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APPLICATION WORKSHOPS FOR HIGH-PERFORMANCE ELECTRONIC DESIGN

Left-Handed Metamaterials for Microwave Engineering Applications

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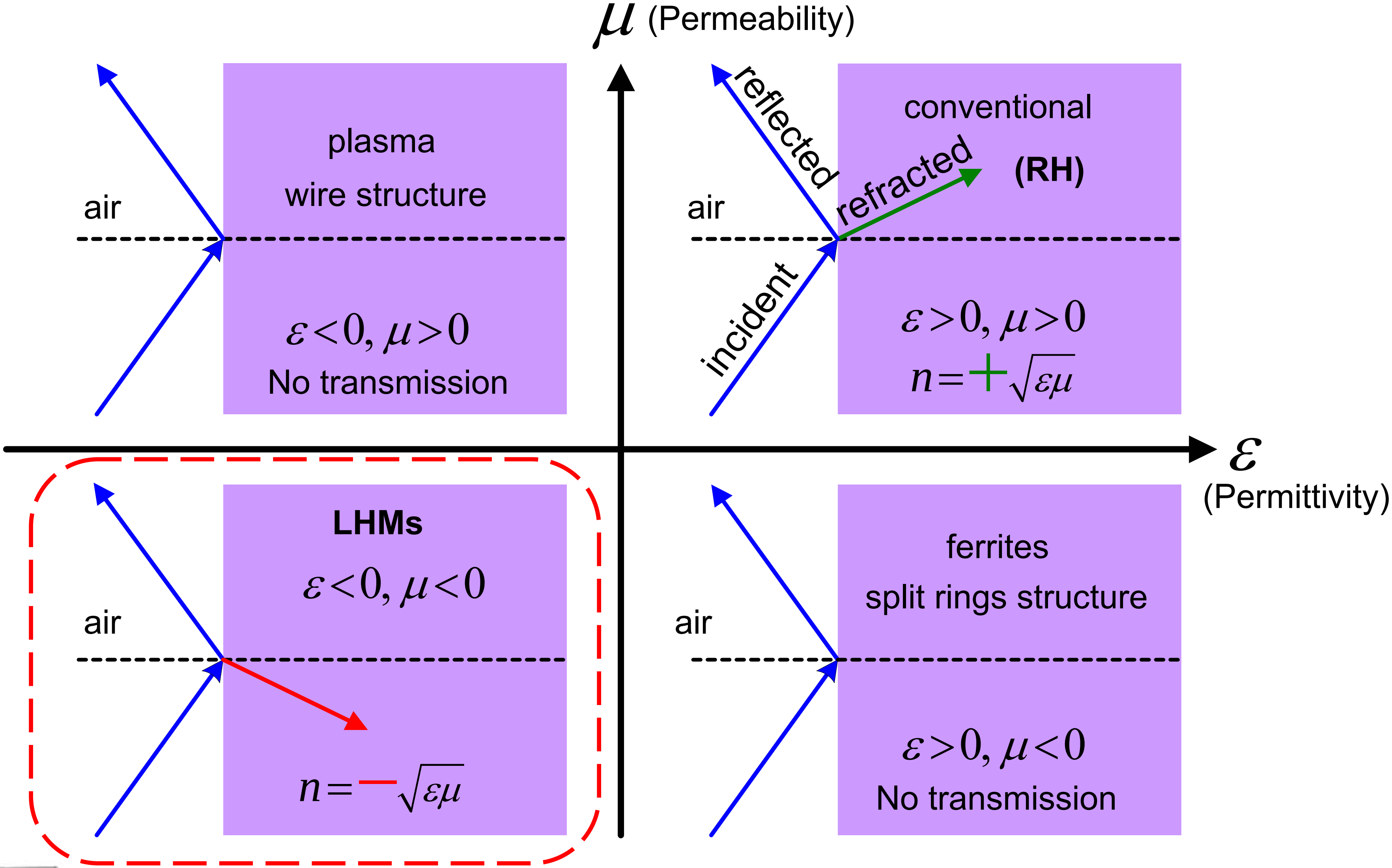
Outline

- Left-Handed Metamaterial Introduction
  - ❖ Resonant approach
  - ❖ Transmission line approach
- Composite Right/Left-Handed Metamaterial
- Metamaterial-Based Microwave Devices
  - ❖ Dominant leaky-wave antenna
  - ❖ Small, resonant backward wave antennas
  - ❖ Dual-band hybrid coupler
  - ❖ Negative refractive index flat lens
- Future Trends
- Summary

What is a Left-Handed Metamaterial?



1967: Veselago speculates about the possibility of LHMs and discusses their properties.

What is a Left-Handed Metamaterial?

Veselago's Conclusions

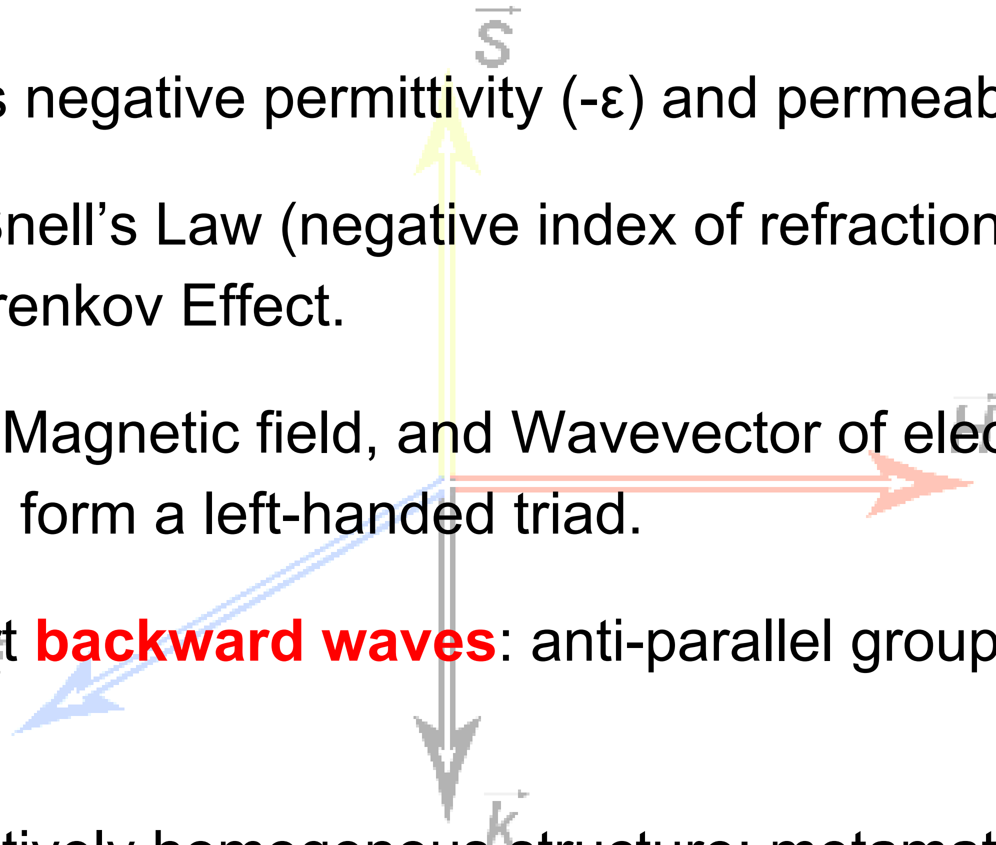
• Simultaneous negative permittivity (-ε) and permeability (-μ).

• Reversal of Snell's Law (negative index of refraction), Doppler Effect, and Cerenkov Effect.

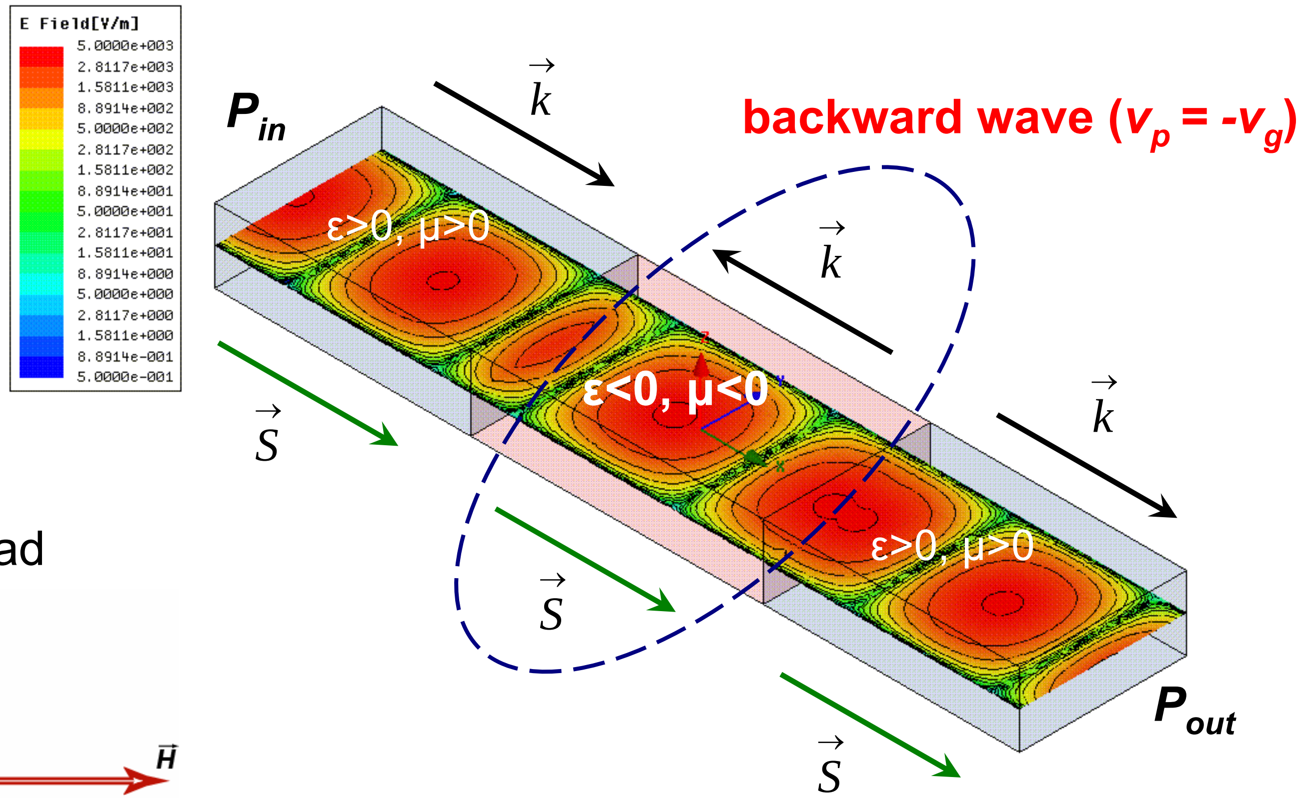
• Electric field, Magnetic field, and Wavevector of electromagnetic wave in a LHM form a left-handed triad.

• LHMs support **backward waves**: anti-parallel group and phase velocity.

• Artificial effectively homogenous structure: metamaterial.

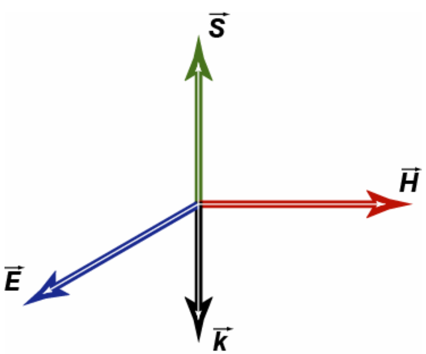


Rectangular Waveguide Filled with LHM



HFSS simulation using effective medium [1]

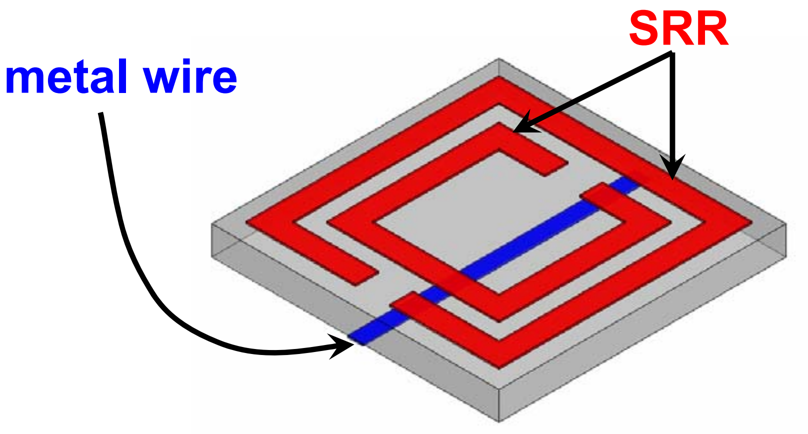
LH Triad



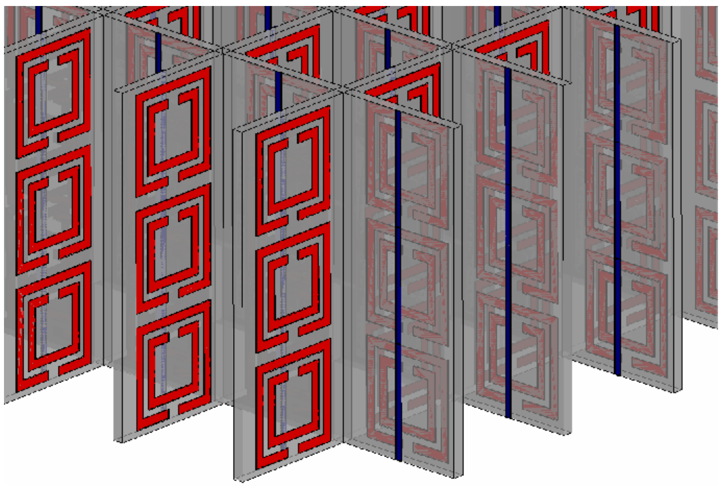
naturally occurring LH material has not yet been discovered

LHM – Resonant Approach

- **1967**: LHM were first proposed by Russian Physicist Victor Veselago
- **2001**: LHM realized based on split ring resonators - ***Resonant Approach*** towards LHMs [2].



SRR-based LHM unit-cell



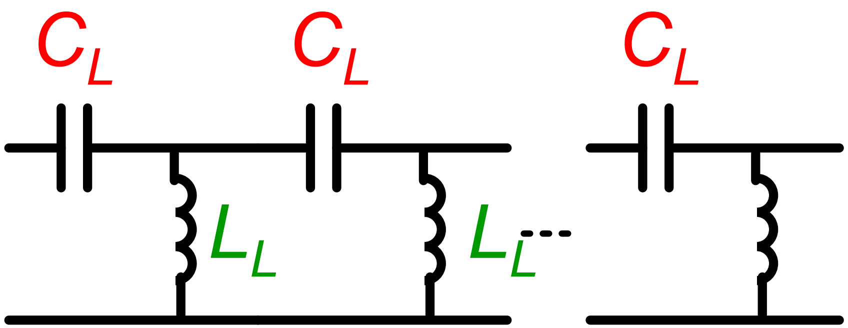
SRR: at ***resonance*** provides μ<0

metal wire: provides ε<0

- SRR-based metamaterials only exhibit LH properties at **resonance** - inherently ***narrow-band*** and ***lossy***.
- SRR-based LHMs are bulky - not practical for microwave engineering applications.

LHM – Transmission Line Approach

- Backward wave transmission line can form a non-resonant LHM [3]-[4].
- ***Transmission Line Approach*** is based on the dual of a conventional transmission line.



Perfect LH transmission line

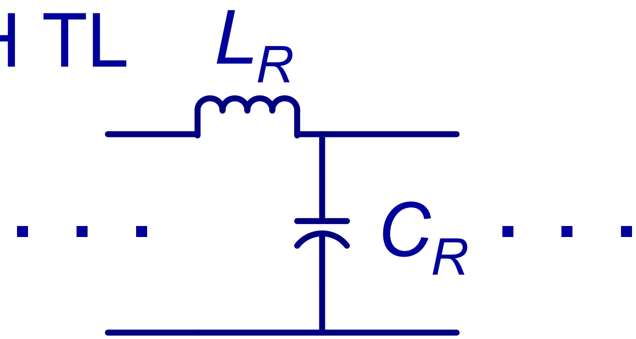
Series capacitance (C_L) and shunt inductance (L_L) combination supports a fundamental backward wave.

$$\beta = \frac{-1}{\omega\sqrt{C_L L_L}}$$

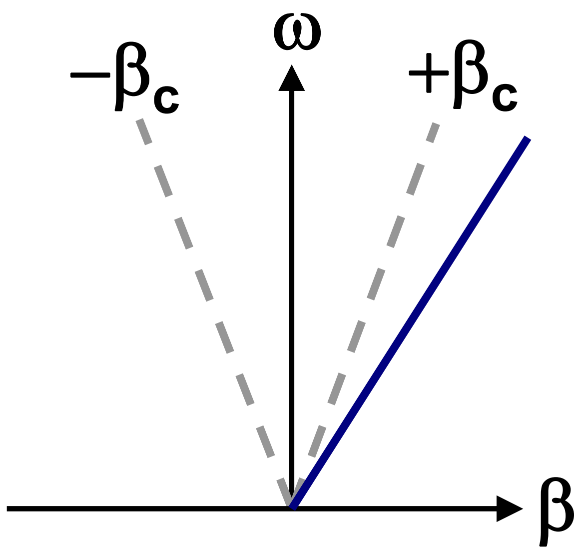
- Perfect LH transmission line not resonant dependent - low-loss and broad-band performance.
- However, perfect LH transmission line is not possible due to unavoidable **parasitic right-handed (RH) effects** occurring with physical realization.

Transmission Line Approach

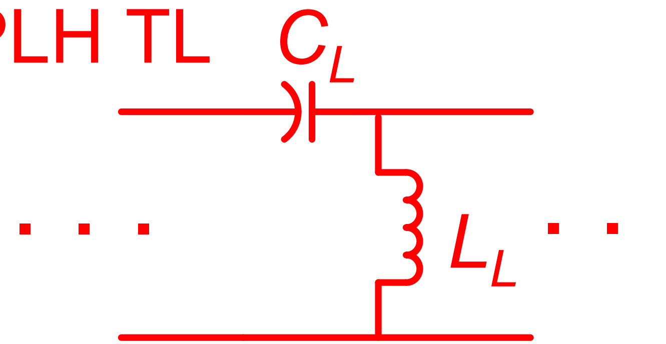
PRH TL



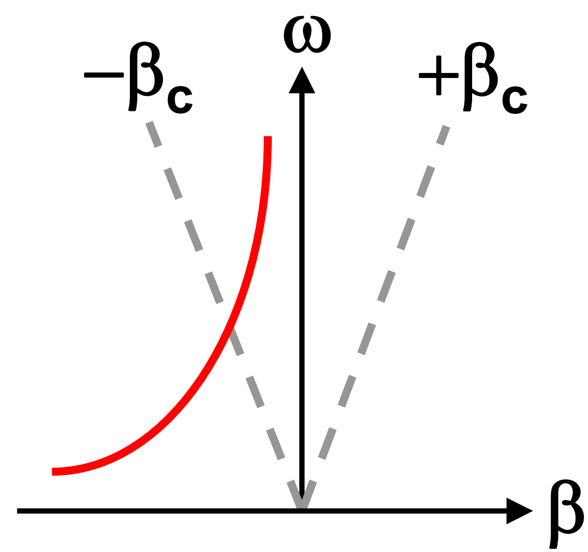
$$\beta_{PRH} = \omega\sqrt{C_R L_R}$$



PLH TL



$$\beta_{PLH} = -\frac{1}{\omega\sqrt{C_L L_L}}$$



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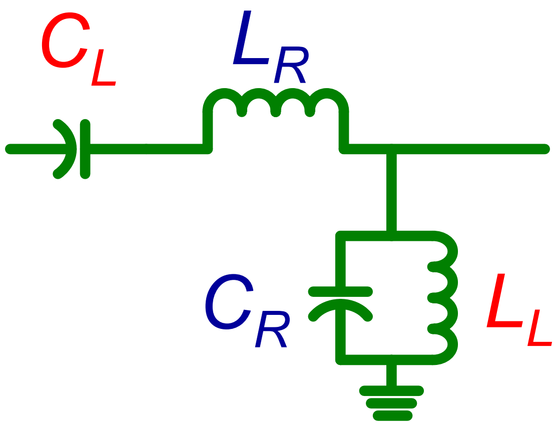
Composite Right/Left-Handed Metamaterial

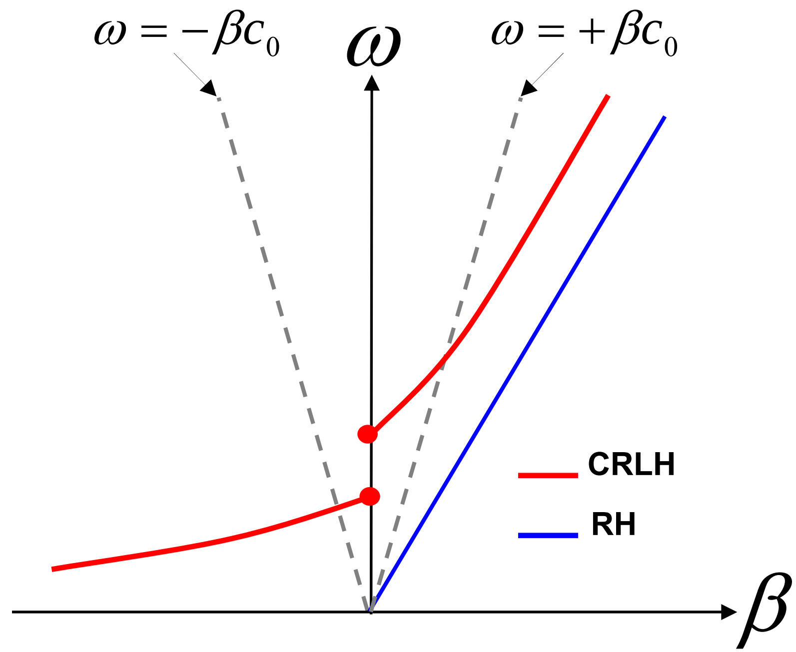


$$\beta = s(\omega)\sqrt{\omega^2 C_R L_R + \frac{1}{\omega^2 C_L L_L} - \left(\frac{L_R}{L_L} + \frac{C_R}{C_L}\right)},$$

$$s(\omega) = \begin{cases} -1 \text{ if } \omega < \min(\omega_{se}, \omega_{sh}) \\ +1 \text{ if } \omega > \max(\omega_{se}, \omega_{sh}) \end{cases},$$

where

$$\omega_{se} = \frac{1}{\sqrt{C_L L_R}} \text{ and } \omega_{sh} = \frac{1}{\sqrt{C_R L_L}}$$



- Low frequencies: supports backward wave
- High frequencies: supports forward wave
- Two cases
  - ❖ Unbalanced: $\omega_{se} \neq \omega_{sh}$
  - ❖ Balanced: $\omega_{se} = \omega_{sh0}$

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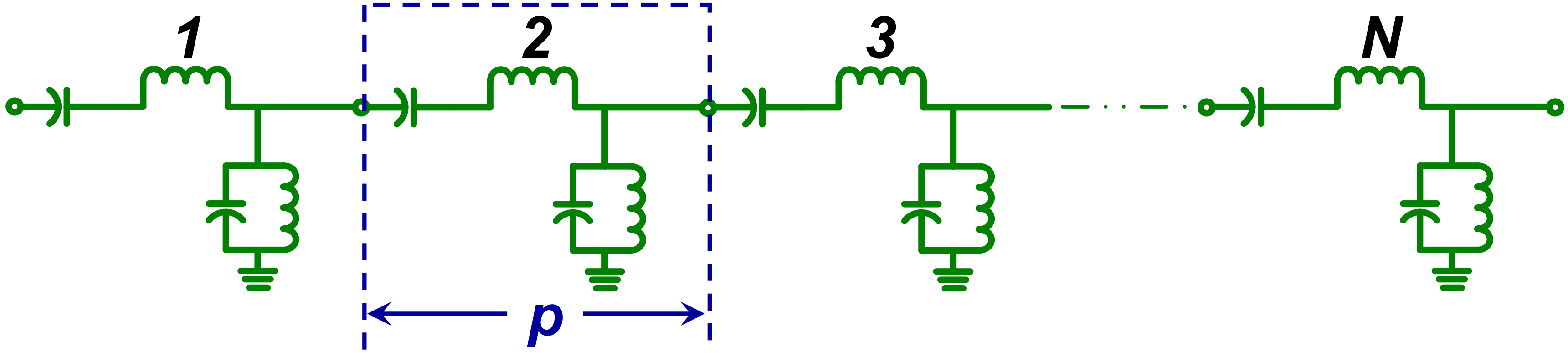
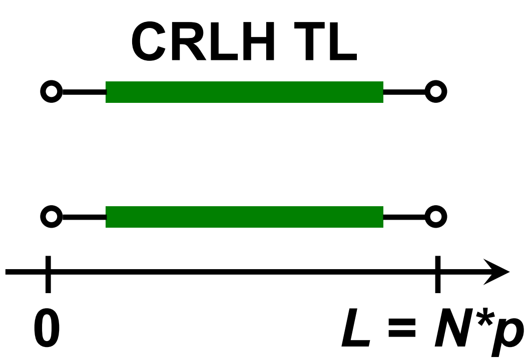
CRLH Metamaterial





Homogeneity Condition

- **Long wavelength regime**
- $p < \lambda_g/4$

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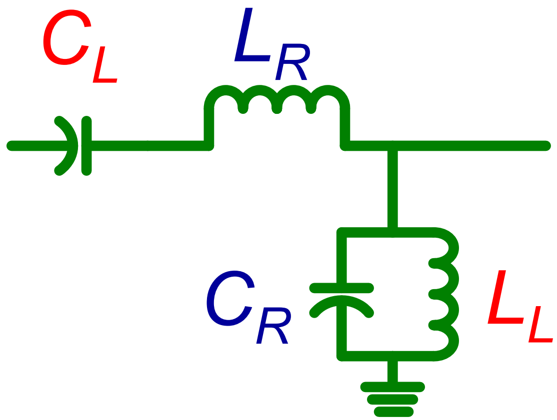
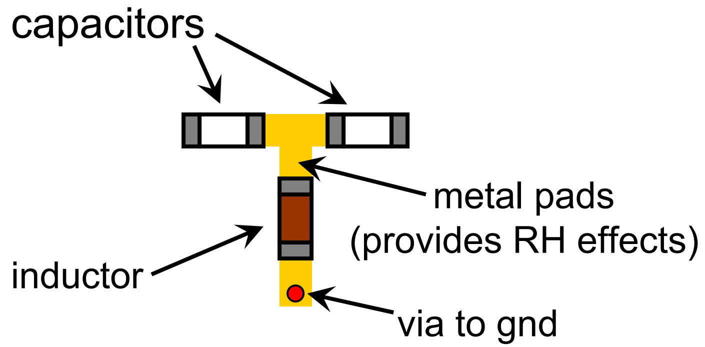
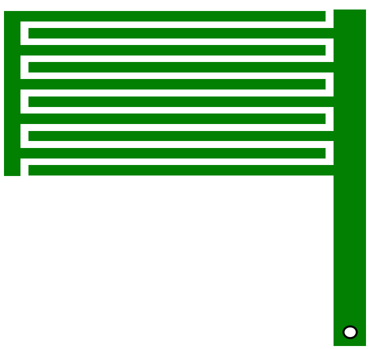
CRLH Metamaterial – Physical Realization



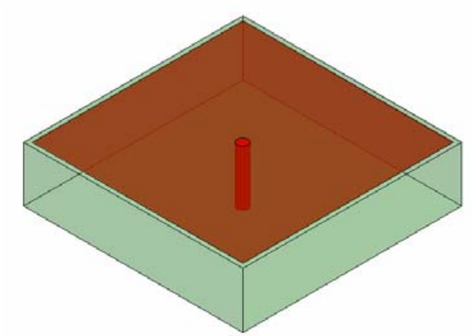
Composite right/left-handed (CRLH) unit-cell



Lumped element implementation



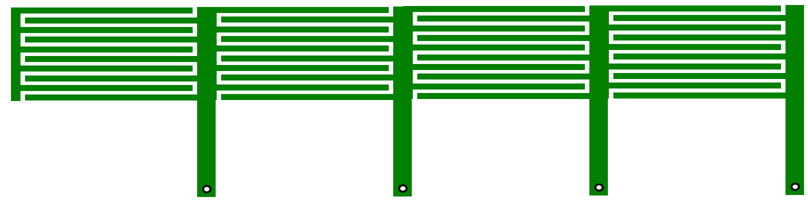
Distributed microstrip implementation based on interdigital capacitor

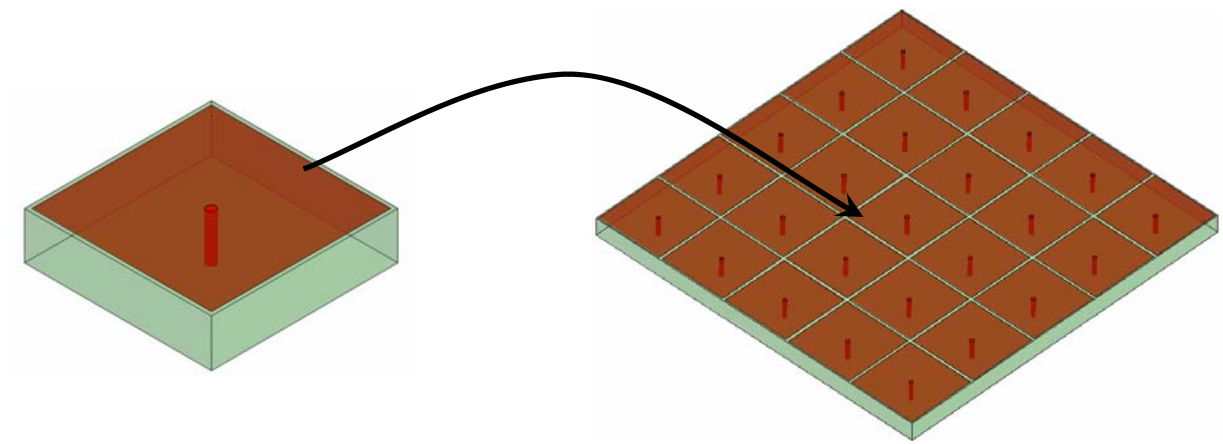


Distributed microstrip implementation based on Sievenpiper mushroom structure [5]

CRLH – Implementation and Analysis

Cascade periodic unit-cell to form one- or two-dimensional CRLH metamaterial TL.





How to Characterize a CRLH Unit-Cell

Propagation Constant – Dispersion Diagram

Impedance – Bloch Diagram

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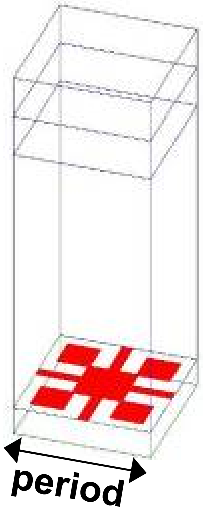
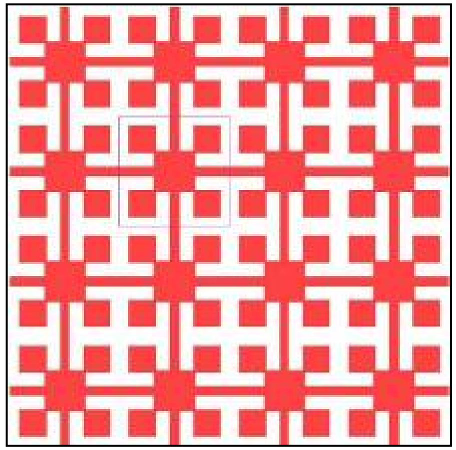
Comparison of LHMs to PBGs and Filters

Photonic Bandgap (PBG)

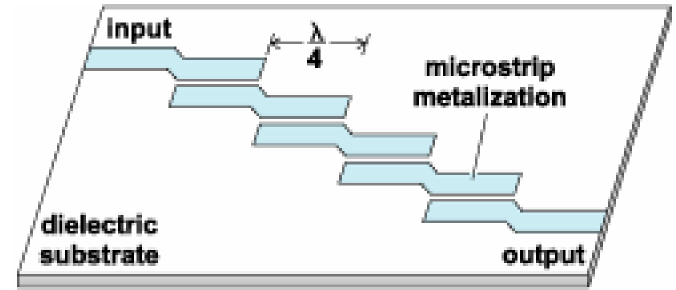




Similarities
- periodic structures
- can be more than one-dimensional

Differences
- PBGs have to be periodic; lattice period determines scattering
- PBG operated at frequencies where lattice period is multiple of $\lambda_g/2$; LHMs operated at frequencies where period < $\lambda_g/4$.

Filters



Similarities
- periodic structures
- based on low-pass/high-pass structures

Differences
- Filters generally designed to meet magnitude specifications; LHMs designed to meet both magnitude and phase.
- Node-to-node phase shifts of 180° required for filters.
- LHMs can be one-, two-, or three-dimensional and are used as bulk “mediums.”

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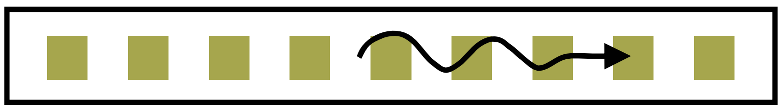
Dominant-Mode Leaky Wave Antenna

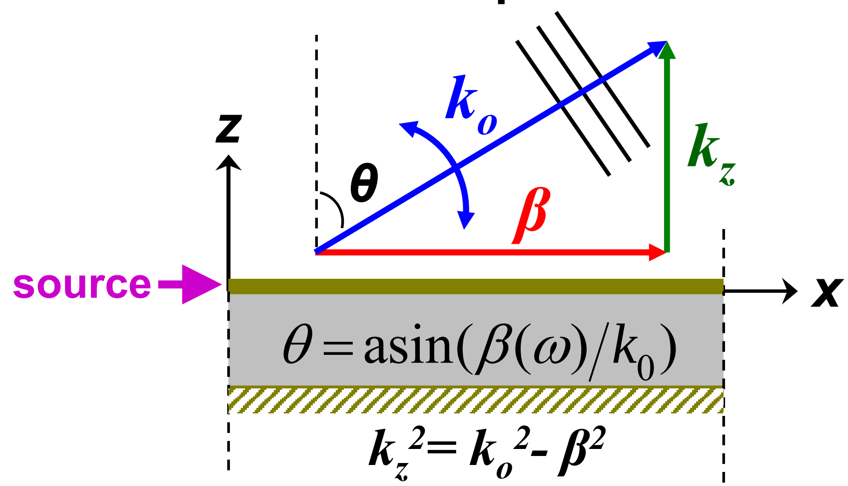
Leaky-Wave Antenna Theory

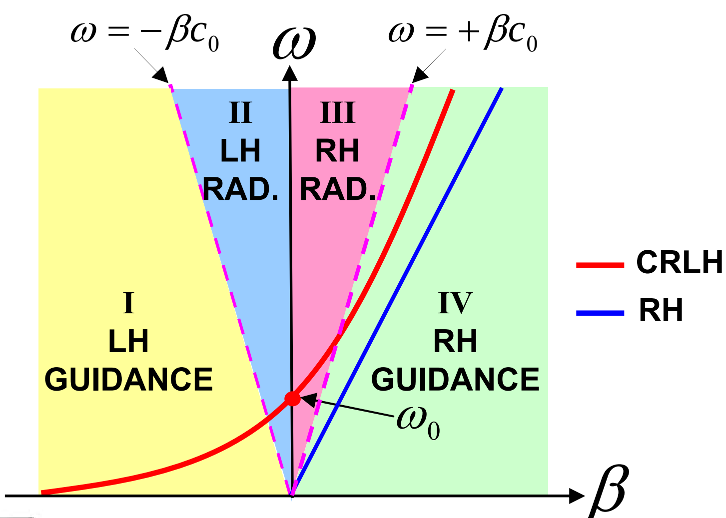
Conventional RH Leaky-Wave Antenna
(operated at higher-order mode)



CRLH Leaky-Wave Antenna [6]
(operated at dominant mode)

Principle





Characteristics:

- **Operating in leaky regions**
  - **II : BACKWARD ($\beta < 0$)**
  - **III : FORWARD ($\beta > 0$)**
- **BROADSIDE radiation ($\beta = 0$)**
  - ***balanced* case: $v_g(\beta = 0) \neq 0$**
- **Fundamental mode**

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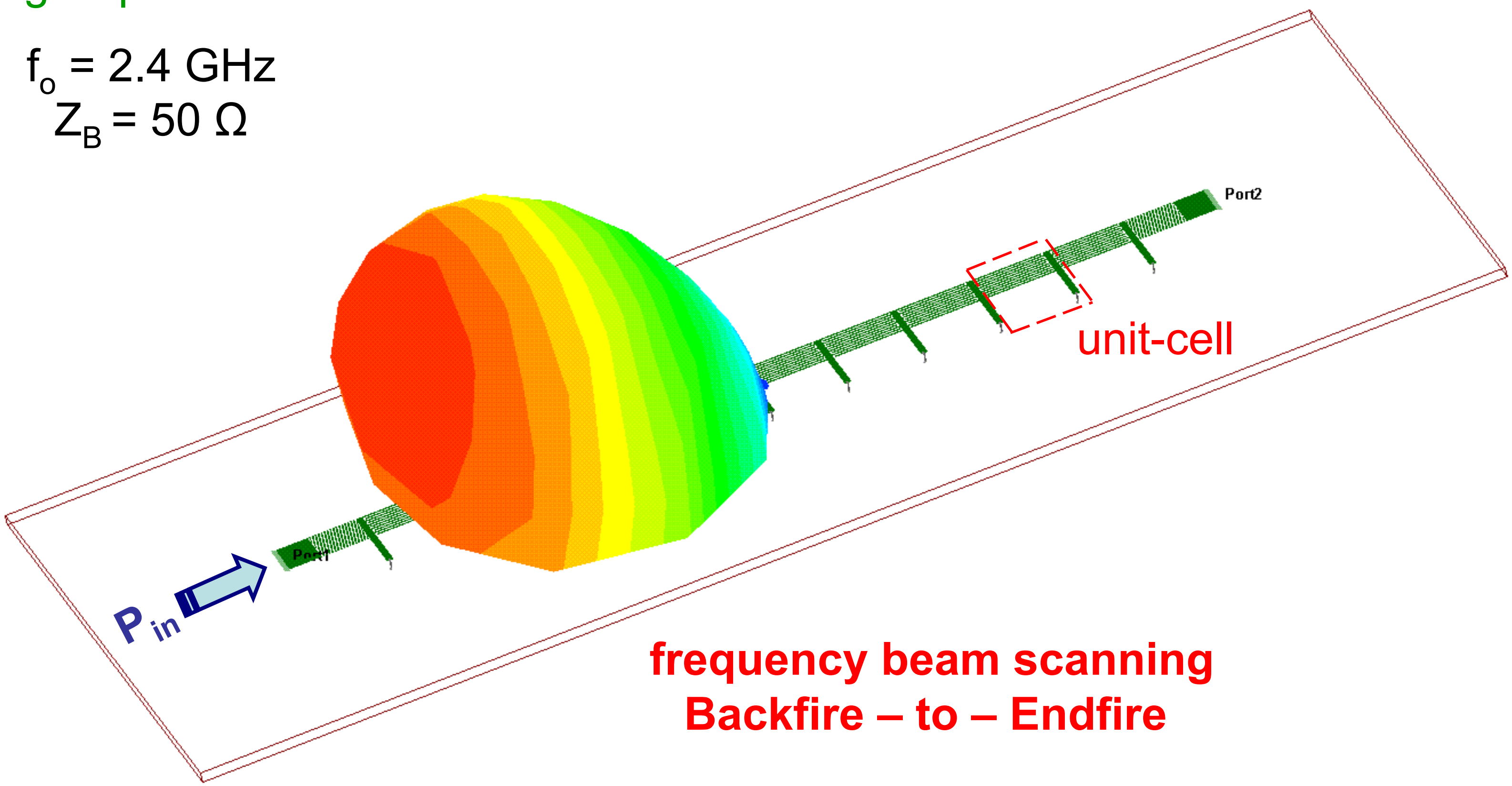
1-D Dominant Mode Leaky-Wave Antenna

3-D Far-field Pattern for Several Frequencies

Design Specifications

f_o = 2.4 GHz
Z_B = 50 Ω



frequency beam scanning
Backfire – to – Endfire

Design Flow

Unit-cell parameter – Design Guidelines

Dispersion/Bloch Diagrams – Driven Mode

Optimize unit-cell for specifications

Cascade unit-cells to form CRLH transmission line

Simulate CRLH transmission line

- S-Parameters: matching
- Far-field: fast-wave region for leaky-wave application

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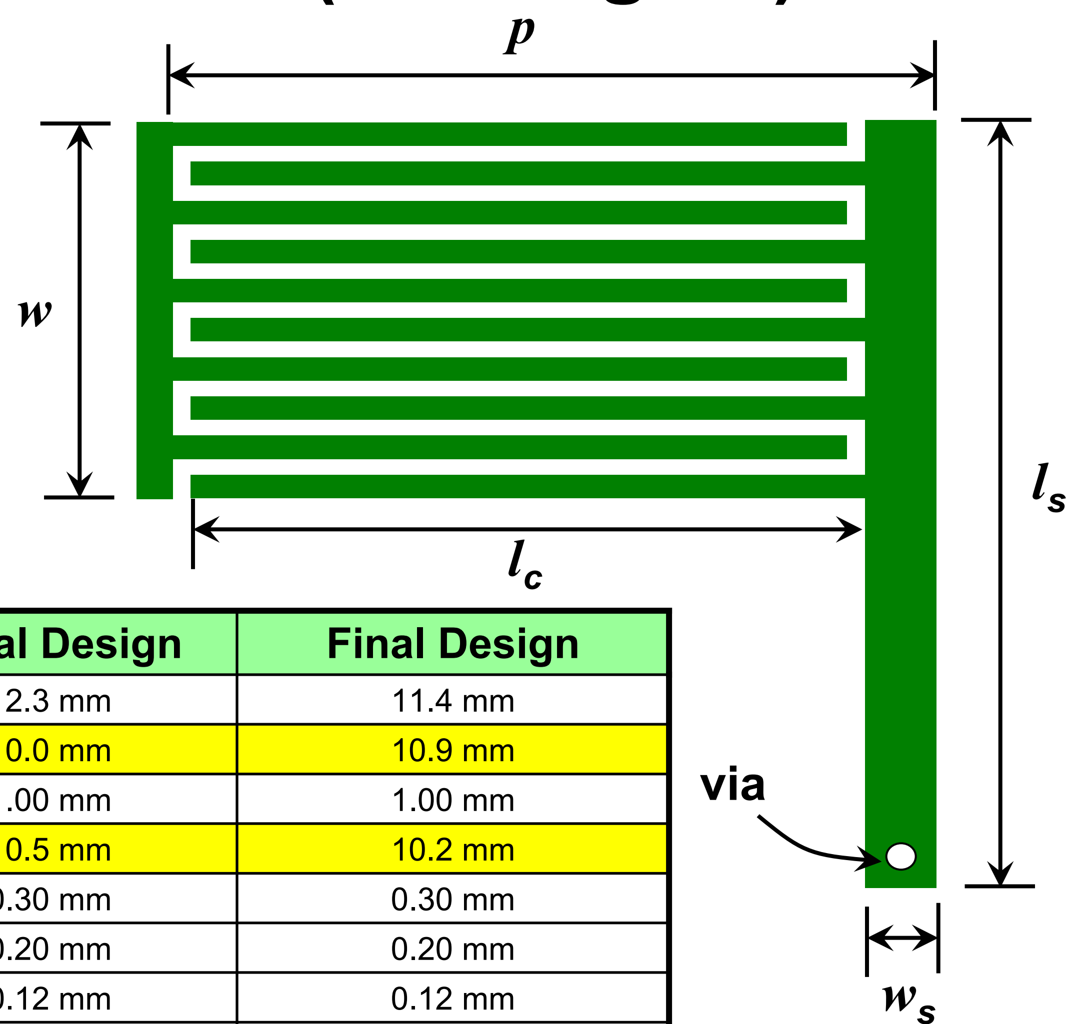
1-D CRLH Unit-Cell (Interdigital)

- Distributed unit-cell
  - ❖ series capacitance provided by interdigital capacitor
  - ❖ shunt inductance provided from shorted stub
  - ❖ shunt capacitance from top metal to ground plane
  - ❖ series inductance from current on interdigital capacitor



Variables		Initial Design	Final Design
unit-cell period	p	12.3 mm	11.4 mm
stub length	l_s	10.0 mm	10.9 mm
stub width	w_s	1.00 mm	1.00 mm
interdigital finger length	l_c	10.5 mm	10.2 mm
interdigital finger width	w_c	0.30 mm	0.30 mm
spacing between fingers	S	0.20 mm	0.20 mm
via radius	r	0.12 mm	0.12 mm
substrate height	h	1.57 mm	1.57 mm
substrate permittivity	ε_r	2.2	2.2

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1-D CRLH Unit-Cell Design Guidelines*

For 2-D space scanning, we need to design a balanced ($\omega_{se} = \omega_{sh}$) CRLH unit-cell so that there is a seamless transition from LH to RH operation.

1. Choose center frequency, f_o, which represents broadside radiation. (f_o=2.4 GHz)

2. Calculate width required to obtain Z_o, set w to this value. (w~5.0 mm)

3. Set stub width, w_s, to 20% of w. (w_s=1.0 mm)

4. Set stub length ($l^{si}=l_s$- w) to w; the electrical length of the stub has to be less than π/2.

5. Set the number of fingers, N, to 8 or 10. Then determine required w_c and S=2w_c/3. N=10 chosen.

$$w_c \approx \frac{w}{\left(\frac{5N}{3} - \frac{2}{3}\right)} \approx 0.3\,\text{mm}$$

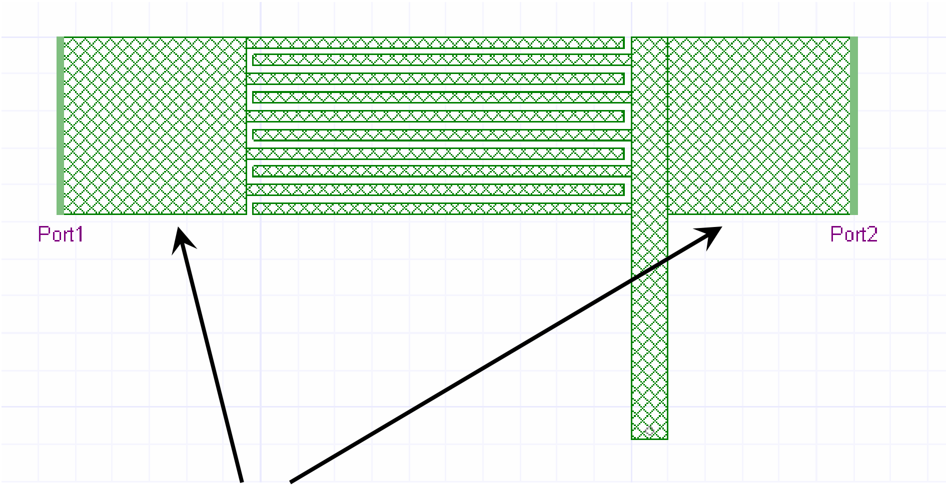
$$S = 0.2\,\text{mm}$$

6. Calculate length of interdigital finger.

$$l_c \approx \frac{\lambda_g}{8} \approx \frac{c_o}{8 f_o \sqrt{\varepsilon_r}} \approx 10.5\,\text{mm}$$

* Guidelines have been test on Rogers Duroid 5870 (er=2.33) and 5880 (er=2.2) for various substrate heights; for high permittivity substrate, the number of fingers should be reduced.

Dispersion/Bloch Diagram Extraction



extra section of mircostrip (5 mm each)

Design Specifications

f_o = 2.4 GHz

Z_B = 50 Ω

Planar EM simulation

S-Parameter extraction

$$\beta p = \cos^{-1}\left(\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}}\right)$$

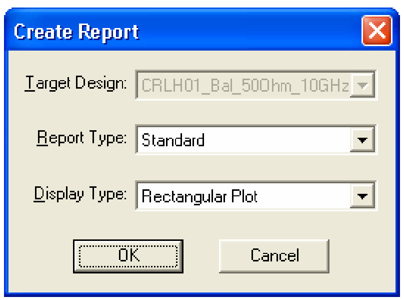
$$Z_B = \frac{2jZ_oS_{21}\sin(\beta p)}{(1 - S_{11})(1 - S_{22}) - S_{21}S_{12}}$$

Dispersion Diagram Extraction

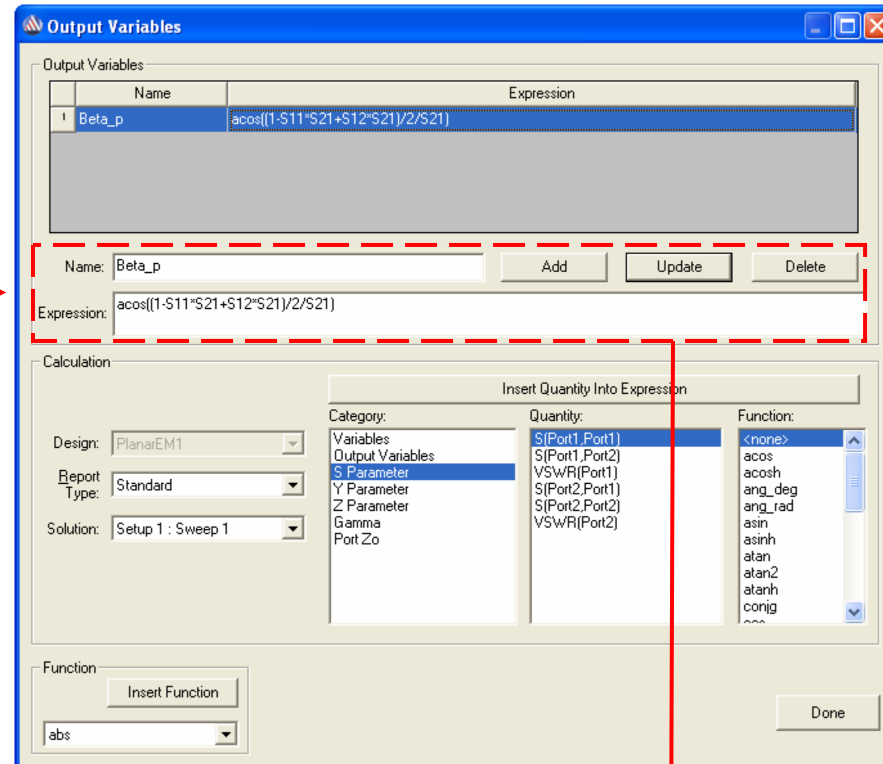
Setup dispersion equation; this can be obtained directly from the S-parameters.

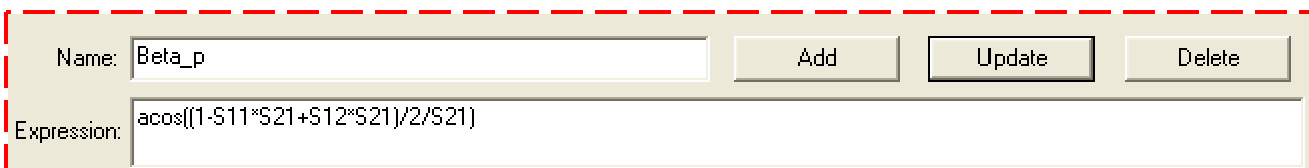
$$\beta p = \cos^{-1}\left(\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}}\right)$$

Go to *Results > Create Report*



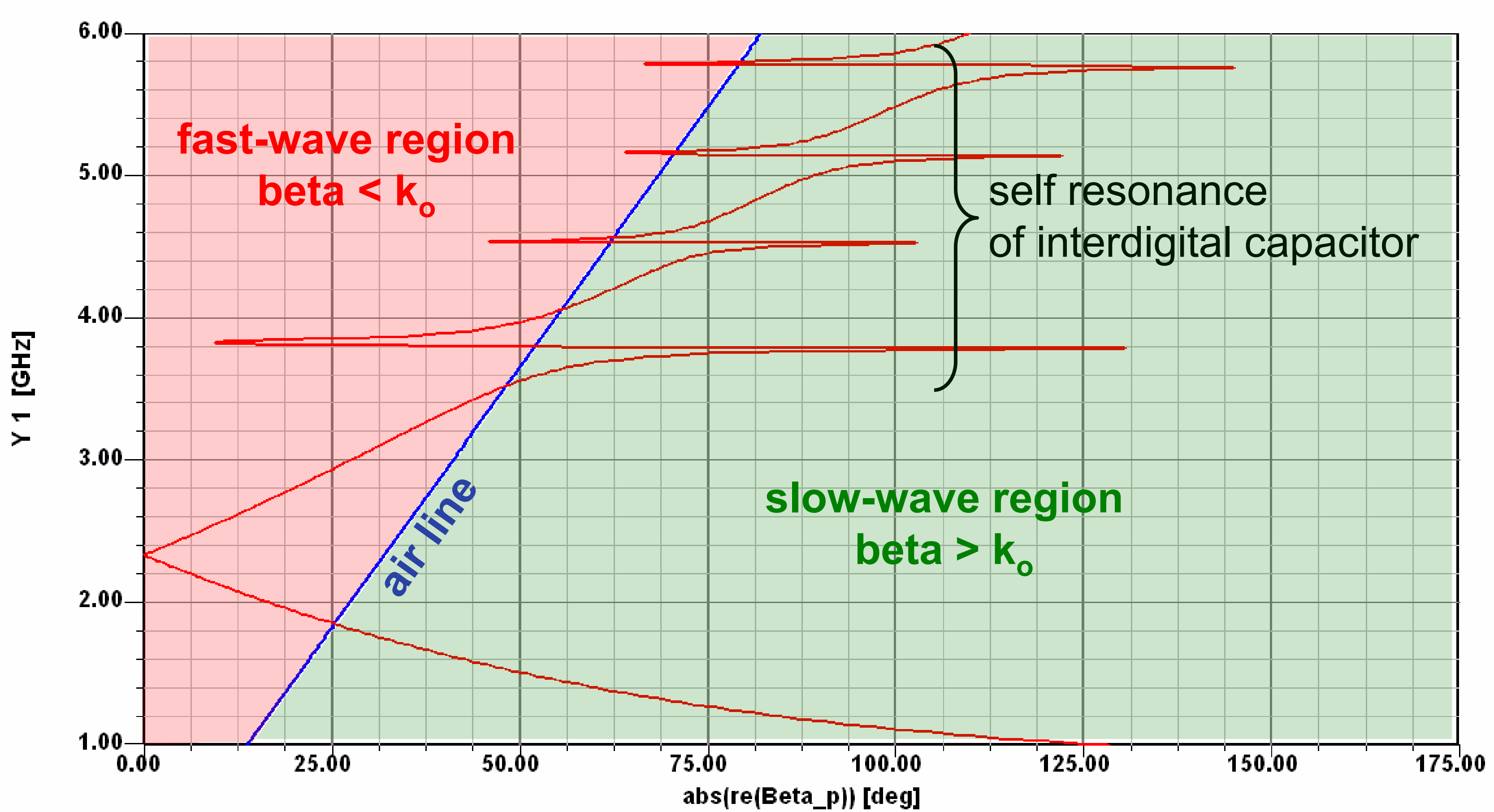
Then click on *Output Variables*





Dispersion Diagram

Final Design Dispersion Diagram in Ansoft Designer



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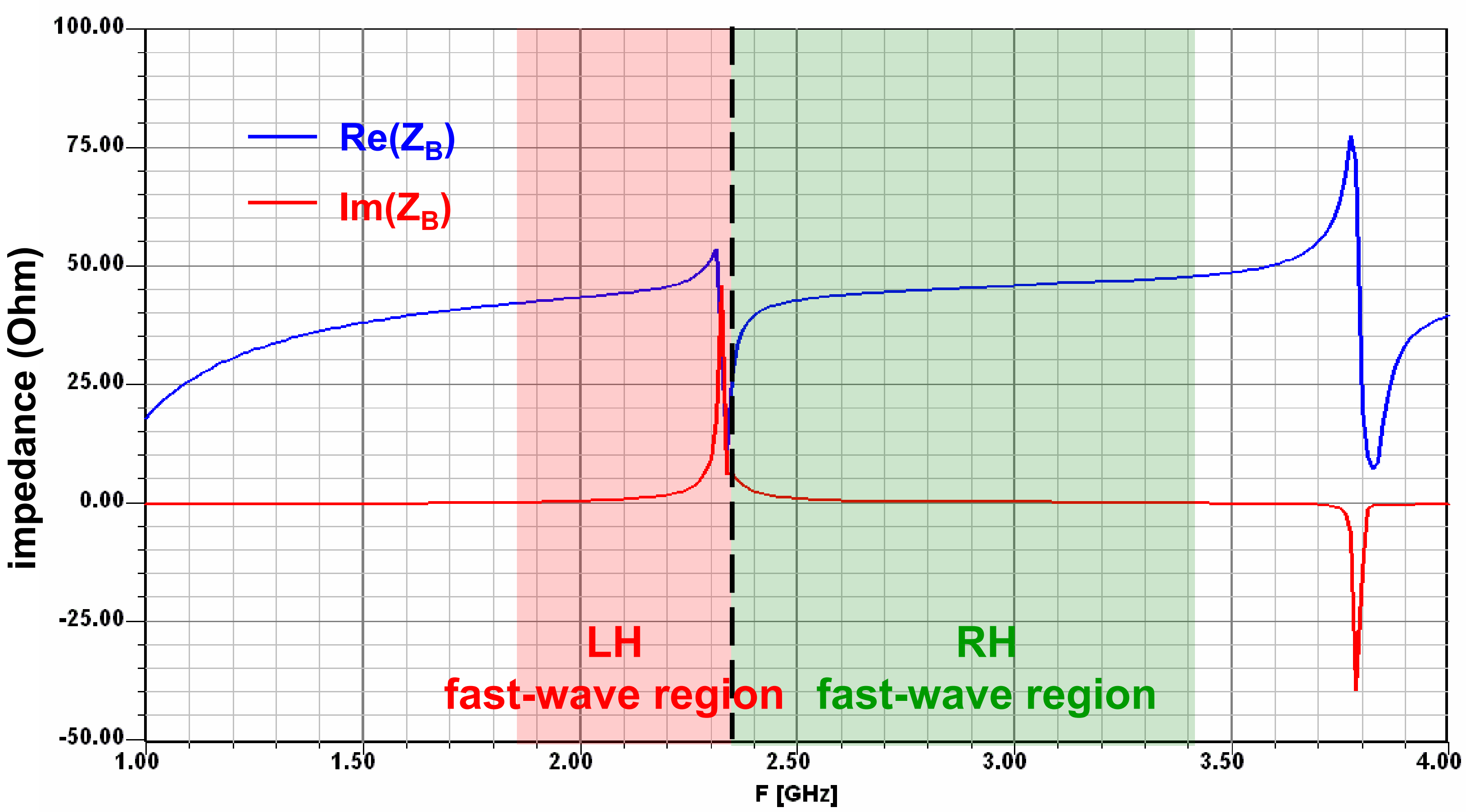
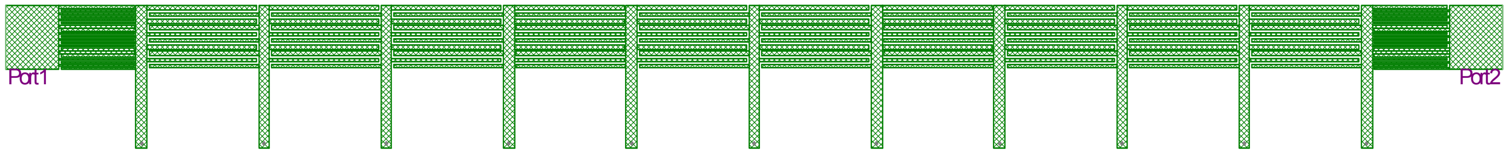
Bloch Impedance Diagram

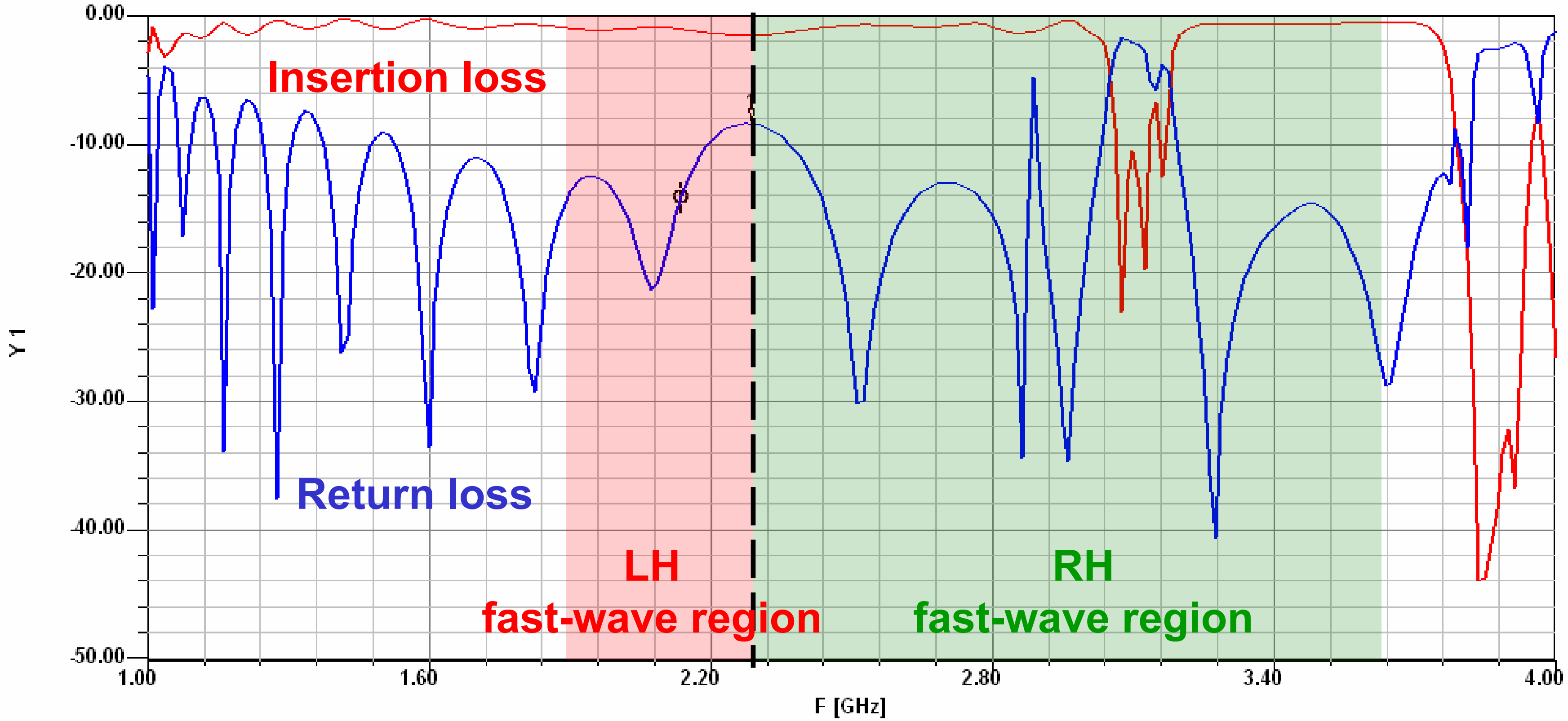
Resulting Bloch Impedance Diagram in Ansoft Designer



10-Cell CRLH Leaky-Wave Antenna

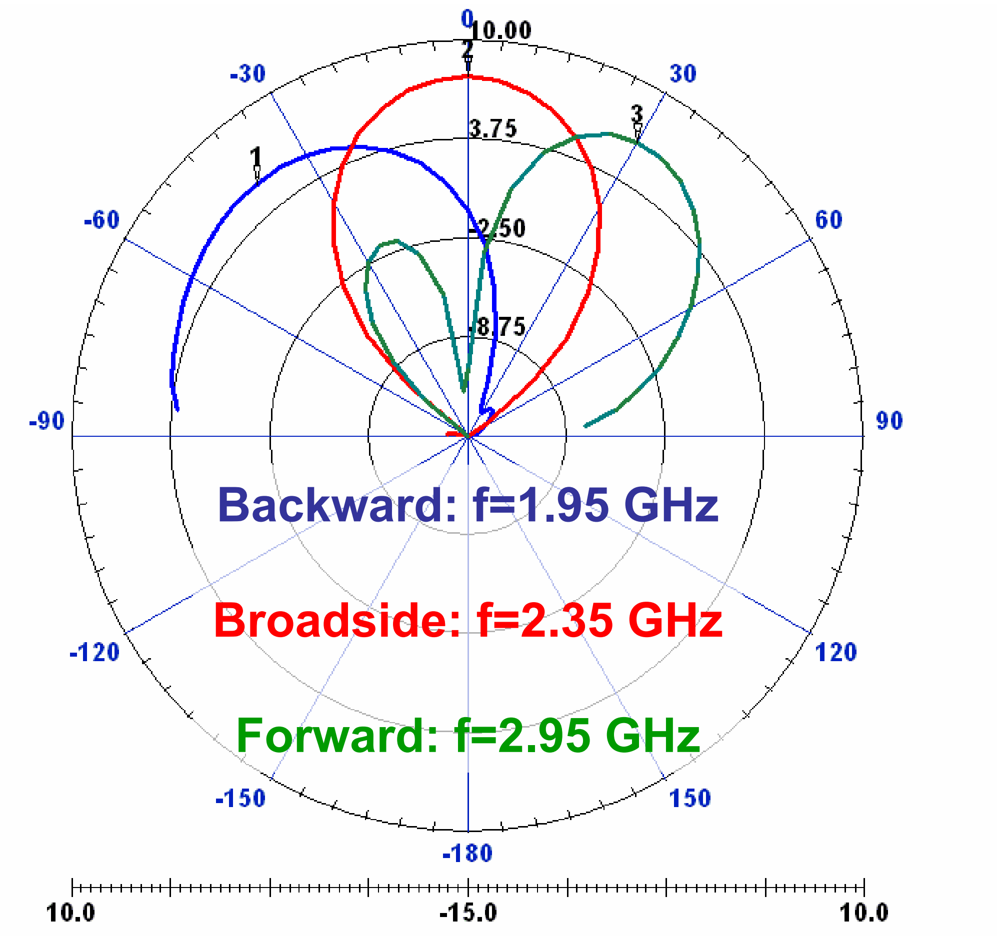


Return/Insertion Loss



10-Cell CRLH Leaky-Wave Antenna

Far-field Pattern for Several Frequencies



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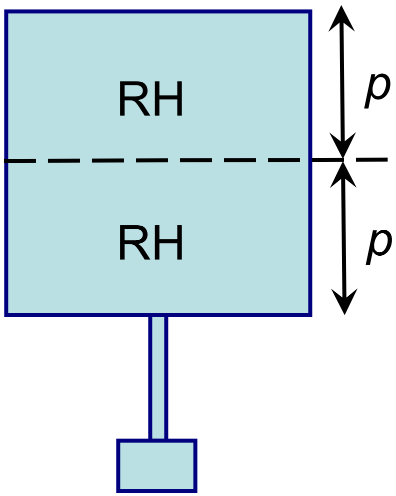
Small Metamaterial Antennas

Resonant Antenna Theory

Conventional RH Patch Antenna
(treat as periodic, consisting of 2 RH “unit-cells”)

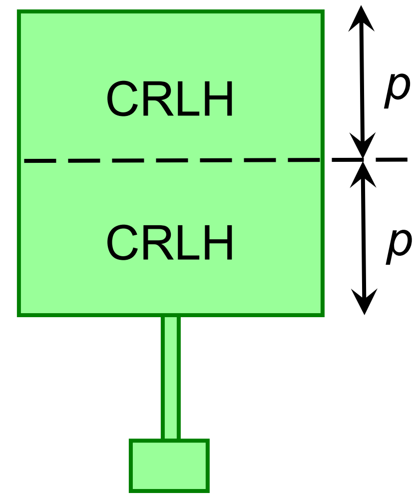


n = +1, +2, …

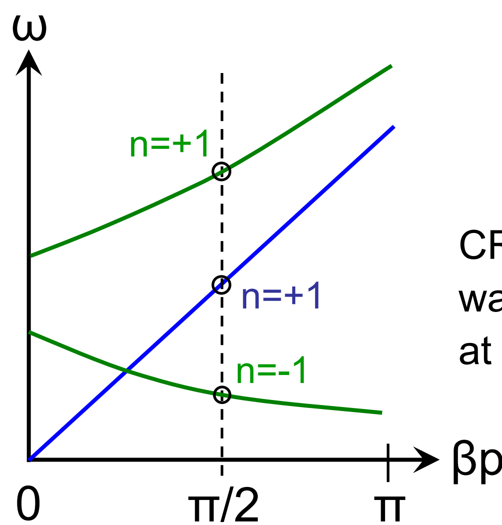
resonance condition

$$\beta_n = \frac{n\pi}{2p}$$

CRLH Patch Antenna
(2 CRLH unit-cells)



n = 0, ±1, ±2, …



CRLH can have same half-wavelength field distribution, but at much lower frequency

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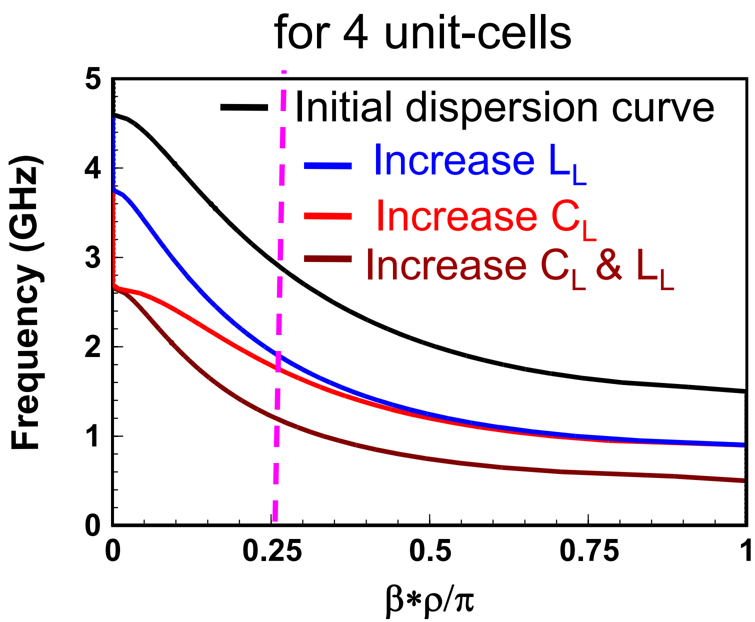
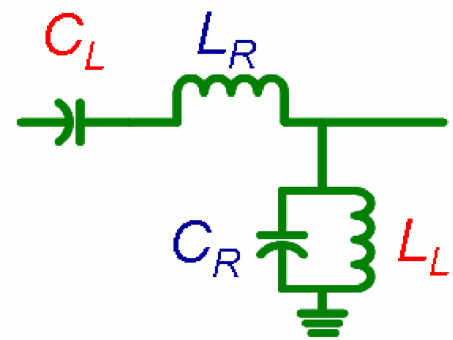
1.0 GHz CRLH n=-1 Antenna [7]

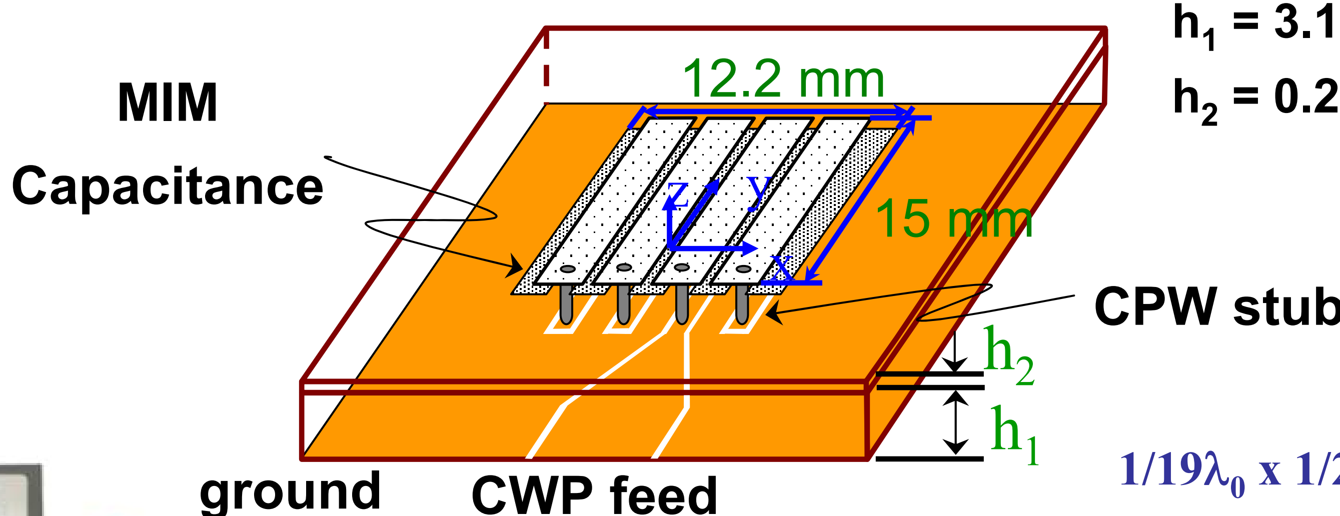




n= -1 mode is used

h_1 = 3.16 mm

h_2 = 0.254 mm



$1/19\lambda_0 \times 1/23\lambda_0 \times 1/88\lambda_0$

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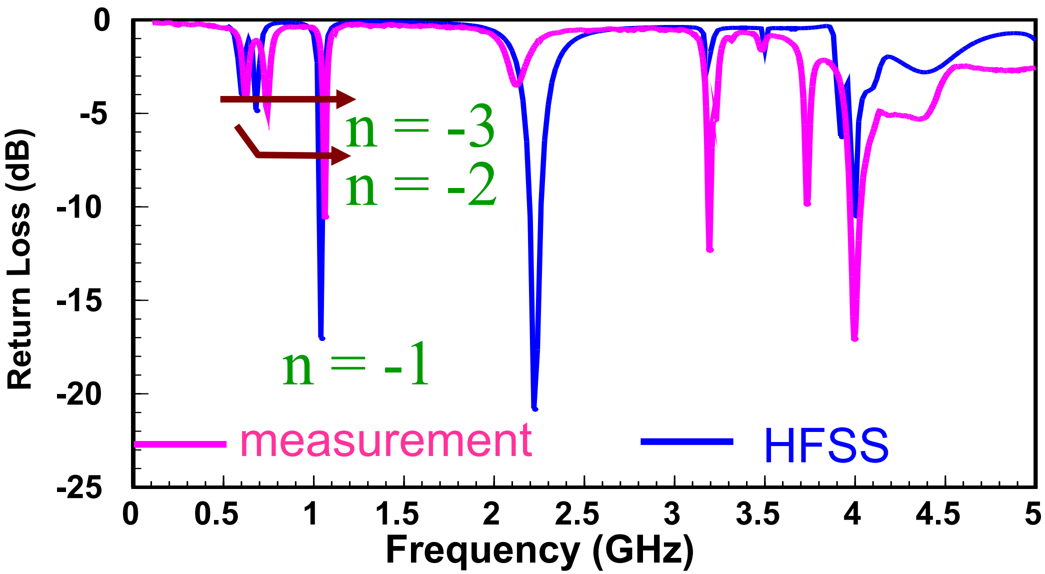
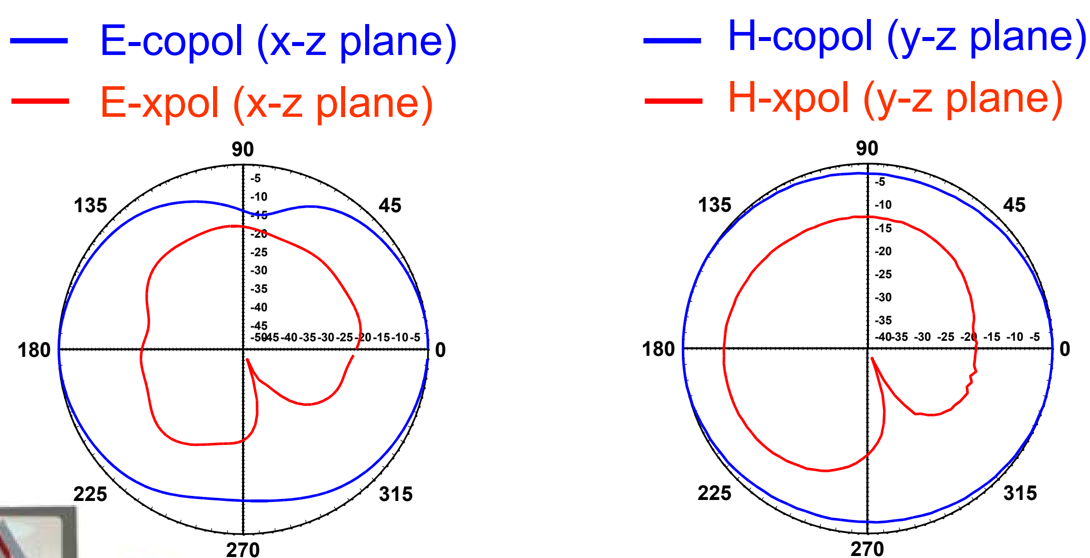
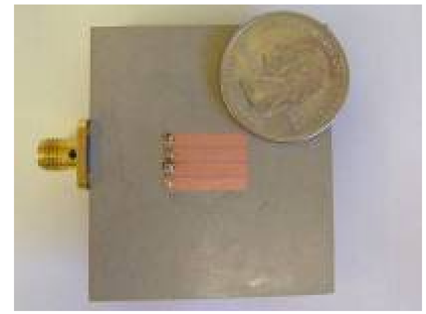
1.0 GHz CRLH n=-1 Antenna [7]

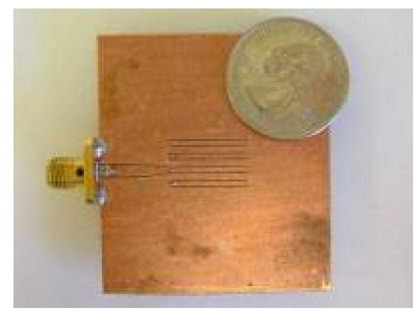




top view



back view



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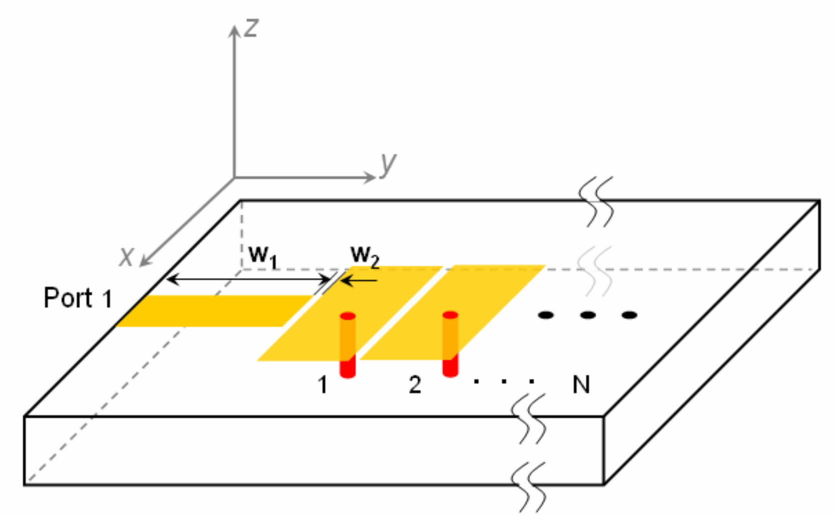
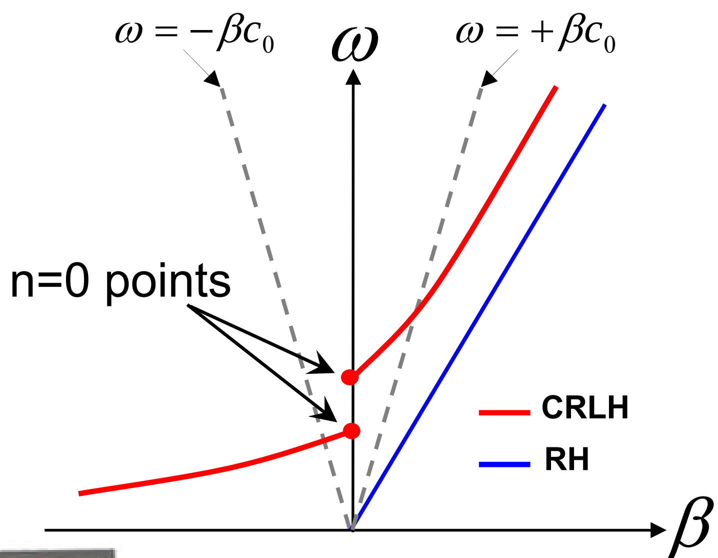
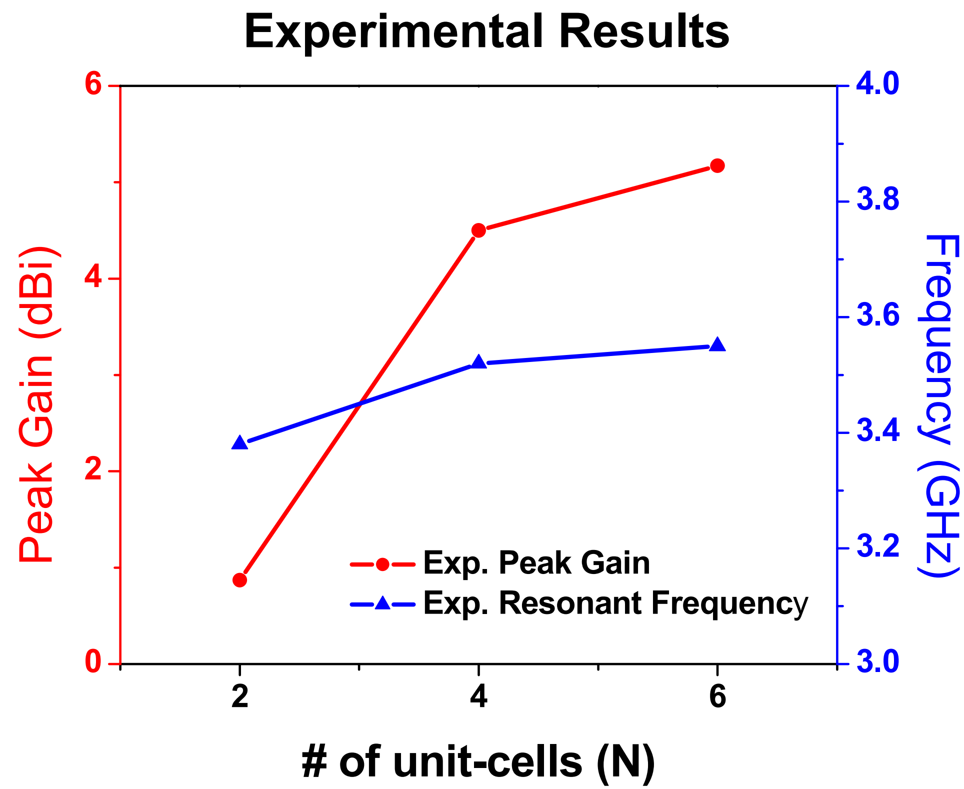
CRLH n=0 Antenna (Monopolar) [8]







As N increases…

- **Gain increases.**
- **Resonant frequency does not change much.**

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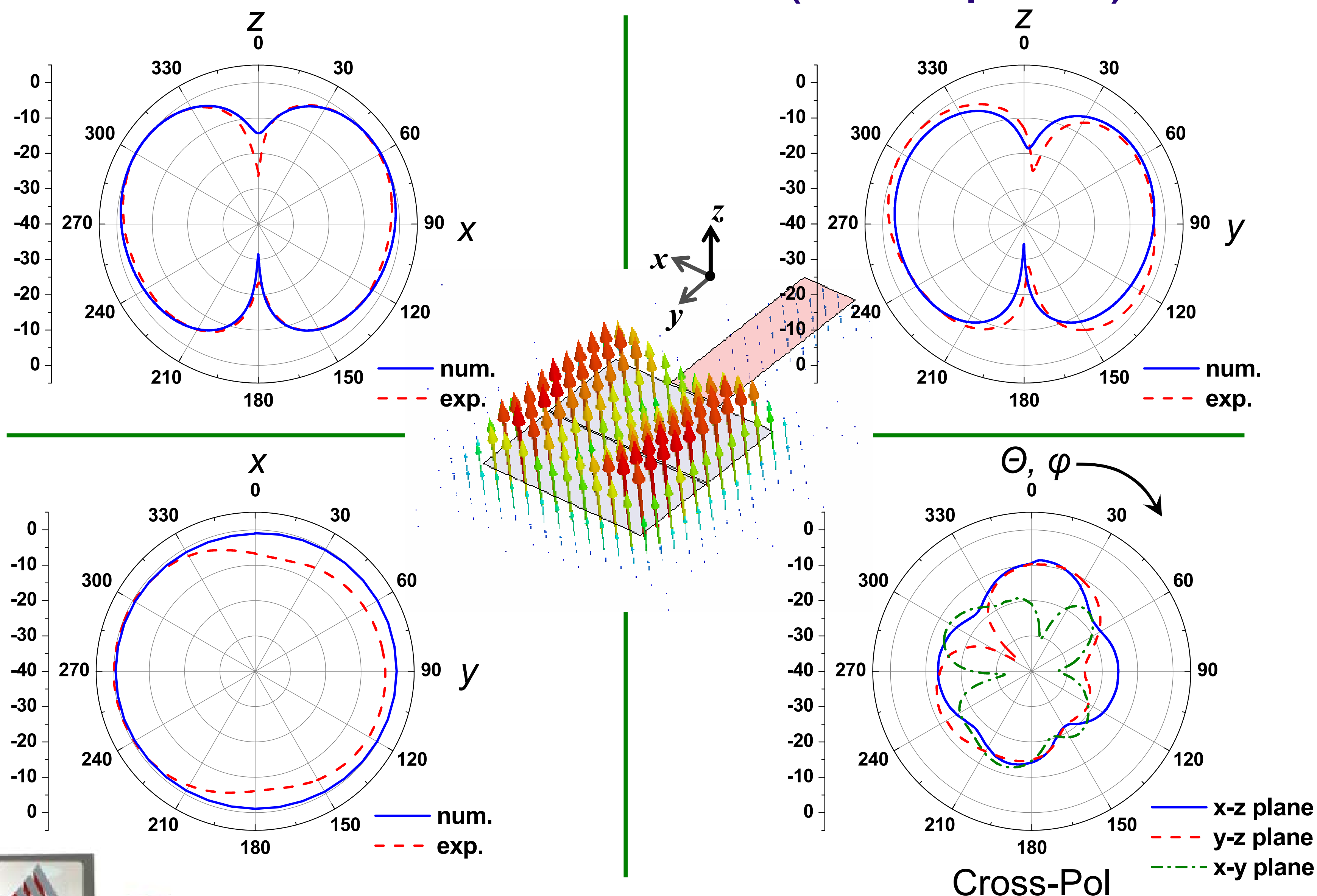
CRLH n=0 Antenna (Monopolar)



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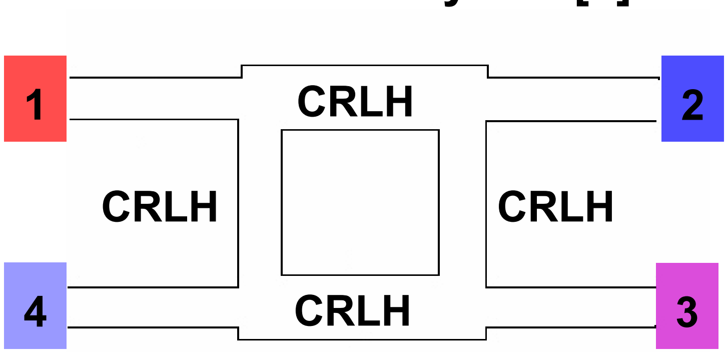
Dual-/Multi-Band Metamaterial Components

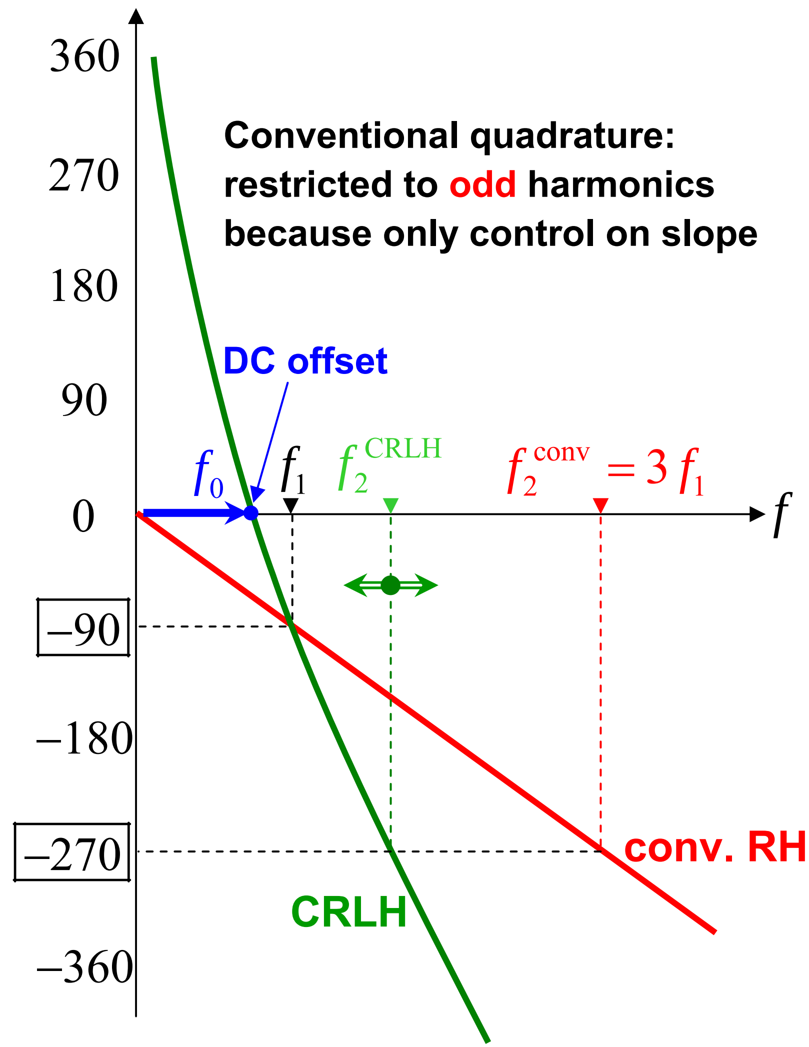
Dual-Band Hybrid Coupler

CRLH / CRLH hybrid [9]



Characteristics:

- dual-band functionality for an arbitrary pair of frequencies f_1, f_2
- principle: transition frequency (f_o) provides *DC offset* additional degree of freedom with respect to the *phase slope*
- applications in multi-band systems



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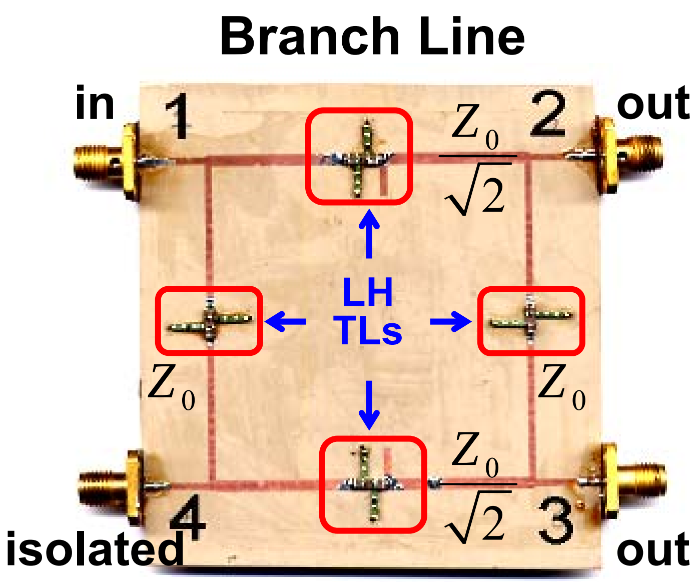
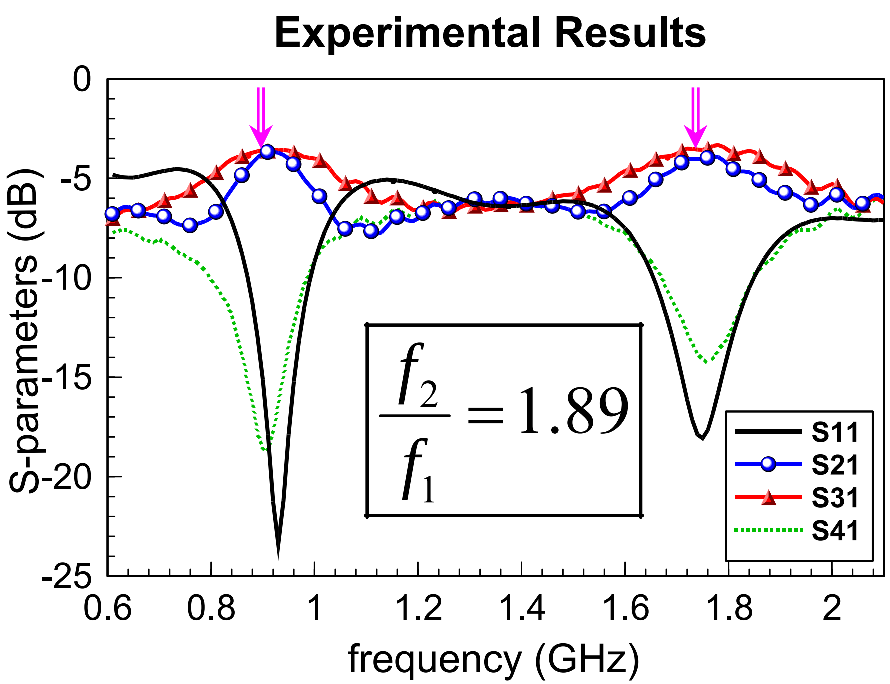
Dual-Band Hybrid Coupler



Band # 1: 0.92 GHz

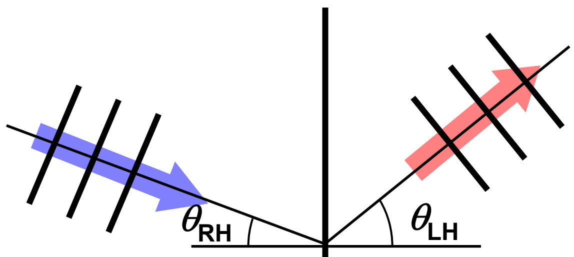
Band # 2: 1.74 GHz



Negative Refractive Index Lenses

Negative Refractive Index Flat Lens [10]

$$(n_{LH})\sin\theta_{LH} = (n_{RH})\sin\theta_{RH}$$



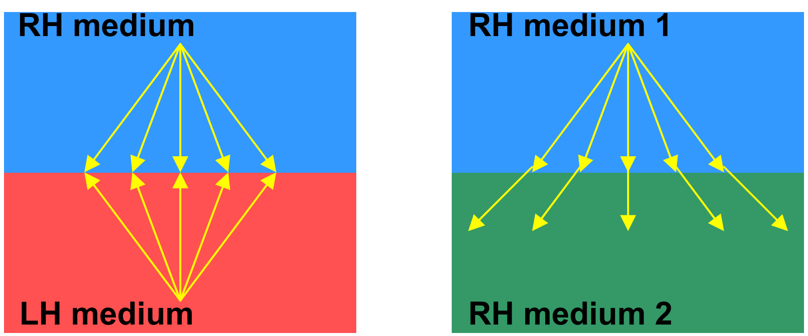
RH medium

refractive index $n_{RH} > 0$

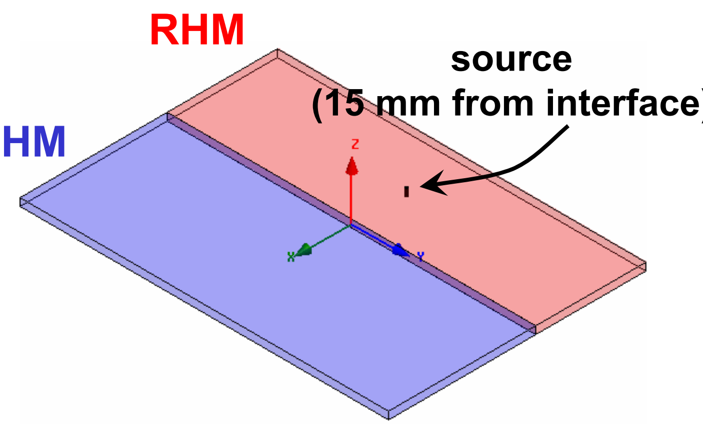
LH medium

refractive index $n_{LH} < 0$

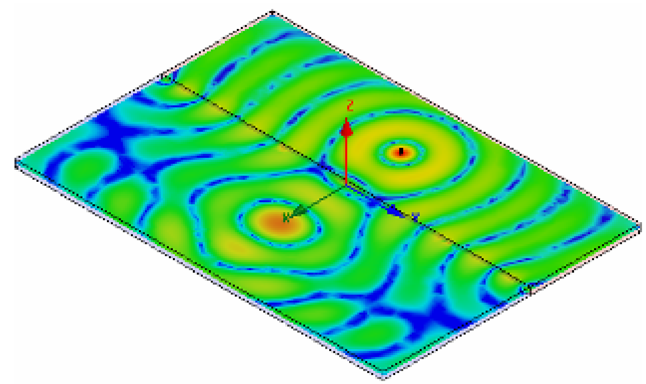
Possibility of realizing a flat lens



Effective medium HFSS simulation

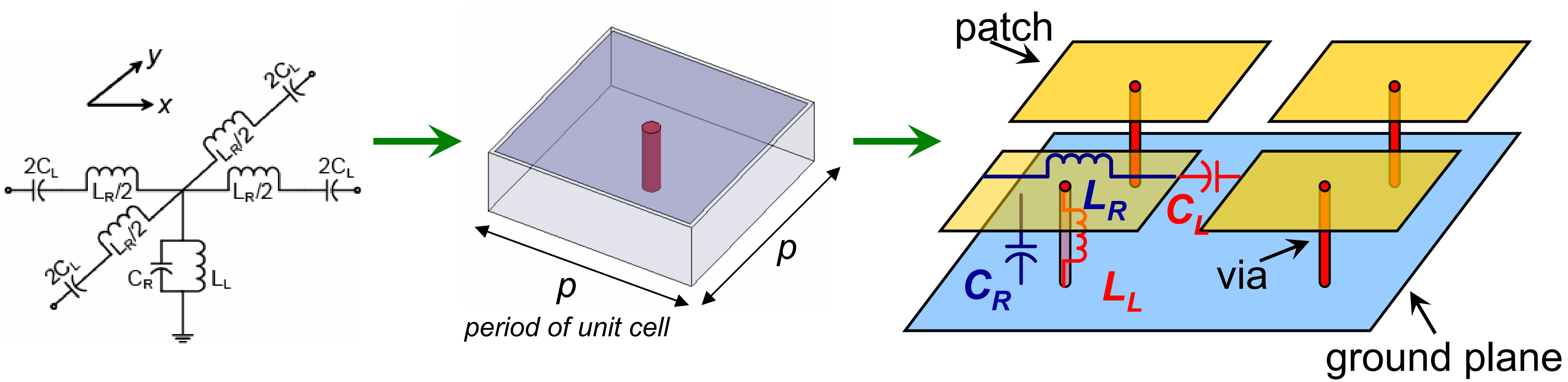


E-field magnitude



Two-Dimensional CRLH Realization

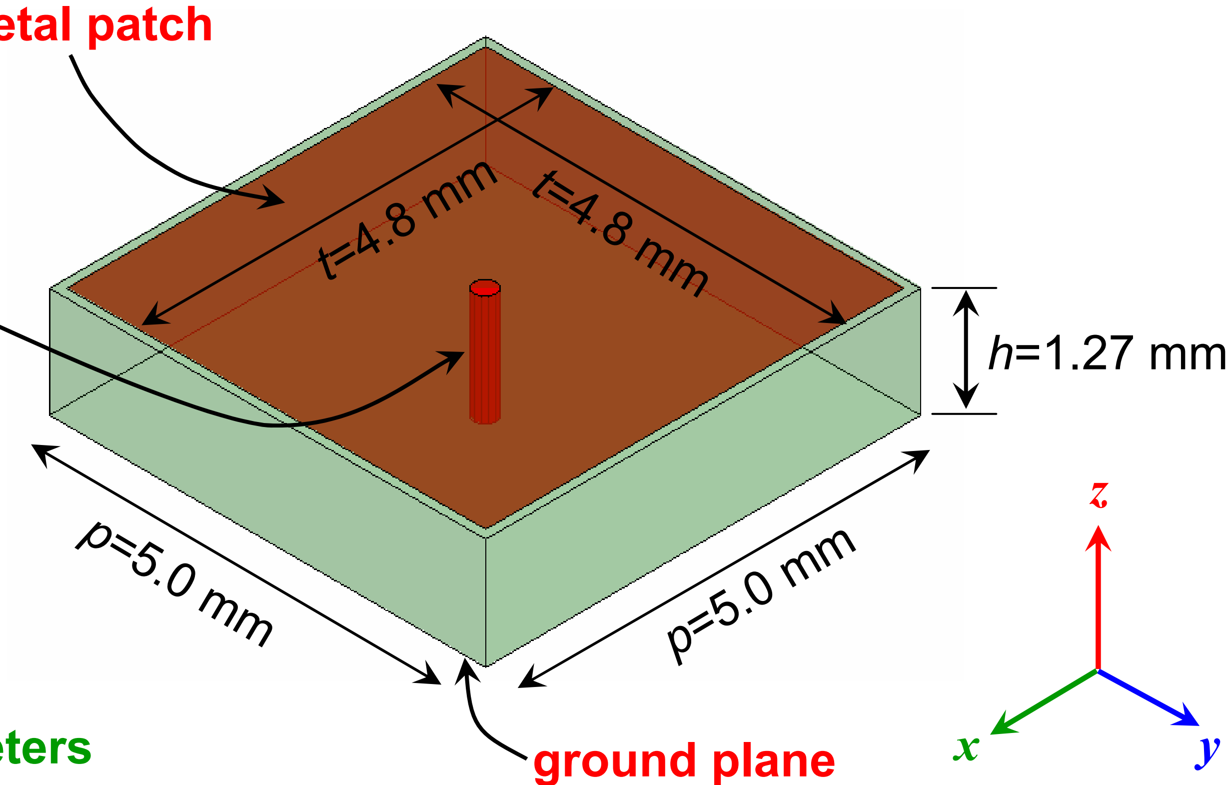
Based on Sievenpiper High-Impedance Structure



How to obtain dispersion characteristics?

1. Drivenmode Approach – Simple, quick, 1-D dispersion diagram.
2. Eigenmode Approach – Requires more processing time, accounts for mode coupling, 2-D dispersion diagram.

Unit-Cell Setup: Physical Details



substrate parameters
ε_r=10.2, tanδ=0.0023 Np/m

*** patch,via, and ground plane are assigned as copper.**

Design Flow

Unit-Cell Parameters – 1st Order Calculation

Dispersion Characteristics

Design

Driven Mode Approach
- 1-D dispersion
- No mode coupling

Verify

Eigen Mode Approach
- 2-D dispersion
- Mode coupling

Flat Lens Realization – Phase Matching

HFSS Simulation Flat Lens
- Symmetry Conditions: Reduce Simulation Time
- Field Plots: Magnitude & Phase

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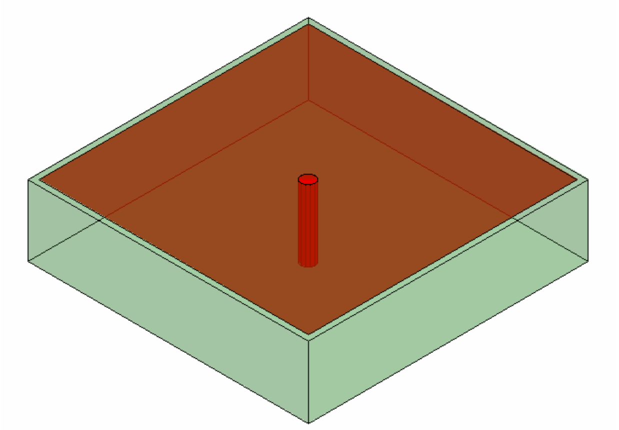
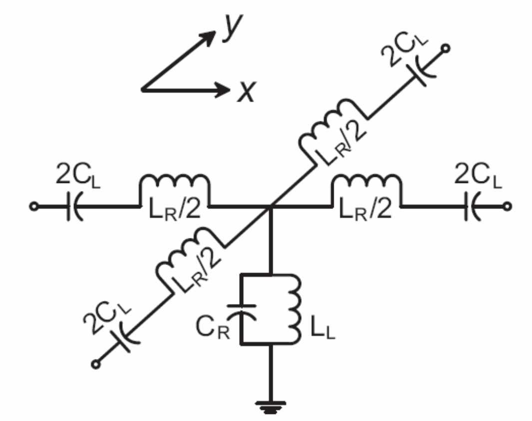
Sievenpiper Unit-Cell: 1st Order Calculation

distributed unit-cell



equivalent circuit model



$$f_{sh} = 1/\{2\pi \mathrm{sqrt}(C_R \times L_L)\}$$

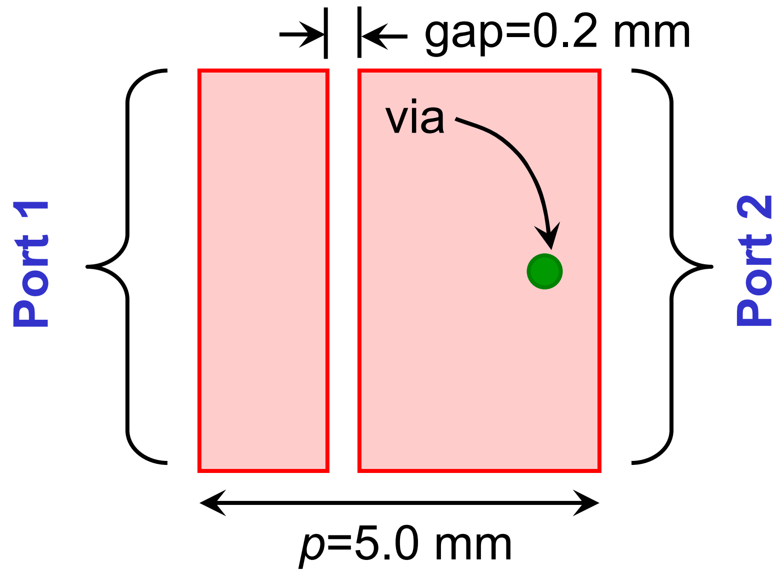
series capacitance: C_R ~ substrate permittivity x (patch area/substrate height)

shunt inductance: L_L ~ 0.2 x substrate height x ln[(2 x substrate height/via radis) – 1]

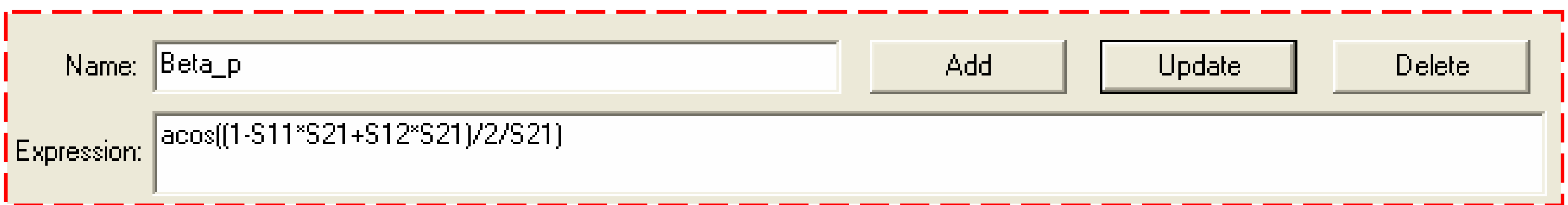
* Left-handed mode will always occur below the shunt resonance (ω_{sh}). Therefore, design dimensions such that w_{sh} occurs at higher limit of frequency of interest.

f_{sh} ~ 5 GHz for the dimensions shown in previous slide.

Sievenpiper Unit-Cell: Driven Mode

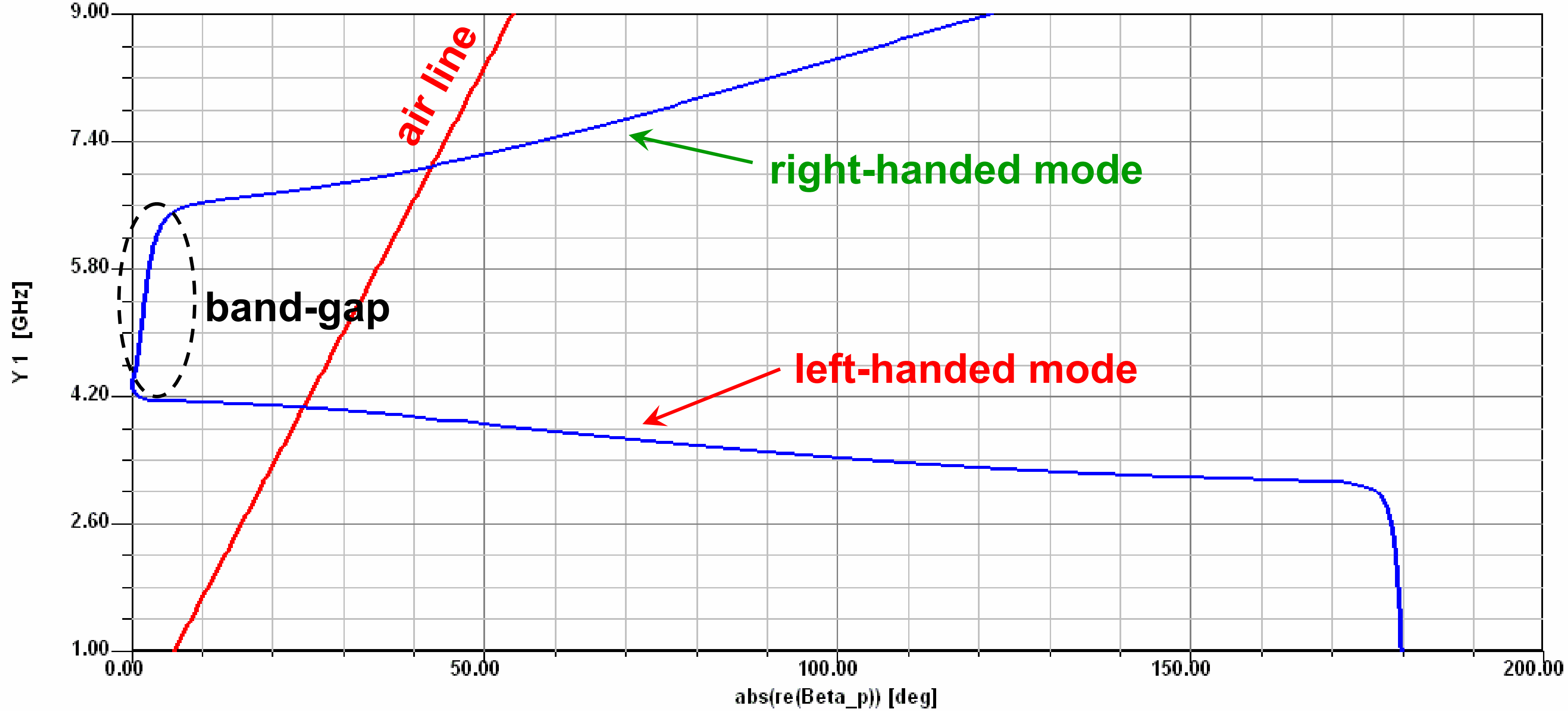


- Modify unit-cell so that ports can be placed on it, while keeping dimensions the same. Unit-cell becomes asymmetrical.
- Run driven mode solution; set mesh frequency to ω_{sh} from 1st order calculation.
- Obtain S-parameters, use following expression to calculate propagation constant.

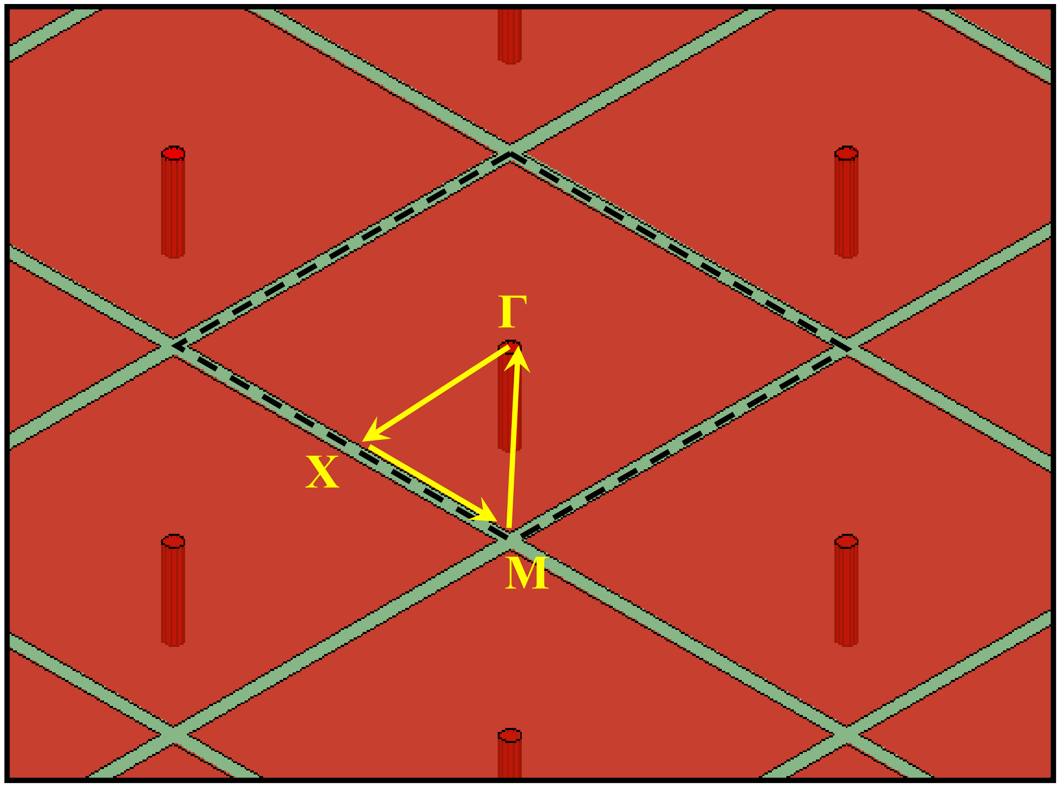


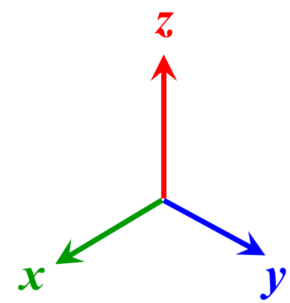
Sievenpiper Unit-Cell: Driven Mode

1-D dispersion diagram (from Port 1 to Port 2)



Eigenmode Solver: 2-D Dispersion Diagram





Γ to X: px=0°, py=0°→180°

X to M: px=0°→180°, py=180°

M to Γ : px, py: 0°→180°

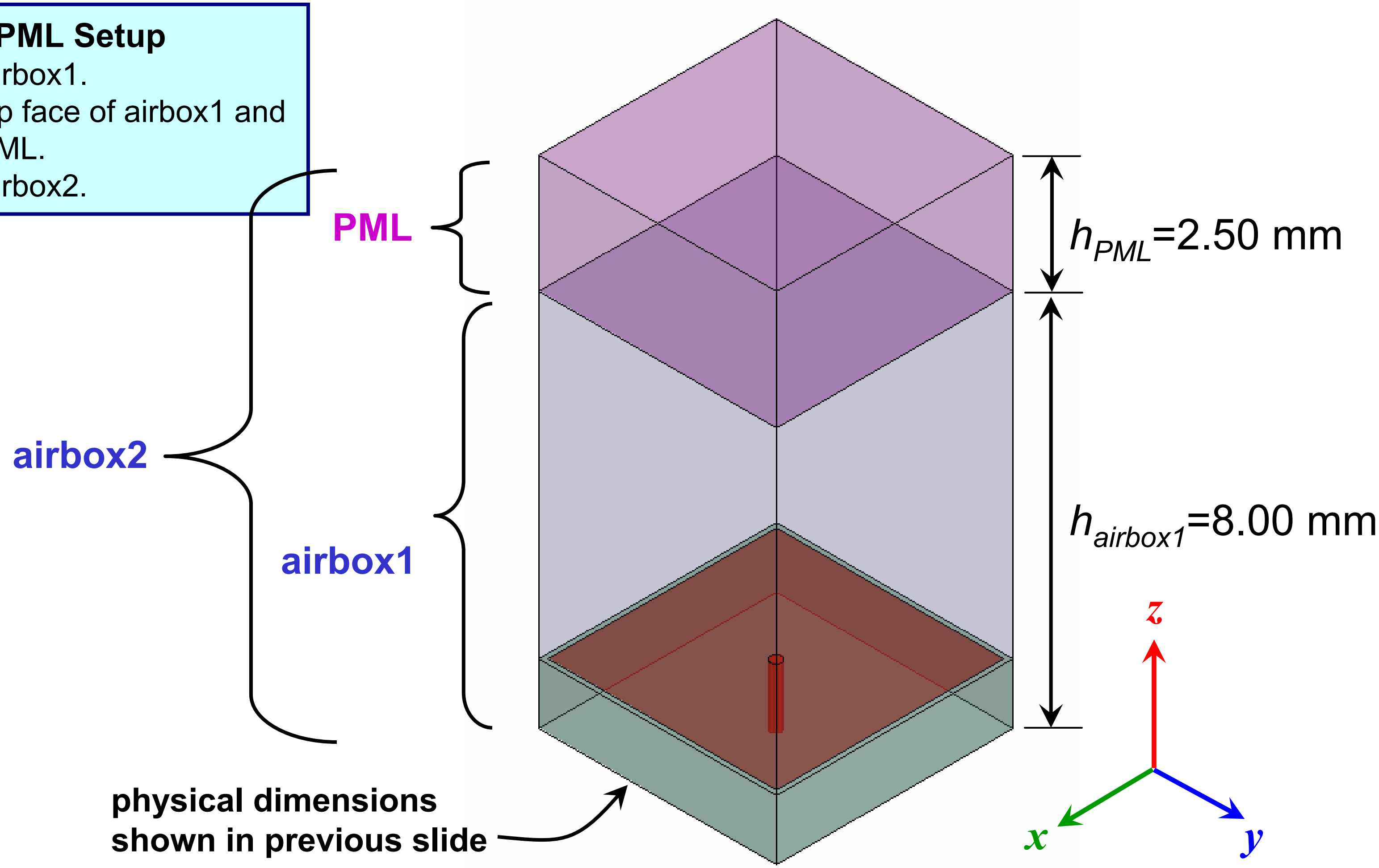
- px: phase offset in x-direction
- py: phase offset in y-direction

Use Linked Boundary Conditions (LBCs) in HFSS to apply required phase shifts.

Sievenpiper Unit-Cell Setup

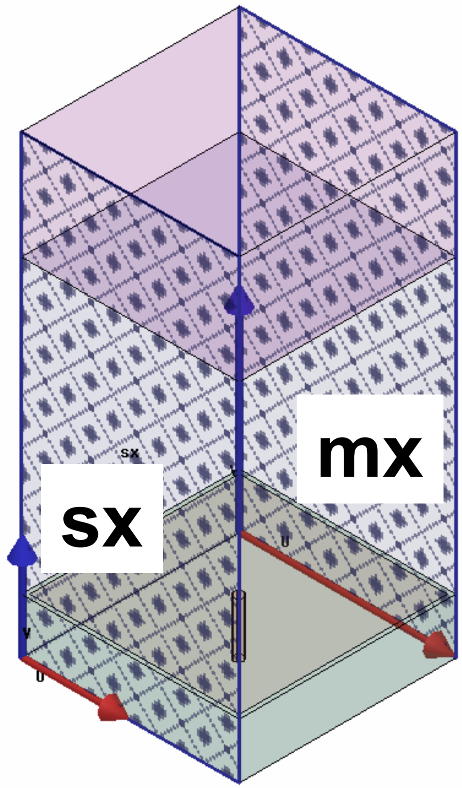
Airbox and PML Setup

1. Create airbox1.
2. Select top face of airbox1 and assign PML.
3. Create airbox2.

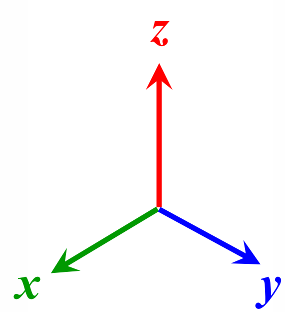


Unit-Cell Setup: Linked Boundaries

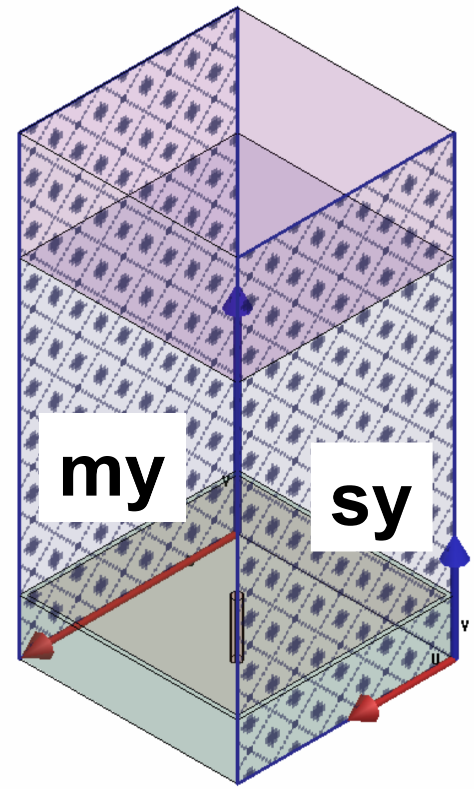
XZ - Planes



Slave BC: sx
- **phase delay: px (180 deg)**



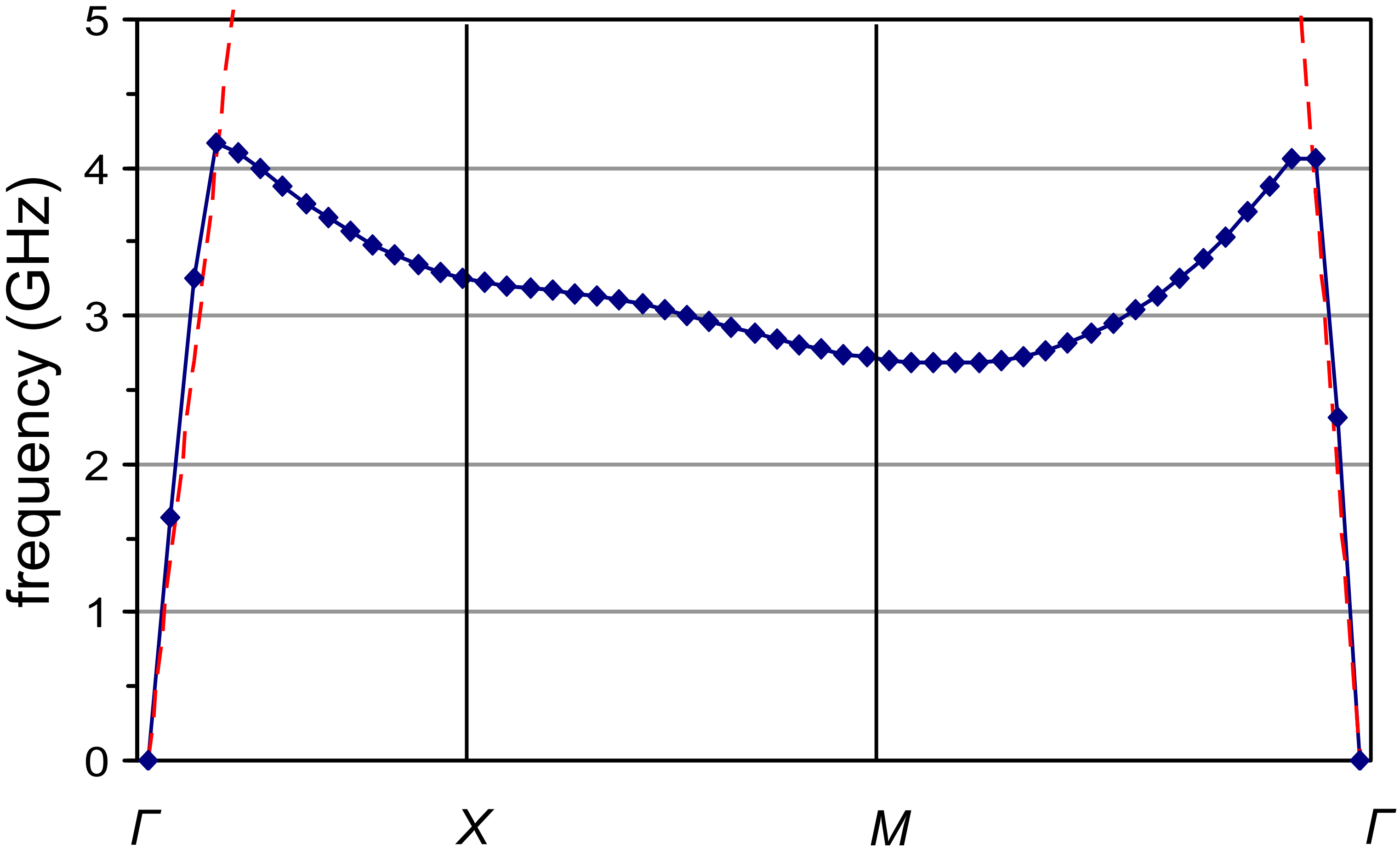
YZ - Planes



Slave BC: sy
- **phase delay: py (0 deg)**

Eigenmode 2-D Dispersion Diagram

Plotted in Microsoft Excel



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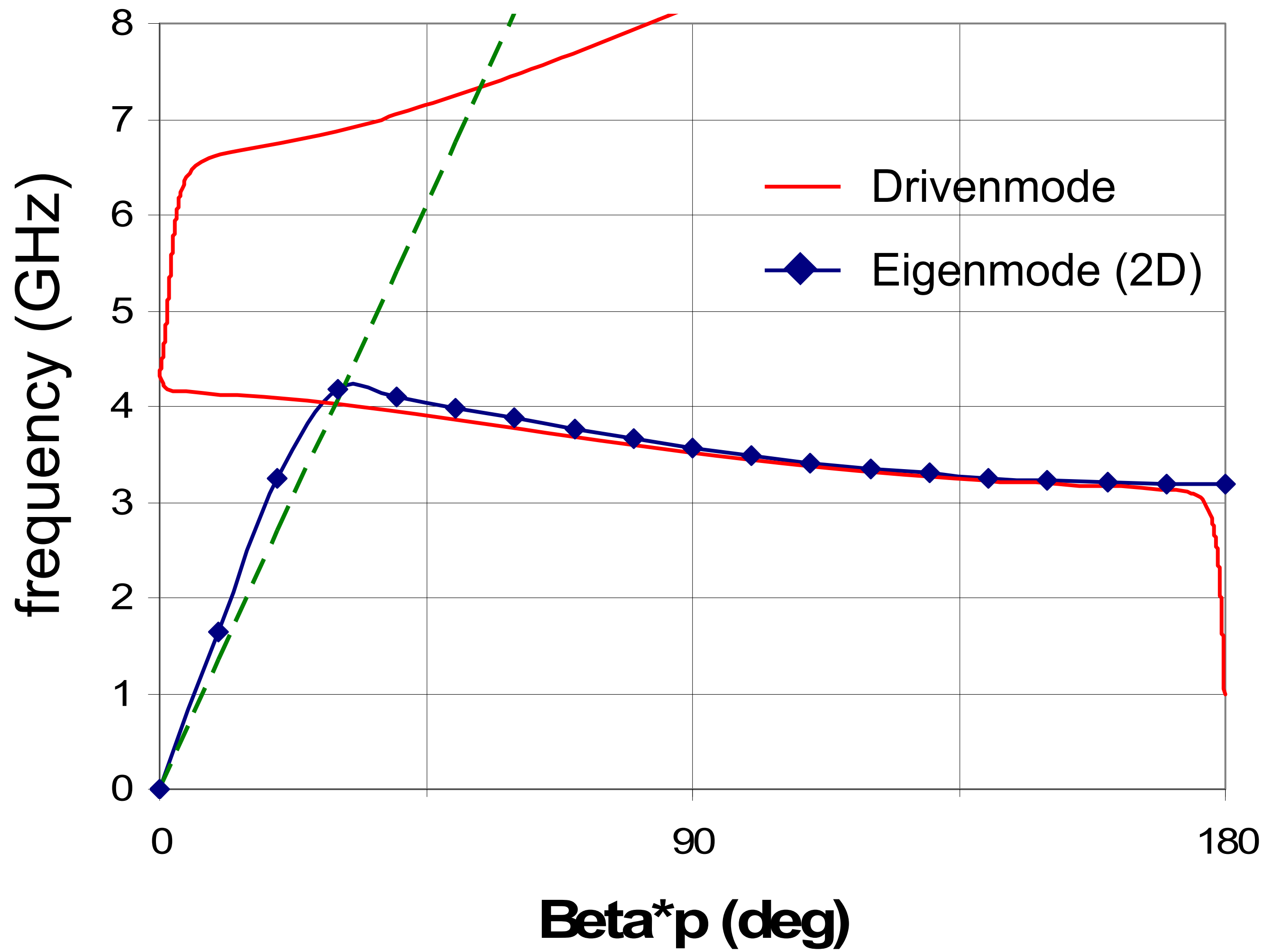
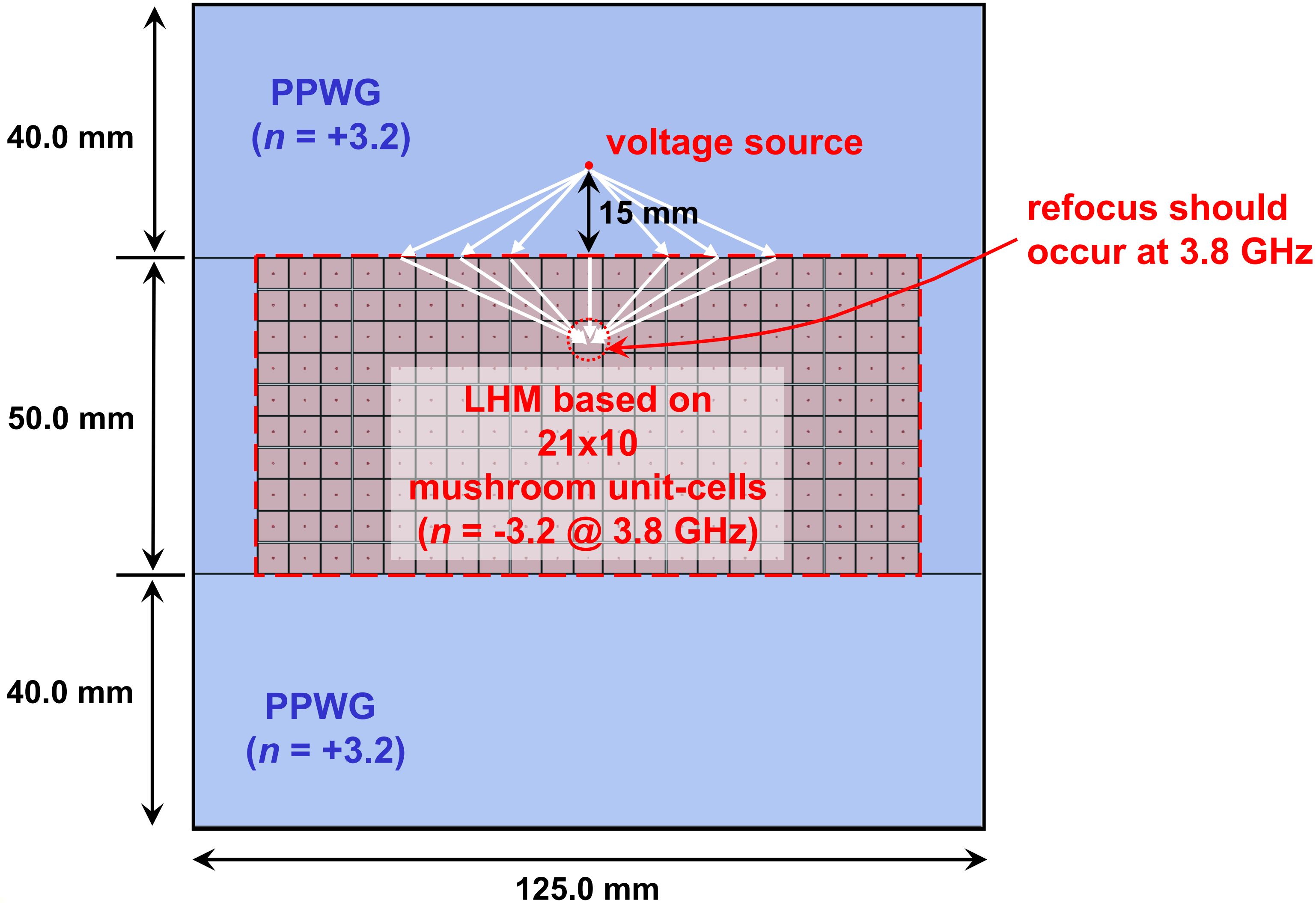
Dispersion Comparison: 1-D vs 2-D Solve



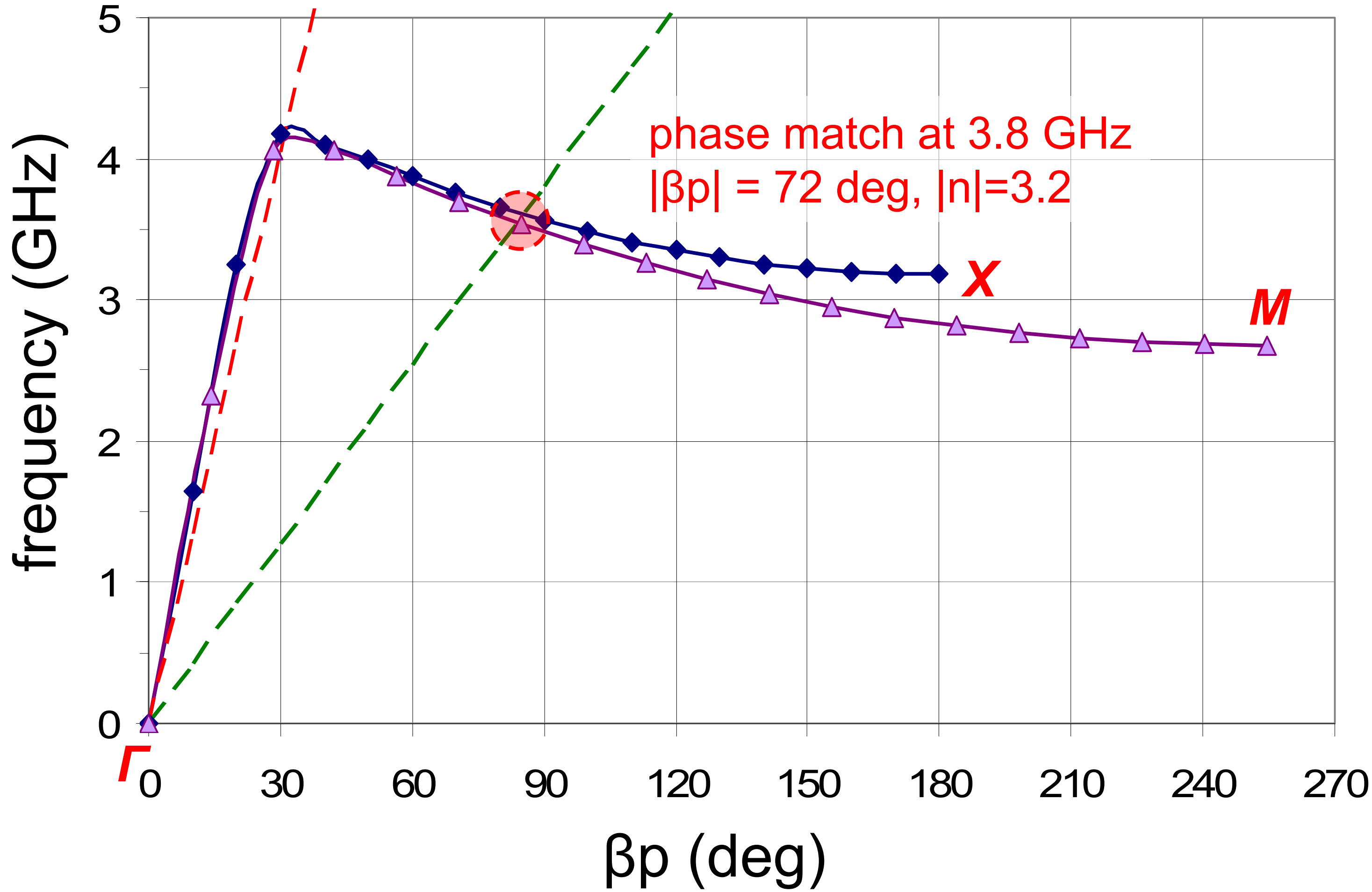
Use drivenmode to quickly characterize/design, eigenmode to verify

Flat Lens – Physical Realization

Entire circuit on Roger RT 6010 substrate with ε_r = 10.2 and h = 1.27mm

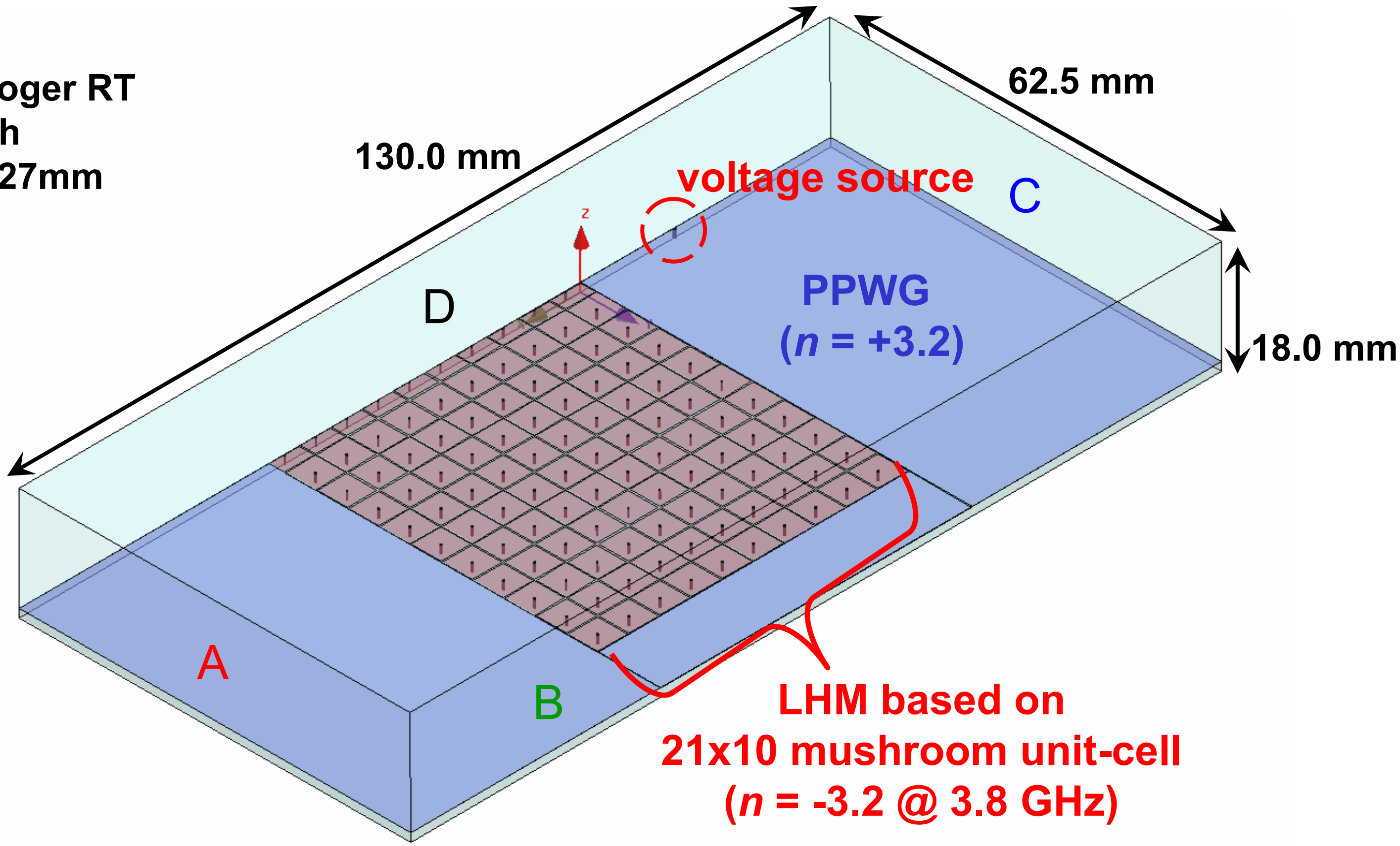


Flat Lens – Phase Matching Condition



Flat Lens – Simulation Setup

Entire circuit on Roger RT 6010 substrate with ε_r = 10.2 and *h* = 1.27mm



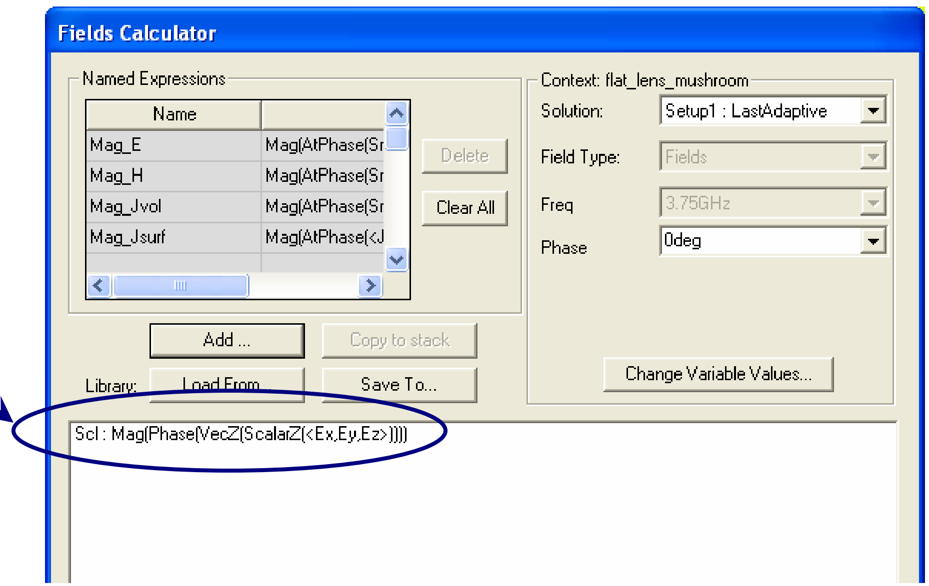
Boundary Conditions

- Radiation boundary applied on Top and Side A, B, and C of air box.
- Finite conductivity (Copper) applied on bottom of airbox, PPWG trace, and mushroom patches.
- Symmetry boundary (perfect-H) applied to Side D to reduce problem size.

Flat Lens – Field Calculator for Phase

To plot the E-field phase, the field calculator has to be used.

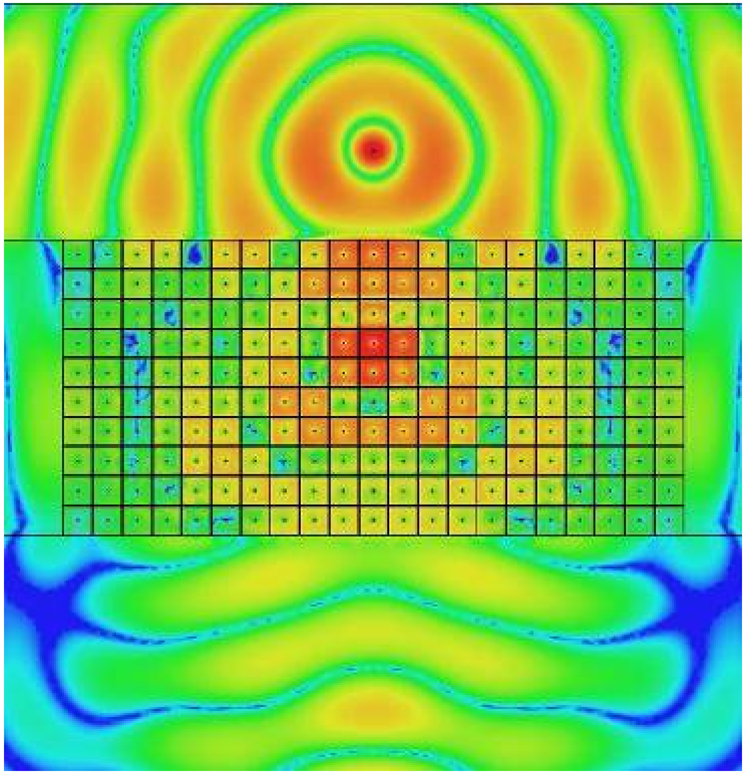
- Go to *HFSS > Fields > Calculator*
- Since the field is quasi-TEM, only the z-component of the E-field is required.
  - ❖ Quantity > *E*
  - ❖ Scal? > *ScalarZ*
  - ❖ Vec? > *VecZ*
  - ❖ Complex > *CmplxPhase*
  - ❖ Mag
  - ❖ Add, give name PhazeZ



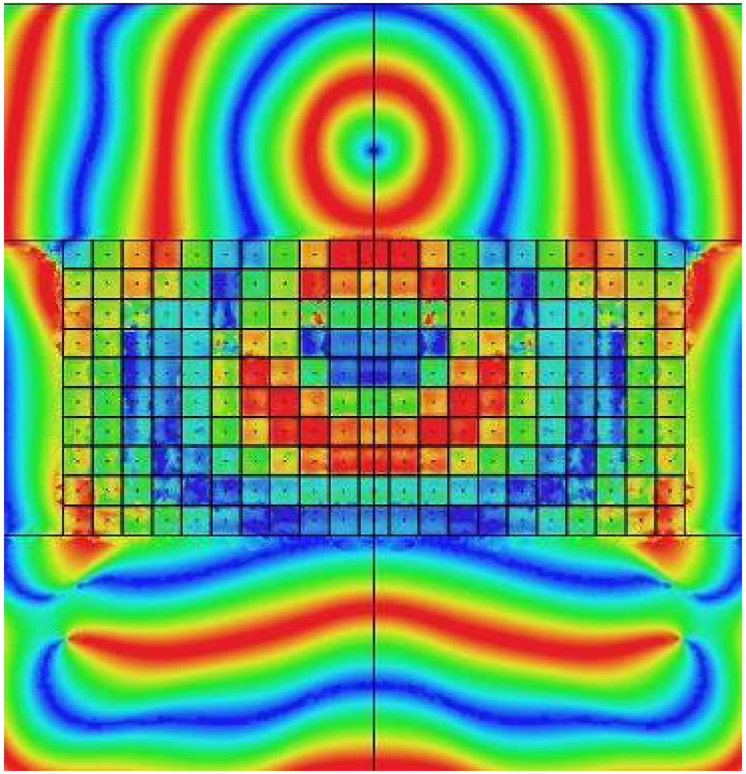
Flat Lens – E-Field Plots (Ground Plane)

field on ground plane @ f=3.75 GHz

Magnitude



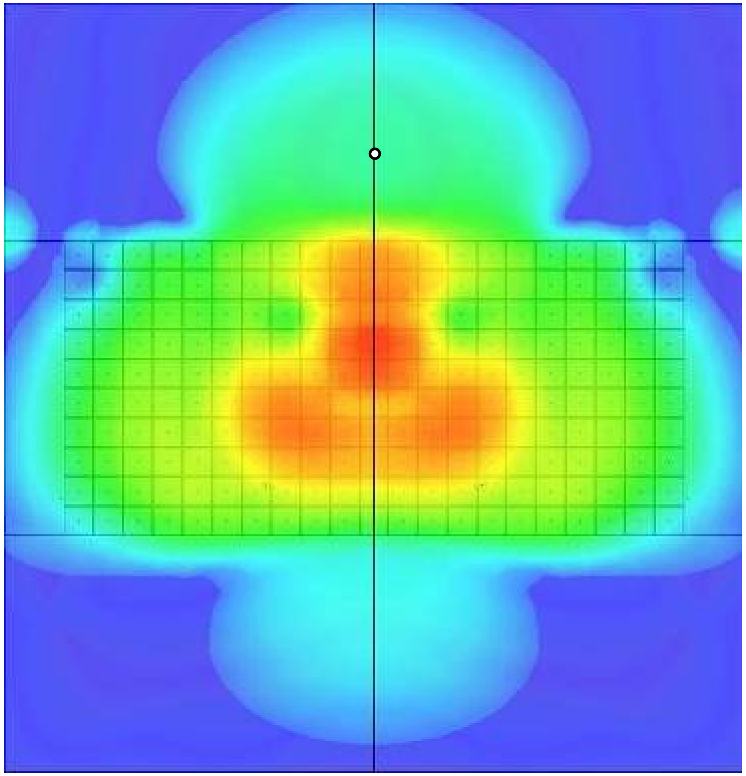
Phase



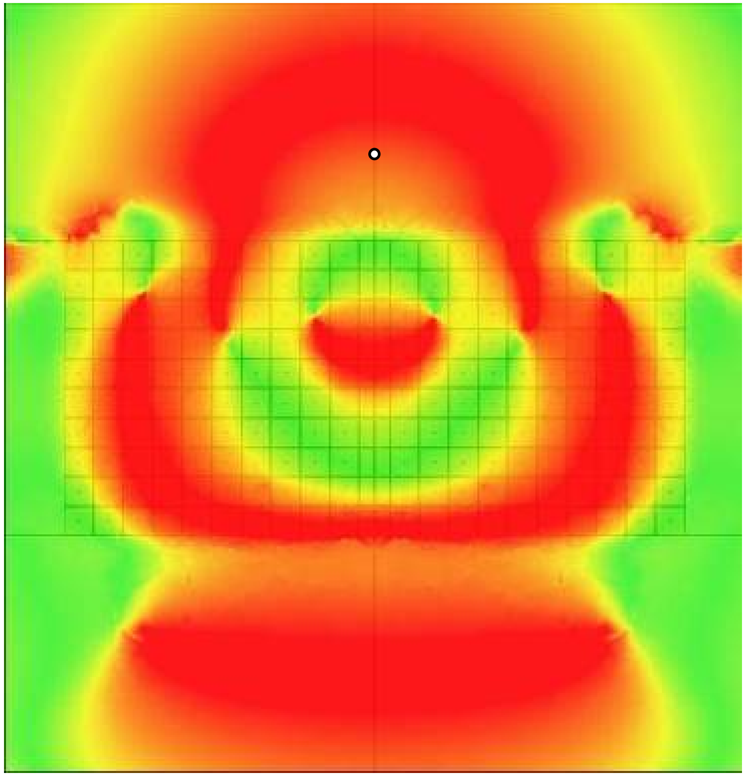
Flat Lens – E-Field Plots (Above Structure)

field on top of structure @ f=3.75 GHz
(3.5 mm above top metal)

Magnitude

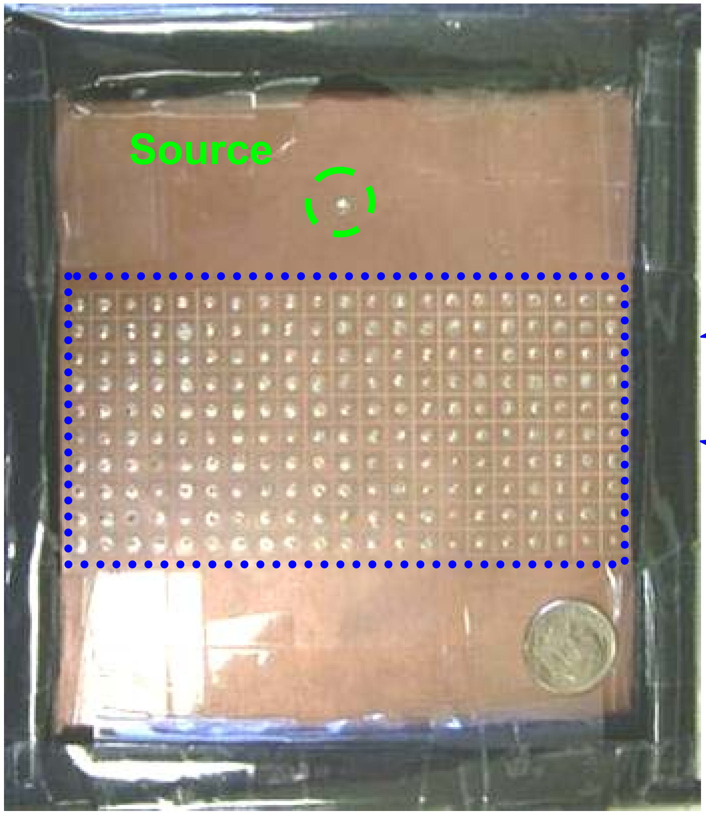


Phase

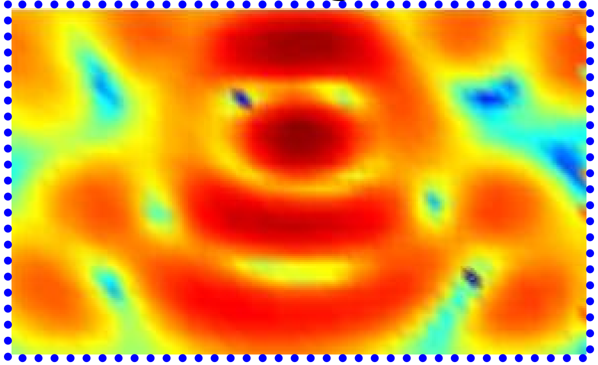


Flat Lens – Experimental Results

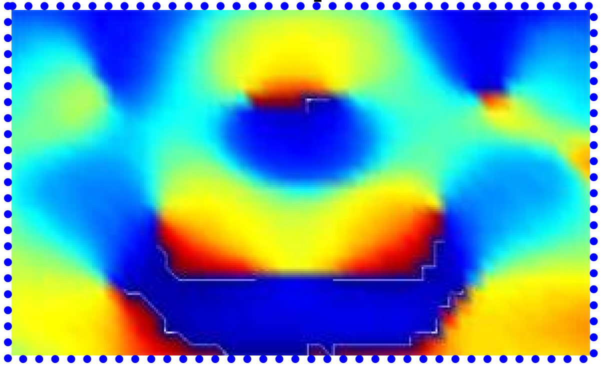
f_0 =3.79 GHz



E-field magnitude



E-field phase



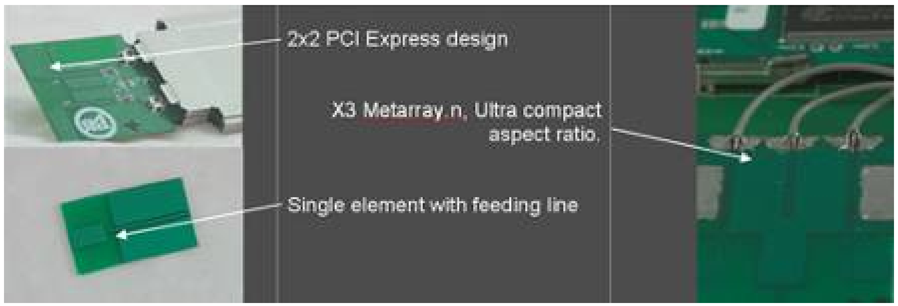
E-field measured ~ 3.5 mm above CRLH region

Future Trends

Applications & Research

Metamaterial Multiple-Input-Multiple-Output (MIMO) Arrays for 802.11n Application [11]

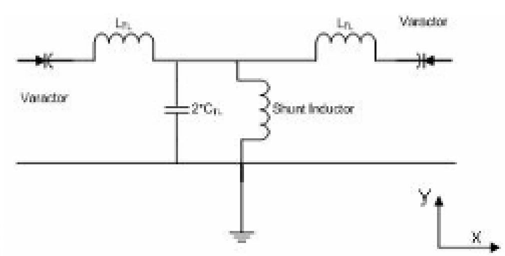
RAYSPAN™

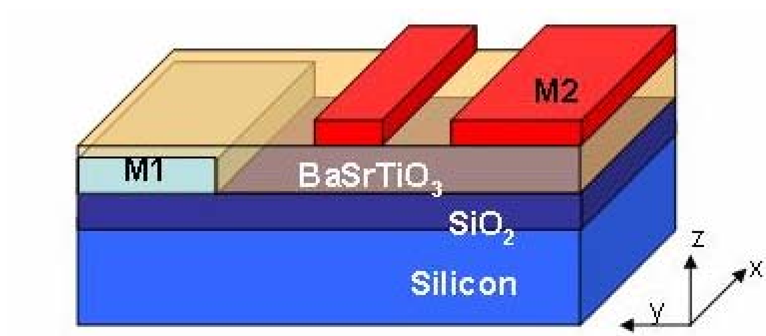


Active CRLH Metamaterials

- High-gain leaky-wave antennas (embed amplifiers in unit-cell) [12]
- Distributed amplifiers [13]

Tunable Phase Shifters [14]





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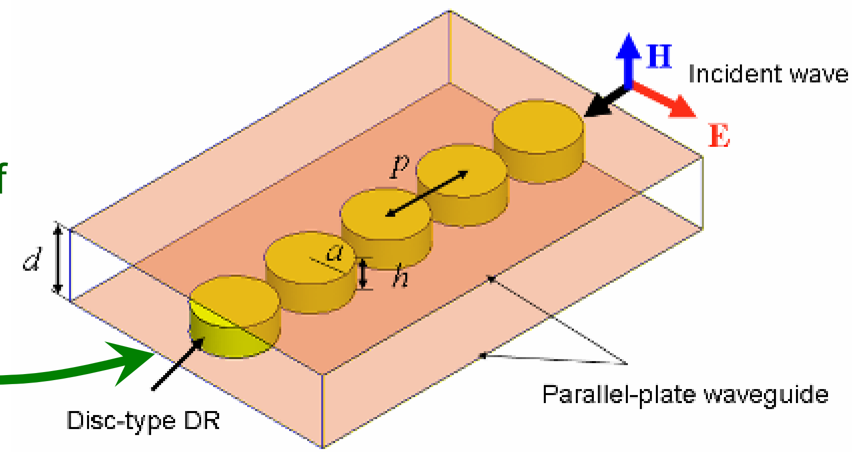
Implementations

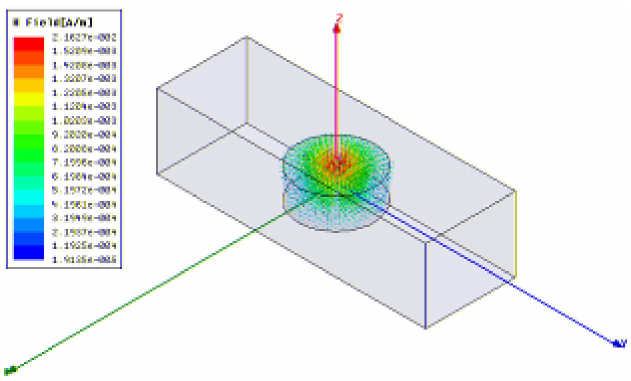
Nano-Metamaterials: optical frequency applications [15]

Evanescent-Mode Metamaterials [16]

1-D LHM: cylindrical DRs in TE mode cutoff parallel plate waveguide (-ε)



H-field Profile ($TE_{01\delta}$ mode, -μ)



Three-Dimensional Metamaterials [17]

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Summary

- Left-Handed Metamaterial Introduction
  - ❖ Resonant approach
  - ❖ Transmission line approach
- Composite Right/Left-Handed Metamaterial
- Metamaterial-Based Microwave Devices
  - ❖ Dominant leaky-wave antenna
  - ❖ Small, resonant backward wave antennas
  - ❖ Dual-band hybrid coupler
  - ❖ Negative refractive index flat lens
- Future Trends

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8) A. Lai, K.M.K.H. Leong, and T. Itoh, "Infinite wavelength resonant antennas with monopolar radiation patterns based on periodic structures," *IEEE Trans. Antennas Propag.,* vol. 55, no. 3, pp. 868-876, Mar. 2007.
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10) A. Lai, "Theory and design of composite right/left-handed metamaterial-based microwave lenses," Master Thesis, Dept. E. E., UCLA, Los Angeles, CA, 2005.
11) Rayspan Corporation, http://www.rayspan.com
12) F. P. Casares-Miranda, C. Camacho Peñalosa, and C. Caloz, "High-gain active composite right/left-handed leaky-wave antenna," *IEEE Trans. Antennas Propag.,* vol. 54, no. 8, pp. 2292-2300, Aug. 2006.
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Design Guide

- Ansoft Designer: 1-D Leaky-Wave Antenna
- Ansoft HFSS: Negative Refractive Index Flat Lens


Chapter 2

Ansoft Designer: Dominant-Mode Leaky-Wave Antenna

Chapter 3

Ansoft HFSS: Negative Refractive Flat Lens