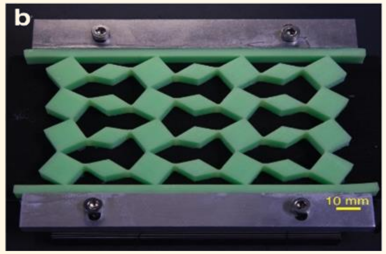

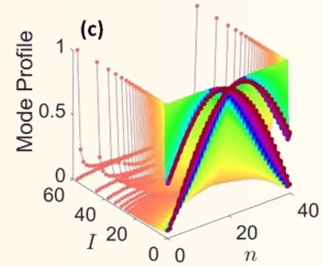

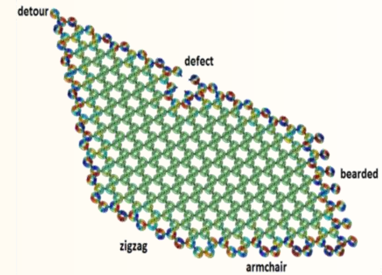

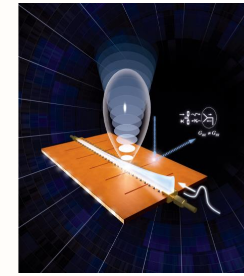

Topological EM: Robust, Broadband One-Way Signal Transport

Andrea Alù

Department of Electrical and Computer Engineering
The University of Texas at Austin
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Supported by Dr. Arje Nachman's program with AFOSR grant No. FA9550-13-1-0204

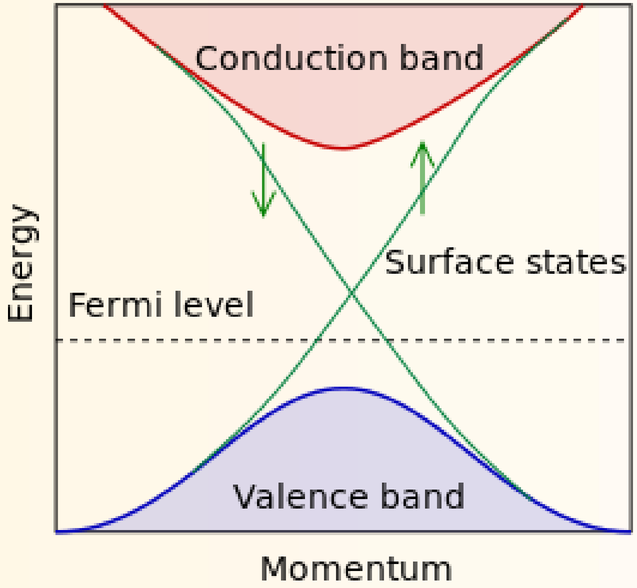
UT ECE | THE UNIVERSITY OF TEXAS AT AUSTIN
DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

METAMATERIALS & PLASMONICS RESEARCH LABORATORY

Electronic Topological Insulators

Symmetry-protected conducting surface states supported by topological order

Quantum Hall effect



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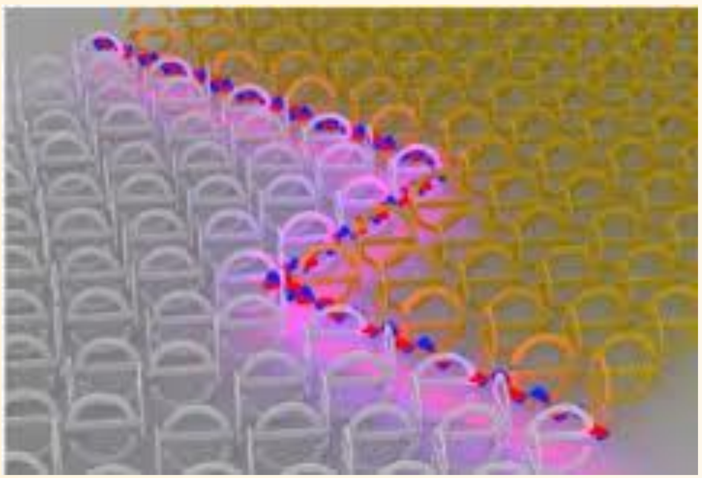
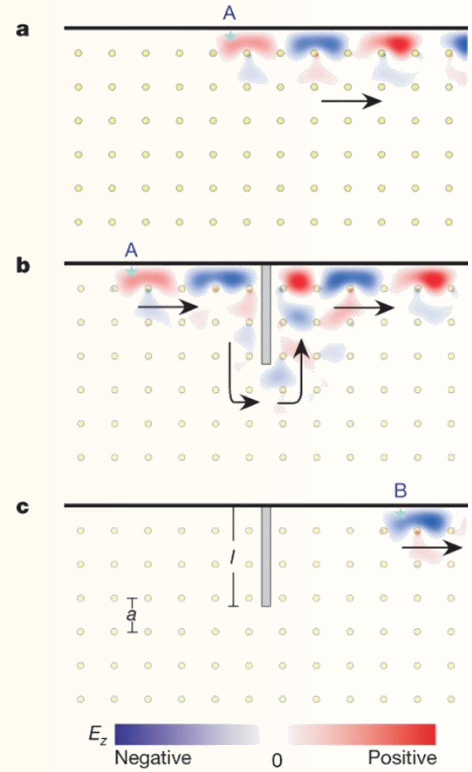
M. Z. Hasan, C. L. Kane, *Rev. Mod. Phys.* **82**, 3045 (2010)

Photonic Topological Insulators

Weak/strong topological protection determined by time-reversal symmetry





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A. P. Slobozhanyuk, A. N. Poddubny, A. E. Miroshnichenko, P. A. Belov, and Y. S. Kivshar, *Phys. Rev. Lett.* **114**, 123901 (2015)

Non-Reciprocity with Magnetic Materials

Lorentz reciprocity theorem

$$\iiint \mathbf{J}_1 \cdot \mathbf{E}_2 dV = \iiint \mathbf{J}_2 \cdot \mathbf{E}_1 dV$$

$$\bar{\bar{\varepsilon}} = \bar{\bar{\varepsilon}}^{\mathrm{T}}$$
$$\bar{\bar{\mu}} = \bar{\bar{\mu}}^{\mathrm{T}}$$

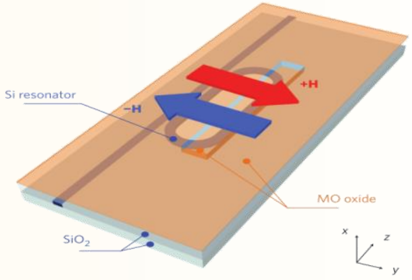
Time-invariant materials

Linear materials

Static magnets

Weak effects → Massive devices

Difficult to integrate



Bi, Nature Photon. 5, 758

Breaking Reciprocity Constraints

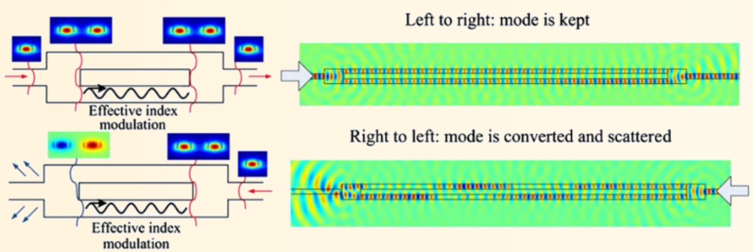
Lorentz reciprocity theorem

$$\iiint \mathbf{J}_1 \cdot \mathbf{E}_2 dV = \iiint \mathbf{J}_2 \cdot \mathbf{E}_1 dV$$

$$\bar{\bar{\varepsilon}} = \bar{\bar{\varepsilon}}^{\mathrm{T}}$$
$$\bar{\bar{\mu}} = \bar{\bar{\mu}}^{\mathrm{T}}$$

Time-invariant materials

Linear materials



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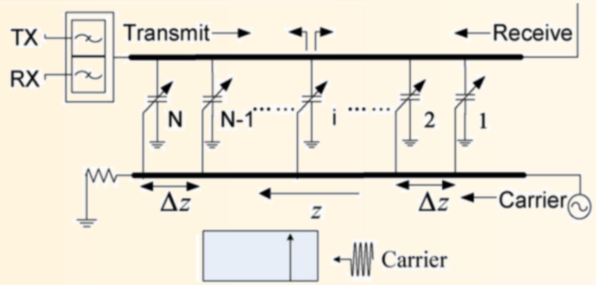

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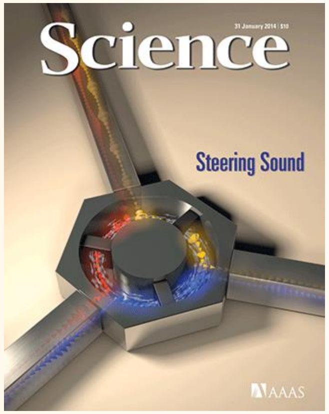

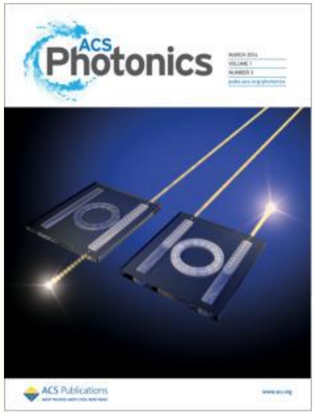

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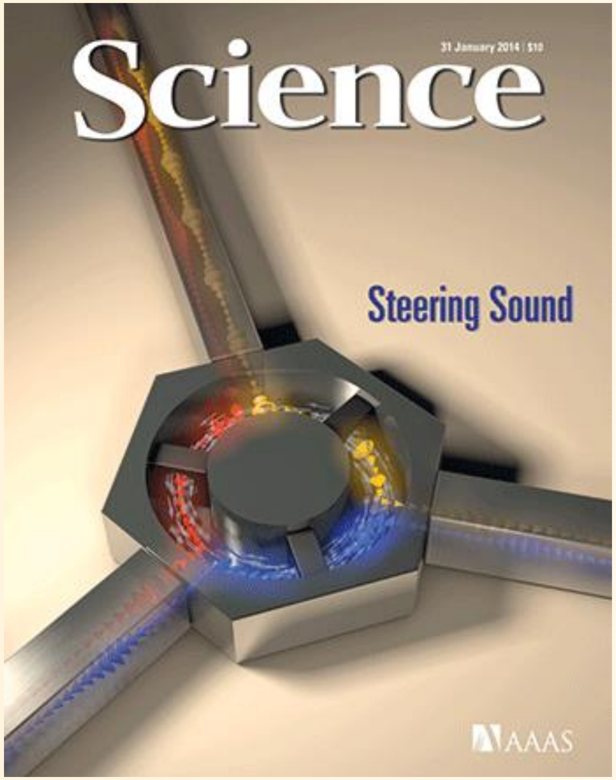
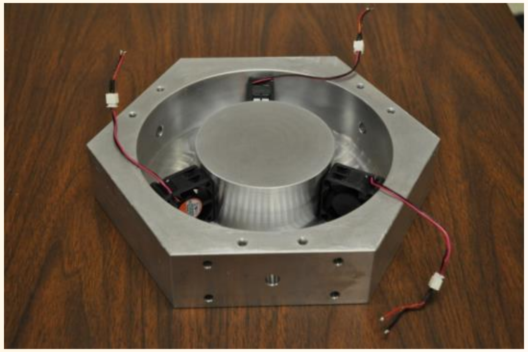
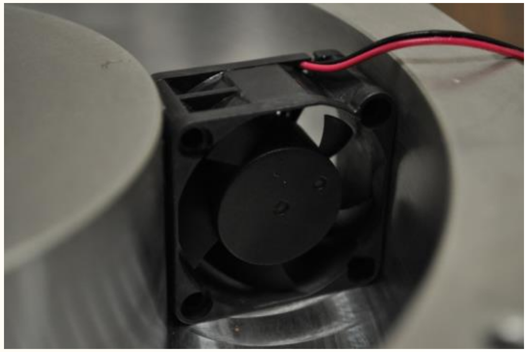
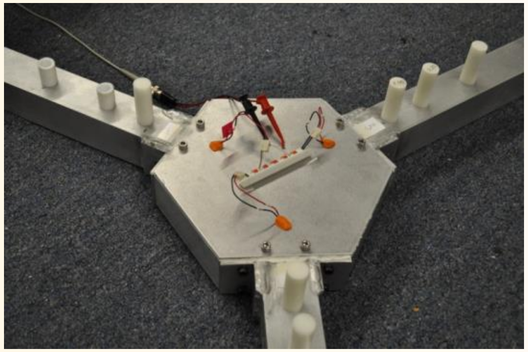
D. L. Sounas, *ACS Photonics* **1**, 198 (2014)
Fleury, *Science* **343**, 516 (2014)
Estep, *Nature Phys.* **10**, 923 (2014)

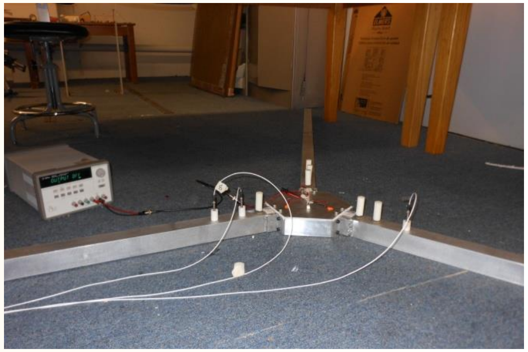
A Circulator For Sound





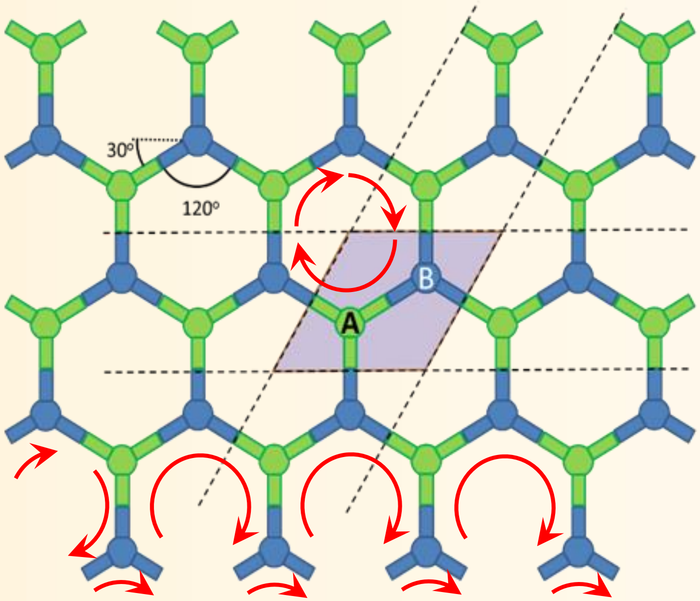




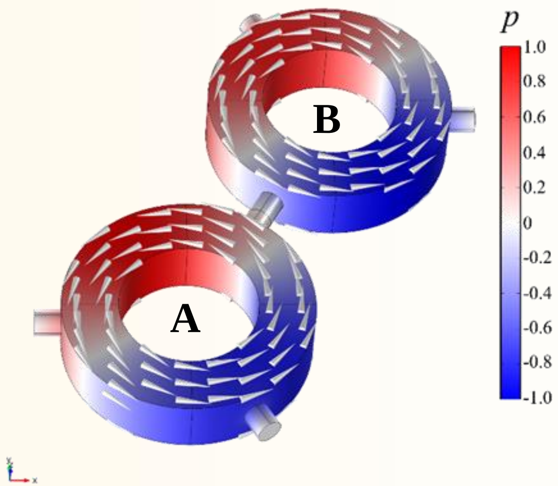


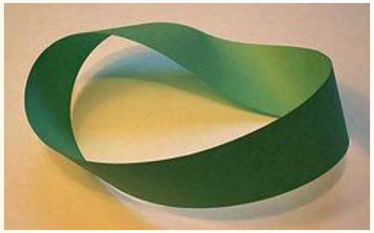
Molding the Topology of the Band Diagram

Lattice



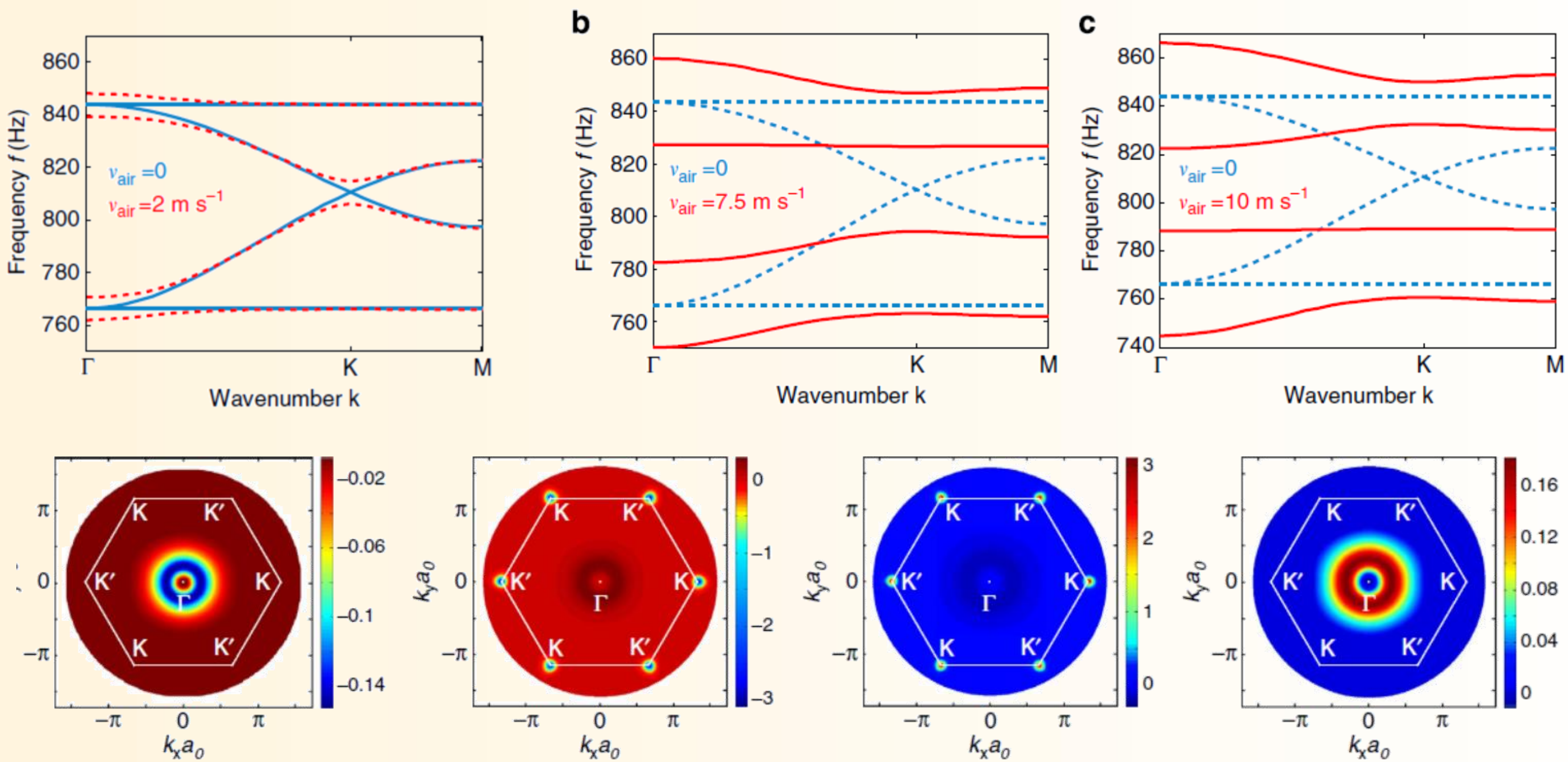
Unit Cell





A. Khanikaev, R. Fleury, H. Mousavi, and A. Alù, *Nat. Comm.* **6**, 8260 (2015)

Non-Trivial Topology of the Band Structure



$$C = \frac{1}{2\pi}\int_{FBZ} \Omega(\mathbf{k})\, d^2\mathbf{k}$$

$$\Omega(\mathbf{k}) = \partial_{k_x} A_y - \partial_{k_y} A_x$$

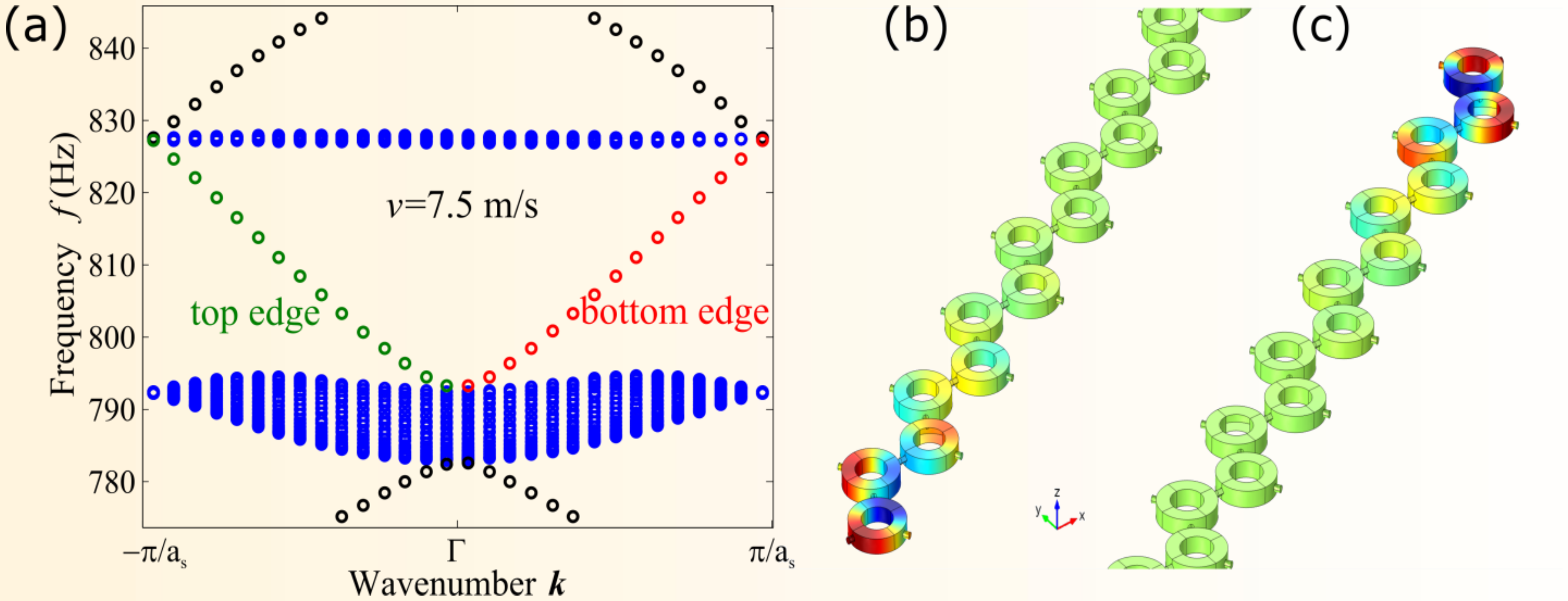
$$\mathbf{A_k} = -i\langle p|\partial_{\mathbf{k}}|p\rangle$$

$C = \{-1, 0, 0, 1\}$ clockwise

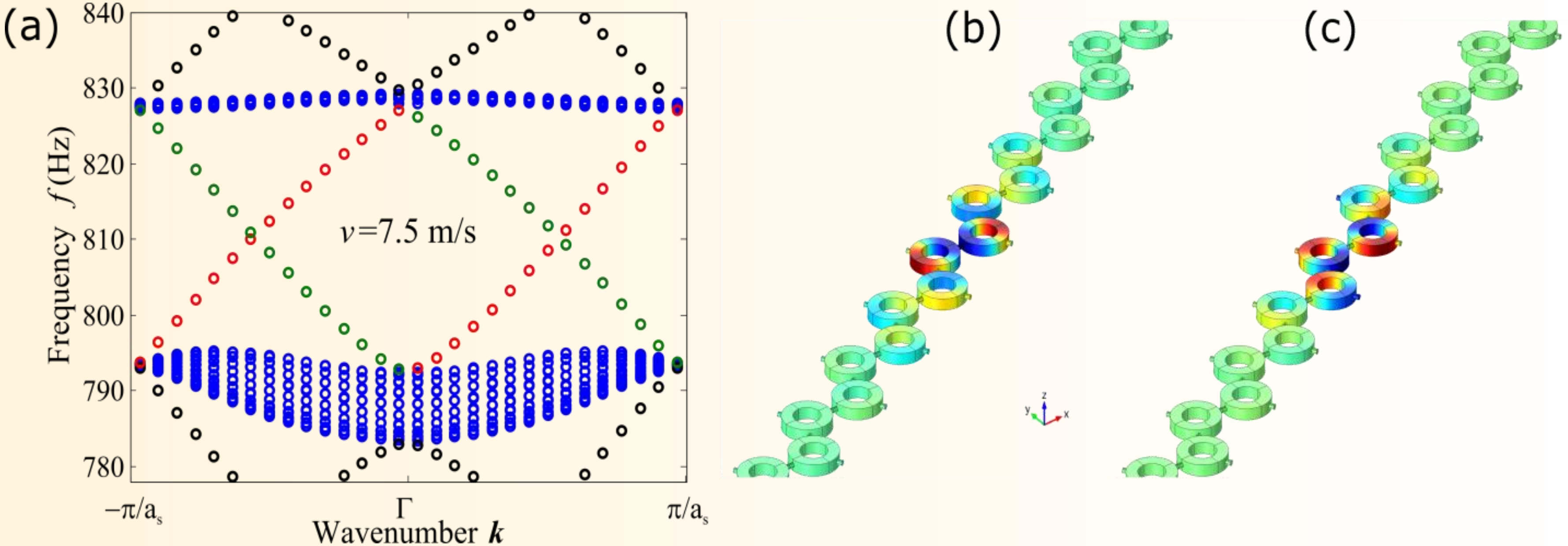
$C = \{1, 0, 0, -1\}$ counterclockwise

A. Khanikaev, R. Fleury, H. Mousavi, and A. Alù, *Nat. Comm.* **6**, 8260 (2015)

Topological Metamaterials

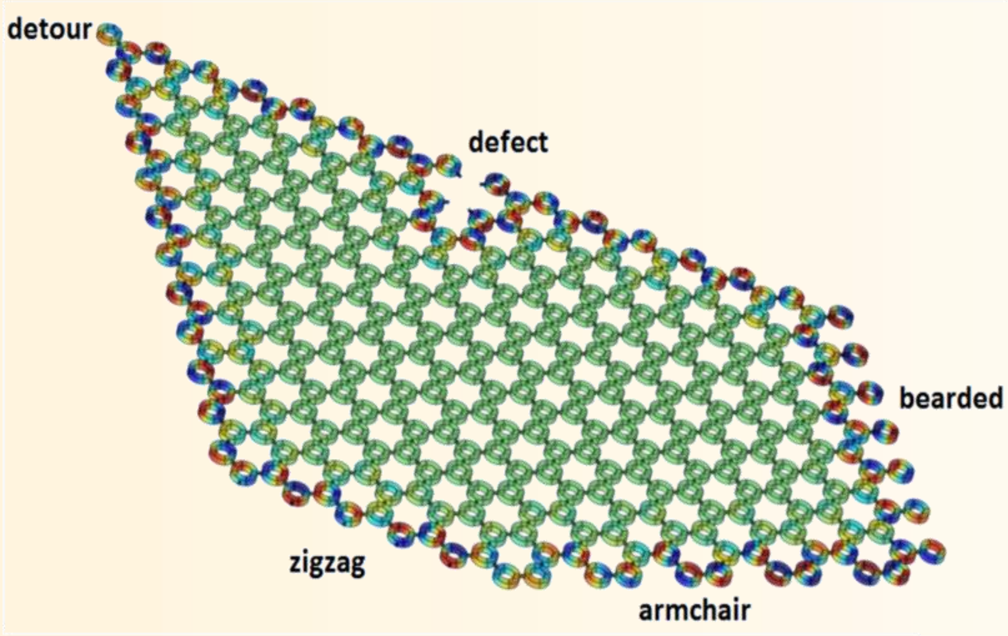


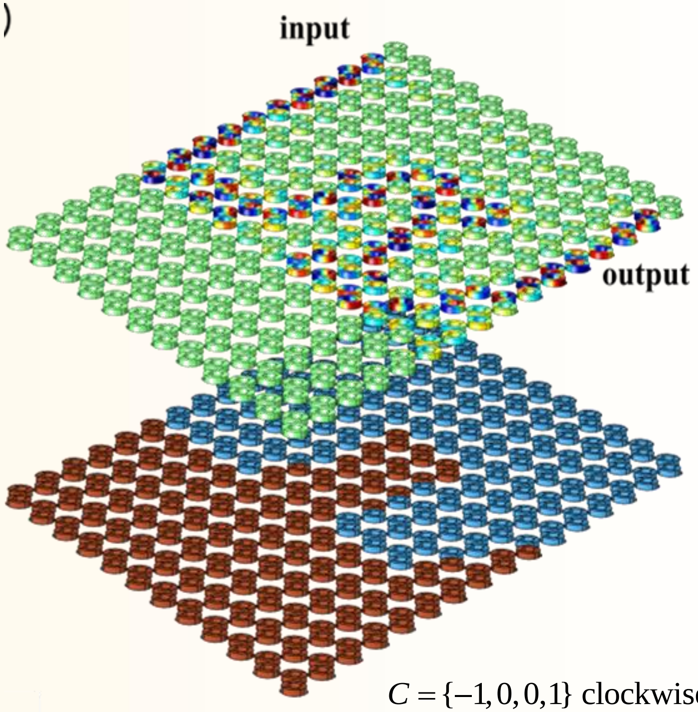
Topological Metamaterials



Topological Metamaterials

Reconfigurable waveguides, broadband isolators…





$C = \{-1, 0, 0, 1\}$ clockwise

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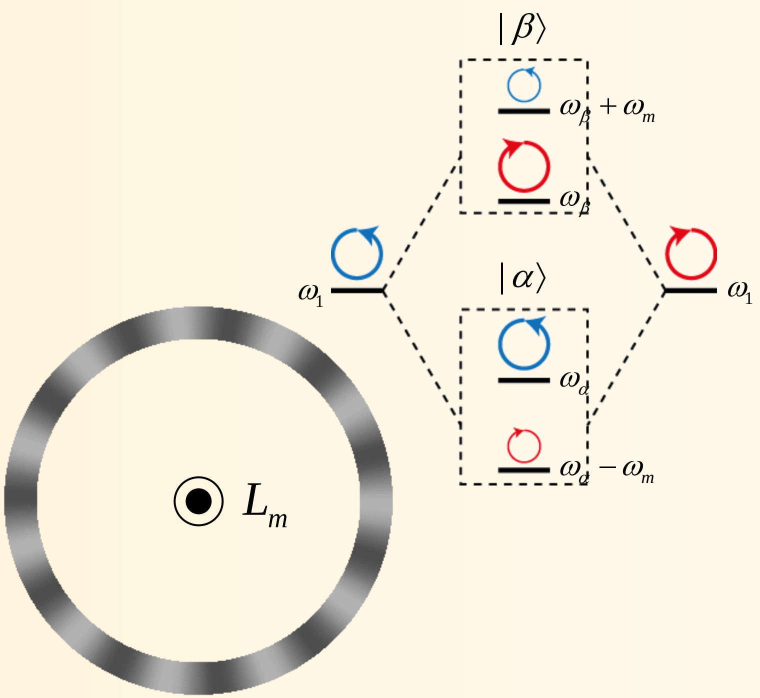
A. Khanikaev, R. Fleury, H. Mousavi, and A. Alù, *Nat. Comm.* **6**, 8260 (2015)

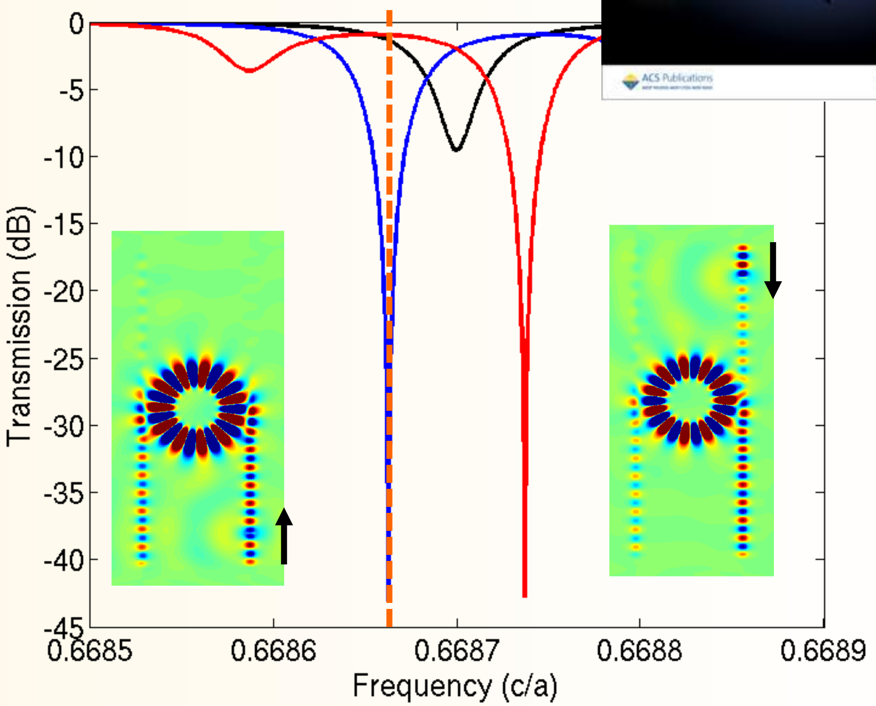
Angular-Momentum-Bias in Nanophotonics

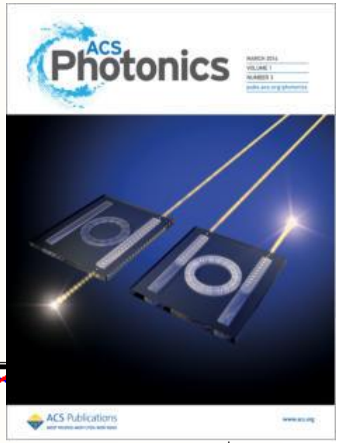
$$\Delta\varepsilon_m = 5\times10^{-4}\varepsilon \ !$$
$$Q \sim 7,000$$

$$Q\Delta\varepsilon_m \approx 1$$



$$\Delta\varepsilon(\varphi,t) = \Delta\varepsilon_m \cos(\omega_m t - L_m\varphi)$$





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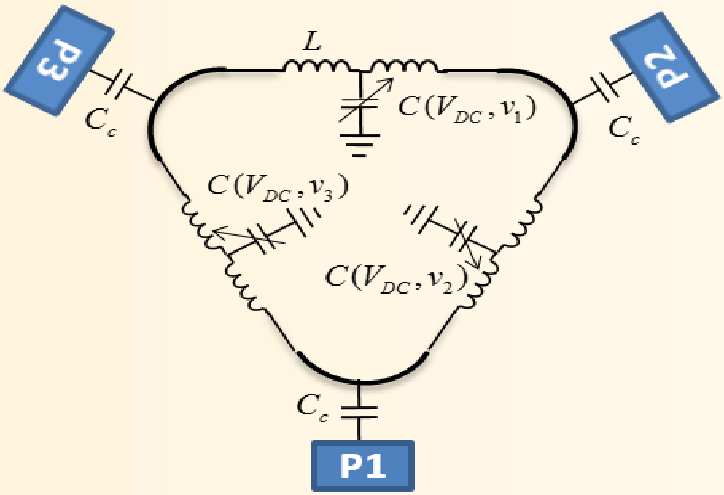
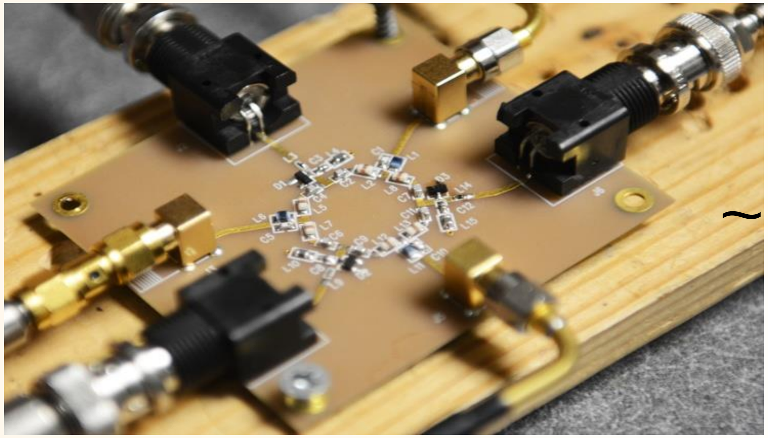
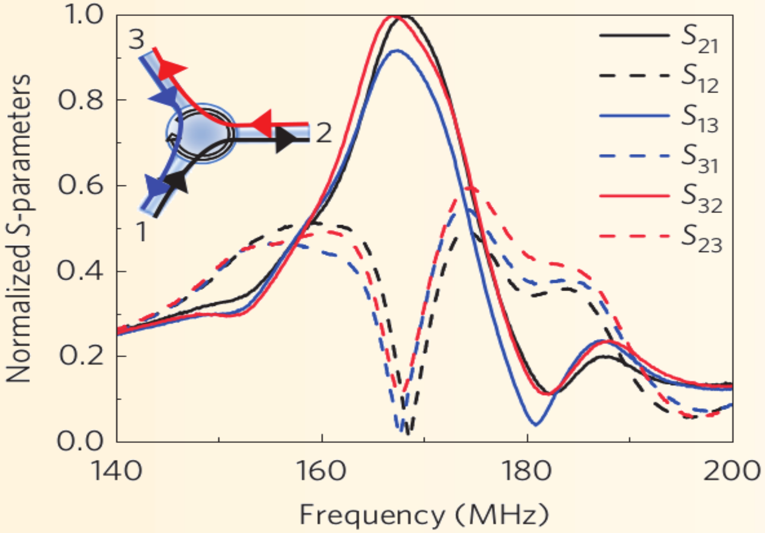
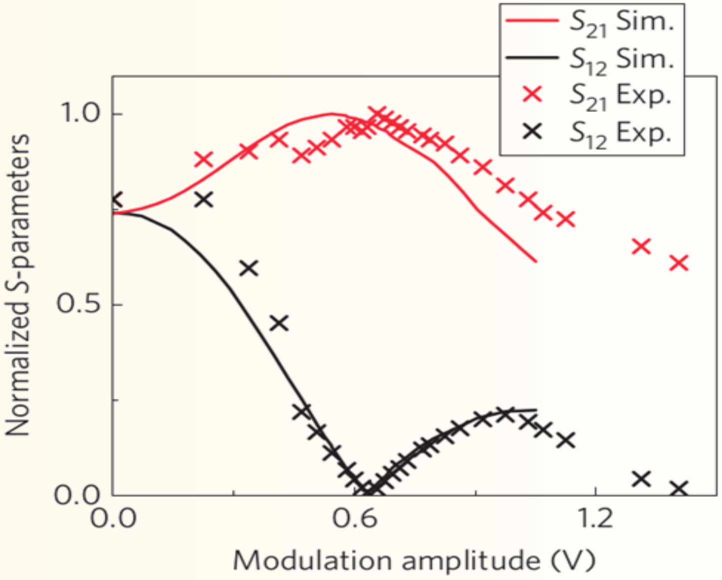
RF Magnet-Less Integrated Circulator





$\sim \lambda/70$





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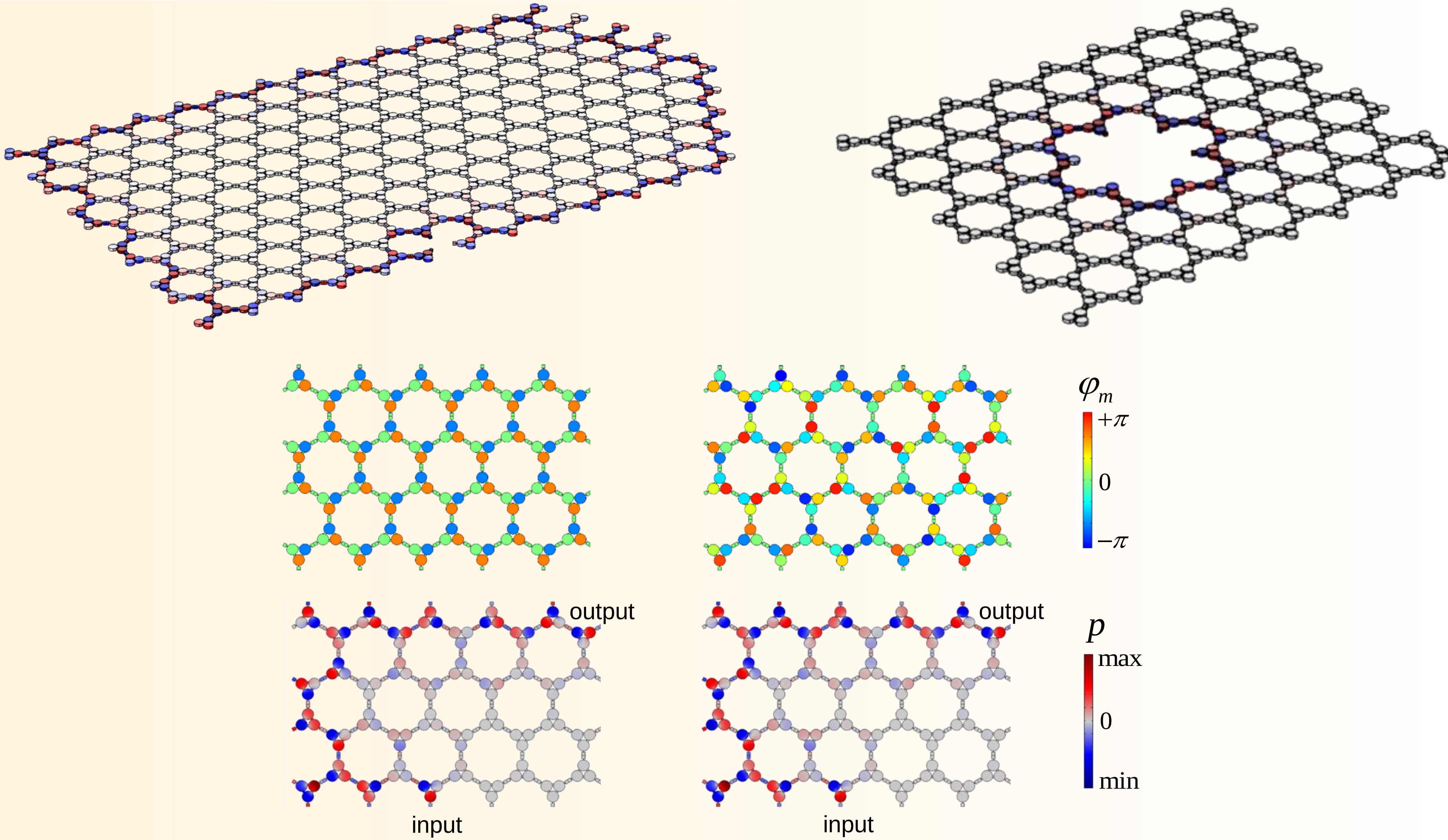
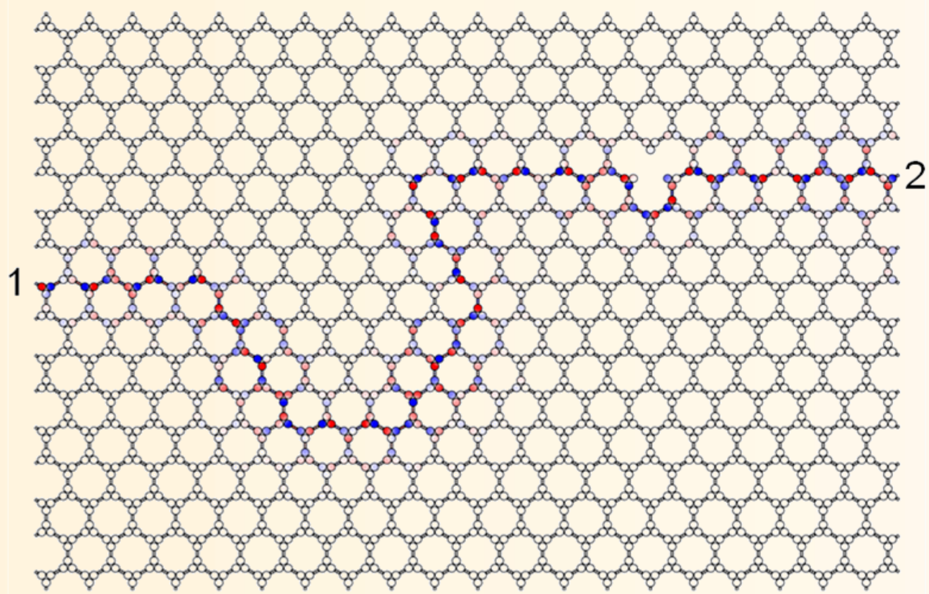
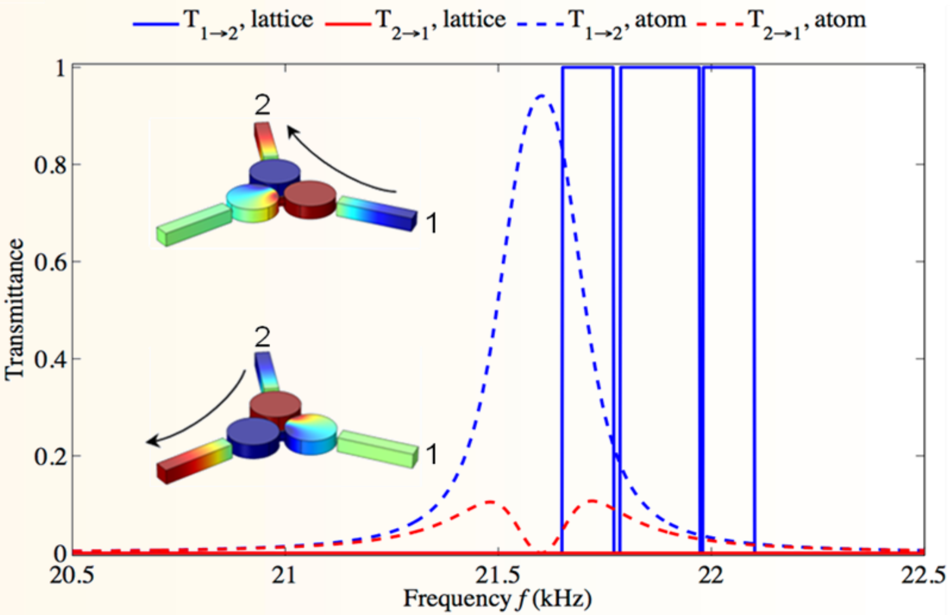
Floquet Topological Insulators for Light



R. Fleury, A.B. Khanikaev and A. Alù,, *Nature Communications*, **7**, 11744 (2016)

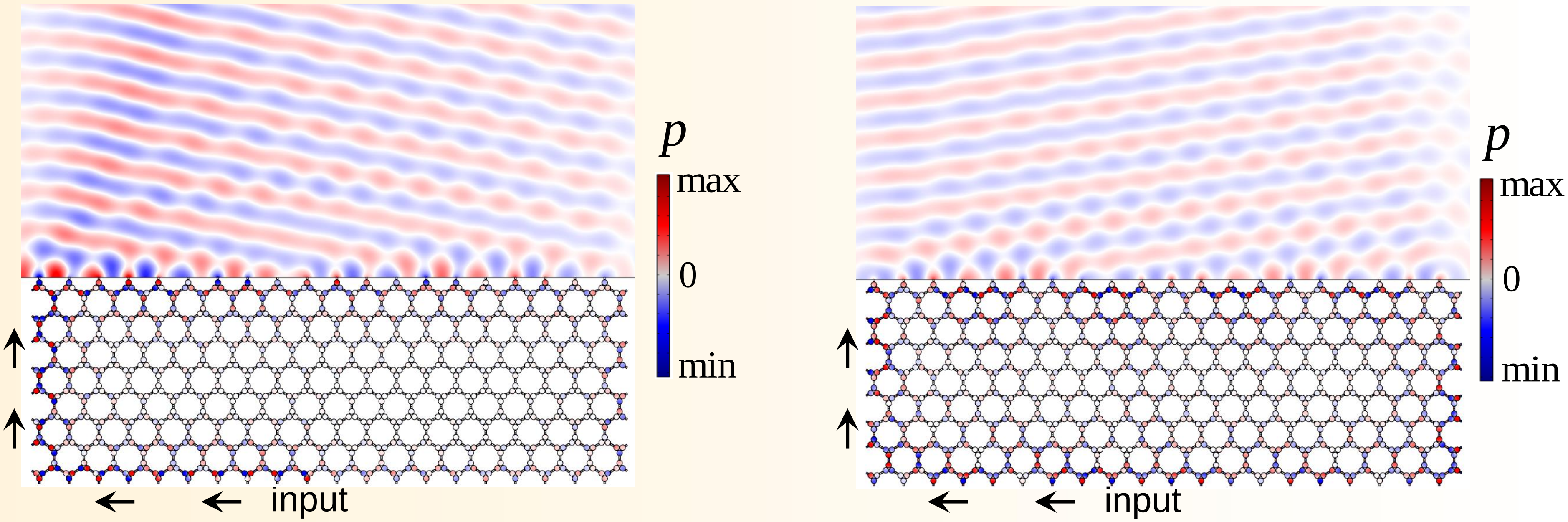
Continuous Bandwidth of Isolation





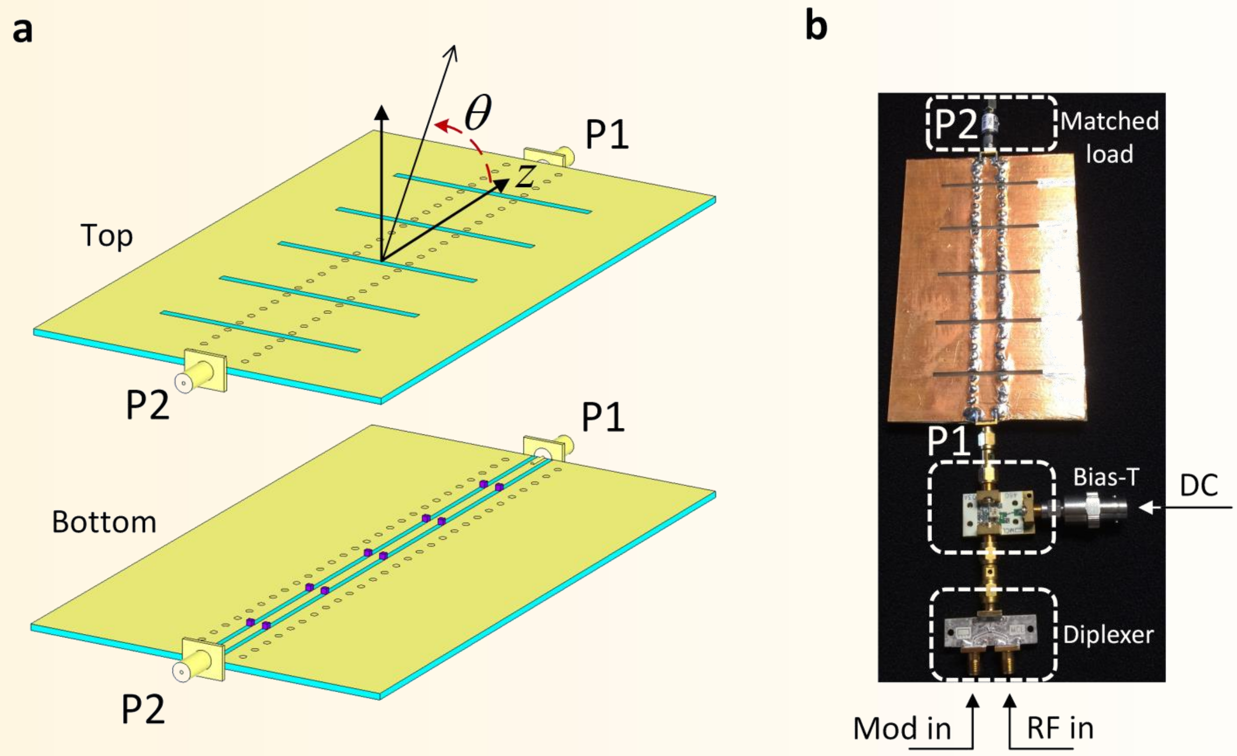
R. Fleury, A.B. Khanikaev and A. Alù,, *Nature Communications*, **7**, 11744 (2016)

Topologically Protected Leaky-Wave Radiation



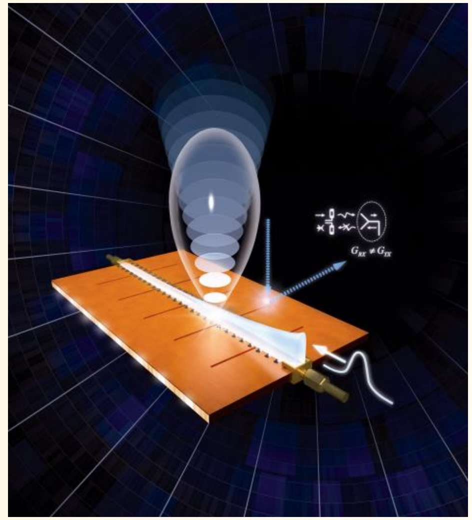
R. Fleury, A.B. Khanikaev and A. Alù,, *Nature Communications*, **7**, 11744 (2016)

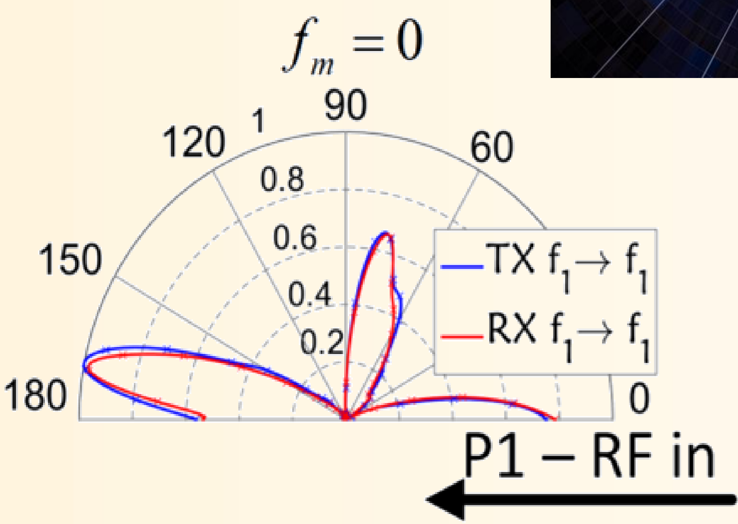
Non-Reciprocal Metasurfaces Based on ST Modulation

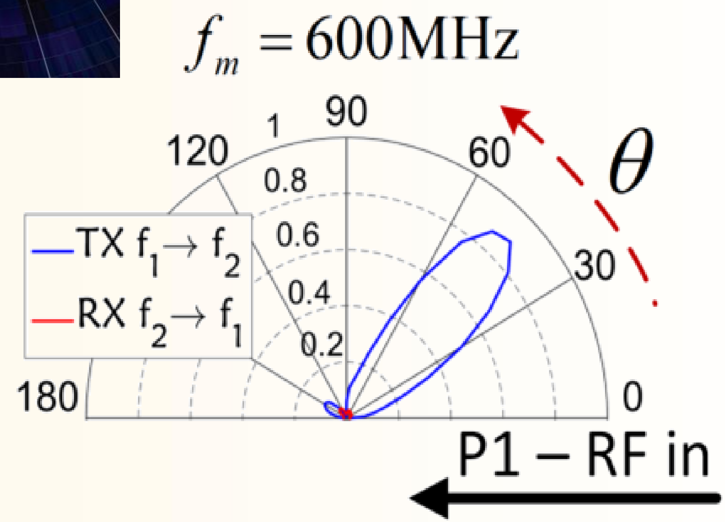


Y. Hadad, J. C. Soric, and A. Alù, *PNAS* **113**, 33471 (2016)

Non-Reciprocal Metasurfaces Based on ST Modulation







Y. Hadad, J. C. Soric, and A. Alù, *PNAS* **113**, 33471 (2016)

Non-Reciprocity Based on Non-Linear Effects

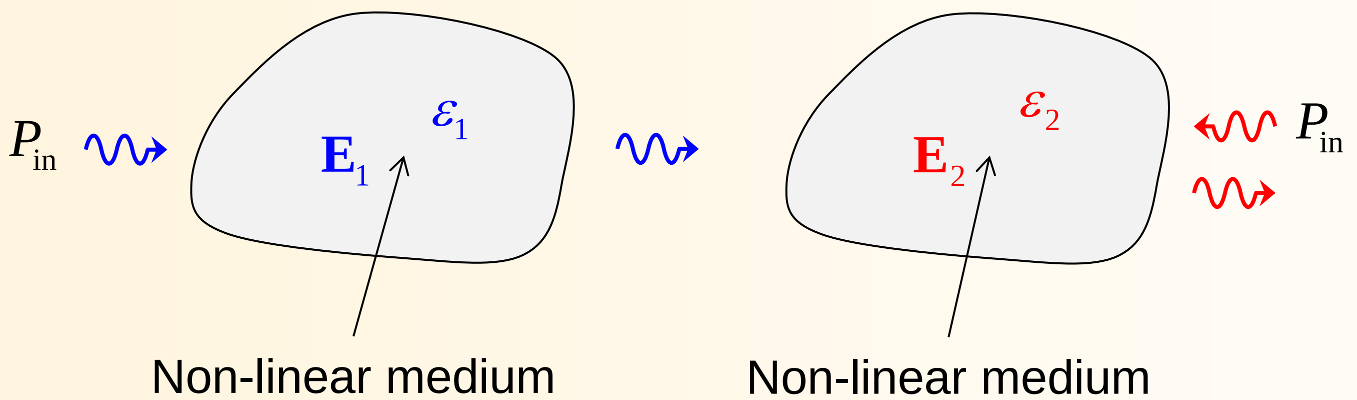
Lorentz reciprocity theorem

$$\iiint \mathbf{J}_1 \cdot \mathbf{E}_2 dV = \iiint \mathbf{J}_2 \cdot \mathbf{E}_1 dV$$

$$\bar{\bar{\varepsilon}} = \bar{\bar{\varepsilon}}^{\mathrm{T}}$$
$$\bar{\bar{\mu}} = \bar{\bar{\mu}}^{\mathrm{T}}$$

Time-invariant materials

Linear materials

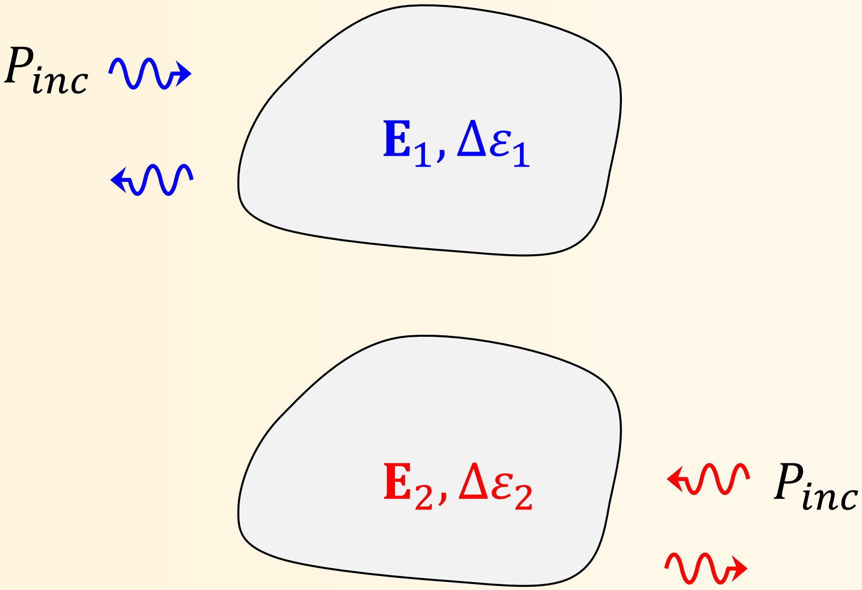


Chi-3 non-linearity

$$\Delta\varepsilon_{NL} = \chi^{(3)} |\mathbf{E}|^2$$

P. Saboo, J. Joseph, *Appl. Opt.* **52,** 8252–8257 (2013)
L. Fan, et al., *Opt. Lett.* **38,** 1259–1261 (2013)
Y. Shi, Z. Yu, S. Fan, *Nature Photon.* **9,** 388–392 (2015)
A. M. Mahmoud, A. Davoyan, N. Engheta, *Nature Comm.* **6**, 8359 (2015)

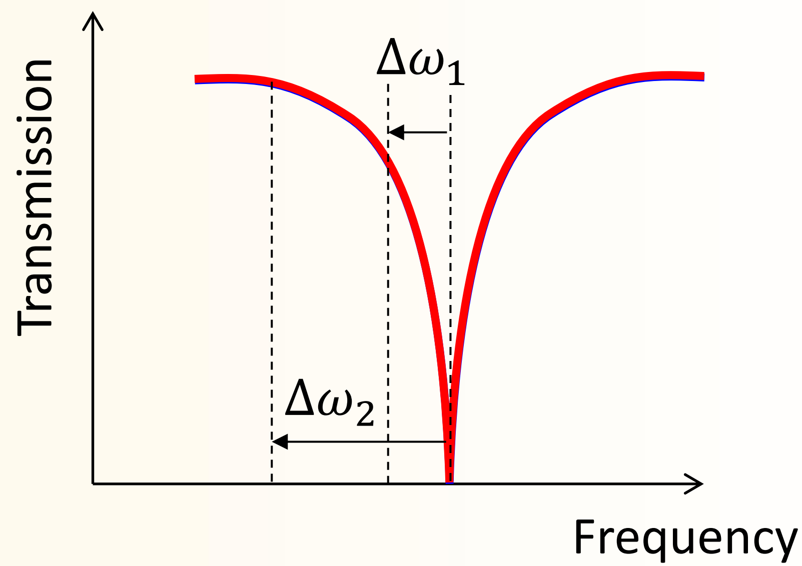
Basic Operation – Single Resonance



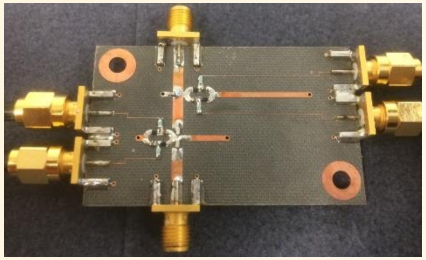
$$\varepsilon_{NL} = \varepsilon + \chi^{(3)}|\boldsymbol{E}|^2$$

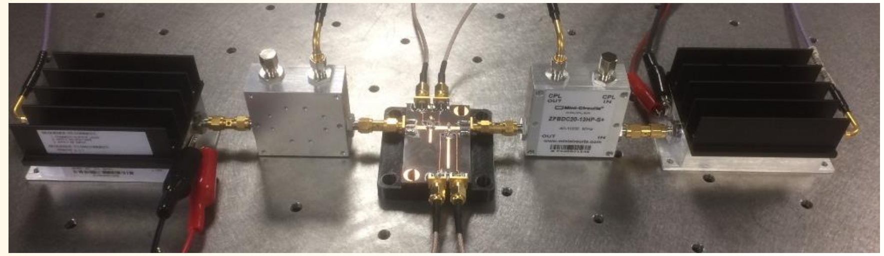
$$\Delta\omega = -\omega_0 \frac{\int \Delta\varepsilon|\mathbf{E}_0|^2 dV}{\int \varepsilon|\mathbf{E}_0|^2 dV}$$

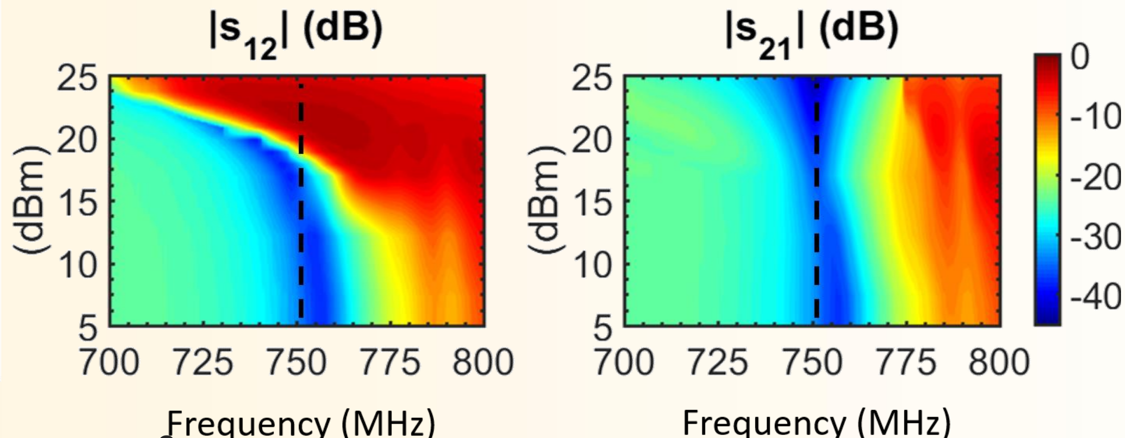
$$\kappa = \frac{|\mathbf{E}_2|^2}{|\mathbf{E}_1|^2} > 1$$

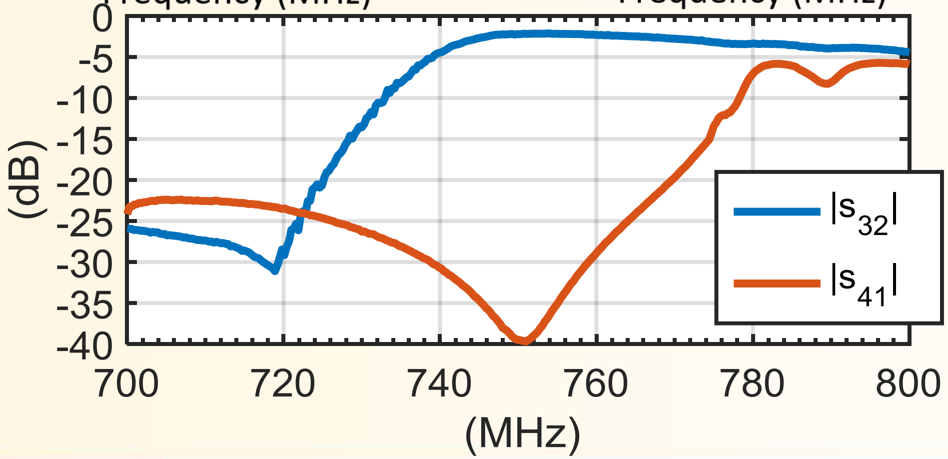


Experimental Results at RF



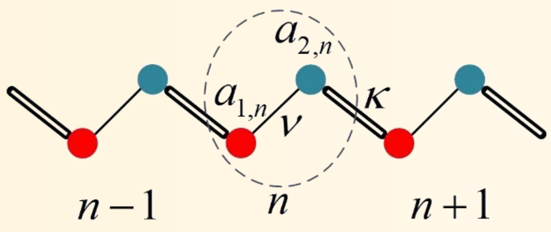






Supported by AFOSR (A. Sayir)

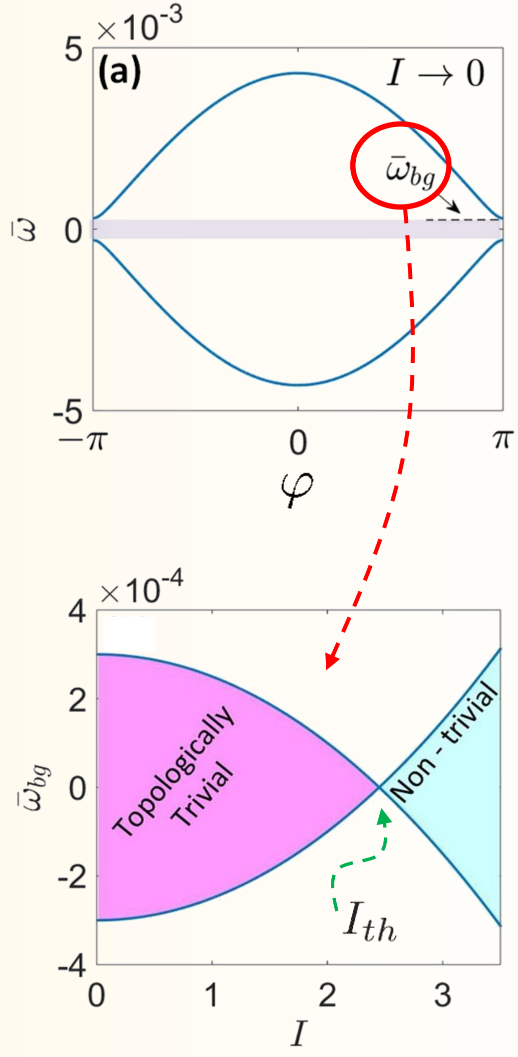
Nonlinearity-Induced Topological Transitions



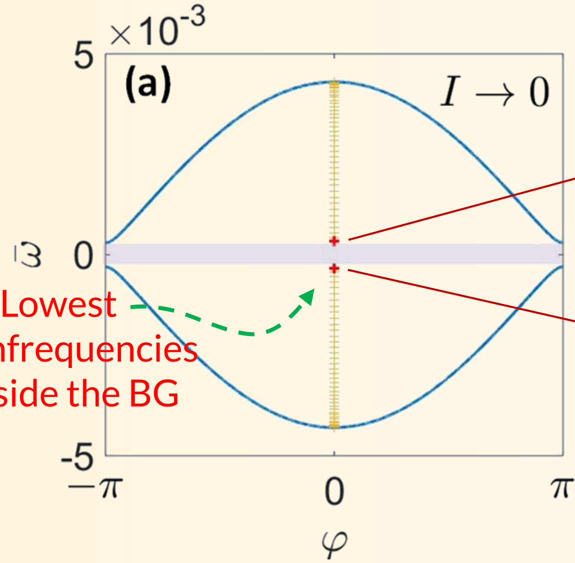
$$i\frac{d\Psi_n}{dt} = \mathbf{\Omega}\Psi_n + \mathbf{K}_m\Psi_{n-1} + \mathbf{K}_p\Psi_{n+1}$$

$$\nu > \kappa_0$$

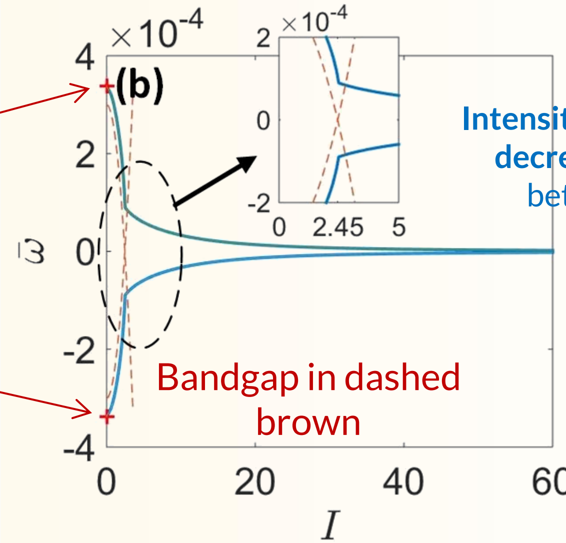
$$\bar{\omega}_{bg} = \pm|\nu - \kappa_0 - \alpha I^2| \Rightarrow I_{th} = \sqrt{\frac{\nu-\kappa_0}{\alpha}}$$



Finite Array: 40 Element Chain

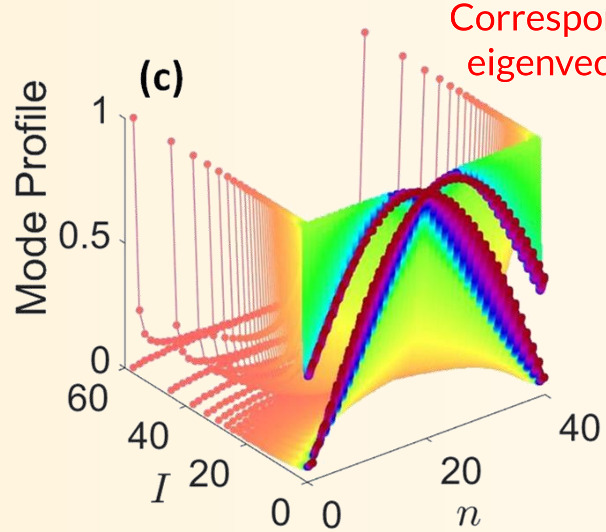


Lowest eigenfrequencies outside the BG

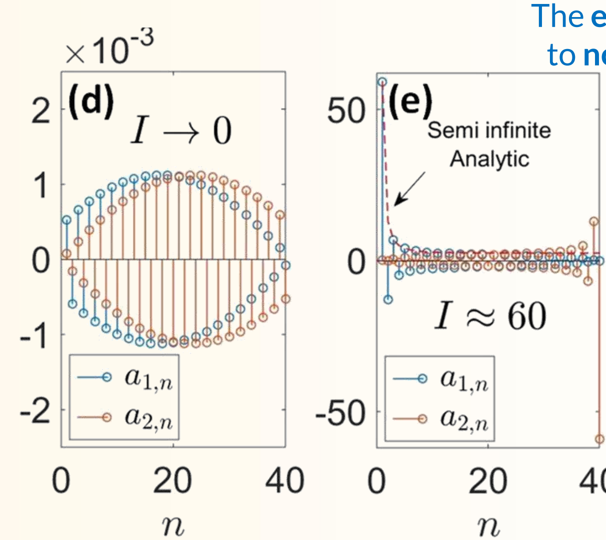


Intensity increase yields **decreased coupling** between **edges**

Bandgap in dashed brown



Corresponding eigenvectors

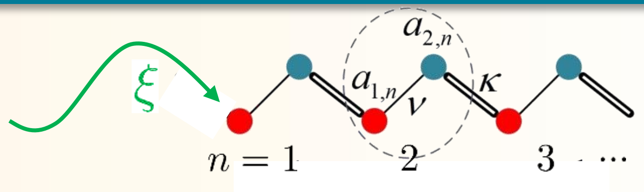


The **edge state decays** to **non-zero plateau**

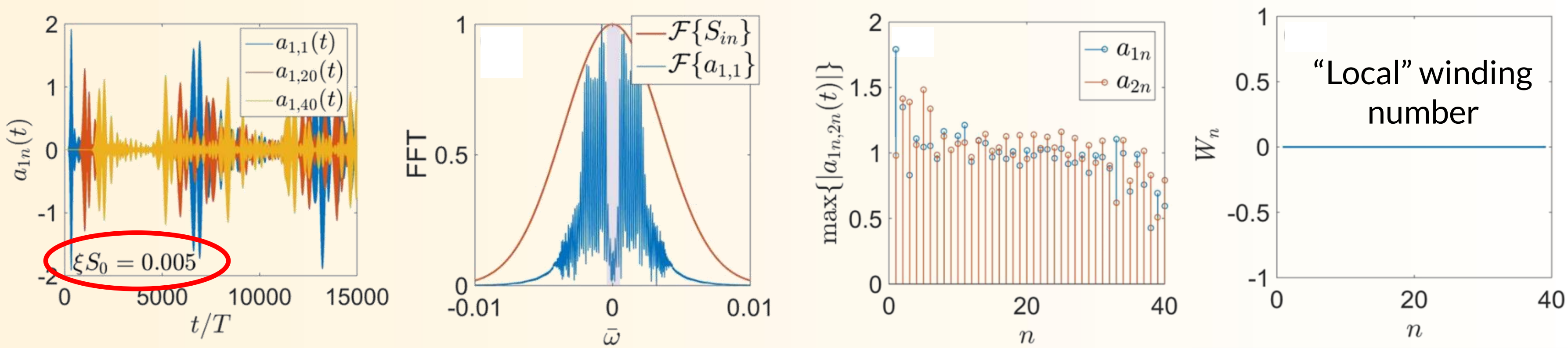
$$a_{1,\infty} = \sqrt{\frac{\nu - \kappa_0}{\alpha}} = I_{th}$$

Nonlinearity-Induced Topological Transitions

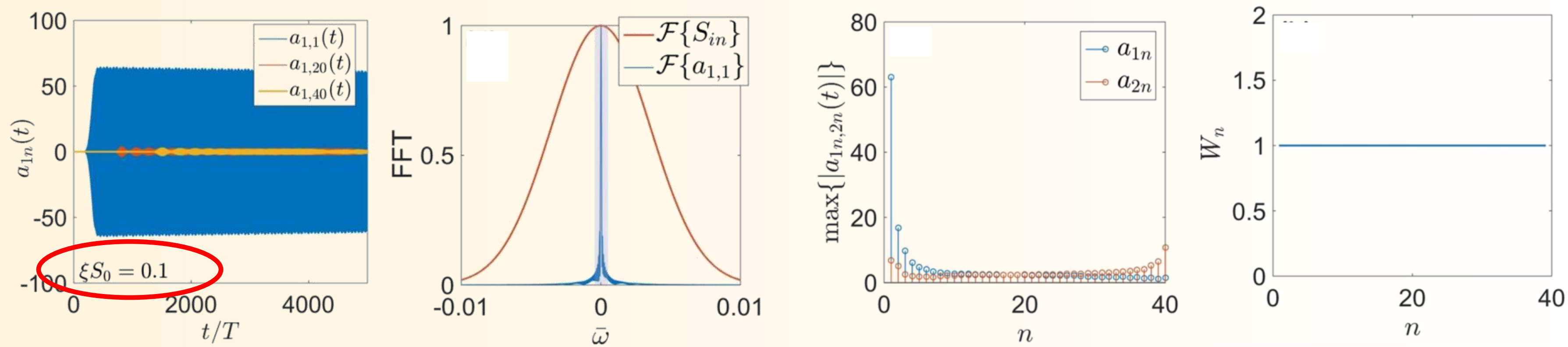
$$S_{in} = S_0 e^{i\omega t} e^{-(t-t_0)^2/T^2}$$



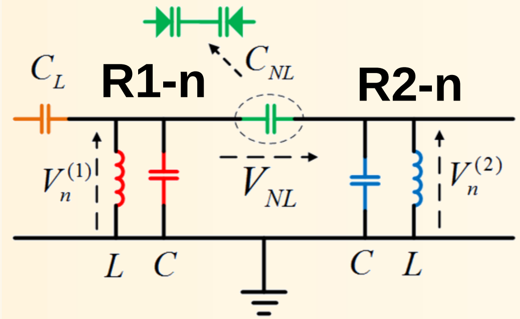
Low input intensity:

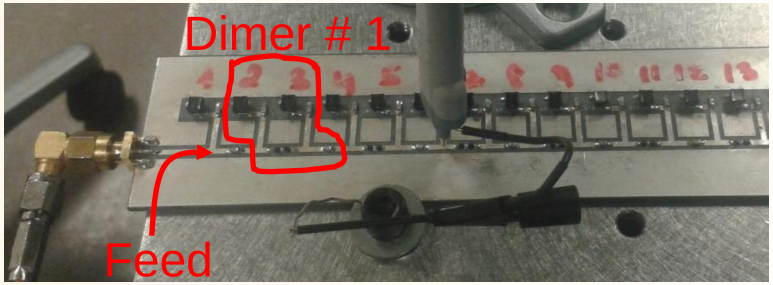


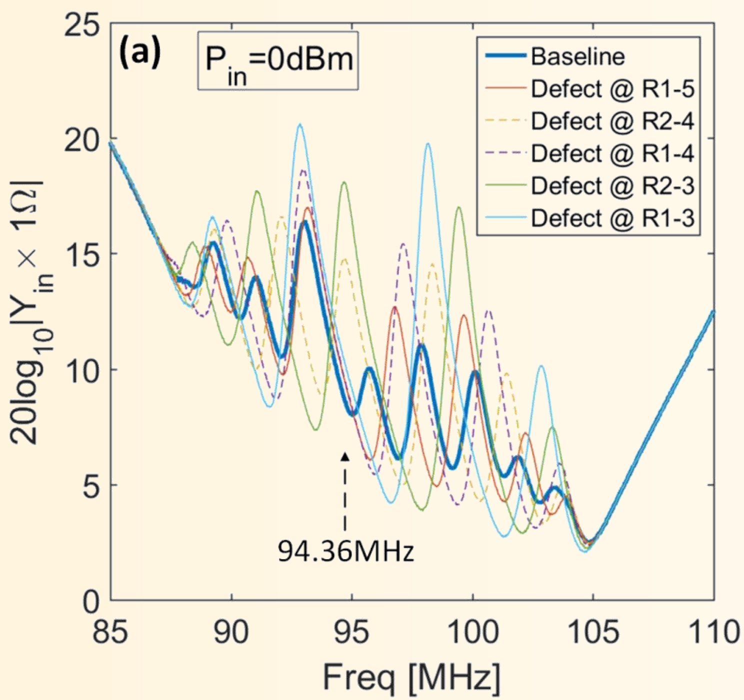
High input intensity:

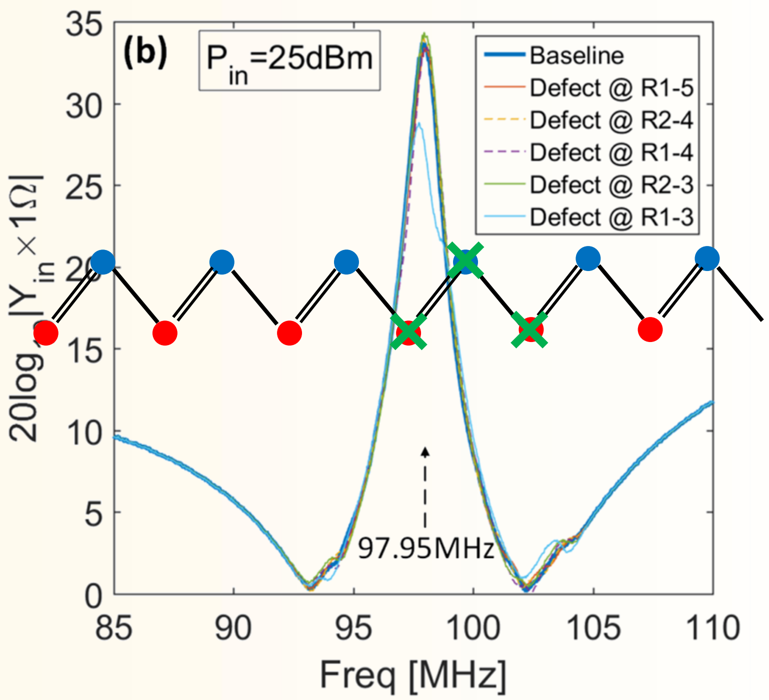


Nonlinearity-Induced Topological Transitions









Equivalent Continuum Model

Continuum limit — Moving frame $\xi = x - ct$

$$q_n(t), \alpha_n(t) \mapsto q(x,t), \alpha(x,t) \mapsto q(\xi), \alpha(\xi)$$

Stored energy in dimer $q_n(t) = \sqrt{\left|a_n^{(1)}\right|^2 + \left|a_n^{(2)}\right|^2}$

Relative phase in dimer $\alpha_n(t) = \tan^{-1}\left(j \frac{a_n^{(2)}}{a_n^{(1)}} \right)$

Continuum model:

$$\frac{d}{d\xi}\begin{pmatrix} q \\ \alpha \end{pmatrix} = F(q)\begin{pmatrix} \kappa\Delta q \cos 2\alpha \\ -c - \kappa\Delta \sin 2\alpha \end{pmatrix}$$

<u>Fixed points</u> $\underline{x}^* = (q^*; \alpha^*)$

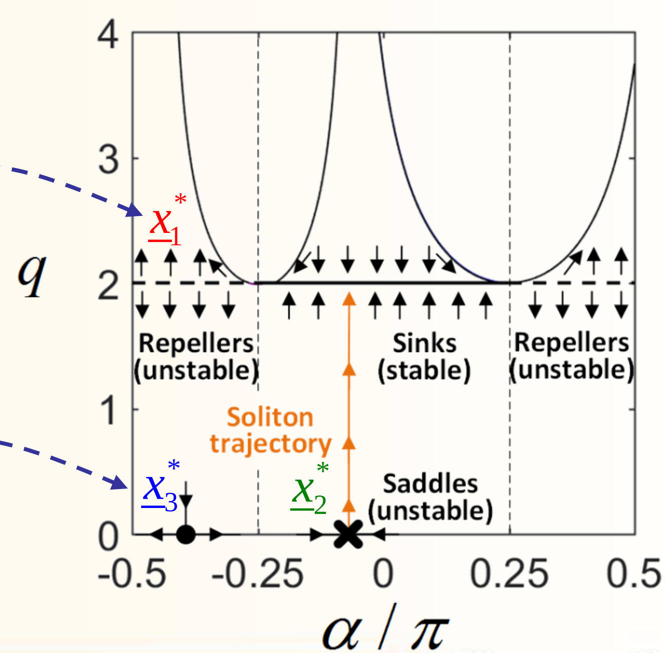
- <u>line</u> of unstable/stable nodes

$$\underline{x}_1^* \to q_1^* = (\nu_0 - \kappa)/(\kappa - \nu_\infty), \ \forall \alpha_1^*$$

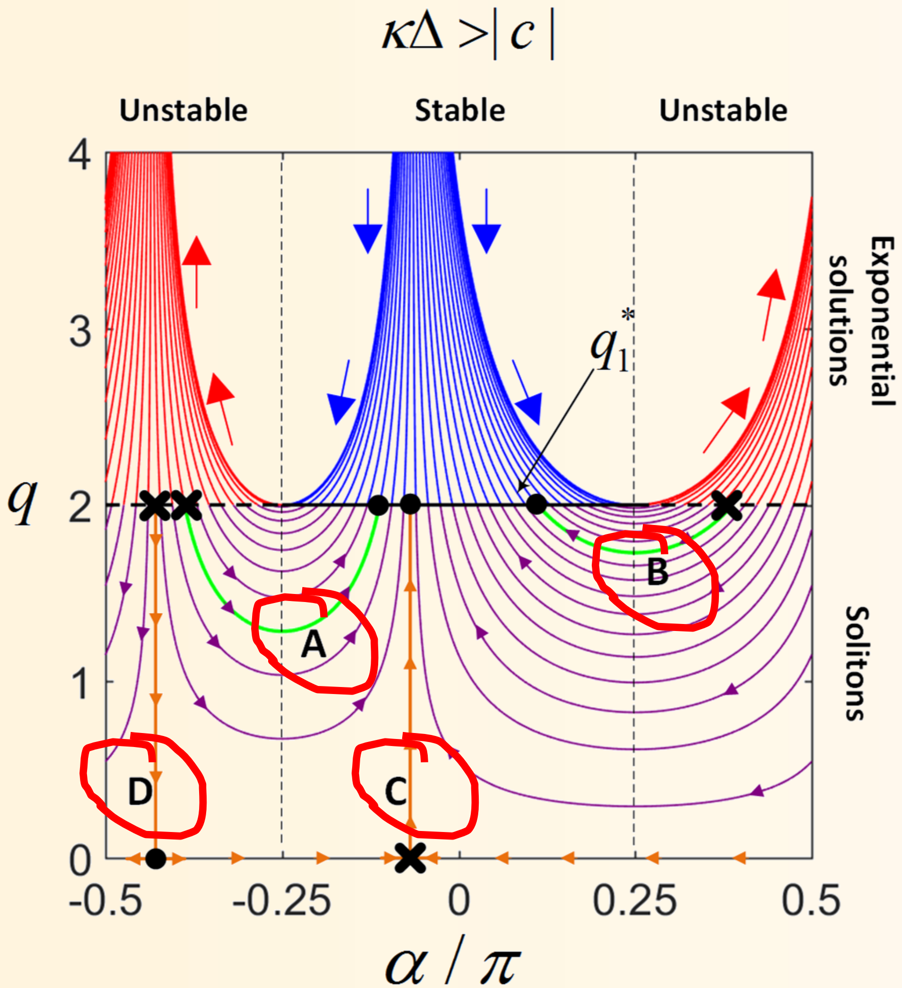
- Saddle (unstable) nodes (only if $|c| < \kappa\Delta$)

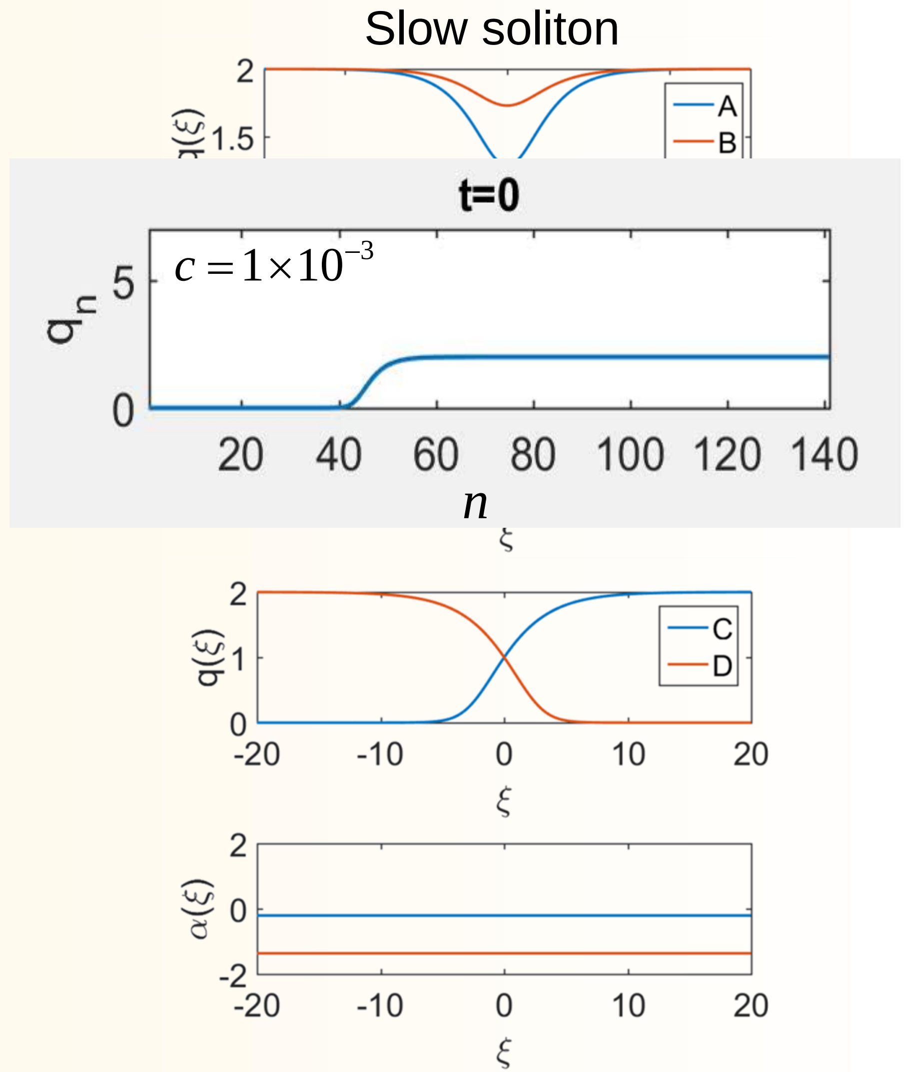
$$\underline{x}_2^* \to q_2^* = 0, \ \alpha_2^* = -0.5 \sin^{-1}[c/\kappa\Delta],$$

$$\underline{x}_3^* \to q_3^* = 0, \ \alpha_3^* = -\pi/2 - \alpha_2^*$$

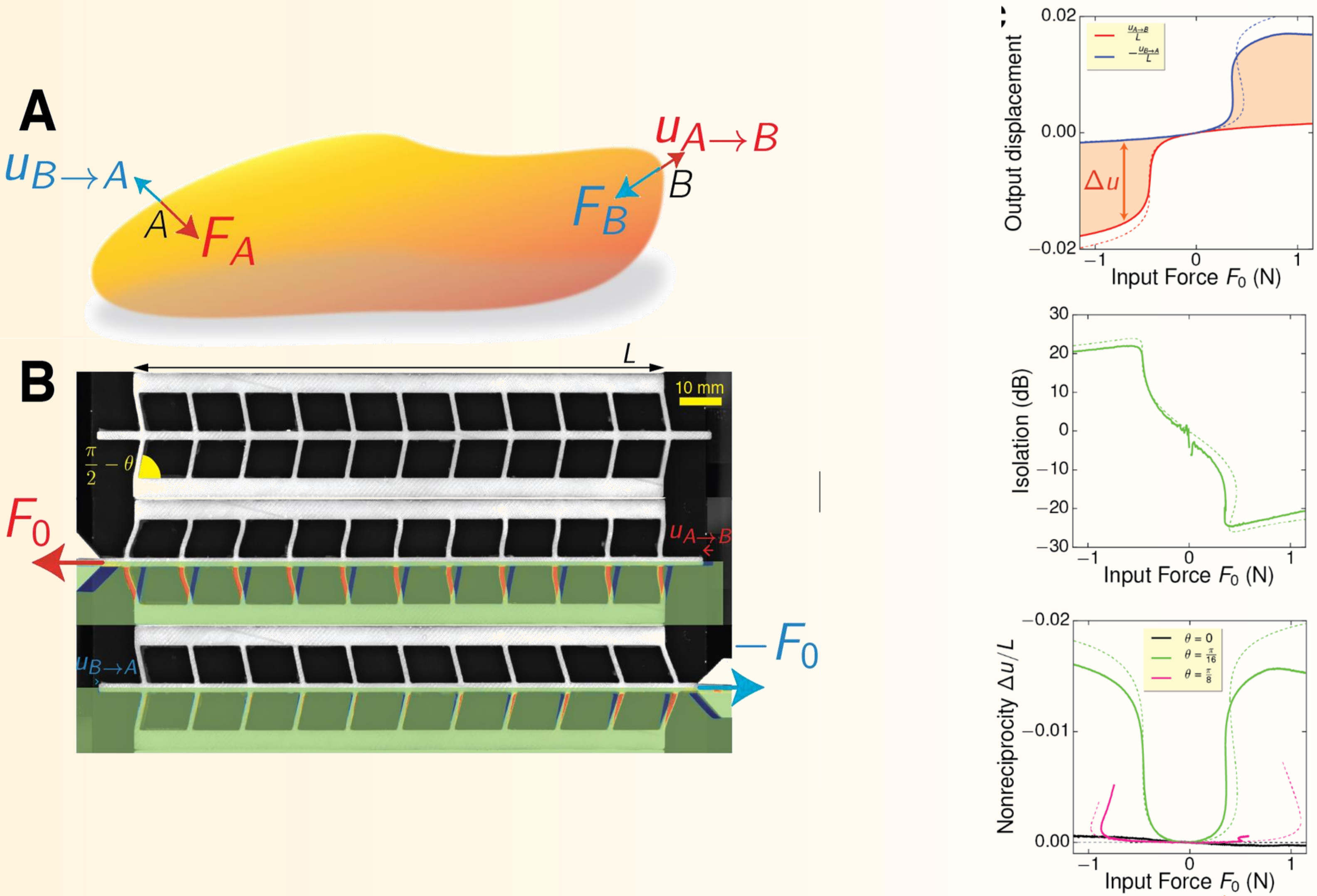


Phase Diagrams and Solitons



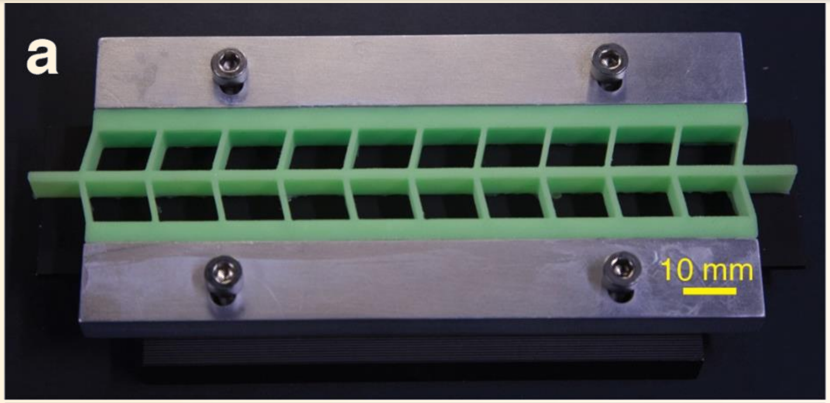


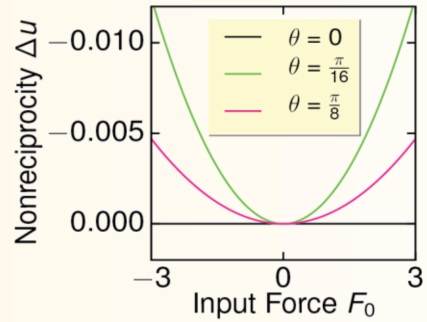
Non-Reciprocity in Statics

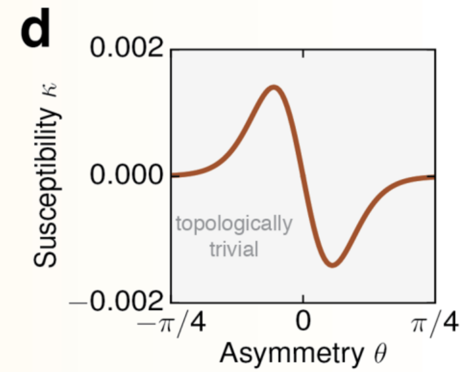


C. Coulais, D. Sounas, A. Alù, *Nature*, in press (2017)

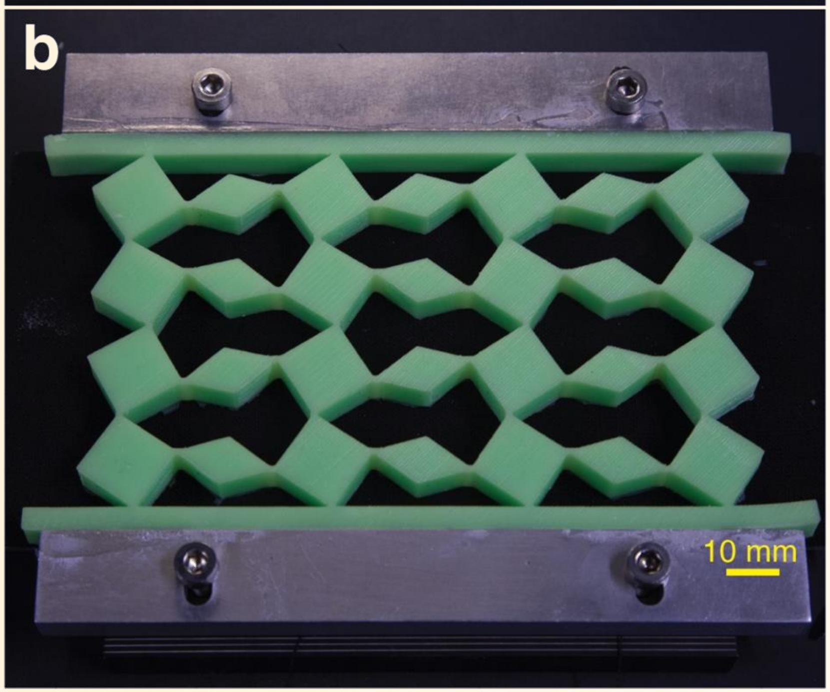
NON-RECIPROCITY IN STATIC TOPOLOGICAL METAMATERIALS

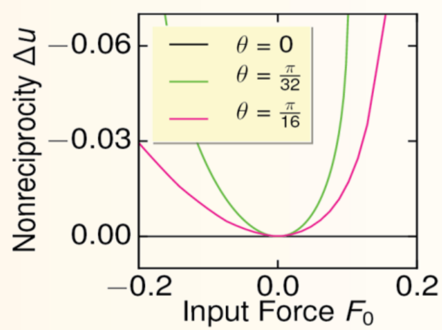


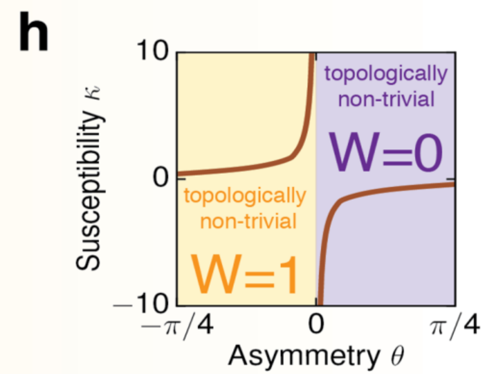




$$\Delta u = \kappa(\theta) {F_0}^2$$

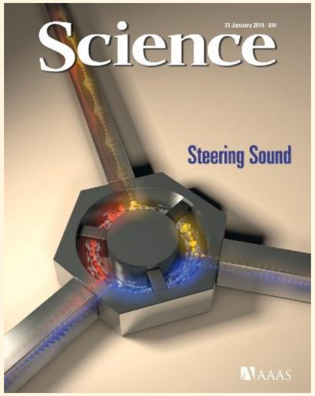


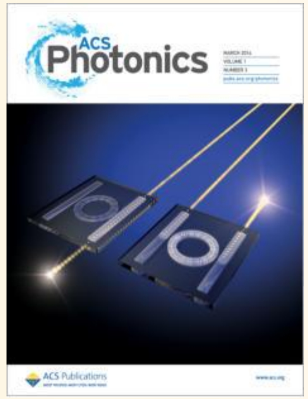




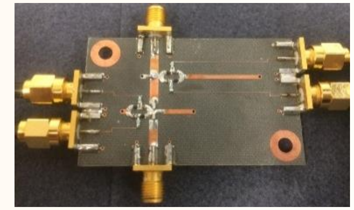
C. Coulais, D. Sounas, A. Alù, *Nature*, in press (2017)

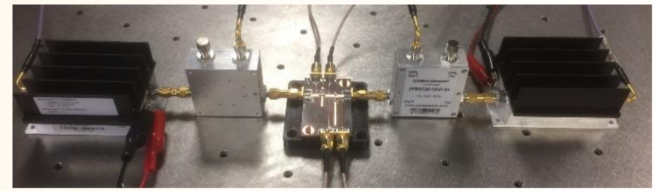
Topological Electromagnetics



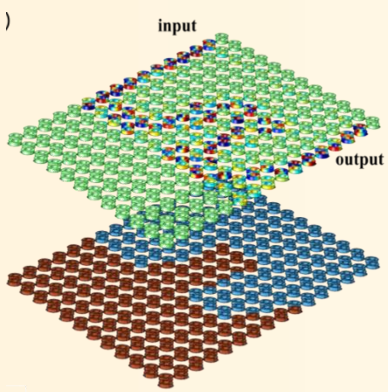


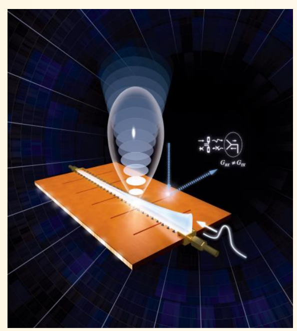
Magnetic-free, linear nonreciprocity at the subwavelength scale: angular-momentum biased meta-atoms



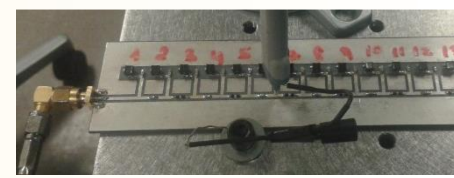


Nonlinearity and asymmetry to build bias-free isolators and non-reciprocal devices





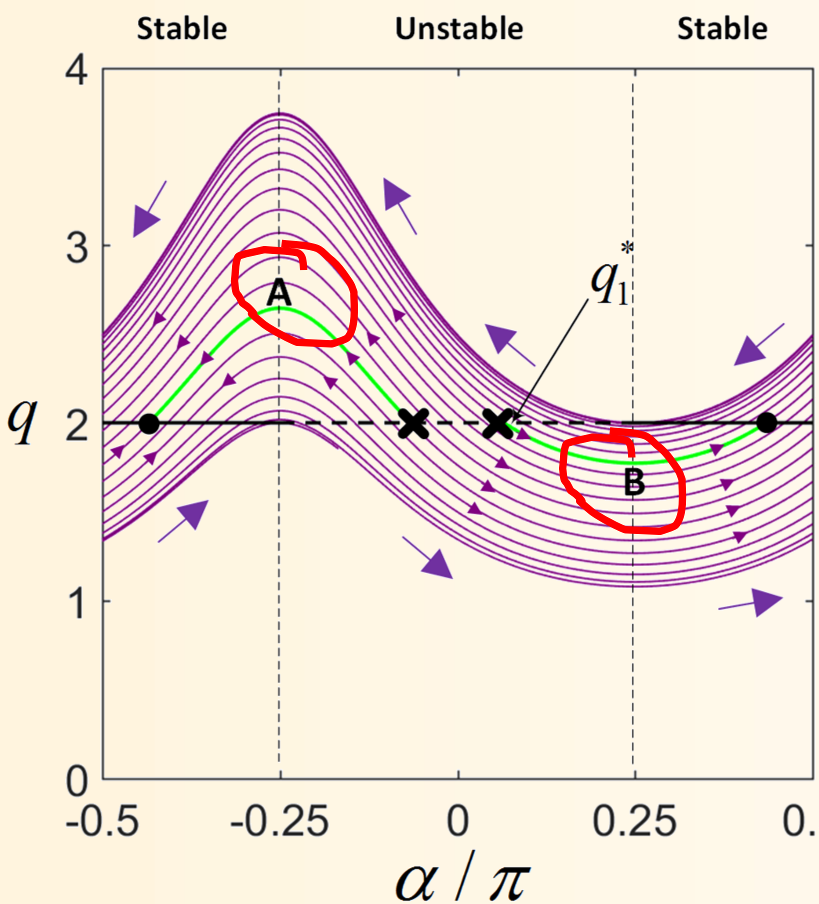
Topological protection in momentum-biased arrays for reconfigurable, broadband isolation and one-way signal transport



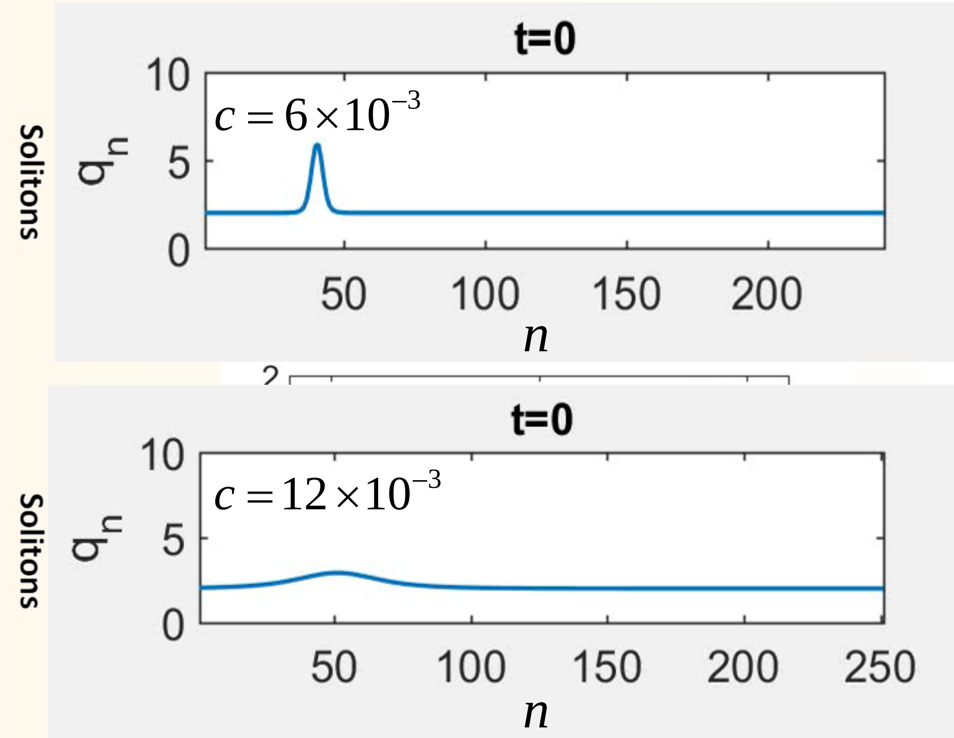
Intensity-induced topological protection in nonlinear arrays

Phase Diagrams and Solitons

$\kappa\Delta < |c|$



Fast soliton



Edge States

Limit case of moving solitons with ZERO velocity