Synthetic Dimension Photonic Frequency Lattices in Modulated Thin-film Lithium Niobate Micro-Resonators

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Outline

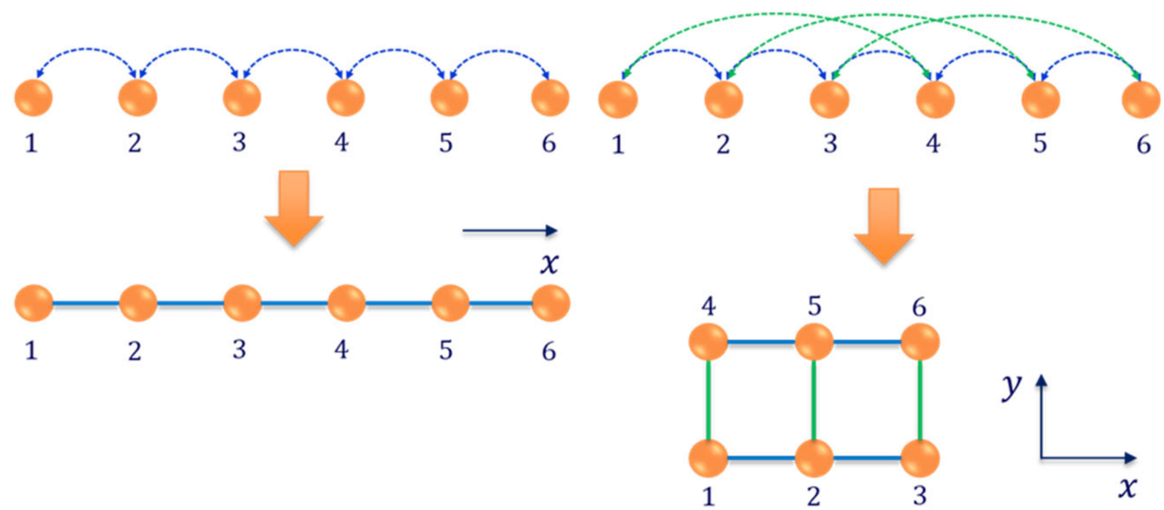
- Introduction to synthetic dimensions
  - Definition and purpose
  - Photonic synthetic dimensions
- Lithium Niobate on Insulator (LNOI) frequency dimension devices:
  - Reconfigurable lattice models
  - SSH model
  - Lattices with boundaries
- Summary

Synthetic dimensions

Simulation of a spatial dimension using non-spatial internal degrees of freedom
- to allow exploring high-dimensional physics in lower-dimensional physical systems

Requirements:

- Set of states to represent the lattice sites along a synthetic dimension
- Coupling mechanism between states



T. Ozawa & H. M. Price, *Nat. Rev. Phys.* **1**, 349 (2019)
L. Yuan et al., “Synthetic dimension in photonics,” Optica 5, 2018
A. Dutt et al, *Nat. Commun.* **10**, 3122, 2019

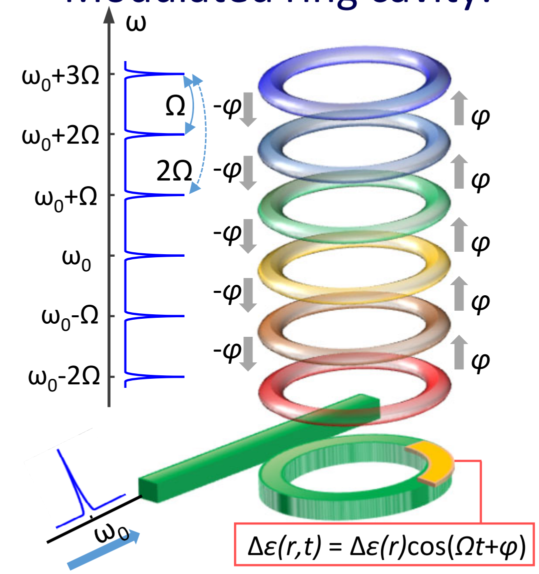
Synthetic dimensions in photonics

Three types of non-spatial degrees of freedom:

- Parametric – adiabatically changing a Hamiltonian
- Mode ladder – frequency, polarization, OAM, …
- Time-bins – pulses along a temporal coordinate

Combinations of different synthetic dimensions are possible.

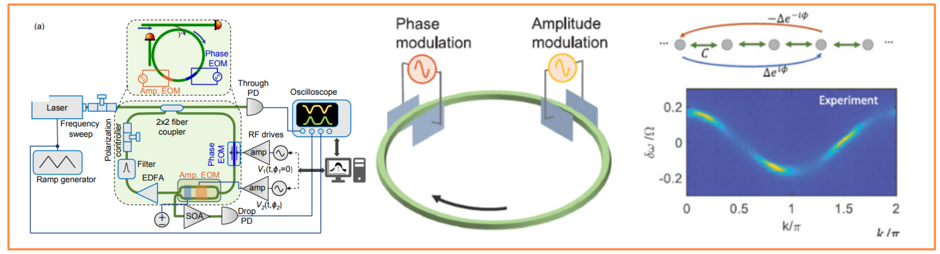
Modulated ring cavity:



Key synthetic frequency dimension results

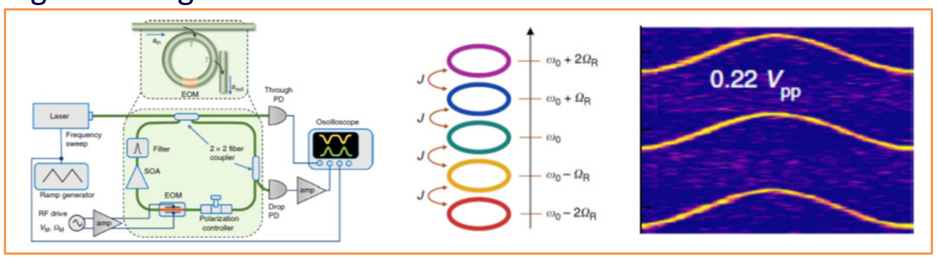
Fiber loop setups have been the primary test-bed on which many first photonic demonstrations of lattice and topological models were achieved

Non-Hermitian bands



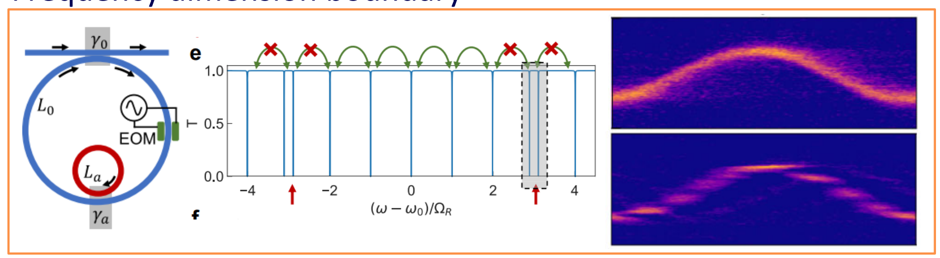
K. Wang et al, *Science* **371**, 1240, 2021

Tight-binding model lattice



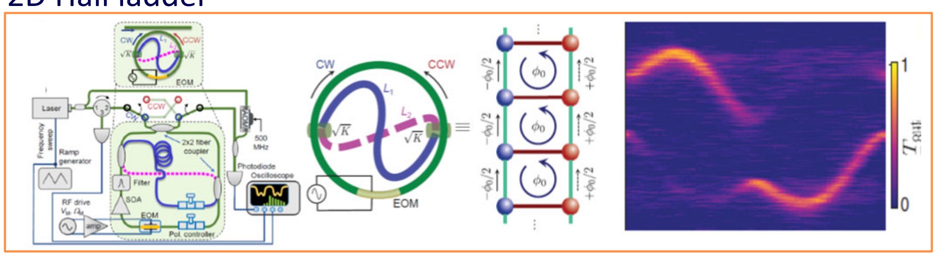
A. Dutt et al, *Nat. Commun.* **10**, 3122, 2019

Frequency dimension boundary



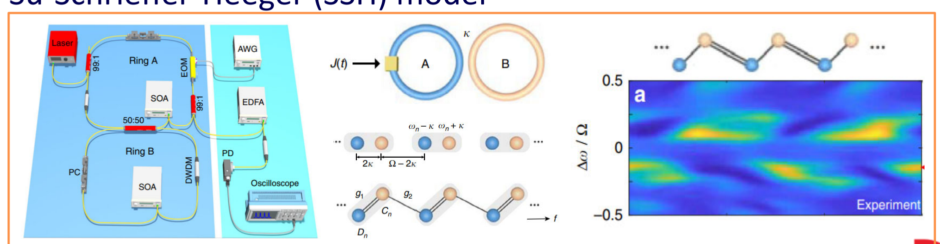
A. Dutt et al, *Nat. Commun.* **13**, 3377, 2022

2D Hall ladder



A. Dutt et al, *Science* ***367***, 59, 2020

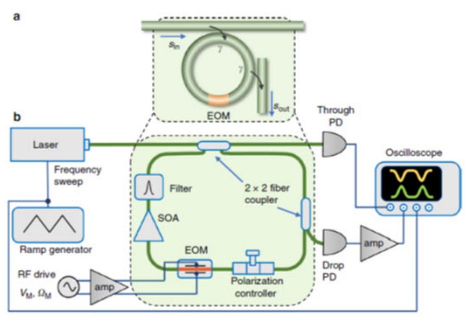
Su-Schrieffer-Heeger (SSH) model



G. Li et al, *Light: Sci. Appl.* **12**, 81, 2023

Synthetic dimension in LNOI

Fibre loop rings:

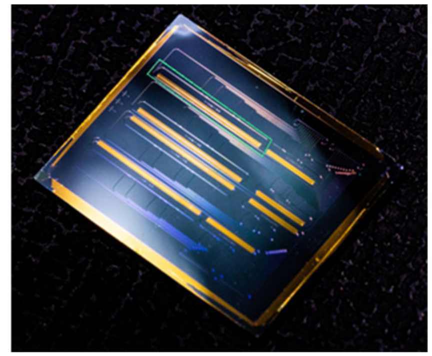


A. Dutt et al, *Nat. Commun.* **10**, 3122, 2019

- Rapid off-the-shelf assembly
- Mix and match best performance components
- Table-top device size
- Megahertz-scale process rates
- Long optical path susceptible to perturbations
- Limitations on device scalability

Our work:

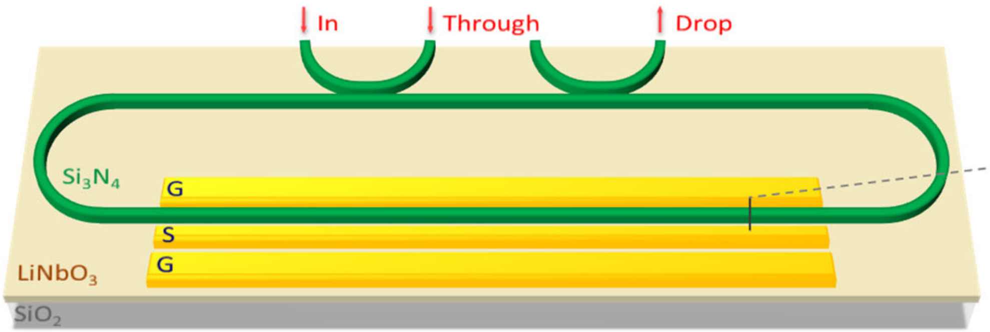
Integrated Lithium Niobate-on-Insulator (LNOI) platform

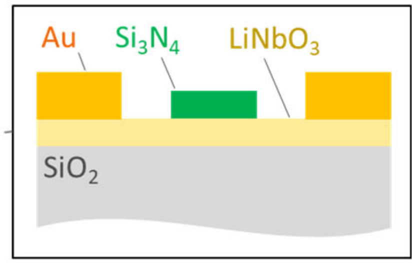


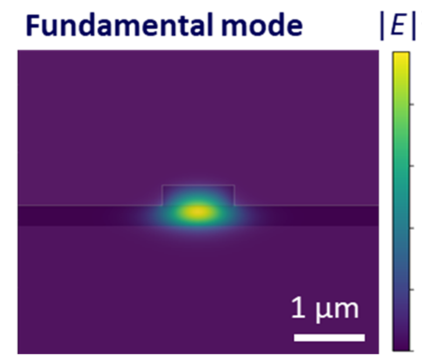
- Strong optical guiding with low loss – Compact devices
- Strong electro-optic effect – Effective mode coupling for synthetic dimension using RF modulation
- High power handling capability – Further enhance mode coupling
- High $\chi^{(2)}$ coefficient – explore **all new phenomena** in nonlinear systems

Modulated LNOI ring cavity

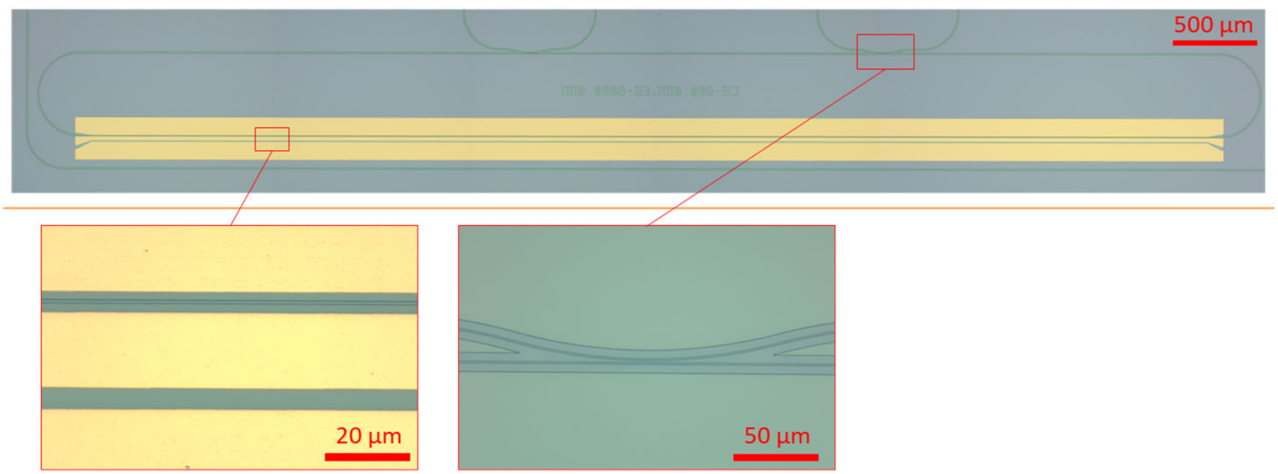
Silicon-Nitrite loaded LNOI waveguide platform with a high-speed RF modulator



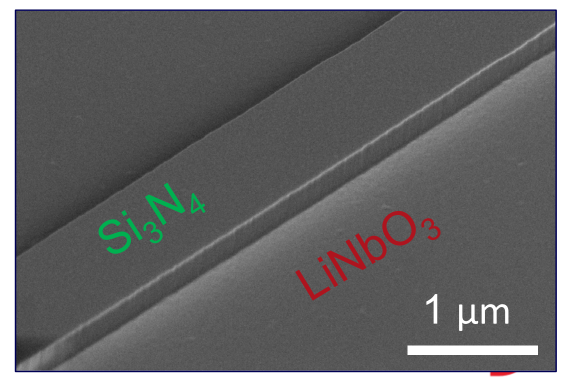




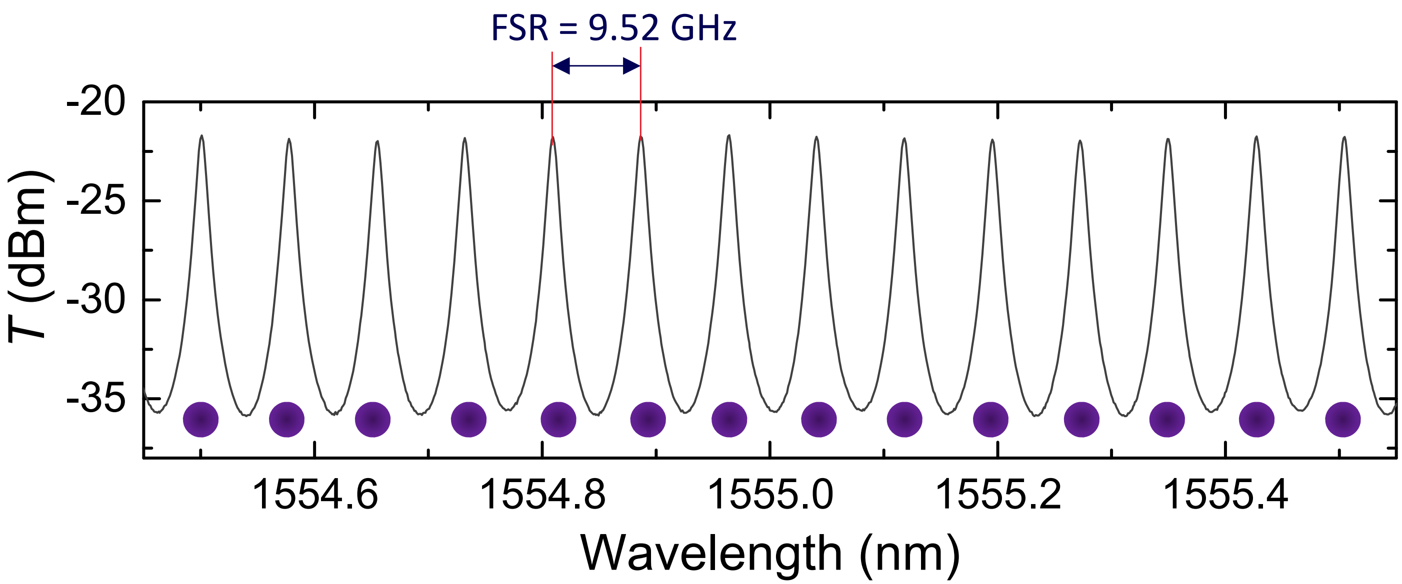
Waveguides are EBL fabricated, and gold travelling wave electrodes are patterned by laser lithography



SEM image



LNOI synthetic frequency dimension device

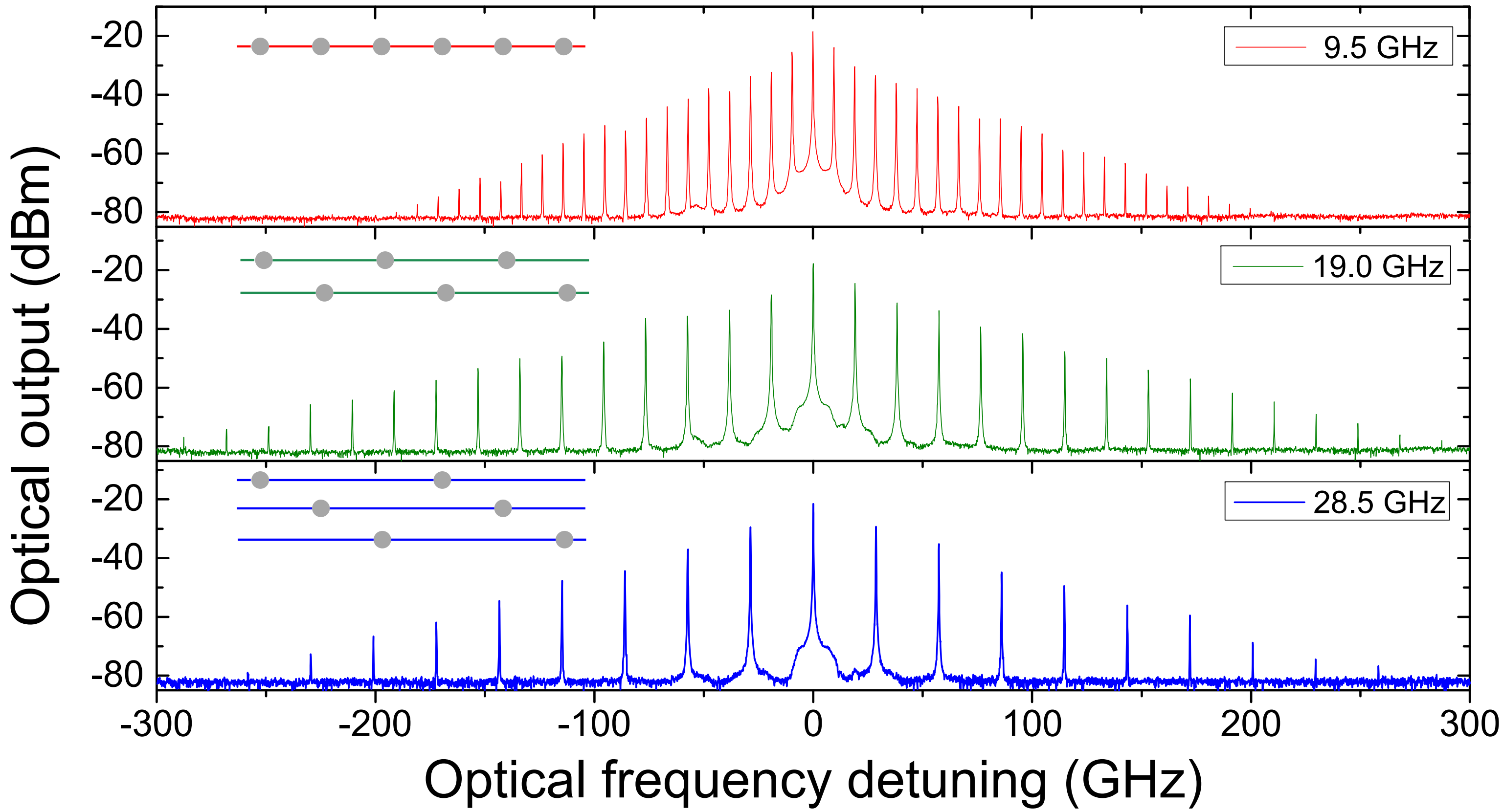


Measured drop-port transmission:

- Equal spacing resonant modes
- Each resonant mode represent one lattice site

Steady state modulation response

Pump the ring with a CW laser at one resonance and modulate at frequencies Ω_{FSR}, $2\Omega_{FSR}$, and $3\Omega_{FSR}$ at a moderate 20 dBm RF power



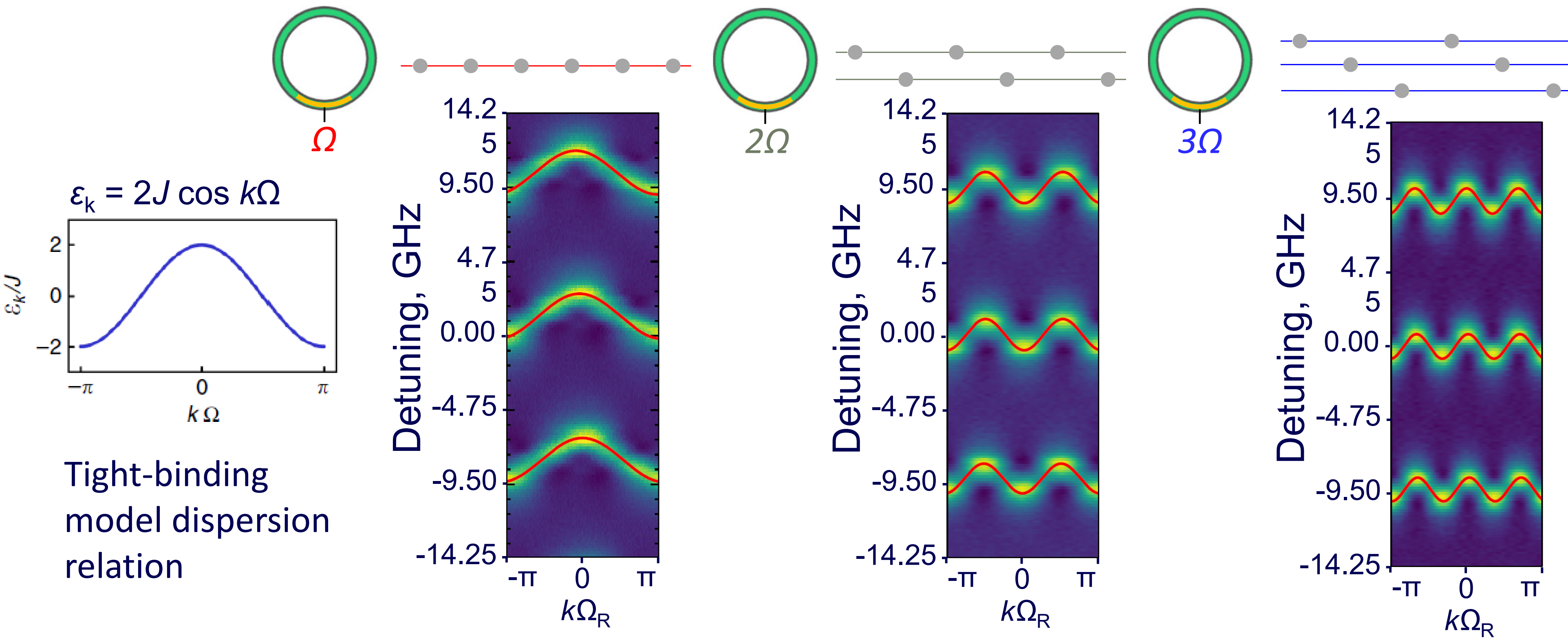
40 lattice sites

30 lattice sites

18 lattice sites

Synthetic band structures

V|qwkhwlf#VVK#edqg#vwuxfwxuh#vshfwurvfrs|#z dv#p hdvxuhg#e|#ghwhfwlqj#wlp h0uhvroyhg#wudqvp lwwdqfh#ri#wkh#ulqj#v|vwhp #gxulqj#p rgxodwlrq

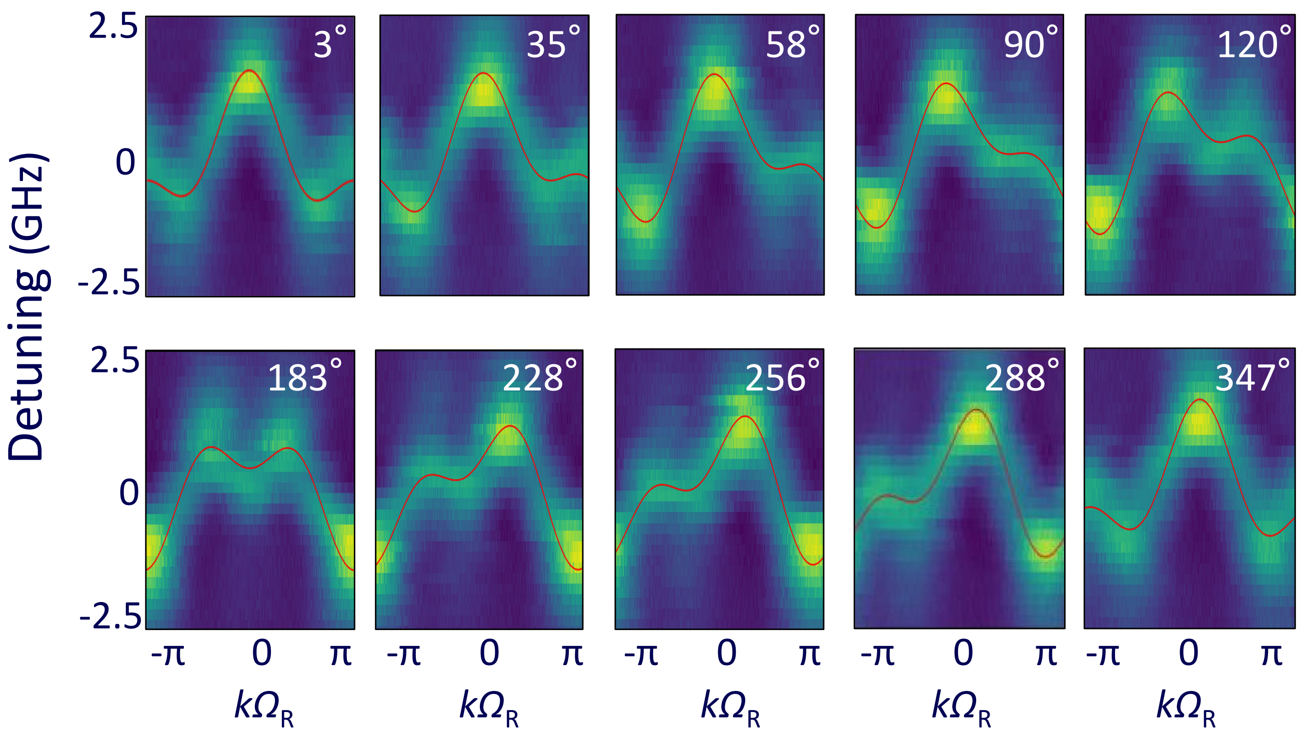


H. X. Dinh et al, *Commun Phys* **7**, 185 (2024)

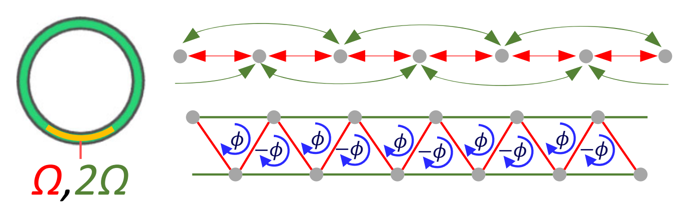
Additional RF modulation

Increasing lattice interconnectivity

Simultaneous on-resonance FSR modulation at frequencies Ω_{FSR} and $2\Omega_{FSR}$ both at 16 dBm RF powers



$\varepsilon_k = 2J_1\cos k\Omega_R + 2J_2\cos(k2\Omega_R + \phi)$



$J_1 = 0.51$ GHz $J_2 = 0.28$ GHz

Equivalent lattice representation by a triangular chain threaded by a phase ϕ per plaquette

- Exhibit an effective gauge potential

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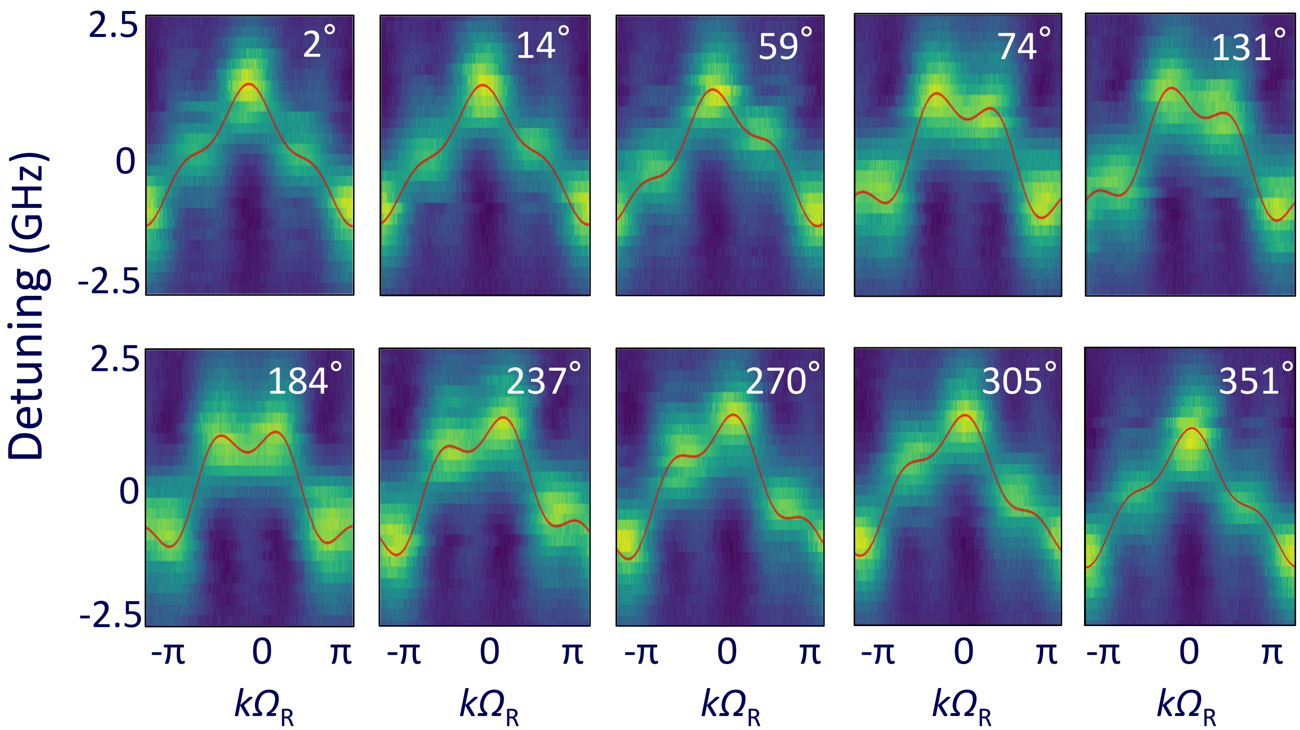
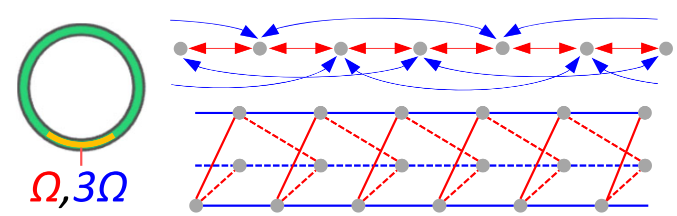
Additional RF modulation:
Increasing lattice interconnectivity

Simultaneous on-resonance FSR modulation at frequencies Ω_{FSR} and $3\Omega_{FSR}$ both at 16 dBm RF powers



$\varepsilon_k = 2J_1 \cos k\Omega_R + 2J_3 \cos(k3\Omega_R + \phi)$



J_1 = 0.49 GHz J_3 = 0.14 GHz

Longer range coupling can form a rudimentary chiral tube-like lattice structure

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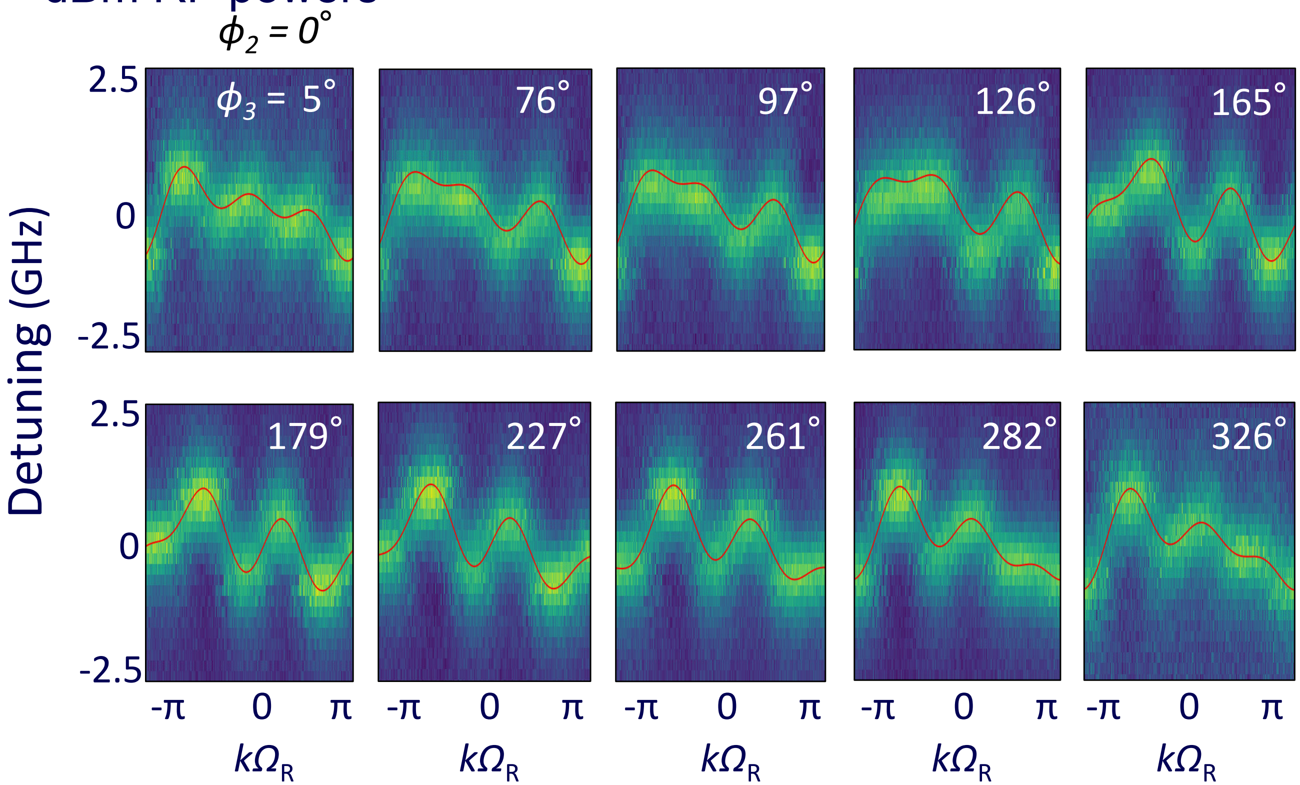
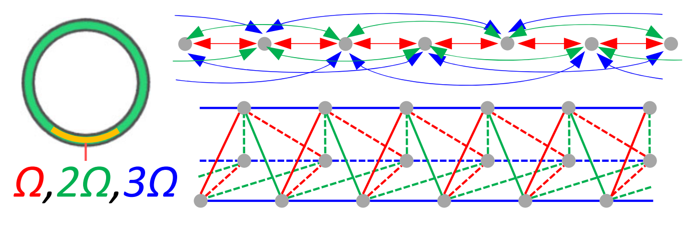
Additional RF modulation:

Increasing lattice interconnectivity

Simultaneous on-resonance FSR modulation at frequencies Ω_{FSR}, $2\Omega_{FSR}$ and $3\Omega_{FSR}$ all at 12 dBm RF powers



$\varepsilon_k = 2J_1\cos k\Omega_R + 2J_2\cos(k2\Omega_R + \phi_2) + 2J_3\cos(k3\Omega_R + \phi_3)$



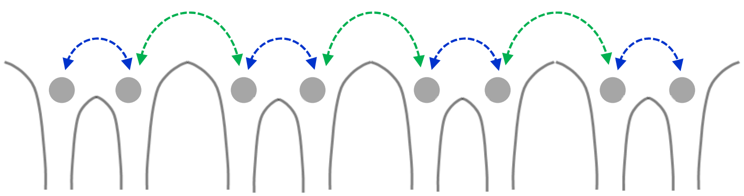
$J_1 = 0.24$ GHz $J_2 = 0.20$ GHz

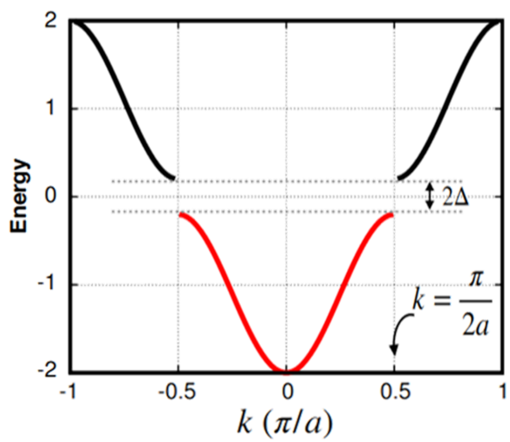
$J_3 = 0.17$ GHz

Additional RF signals increase lattice interconnectivity

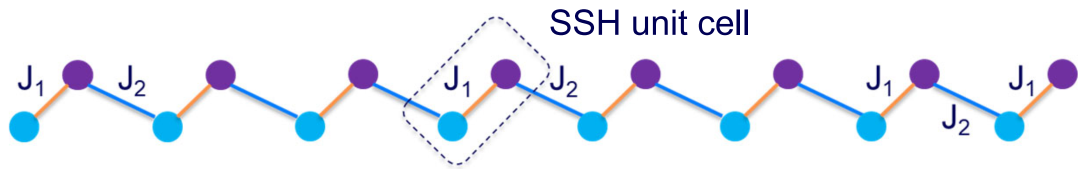
The Su-Schrieffer-Heeger (SSH) model

Su-Schrieffer-Heeger (1D):





Two bands



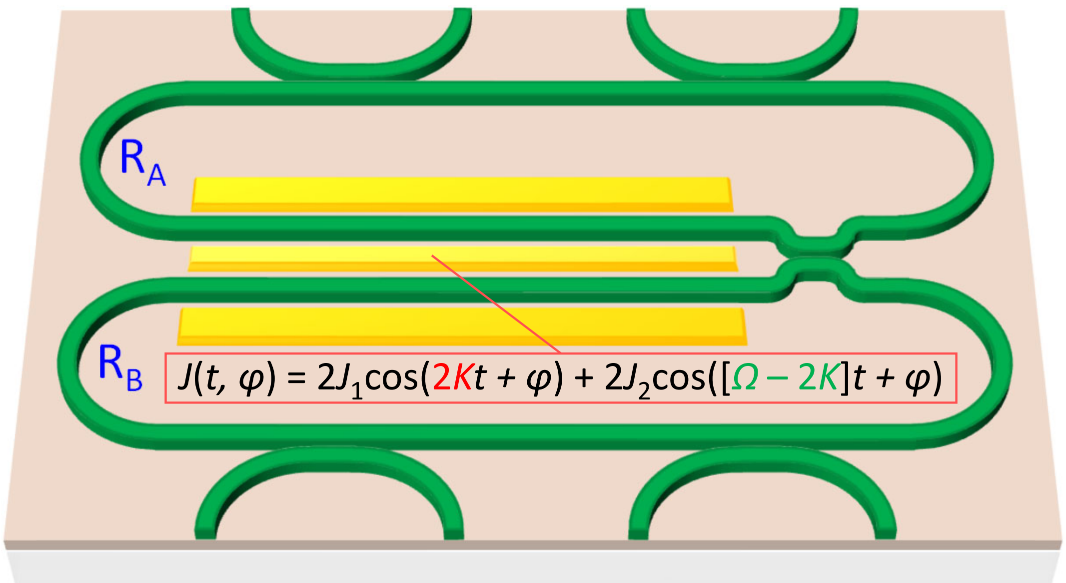
- Simplest model exhibiting non-trivial topological phase
- SSH topology: $J_1 \neq J_2$
  - Trivial case
  - Non-trivial case

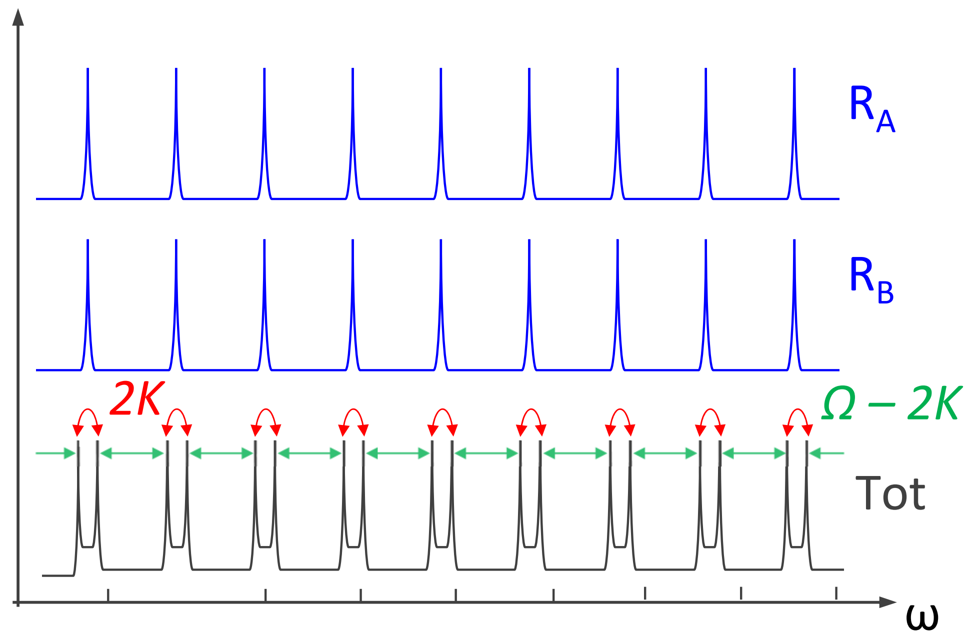
$$H = \boxed{\sum_k \varepsilon_k c_k^\dagger c_k} - \sum_k u_k c_{2k-1}^\dagger c_{2k} - v_k c_{2k}^\dagger c_{2k+1} + h.c.$$

Hamiltonian comprised of on-site potential and inter-site hopping terms

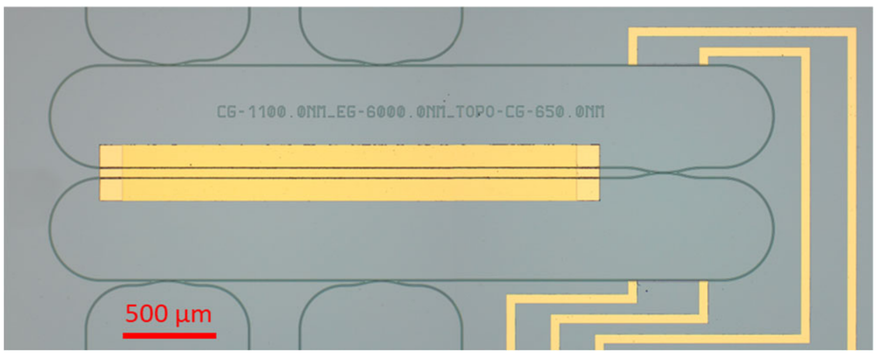
SSH model in coupled LNOI rings

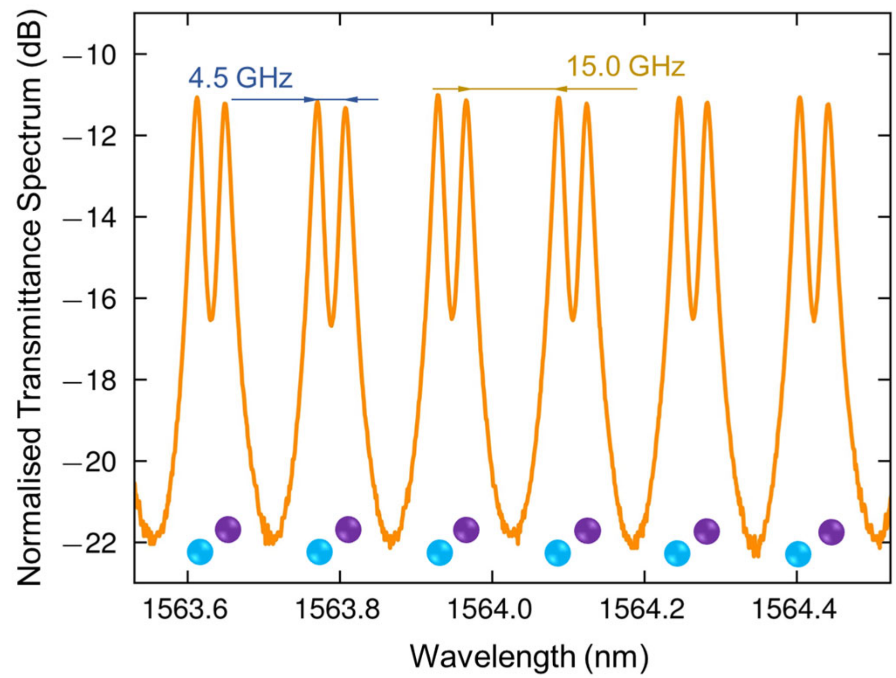
Mode hybridization of two equivalent strongly coupled rings creates a synthetic frequency dimension equivalent to the dimerized 1D Su-Schrieffer-Heeger (SSH) model





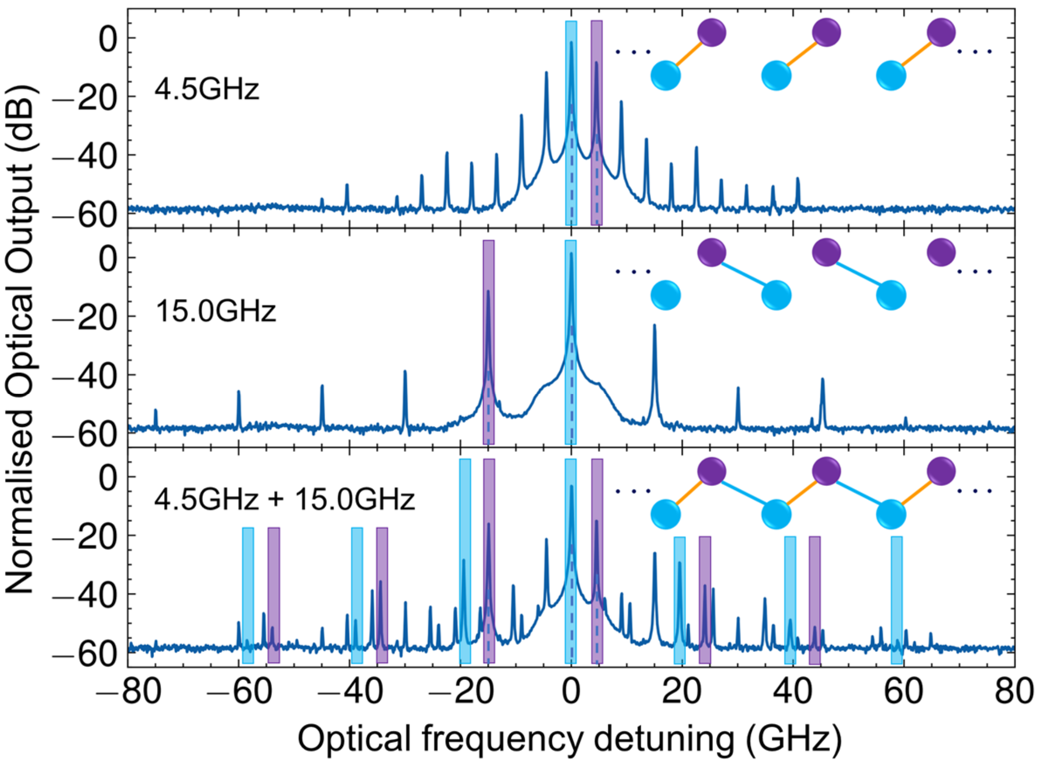
Fabricated LNOI SSH device

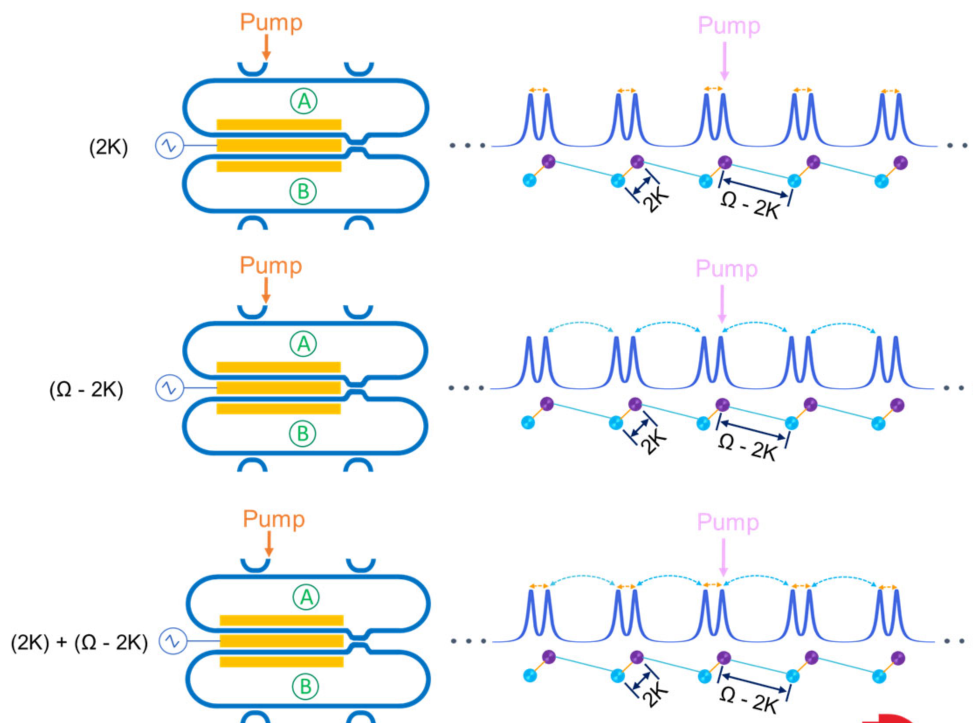




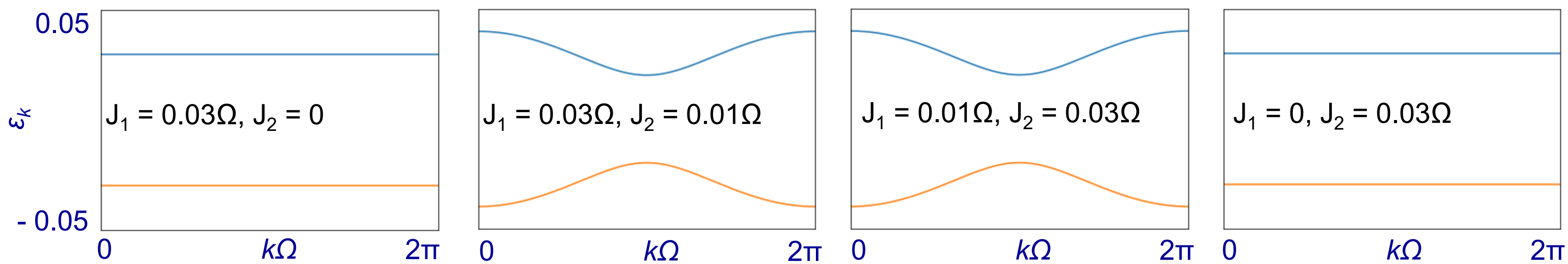
SSH device – State modulation response

On-resonance RF modulation at a moderate 20 dBm RF power.

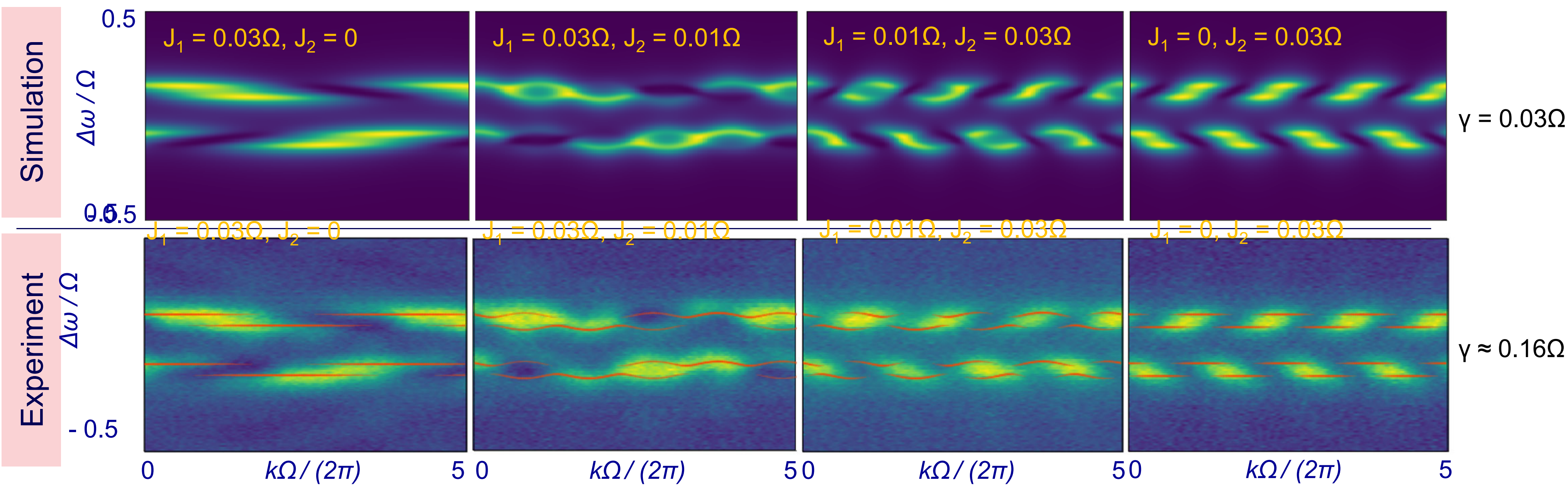




SSH band structure

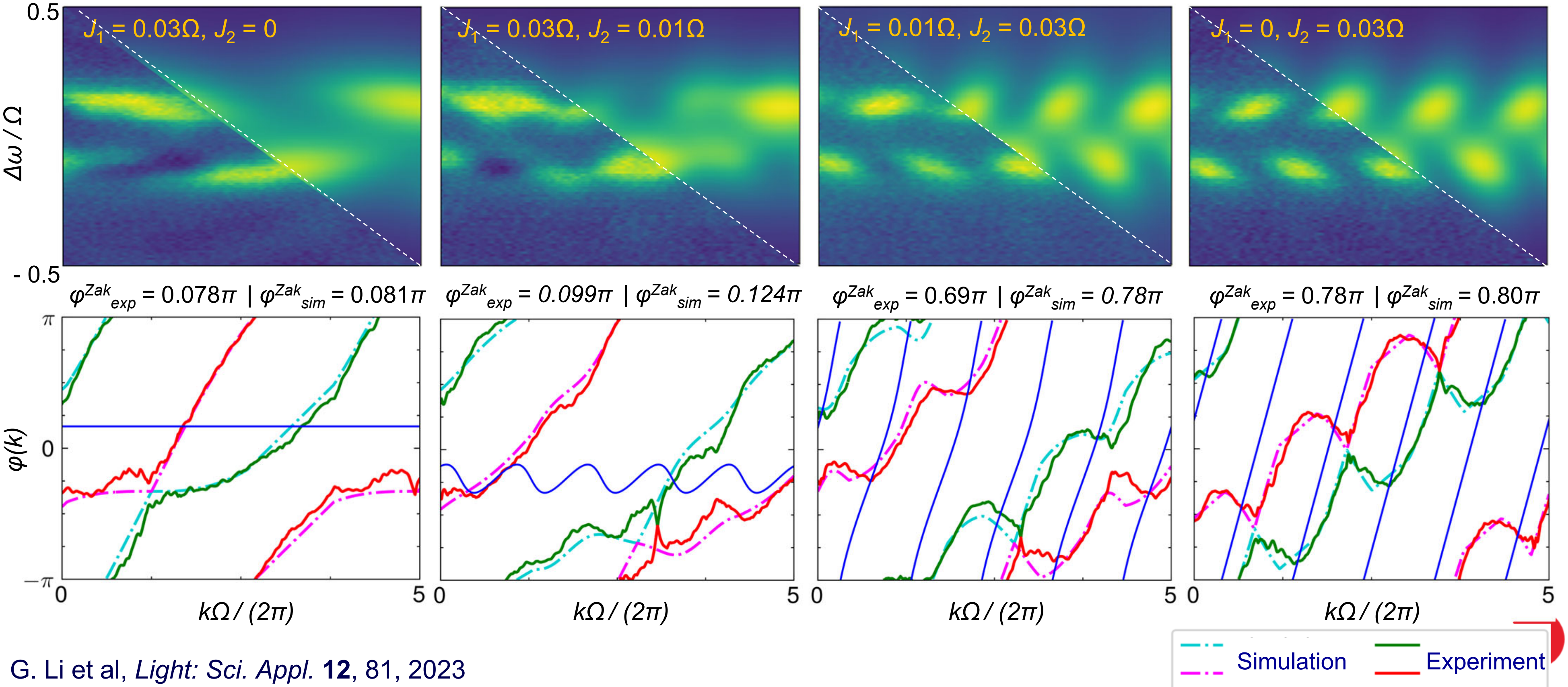


Intra-cell and inter-cell couplings are tuned by alteration of appropriate modulation amplitudes.



SSH Zak phase extraction

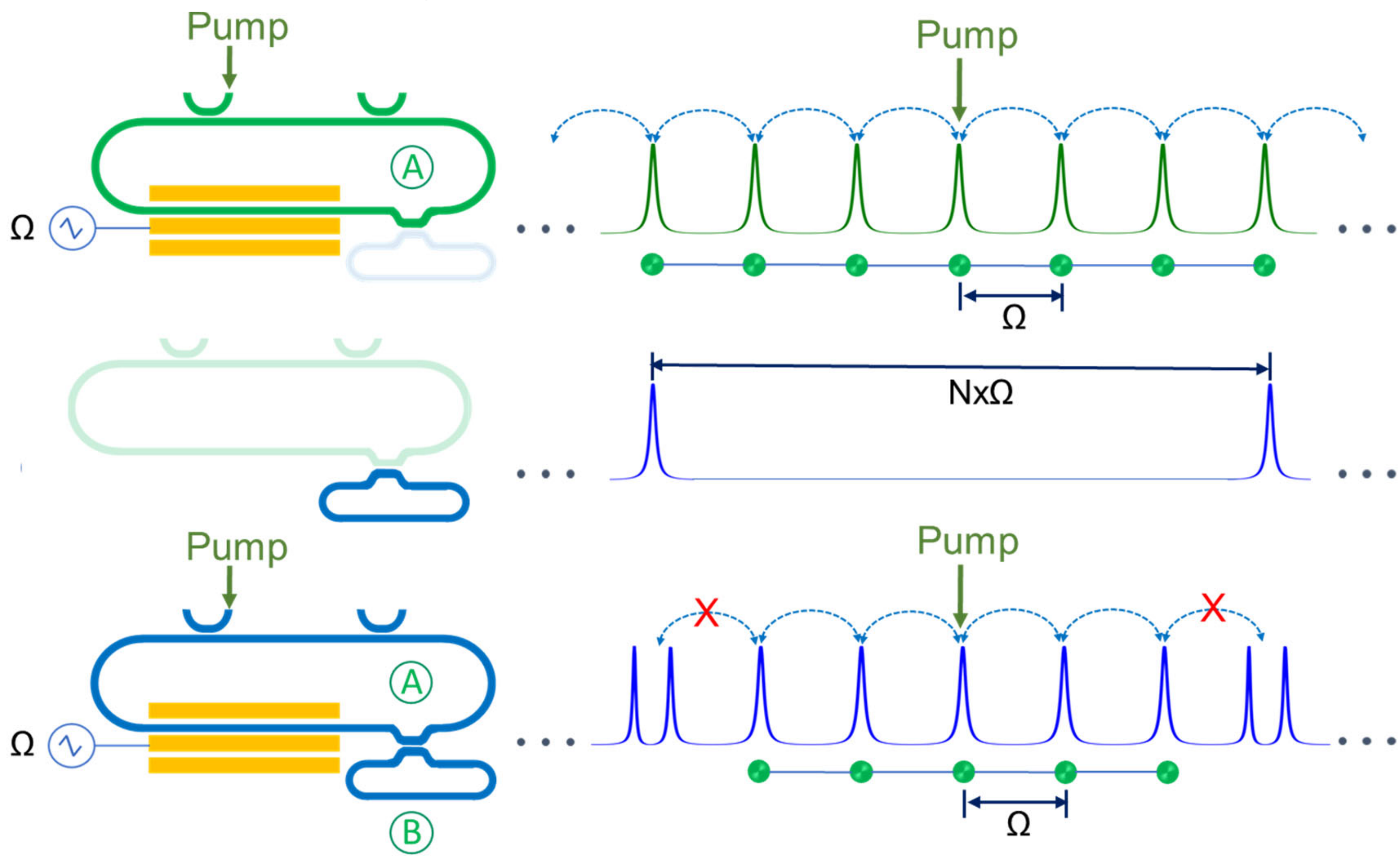
SSH topology is characterized by the Zak phase (0 or π)
- can be extracted from the bulk band structure



G. Li et al, *Light: Sci. Appl.* **12**, 81, 2023

Lattice with boundaries

Realisation of bulk-edge correspondence requires lattices with boundaries



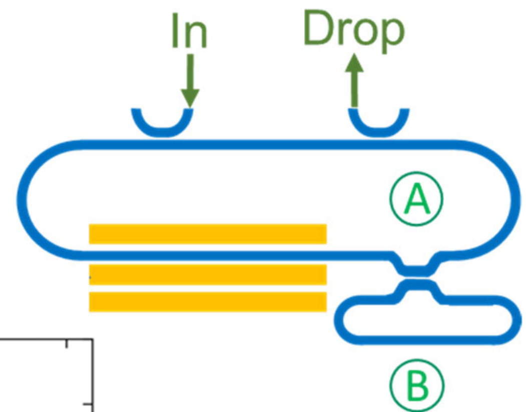
Single ring: free particle movement in a one-dimensional lattice with uniform coupling

Coupling between rings of different sizes: localized defects to the lattice stop particle movement

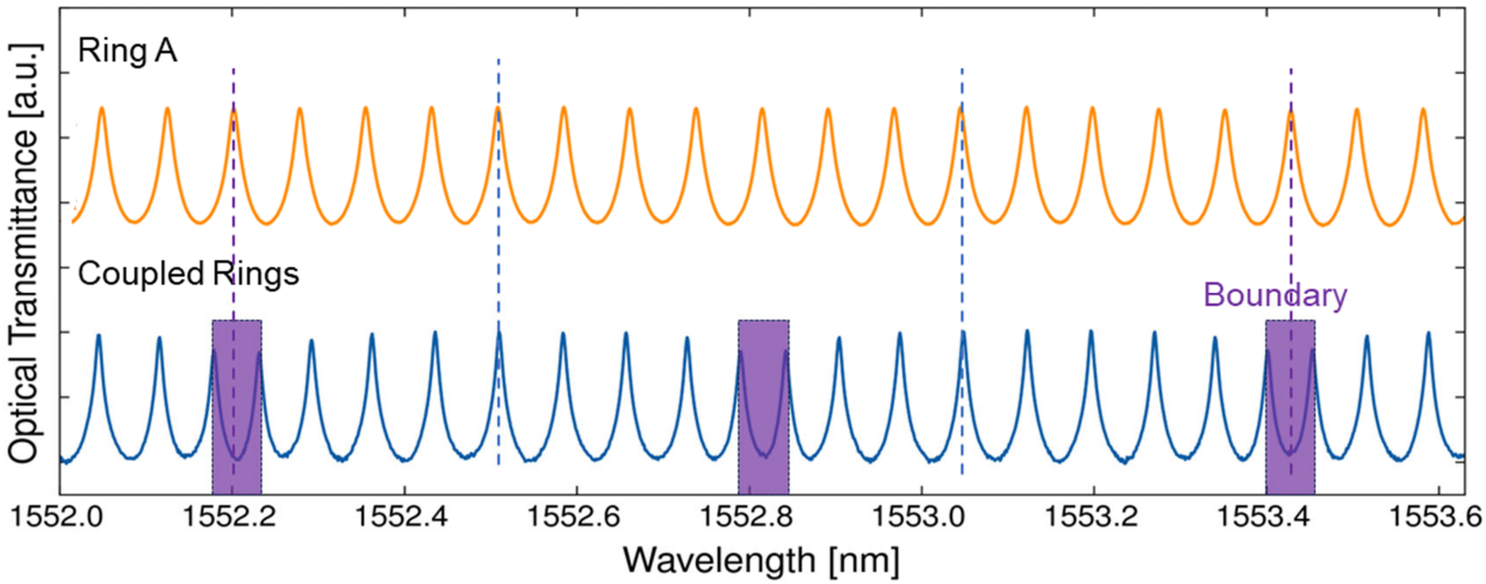
Lattice with boundaries

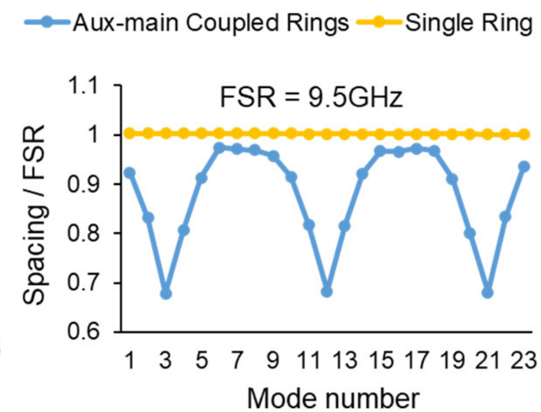
FSR_A = 9.5 GHz

FSR_B = 8x FSR_A



Measured optical transmission of drop-port:

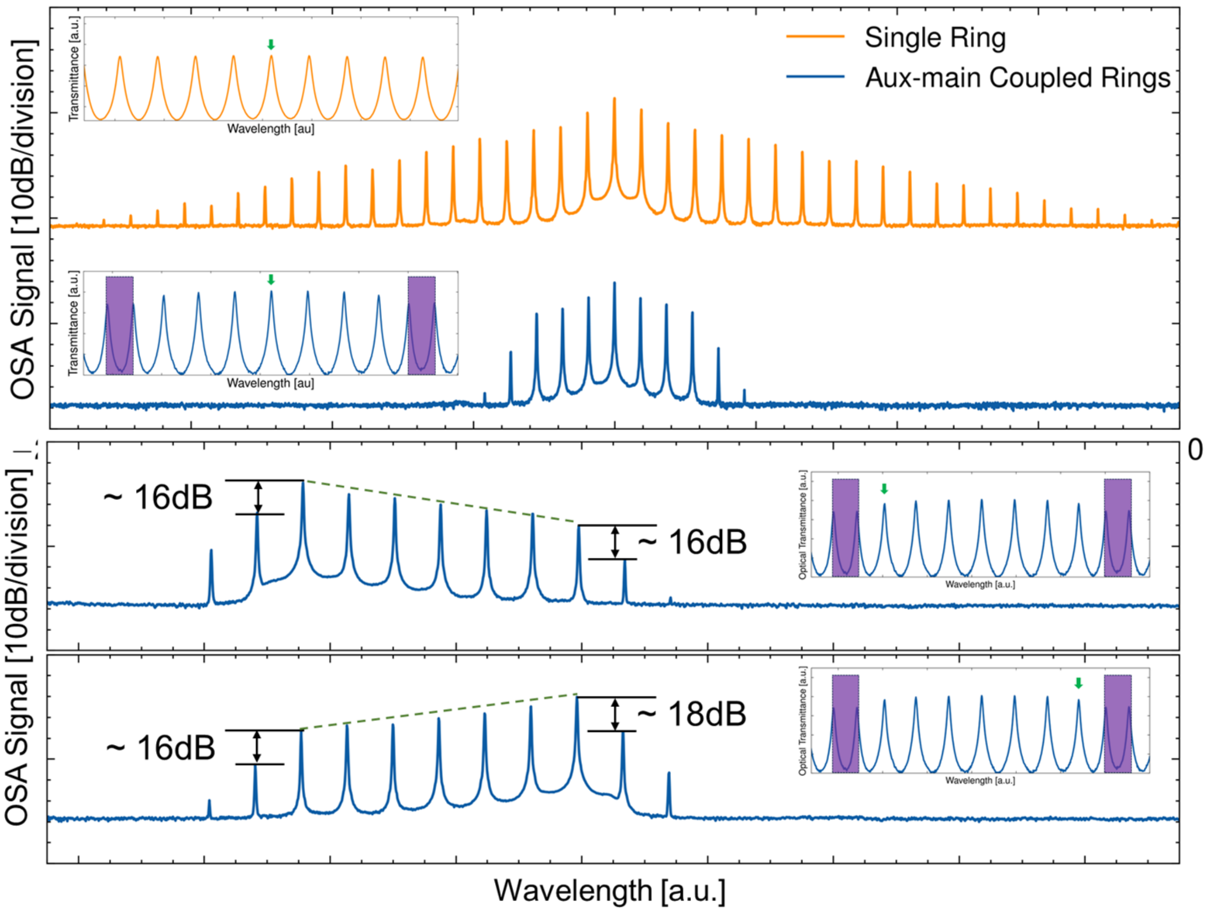


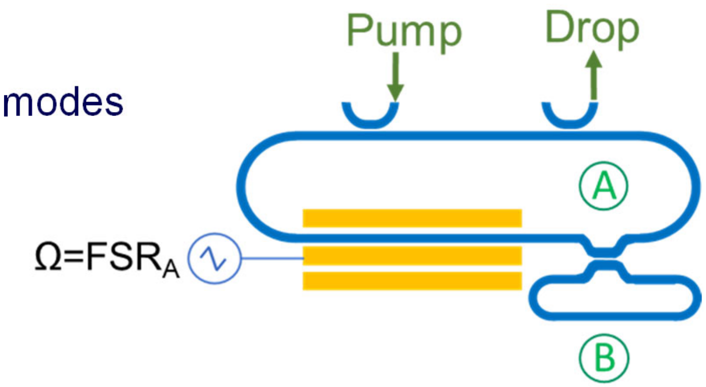


Mode-splitting with significant different mode spacing due to coupling

Lattice with boundaries

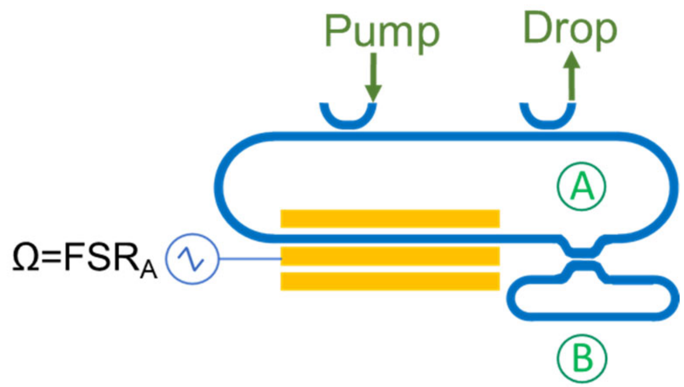
Steady-state response to RF modulation pumping at different resonant modes





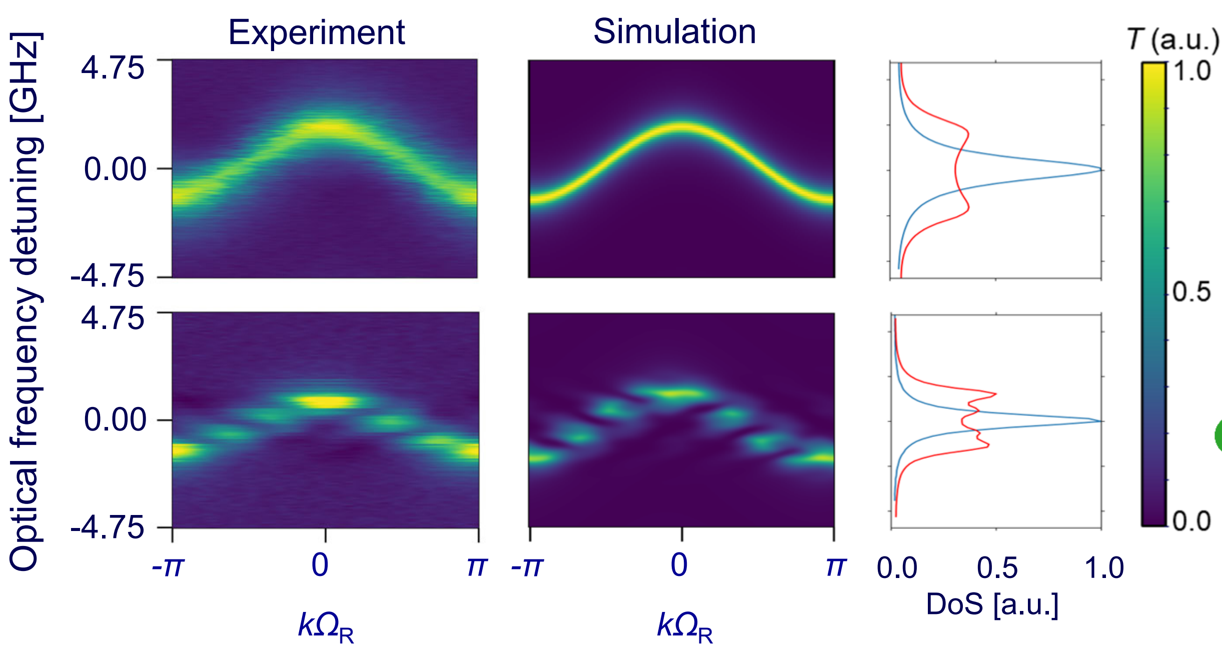
- Photon hoping is disrupted at the boundaries
- Only a limited number of sidebands between the boundaries

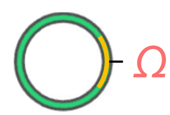
Lattice with boundaries



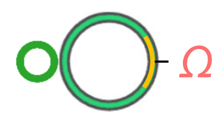
$$H = \sum_{N} \varepsilon \hat{b}_m^{\dagger} \hat{b}_m - \sum_{N} J_{\eta} \left(\hat{b}_m^{\dagger} \hat{b}_{m+\eta} + \hat{b}_{m+\eta}^{\dagger} \hat{b}_m \right)$$

Synthetic band structure





- Lattice without boundaries: ***Continuous*** band structure



- Lattice with boundaries: ***discrete*** band structure

Summary

- On-chip photonic integration of synthetic frequency dimension devices produces a qualitative leap in their robustness and scalability
- LNOI integrated photonic circuits possess highly efficient low loss modulators, good optical transparency, and attractive nonlinear properties, making it especially well suited for dimension synthesis
- Using multiple RF modulation signals a single ring cavity device can be used to simulate a complex multi-dimensional chiral frequency domain lattice with controllable coupling strengths and gauge potentials
- Hybridised dual ring cavity mode structure exhibits two distinct frequency dimension spacings that makes it able to simulate the staggered coupling of an SSH lattice
- Mode-coupling between rings of different sizes can be harnessed to realise lattices with boundaries

Acknowledgement

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