UC San Diego

Fundamental Analyses and Discovery of Topological EM Materials

AFOSR EM Portfolio Review

Daniel Sievenpiper, UC San Diego

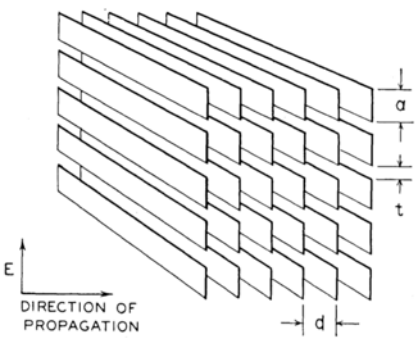
January 8, 2025

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

From Artificial Dielectrics to Topological Metamaterials

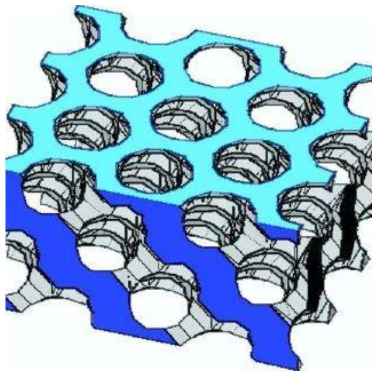
Artificial Dielectrics



Sharpless
1940s to 1960s

Metal strips, plates, or spheres in dielectric change effective permittivity

Photonic Crystals



Yablonovitch et. al.
1980s and 1990s

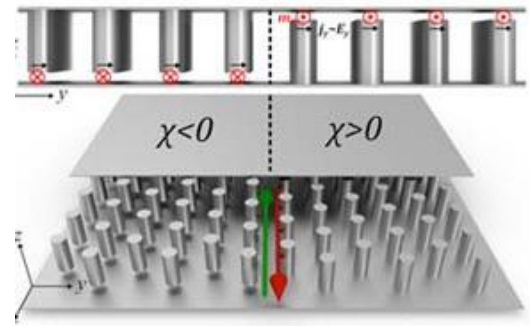
Specific lattices (periodicity) can create band gaps (omnidirectional frequency filters)

Metamaterials

Smith et. al.
2000s

Resonance can create any value of permittivity and/or permeability, including negative or near zero

Photonic Topological



Shvets et. al.
2010s

"Spin-orbit coupling" for unidirectional modes (two opposite polarizations propagate in opposite directions)

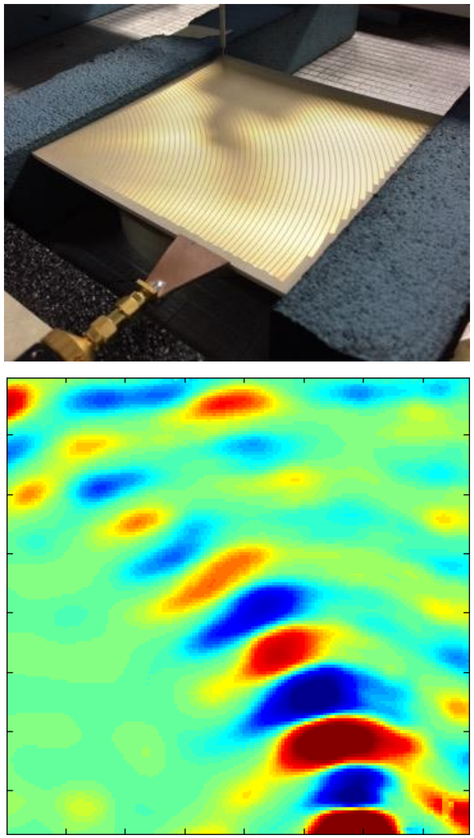
- **Topological electromagnetic structures represent the next advancement and new degree of freedom in artificial media or metamaterials**

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

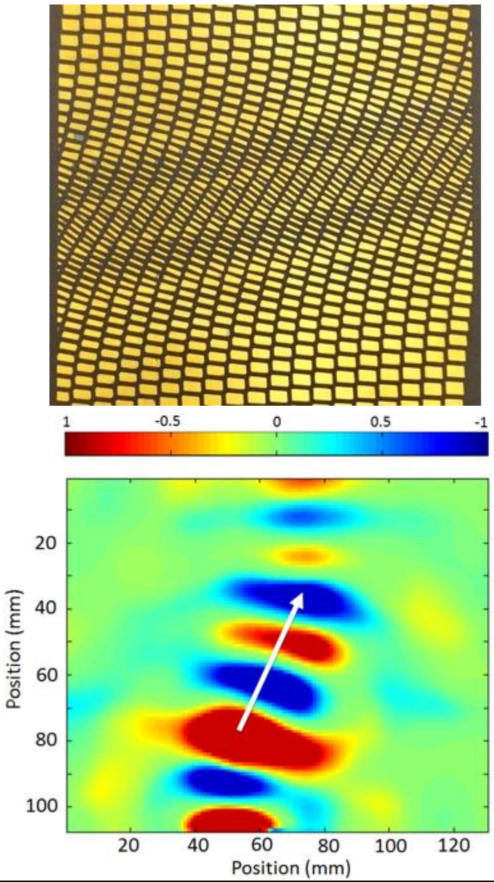
UC San Diego

Examples of Patterned Metasurfaces for Various Functions

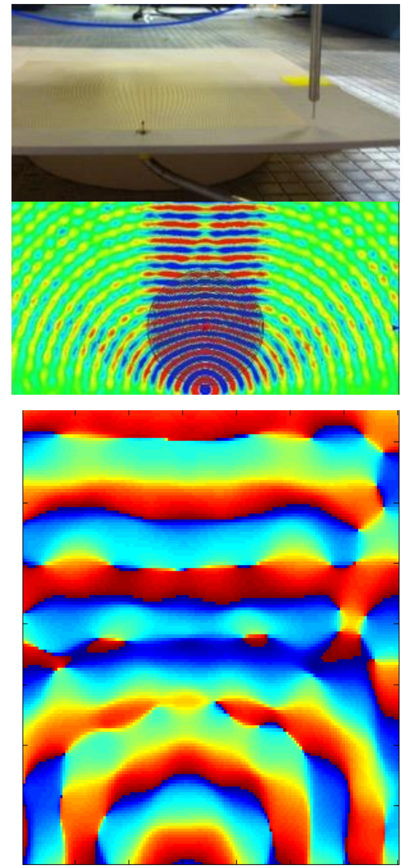
Bend Around Curve



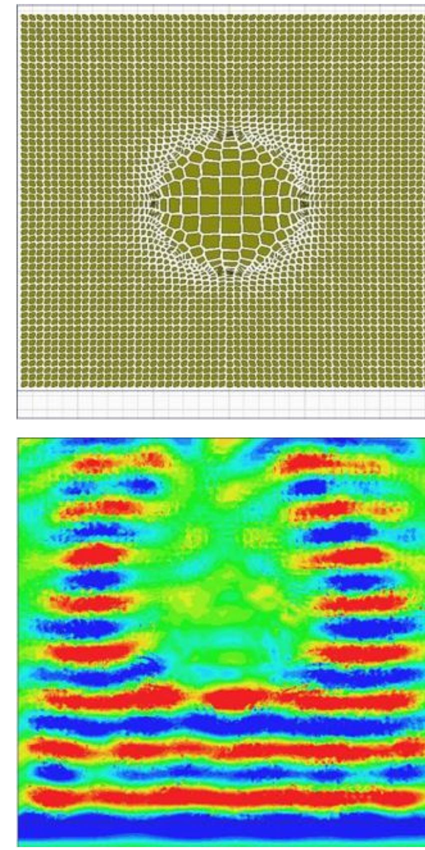
Beam Shifter



Planar Lens



Avoiding Hole



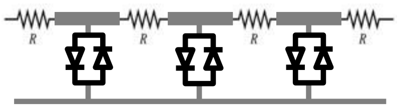
- Patterning method allows for wide range of impedance functions
- Enables control over surface wave propagation and radiation

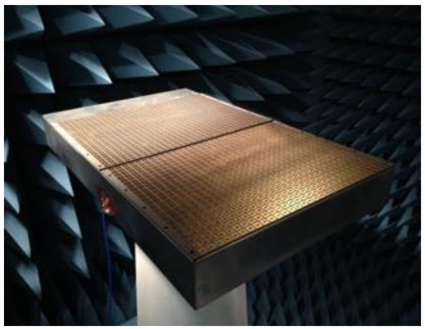
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

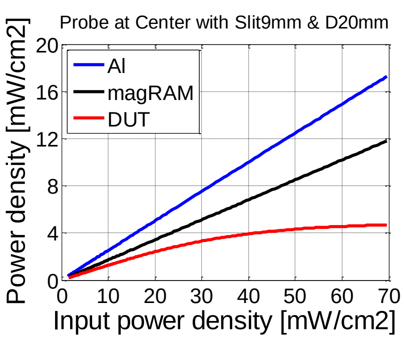
UC San Diego

Examples of Active Metasurfaces for Various Functions

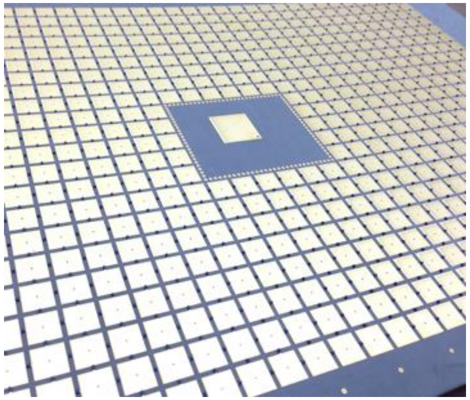
Nonlinear Absorber

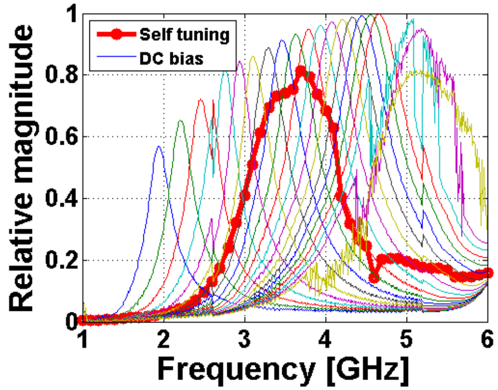




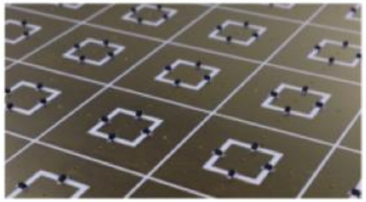


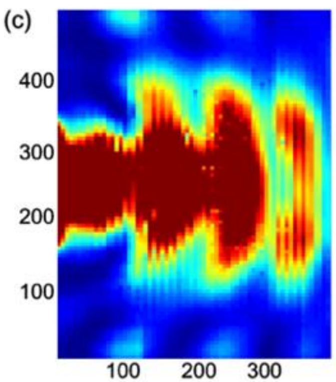
Self-Tuning Surface



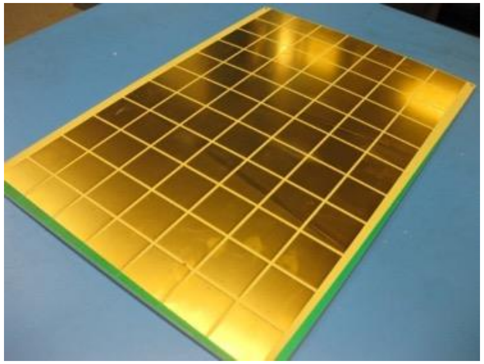


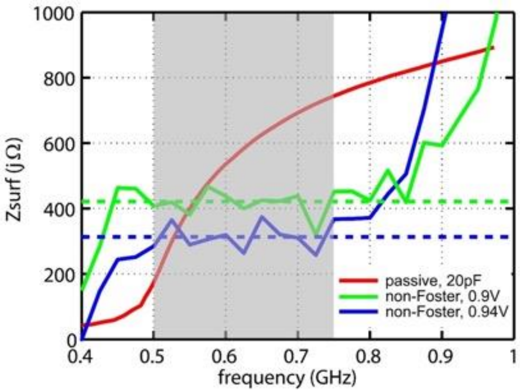
Self-Focusing Surface





Broadband Non-Foster Based Surface





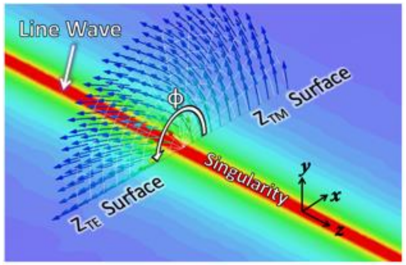
- **A wide range of new surface properties are enabled by including nonlinear, active, feedback, or non-Foster circuits**

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

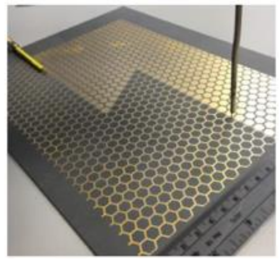
UC San Diego

Overview of Topological and Chiral Structures Studied Recently

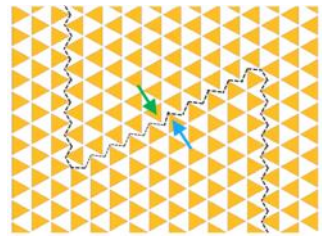
Line waves



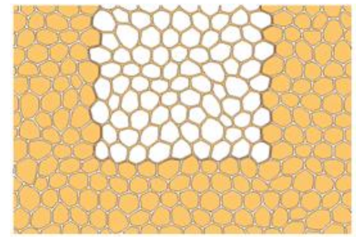
Metallic PTI (spin)



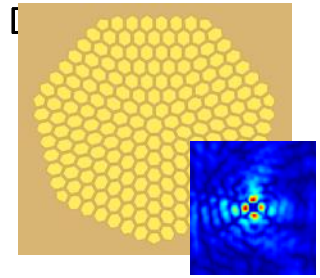
Metallic PTI (valley)



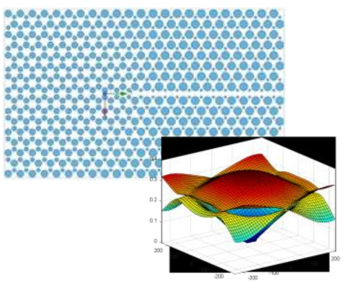
Effects of Disorder



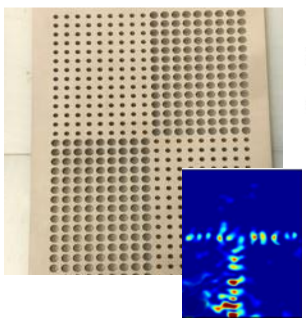
Real Space D



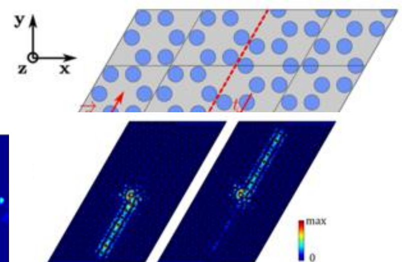
Dirac Point Propagation



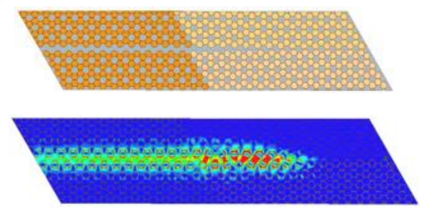
Zak Phase Structures



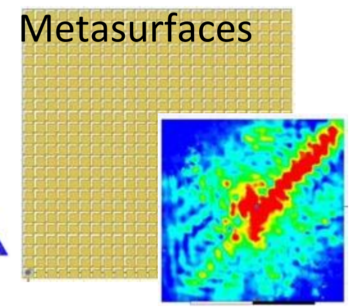
Antiphase Boundaries



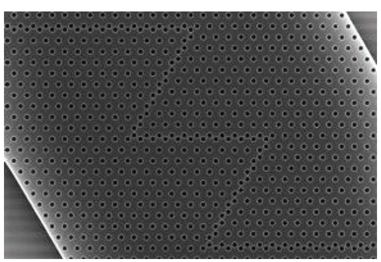
Vernier/Zipper Structures



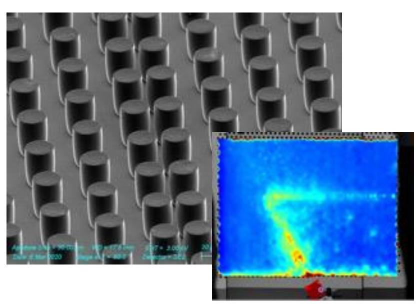
Chiral Metasurfaces



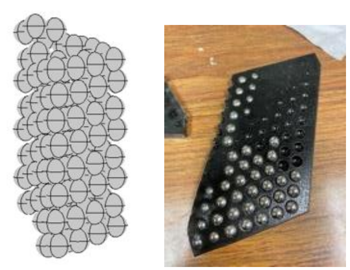
Triangular Lattice Boundaries (Photonic)



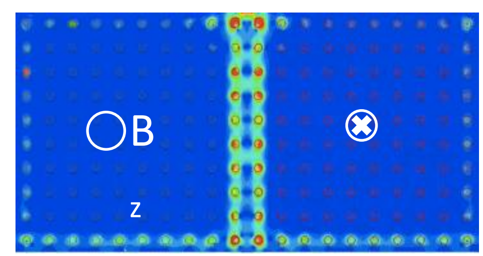
Triangular Lattice Boundaries (Phononic)



Acoustic & EM 3D Screw Discontinuities



Topological Plasma Structures

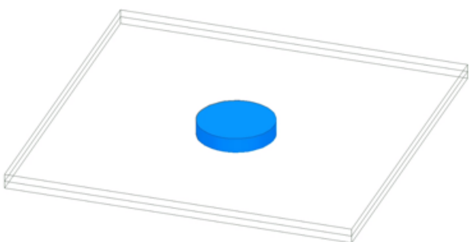


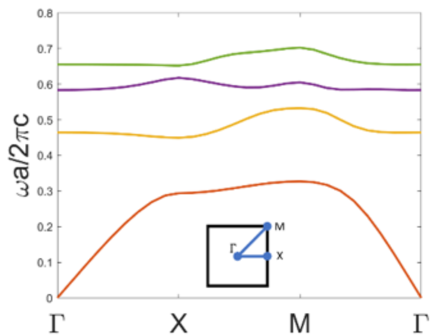
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

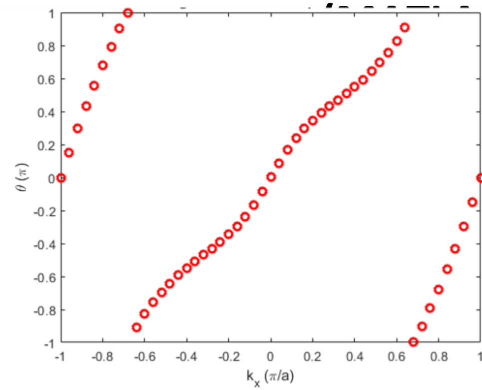
Characterizing Topological Modes Numerically

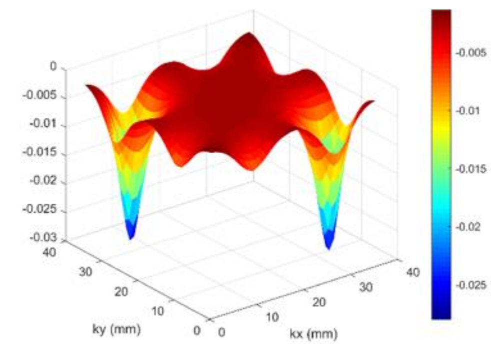
Unit cell design (HFSS)





Topological Analysis





Automation Tools

- Dispersion diagram generators
- Eigenfield extractors
- Lattice constructors

Analysis Packages

- Mode profile
- Berry curvature
- Chern number
- Spin Chern number
- Valley Chern number
- Wilson loops
- Real space invariants

$$C = \frac{1}{2\pi}\sum_{\mathrm{BZ}}\phi_j = \frac{1}{2\pi}\sum_{\mathrm{BZ}}\mathrm{Im}\left[\log\prod_i \langle u_{\mathbf{k}_i}|u_{\mathbf{k}_{i+1}}\rangle\right]$$

$$D_{\mathrm{L}} \equiv \frac{1}{2\pi \mathrm{i}}\left[\sum_{k_\ell\in\partial\mathcal{B}^-} A_1(k_\ell) - \sum_{k_\ell\in\mathcal{B}^-} F_{12}(k_\ell)\right]$$

$$W(k_i) = -\mathrm{Im}\left(\log\prod_{k_j}\langle u_{(k_i,k_j)}(\mathbf{r})|u_{(k_i,k_{j+1})}(\mathbf{r})\rangle\right)$$

- **We have made all these codes freely available**
- **https://github.com/Applied-Electromagnetics-Lab**

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

Current Goals

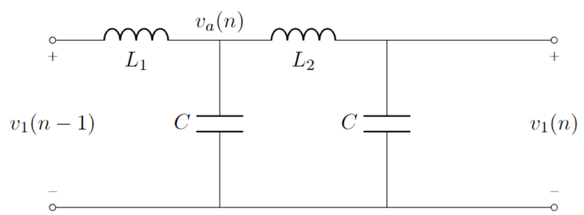
- Conduct topological electromagnetic material discovery and optimization using random patterns
  - Which geometrical features cause which effects, and why?
- Create circuit models for topological effects to allow improved understanding and integration with circuit components
  - Can we explain these effects with something we already understand?
- Explore the possibility of unidirectional bulk surface waves or unidirectional bulk 3D wave propagation
  - Create structures that control scattering or thermal propagation
- Answer fundamental questions about the rules that govern various classes of topological materials
  - Which geometrical structures have which properties, and are they consistent?

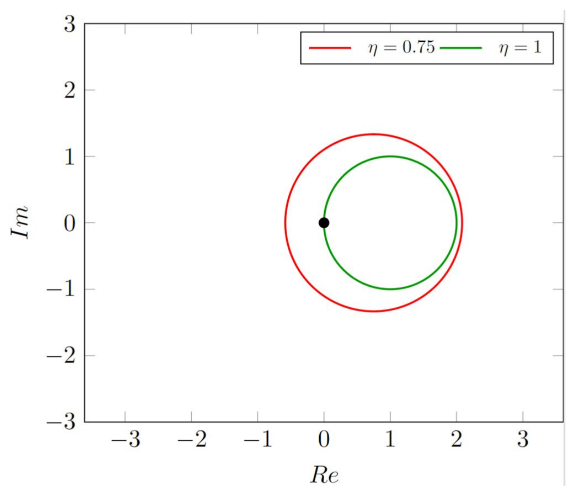
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

Circuit Models of Topological EM Structures

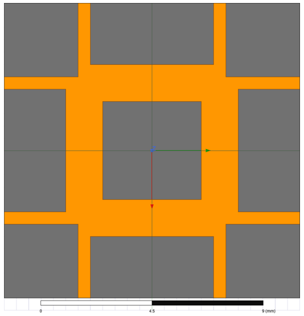
1D Structures

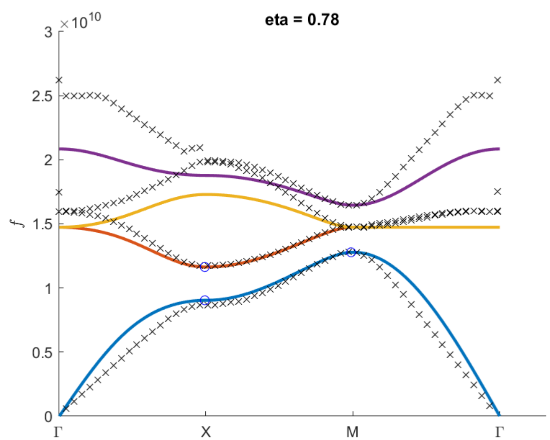




- Emergent Zak phase from circuit model

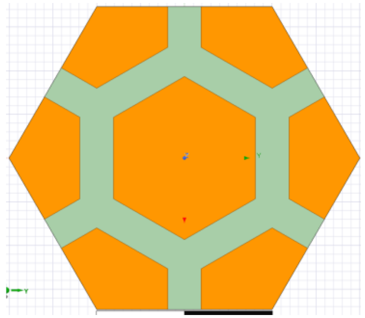
2D Structures | Square Lattice

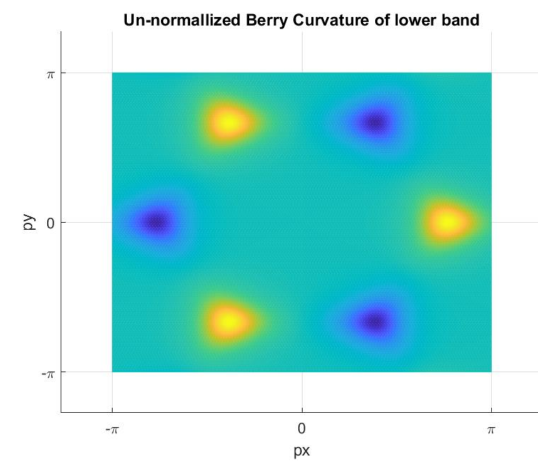




- Stepping stone for Hexagonal lattices

2D Structures | Hexagonal Lattice



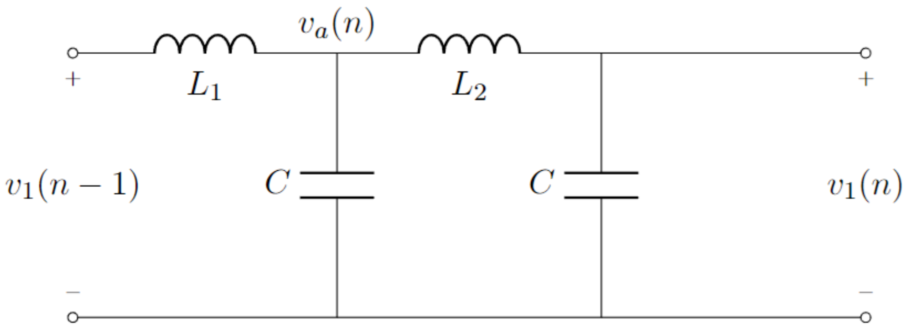


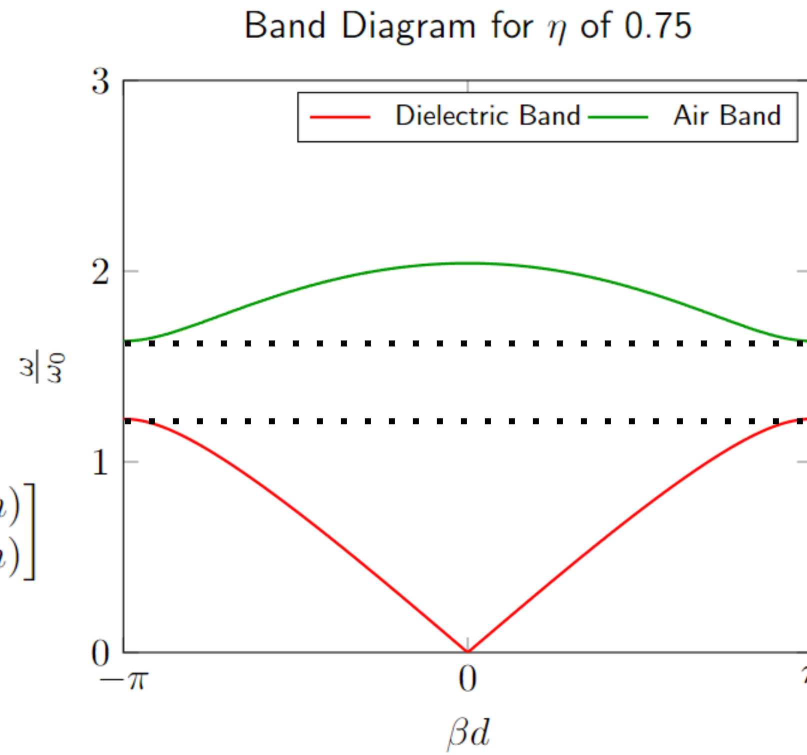
- Emergent winding/Chern numbers

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

TxLine Modelling of PTIs | 1D





$$j\omega C \begin{bmatrix} v_a(n) \\ v_1(n) \end{bmatrix} = \frac{1}{j\omega} \begin{bmatrix} \left(\frac{1}{L_1} + \frac{1}{L_2}\right) & \left(\frac{e^{j\beta d}}{L_1} + \frac{1}{L_2}\right) \\ \left(\frac{1}{L_2} + \frac{e^{-j\beta d}}{L_1}\right) & \left(\frac{1}{L_1} + \frac{1}{L_2}\right) \end{bmatrix} \begin{bmatrix} v_a(n) \\ v_1(n) \end{bmatrix}$$

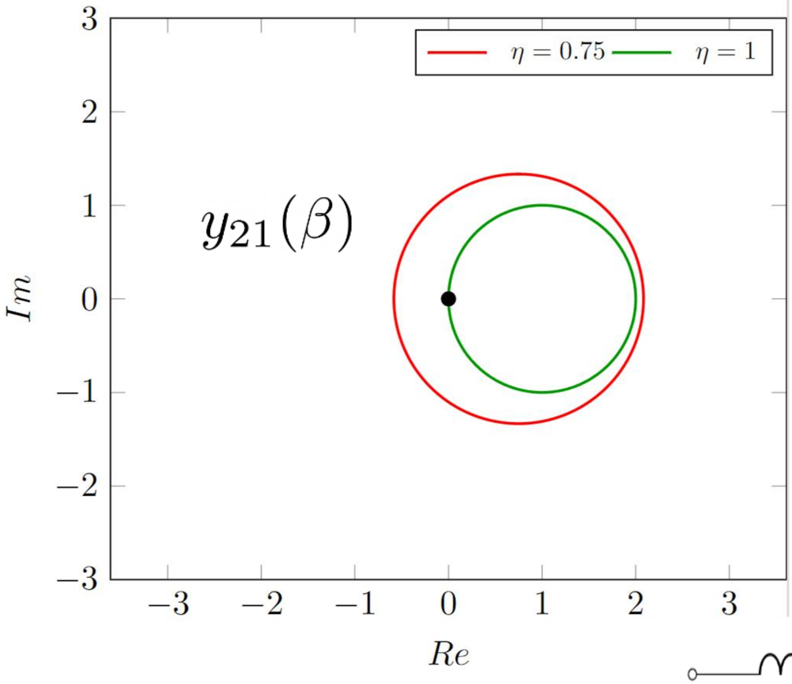
$$\frac{v}{Z} = \mathbf{Y_p} v \qquad \eta = \sqrt{\frac{L_2}{L_1}}$$

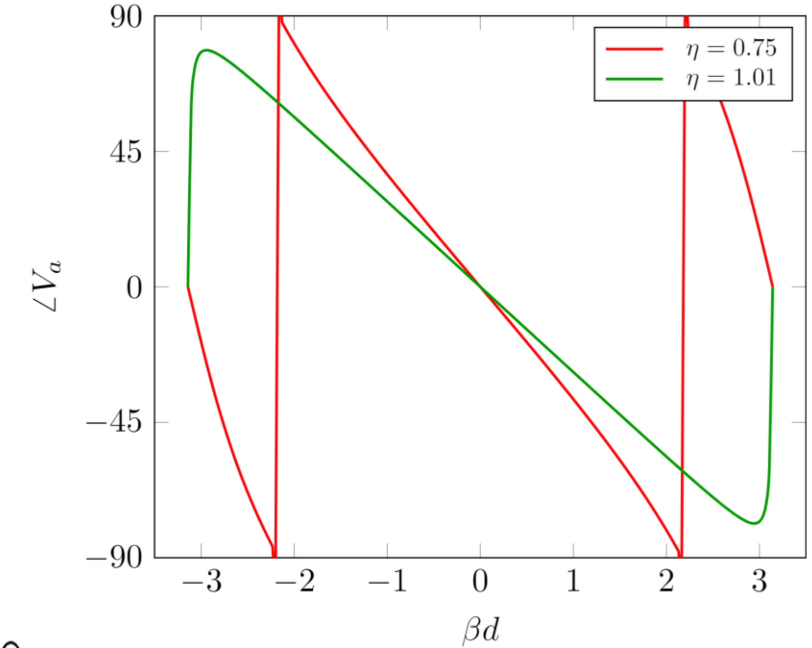
- **Periodic circuit analysis can be easily carried out by writing KCL and enforcing periodic boundary conditions. Similar to Blochwave analysis with Y parameter matrices**
- **Alternating the inductors (or capacitors) opens up a band gap which is topologically non-trivial for η<1**

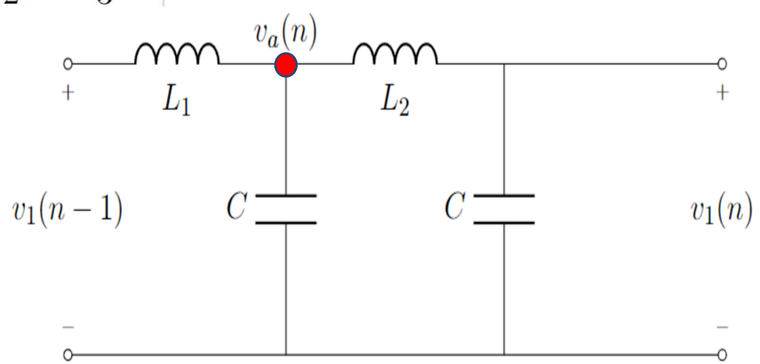
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

Circuit Models for Photonic Topological Insulators







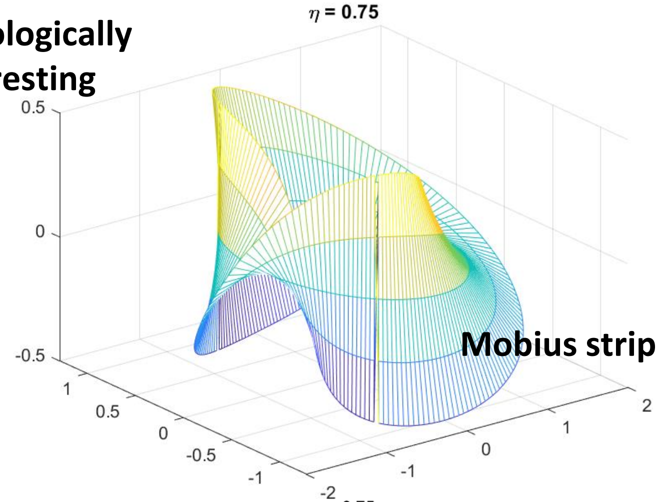
- y_{21} encircling the origin is indicative of a pole (or zero) and is the Zak phase
- The phase of the voltage at the internal node has abrupt phase discontinuities which gives rise to topological protection

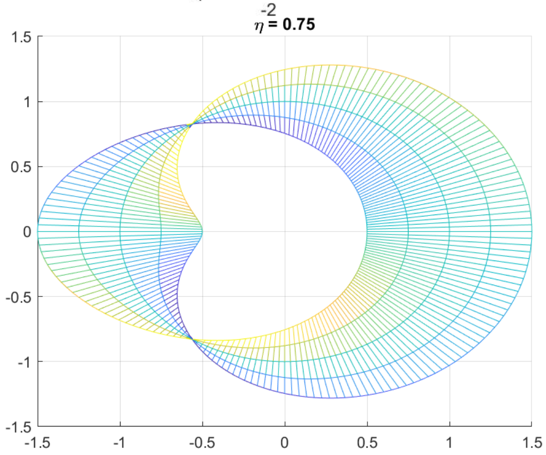
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

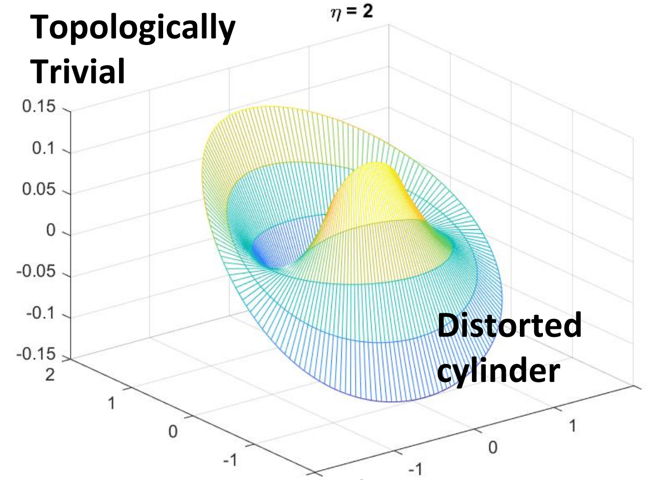
Circuit Models for Photonic Topological Insulators

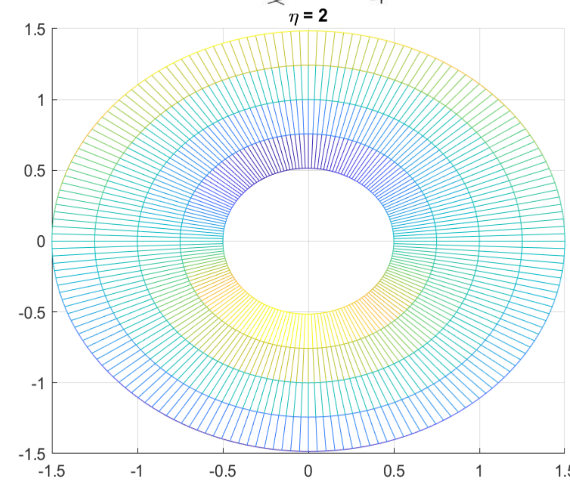
Topologically Interesting





Topologically Trivial





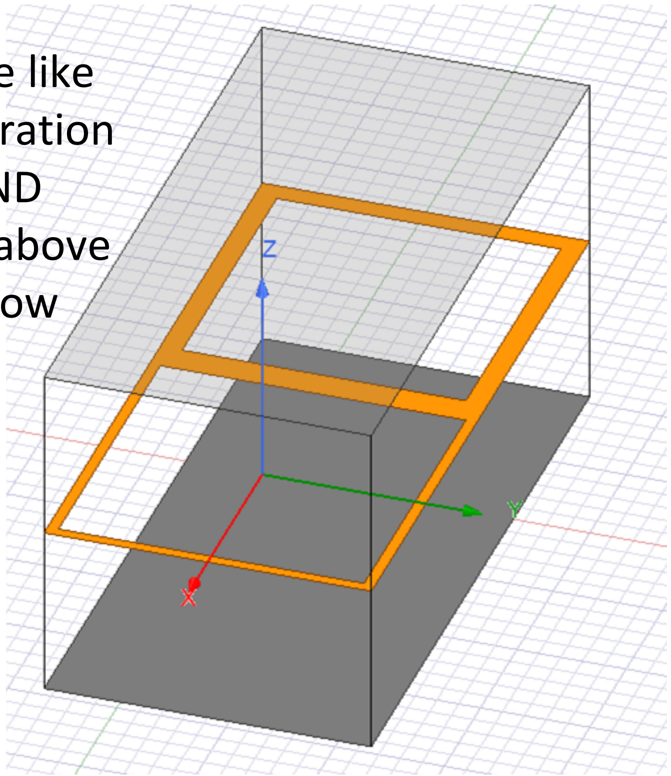
- **Figure formed by plotting the phase of the internal node (a 3D vector in the xz and yz plane) over the full Brillouin Zone (a circle in the xy plane)**
- **Topologically nontrivial structures form a Mobius strip, while trivial structures form a cylindrical loop**

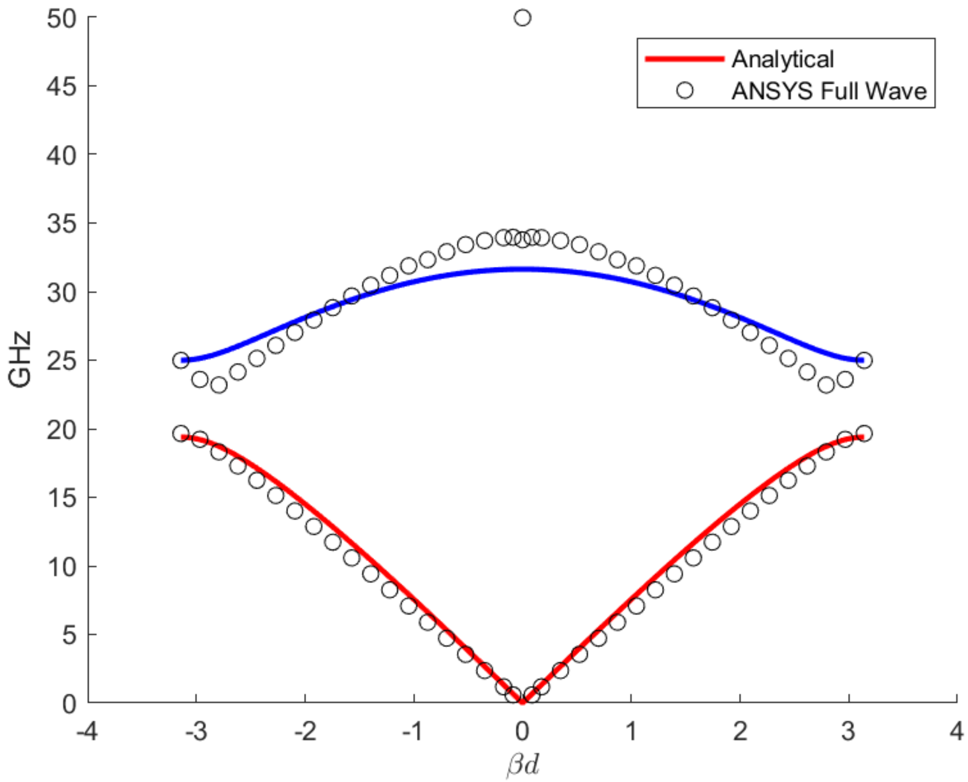
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

Simple EM Structure Implementation

Stripline like configuration with GND planes above and below





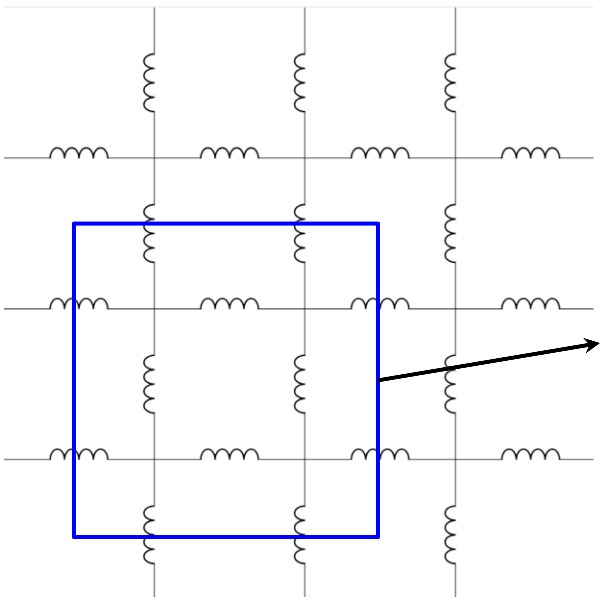
w1 (Ring 1 Thickness)	0.1mm
w2 (Ring 2 Thickness)	0.2mm
d (Cell Periodicity)	3mm

Circuit Model is in good agreement with fullwave simulation conducted using Ansys HFSS

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

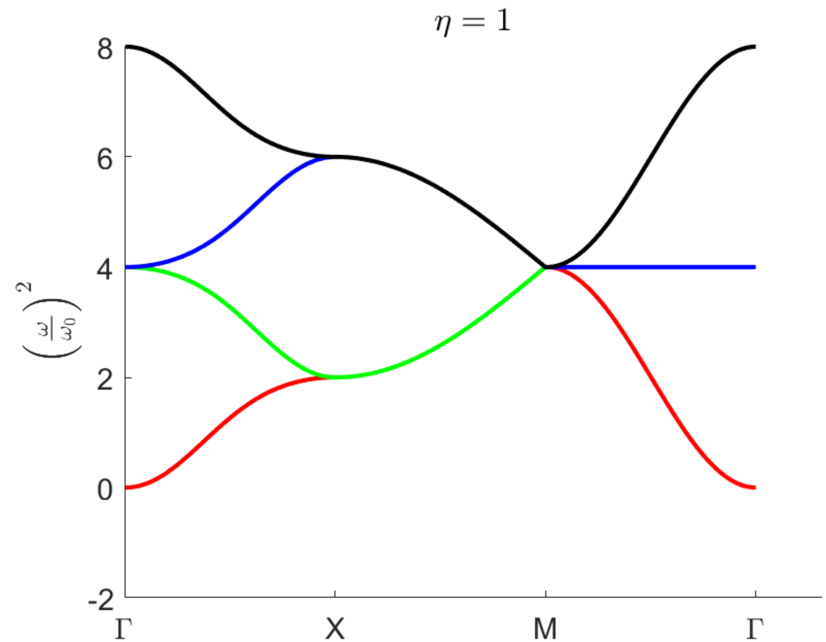
UC San Diego

2D Square Lattice and Band Structure



Unitcell highlighted

Capacitors to ground not shown



$$\begin{bmatrix} 2\left(\eta+\frac{1}{\eta}\right) & -\left(\eta e^{jk_y a_y}+\frac{1}{\eta}\right) & 0 & -\left(\eta e^{jk_x a_x}+\frac{1}{\eta}\right) \\ -\left(\eta e^{-jk_y a_y}+\frac{1}{\eta}\right) & 2\left(\eta+\frac{1}{\eta}\right) & -\left(\eta e^{-jk_x a_x}+\frac{1}{\eta}\right) & 0 \\ 0 & -\left(\eta e^{-jk_x a_x}+\frac{1}{\eta}\right) & 2\left(\eta+\frac{1}{\eta}\right) & -\left(\eta e^{-jk_y a_y}+\frac{1}{\eta}\right) \\ -\left(\eta e^{jk_x a_x}+\frac{1}{\eta}\right) & 0 & -\left(\eta e^{jk_y a_y}+\frac{1}{\eta}\right) & 2\left(\eta+\frac{1}{\eta}\right) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \\ v_d \end{bmatrix} = \left(\frac{\omega}{\omega_0}\right)^2 \begin{bmatrix} v_a \\ v_b \\ v_c \\ v_d \end{bmatrix}$$

$$\eta = \sqrt{\frac{L_u}{L_c}} \qquad \omega_0^2 = \frac{1}{C\sqrt{L_u L_c}}$$

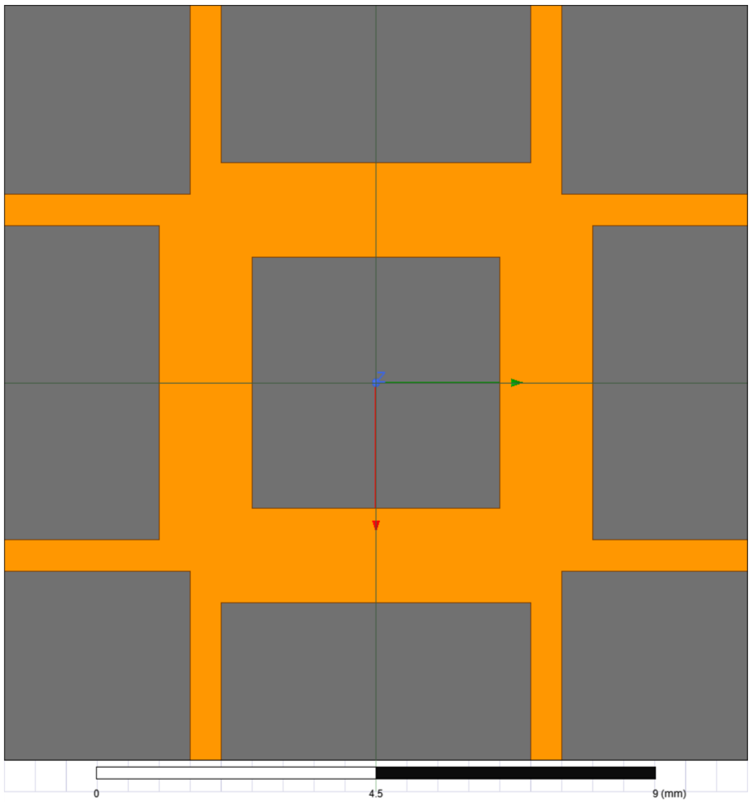
- **Similar to the 1D case, simple LC circuits can be written for 2D square lattices which accurately describes the dispersion relation.**

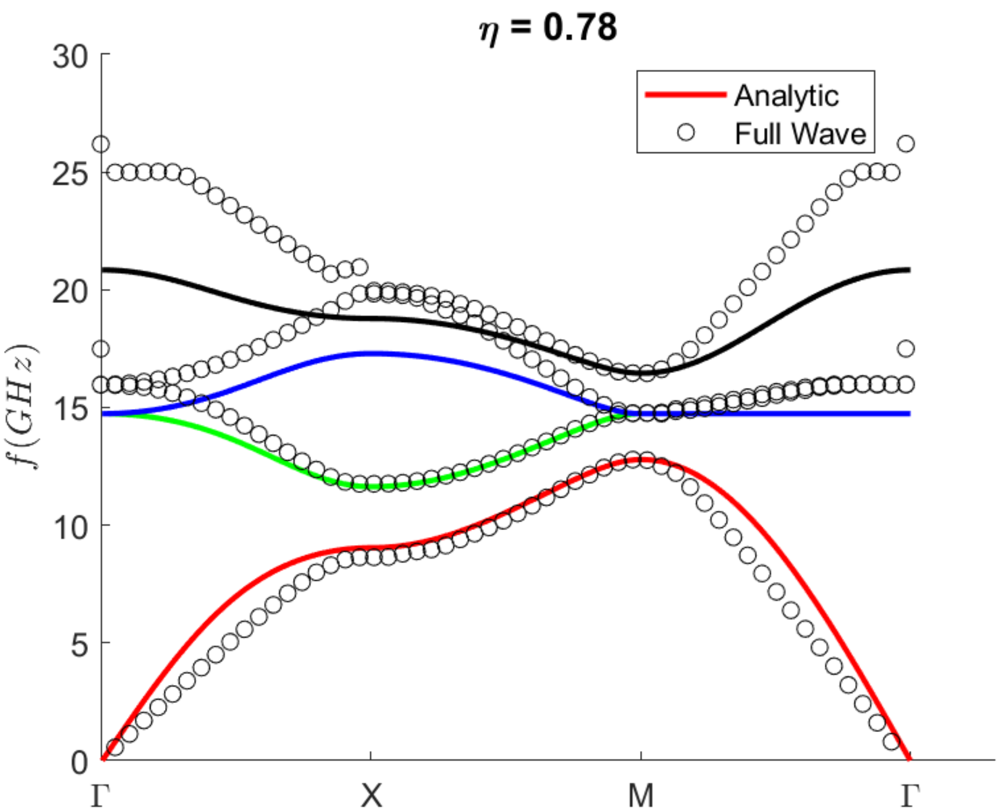
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

Comparing 2D Square Lattice Analytical Approximation with Full EM Simulation

Microstrip like configuration with GND plane below



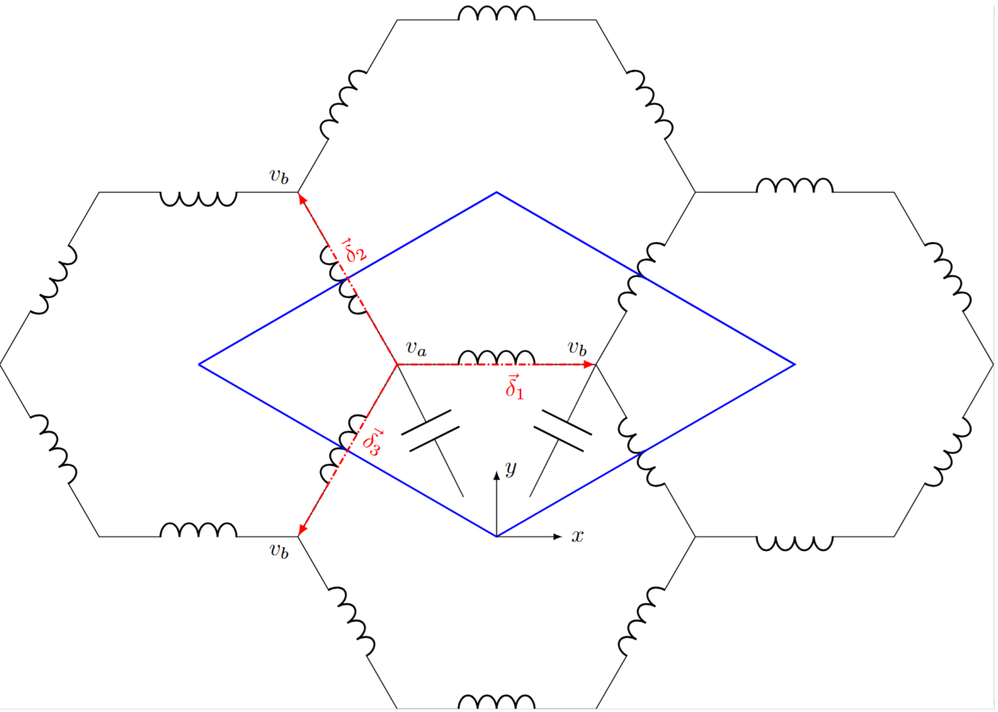


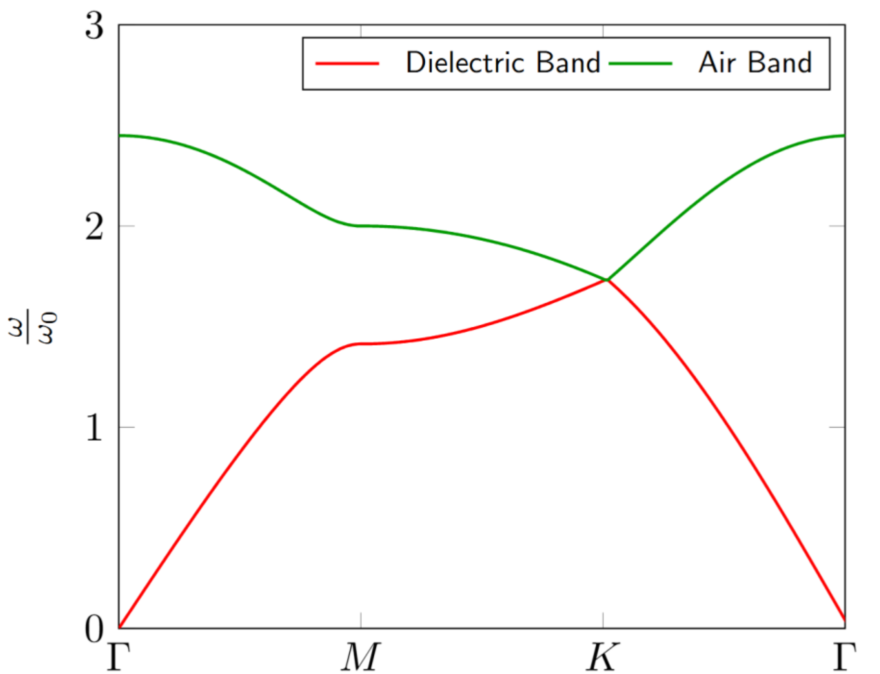
- **Circuit Model is in good agreement with full wave simulation using Ansys HFSS for lower bands**

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

Simple 2D Hexagonal Lattice





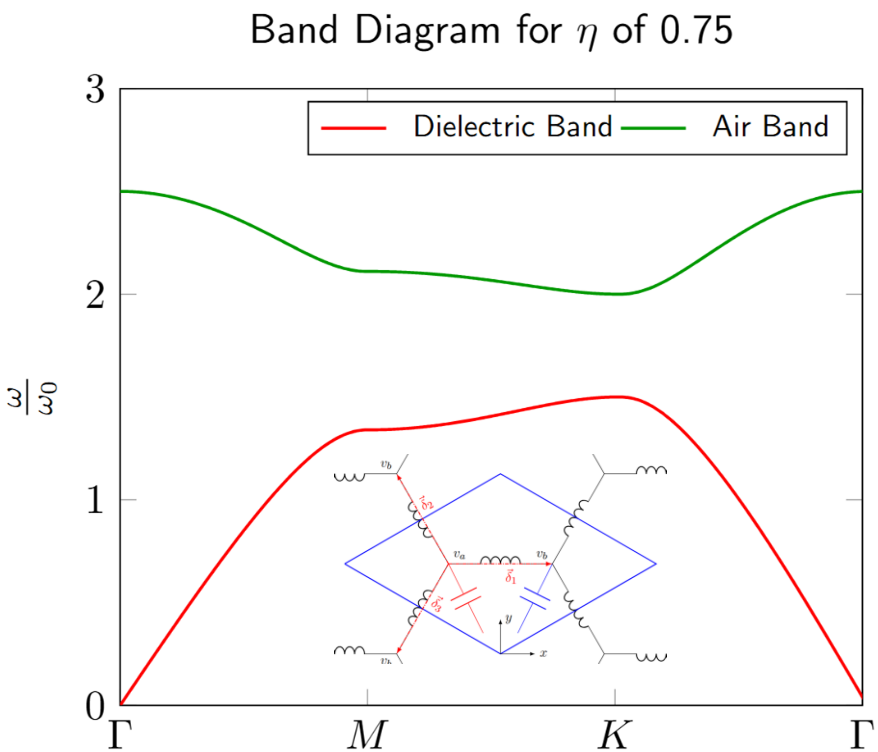
$$\begin{bmatrix} 3 & -\Sigma_i e^{-j\vec{k}.\vec{\delta}_i} \\ -\Sigma_i e^{+j\vec{k}.\vec{\delta}_i} & 3 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \end{bmatrix} = \left(\frac{\omega}{\omega_0}\right)^2 \begin{bmatrix} v_a \\ v_b \end{bmatrix} \quad \omega_0 = \frac{1}{\sqrt{LC}}$$

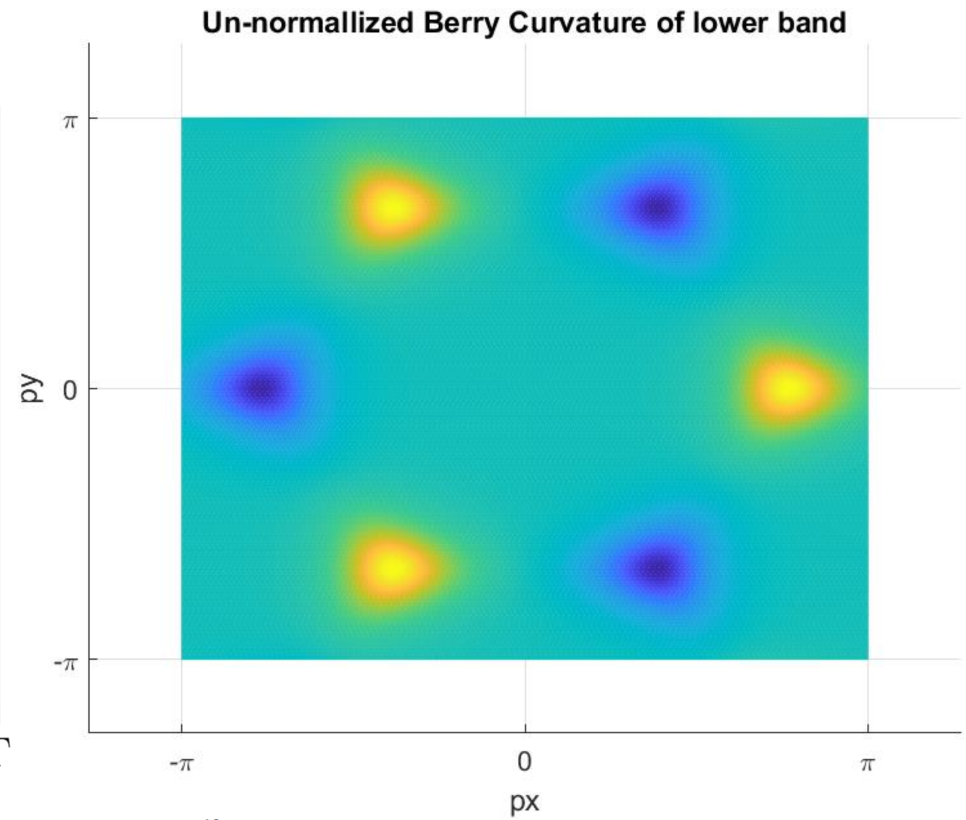
- **Simple 2D LC Circuits predict Dirac Cones at K(K’) points which can be broken through varying C values**
- **Circuit model provides a path to engineer the dispersion relation near the K(K’) points with different topological properties**

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

2D Hexagonal Lattice Band Structure and Berry Curvature Calculated from Circuit Model





$$\begin{bmatrix} 3\eta & -\eta\sum_i e^{-j\vec{k}.\vec{\delta}_i} \\ -\frac{1}{\eta}\sum_i e^{-j\vec{k}.\vec{\delta}_i} & \frac{3}{\eta} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \end{bmatrix} = \left(\frac{\omega}{\omega_0}\right)^2 \begin{bmatrix} v_a \\ v_b \end{bmatrix}$$

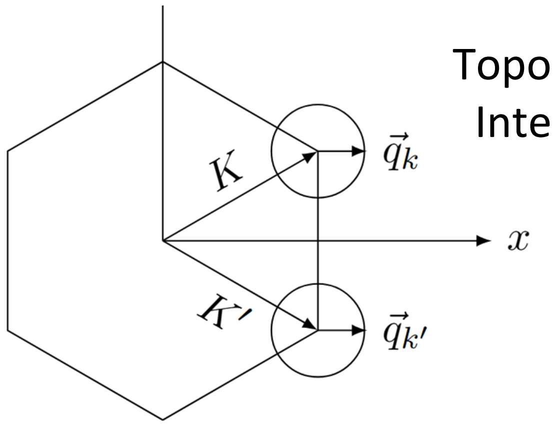
$\eta = \sqrt{\frac{C_2}{C_1}}$ and $\omega_0^2 = \frac{1}{L\sqrt{C_1 C_2}}$

- **Circuit model predicts alternating Berry Curvature at K and K’ points indicating topological protection at these High Symmetry Points.**
- **Width of curvature depends on band gap. If curvature at K and K’ touch, they cancel each other**

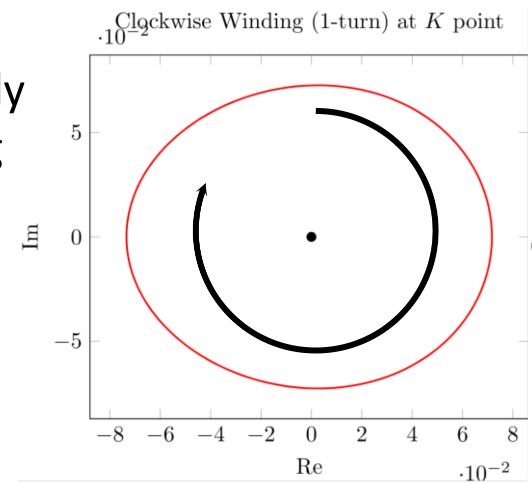
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

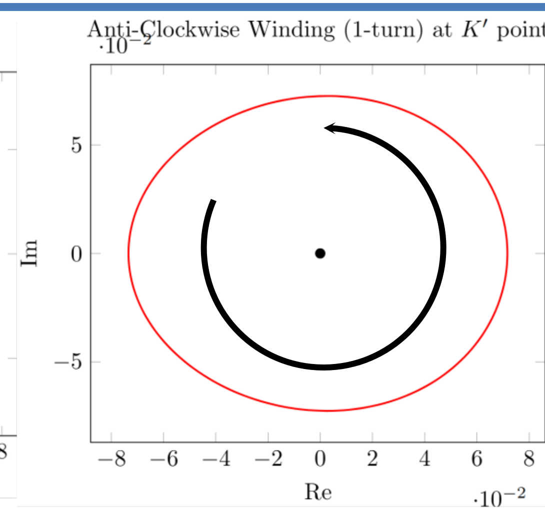
UC San Diego

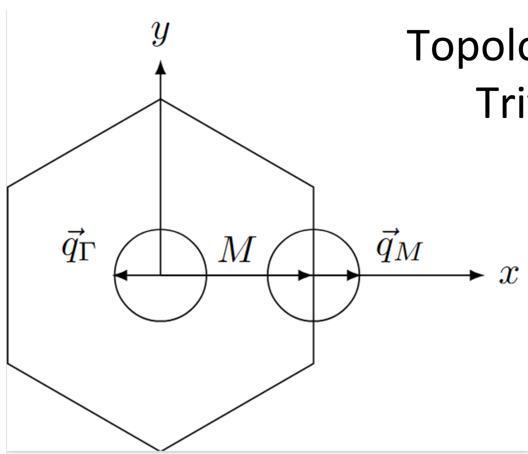
2D Hexagonal Lattice Analysis at K and K' Points



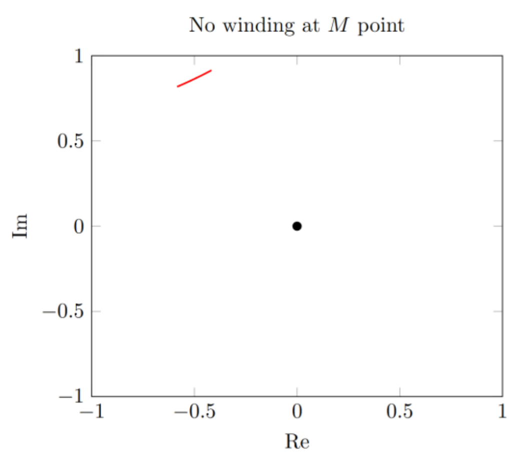
Topologically Interesting

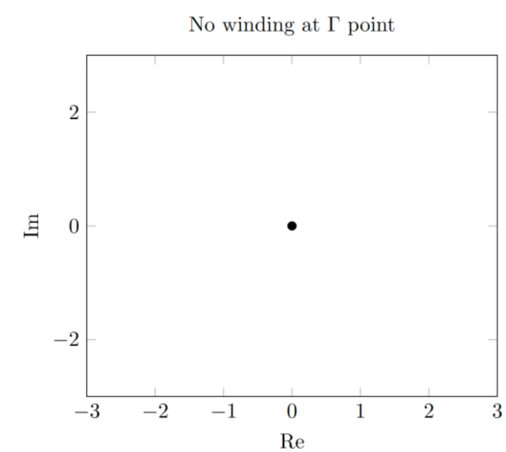






Topologically Trivial





- **In the vicinity of the K and K' points, y_{21} traces out a circle which encloses the origin indicating the presence of a pole (or zero). The phase acquired is ±π ⇒ Valley Chern Number = ±0.5**
- **Near the Γ and M point, there is no such winding**

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

Constructing Random Patterns of Hexagons with Desired Symmetry Properties

Generate C6 Symmetric Pattern

↓

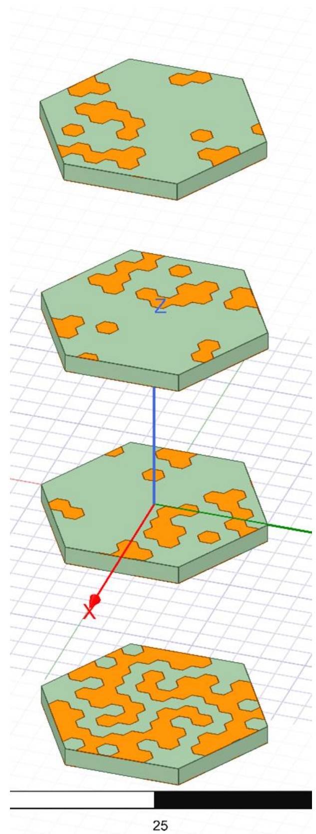
Generate Low density C3 Symmetric Pattern

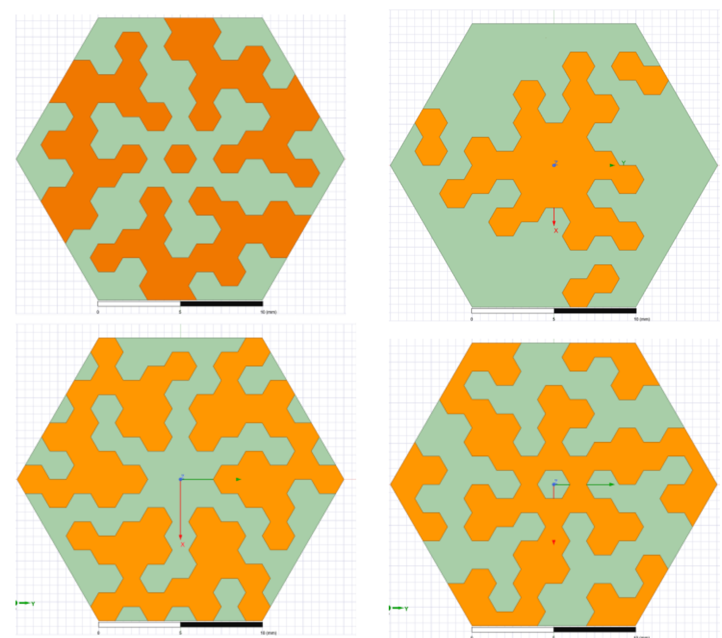
↓

Subtract the 2 to make C3 pattern

↓

Automate Band and Chern Number Calculation

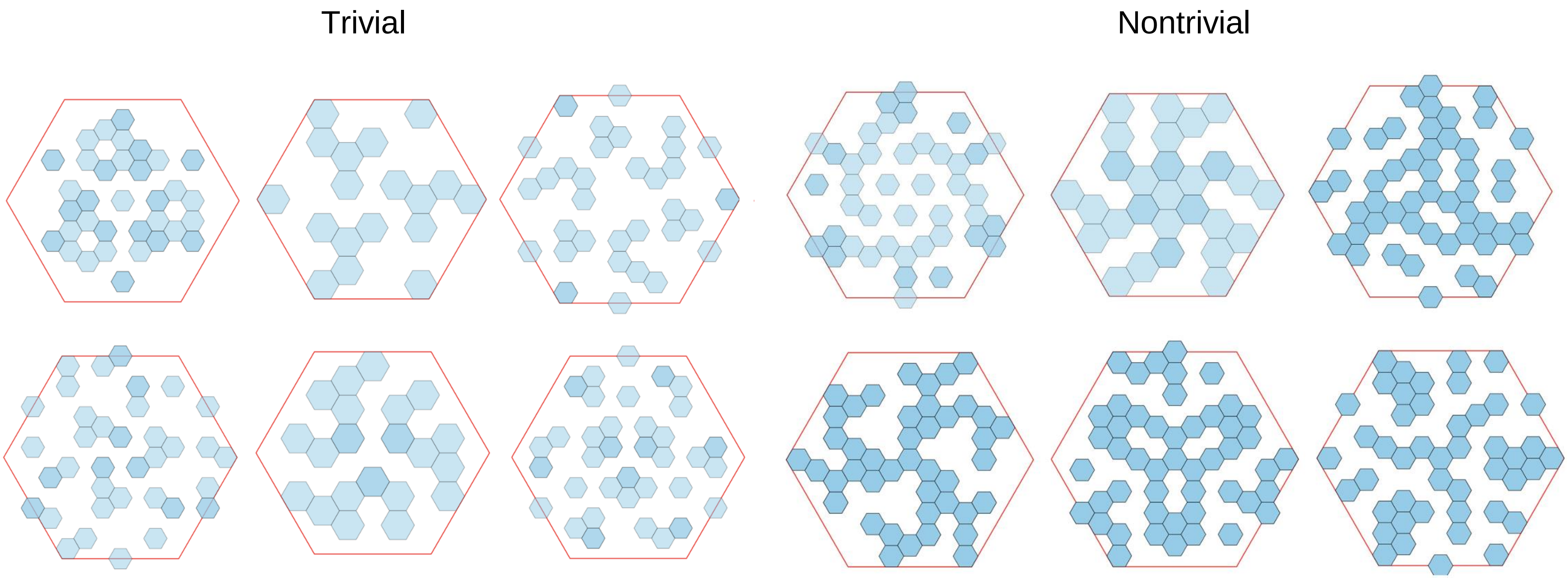




Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

Discovering Trivial vs. Nontrivial Structures Through Random Patterns

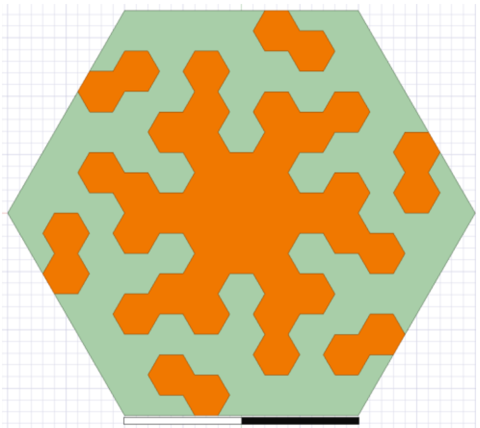


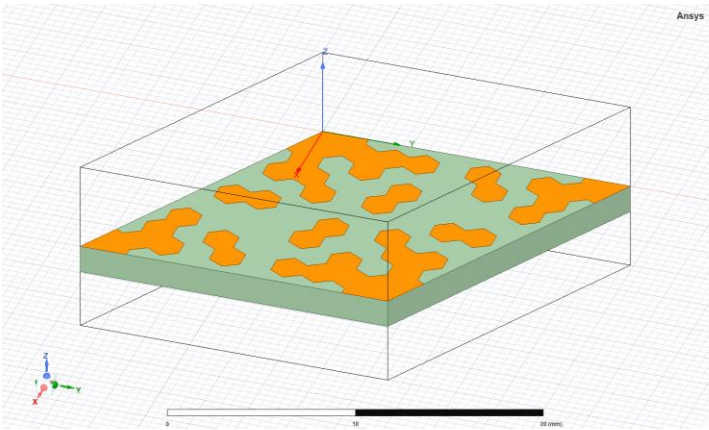
- Most research today is based on certain geometries with no clear reason for why they were chosen
  - Someone else studied this one in the past?
  - A grad student somehow happened to find a good one?
- Automating simulation of random patterns will allow us to develop an understanding of which geometrical features lead to which properties, e.g. …
  - Wide band gap
  - Nontrivial topological behavior

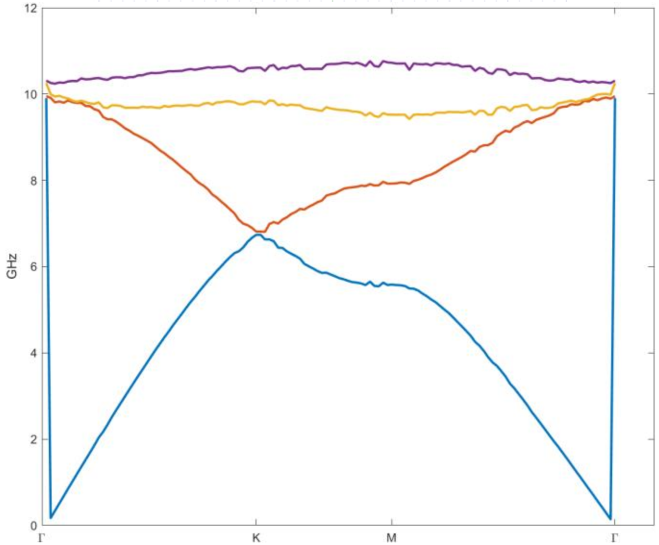
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

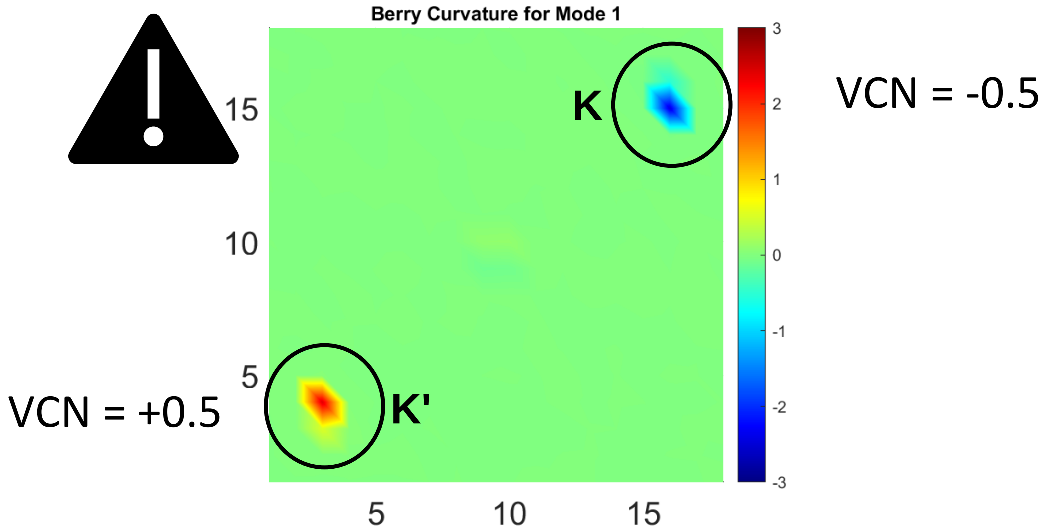
UC San Diego

Random Patterns on Hexagonal Lattice and Some Challenges of Identifying Nontrivial Structures







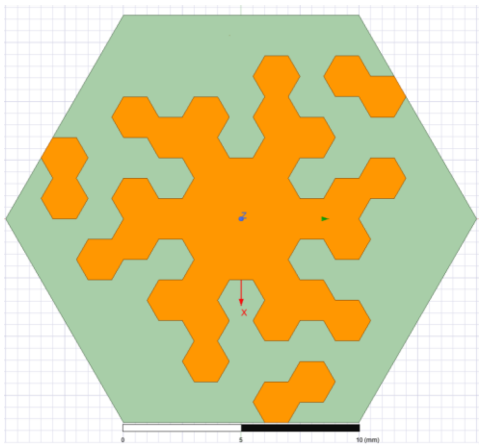


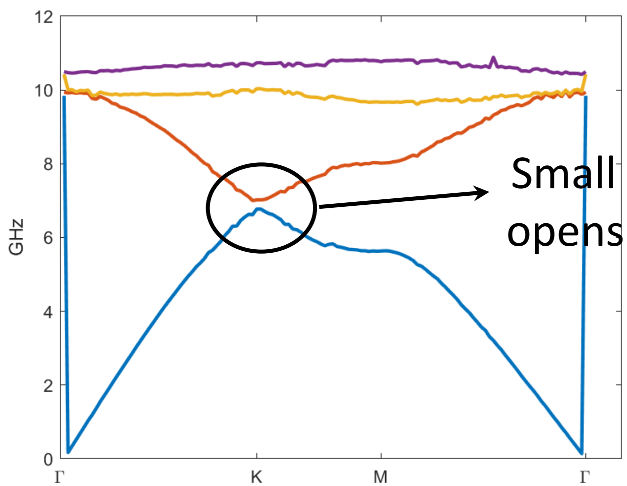
Such a C6 symmetric structure might show curvature at the K and K' points for a single band, but in reality as 2 bands become degenerate at the same point, you have to sum curvatures from both bands which will add to 0

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

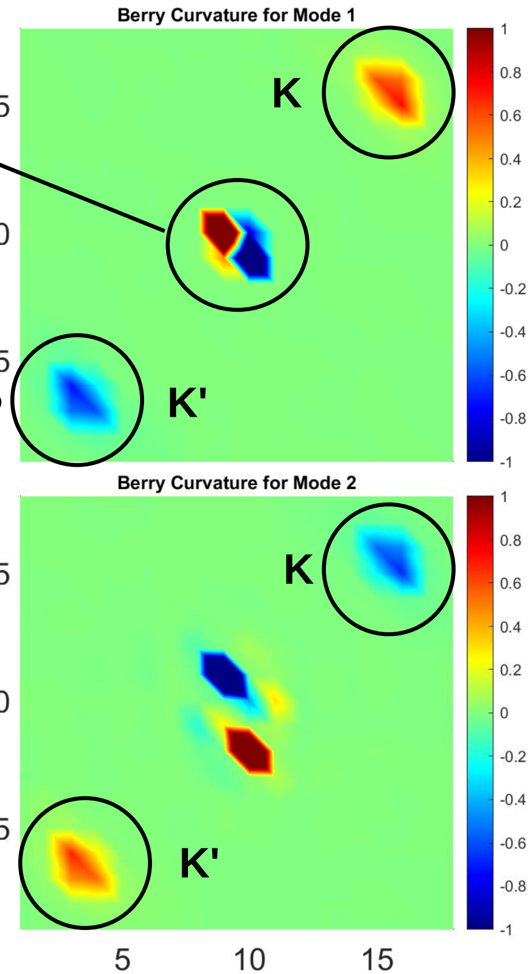
Random Patterns on Hexagonal Lattice: C3 Structures with Gaps





Small perturbation opens a small band gap

HFSS Convergence issue



VCN = 0.4495

VCN = -0.4495

Opposite sign across bands

VCN = -0.4495

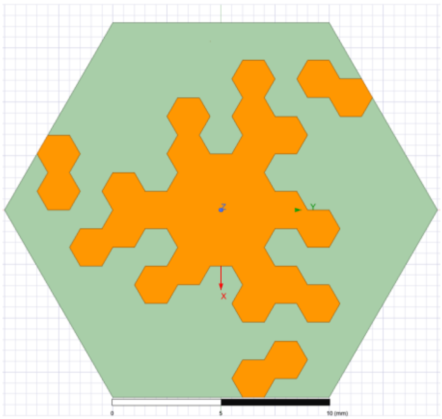
VCN = 0.4495

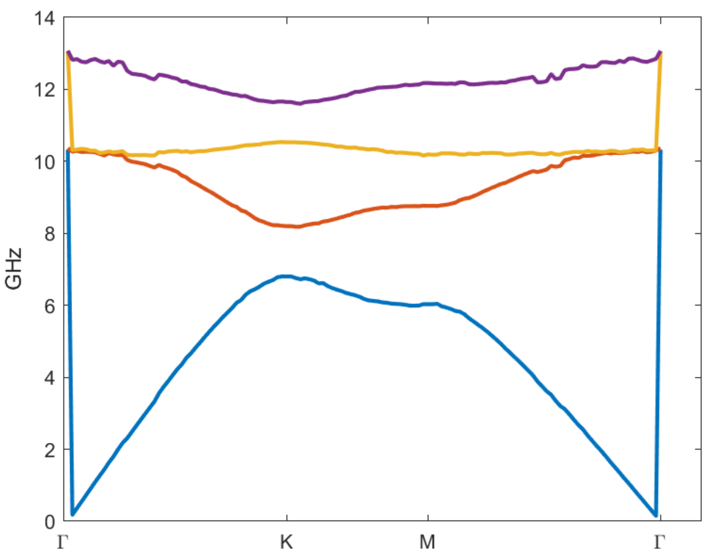
- Generated Random Pattern is topologically interesting and can form a Valley type PTI
- A very narrow bandgap makes it difficult to excite only the edge mode. To increase the width of the band gap, degree of perturbation is increased

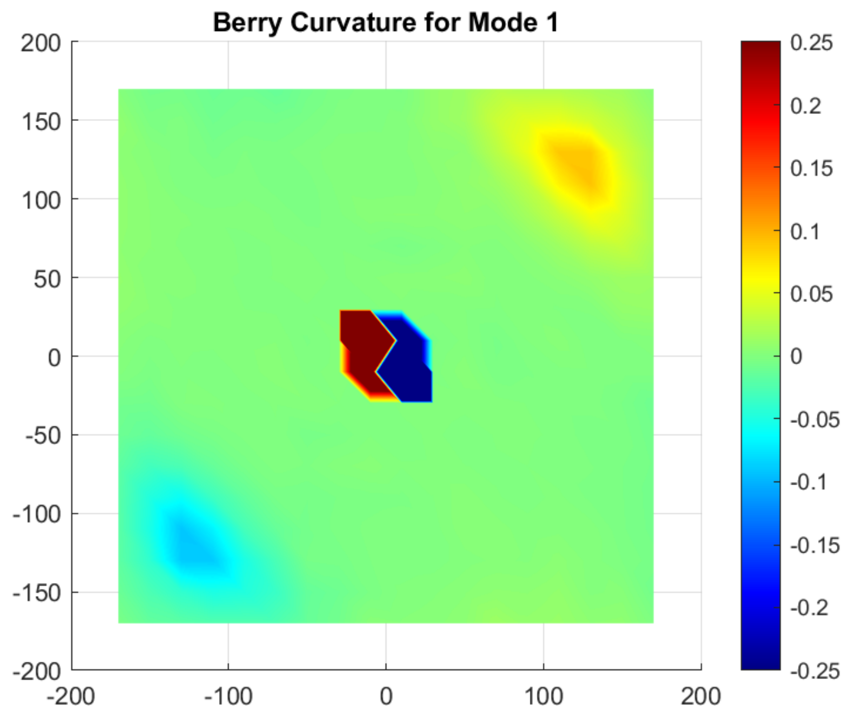
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

Random Patterns on Hexagonal Lattice: Wider Band Gaps with Greater Perturbation







- **As strength of perturbation is increased, the band gap increases as predicted by the model**
- **As the degree of perturbation is increased, the region of Berry curvature widens**
- **Can be used to construct a Valley type PTI with a unidirectional edge mode**

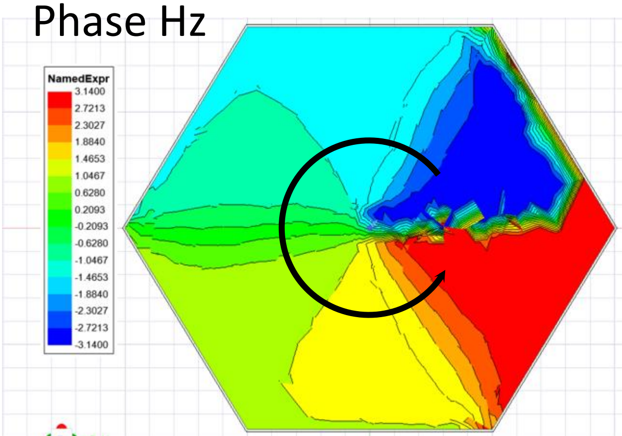
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

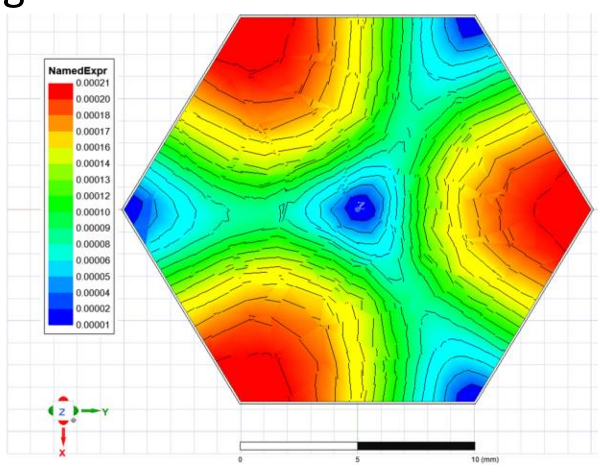
Unit Cell Phase Profile at K(K') point

K Point

Phase Hz

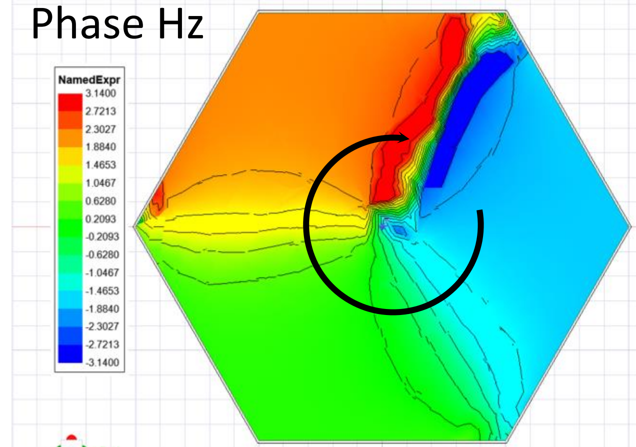


Magnitude Hz

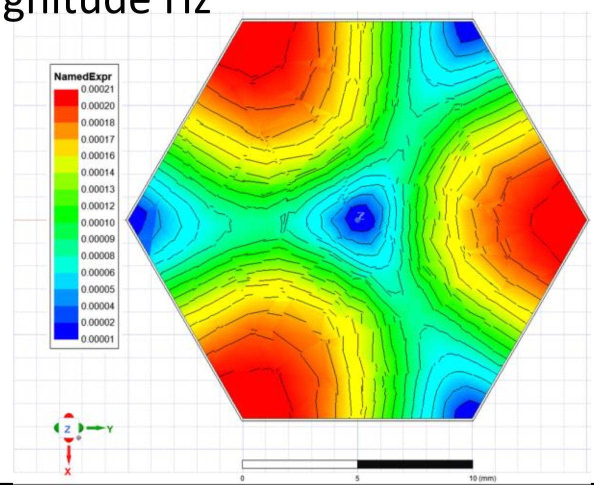


K' Point

Phase Hz



Magnitude Hz

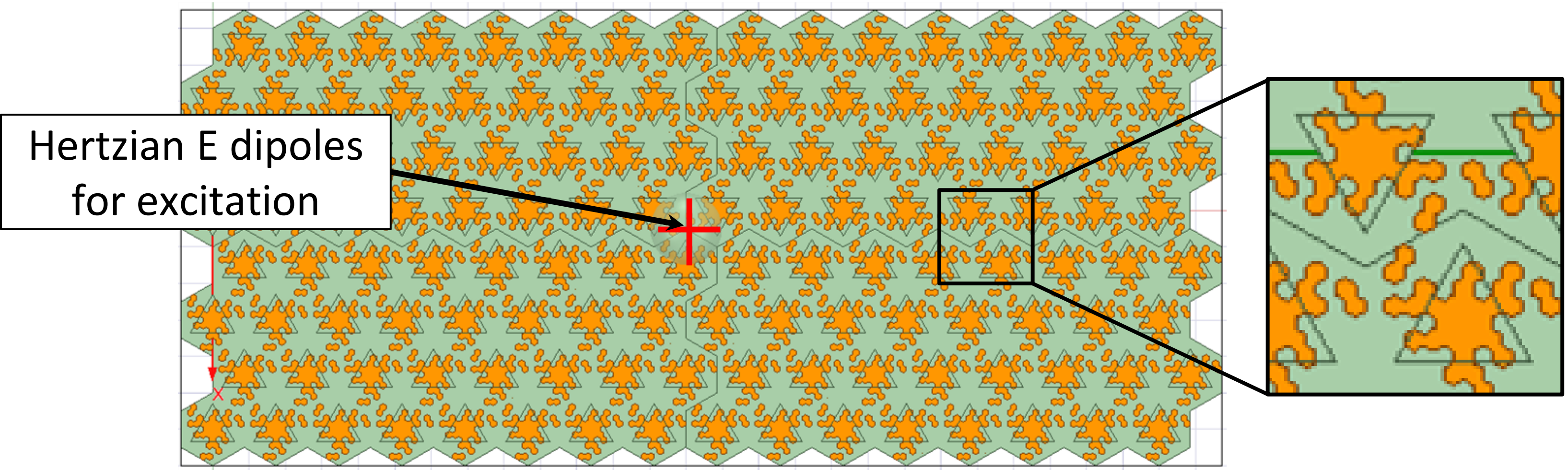


- **Counter rotating phase profiles on the unitcell at K and K' points as predicted**
- **The fields at K and K' points are indistinguishable**

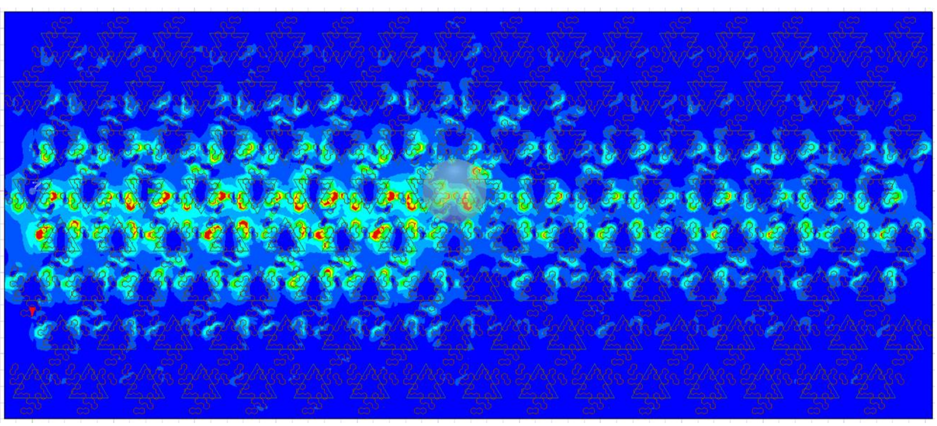
Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

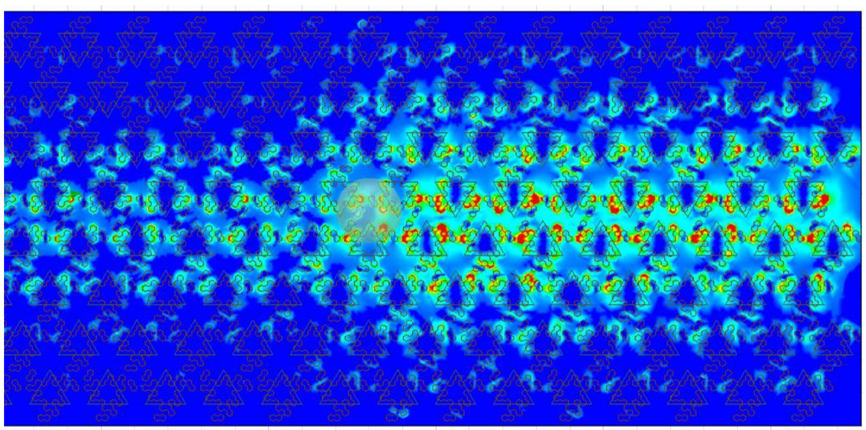
UC San Diego

Unidirectional Edge Mode in a Lattice of Random C3 Cells



Interface formed between rotated unitcells

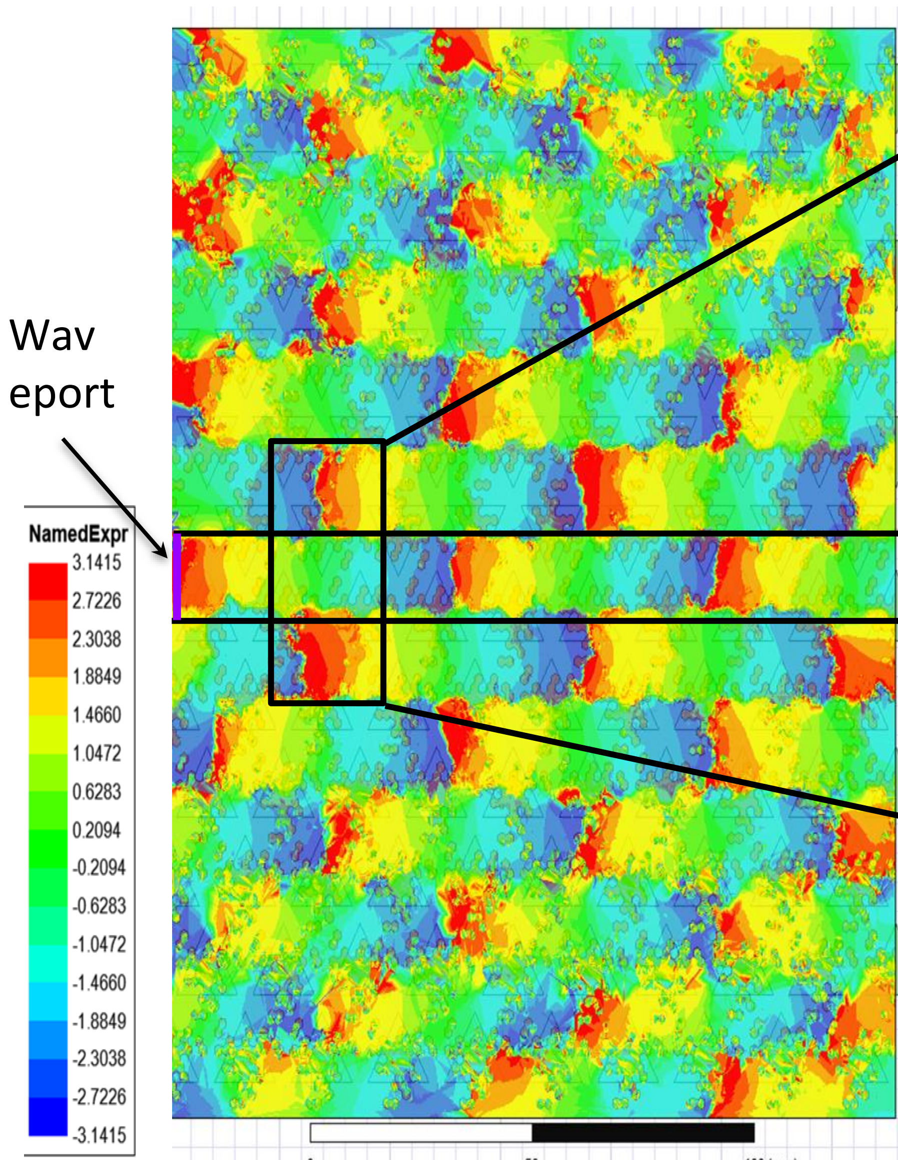


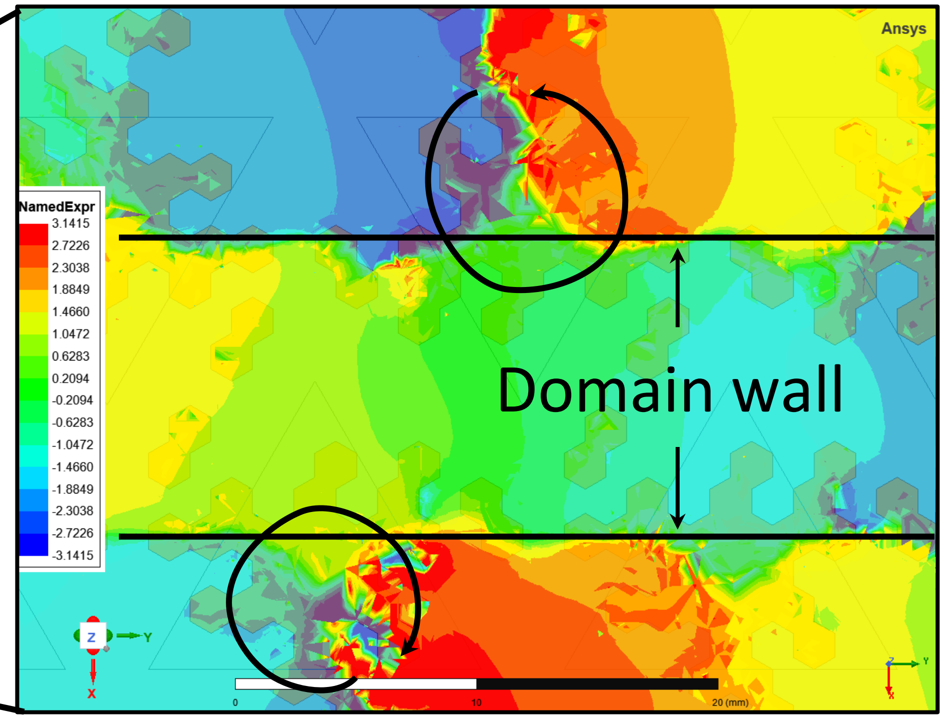


- **Unidirectional edge mode is excited using 2 inplane orthogonal electric dipoles**
- **LHCP and RHCP excitation selectively couples into forward and backward modes**

UC San Diego

Unidirectional Edge Mode: Phase of transverse field





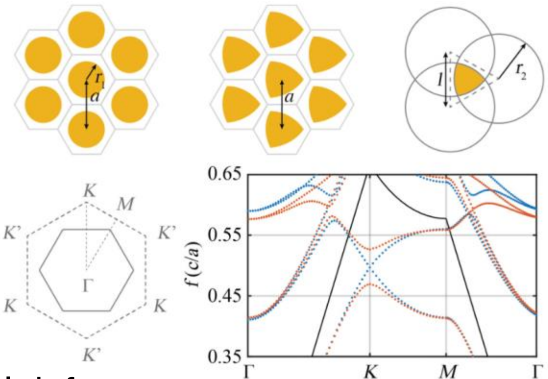
Counter rotating phase profiles across the domain wall which is responsible for unidirectional propagation

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

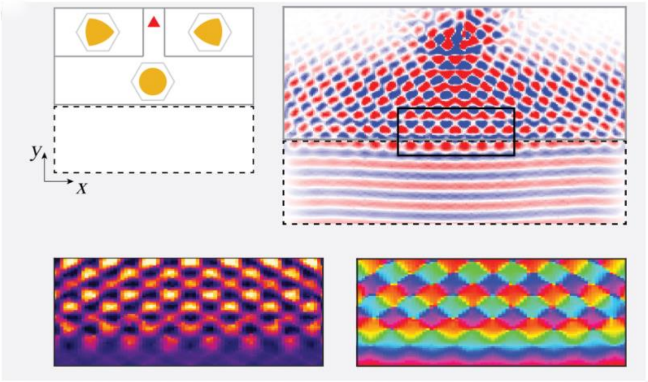
UC San Diego

Recent Work in Topology and Metasurfaces with Applications in Novel Energy Transport Mechanisms

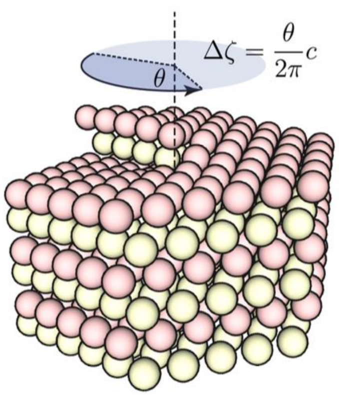
Band structure of grounded metal patch arrays showing Dirac point



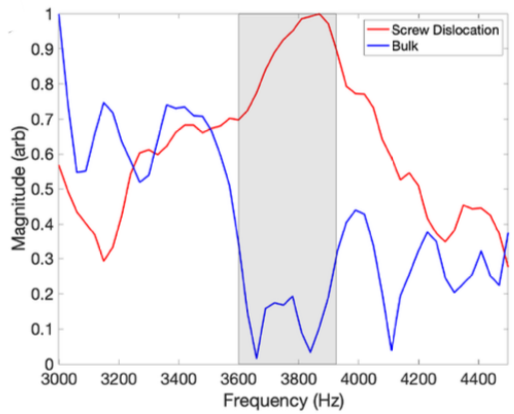
Pseudodiffusive transport with broad, highly coherent wavefront



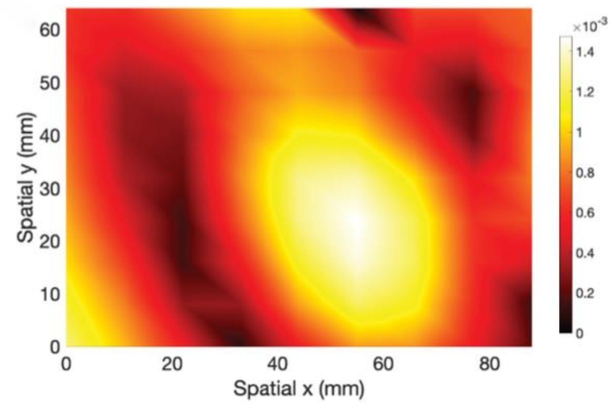
Helical defect (screw discontinuity) in 3D phononic crystal



Measured transport within bulk band gap



Measured hot spot at screw discontinuity



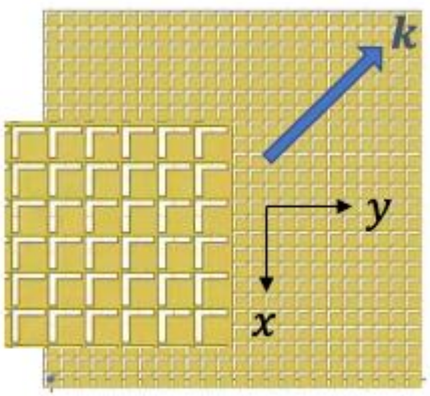
- **Unique transport properties such as coherent phase locking in a broad beam**
- **Unidirectional propagation in 3D structures – bulk unidirectional waves?**

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

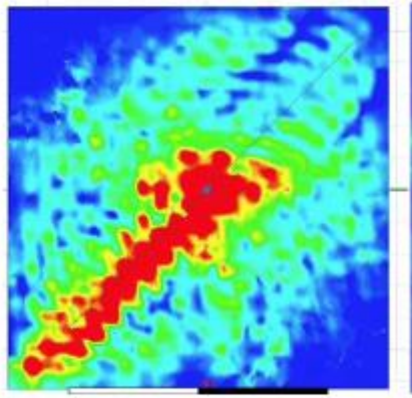
UC San Diego

Chiral Materials Effect on Scattering and Electrically Controlled Impedance Surfaces

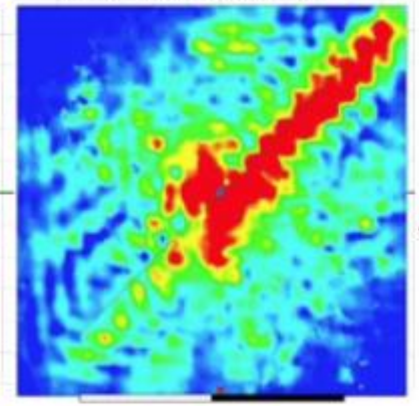
Chiral Metasurface



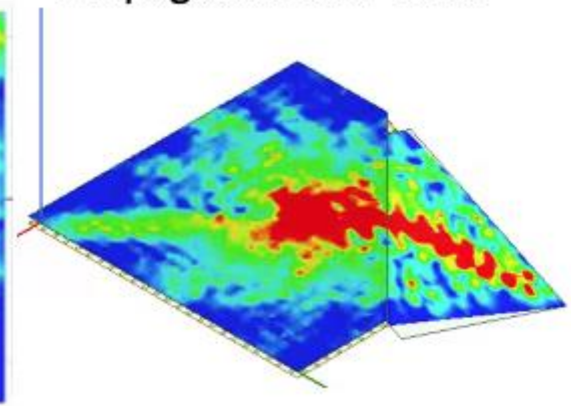
RCP Excitation

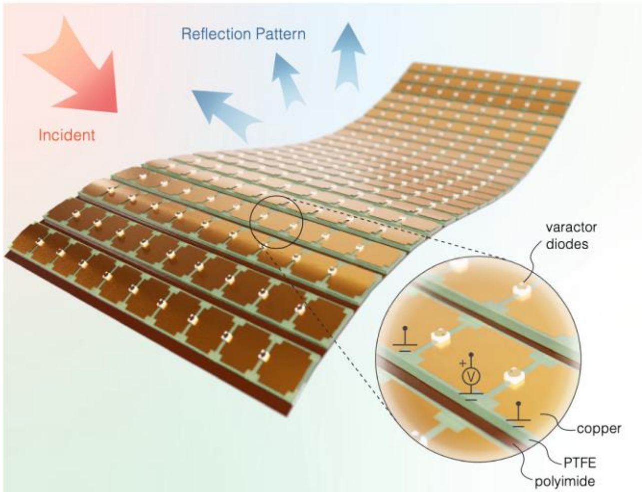


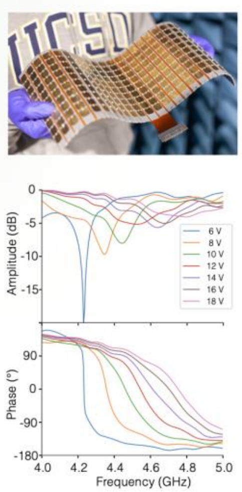
LCP Excitation

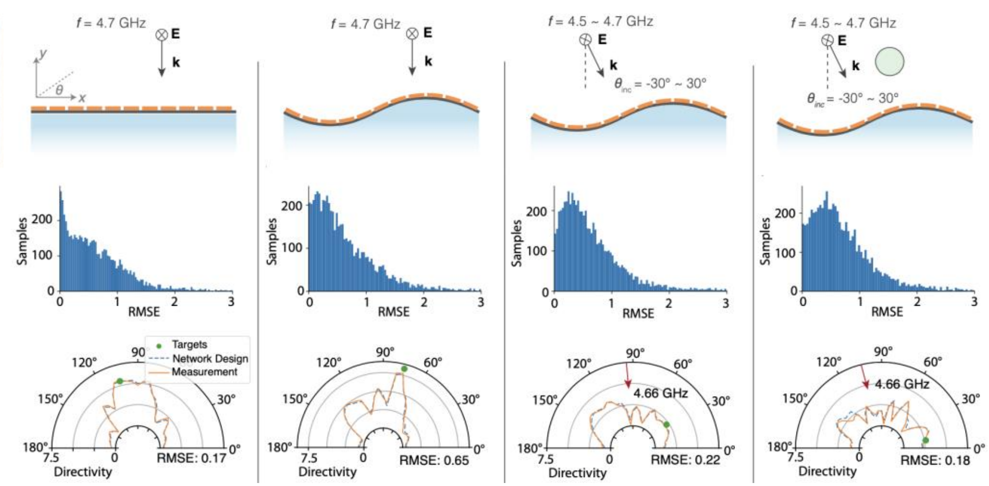


Propagation over Bend







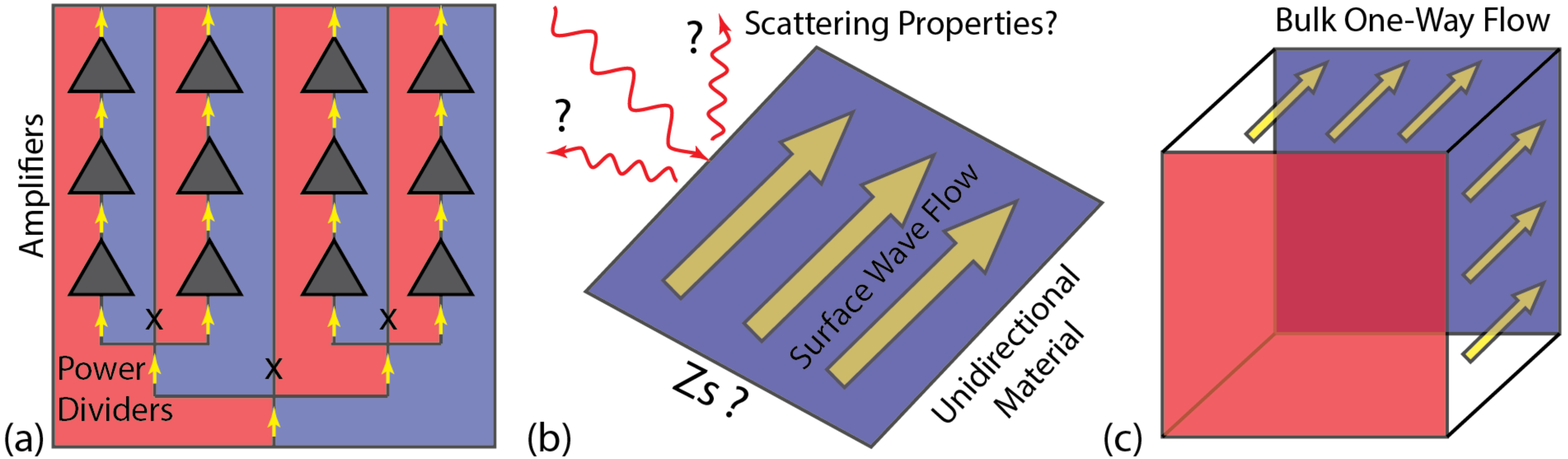


- **Potential applications in scattering control using chiral surfaces**
- **Combine with electronic control of surface properties**

Dan Sievenpiper - UCSD, 858-822-6678,dsievenpiper@ucsd.edu

UC San Diego

Other Potential Applications of Unidirectional Transport in Topological Materials



- **Combine with circuit components for compact amplifiers with reduced feedback based on one-way propagation along interfaces**
- **New surfaces with unique scattering properties based on unidirectional surface wave flow (free-space scattering is linked to surface wave properties)**
- **One-way bulk propagation in 2D or 3D materials for EM or thermal transport**