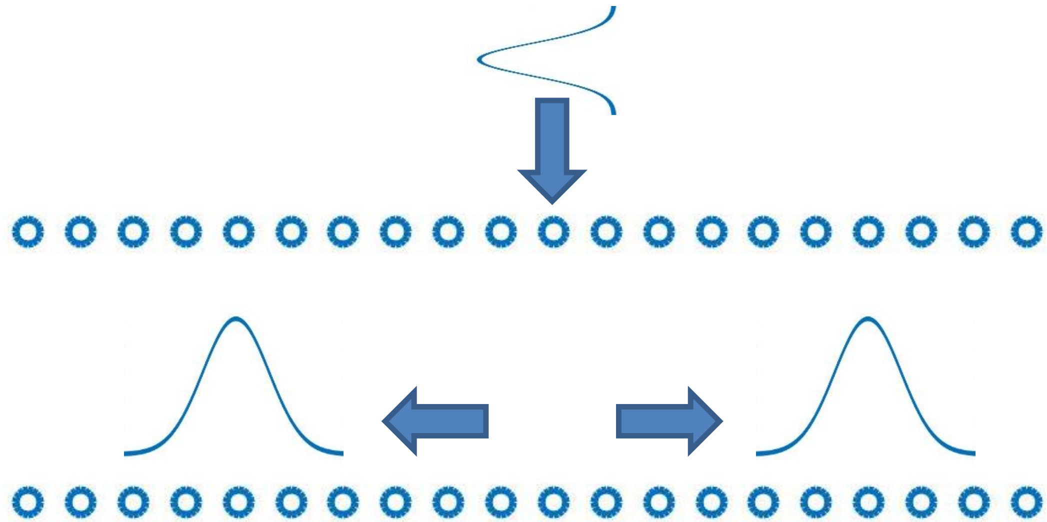
Typically, the bandwidth is about 100MHz

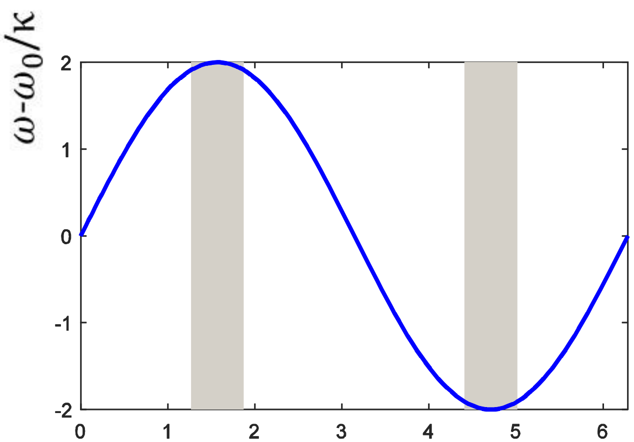
Quantum memory

$$v_g = 2\kappa \sin(K - \phi)$$

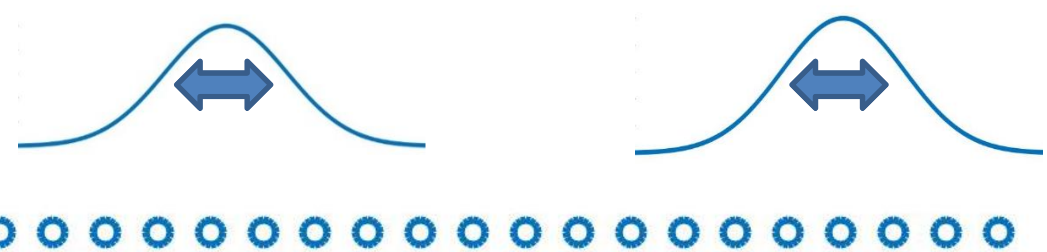


$\phi = 0$





$\phi = \pi/2$



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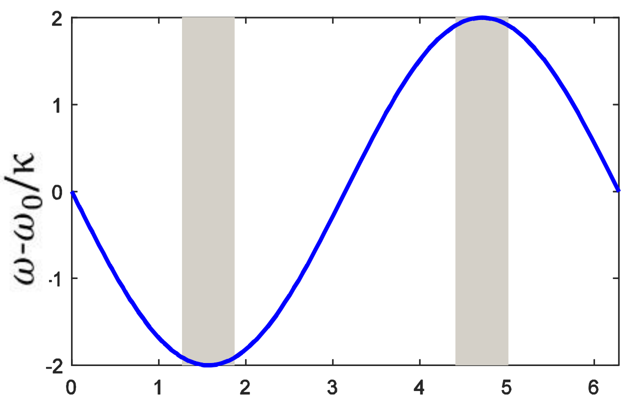
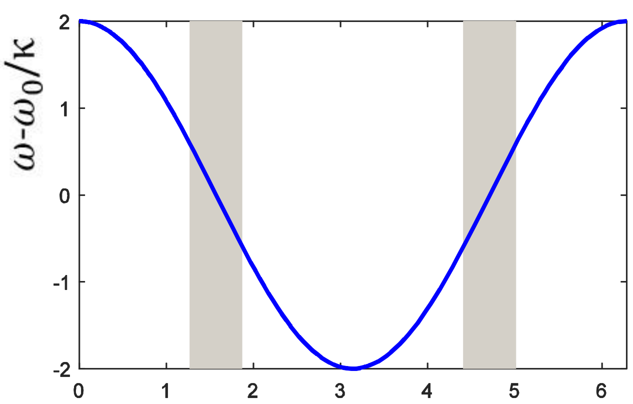
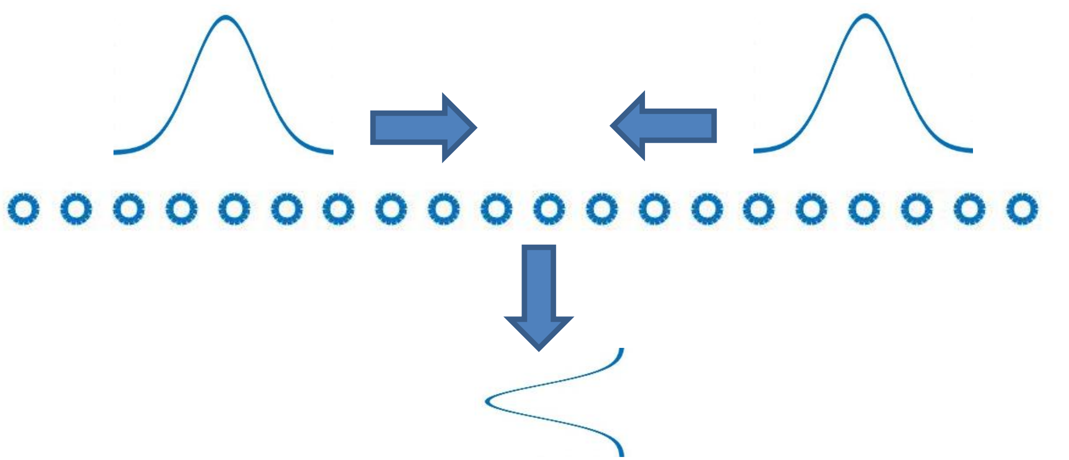
Quantum memory



$$\phi = -\pi/2$$



$$\phi = -\pi$$

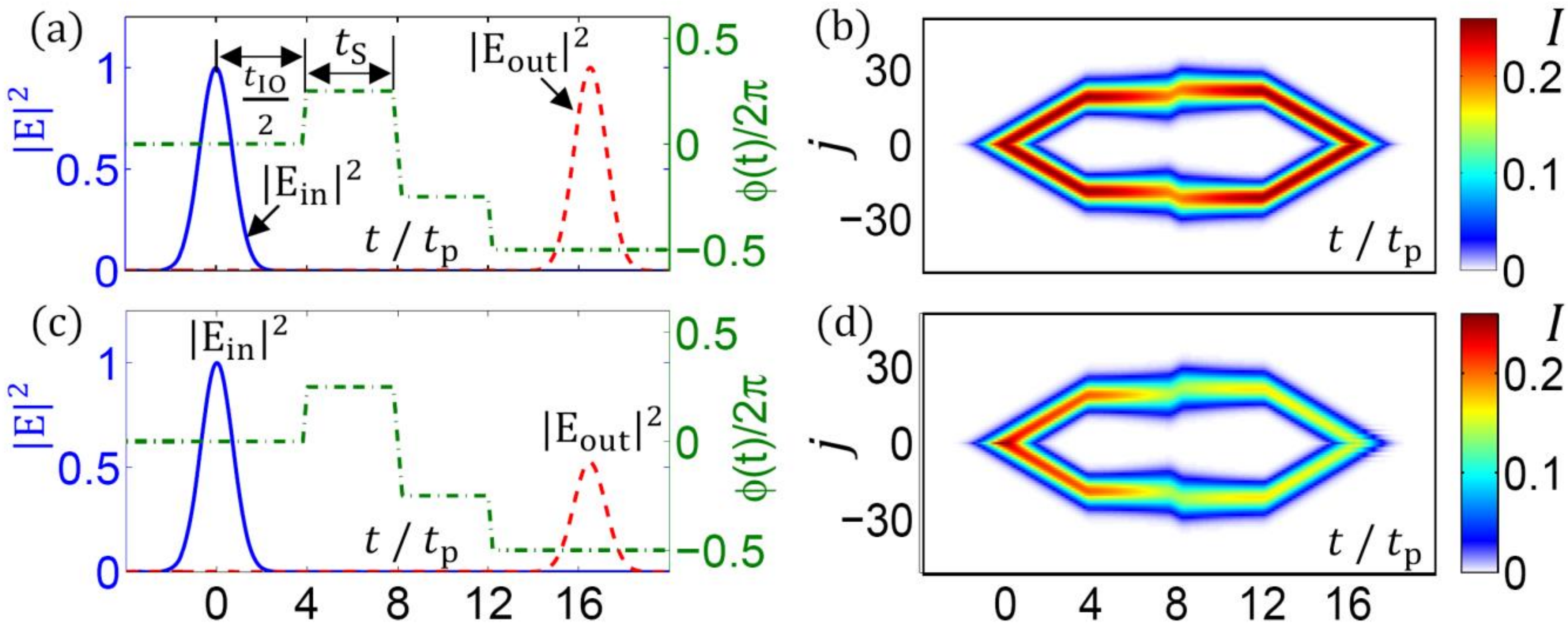


Storage time : $t_{\mathrm{IO}} + 2t_{\mathrm{S}}$

Quantum memory

Pulse propagation:

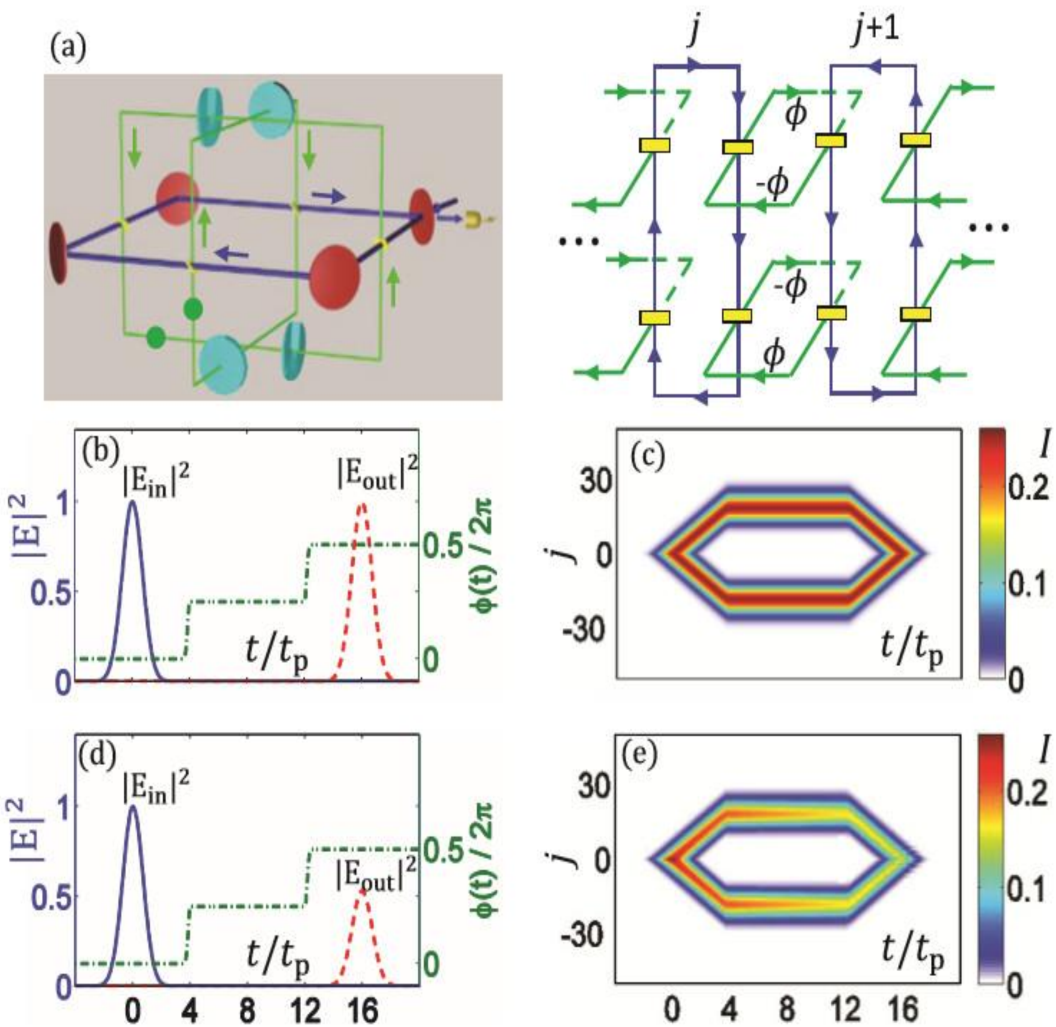
$$E_{\rm in}^0 = \exp\left(-\frac{t^2}{2t_{\rm p}^2} - i\omega_0 t\right)$$



Storage time : $t_{\rm IO} + 2t_{\rm S}$

Not on-demand

On-demand Quantum Memory



Interference between 2 auxiliary cavities

$$\omega = \omega_0 - 2\kappa \cos\phi \cos K$$

$$v_g = 2\kappa \cos\phi \sin K$$

Bandwidth reversibly compressed

No distortion during storage

summary

- About Synthetic Dimension based on Degenerate Cavity
- Simulating Photonics Topological Matter
- Quantum Memory
- New Applications…

In collaboration with

Univ. of Sci. & Tech. of China

X. -W. Luo (罗希望)   X.-F. Zhou (周祥发)
Su Wang (王 塑)   X.-X. Zhou (周幸祥)
C. -F. Li (李传锋)   J. -S. Xu (许金时)
G.-C. Guo (郭光灿)

Rice Univ.

Han Pu (浦晗)

UT Dallas

Chuanwei Zhang (张传伟)

Thanks for your attention !