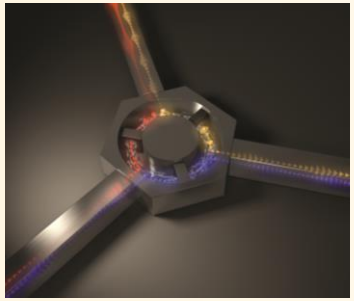
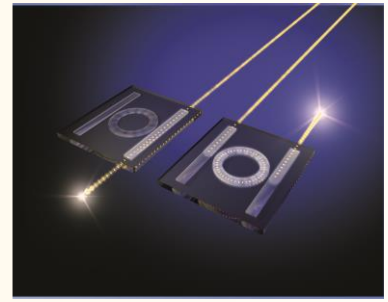
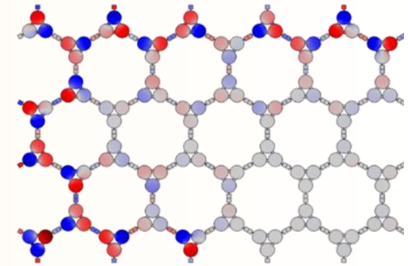


Topological Photonics and Phononics in Metamaterials

Andrea Alù

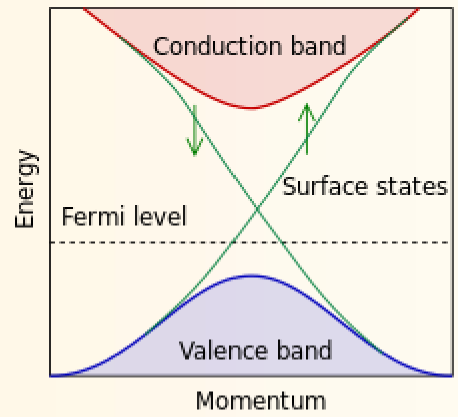
Credits to: **D. Sounas, Y. Radi, A. Kord, L. Quan, D. Farfan, Z. Xiao, H. Kwon, G. D'Aguanno**

Collaborators: **A. Khanikaev (CUNY), H. Krishnaswamy (Columbia), Y. Hadad (TAU), C. Coulais (AMOLF),**

Funding: **AFOSR, NSF, DARPA, Simons Foundation, Qualcomm, Lockheed Martin**

Department of Electrical and Computer Engineering, The University of Texas at Austin
http://users.ece.utexas.edu/~aalu, alu@mail.utexas.edu

Electronic Topological Insulators



A topological insulator is a material with non-trivial topological order, which enables the operation as an ***insulator*** in the bulk, but that ***conducts*** on the surface.

The conduction states are ***symmetry protected***, and they are associated with unsual phenomena, such as ***strong robustness to disorder***, and the ***quantum Hall effect***

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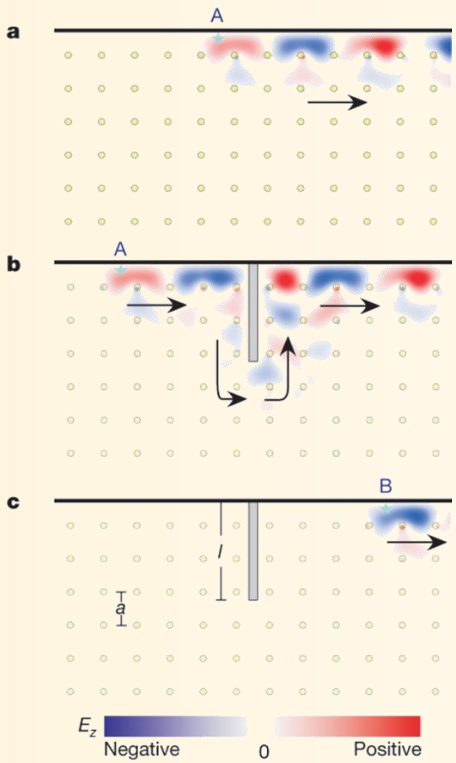
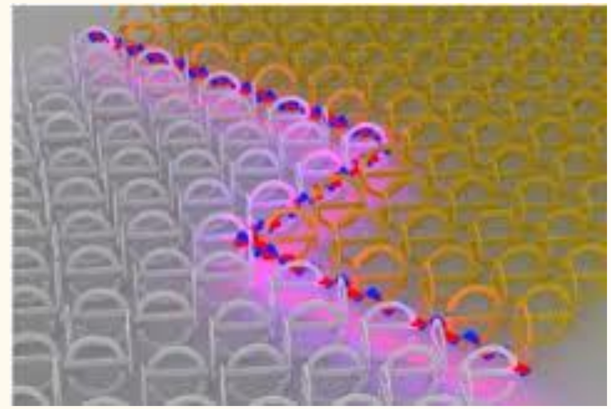
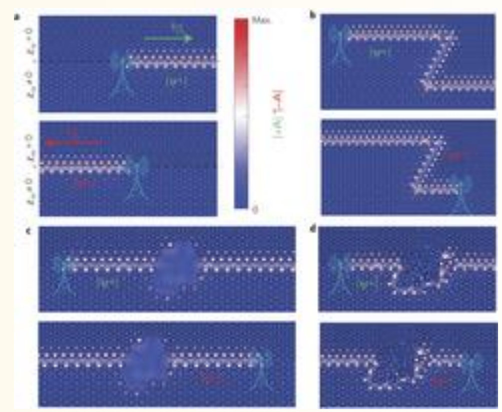
Photonic and Phononic Topological Insulators

Strong protection (non-reciprocal)



Weak protection (reciprocal)





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Z Wang, Y. Chong, J. D. Joannopoulos, M. Soljačić, *Nature* **461**, 772 (2009)
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NON-RECIPROCITY WITH MAGNETIC BIAS

Lorentz reciprocity theorem

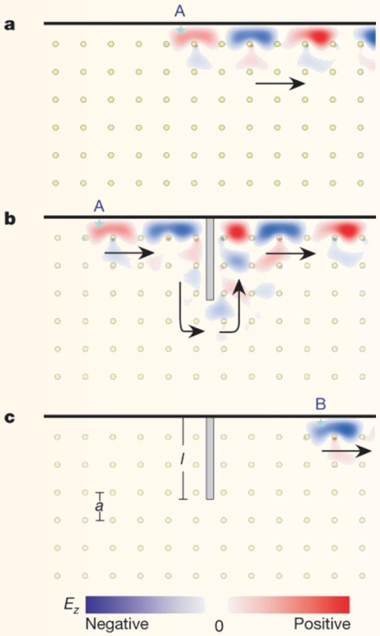
$$\iiint \mathbf{J}_1 \cdot \mathbf{E}_2 dV = \iiint \mathbf{J}_2 \cdot \mathbf{E}_1 dV$$

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

Time-invariant materials

Linear materials

Static Magnets



Z Wang, Y. Chong, J. D. Joannopoulos, M. Soljačić, *Nature* **461**, 772 (2009)

Breaking Reciprocity Constraints

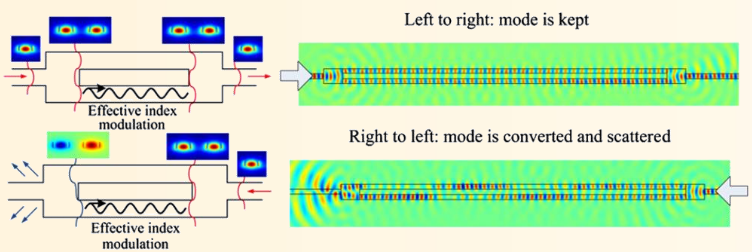
Lorentz reciprocity theorem

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

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

Time-invariant materials

Linear materials



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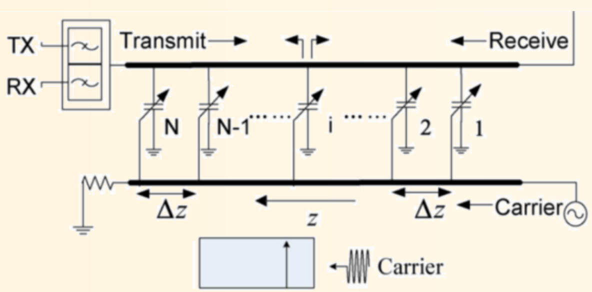

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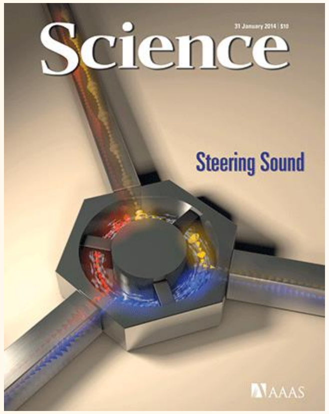

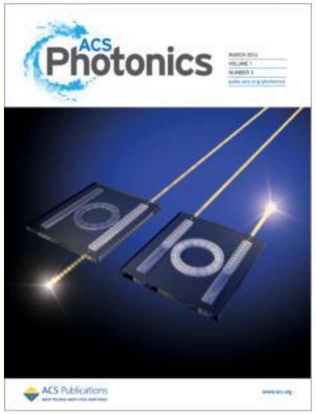

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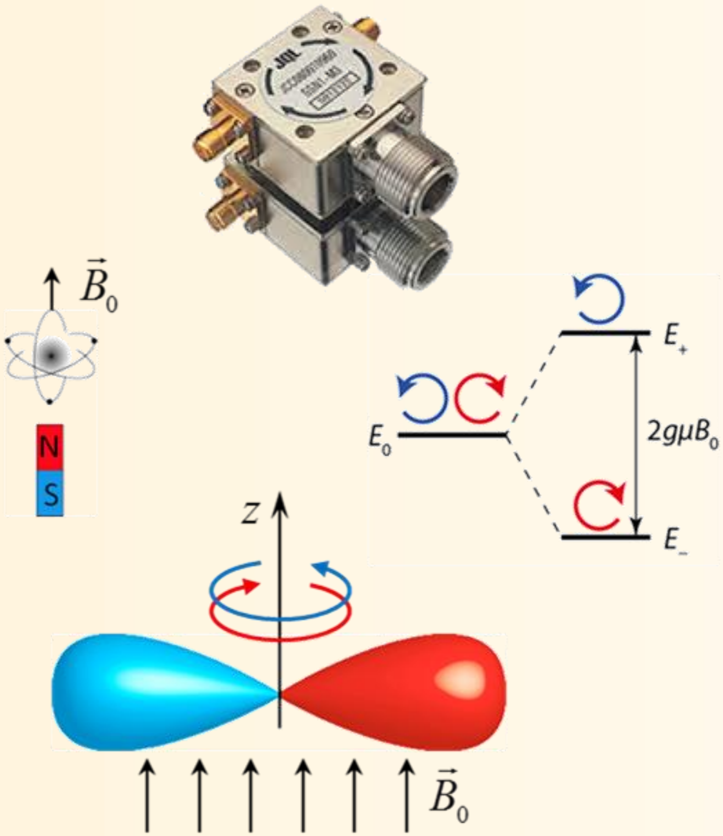
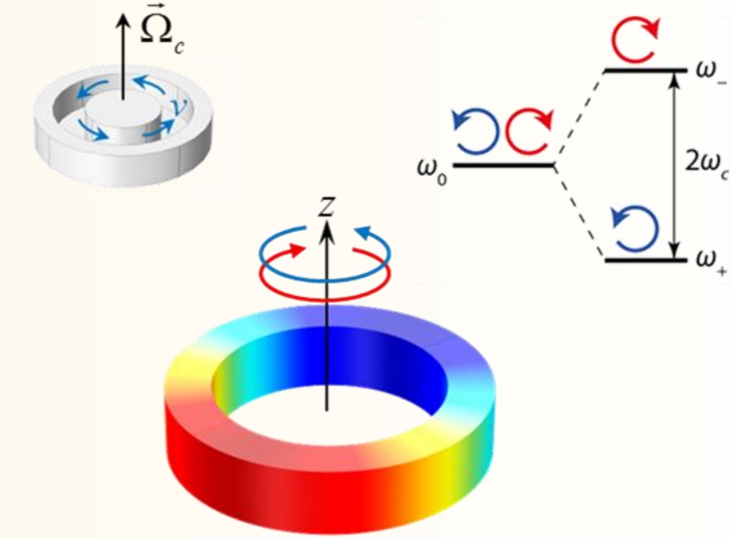
Estep, *Nature Phys.* **10**, 923 (2014)

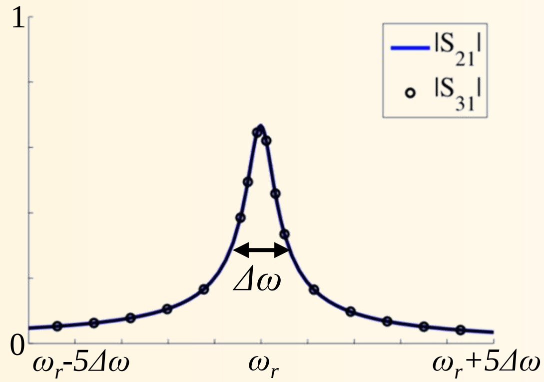
Angular-Momentum Biasing: a Zeeman Meta-Molecule

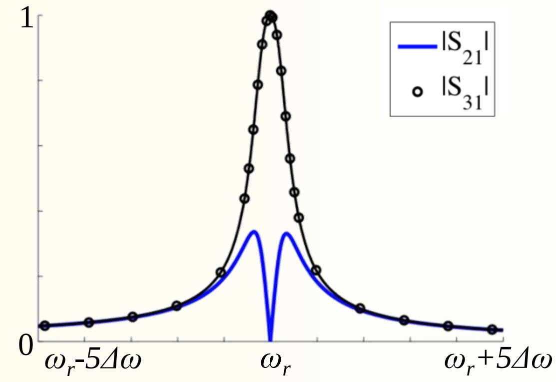


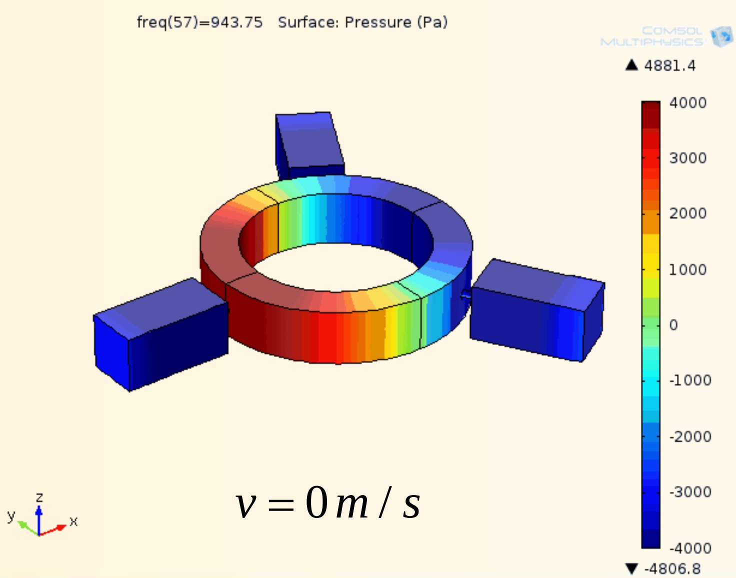


R. Fleury, D. L. Sounas, C. Sieck, M. Haberman, A. Alù, *Science* 343, 516 (2014)

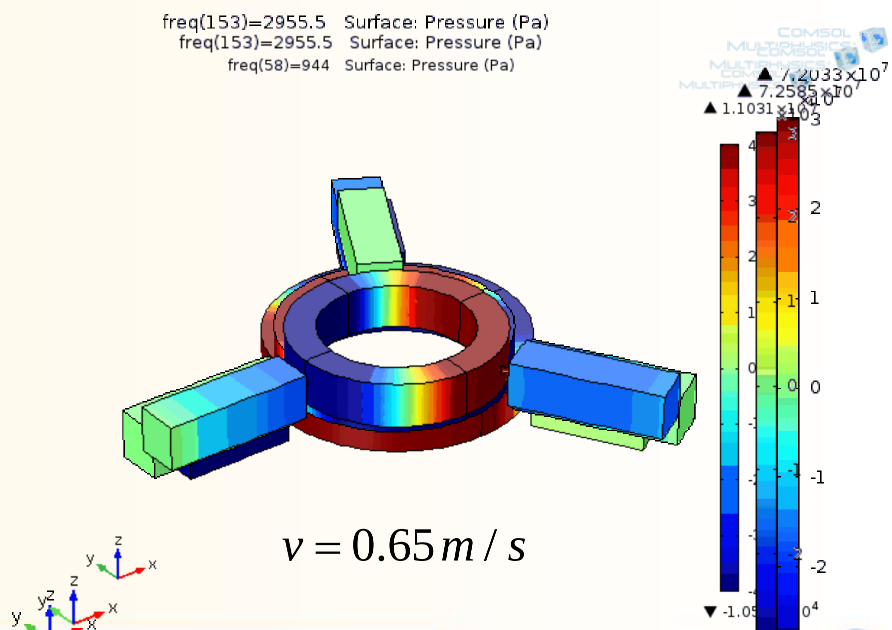
An Acoustic Circulator





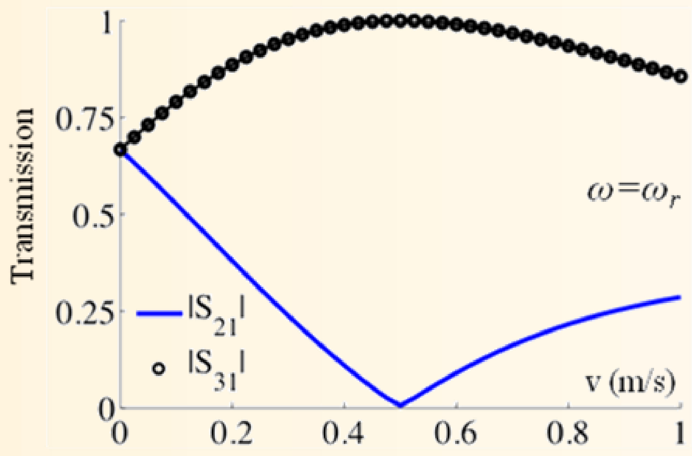


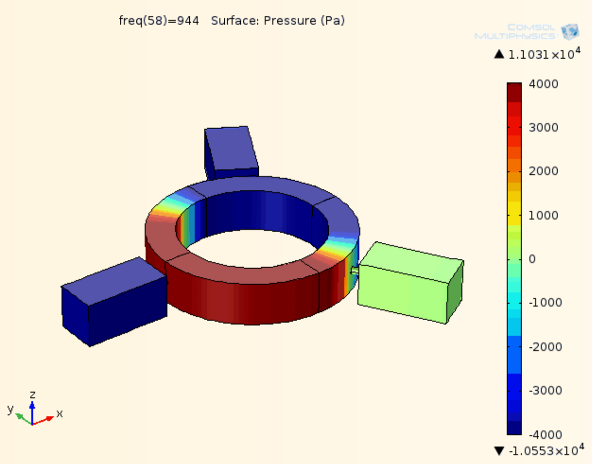
$v = 0\,m/s$



$v = 0.65\,m/s$

Mode Evolution





$$T_{1\to 2} = \left| \frac{2}{3} \left(\frac{e^{-i4\pi/3}}{1 - i(\omega - \omega^-)/\gamma^-} + \frac{e^{-i2\pi/3}}{1 - i(\omega - \omega^+)/\gamma^+} \right) \right|^2$$

$$T_{1\to 3} = \left| \frac{2}{3} \left(\frac{e^{-i2\pi/3}}{1 - i(\omega - \omega^-)/\gamma^-} + \frac{e^{-i4\pi/3}}{1 - i(\omega - \omega^+)/\gamma^+} \right) \right|^2$$

$$\omega^\pm = \omega_r \pm \gamma / \sqrt{3}$$

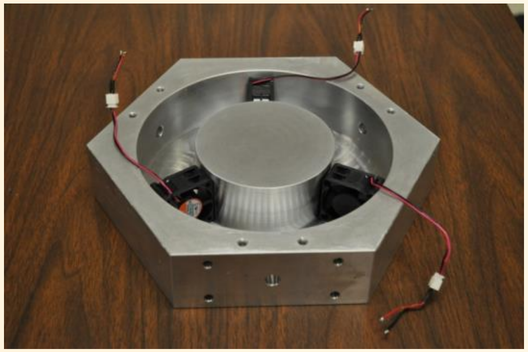
$$v_{opt} = \gamma R_{av} / \sqrt{3}$$

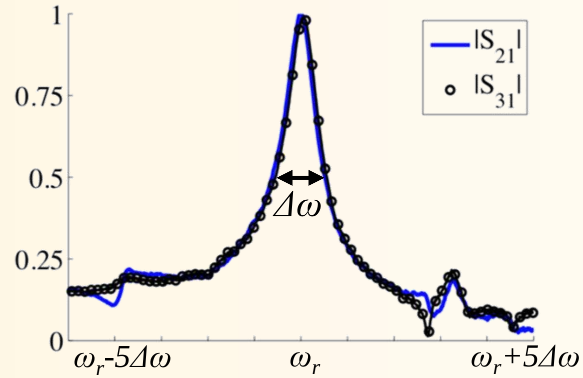
$\omega_0 = c_0 / R_{av}$ $Q = \omega_0 / (2\gamma)$

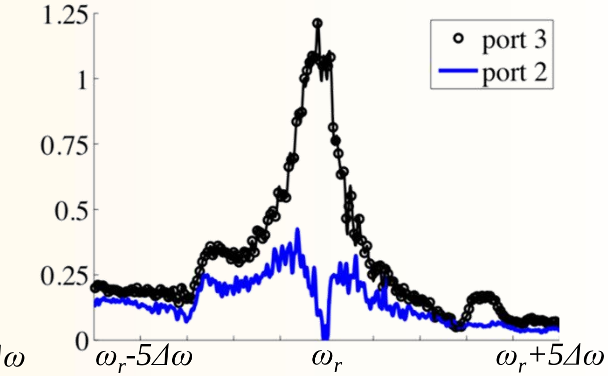
$$v_{opt} / c_0 = 1 / \left(2Q\sqrt{3} \right)$$

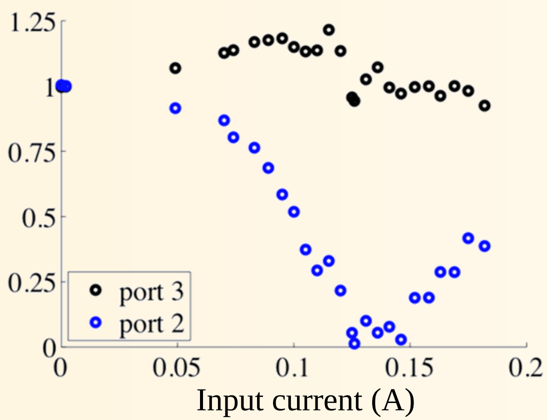
R. Fleury, D. L. Sounas, C. Sieck, M. Haberman, A. Alù, *Science* 343, 516 (2014)

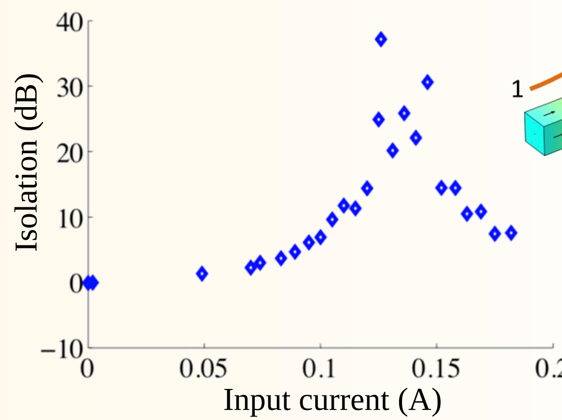
An Acoustic Circulator

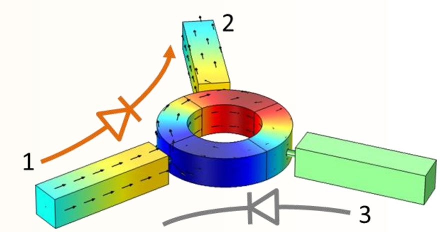








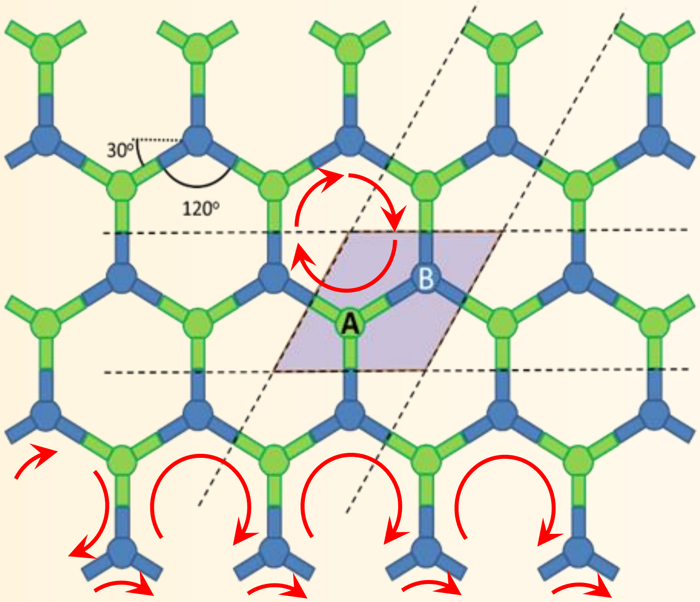




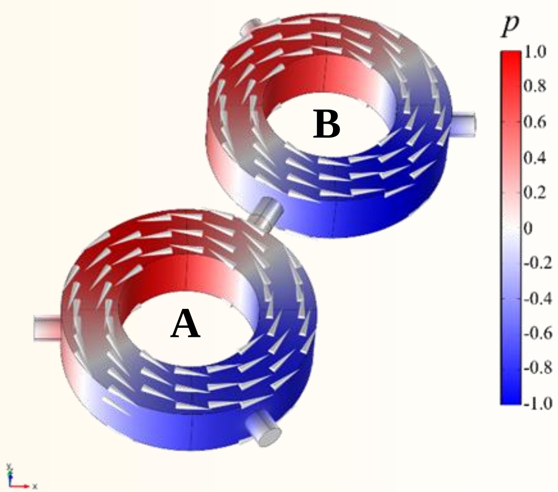
R. Fleury, D. L. Sounas, C. Sieck, M. Haberman, A. Alù, *Science* 343, 516 (2014)

Molding the Topology of the Acoustic Band Diagram

Lattice

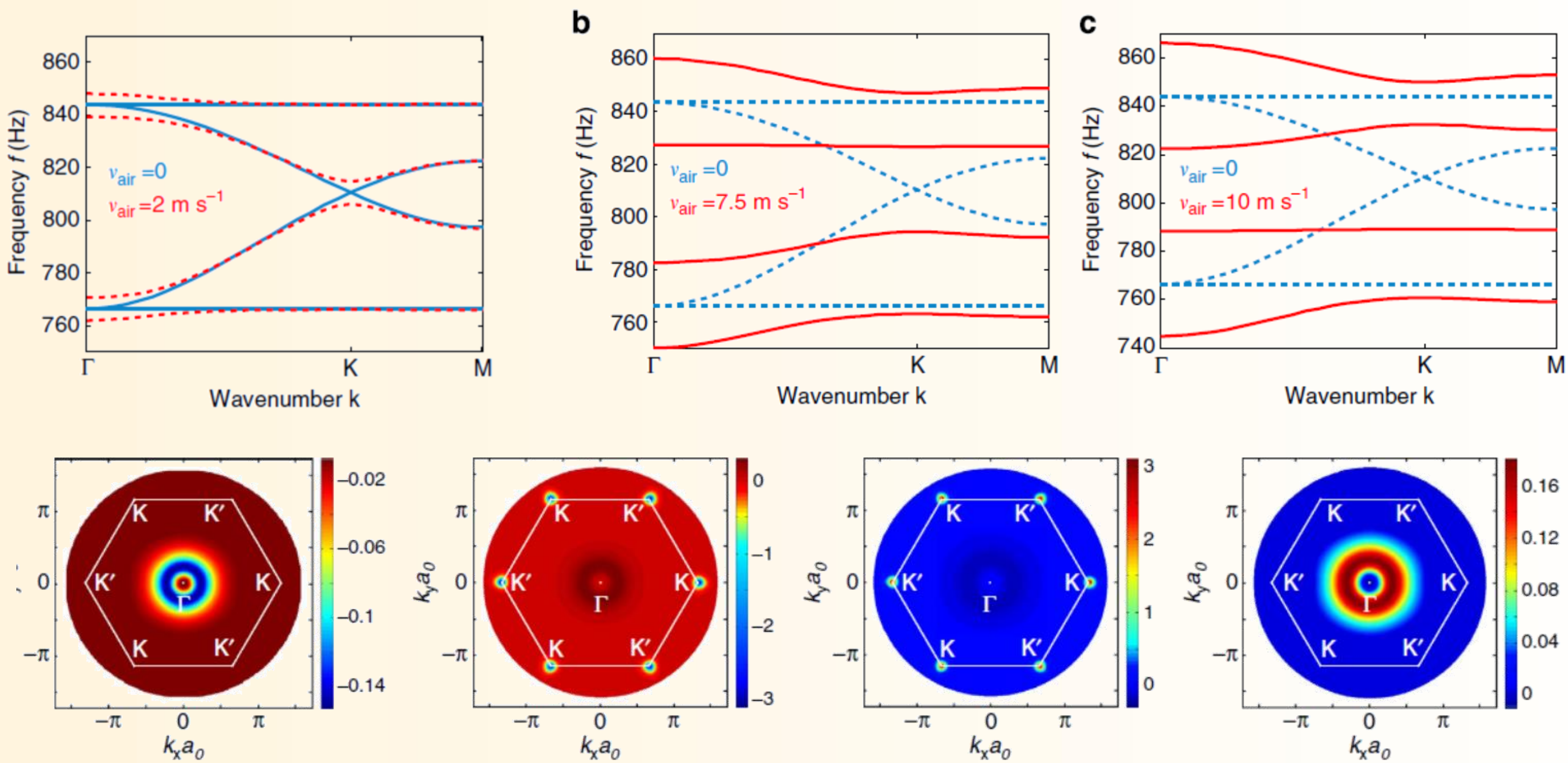


Unit Cell



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

Non-Trivial Topology of the Band Structure



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

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

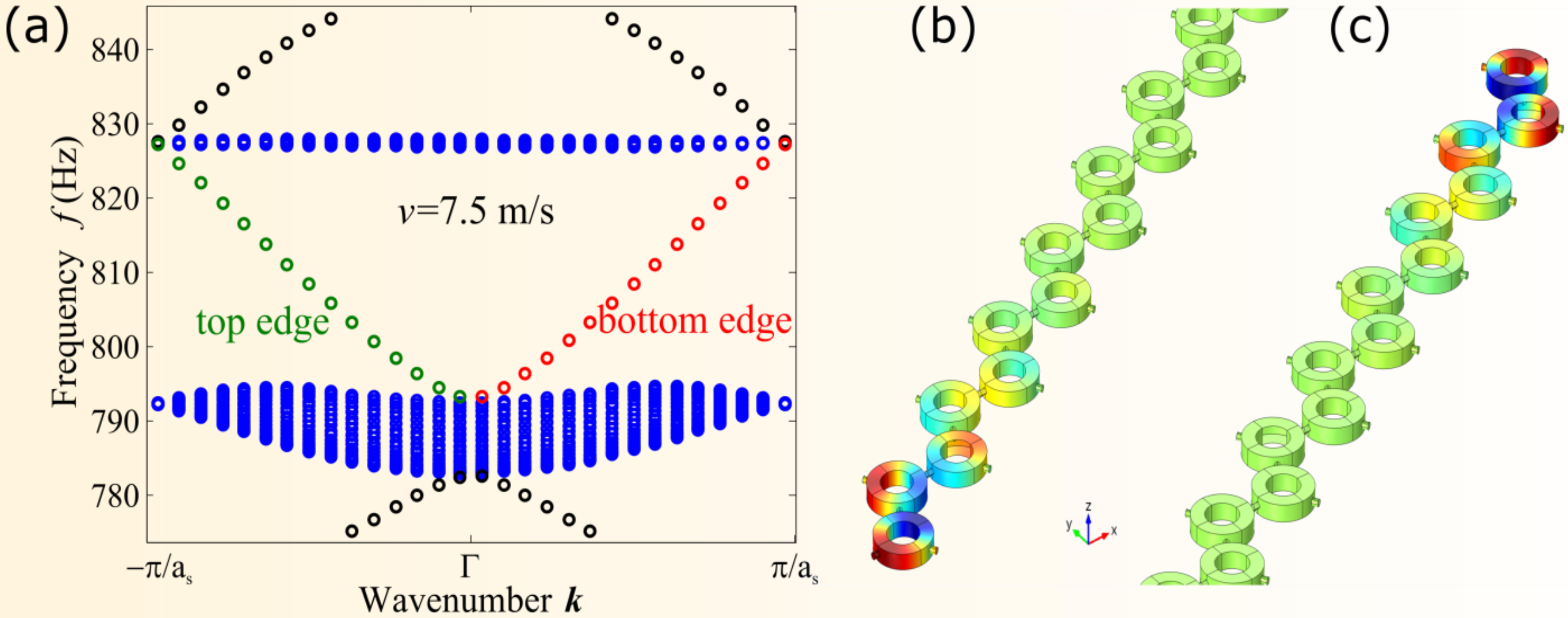
$$\mathbf{A}_\mathbf{k} = -i\langle p|\partial_\mathbf{k}|p\rangle$$

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

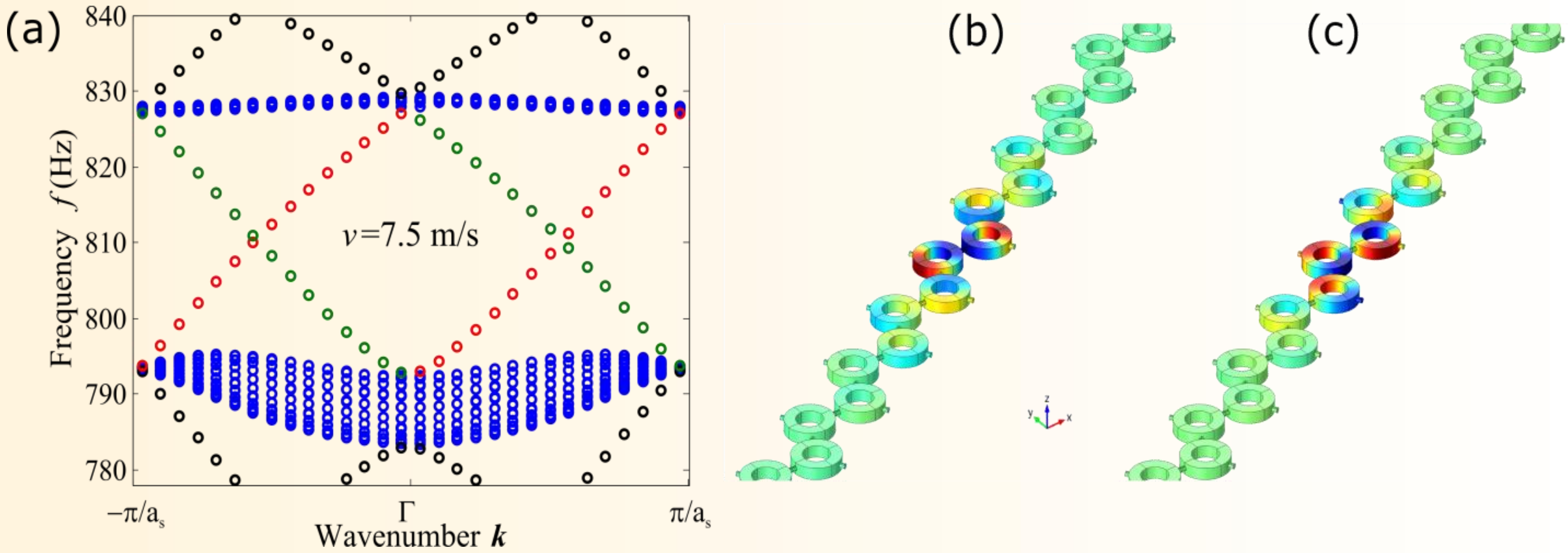
$C = \{1, 0, 0, -1\}$ counterclockwise

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

Topological Metamaterials

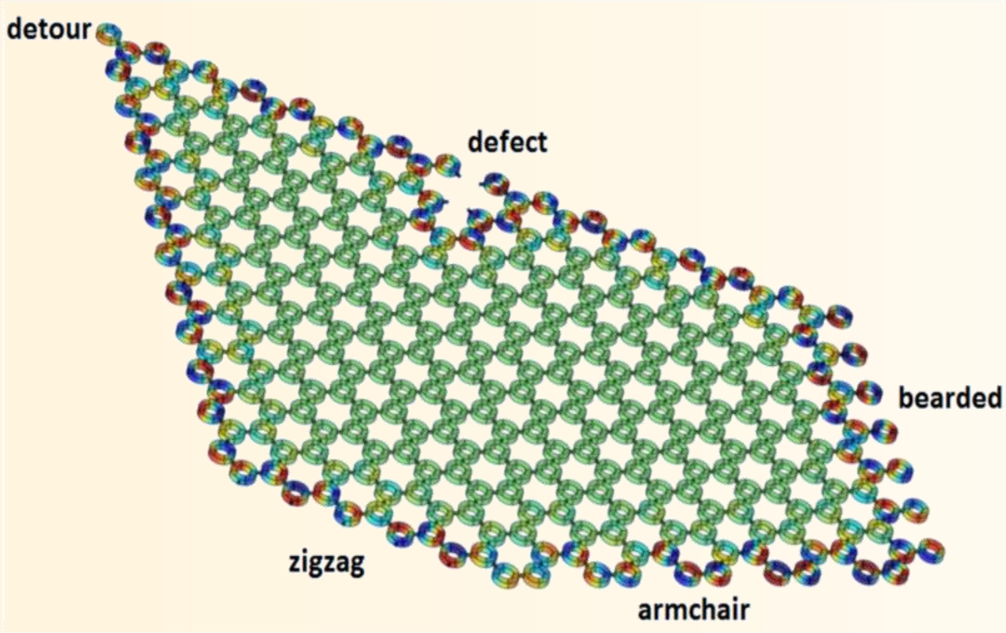


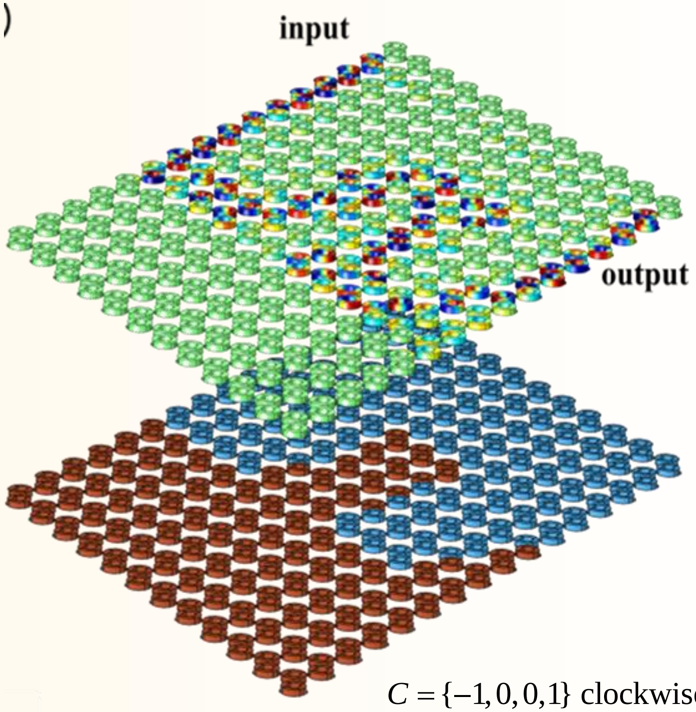
Topological Metamaterials



Topological Phononic Metamaterials

Reconfigurable waveguides, broadband isolators…



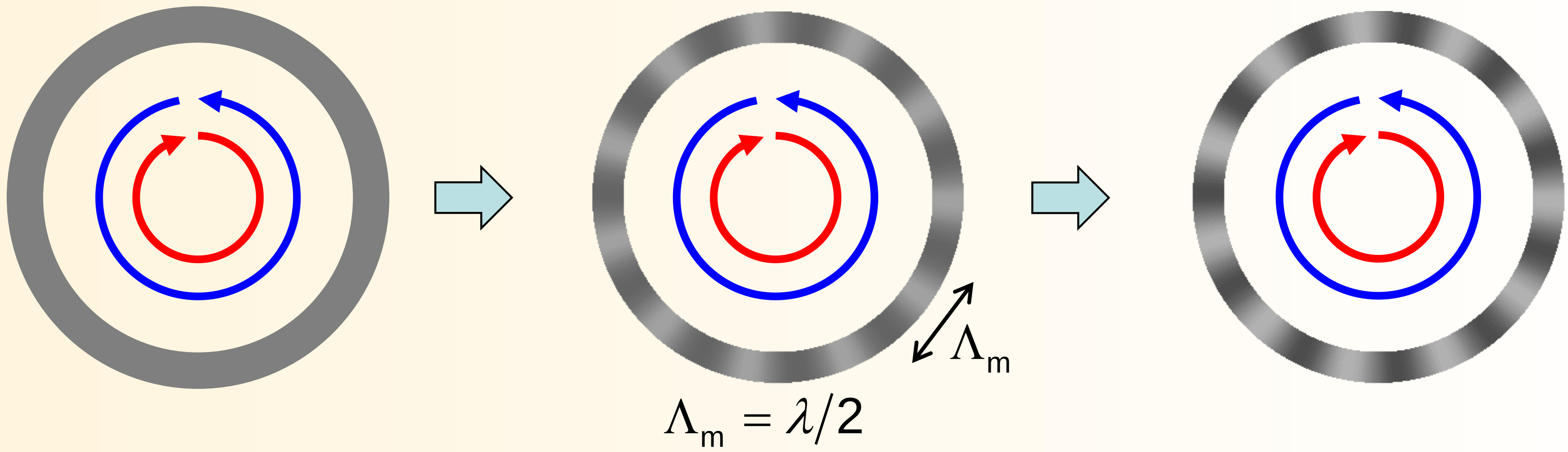


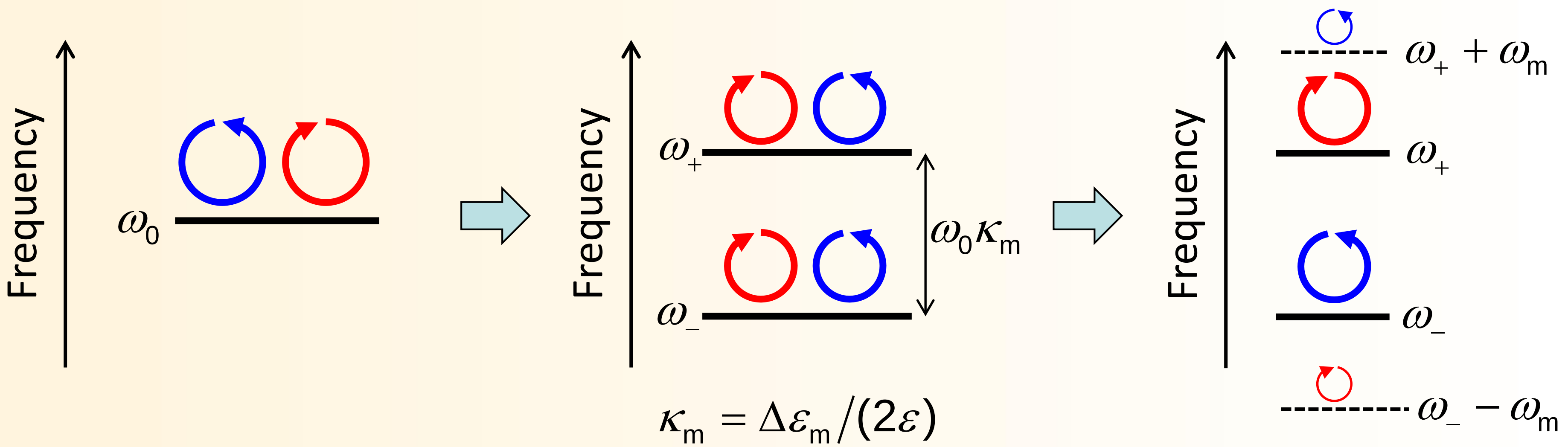
$C = \{-1, 0, 0, 1\}$ clockwise

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

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

Effective Spinning with Spatiotemporal Modulation



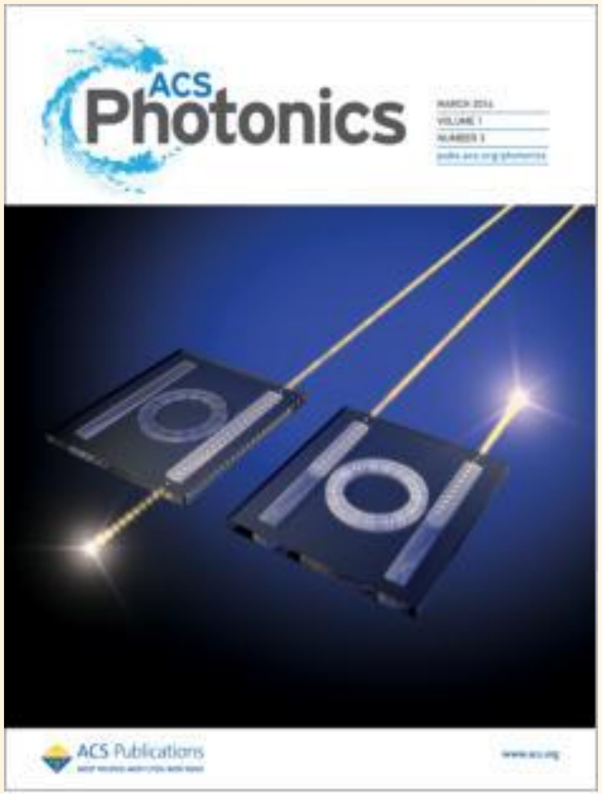


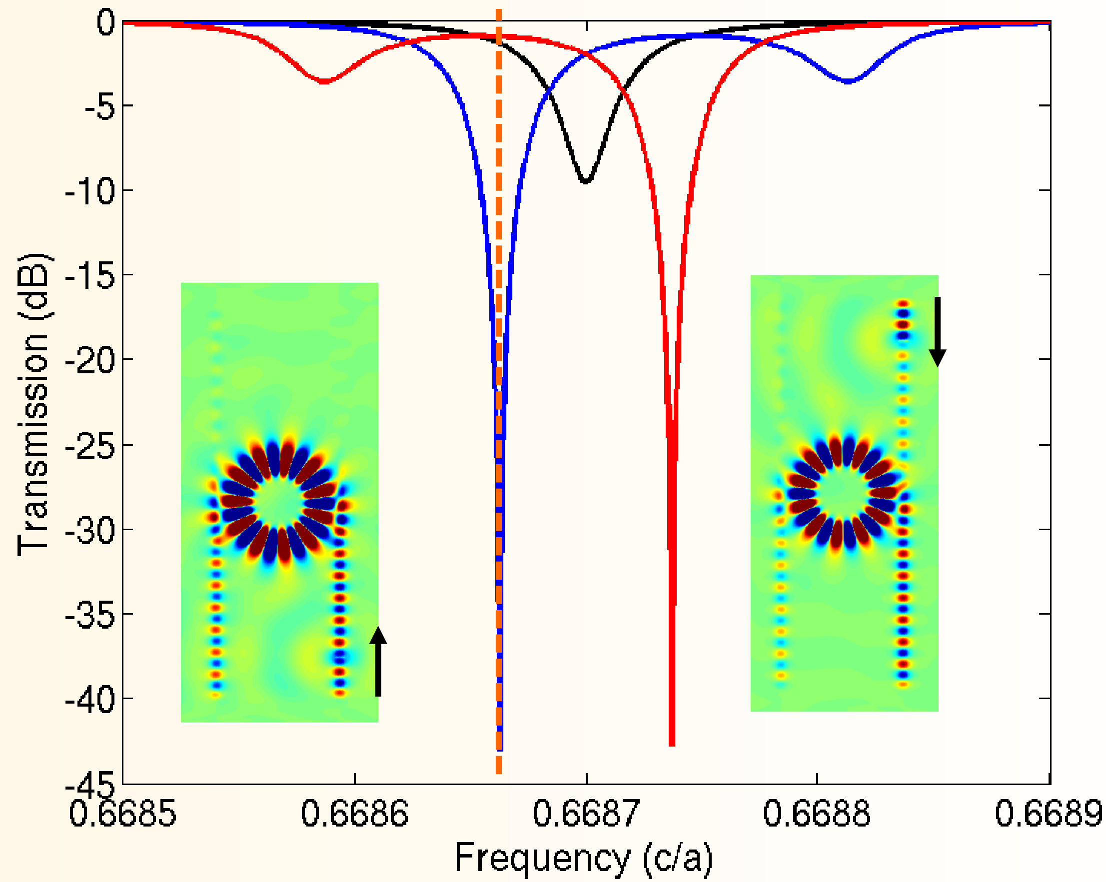
Angular-Momentum-Biased Optical Isolator

$$\Delta\varepsilon_m = 5\times10^{-4}\varepsilon \;!$$

$$Q \sim 7{,}000$$

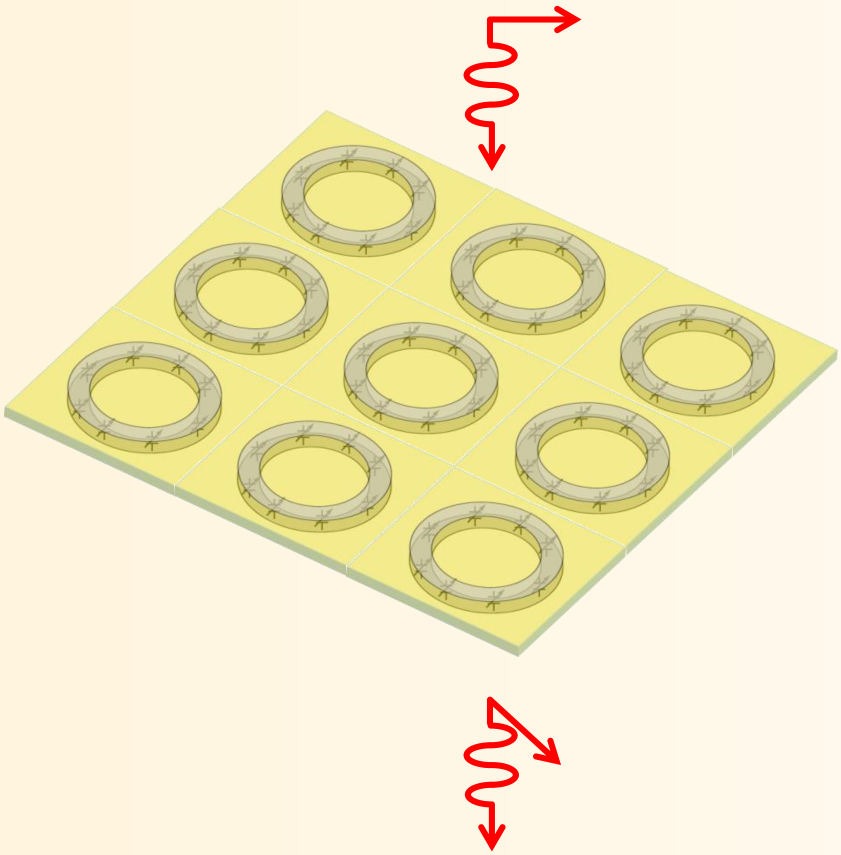
$$Q\Delta\varepsilon_m \approx 1$$

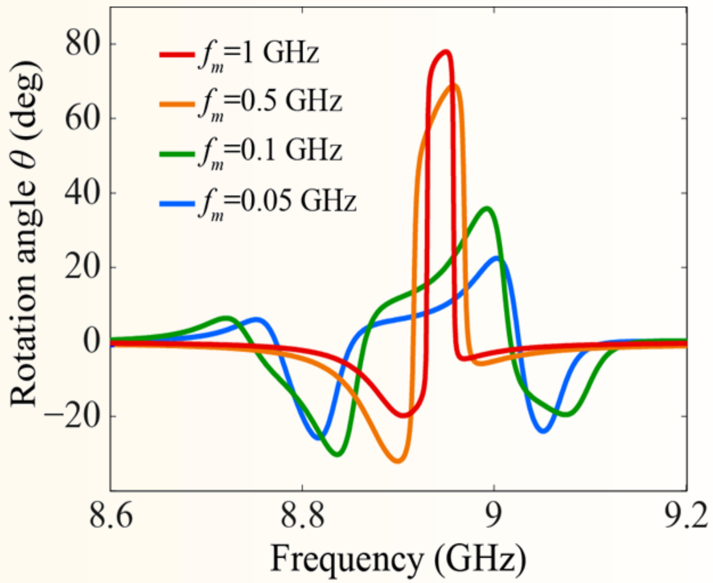




D. L. Sounas, A. Alù, *ACS Photonics* 1, 198 (2014)

Angular-Momentum Non-Reciprocal Metasurface

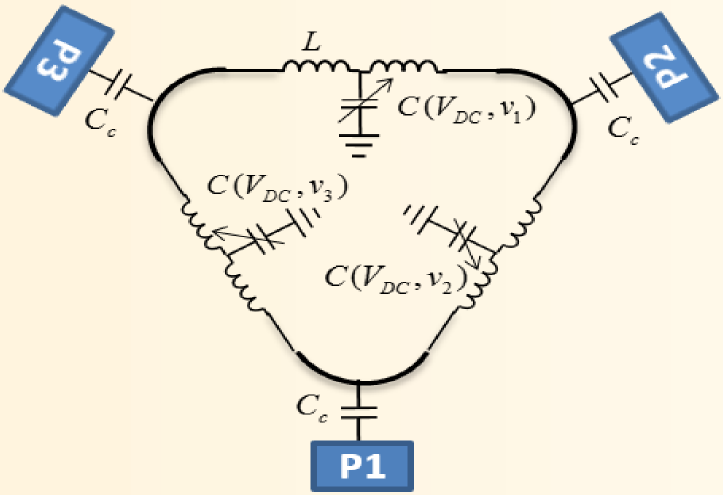


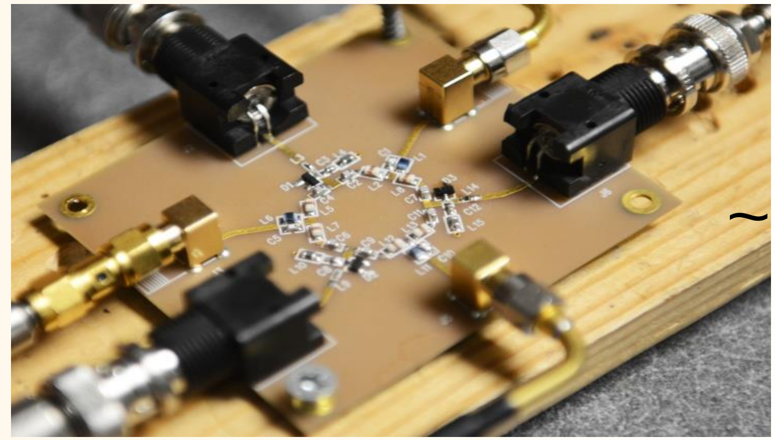


6000 deg/wavelength!

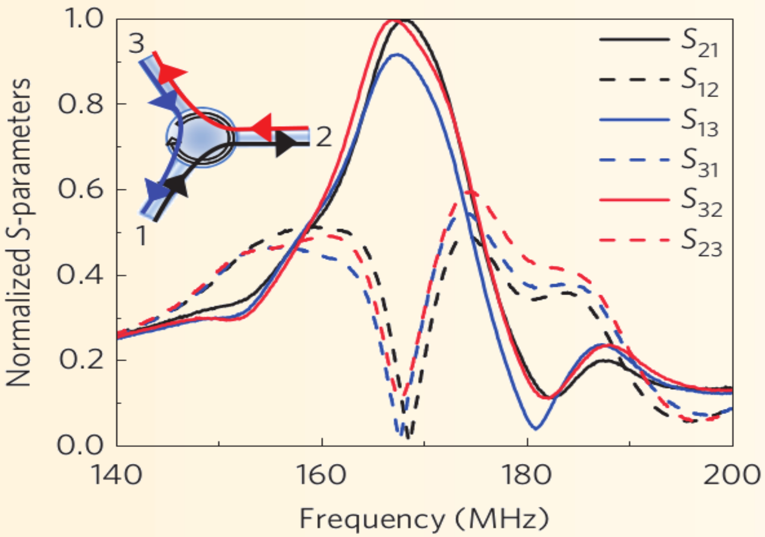
D. L. Sounas, C. Caloz, and A. Alù, *Nature Commun.* **4**, 2407 (2013)

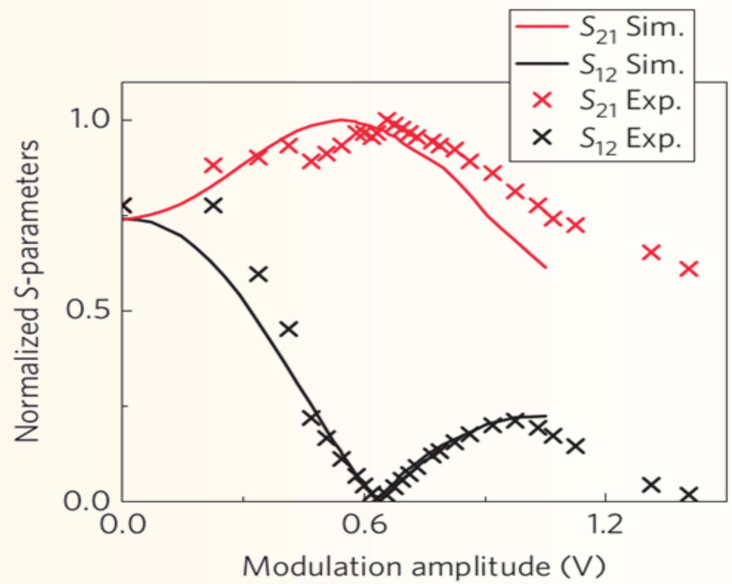
RF Magnet-Less Integrated Circulator





~ $\lambda/70$

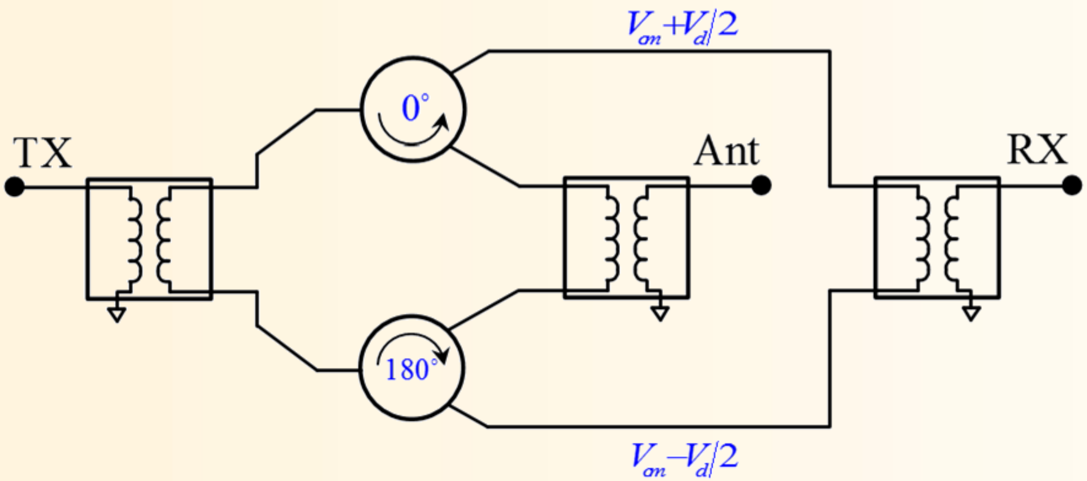


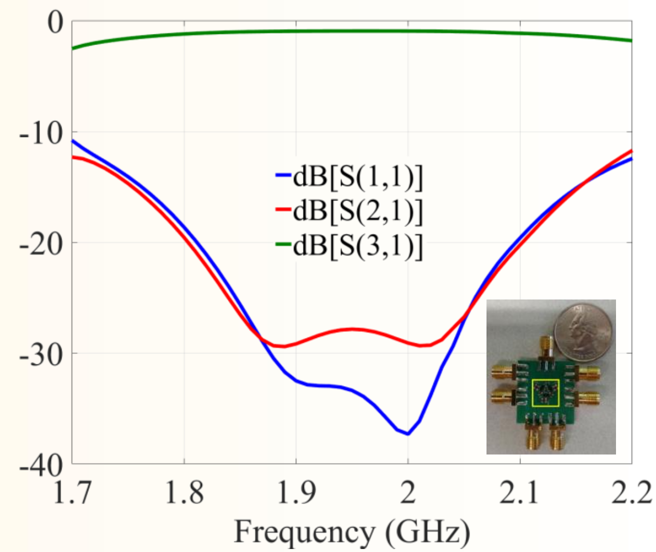


N. A. Estep*, D. L. Sounas*, J. Soric, and A. Alù, *Nature Phys.*, **10**, 923 (2014)

RF Circulator with Coupled Modulated Resonators

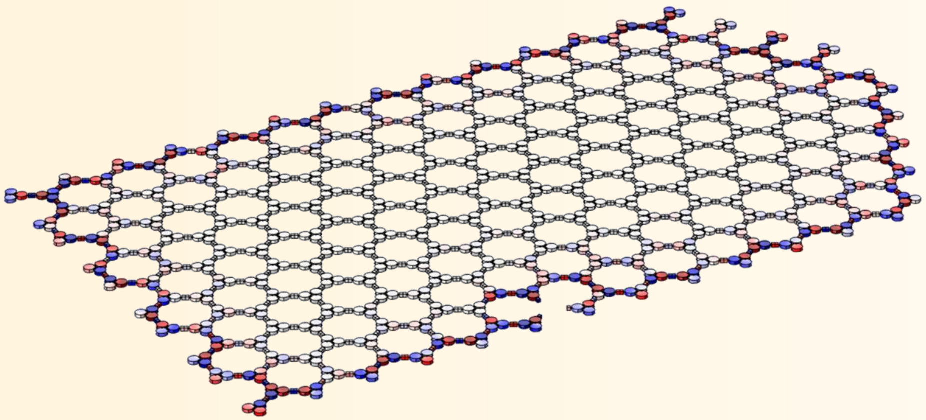
Differential 1st Order Bandpass Delta

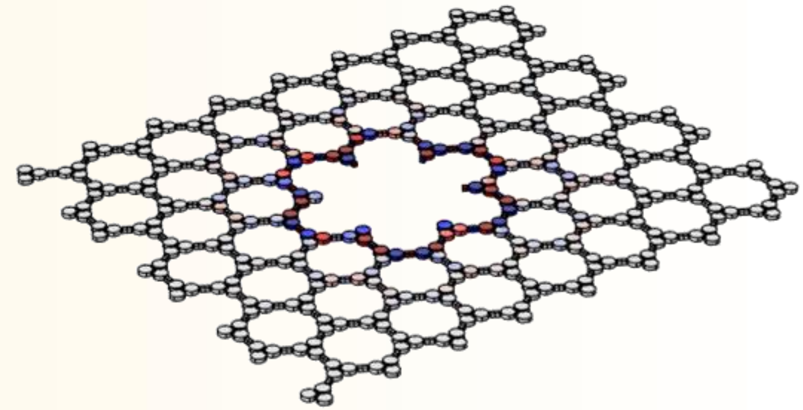


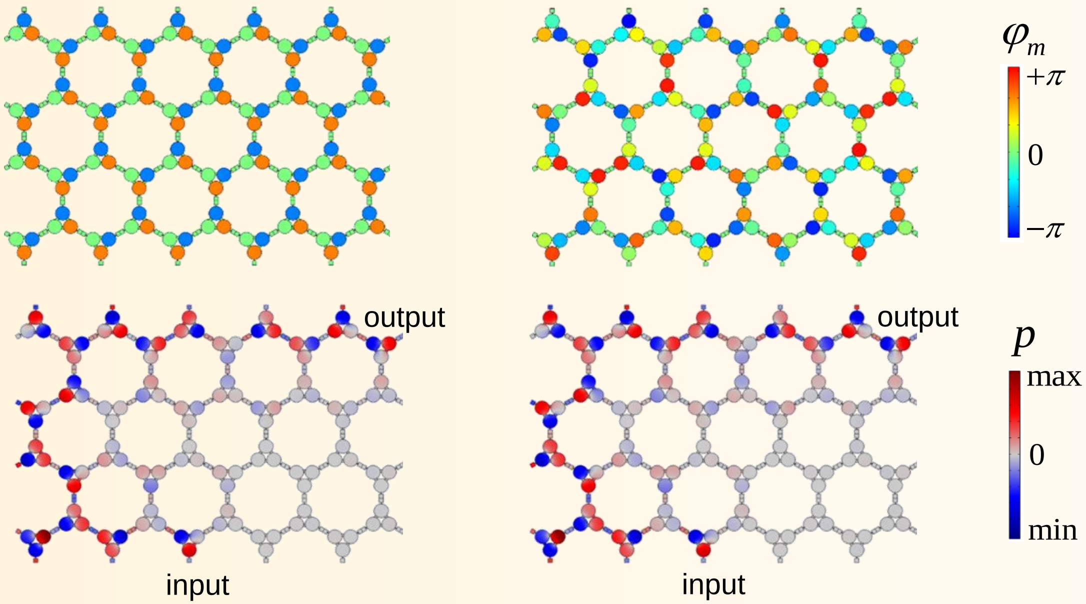


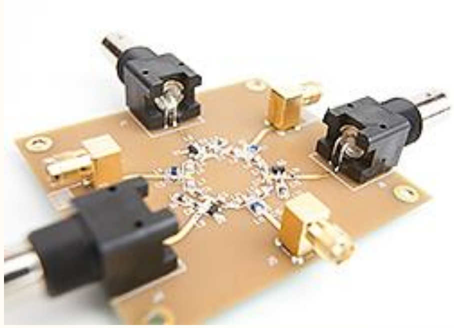
- Reduction of all IM products (entire cancellation without random mismatches)
- Improves several metrics including IL and BW
- Reduces modulation frequency and power consumption
- Allows the use of less-scaled technologies to improve power handling

Floquet Topological Insulators for EM Waves



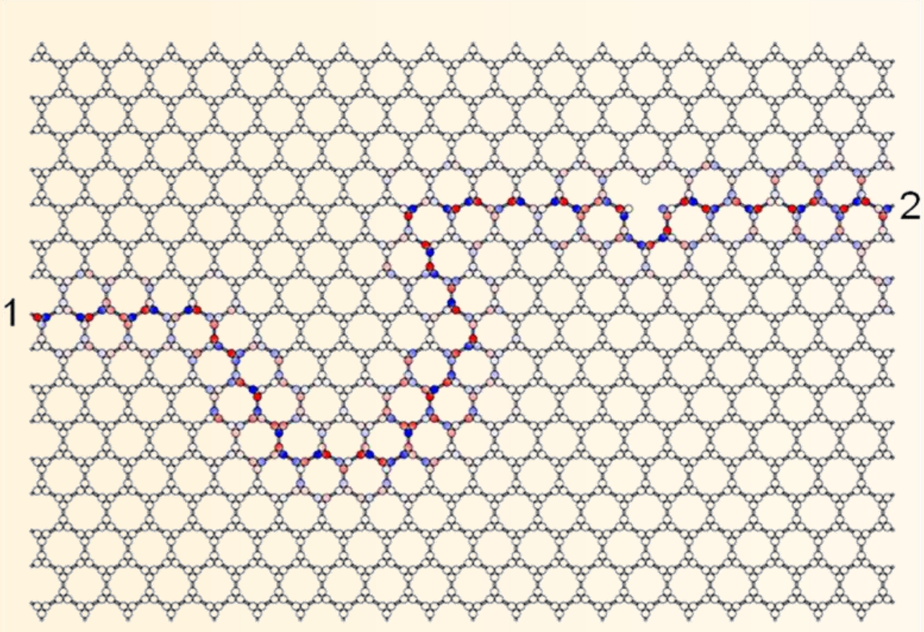


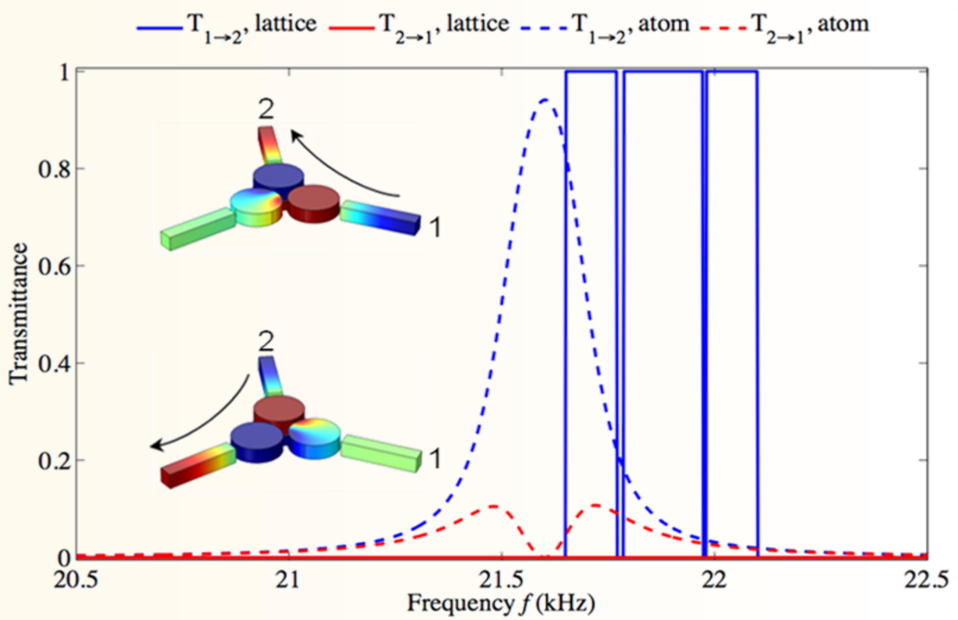




N. Estep. D. Sounas. A. Alù, *Nature Physics* **10**, 923 (2014)
R. Fleury, A.B. Khanikaev and A. Alù,, *Nature Communications*, **7**, 11744 (2016)

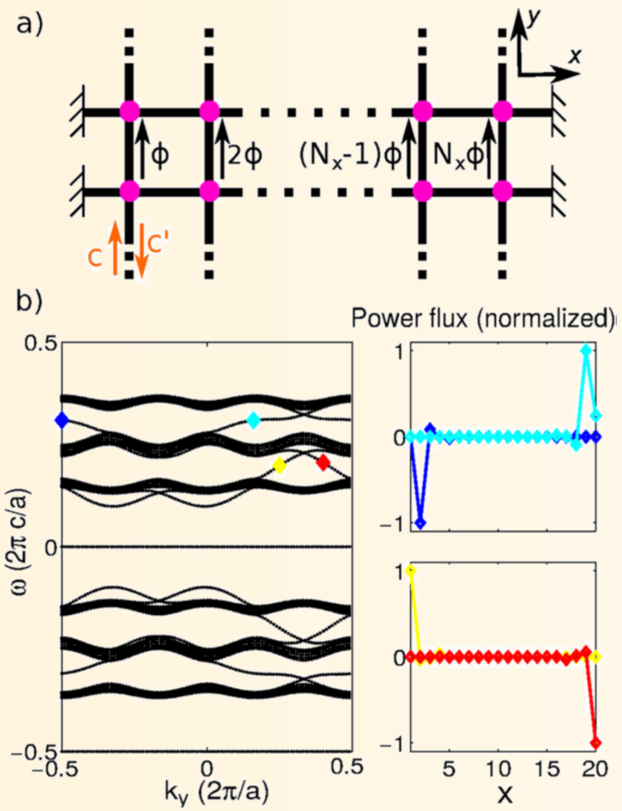
Continuous Bandwidth of Isolation

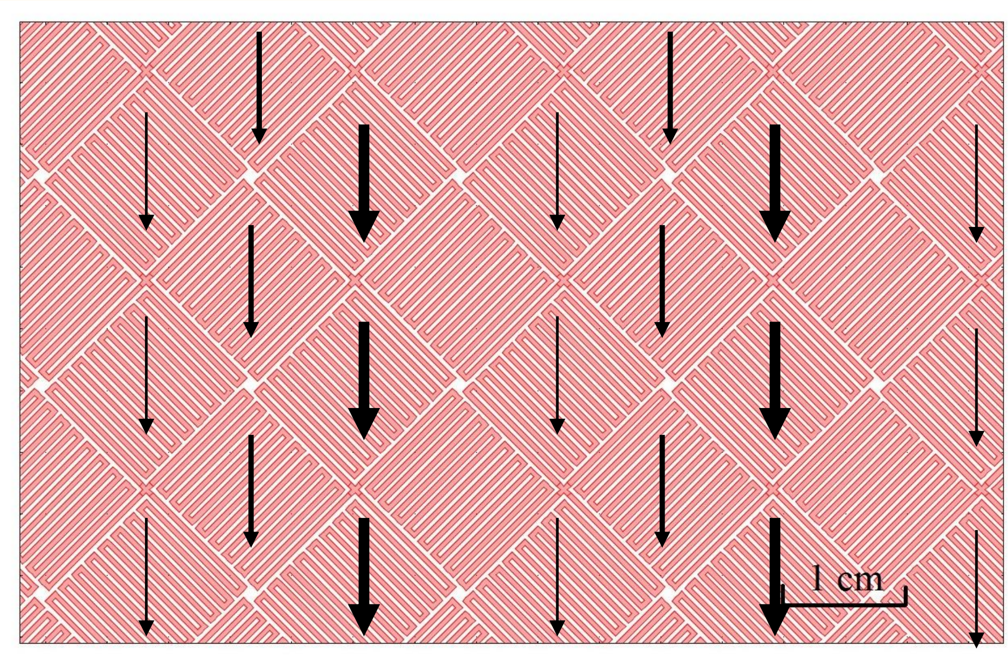




R. Fleury, A.B. Khanikaev and A. Alù,, *Nature Communications*, **7**, 11744 (2016)

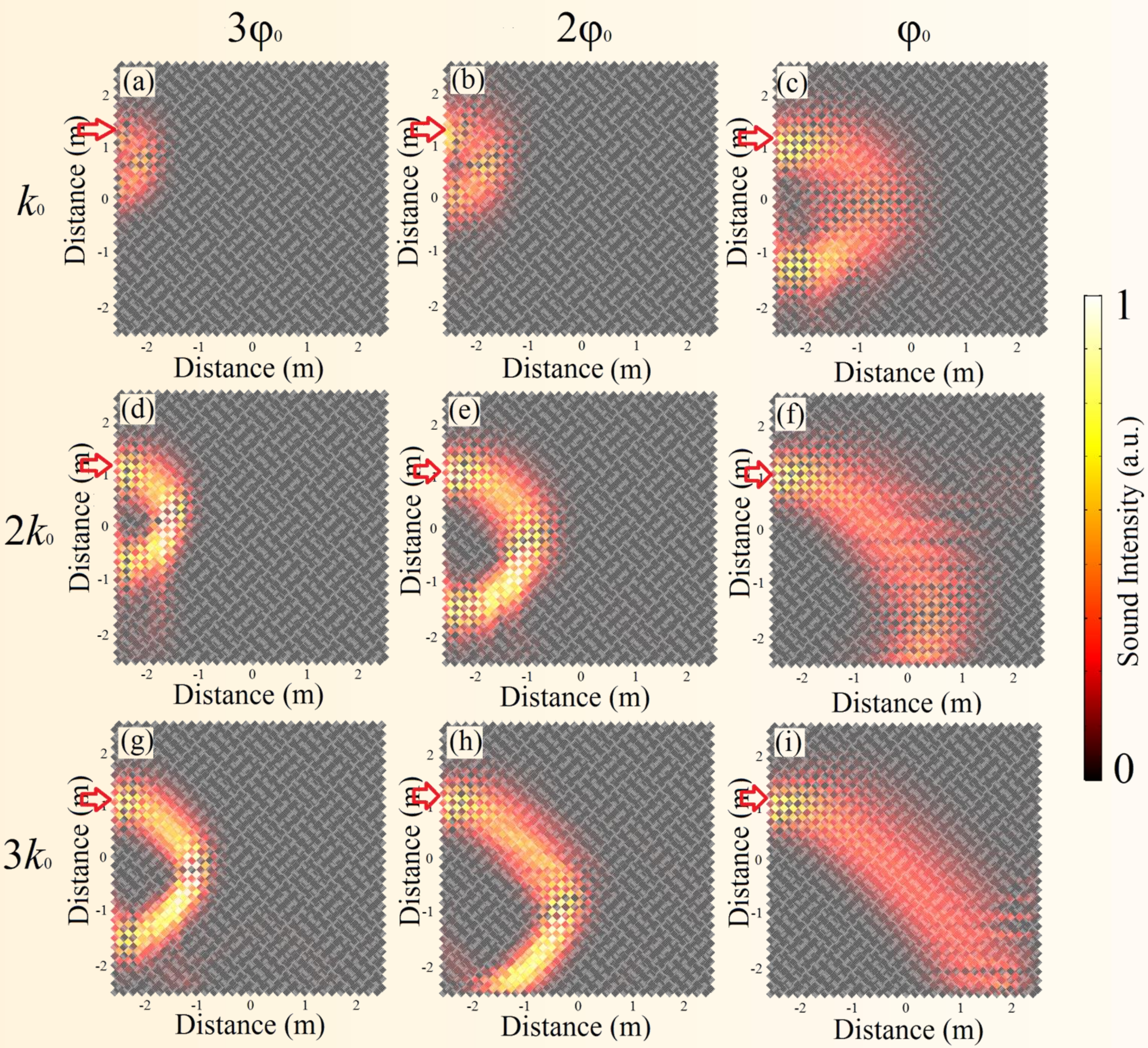
Phase Gradients to Induce Topological Protection





Q Lin, S. Fan, *New J. Phys.* **17**, 075008 (2015)

Effective Gauge Field Bias



$\varphi_0 = 5\deg$

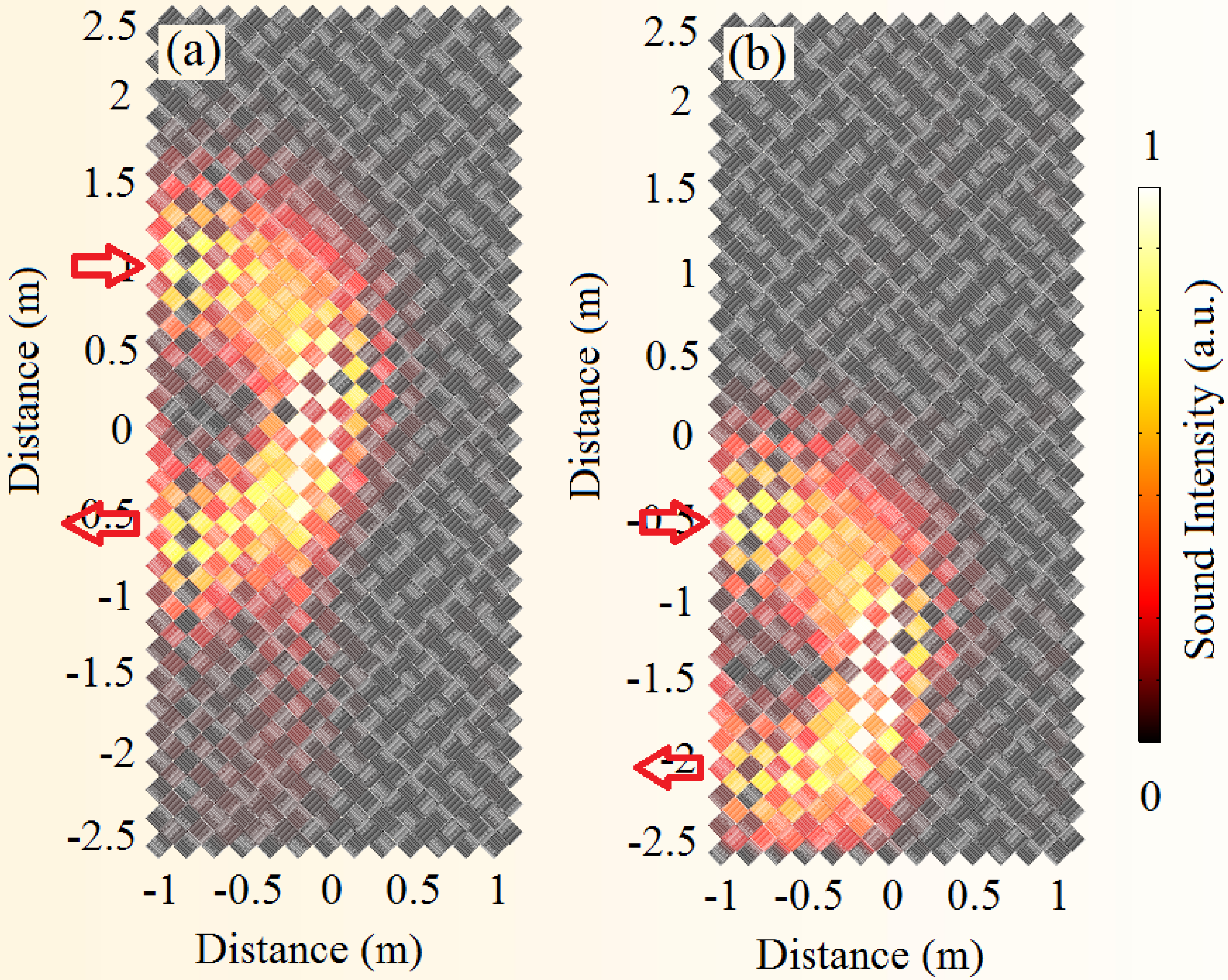
$v_{air} < 6m/s$

$F = qvB = mv^2/R$

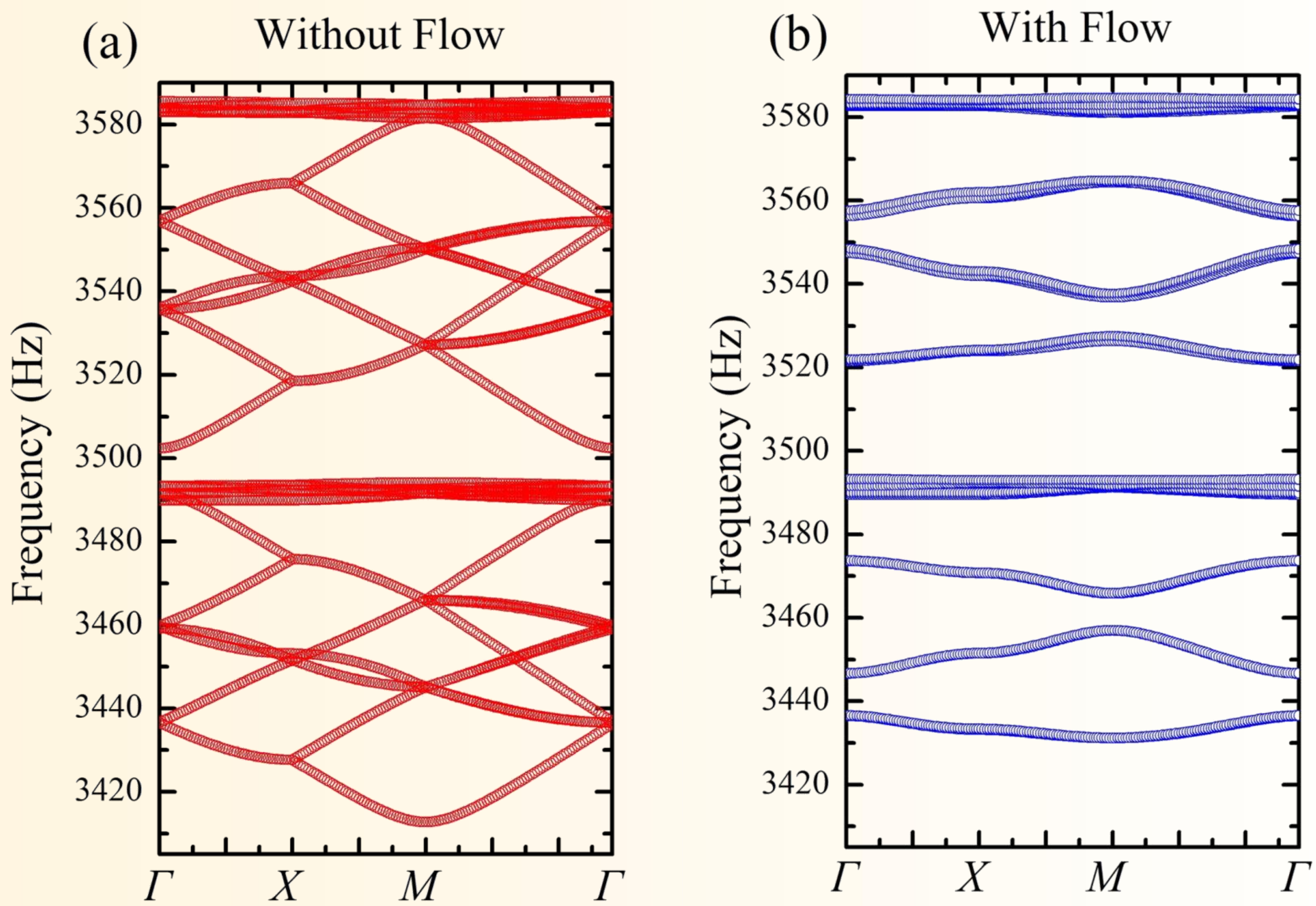
↓

$R = mv/qB$

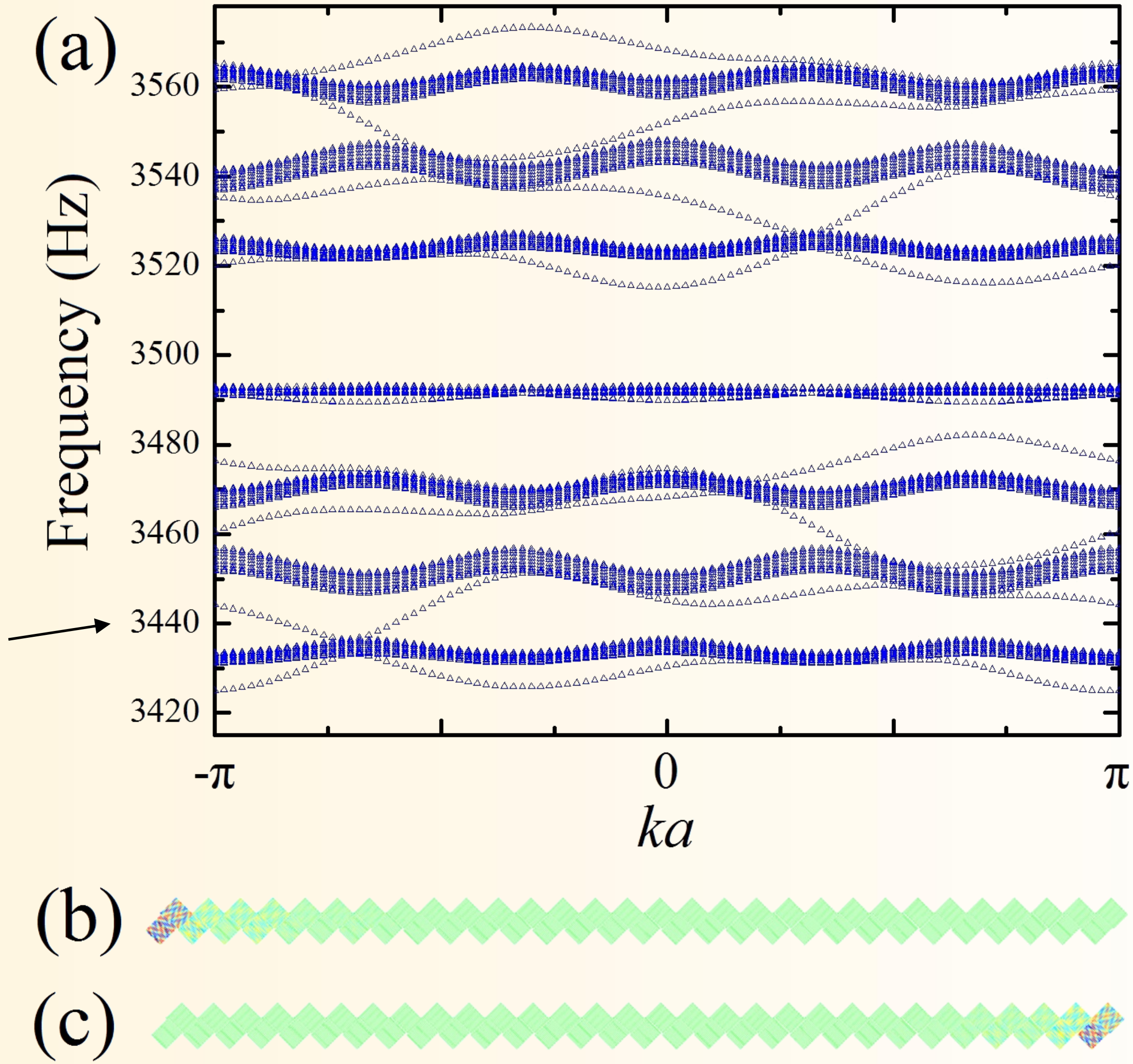
Non-Reciprocal Transmission



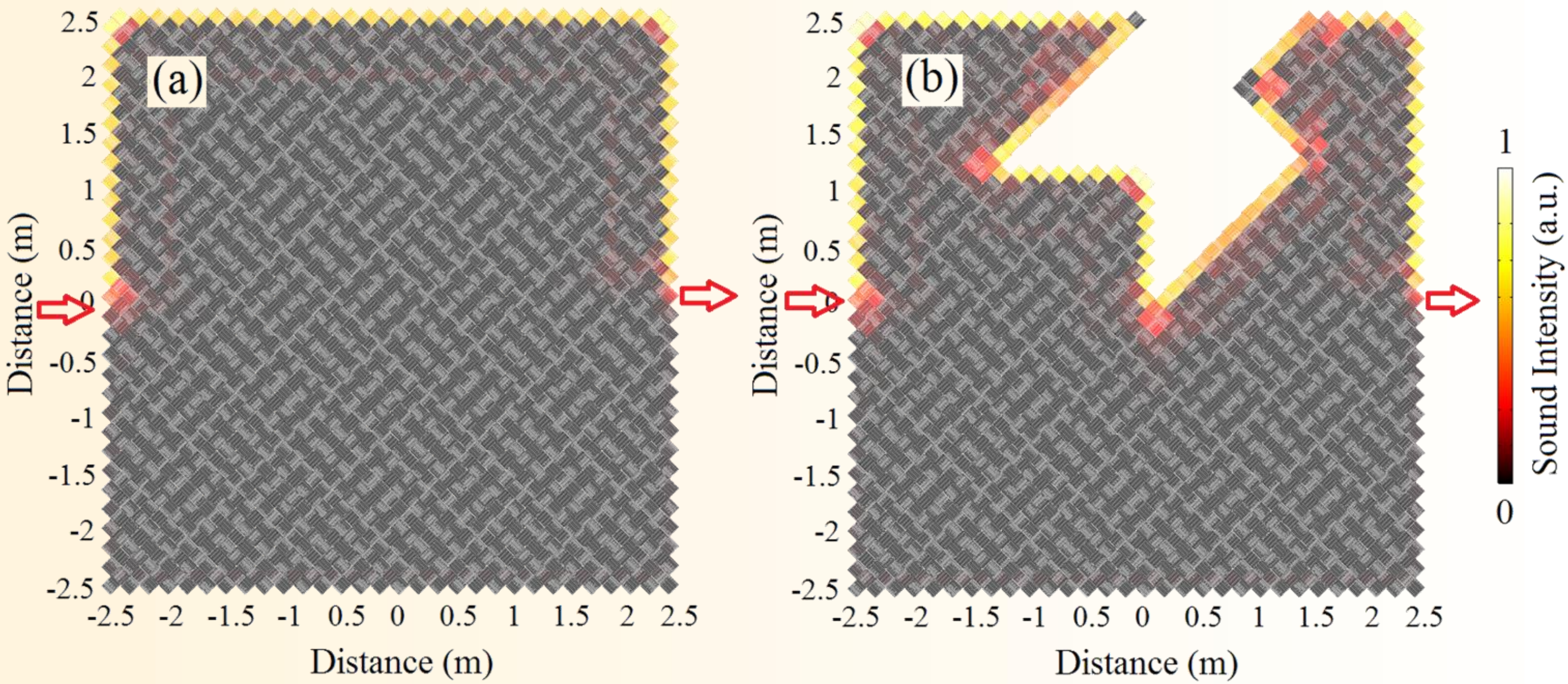
Topological Phononics



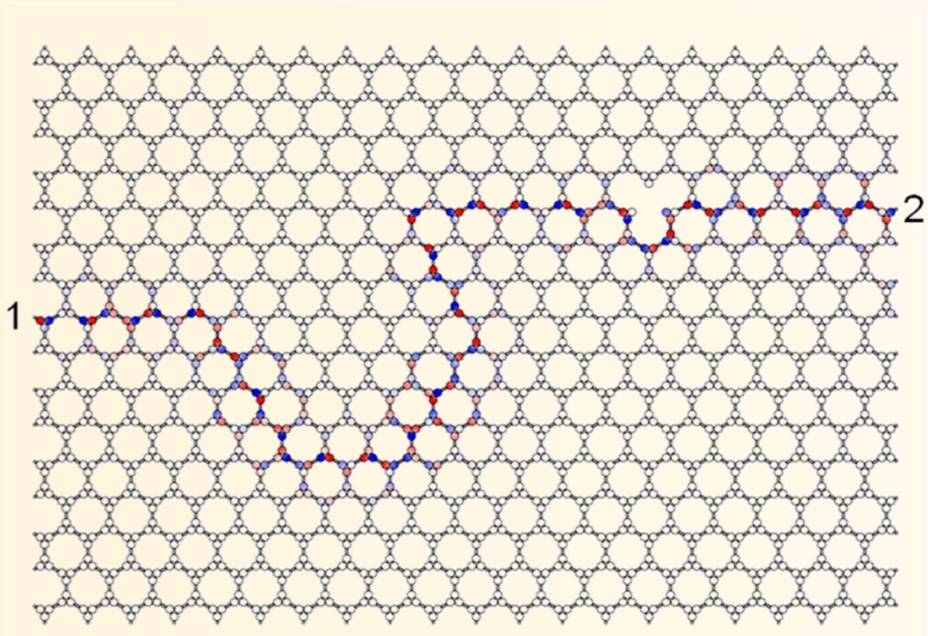
Edge Mode Dispersion

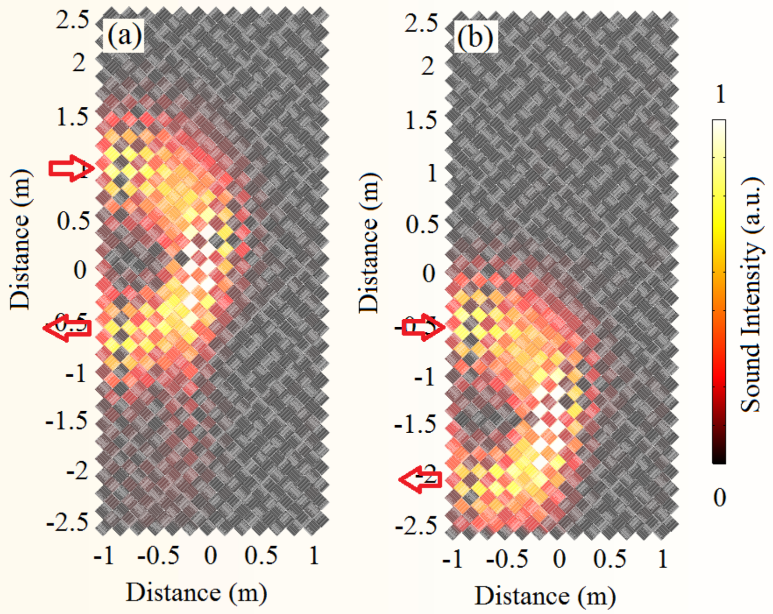


Robust Edge Mode Propagation



Introducing Phase Delays in a Small Footprint



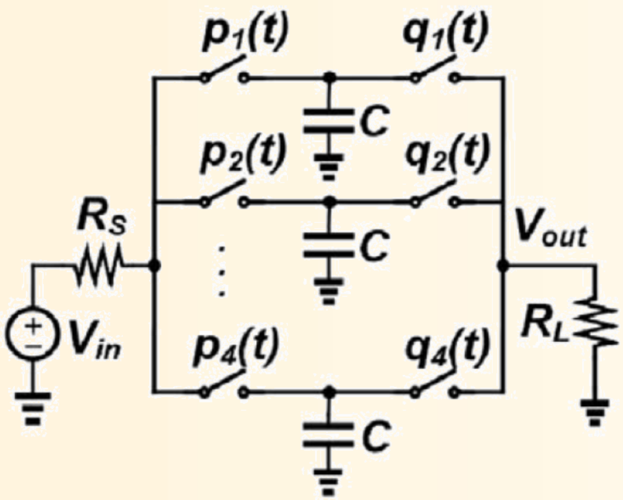


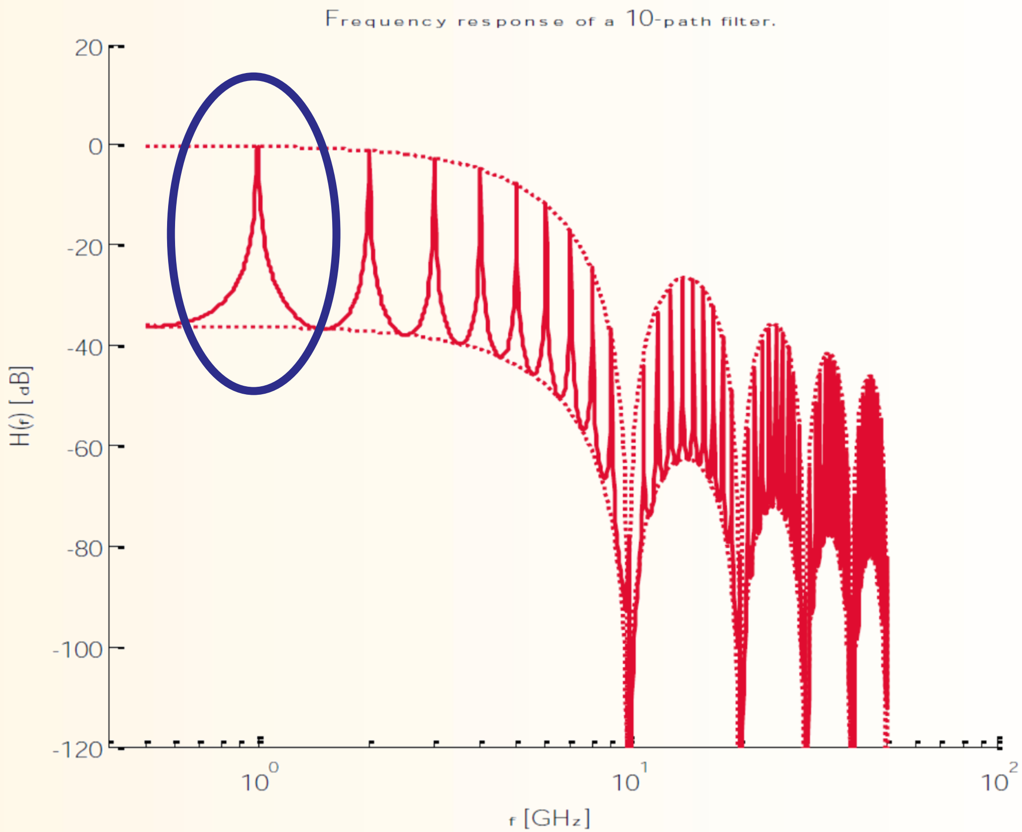
Topological propagation requires large phase delays across unit cells
Can we induce large phase delays within deeply subwavelength footprints?

Introducing Phase Delays in a Small Footprint

In a totally different field, the integrated circuit community has been solving this problem using time modulation!

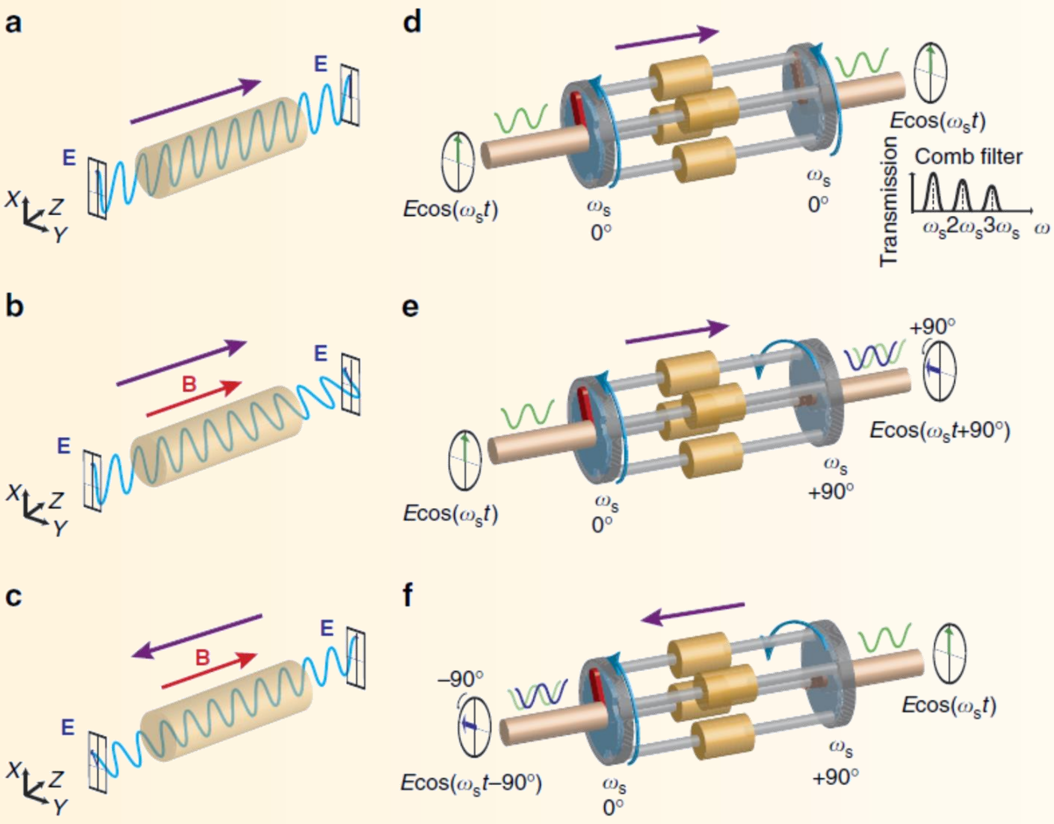
N-path filter

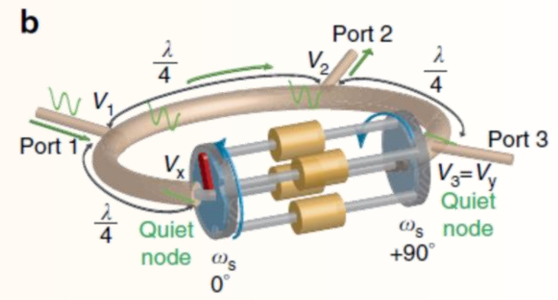


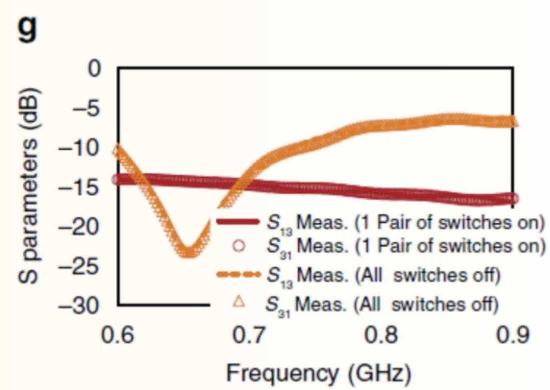


M. Darvishi, R. van der Zee, B. Nauta, IEEE JSSC 48, 2962 (2013)
N. Reiskarimian, et al., IEEE T-CS-II 63, 728 (2016)

Non-Reciprocal Phase Shifter Based on N-Path Filters

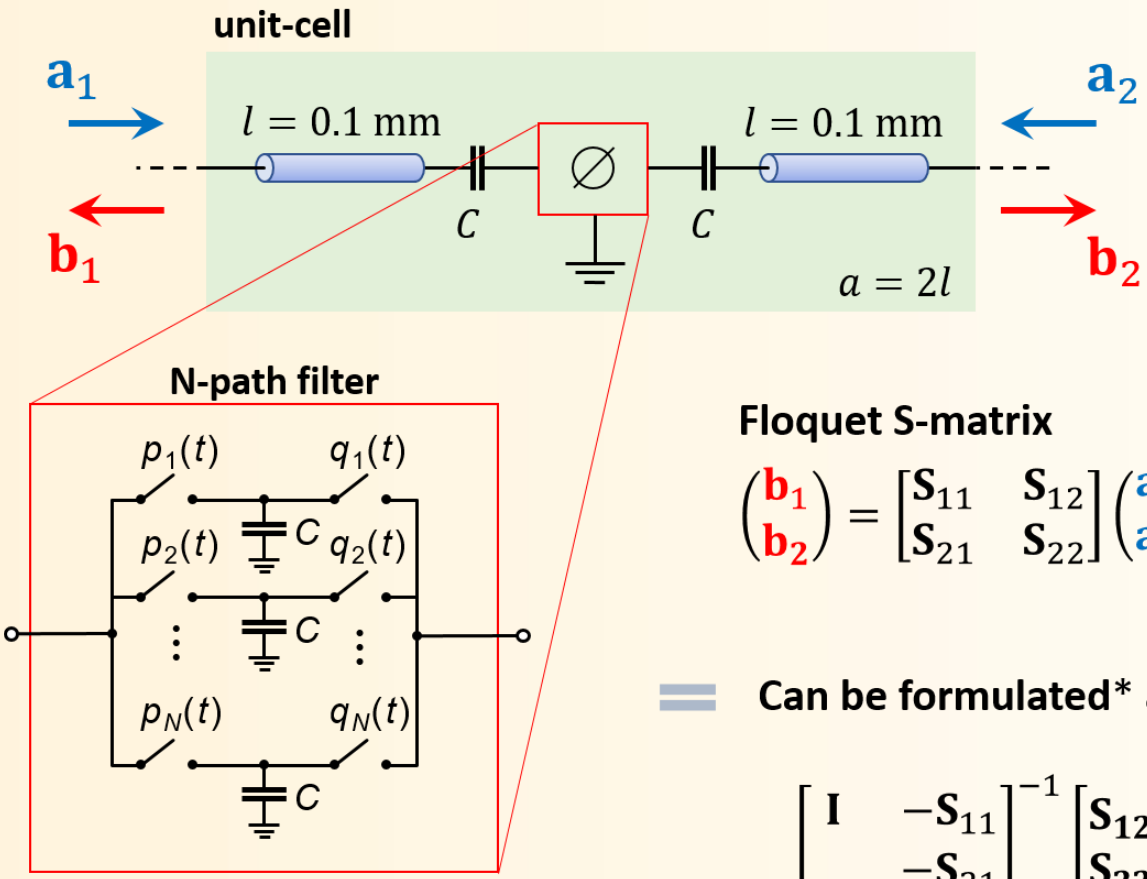






N. Reiskarimian, H. Krishnaswamy, *Nature Comm.* **7**, 11217 (2016)

Propagation Along a Lattice of N-Path Filters



$$\boldsymbol{V}_i = \frac{\mathbf{a}_i + \mathbf{b}_i}{\sqrt{Z_0}}$$

$$\boldsymbol{I}_i = \frac{\mathbf{a}_i - \mathbf{b}_i}{\sqrt{Z_0}}$$

Floquet S-matrix + **Bloch periodicity**

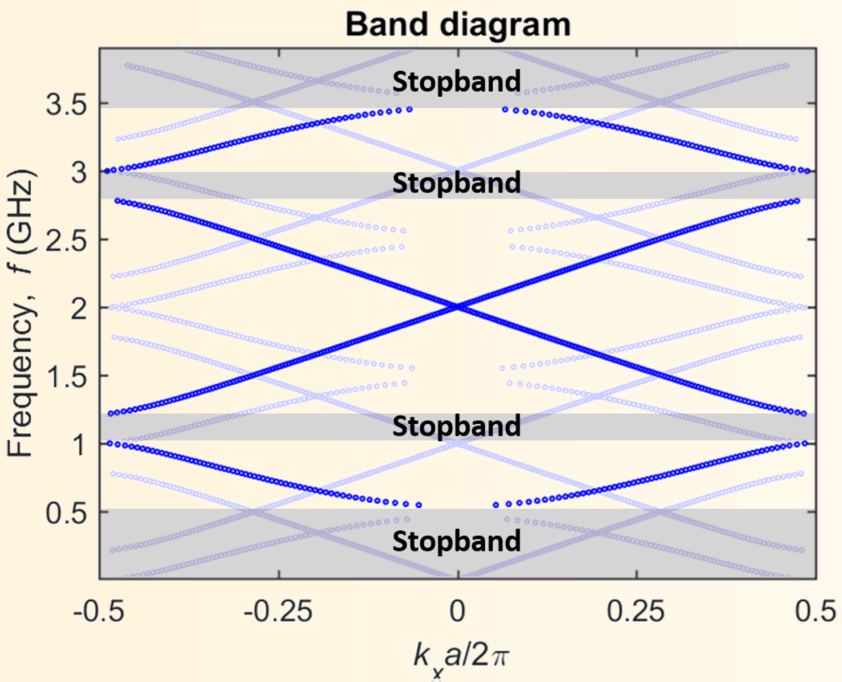
$$\begin{pmatrix}\mathbf{b}_1\\ \mathbf{b}_2\end{pmatrix} = \begin{bmatrix}\mathbf{S}_{11} & \mathbf{S}_{12}\\ \mathbf{S}_{21} & \mathbf{S}_{22}\end{bmatrix}\begin{pmatrix}\mathbf{a}_1\\ \mathbf{a}_2\end{pmatrix} \qquad \begin{pmatrix}\mathbf{b}_1\\ \mathbf{b}_2\end{pmatrix} = \begin{bmatrix} & e^{jk_x a}\\ e^{-jk_x a} & \end{bmatrix}\begin{pmatrix}\mathbf{a}_1\\ \mathbf{a}_2\end{pmatrix}$$

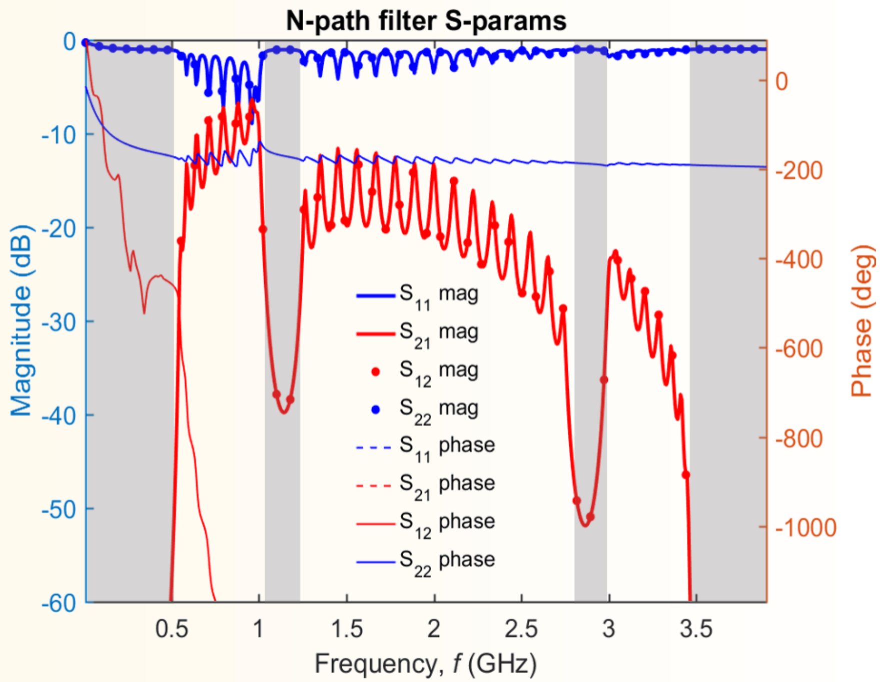
= **Can be formulated* as an eigenvalue problem!**

$$\begin{bmatrix}\mathbf{I} & -\mathbf{S}_{11}\\ & -\mathbf{S}_{21}\end{bmatrix}^{-1}\begin{bmatrix}\mathbf{S}_{12} & \\ \mathbf{S}_{22} & -\mathbf{I}\end{bmatrix}\begin{pmatrix}\mathbf{a}_2\\ \mathbf{b}_2\end{pmatrix} = e^{jk_x a}\begin{pmatrix}\mathbf{a}_2\\ \mathbf{b}_2\end{pmatrix}$$

*only for S_{12} and S_{21} do not have empty rows

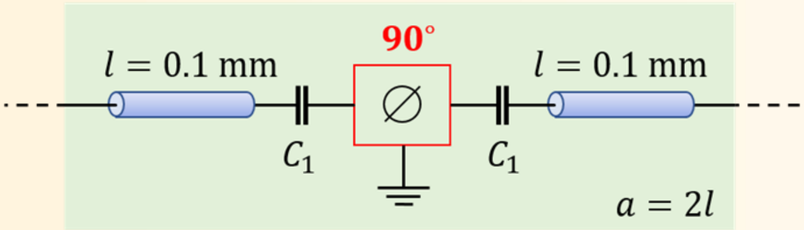
Propagation Along a Lattice of N-Path Filters





Non-Reciprocal Transport

unit-cell



N-path filter params

$f_s = 1$ GHz

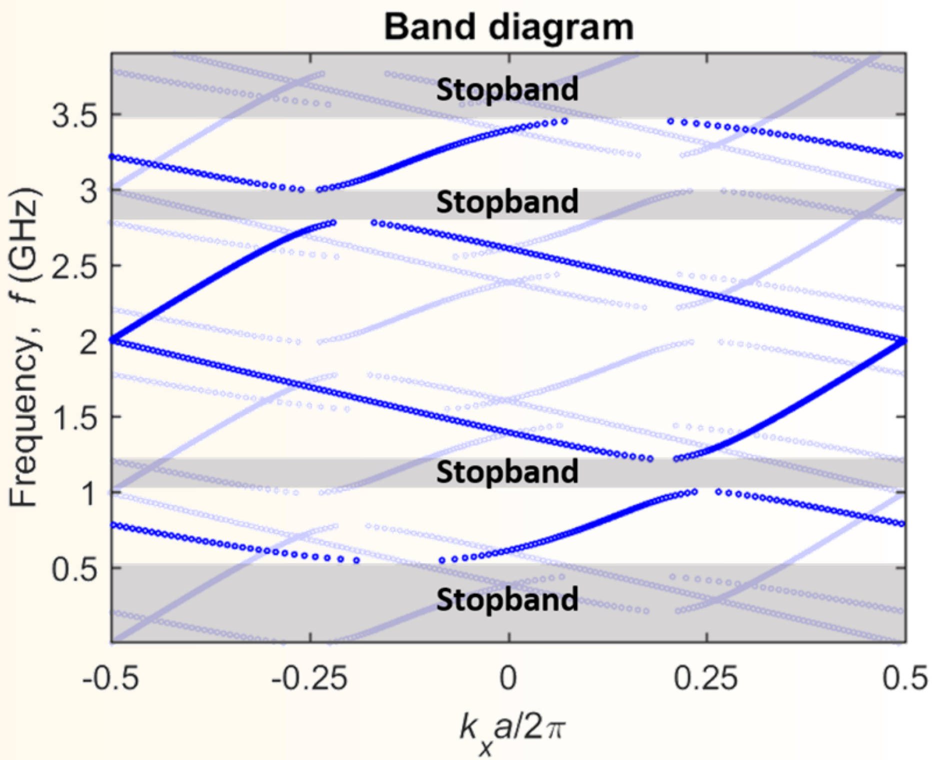
$C = 25$ ohm

$N = 4$ (non-overlapping clocks)

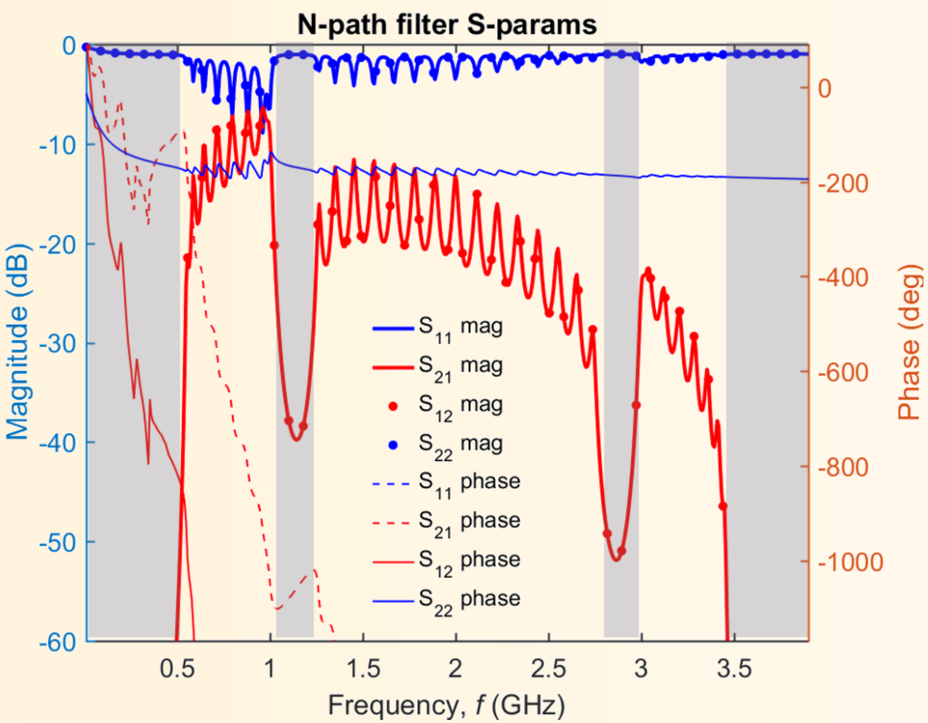
Transmission line params

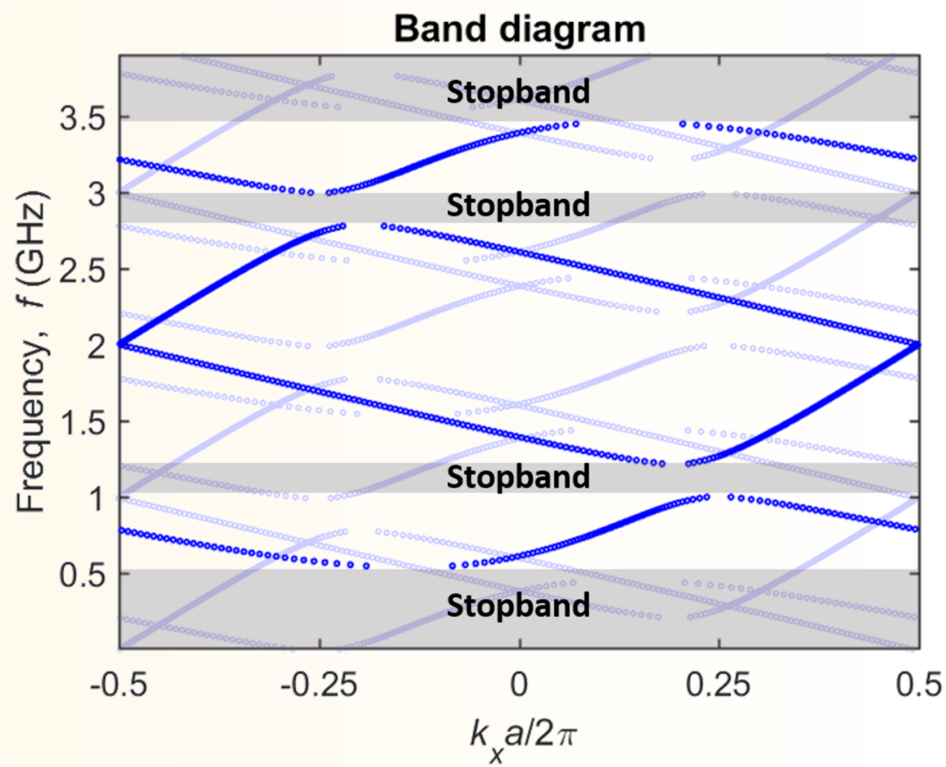
$C_1 = 50$ ohm

$\beta = c_0/\sqrt{3}$



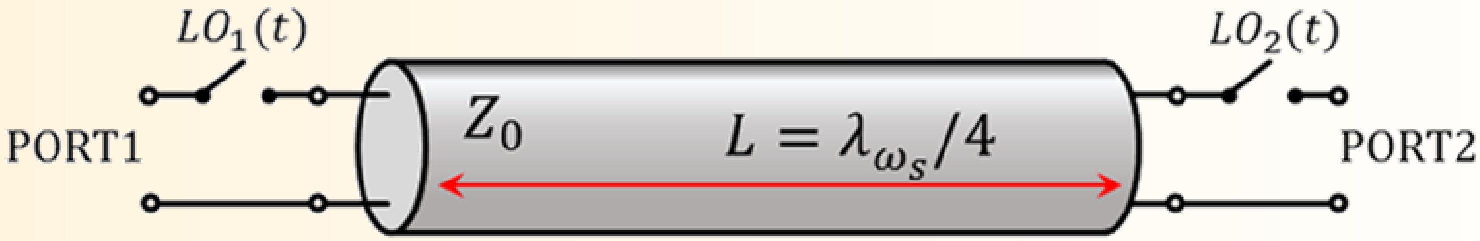
Non-Reciprocity and Topological Transport

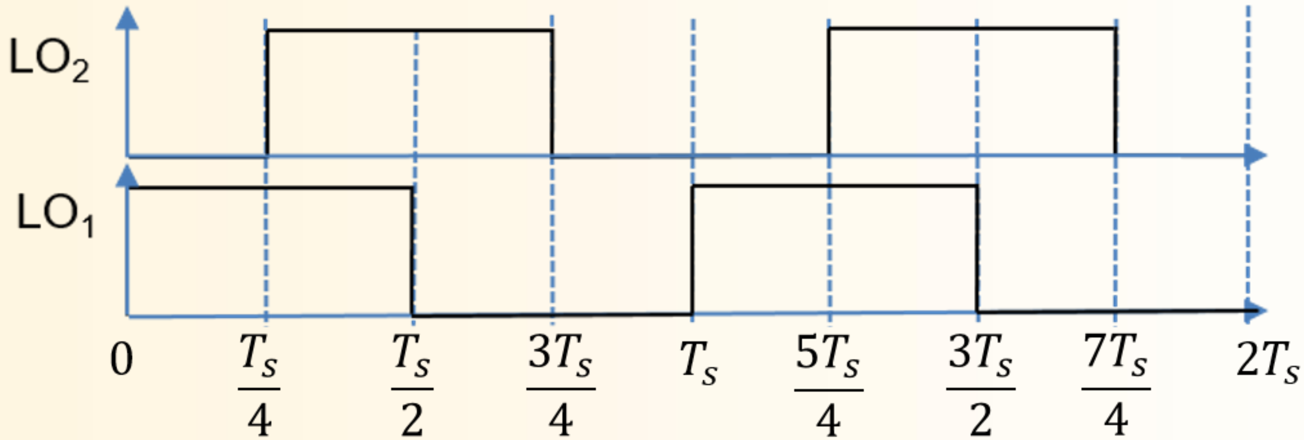




Towards Ultra-Broadband Non-Reciprocal Elements

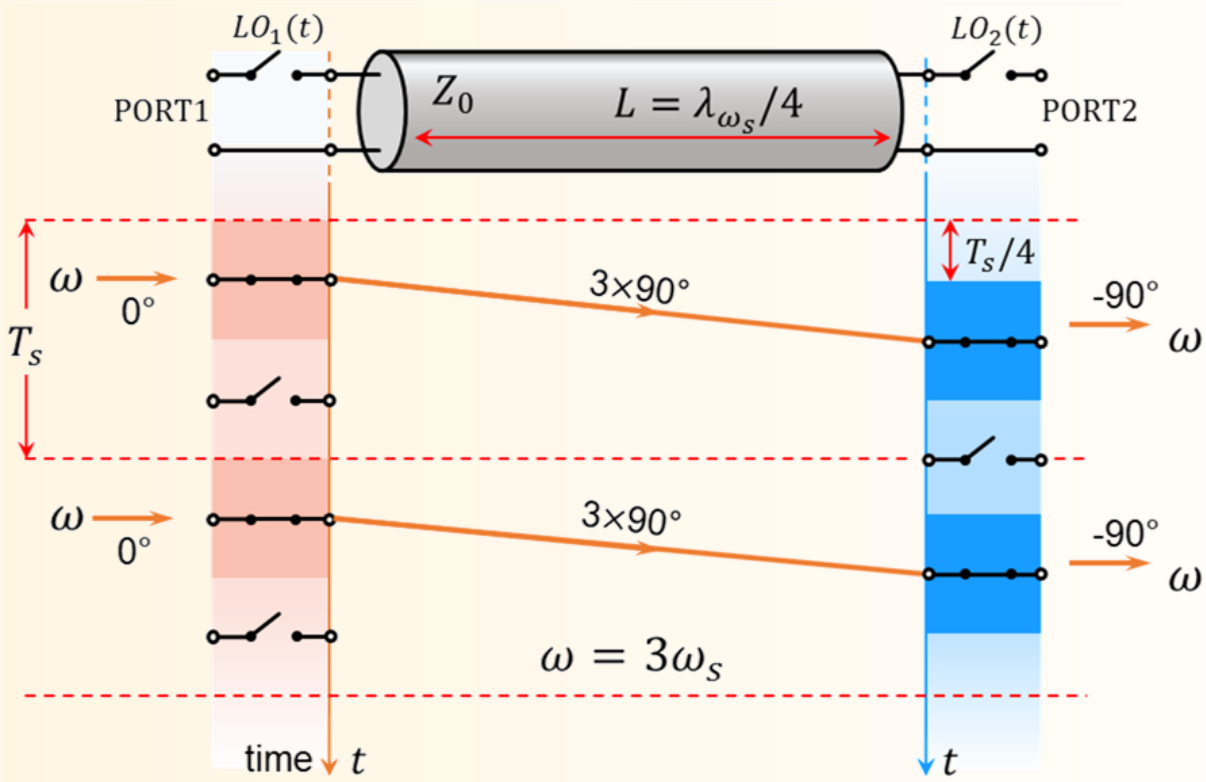
Generalizing N-path filters: commutated delay lines





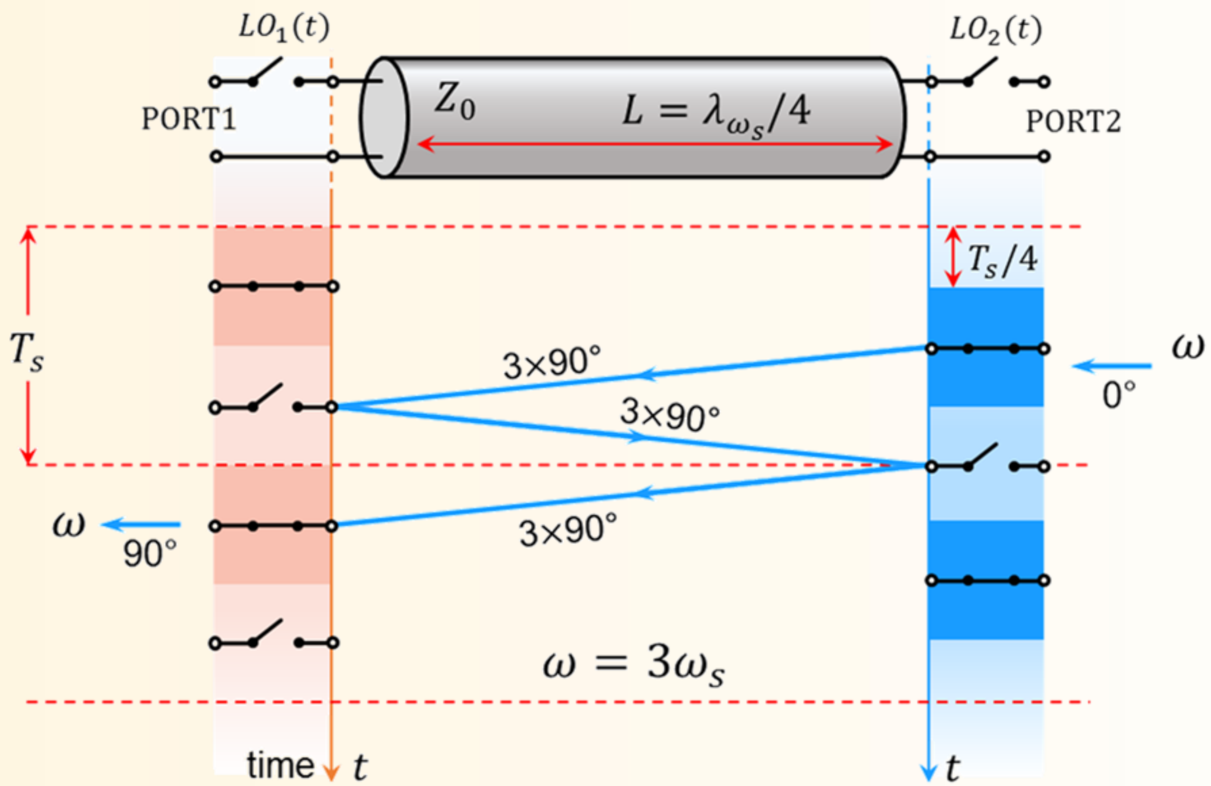
T. Dinc, M. Tymchenko, A. Nagulu, D. Sounas, A. Alù, H. Krishnaswamy, under review (2017)

Forward Direction



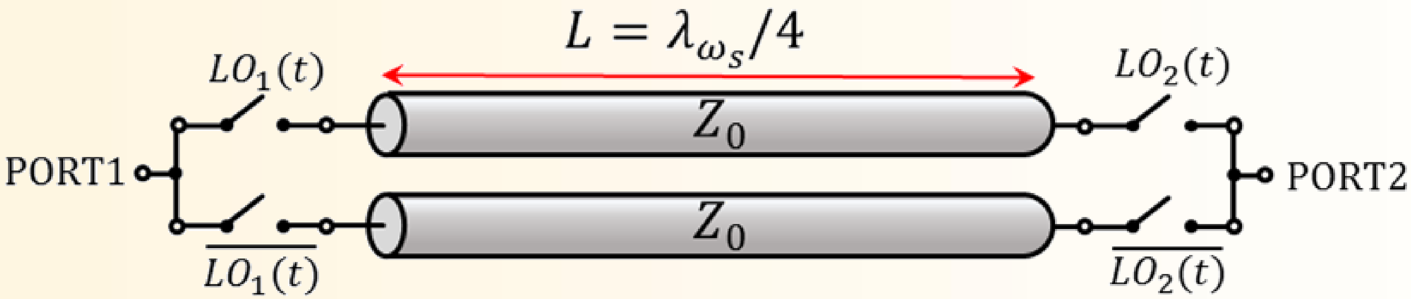
$$v_2^-(t) = v_1^+\left(t - \frac{T_s}{4}\right) LO_1\left(t - \frac{T_s}{4}\right) \rightarrow \; S_{21}(\omega) = \frac{1}{2} e^{-j\omega\frac{T_s}{4}}$$

BACKWARD DIRECTION



$$v_1^-(t) = v_2^+\left(t - \frac{3T_s}{4}\right) LO_2\left(t - \frac{3T_s}{4}\right) \rightarrow S_{12}(\omega) = \frac{1}{2} e^{-j\omega\frac{3T_s}{4}}$$

Ultra-Broadband Gyrator: Single Balanced



To avoid reflections, a parallel path with complementary switching can be added

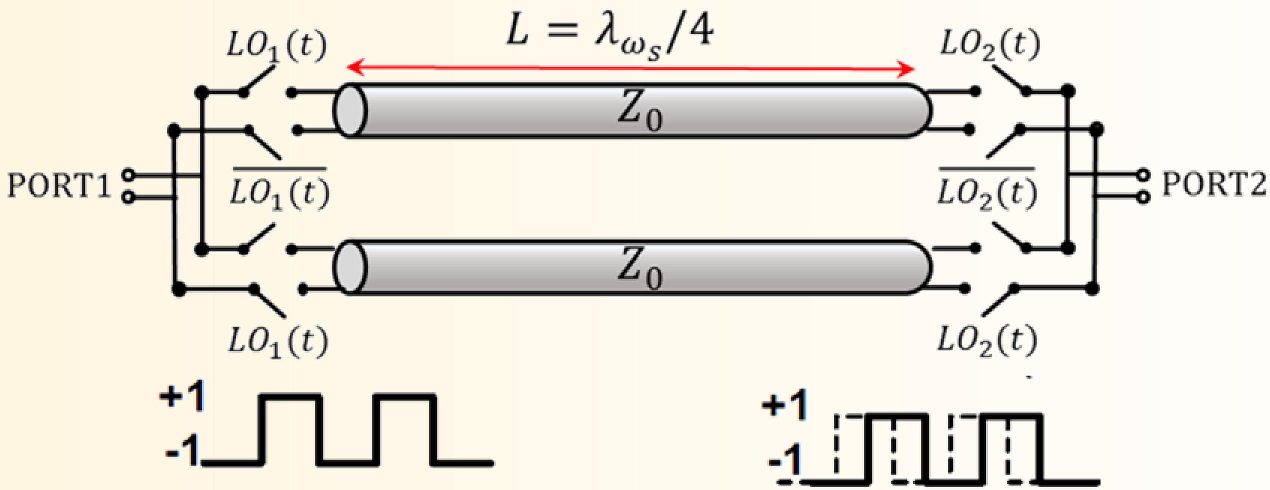
S-parameters

$$\begin{pmatrix} 0 & e^{-j\frac{3\pi}{2}\left(\frac{\omega}{\omega_s}\right)} \\ e^{-j\frac{\pi}{2}\left(\frac{\omega}{\omega_s}\right)} & 0 \end{pmatrix}$$

Non-Reciprocal Phase!

Non-reciprocal phase with no transmission loss

Ultra-Broadband Gyrator: Doubly Balanced



S-parameters

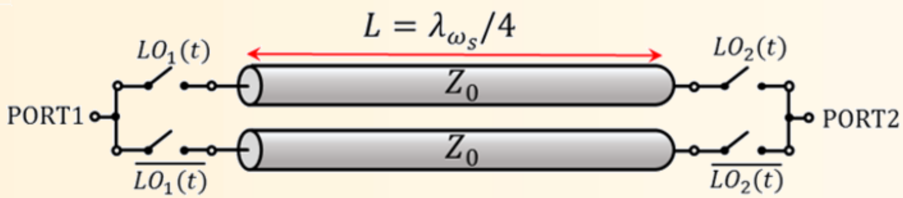
$$\begin{pmatrix} 0 & -e^{-j\frac{\pi}{2}\left(\frac{\omega}{\omega_s}\right)} \\ e^{-j\frac{\pi}{2}\left(\frac{\omega}{\omega_s}\right)} & 0 \end{pmatrix}$$

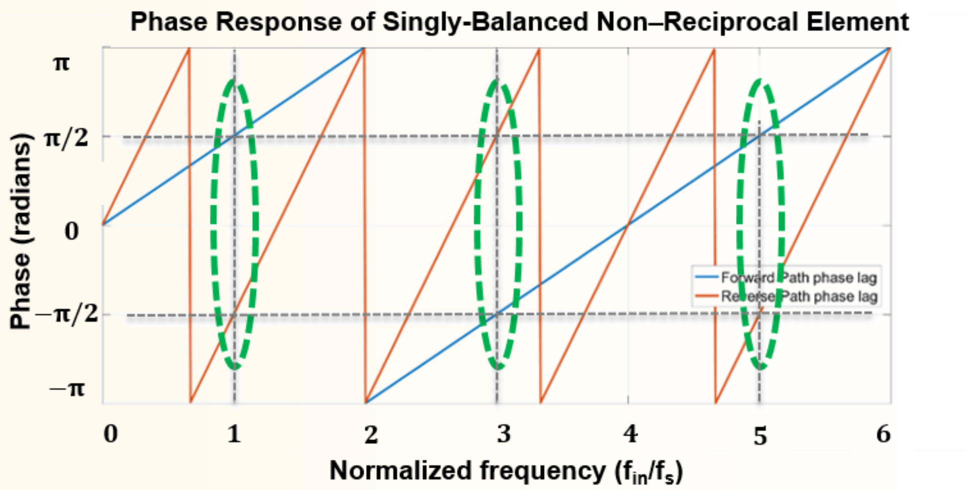
Non-Reciprocal Phase

Non-reciprocal phase difference of 180º over a theoretically infinite BW

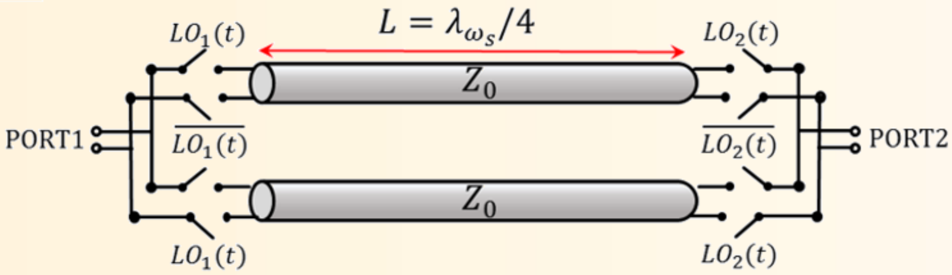
ULTRA-BROADBAND GYRATOR: DOUBLY BALANCED

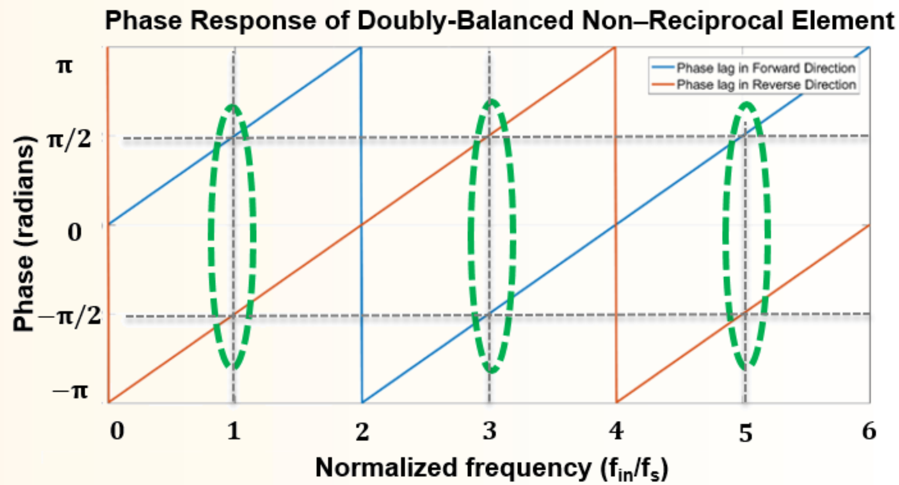
Singly – Balanced NR Element





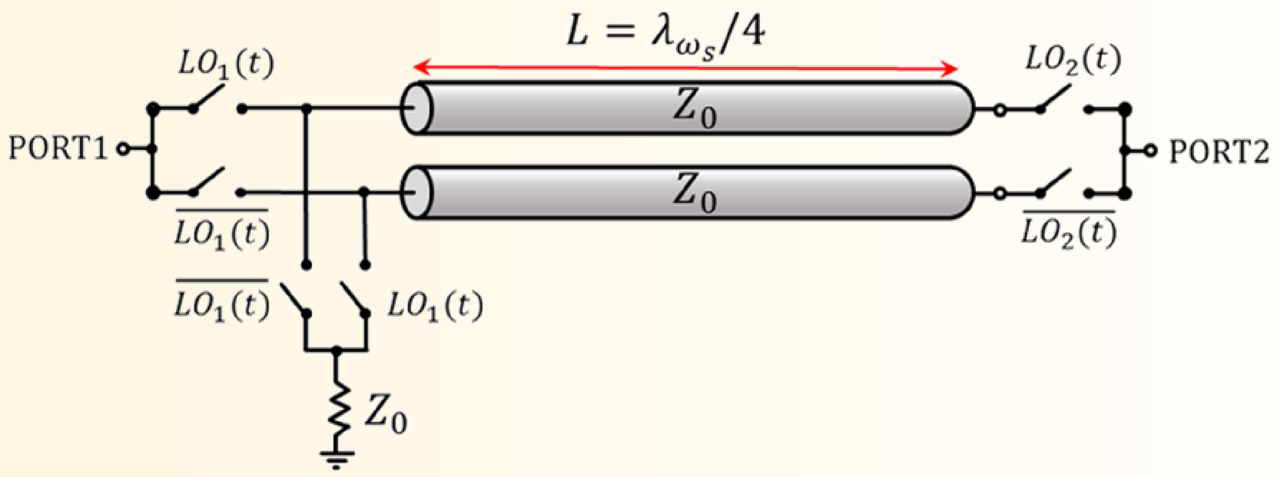
Doubly – Balanced NR Element





Doubly – balanced structure has wider non-reciprocal phase bandwidth

Ultra-Broadband Isolator / Circulator

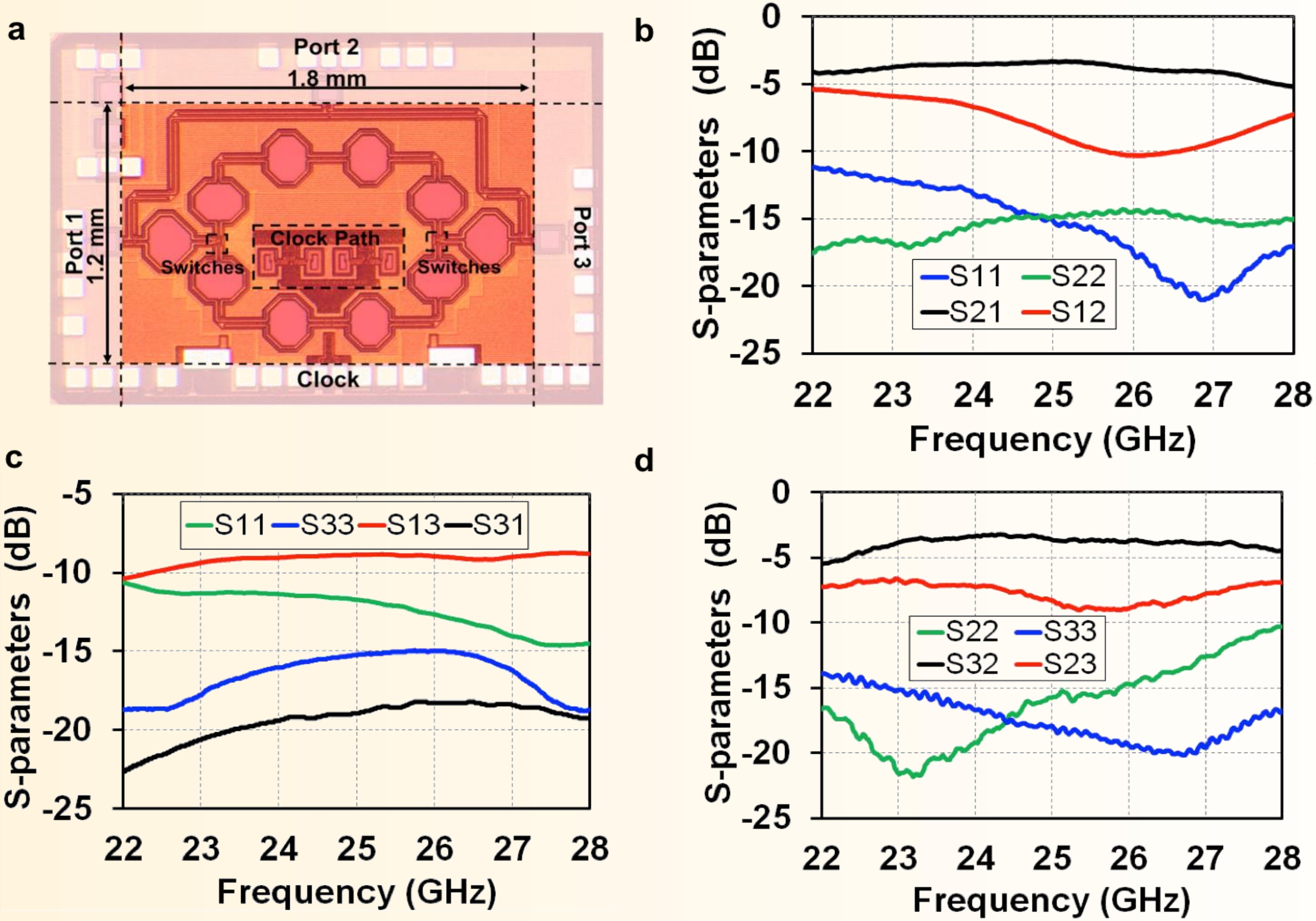


S-parameters

$$\begin{pmatrix} 0 & 0 \\ e^{-j\frac{\pi}{2}\frac{\omega}{\omega_s}} & 0 \end{pmatrix}$$

Lossless transmission in forward direction and perfect isolation in reverse direction over a theoretically infinite BW

Doubly-Balanced Circulator



T. Dinc, M. Tymchenko, A. Nagulu, D. Sounas, A. Alù, H. Krishnaswamy, under review (2017)

Non-Reciprocity Based on Nonlinear Effects

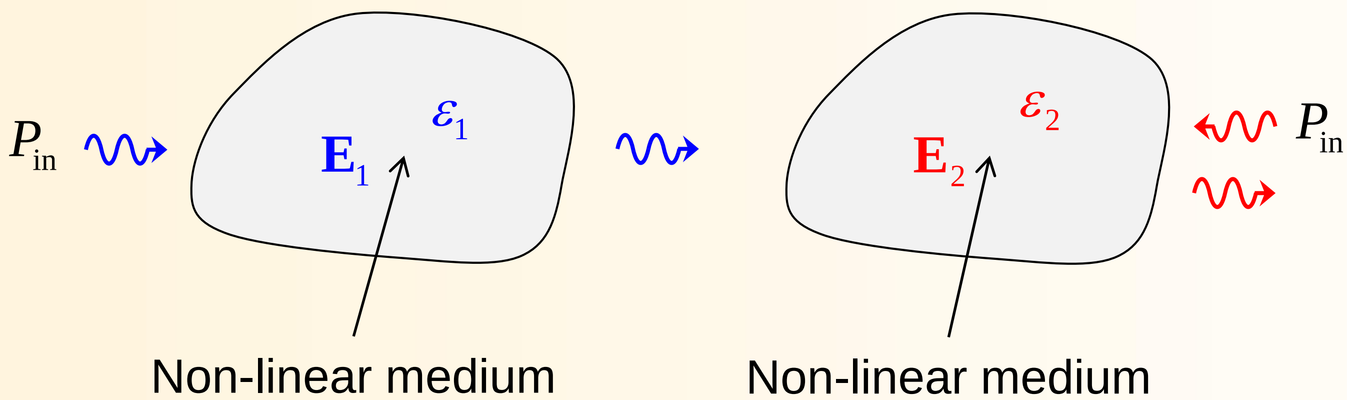
Lorentz reciprocity theorem

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

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

Time-invariant materials

Linear materials



Chi-3 non-linearity

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

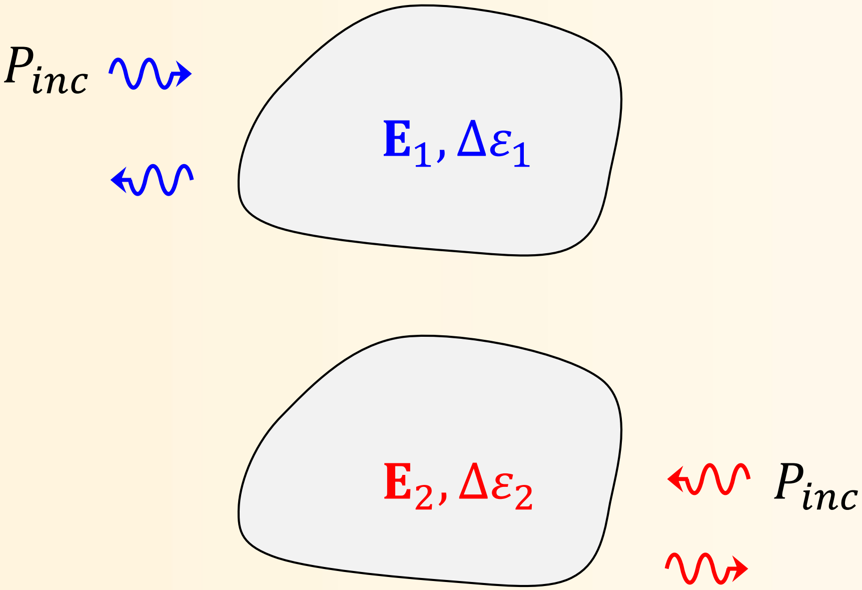
P. Saboo, J. Joseph, *Appl. Opt.* **52,** 8252–8257 (2013)

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)

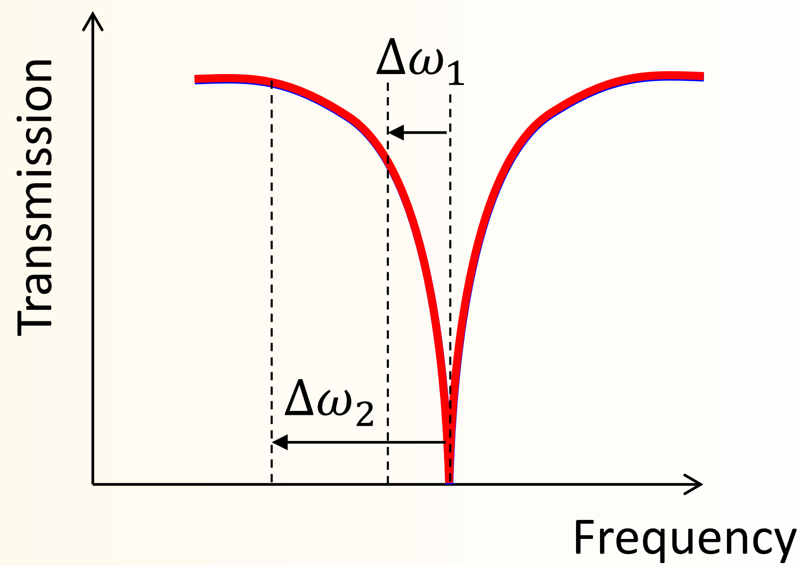
Basic Operation of Nonlinear Isolators



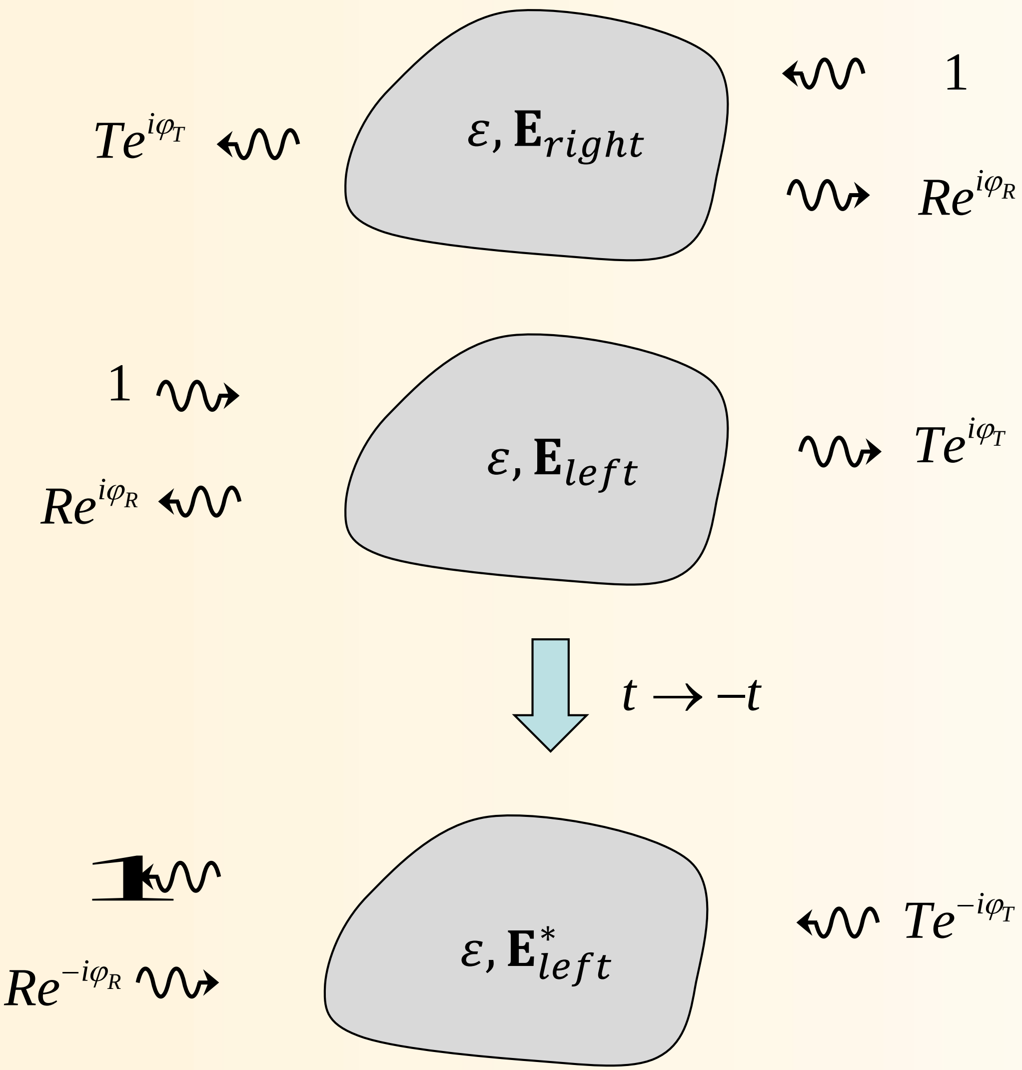
$$\varepsilon_{NL} = \varepsilon + \chi^{(3)}|\boldsymbol{E}|^2$$

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

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



Trade-off between Field Asymmetry & Insertion Loss



$$\mathbf{E}^*_{left} = Re^{-i\varphi_R}\mathbf{E}_{left} + Te^{-i\varphi_T}\mathbf{E}_{right}$$

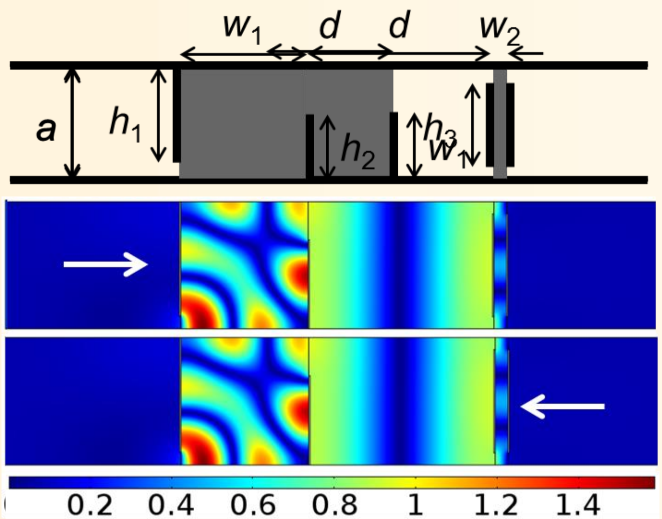
$$-\left|\mathbf{E}_{left}\right|^2 \le \mathrm{Re}\{e^{-i\varphi_R}\mathbf{E}^2_{left}\} \le \left|\mathbf{E}_{left}\right|^2$$

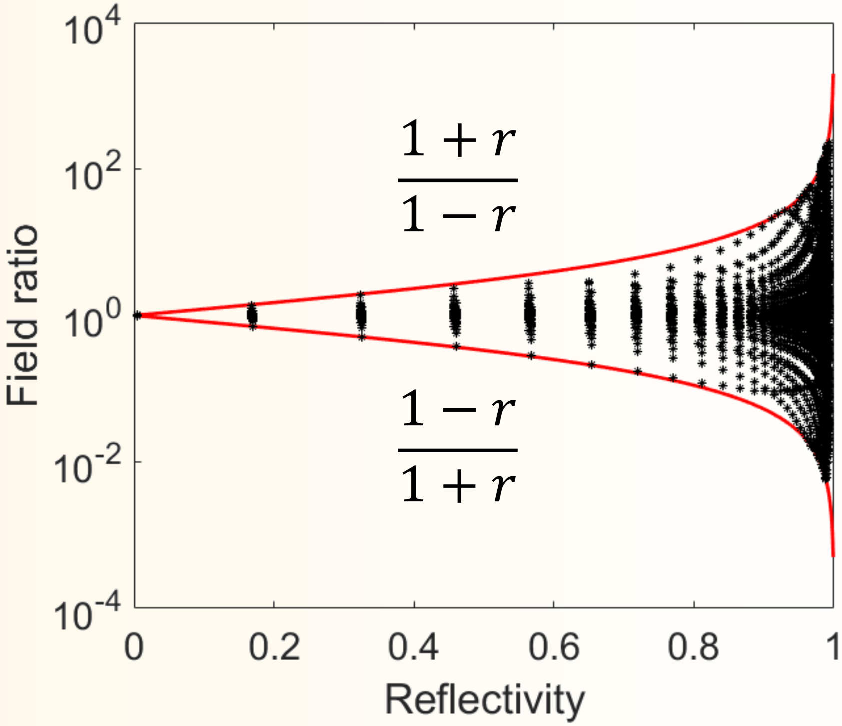
$$\kappa = \left|\mathbf{E}_{right}\right|^2 / \left|\mathbf{E}_{left}\right|^2$$

$$\frac{1-R}{1+R} \le \kappa \le \frac{1+R}{1-R}$$

$$T^2 \le \frac{4\kappa}{(\kappa+1)^2}$$

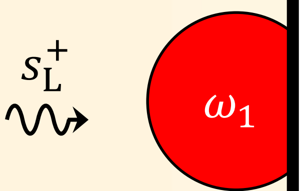
Numerical Validation

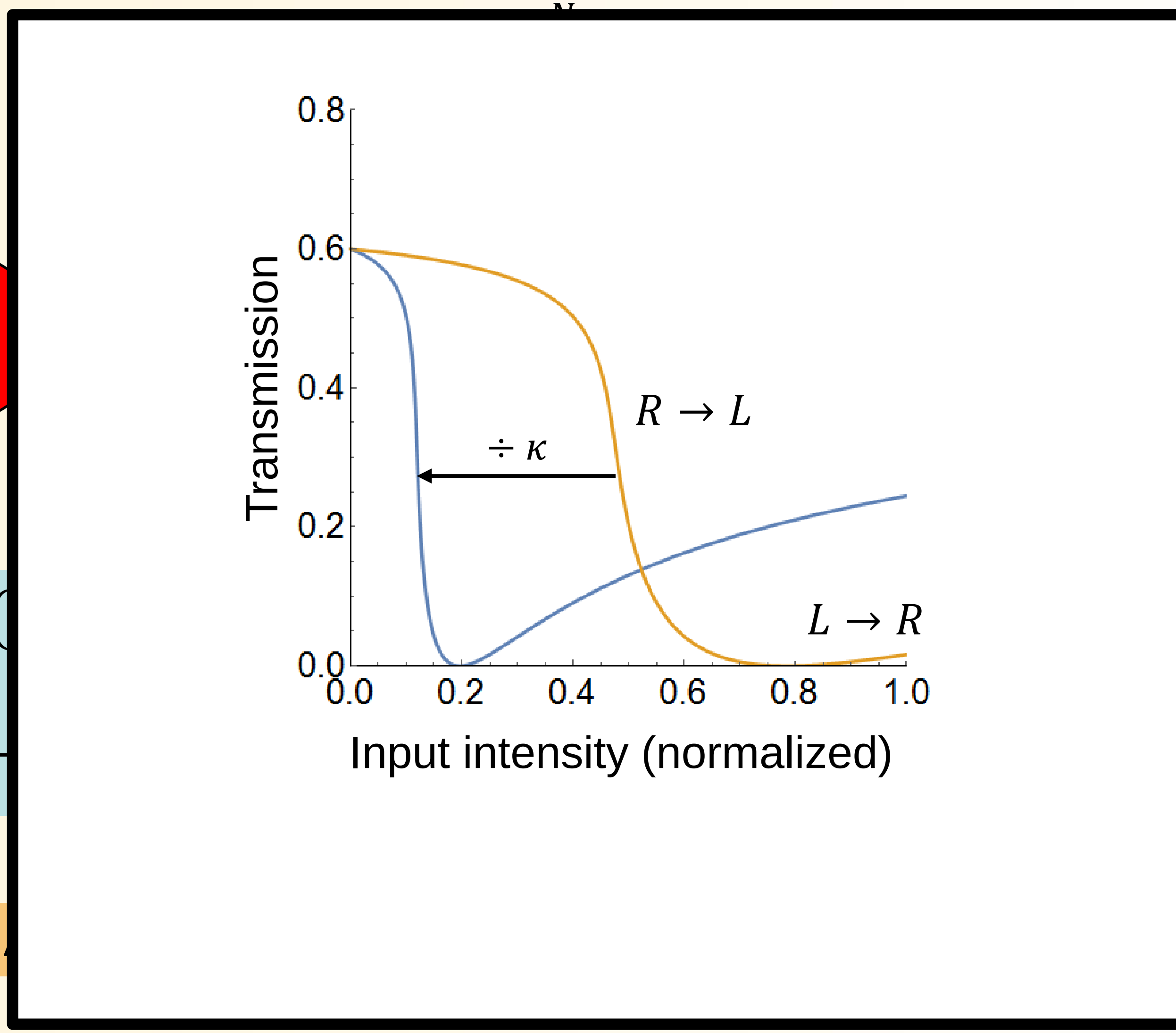




D. Sounas, A. Alù, *Phys. Rev. Lett.* **118**, 154302 (2017)

Coupled-Mode Analysis

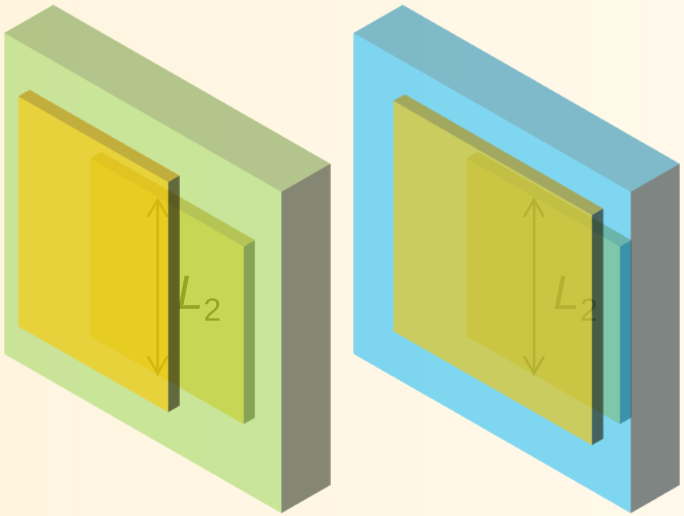


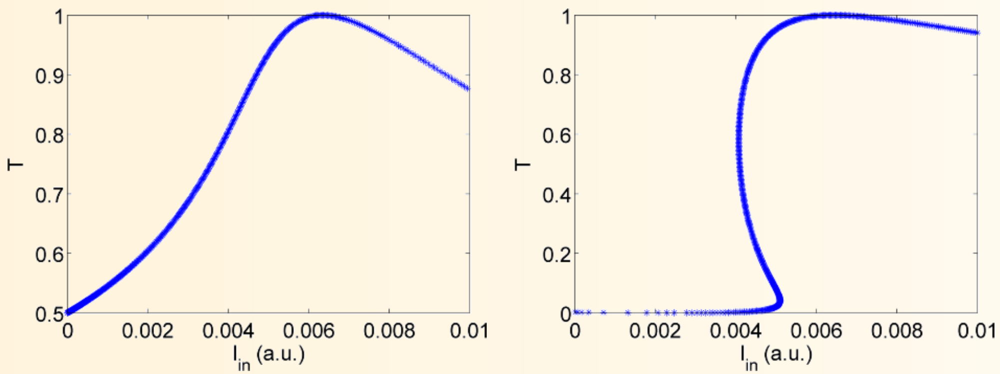


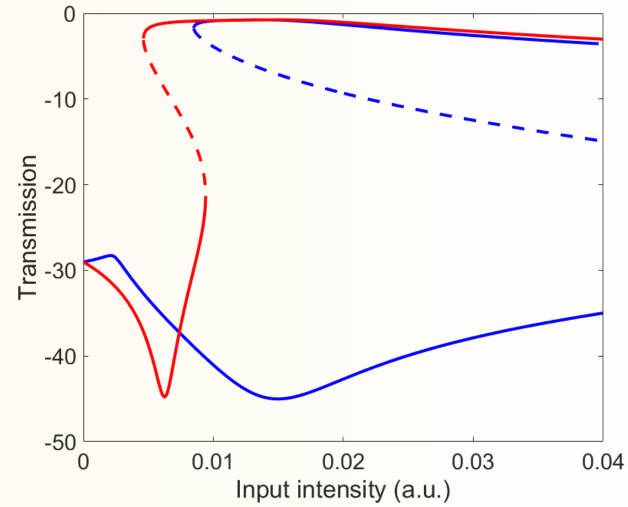
$\Delta\tilde{\omega}_{1L/R} \Big[\Big($ … $+ \bar{\bar{\Gamma}}$ … $\mathrm{Re}\{(\mathbf{H}^{-1})_{11}\}$ … $\frac{\omega_1 - \omega}{\gamma}$

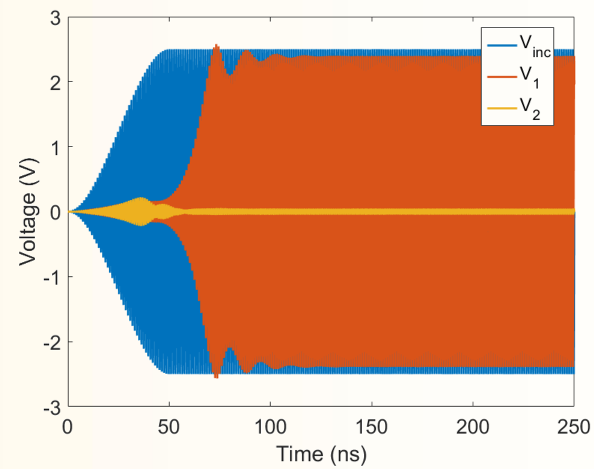
$\Delta\tilde{\omega}_{1L} =$ …

Ideal Isolator Based on Two Non-Linear Resonators



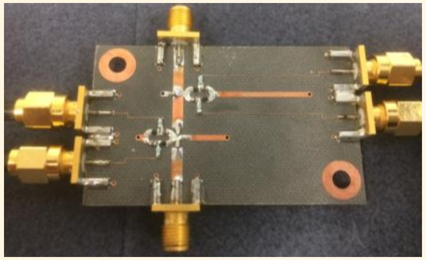


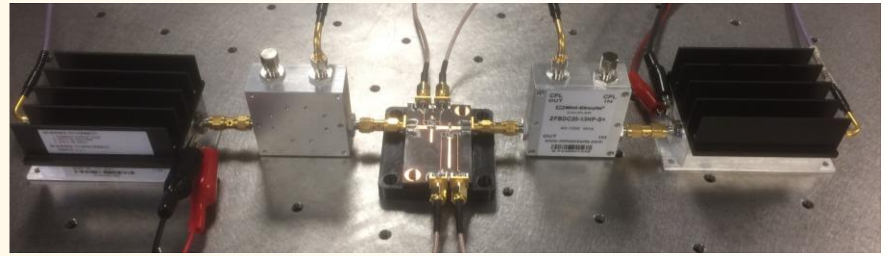


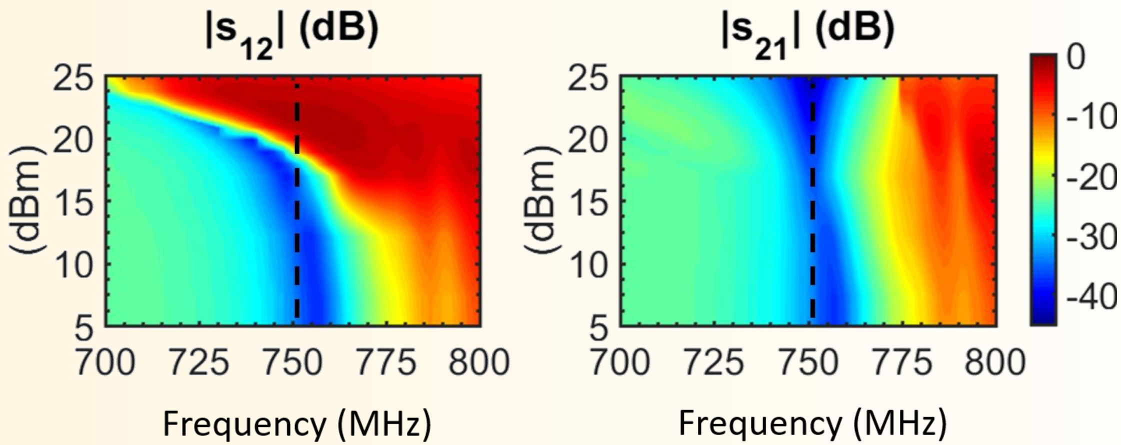


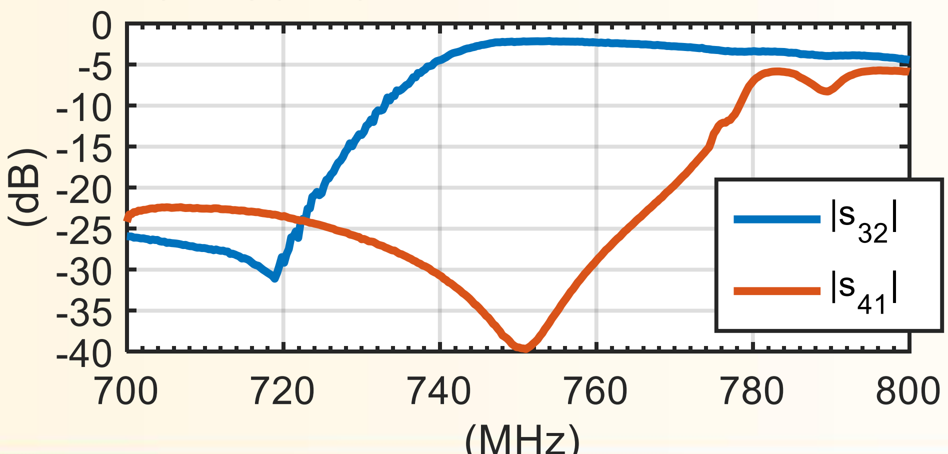
D. L. Sounas, J. Soric, and A. Alù, *under review* (2017)

Experimental Results at RF

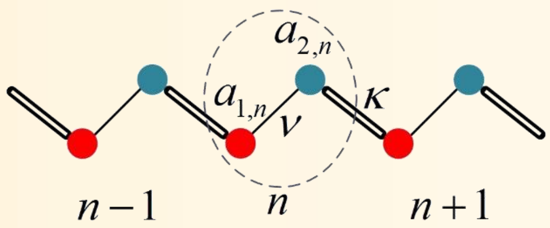








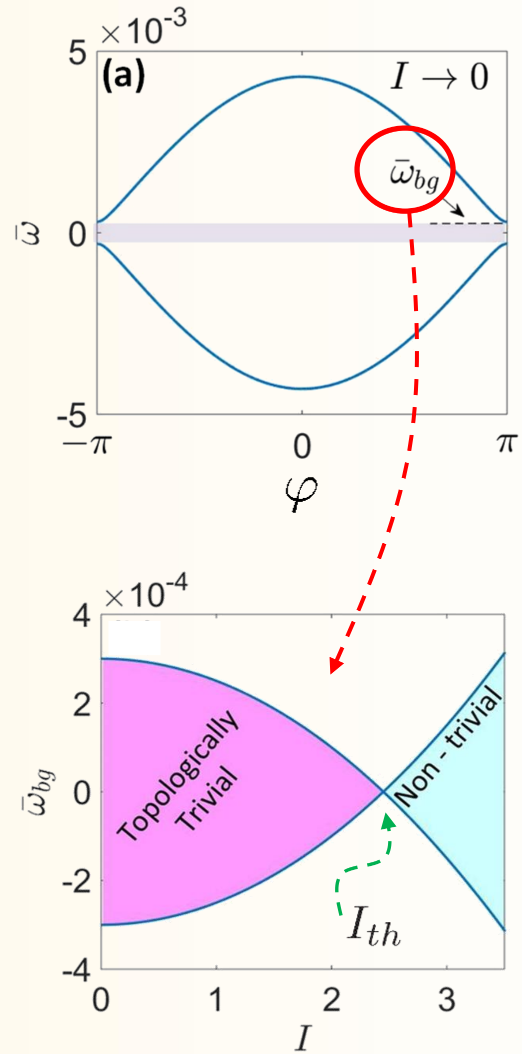
Nonlinearity-Induced Topological Transitions



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

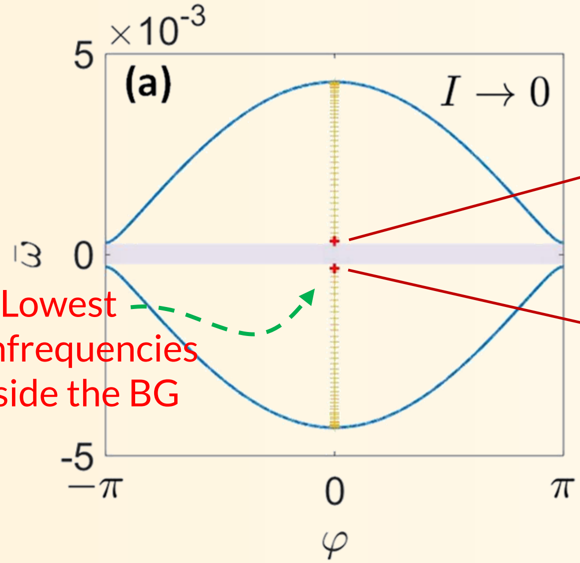
$$\nu > \kappa_0$$

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

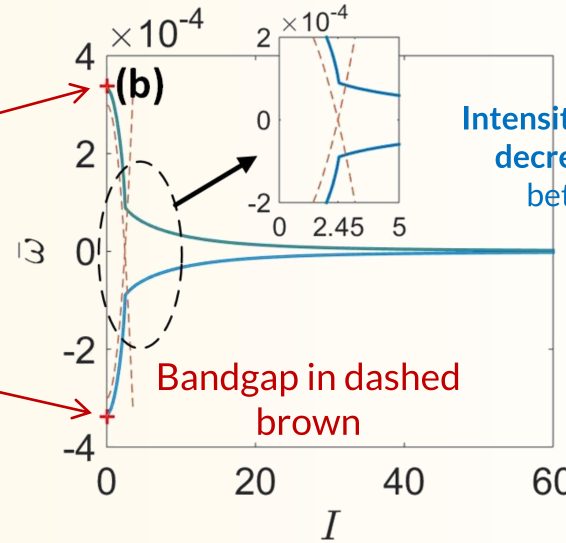


Y. Hadad, A. B. Khanikaev, and A. Alù, *Phys. Rev. B* **93**, 155112 (2016)

Finite Array: 40 Element Chain



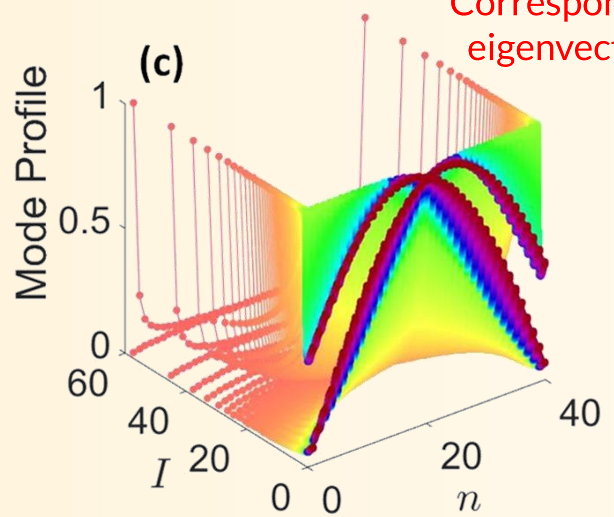
Lowest eigenfrequencies outside the BG



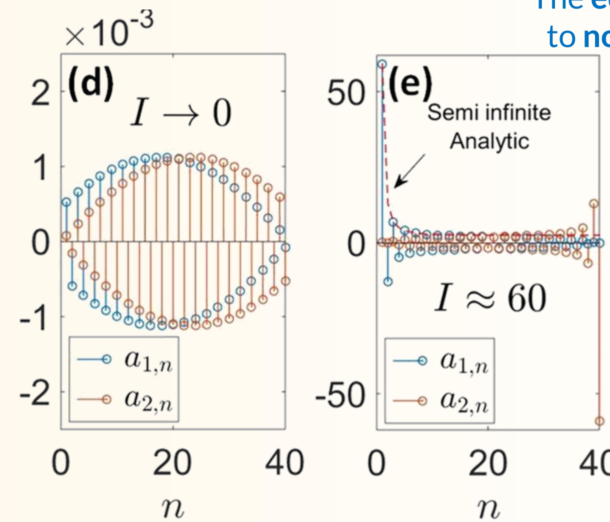
Intensity increase yields **decreased coupling** between **edges**

Bandgap in dashed brown

Corresponding eigenvectors



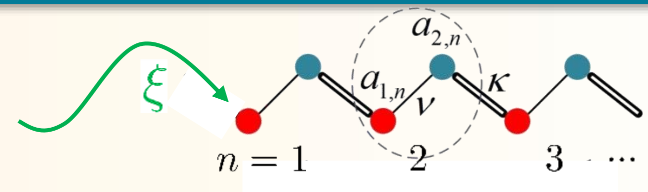
The **edge state decays** to **non-zero plateau**



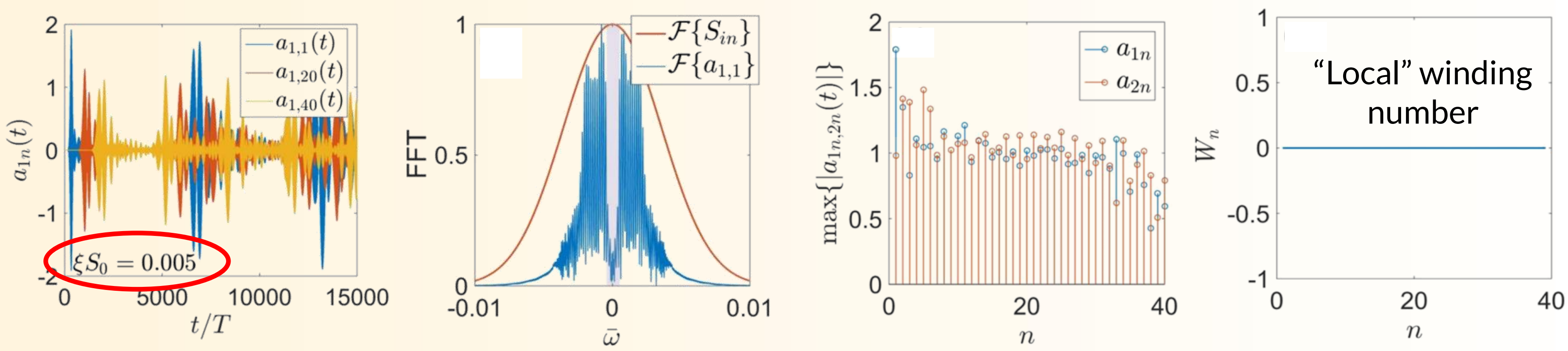
$$a_{1,\infty} = \sqrt{\frac{\nu - \kappa_0}{\alpha}} = I_{th}$$

Nonlinearity-Induced Topological Transitions

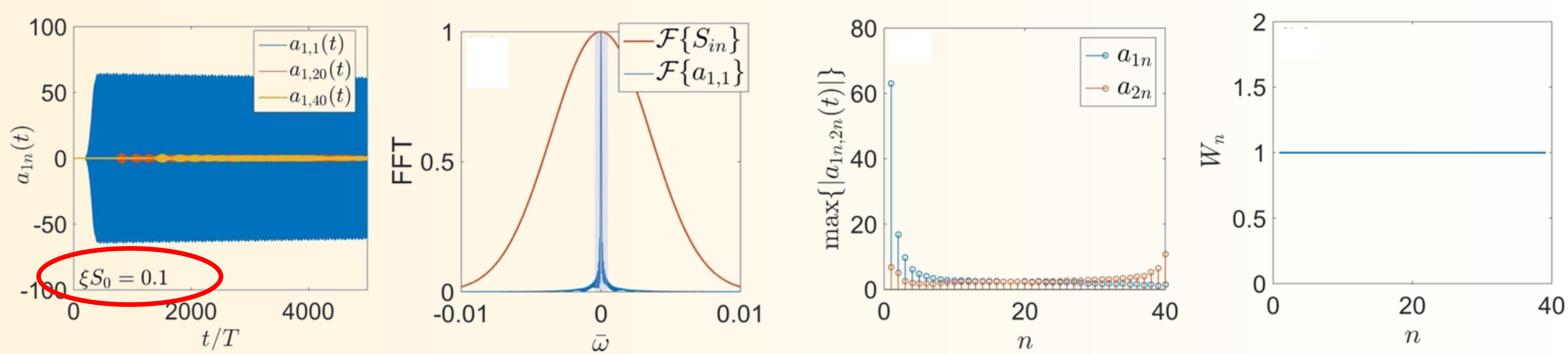
$$S_{in} = S_0 e^{i\omega t} e^{-(t-t_0)^2/T^2}$$



Low input intensity:

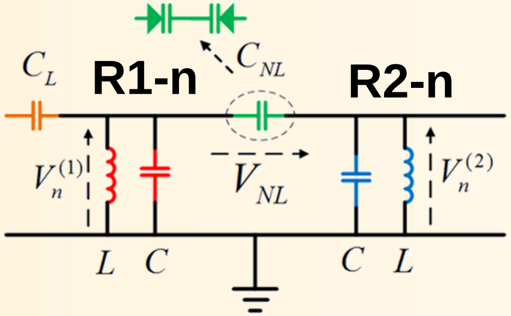


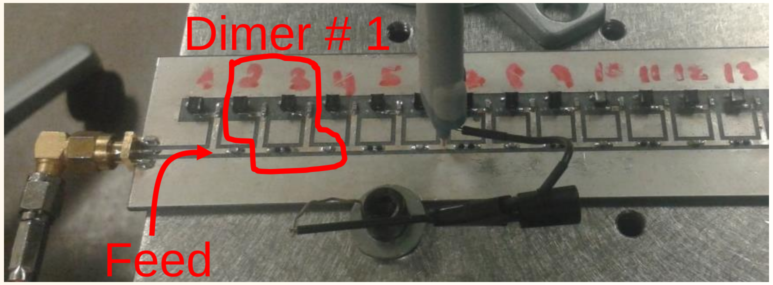
High input intensity:

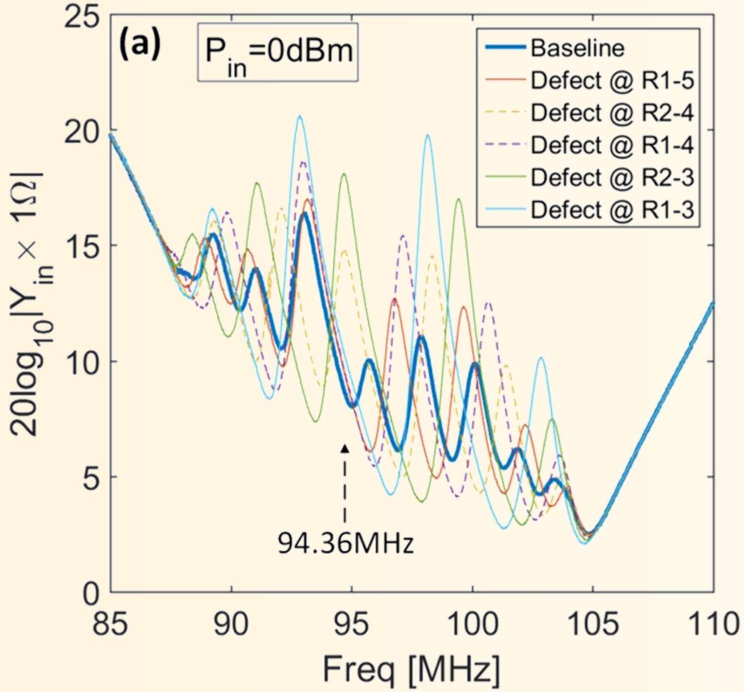


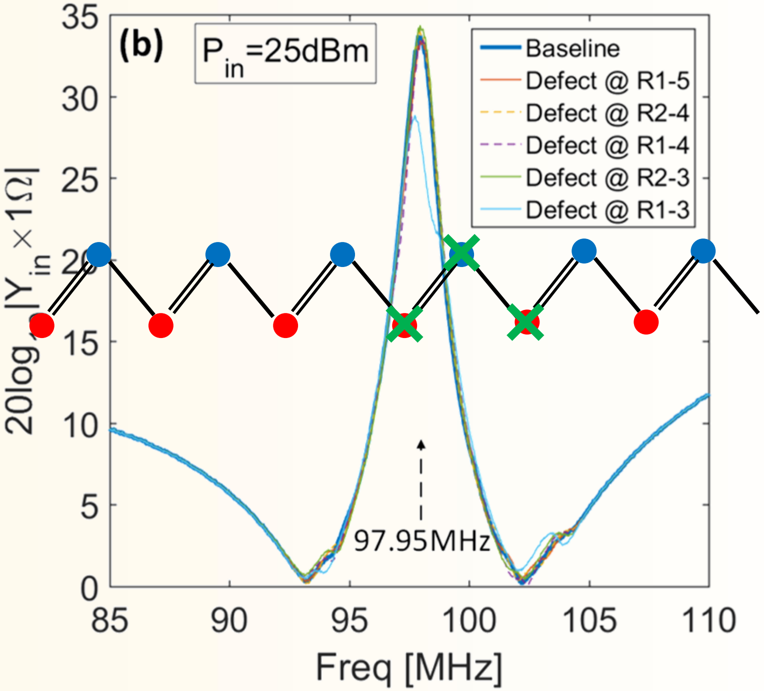
Y. Hadad, A. B. Khanikaev, and A. Alù, *Phys. Rev. B* **93**, 155112 (2016)

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:

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

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

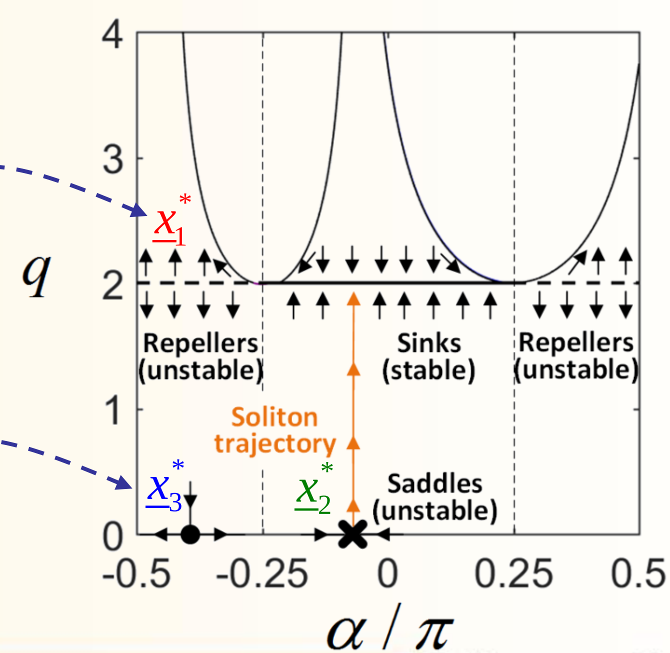
- line of unstable/stable nodes

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

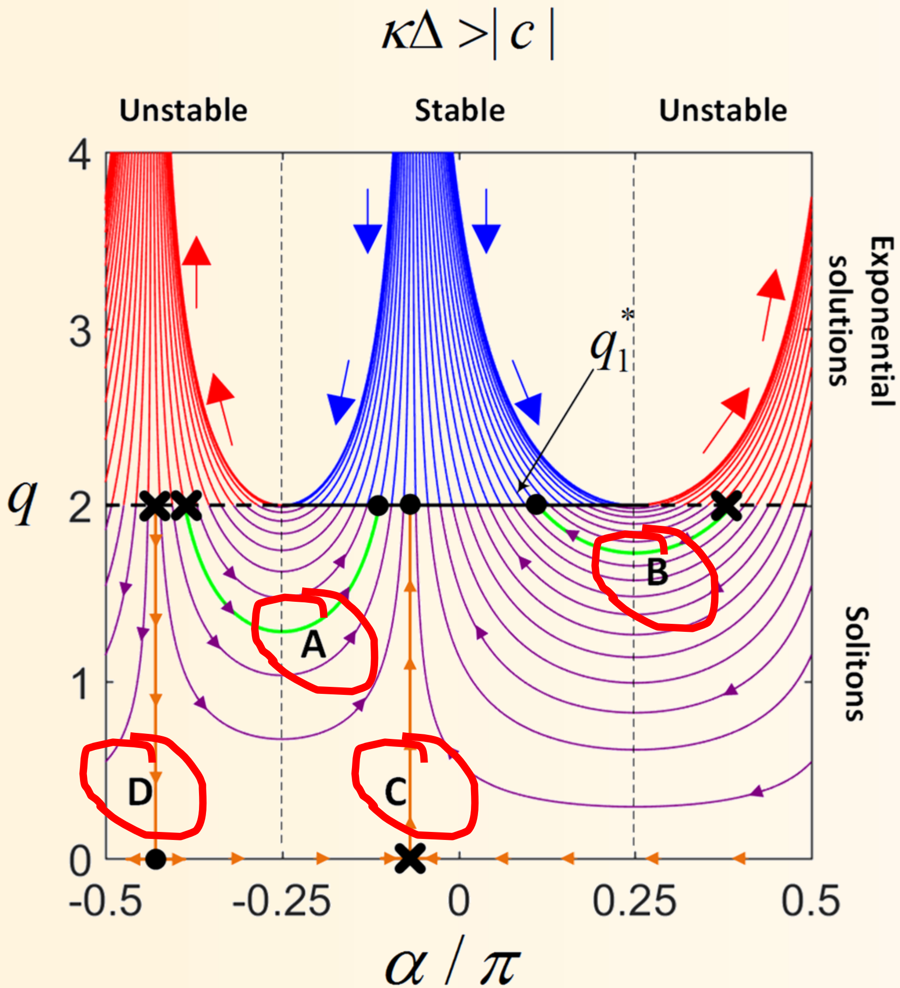
- Saddle (unstable) nodes (only if $|c| < \kappa\Delta$)

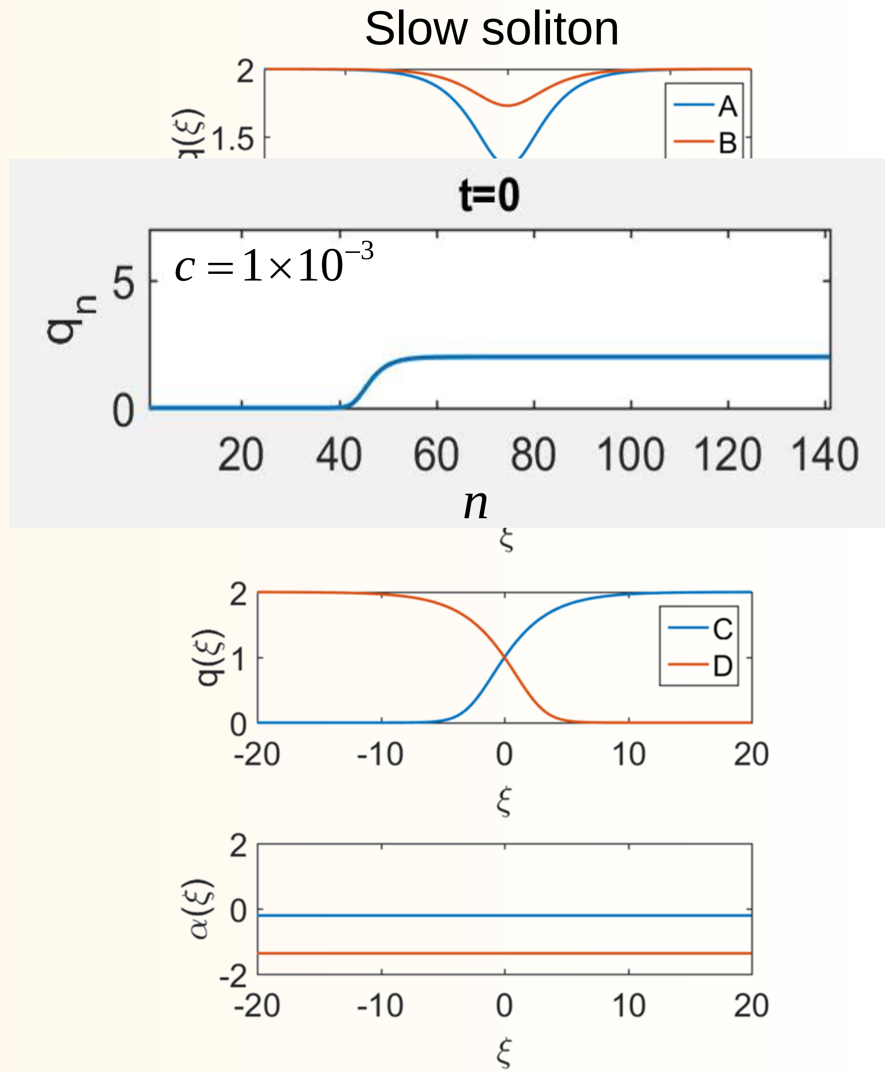
$$\underline{x}_2^* \rightarrow q_2^* = 0, \ \alpha_2^* = -0.5 \sin^{-1}[c / \kappa\Delta],$$

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

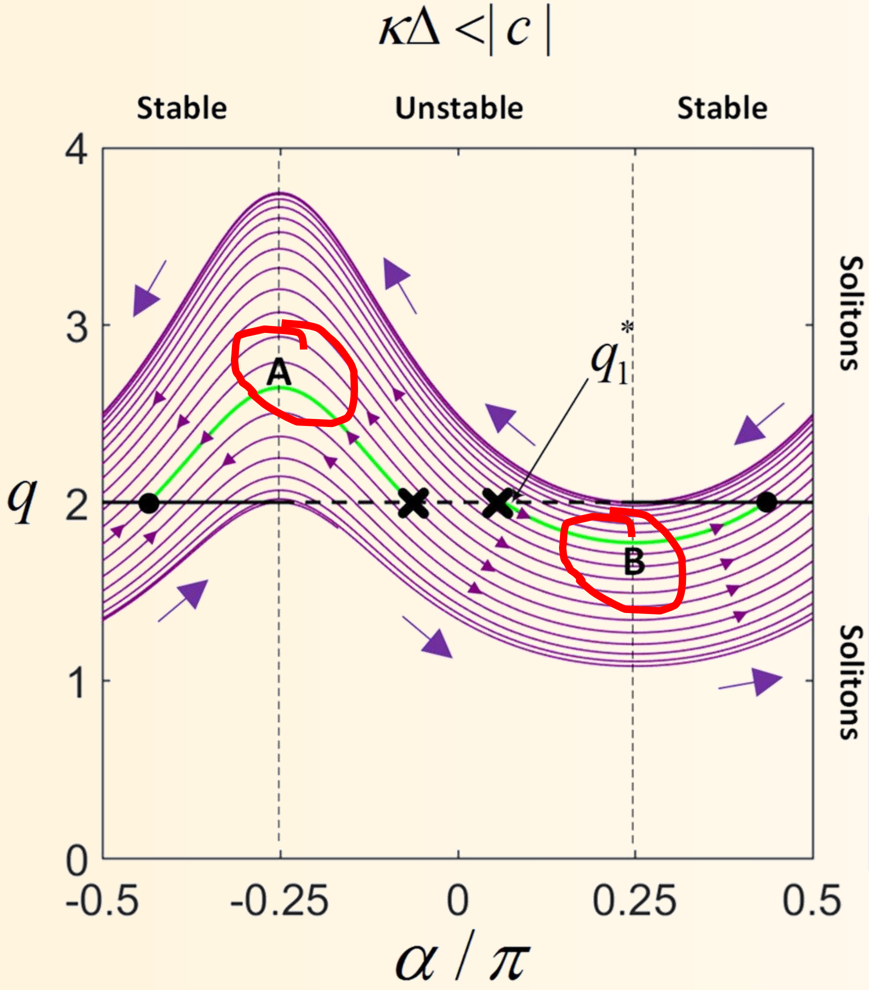


Phase Diagrams and Solitons

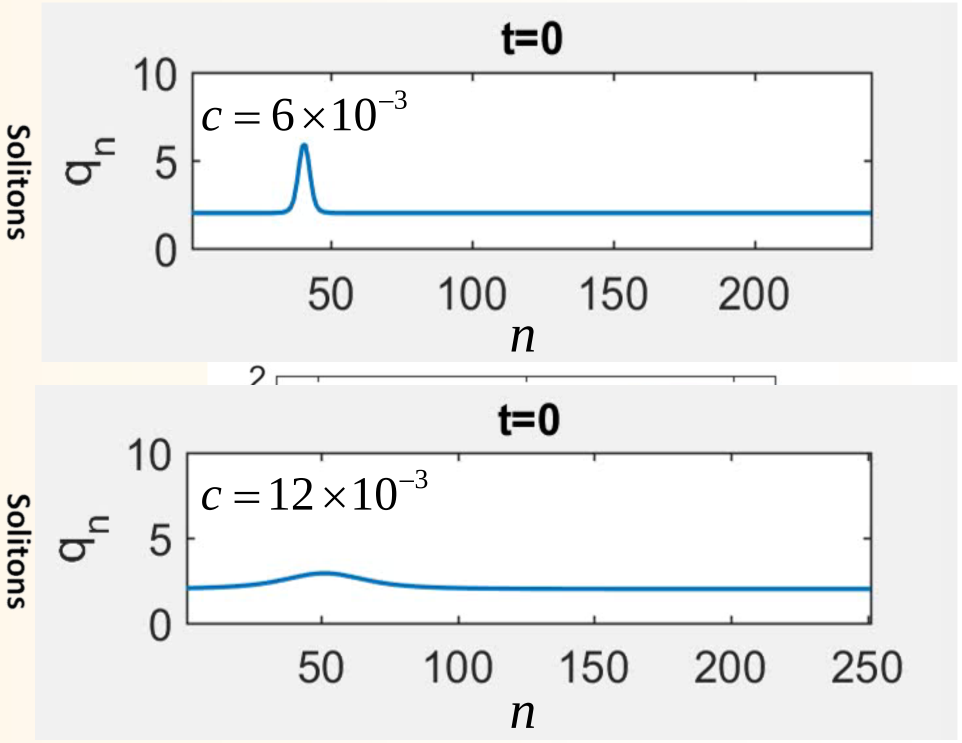




Phase Diagrams and Solitons

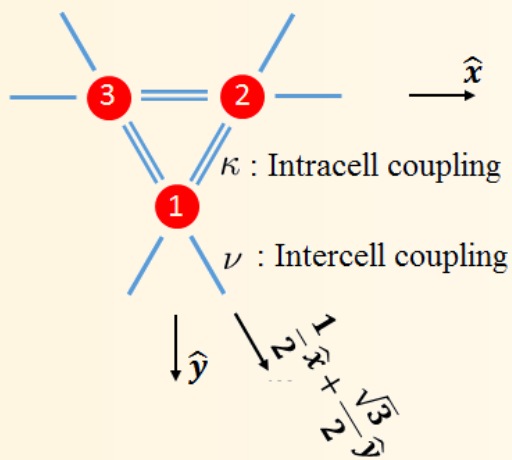


Fast soliton



2D Nonlinear Topological Photonic Insulator

The Elementary Cell: Kagome Lattice



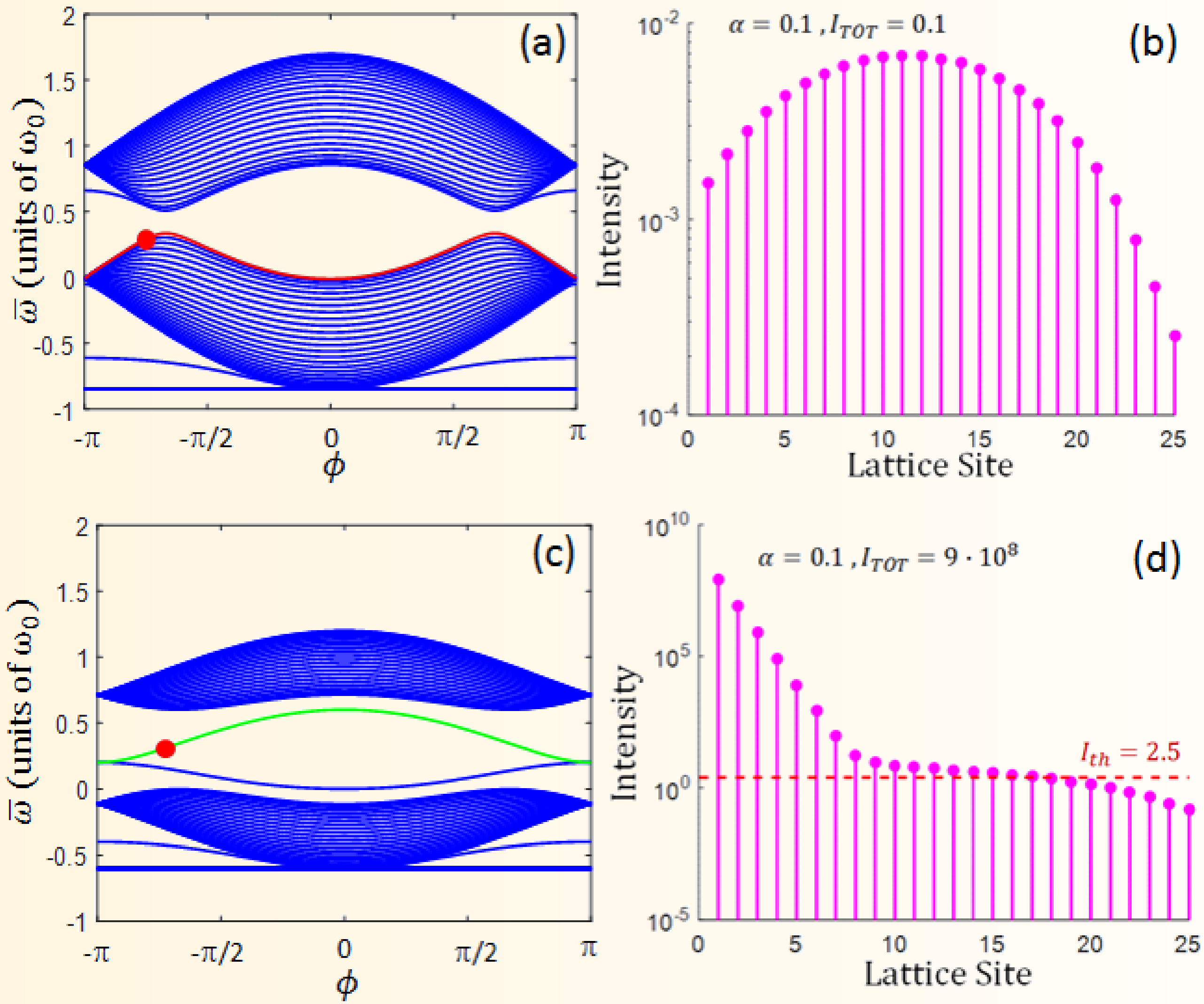
$$\kappa_{m,n}^{(j,k)} = \kappa_\infty + \frac{\kappa - \kappa_\infty}{1 + \alpha \left| a_{m,n}^{(j)} - a_{m,n}^{(k)} \right|^2}$$

$$i\dot{a}_{m,n}^{(1)} = \omega_0 a_{m,n}^{(1)} + \kappa_{m,n}^{(2,1)} a_{m,n}^{(2)} + \kappa_{m,n}^{(3,1)} a_{m,n}^{(3)} + \nu [a_{m+1,n-1}^{(2)} + a_{m+1,n}^{(3)}], \quad (1)$$

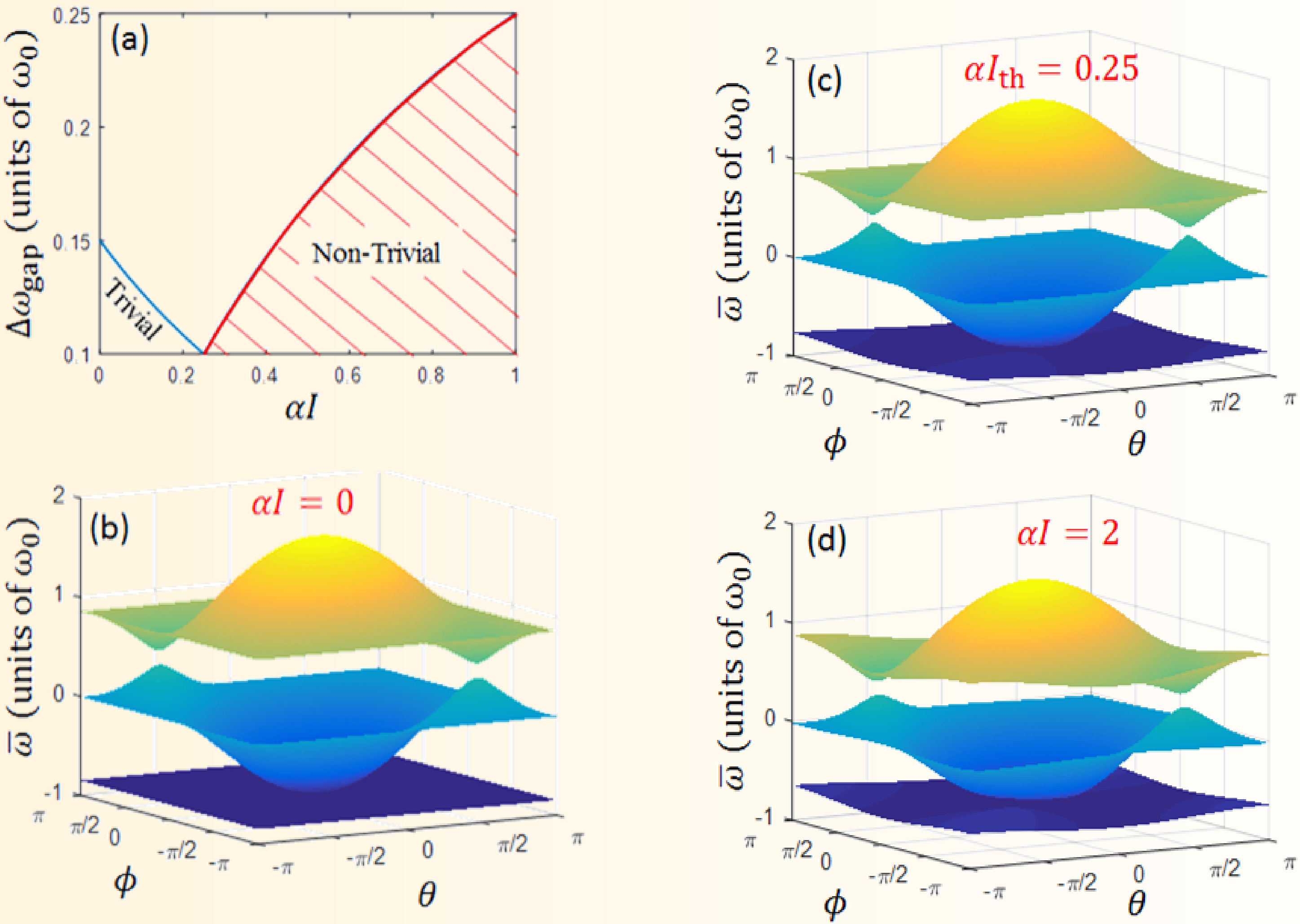
$$i\dot{a}_{m,n}^{(2)} = \omega_0 a_{m,n}^{(2)} + \kappa_{m,n}^{(1,2)} a_{m,n}^{(1)} + \kappa_{m,n}^{(3,2)} a_{m,n}^{(3)} + \nu [a_{m-1,n+1}^{(1)} + a_{m,n+1}^{(3)}], \quad (2)$$

$$i\dot{a}_{m,n}^{(3)} = \omega_0 a_{m,n}^{(3)} + \kappa_{m,n}^{(1,3)} a_{m,n}^{(1)} + \kappa_{m,n}^{(2,3)} a_{m,n}^{(2)} + \nu [a_{m-1,n}^{(1)} + a_{m,n-1}^{(2)}], \quad (3)$$

Topological Transition Triggered by Intensity

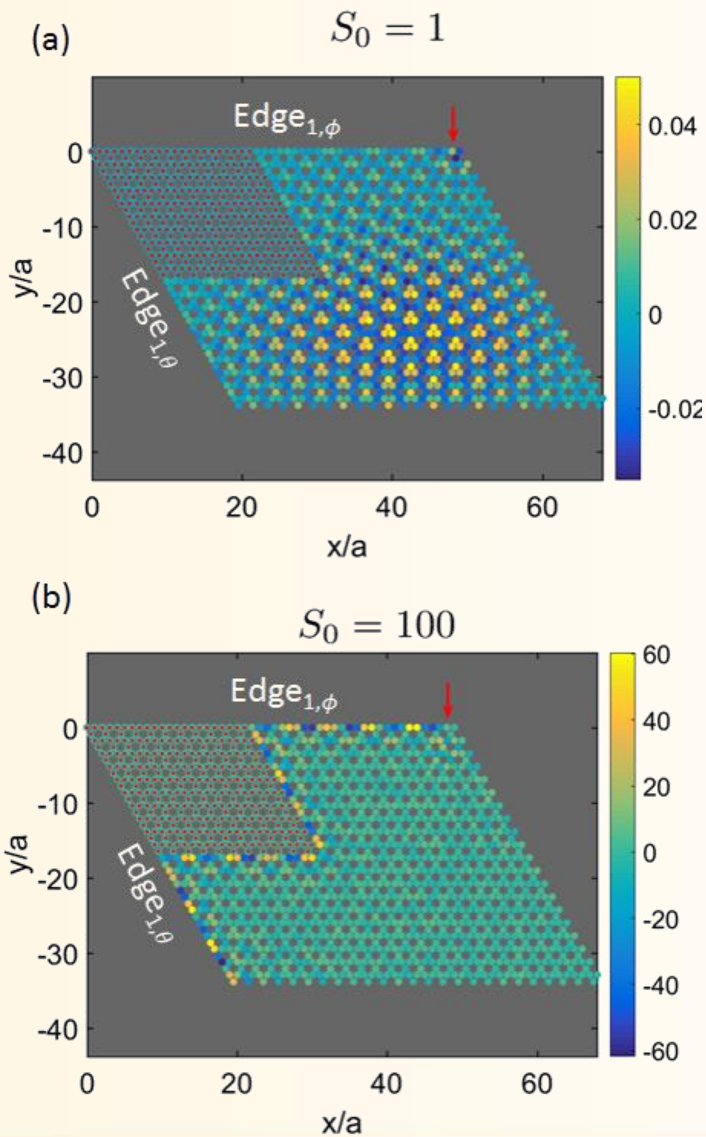


Topological Transition Triggered by Intensity

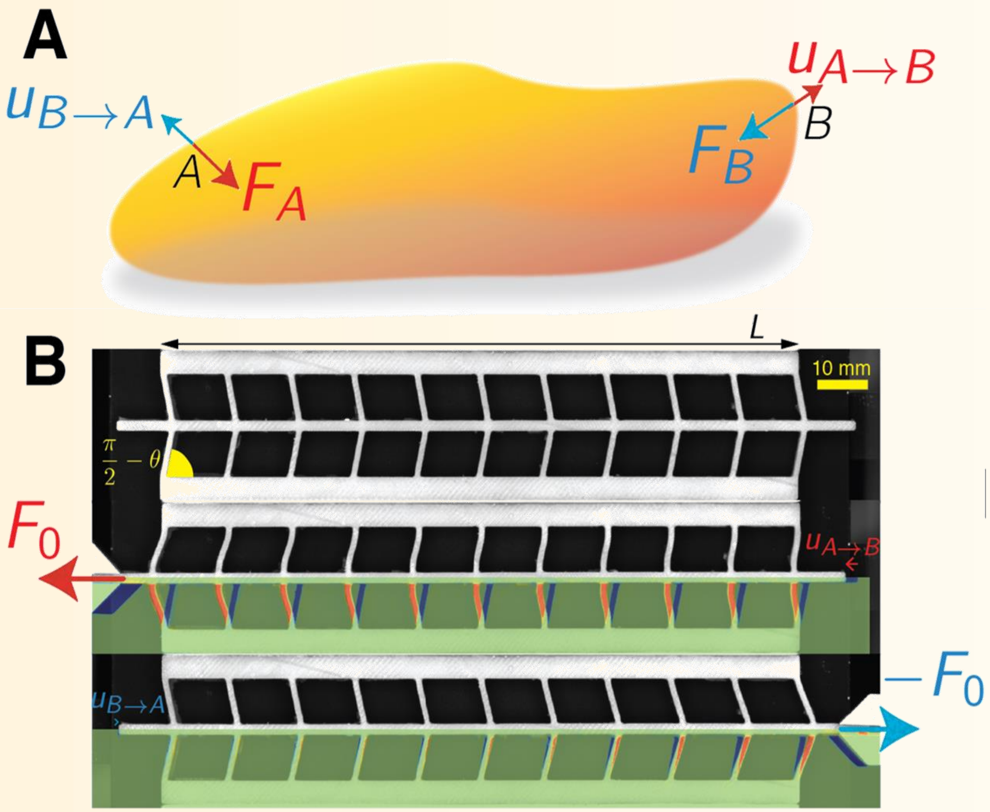


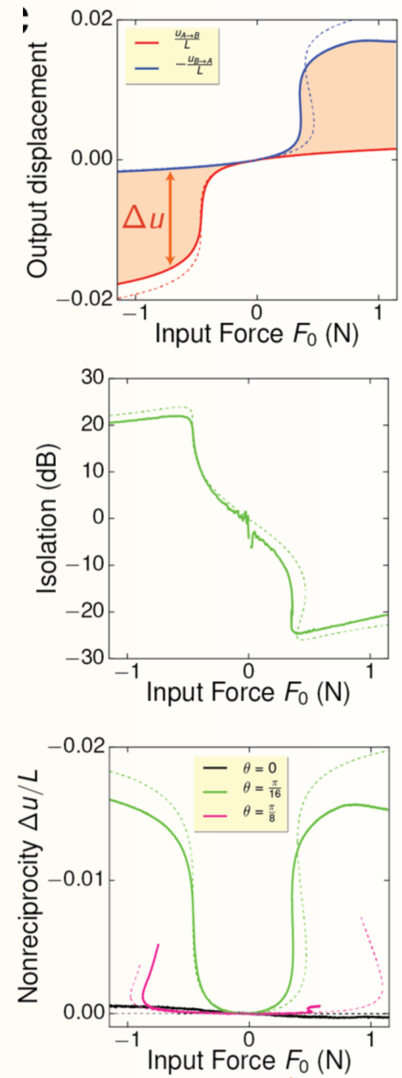
$$\kappa_\infty = 0.2\omega_0, \kappa = 0.45\omega_0, \nu = 0.4\omega_0$$

Topological Transition Triggered by Intensity



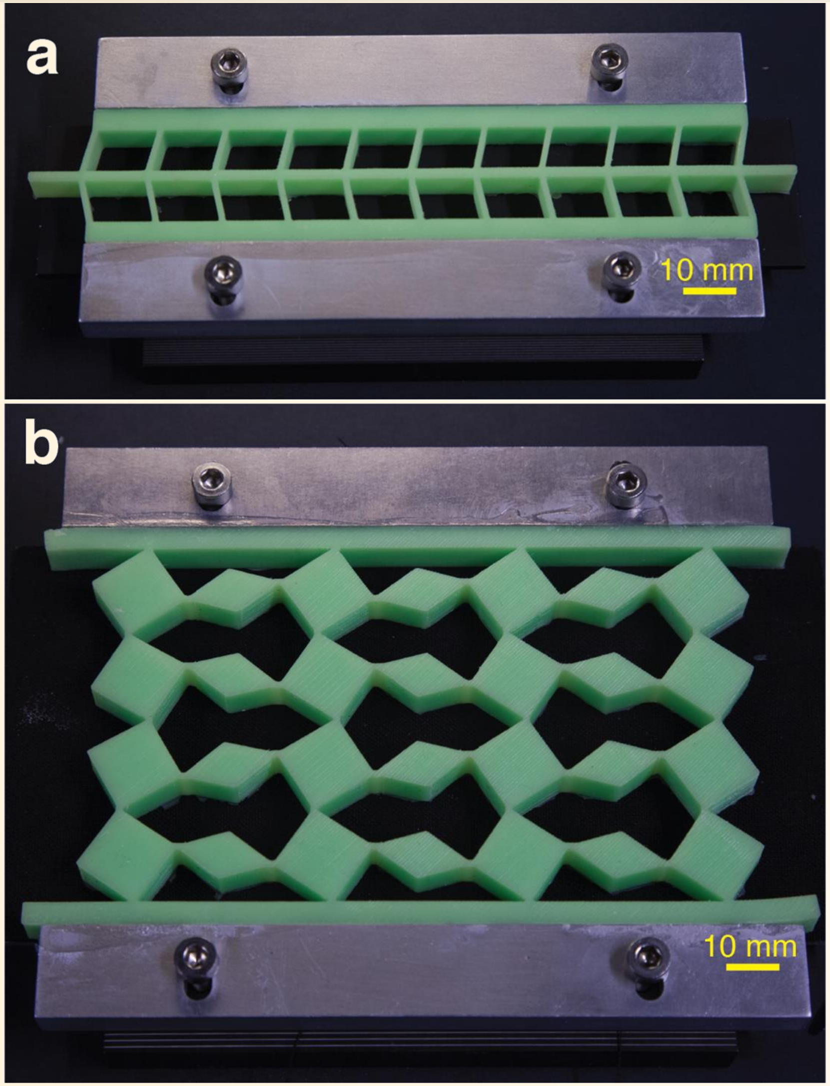
Non-Reciprocity in Statics

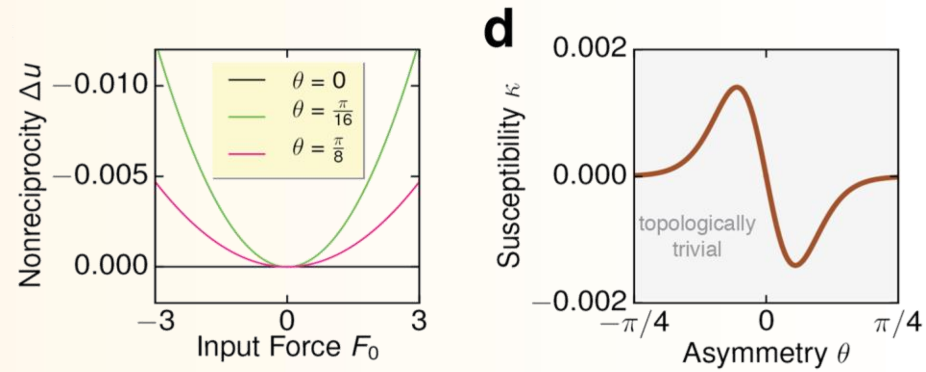




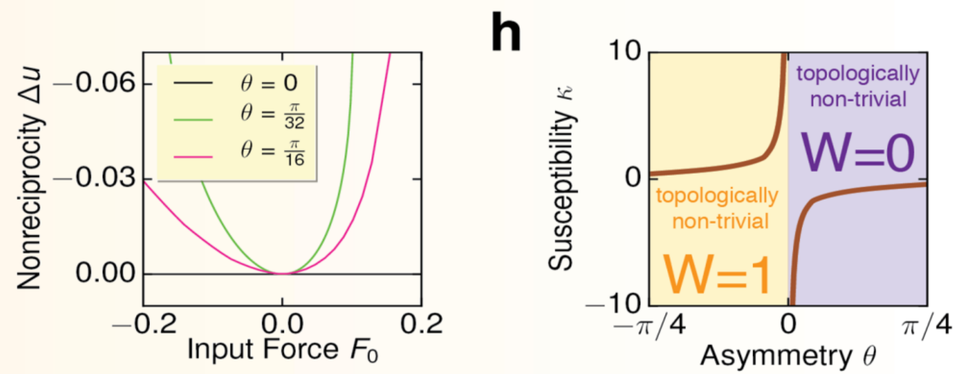
C. Coulais, D. Sounas, A. Alù, *Nature* **542**, 461 (2017)

Non-Reciprocity in Static Topological Metamaterials



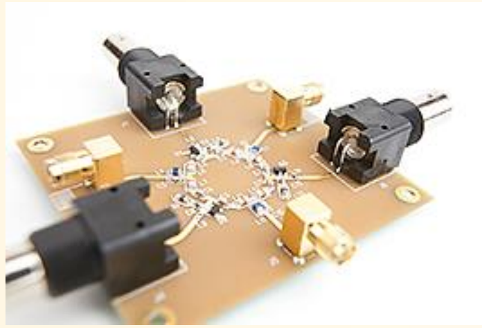


$$\Delta u = \kappa(\theta) {F_0}^2$$

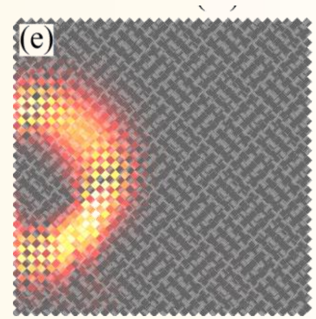


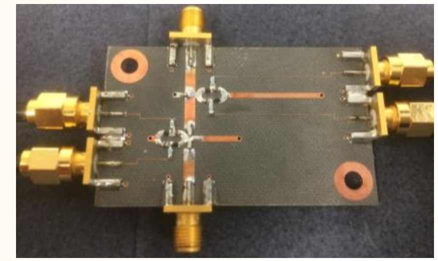
C. Coulais, D. Sounas, A. Alù, *Nature* **542**, 461 (2017)

Topological Photonics and Phononics in Metamaterials

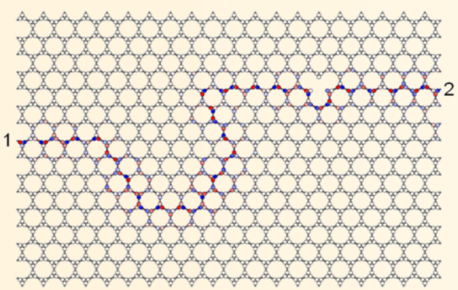



Magnetic-free, linear nonreciprocity at the subwavelength scale: angular-momentum biased meta-atoms

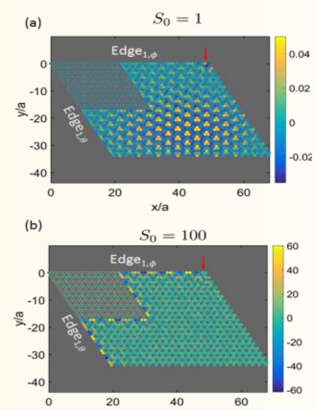


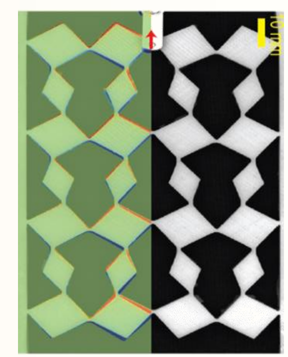


Nonlinearity and asymmetry to build optimal isolators and non-reciprocal devices



Topological metamaterials for broadband, one-way, reconfigurable signal transport





These concepts span a broad range of physical mechanisms, from acoustics to RF, mid-IR, optics, mechanics, statics, and more.