Advances of Composite Right/Left Handed Structures for Microwave Applications

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INTRODUCTION

1. Left-Handed (LH) Metamaterials and Transmission Line Approach
2. Composite Right / Left-Handed (CRLH) Metamaterials
3. Passive Component Applications
4. Antenna Applications
5. Dielectric Resonator Based CRLH
6. SIW based LHM
7. Conclusions

1. Left-Handed (LH) Metamaterials and Transmission Line Approach

Different Approaches of LH Metamaterials

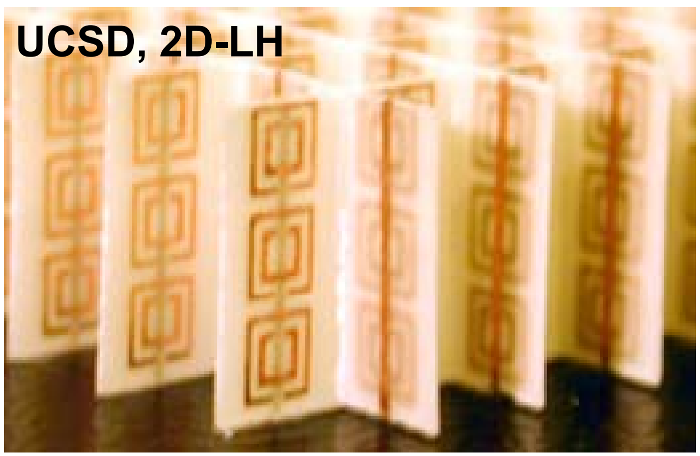
Historical Milestones

- **1968** : theoretical analysis of hypothetical LH materials by **Veselago**
- **1996/9** : introduction of electric (ε<0) / magnetic (μ<0) plasmon by **Pendry**
- **2000** : experimental demonstration of LH structure by **Smith**

LH definition: → **materials with** $\varepsilon < 0 \text{ and } \mu < 0 \;\Rightarrow n < 0 \text{ and } \boxed{v_p - \| v_g}$

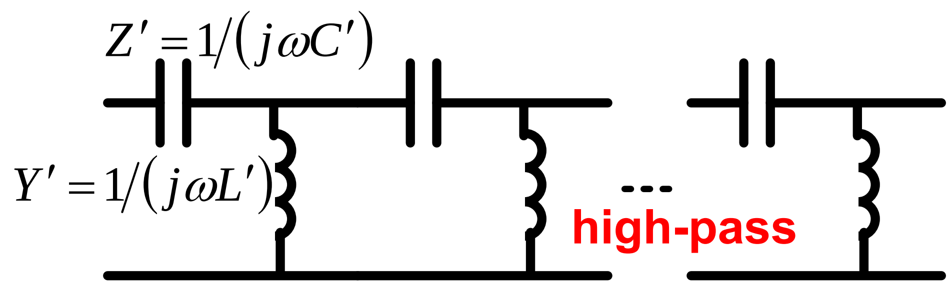
→ **unit-cell << λ → effective / macroscopic / homogeneous**

Resonant Structure Approach



- **approach**: **no simple/rigorous analysis & no design method**
- **structures**: **RESONANT ⇨ lossy & narrow bandwidth & highly dispersive**

Transmission Line Approach



"*BACKWARD WAVES*"

(e.g. Brillouin, Pierce)

- **approach**: **Transmission line analysis & circuit design methods**
- **structures**: ***NON*-RESONANT ⇨ low loss & broad bandwidth & moderate dispersion**

- L. Brillouin, "Wave Propagation in Periodic Structures", Mc Graw Hill, 1946
- J. R. Pierce, "Traveling-Wave Tubes", D. Van Nostrand Company, 1950

Anti-parallel Phase / Group Velocities

- **Definition of LHMs:** $\varepsilon < 0$ and $\mu < 0$ or $v_p = -\| v_g$

$*$ Maxwell: $\nabla \times \vec{E} = -j\omega\vec{B}, \quad \nabla \times \vec{H} = j\omega\vec{D}$

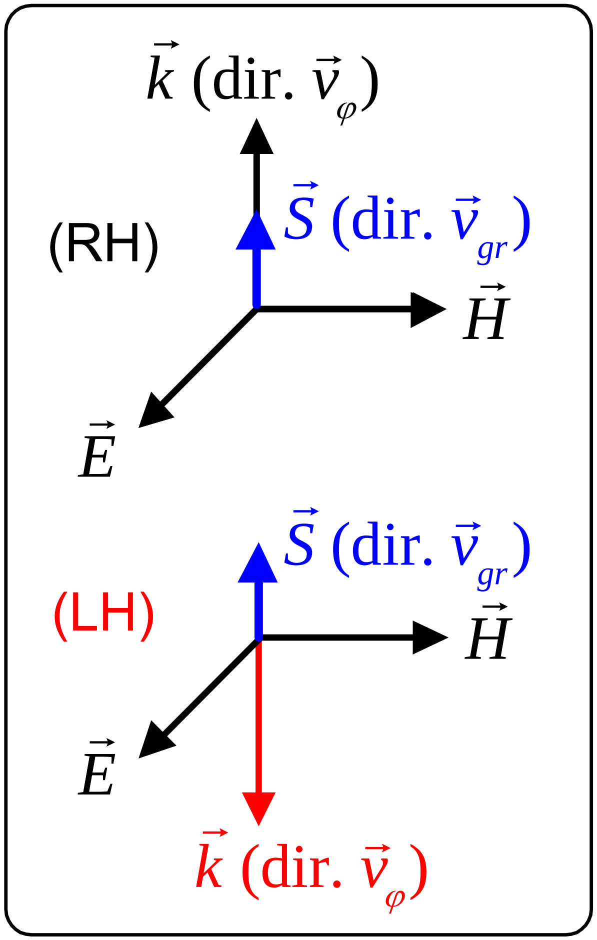
$*$ Plane Wave: $\vec{E} = \vec{E}_0 e^{-j\vec{k}\cdot\vec{r}}, \quad \vec{H} = \vec{H}_0 e^{-j\vec{k}\cdot\vec{r}}$

$*$ Then, the $\left(\vec{E}, \vec{H}, \vec{k}\right)$ triad becomes

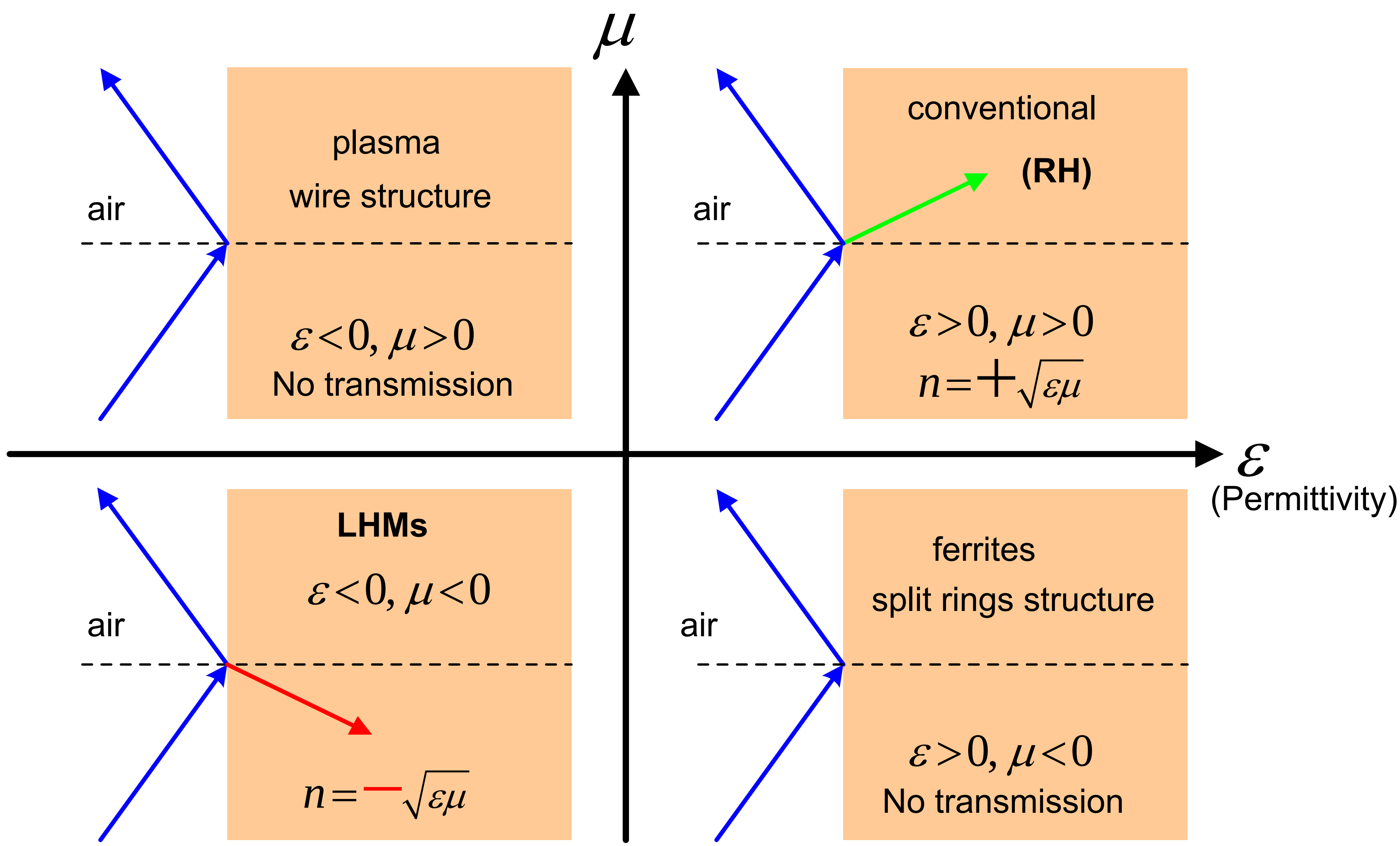
$$\boxed{\vec{k} \times \vec{E}} = \omega\vec{B} = \begin{cases} +\omega|\mu|\vec{H}, & \text{if} \quad \mu > 0 \quad (\text{RH}), \\ \boxed{-\omega|\mu|\vec{H}}, & \text{if} \quad \mu < 0 \quad (\text{LH}), \end{cases}$$

$$\boxed{\vec{k} \times \vec{H}} = -\omega\vec{D} = \begin{cases} -\omega|\varepsilon|\vec{E}, & \text{if} \quad \varepsilon > 0 \quad (\text{RH}), \\ \boxed{+\omega|\varepsilon|\vec{E}}, & \text{if} \quad \varepsilon < 0 \quad (\text{LH}). \end{cases}$$

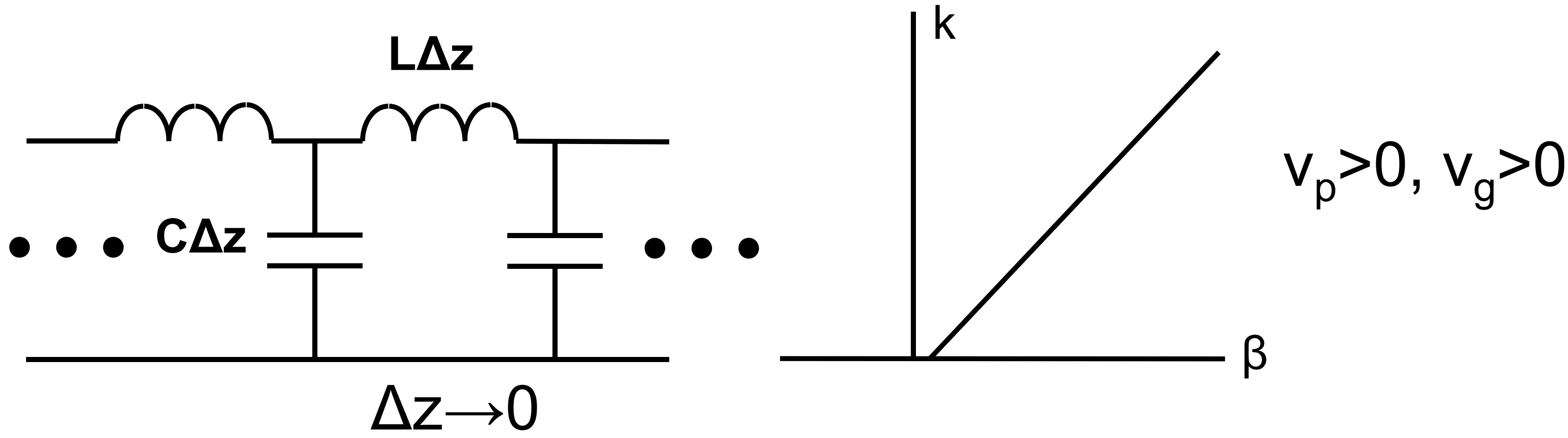
$*$ Poynting Vector: $\vec{S} = \vec{E} \times \vec{H}^* \quad (RH)$

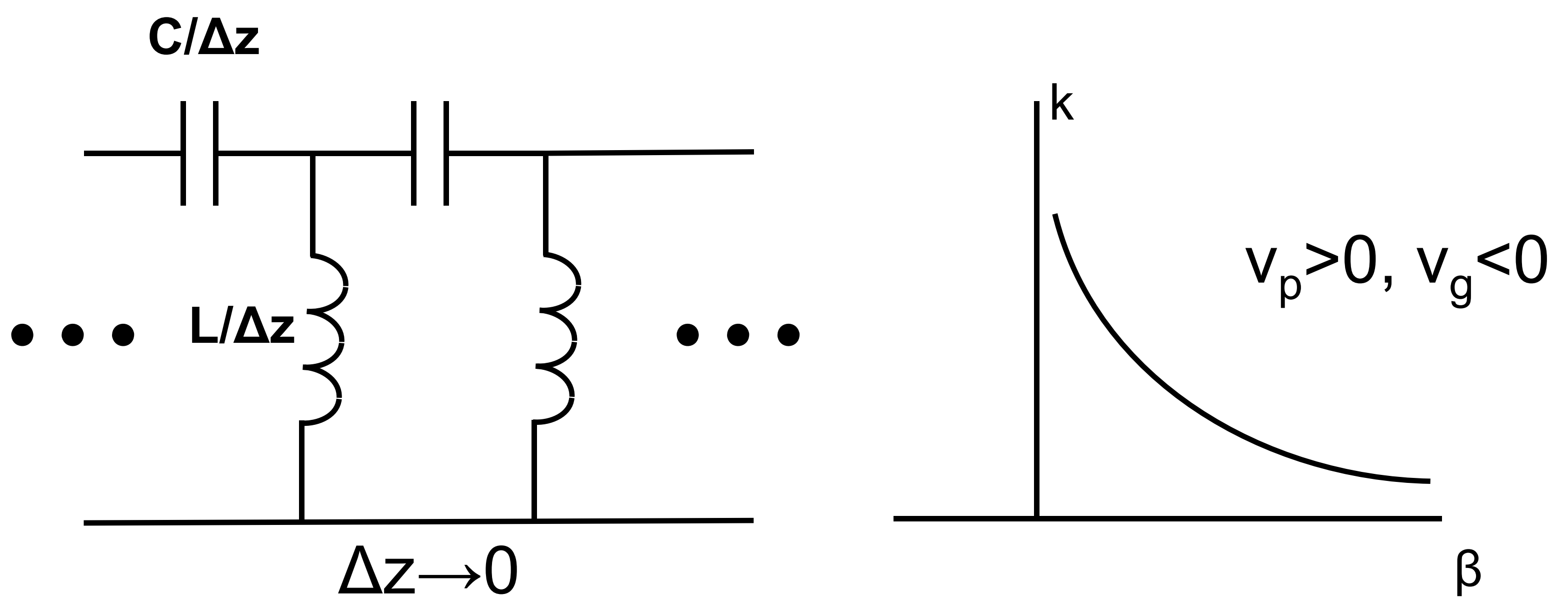


General Classifications of Material Based on (ε,μ)



Distributed Model of Transmission Line LH structure

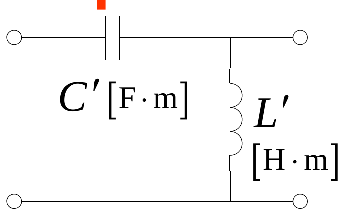




LH TL Material Constitutive Parameters

- **Mapping Maxwell to Telegrapher's eqs :** $\mu = \frac{Z'}{j\omega}$ $\varepsilon = \frac{Y'}{j\omega}$

- **LH TL parameters:** $Z' = 1/(j\omega C')$ $Y' = 1/(j\omega L')$



$$\gamma \overset{\text{lossless}}{=} j\beta = \sqrt{Z'Y'}$$

- **Dispersive ε & μ: *non-resonant***

$$\mu = -1/(\omega^2 C') < 0 \ !$$

$$\varepsilon = -1/(\omega^2 L') < 0 \ !$$

- **Dispersive *n*:**

$$n = \sqrt{\varepsilon_r \mu_r} = \frac{c_0}{\omega}\beta = \frac{c_0}{\omega}\frac{\sqrt{Z'Y'}}{j} = -\frac{c_0}{\omega^2\sqrt{L'C'}} < 0 \ !$$

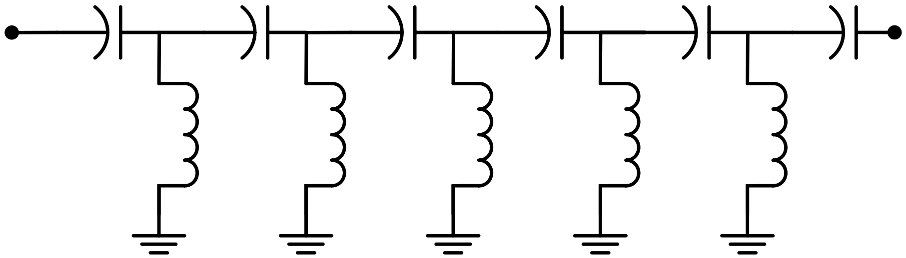
- **Entropy Conditions:**

$$W = \frac{\partial(\omega\varepsilon)}{\partial\omega}E^2 + \frac{\partial(\omega\mu)}{\partial\omega}H^2 > 0 \Bigg\} \Rightarrow \begin{cases} \frac{\partial(\omega\varepsilon)}{\partial\omega} = \frac{1}{L'} > 0 \\ \frac{\partial(\omega\mu)}{\partial\omega} = \frac{1}{C'} > 0 \end{cases}$$

Realization of 1D LH TLs

Lumped Element Implementation

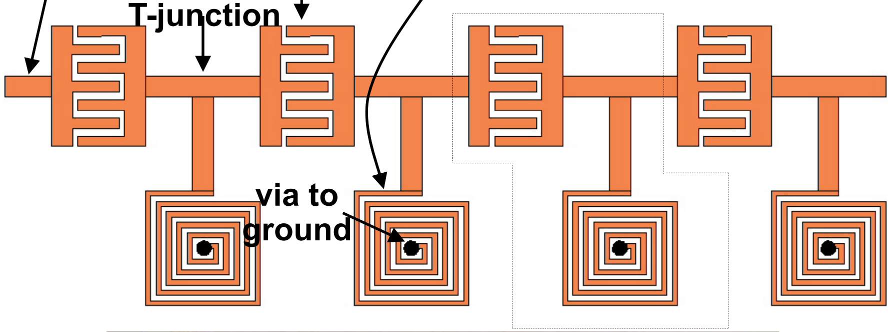
Ideal Elements

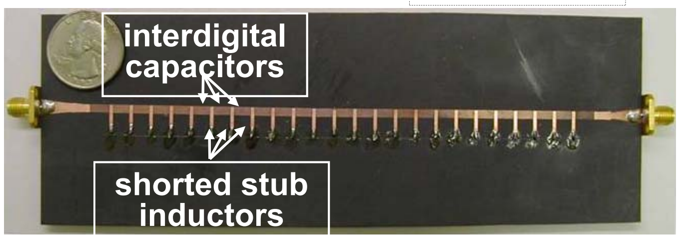


Chip Components

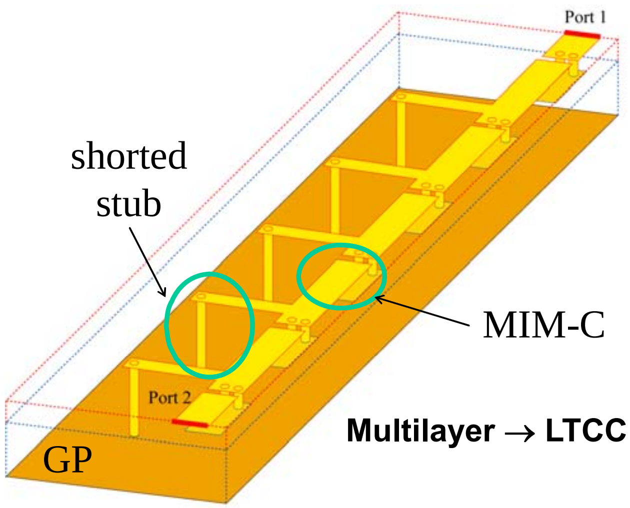
Distributed Implementation (Microstrip)

Interdigital *C* & spiral / stub *L*





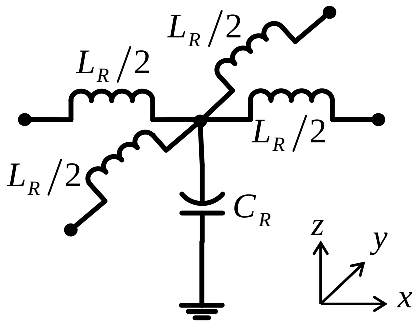
Interdigital *C* & stub *L*



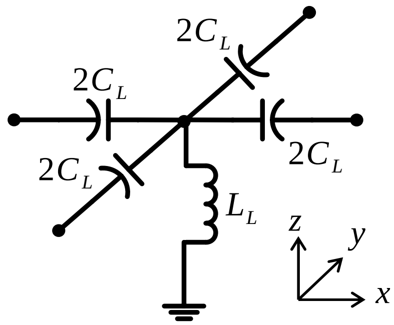
Realization of 2D Metamaterials

2D Lumped Element Structure: Meta-Circuit ("closed")

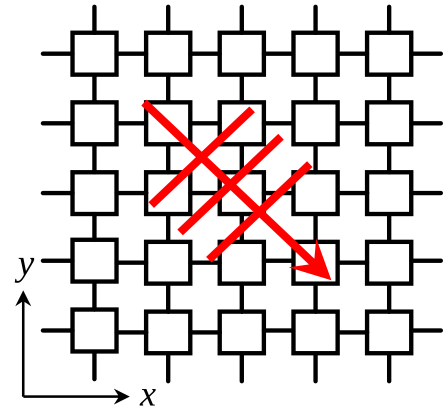
RH



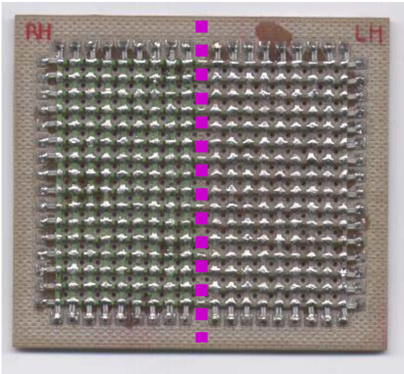
LH



2D interconnection

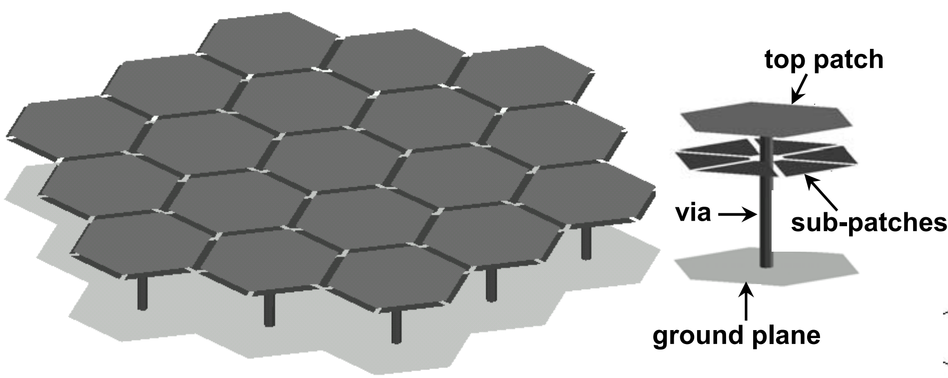


Chip Implementation

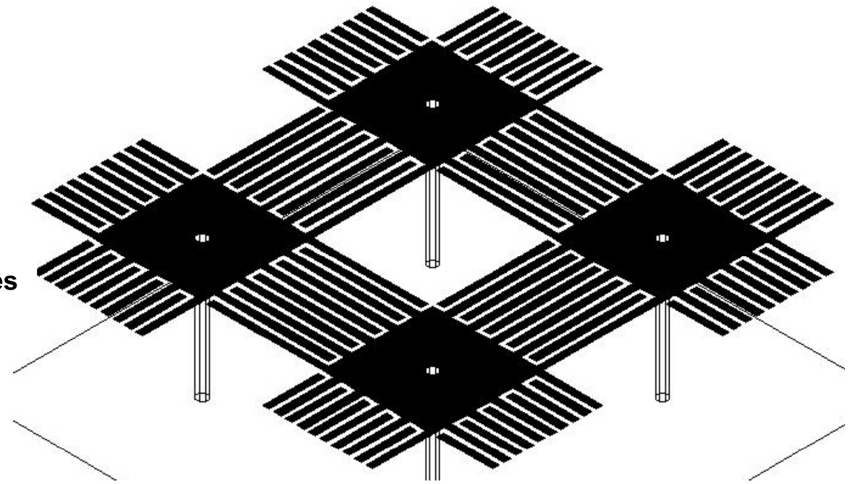


2.5D Textured Structure: Meta-Surface ("open")

Enhanced Mushroom Structure



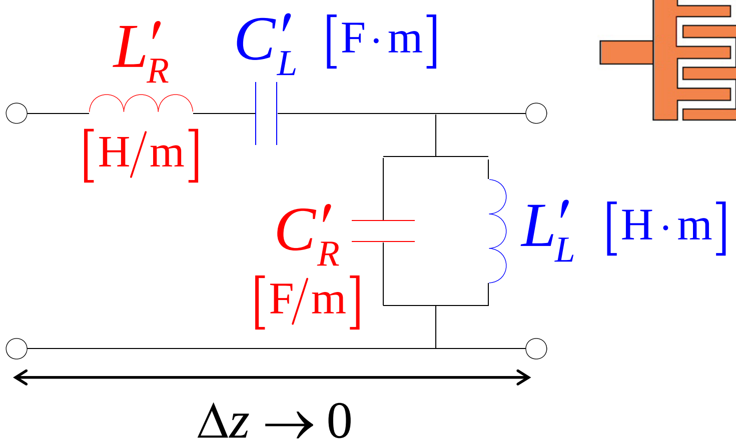
Uniplanar Interdigital Structure

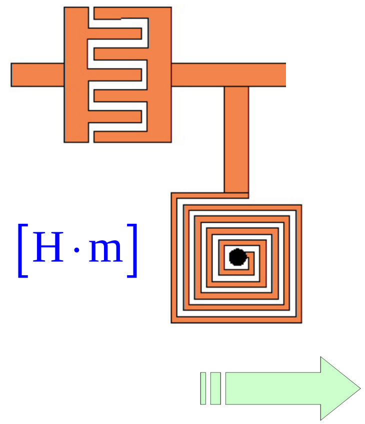


2. Composite Right / Left-Handed (CRLH) Metamaterials

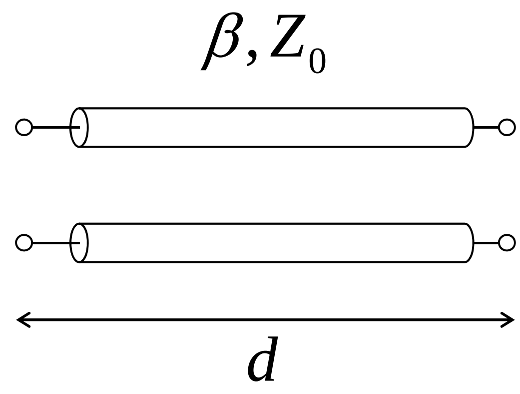
Ideal Composite Right / Left-Handed (CRLH) TL

Infinitesimal Circuit Model





Transmission Line Representation



Propagation Constant

$$\gamma = j\beta = \sqrt{Z'Y'}, \quad \text{where}$$

$$Z' = j\omega L_R' + \frac{1}{j\omega C_L'}, \quad Y' = j\omega C_R' + \frac{1}{j\omega L_L'}$$

$$\Downarrow$$

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

Balanced Case

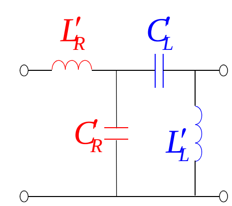
$$\text{Definition: } L_R' C_L' = L_L' C_R' = L' C'$$

$$\downarrow$$

$$\beta = \sqrt{\omega^2 L_R' C_R' + \frac{1}{\omega^2 L_L' C_L'} - 2}$$

$$= \omega\sqrt{L_R' C_R'} - \frac{1}{\omega\sqrt{L_L' C_L'}}$$

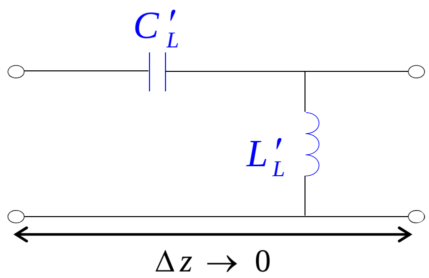
$$= \beta_{RH} + \beta_{LH}$$



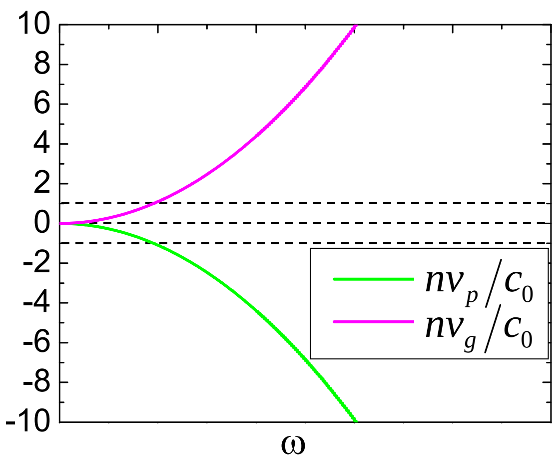
$$s(\omega) = -1 \text{ if } \omega < \omega_{\Gamma 1} = \min\left(\frac{1}{\sqrt{L_R C_L}}, \frac{1}{\sqrt{L_L C_R}}\right) \text{ and } +1 \text{ if } \omega > \omega_{\Gamma 2} = \max\left(\frac{1}{\sqrt{L_R C_L}}, \frac{1}{\sqrt{L_L C_R}}\right)$$

Phase/Group Velocities: No Physical Law Violation

Pure LH TL

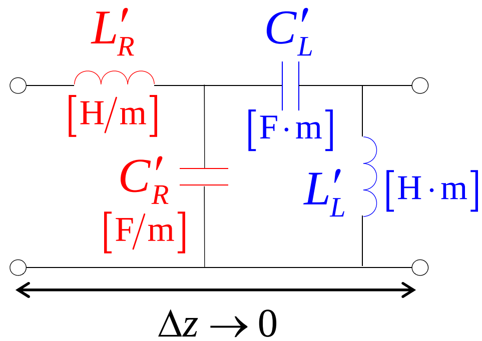


$$\beta = -\frac{1}{\omega^2 L'C'}$$



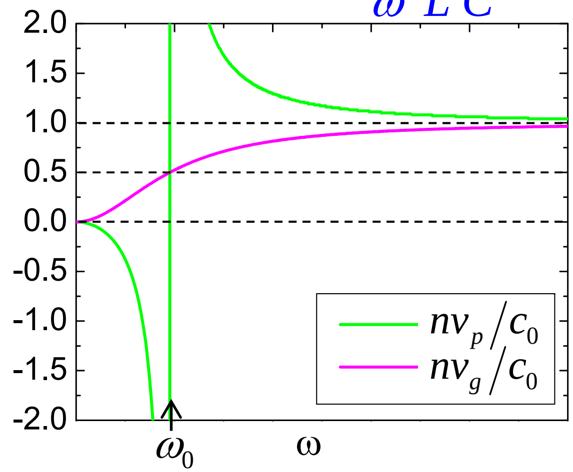
$v_g(\omega \to \infty) = \infty$: not physical!

Balanced CRLH TL



balanced: $L'_R C'_L = L'_L C'_R = L'C'$

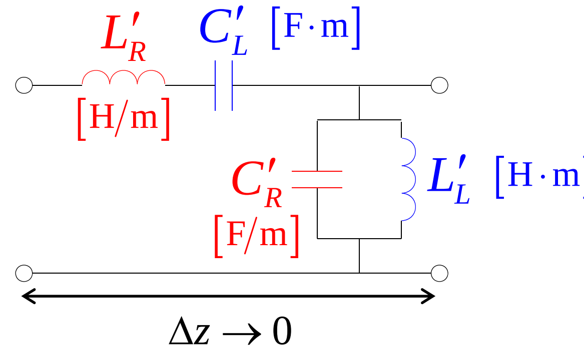
$$\beta = \omega^2 L'C' - \frac{1}{\omega^2 L'C'}$$



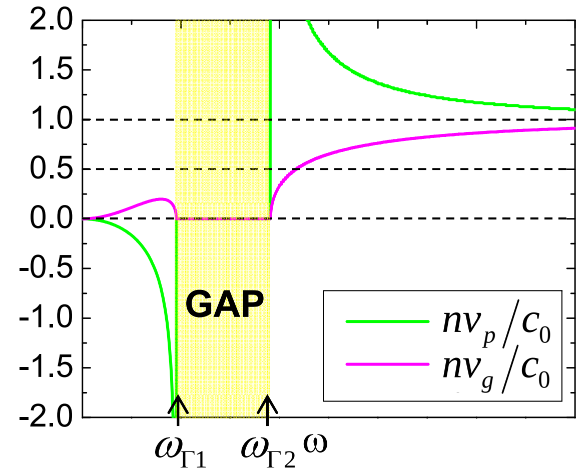
$v_g(\omega \to \infty) = c_0/n$

$v_g(\omega \to \omega_0) = c_0/(2n)$

Unbalanced CRLH TL



$$|\beta| = \sqrt{\omega^2 L'_R C'_R + \frac{1}{\omega^2 L'_L C'_L} - \left(\frac{L'_R}{L'_L} + \frac{C'_R}{C'_L}\right)}$$



$v_g(\omega \to \infty) = c_0/n$

Dispersion Diagram and Group Velocity (CRLH)

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

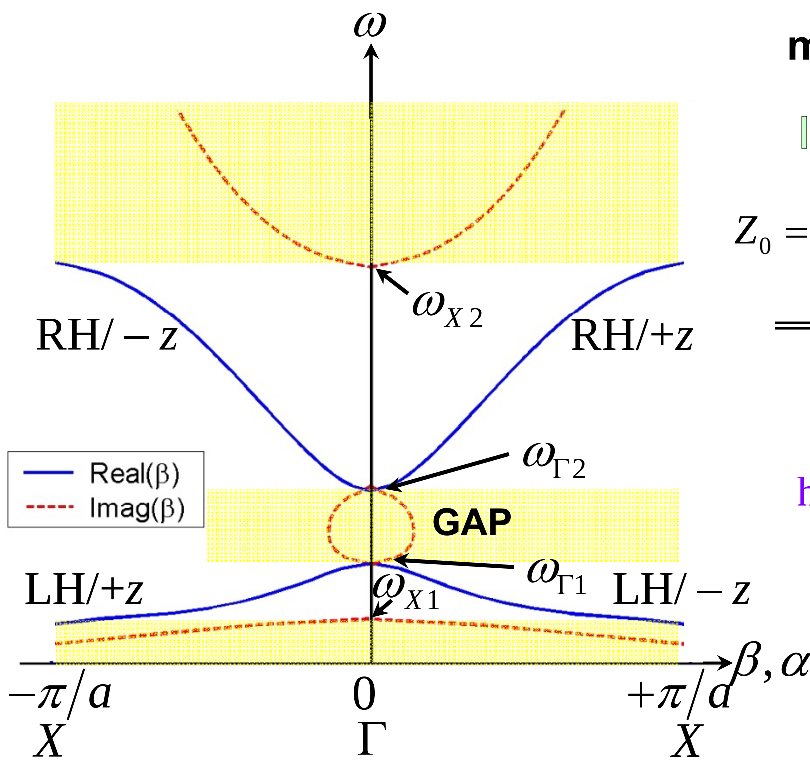
$$v_g = -\frac{a^2 \sin(\beta a)}{\left(\frac{1}{\omega^3 L_L C_L} - \omega L_R C_R\right)}$$

$$\Gamma: \ \omega_{\Gamma 1} = \frac{1}{\sqrt{L_R C_L}}, \quad \omega_{\Gamma 2} = \frac{1}{\sqrt{L_L C_R}}$$

$$X: \ \left.\begin{matrix}\omega_{X1}^2 \\ \omega_{X2}^2\end{matrix}\right\} = \sqrt{\frac{\omega_{01}^2 + \omega_{02}^2}{2} + 2\omega_R^2 \mp \left\{\left(\frac{\omega_{01}^2 + \omega_{02}^2}{2} + 2\omega_R^2\right)^2 - \omega_{01}^2\omega_{02}^2\right\}^{\frac{1}{2}}}$$

unbalanced: $L_R C_L \neq L_L C_R \rightarrow |v_{g\Gamma}| = 0$

balanced: $L_R C_L = L_L C_R \rightarrow |v_{g\Gamma}| = \frac{1}{2a\sqrt{L_R C_R}} \neq 0$!

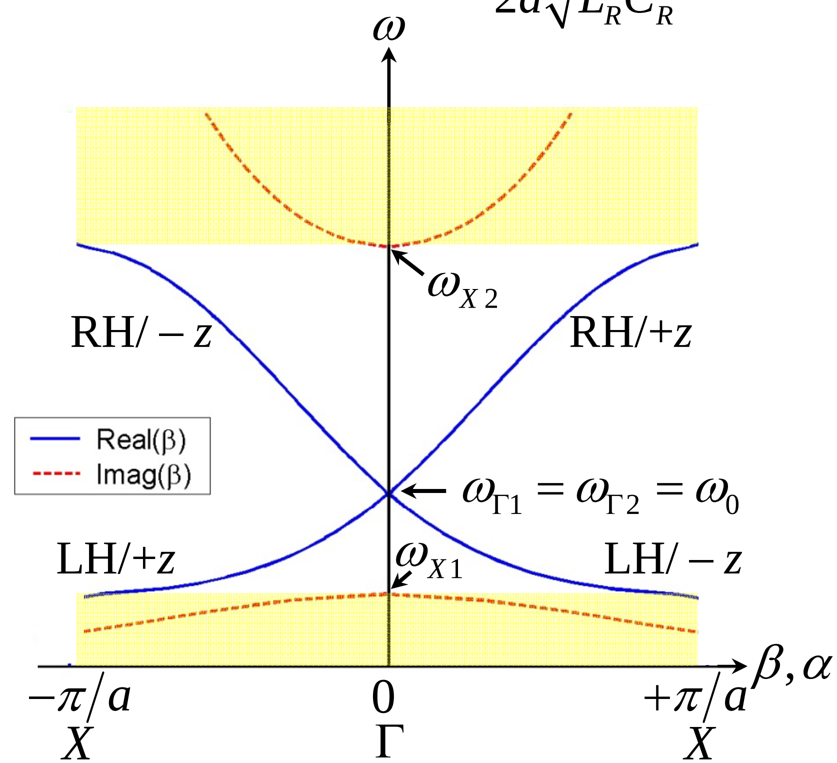


matching

$$Z_0 = \sqrt{\frac{L_R}{C_R}} = \sqrt{\frac{L_L}{C_L}}$$

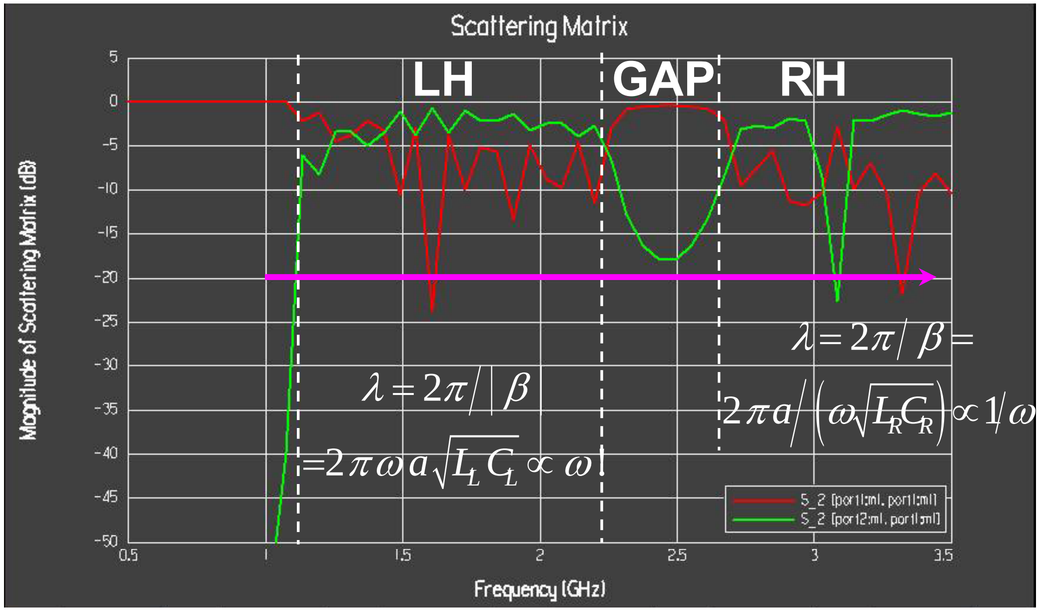
$$\left.\frac{a}{\lambda}\right]_\Gamma = 0$$

homogeneous
isotropic

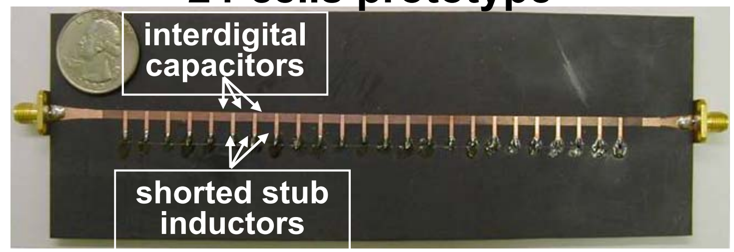


Guided Wavelength along a CRLH-TL

Full-wave simulations (HFSS)

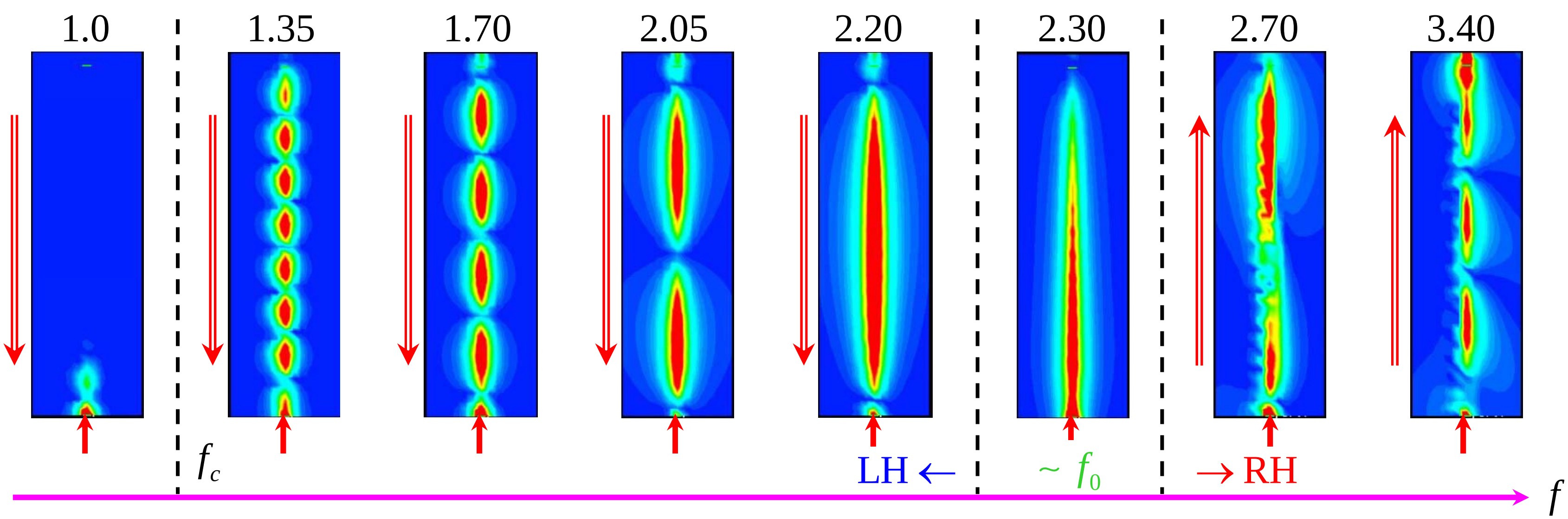


24-cells prototype



Characteristics

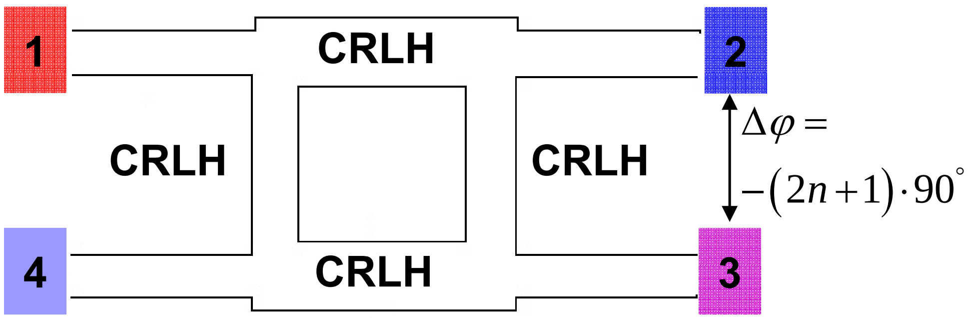
- **LH / RH range: backward / forward propagation verified**
- **λ_g proportional ω in LH range and to $1/\omega$ in RH range verified**

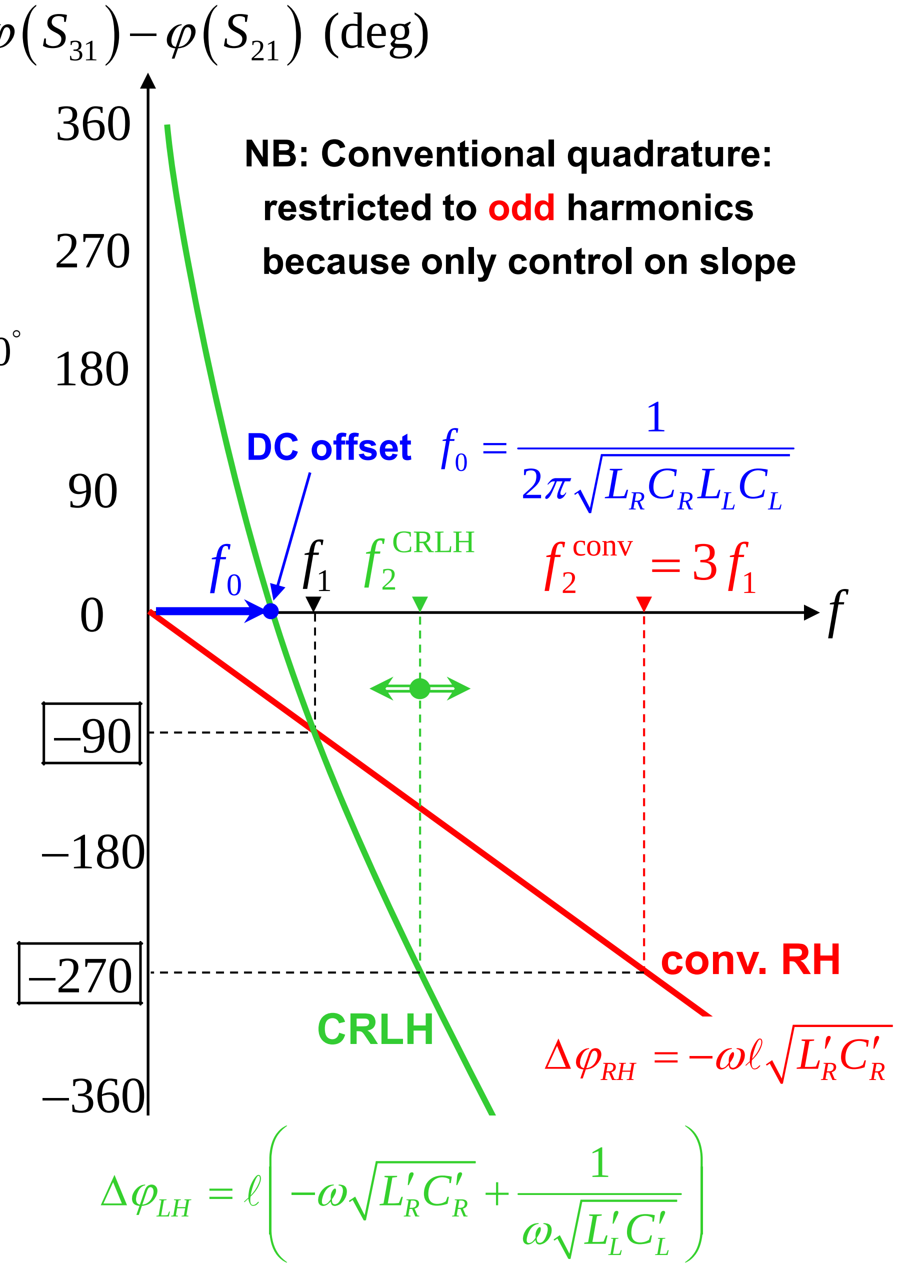


3. Passive Component Applications

Dual-Band Components, E.g.: Quadrature Hybrid

CRLH / CRLH hybrid





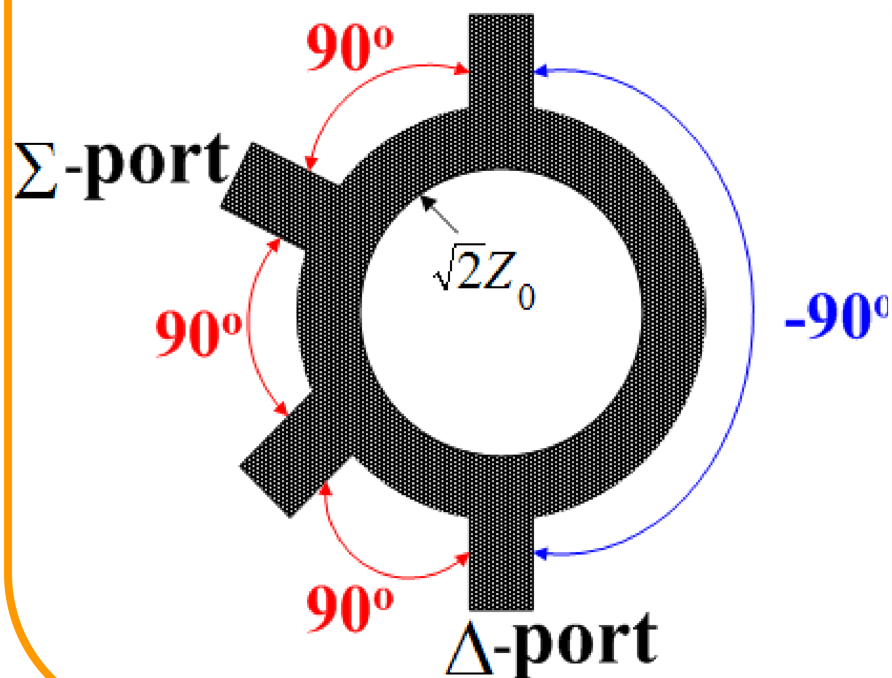
Dispersion Engineering:

- dual-band functionality for an arbitrary pair of frequencies f_1, f_2
- principle: transition freq. (LH-RH) provides *DC offset* additional degree of freedom with respect to the *phase slope* $\varphi(S_{31}) - \varphi(S_{21})$
- BW does not become narrower!
- applications in multi-band systems
- can be extended to many components

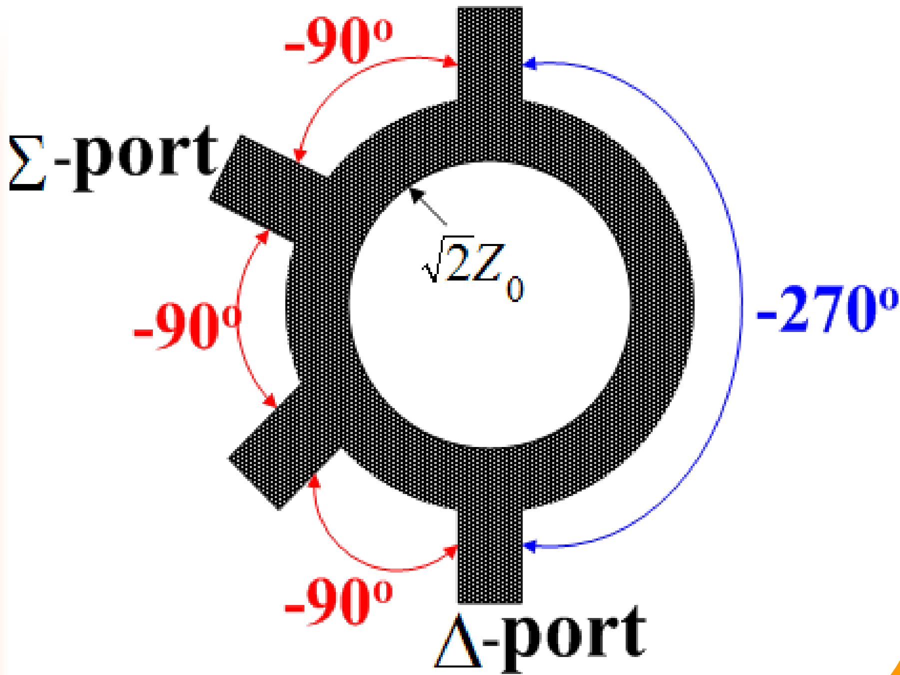
Optimal solution

- **Besides the consideration for minimal length of each CRLH TL, what else needs to be considered?**
  - **Bandwidth**

The final solution: #4

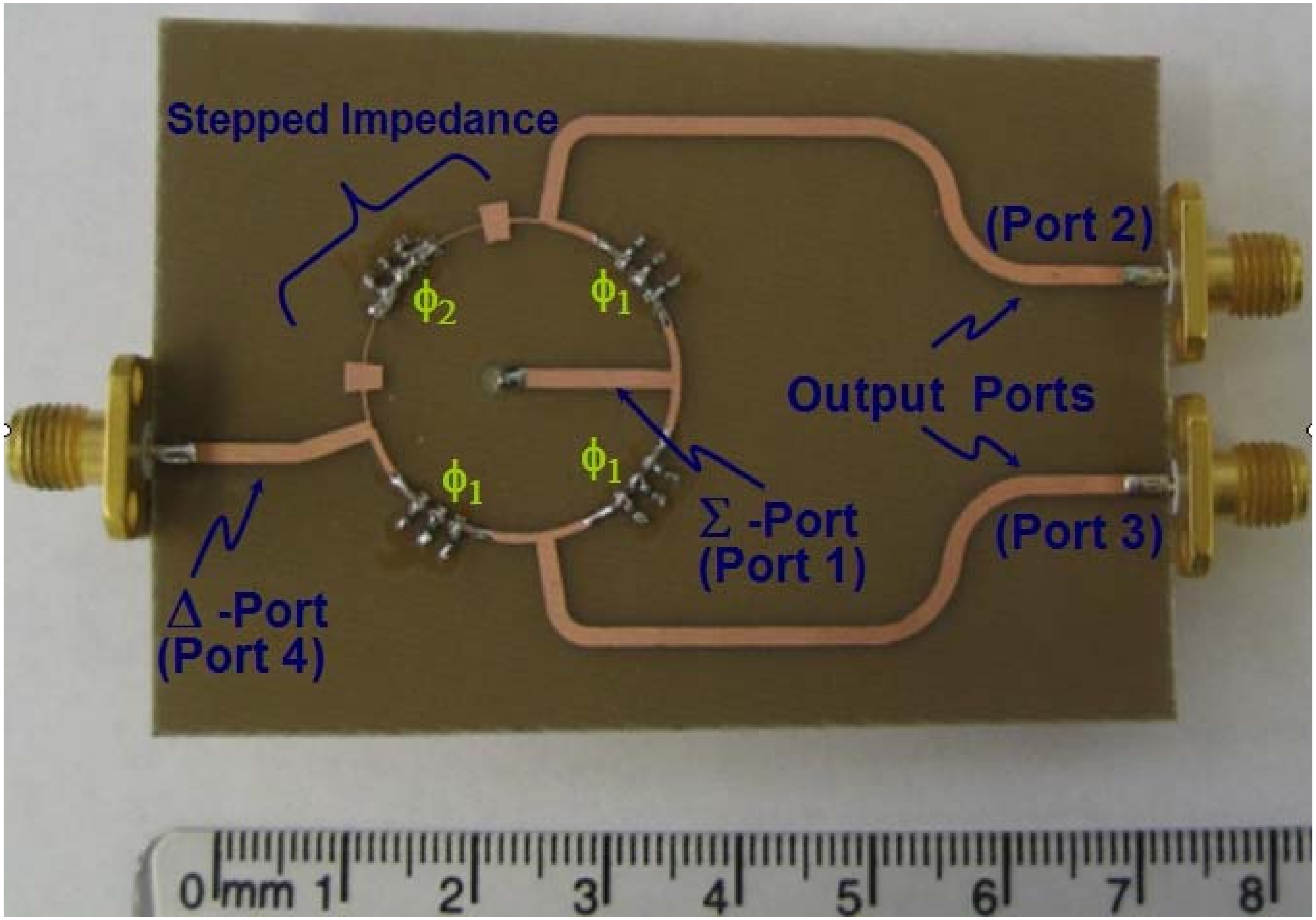


@ 2.4GHz (f_1)



@ 5.2GHz (f_2)

Experiment



Stepped Impedance
ϕ2
ϕ1
ϕ1
ϕ1
(Port 2)
Output Ports
(Port 3)
Σ -Port
(Port 1)
Δ -Port
(Port 4)
0 mm 1 2 3 4 5 6 7 8

Summary of performance

- ***55% size reduction*** **compared to the conventional rat-race coupler at 2.4GHz**

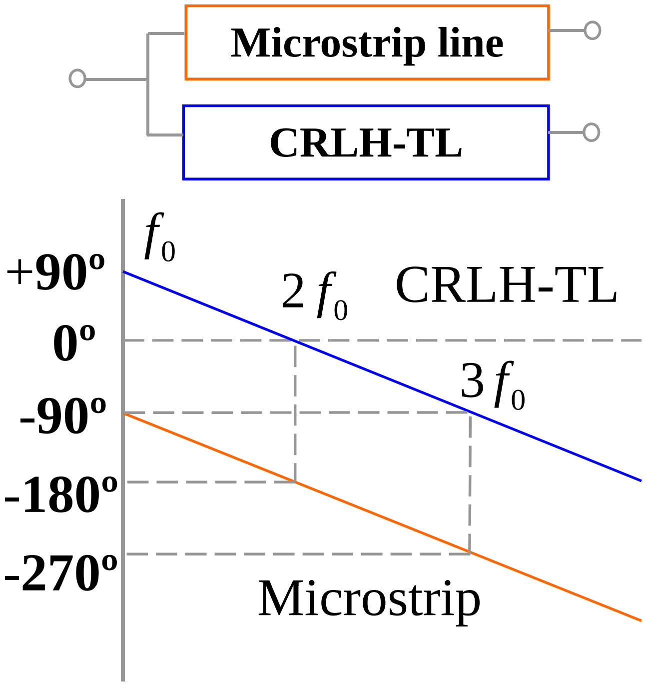
Σ–port Measurement

Measurement		
Operating Frequency	2.4 GHz	5.2 GHz
Isolation	**-29.97 dB**	**-22.11dB**
BW_{20dB} (below 20 dB)	**154.17 %**	**71.15 %**
Magnitude Imbalance	**0.21 dB**	**0.44 dB**
$BW_{1.5dB}$	**62.5 %**	**44.23 %**
Phase Imbalance	**4.3°**	**1.9°**
BW_{10^o}	**52.08 %**	**45.44 %**

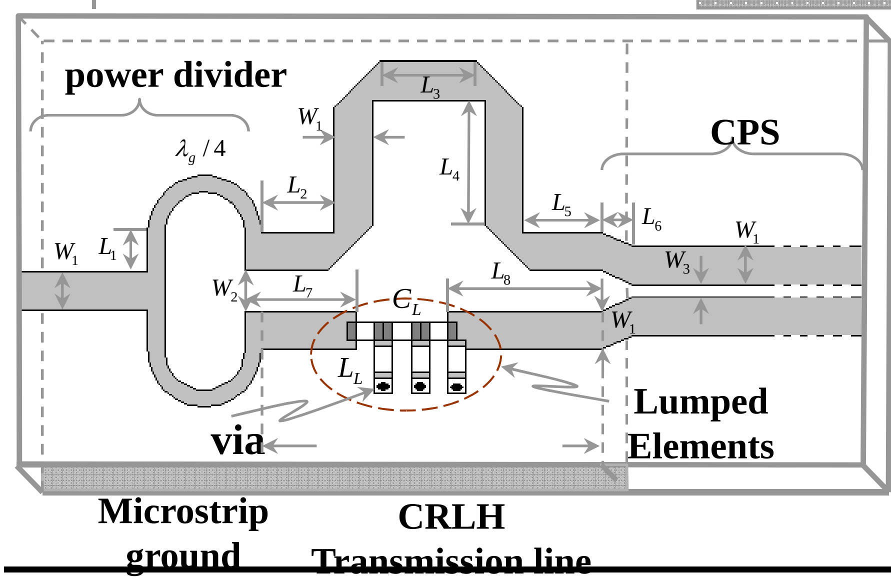
Δ–port Measurement

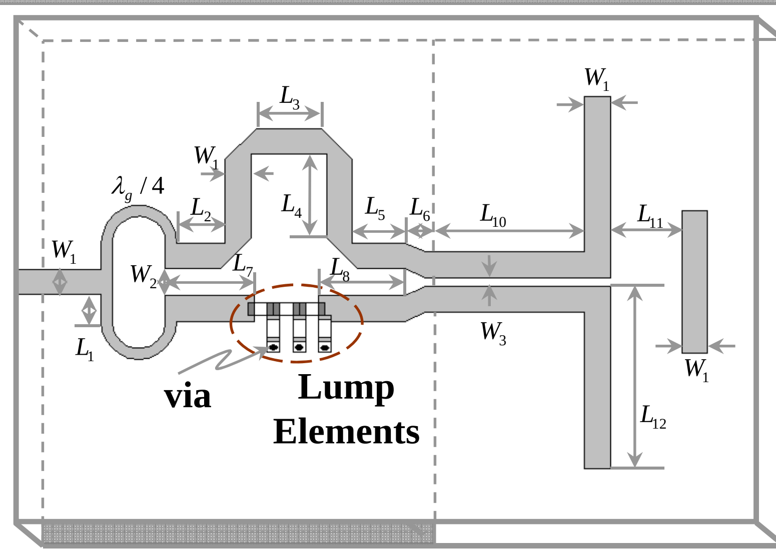
Measurement		
Operating Frequency	2.4 GHz	5.2 GHz
Isolation	**-29.97 dB**	**-22.11dB**
BW_{20dB} (below 20 dB)	**154.17 %**	**71.15 %**
Magnitude Imbalance	**0.41 dB**	**1.03 dB**
$BW_{1.5dB}$	**45.83 %**	**32.69 %**
Phase Imbalance	**185.3°**	**179°**
BW_{10^o}	**58.88 %**	**31.71 %**

Broadband Microstrip-to-CPS Transition and its Antenna Application



- **Using unique phase slope and phase control prosperities of CRLH TL. to have broadband out of phase characteristic. (Dispersion Engg)**
- **85% back-to-back transition.**
- **65% bandwidth of Quasi-Yagi antenna (~15% enhancement)**



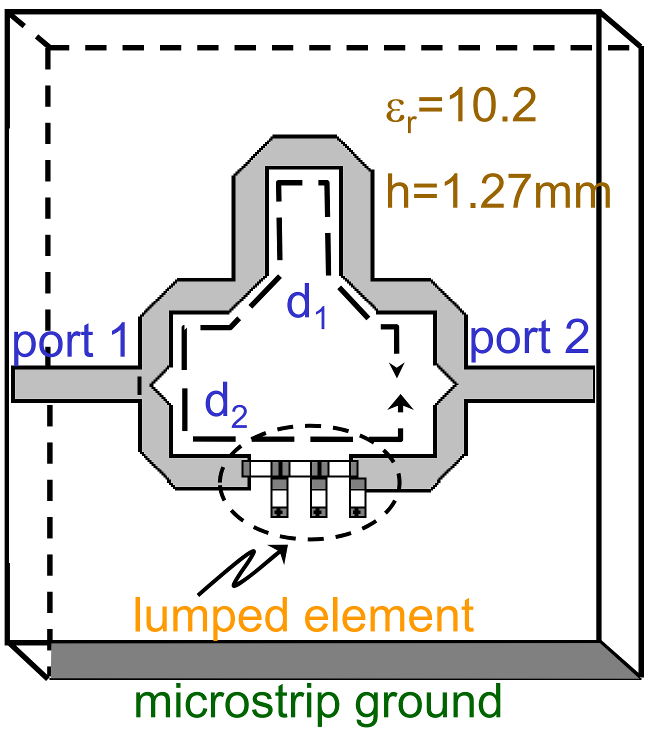


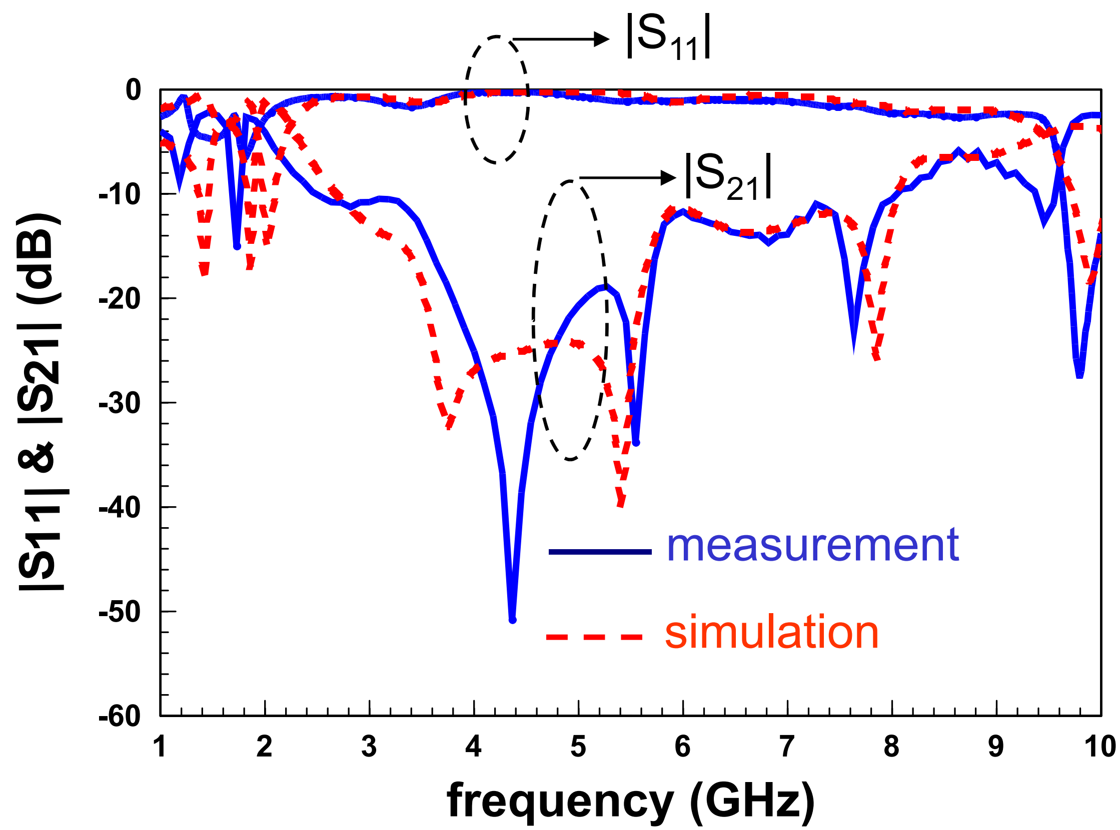
Broadband BSF Measured Results

3dB insertion loss BW : 130% (2GHz~9.6GHz)

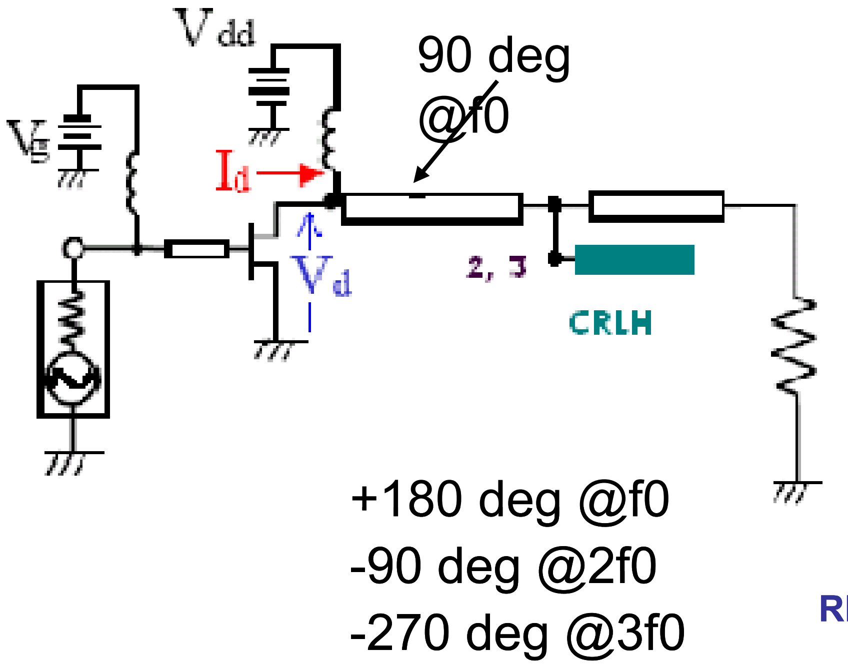
10dB signal rejection BW : 78% (3GHz~8GHz)

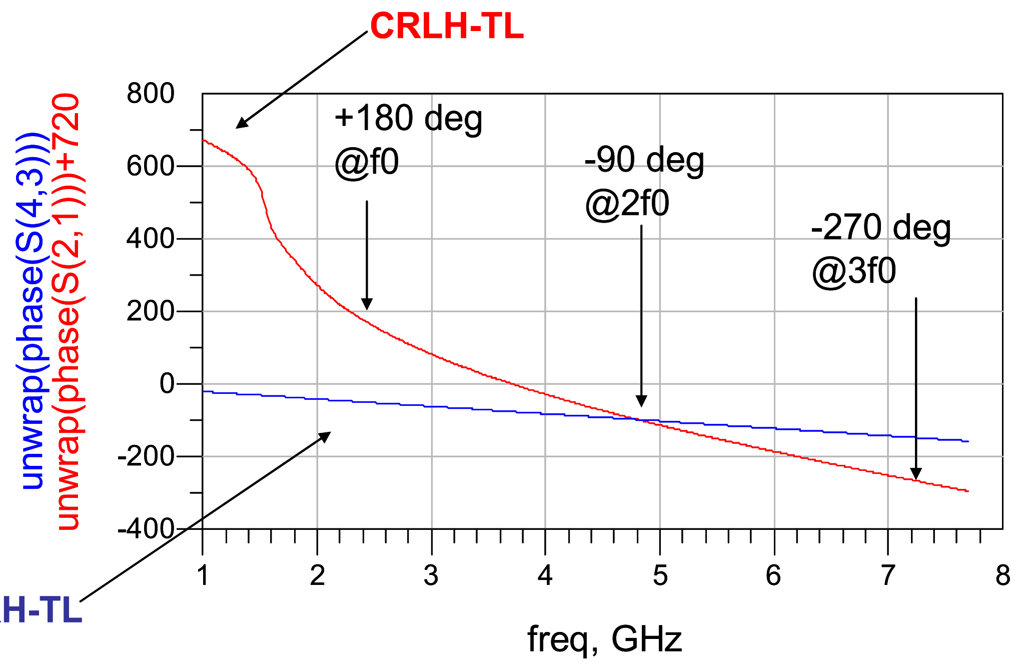
Next passband at higher frequency end with minimum insertion loss of -1.7dB @ 9.8GHz





CRLH Harmonic Tuning Approach



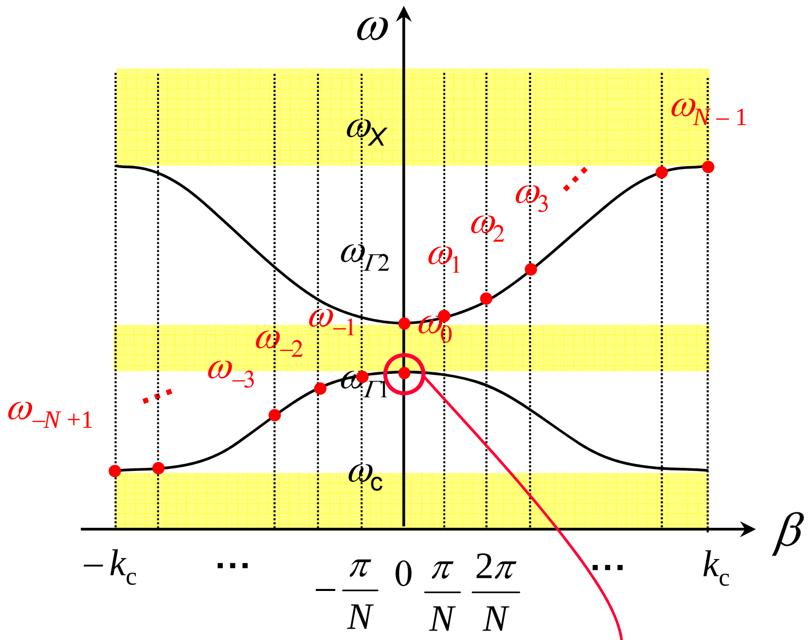


- Single CRLH-TL for two harmonics (Dispersion Engineering)
- Reduced number of stubs leads to: Compact circuit size, Reduced associated loss

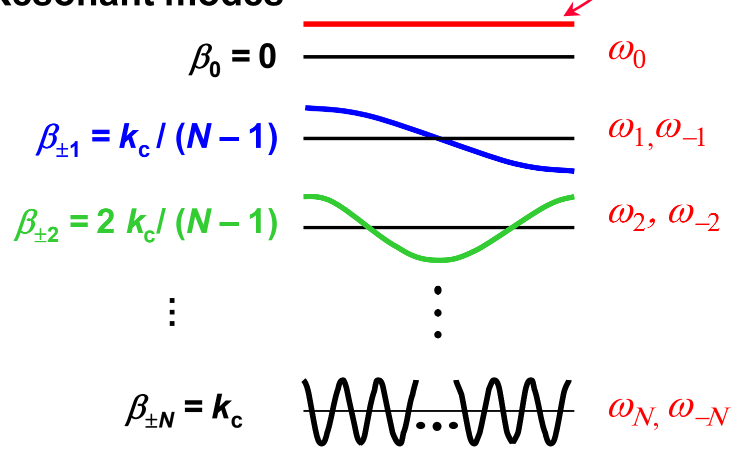
f=2.4 GHz	**P_{1dB}**	**P.A.E**
Class F	24 dBm	63%

Zeroth Order CRLH Resonator

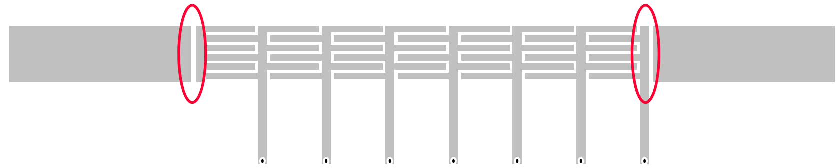
Dispersion diagram



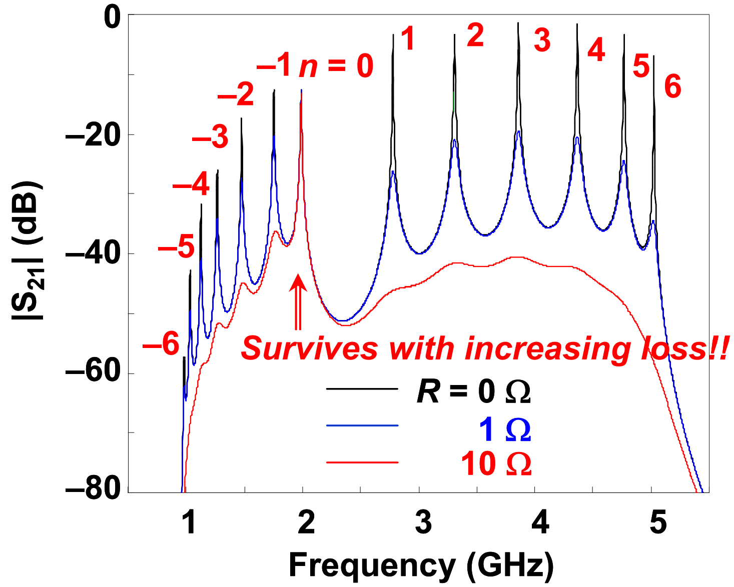
Resonant modes



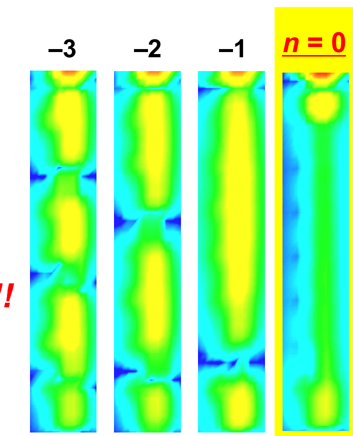
7 cell CRLH resonator



Resonance characteristics



Field distribution

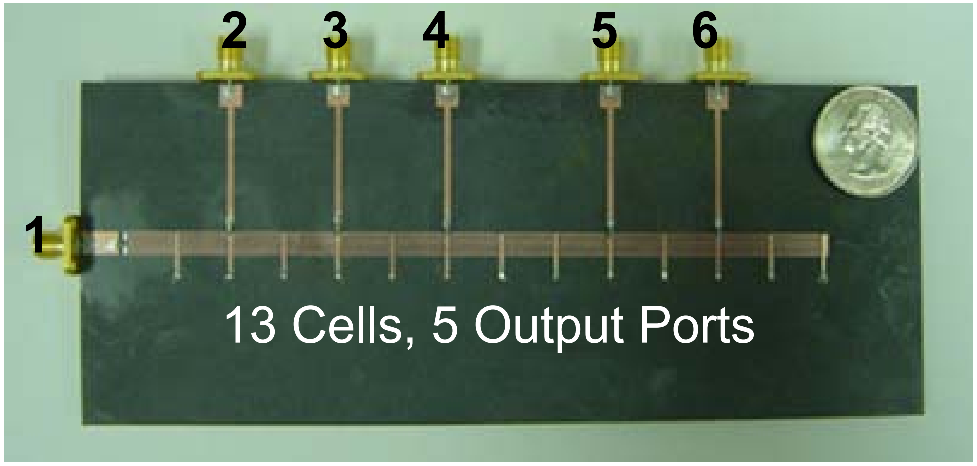


- n=0: no dependence on physical size

⇨ supercompact resonator

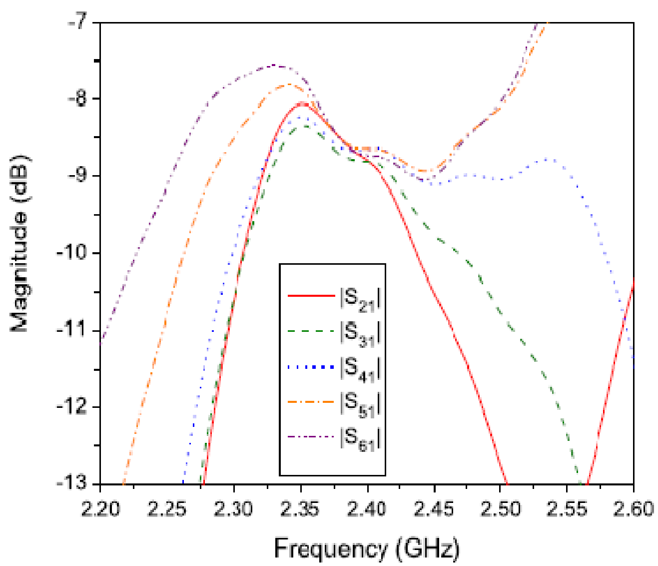
- Initial prototype: more than 2x size reduction and experimental Q_0 = 290 !

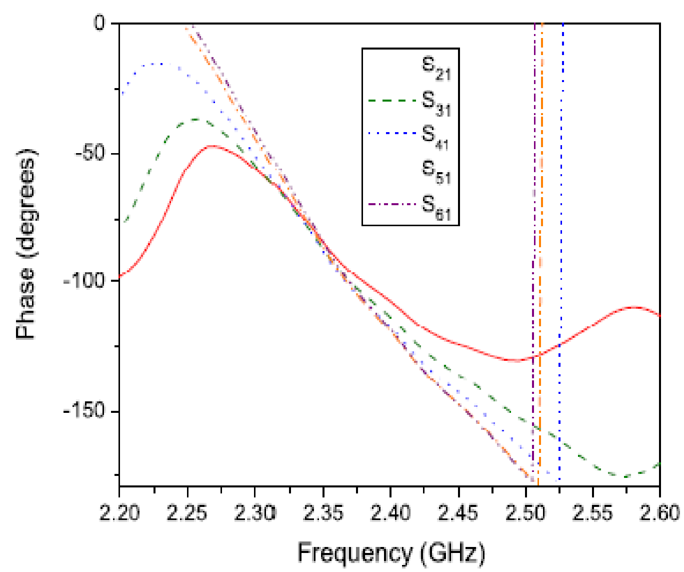
N-Port In-Phase Series Divider Based on Infinite Wavelength



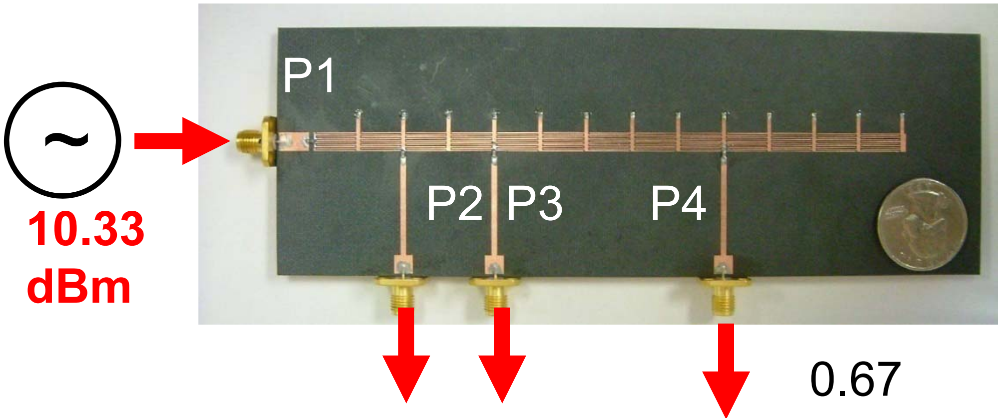
f_∞=2.37 GHz

Experimental Results

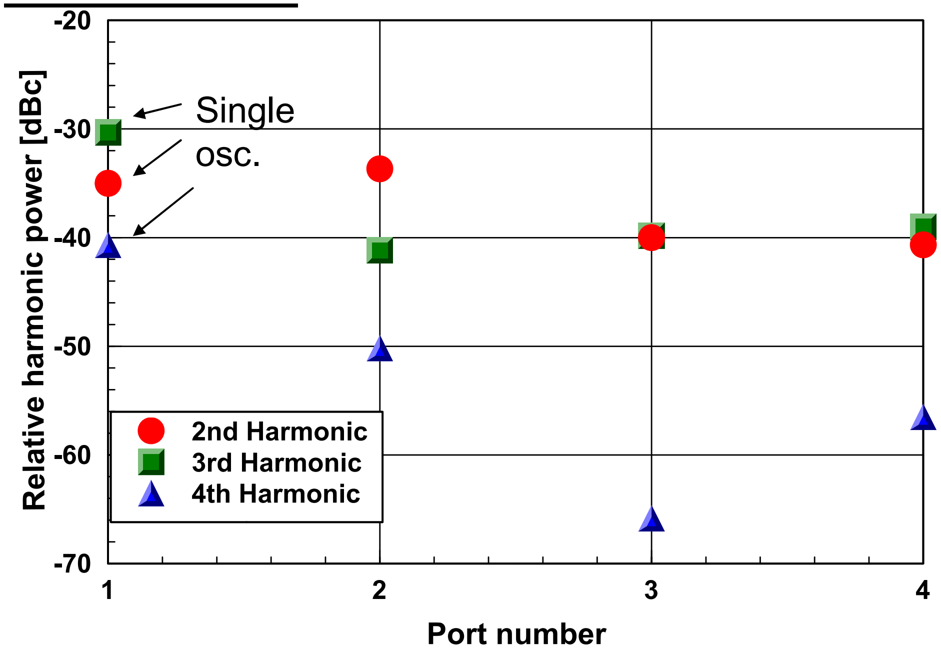




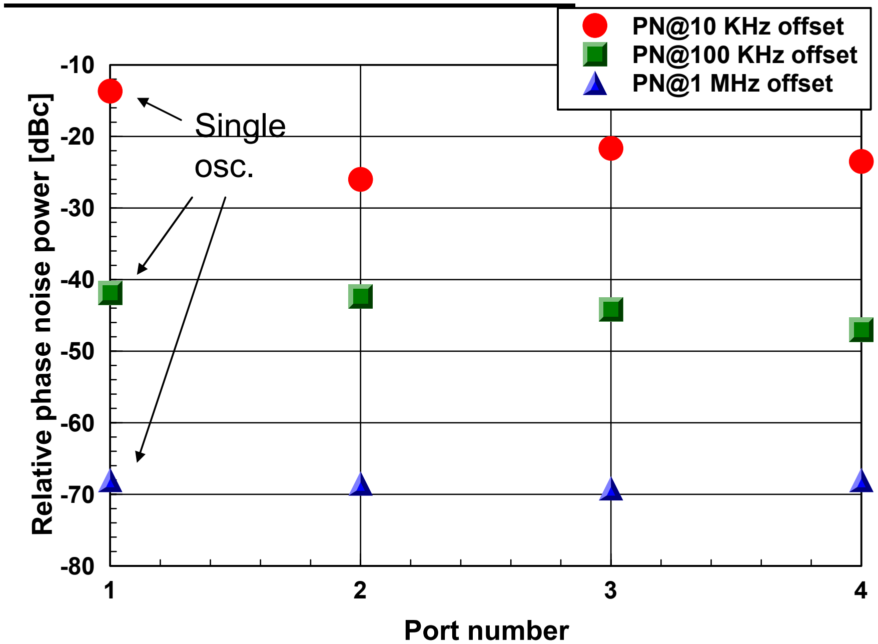
Power Dividing (APMC 2005)



Harmonic measurement

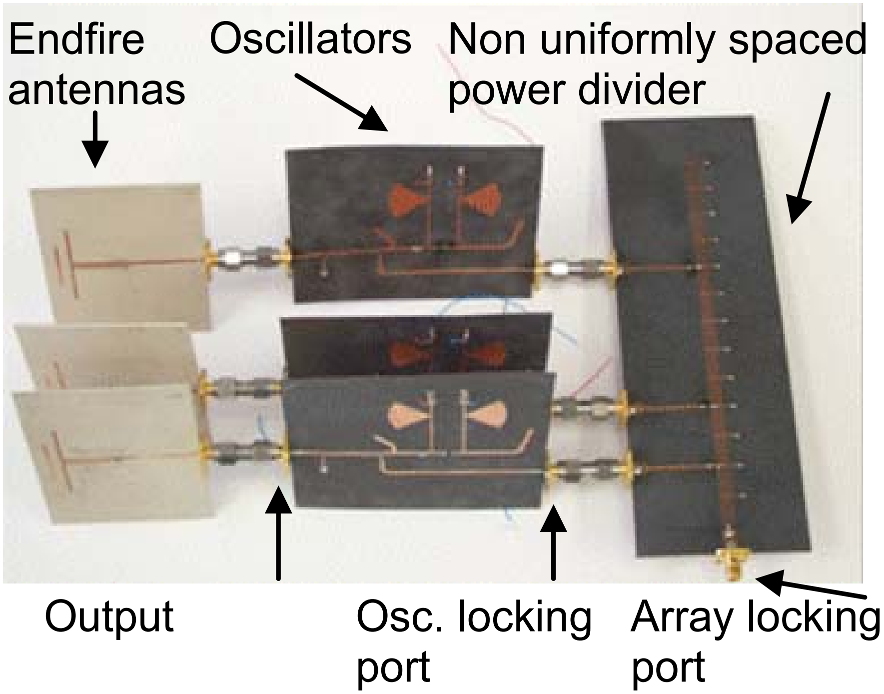


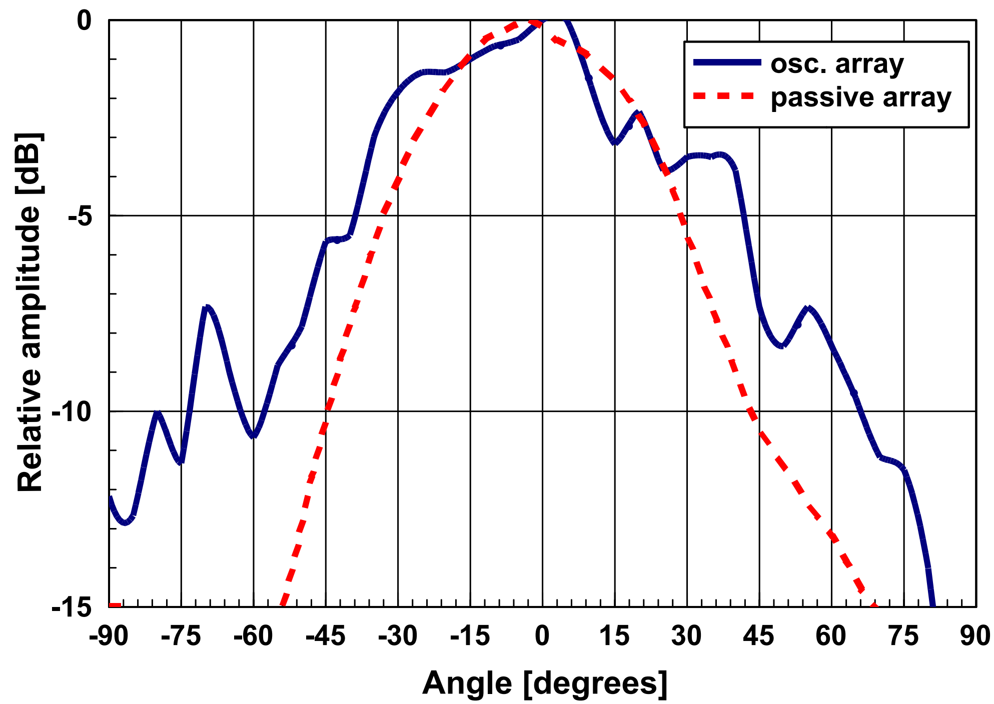
Phase noise measurement



- **Equal amplitude distribution observed**
- **Harmonic suppression observed**
- **Reduction in phase noise**

Free Space Power Combining Using Metamaterial Coupler





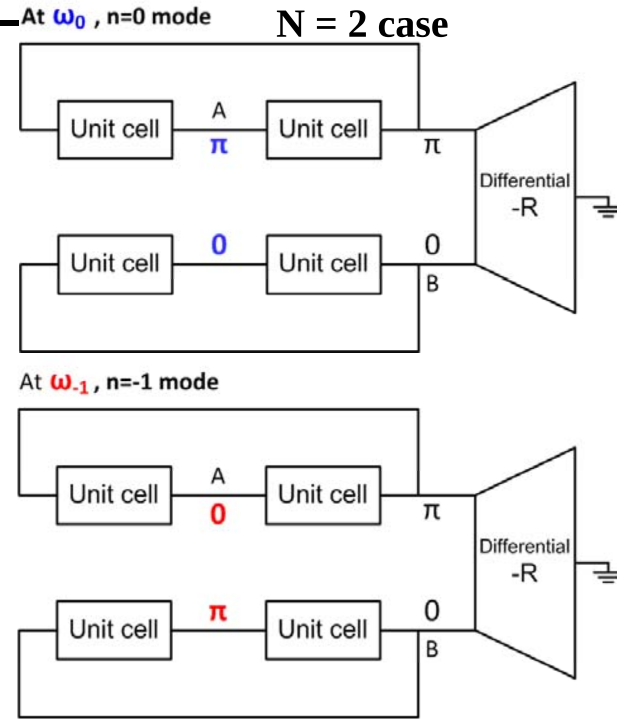
- **Spacing is dense and non-uniform**

Antenna spacing: 0.18λo (23mm), 0.46 λo (58mm),

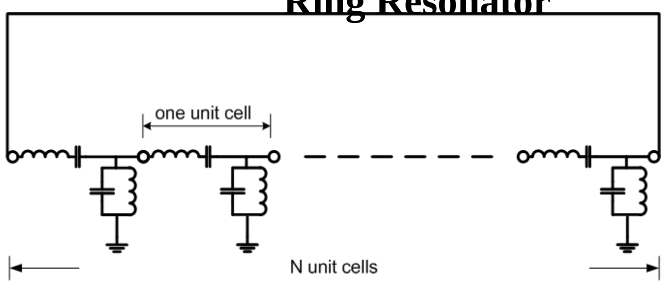
- **Measured array EIRP= 18 dBm**
- **Estimated Posc. = 11.5 dBm based on passive array gain of 6.5 dBi**
- **Estimated combining efficiency of 78%**

CMOS Application

N = 2 case

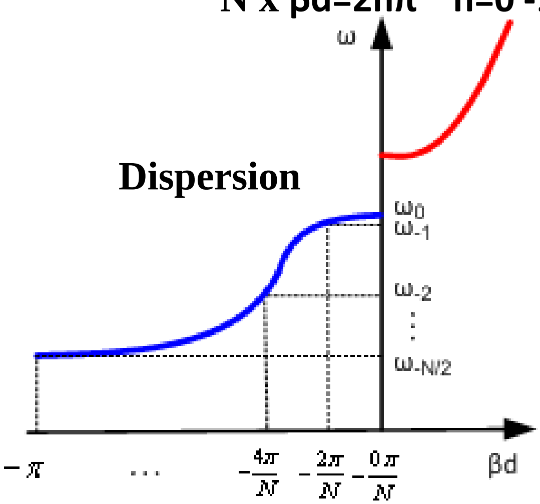


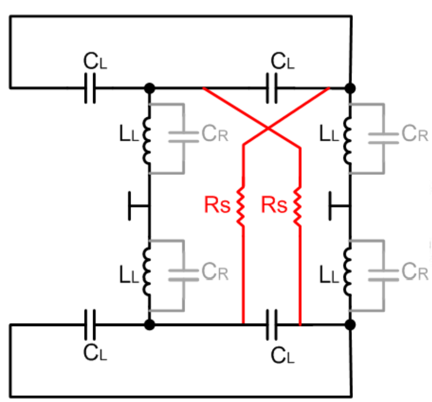
N-Single-Ended-CRLH-Unit-Cell Ring Resonator

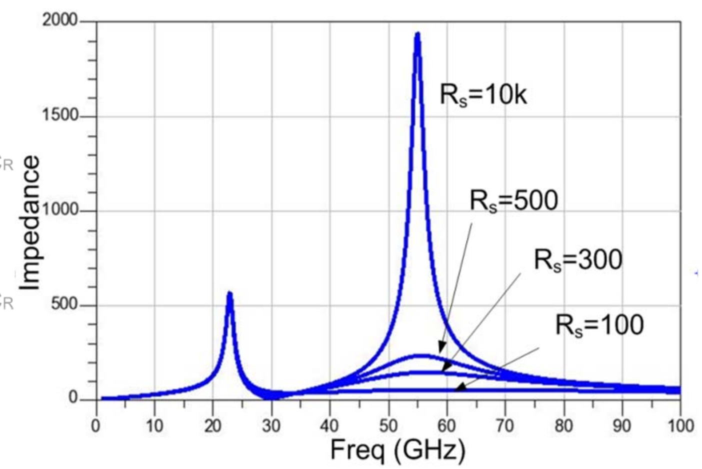


N x βd=2nπ n=0 -1 -2 … -N/2

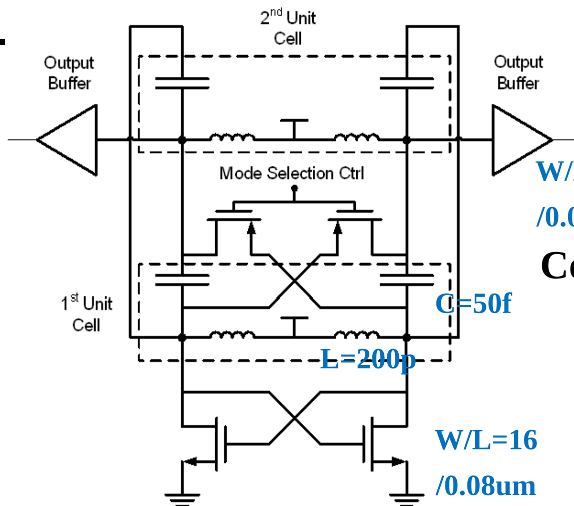
Dispersion





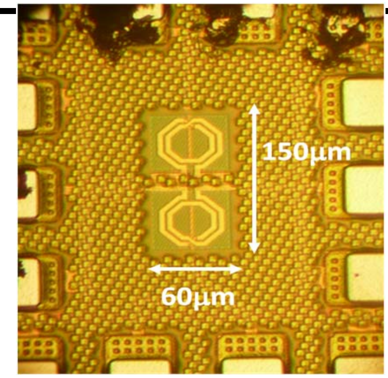


RFIC 2009 RTU3A.2: A Dual Band mm-Wave CMOS Oscillator with Left-Handed Resonator

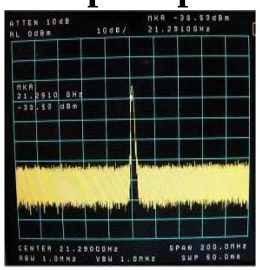


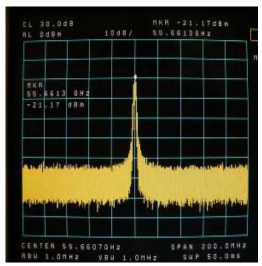
Complete Circuit Schematic

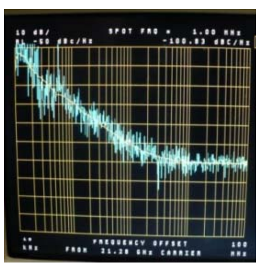
Chip Micro-Photograph



Output Spectrum and Phase Noise



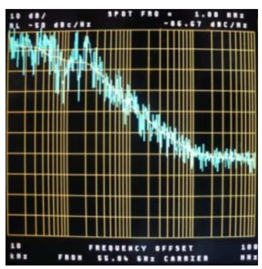




Switch On

Oscillation freq: 21.3GHz

Phase Noise -100.8 dBC/Hz at 1MHz offset



Switch Off

Oscillation freq: 55.6GHz

Phase Noise -86.67 dBC/Hz at 1MHz offset

Measurement Summary

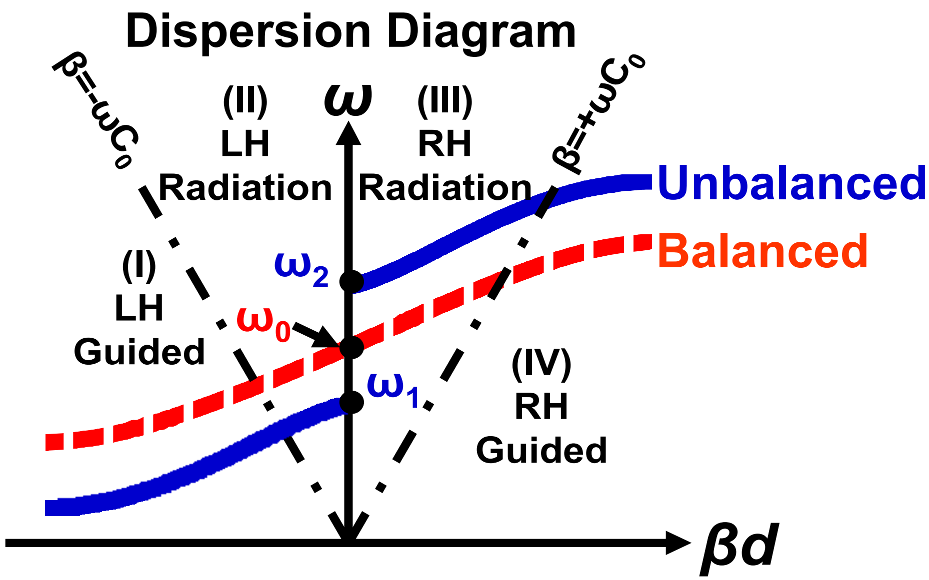
Process	IBM 90-nm Digital CMOS Process
Frequency Band	21 GHz and 55 GHz
Frequency Switching Range (GHz)	34.3 GHz
Frequency Switching Range (%)	62% of highest oscillation frequency
Running at 21 GHz Phase Noise @ 1 MHz offset (dBC/Hz)	-100.8
Running at 55 GHz Phase Noise @ 1 MHz offset (dBC/Hz)	-86.7
VCO-Core Power (mW)	14
VCO-Core Area	150 µm × 60 µm

RFIC 2009 RTU3A.2: A Dual Band mm-Wave CMOS Oscillator with Left-Handed Resonator

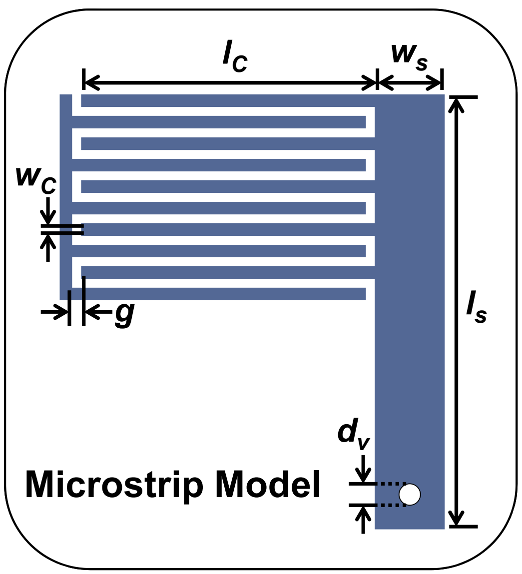
4. Antenna Applications

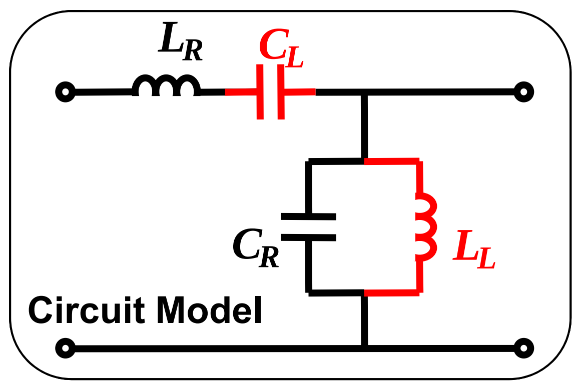
4a. Leaky Wave Antennas

Composite Right/Left-Handed Metamaterials



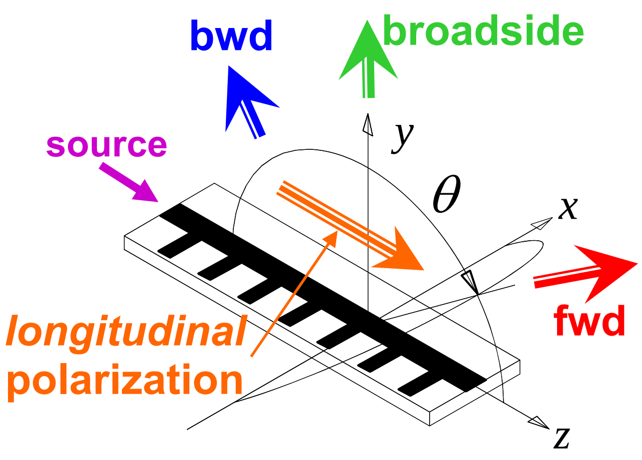
- **Region (I):**
  - $v_g v_p < 0$ →Left-handed
  - $\beta < -\omega c_0$ →Guided mode
- **Region (II):**
  - $v_g v_p < 0$ →Left-handed
  - $\beta > -\omega c_0$ →Radiating mode
- **Region (III):**
  - $v_g v_p > 0$ →Right-handed
  - $\beta < \omega c_0$ →Radiating mode
- **Region (IV):**
  - $v_g v_p > 0$ →Right-handed
  - $\beta > \omega c_0$ →Guided mode





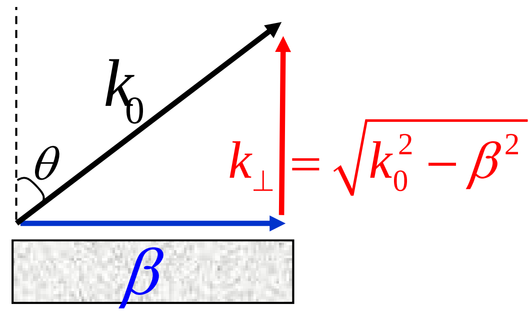
Backfire-to-Endfire Leaky-Wave Antenna

Antenna Configuration

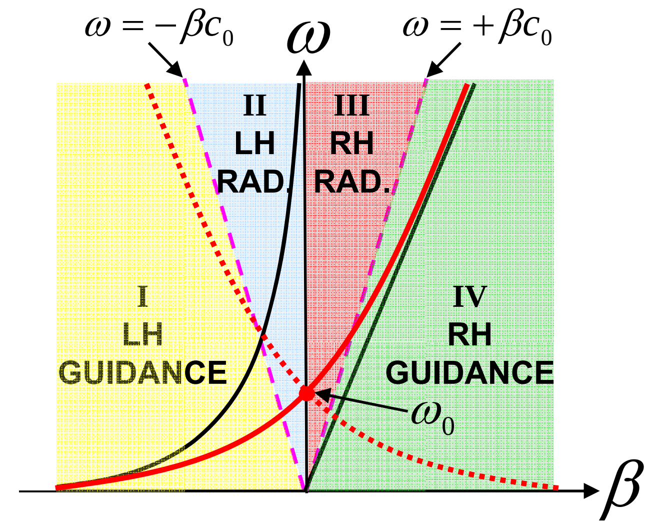


Main Beam Radiation

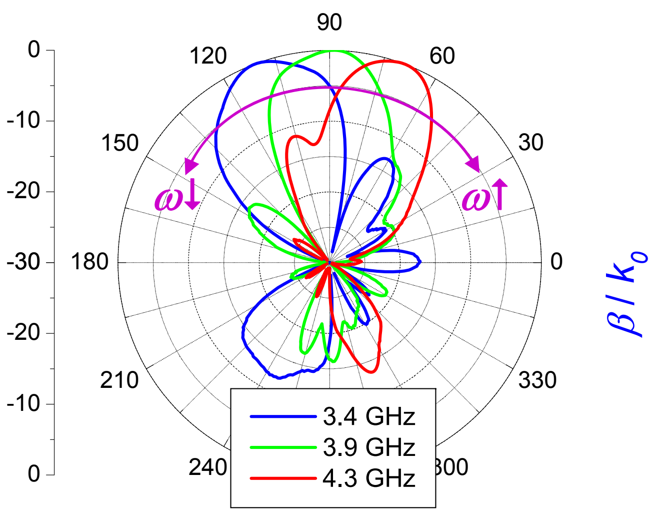
$$\theta_{\text{rad}} = \text{asin}\left(\beta / k_0\right)$$



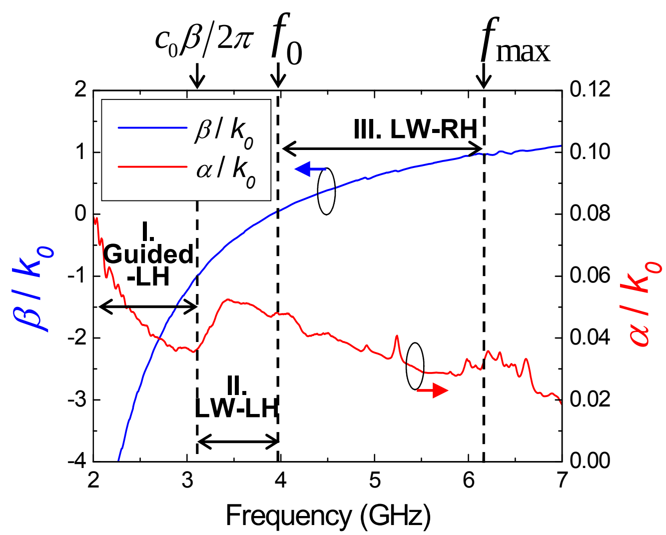
CRLH dispersion diagram



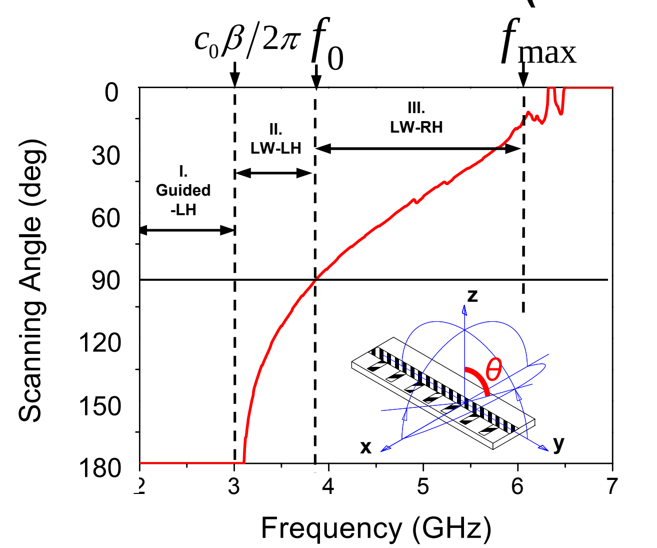
Radiation Patterns (meas.)



α / β diagram (meas.)



Main beam θ versus ω (meas.)

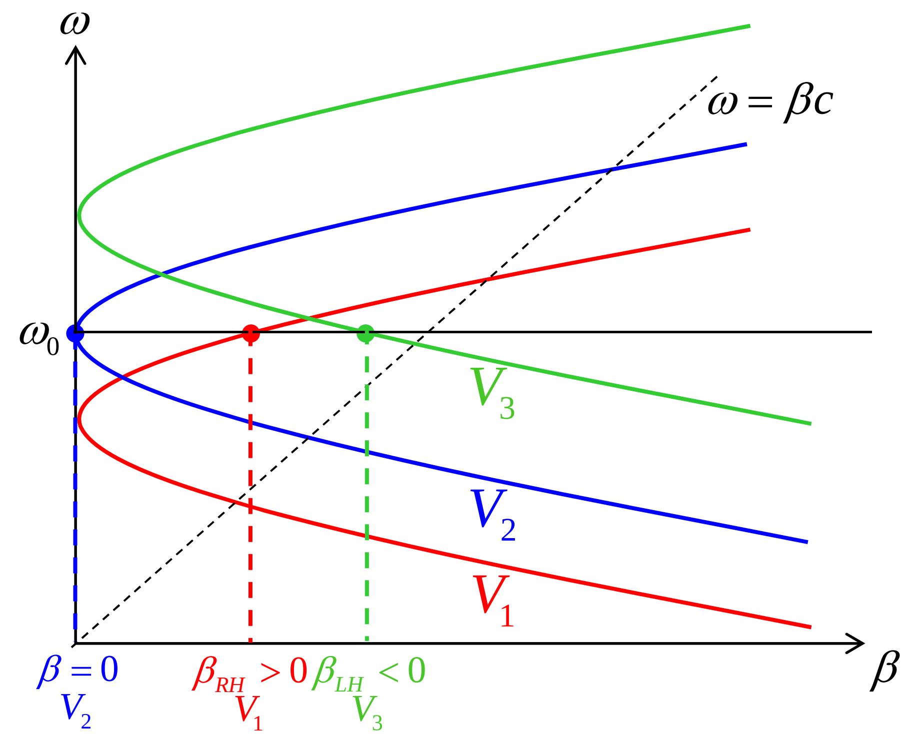


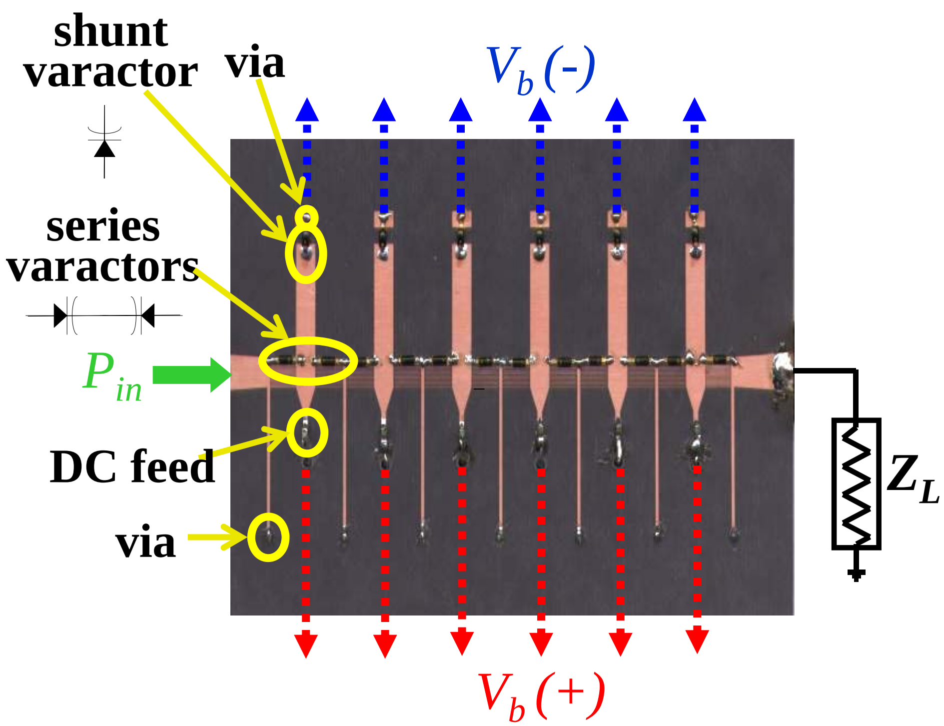
Electronically Scanned LW Antenna

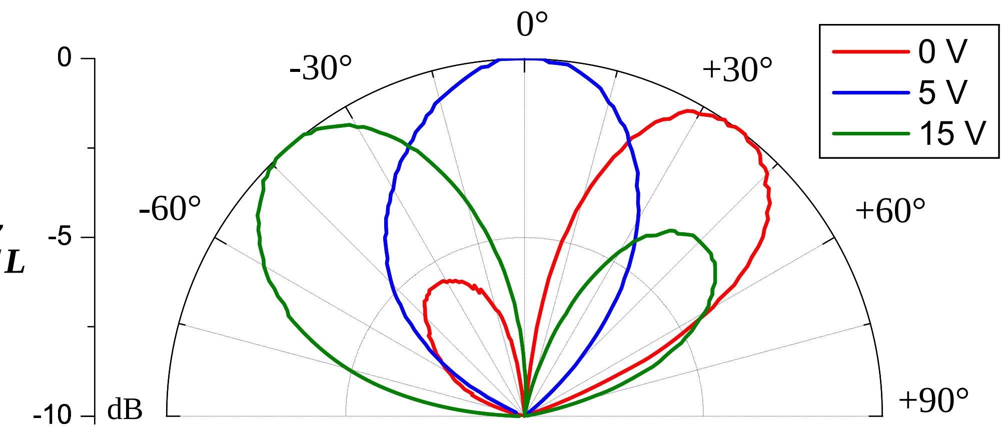
$$\theta = \operatorname{asin}\left(\beta / k_0\right)$$

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

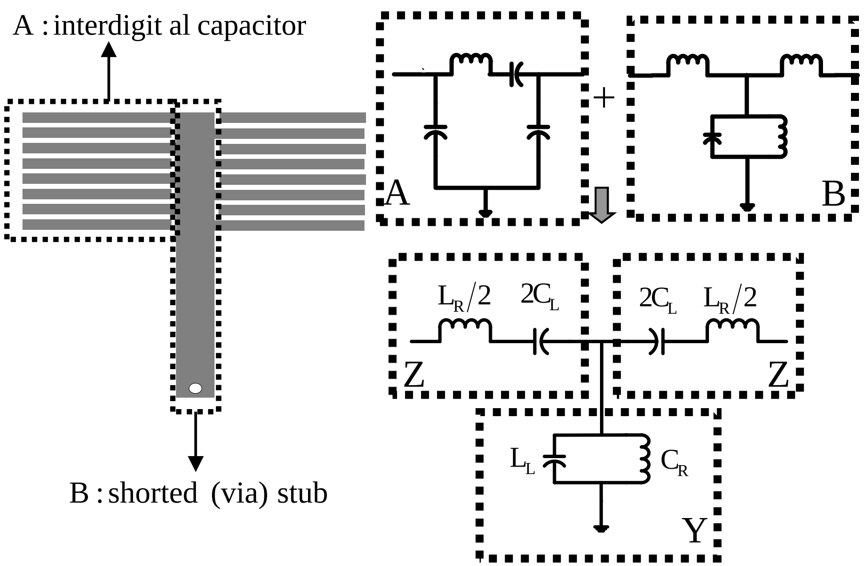
$$Z_0 = \sqrt{\frac{L_R'}{C_R'}} = \sqrt{\frac{L_L'}{C_L'}}$$

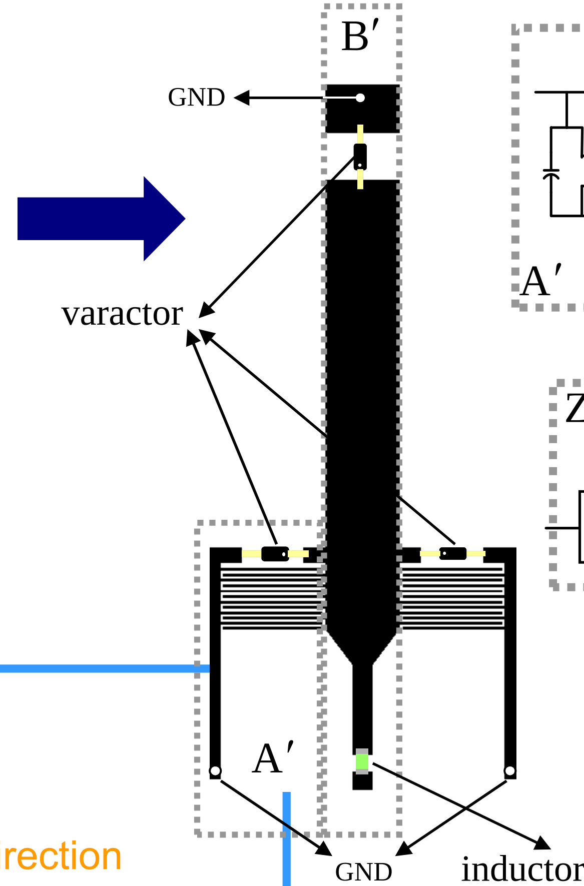


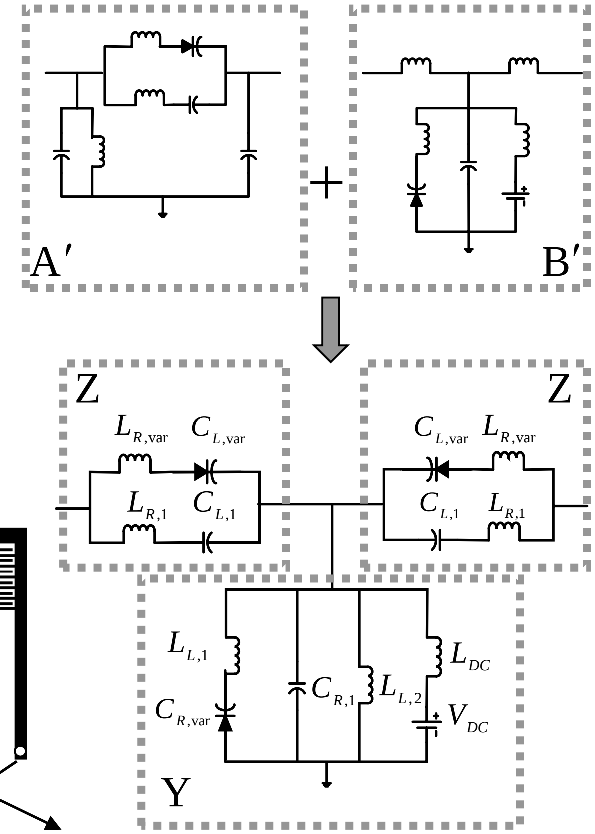




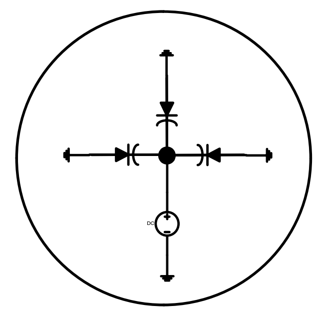
Unit-Cell Implementation







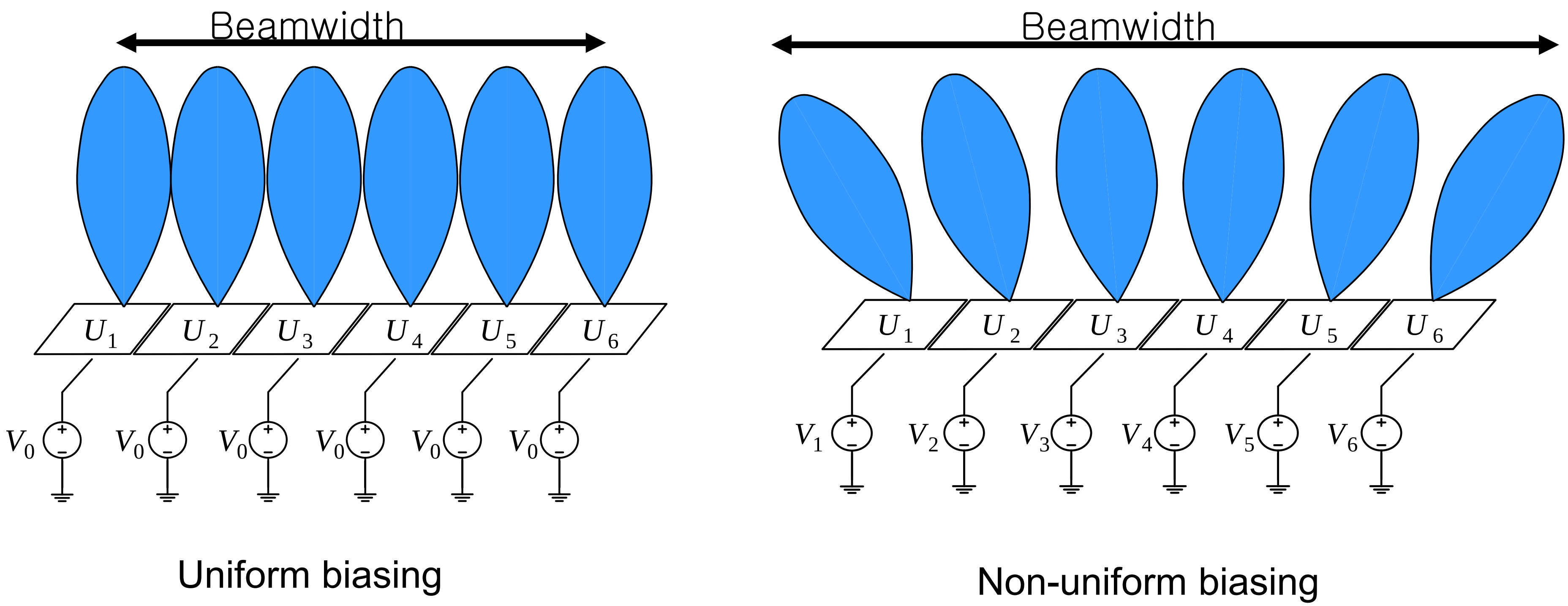
Bias Configuration



- ❑ Reverse biasing to Varactors
  - ➔ Anodes of varactors : GND
  - ➔ Cathodes of varactors: Biasing
- ❑ The cathodes of three varactors in the same direction
  - ➔ Only one bias circuitry in unit cell
- ❑ Series and Shunt Varactors
  - ➔ Fairly constant characteristic impedance
  - ➔ Additional degree of freedom for wider scanning range
- ❑ Back to back configuration of two series varactors
  - ➔ Fundamental signals : in phase and add up
  - ➔ Harmonic signals: out of phase and cancel

[1] S. Lim, C. Caloz and T. Itoh, "Electronically-Controlled Metamaterial-Based Transmission Line as a Continuous-Scanning Leaky-Wave Antenna." *IEEE-MTT Int'l Symp.*, Fort Worth, TX, Jun. 2004.

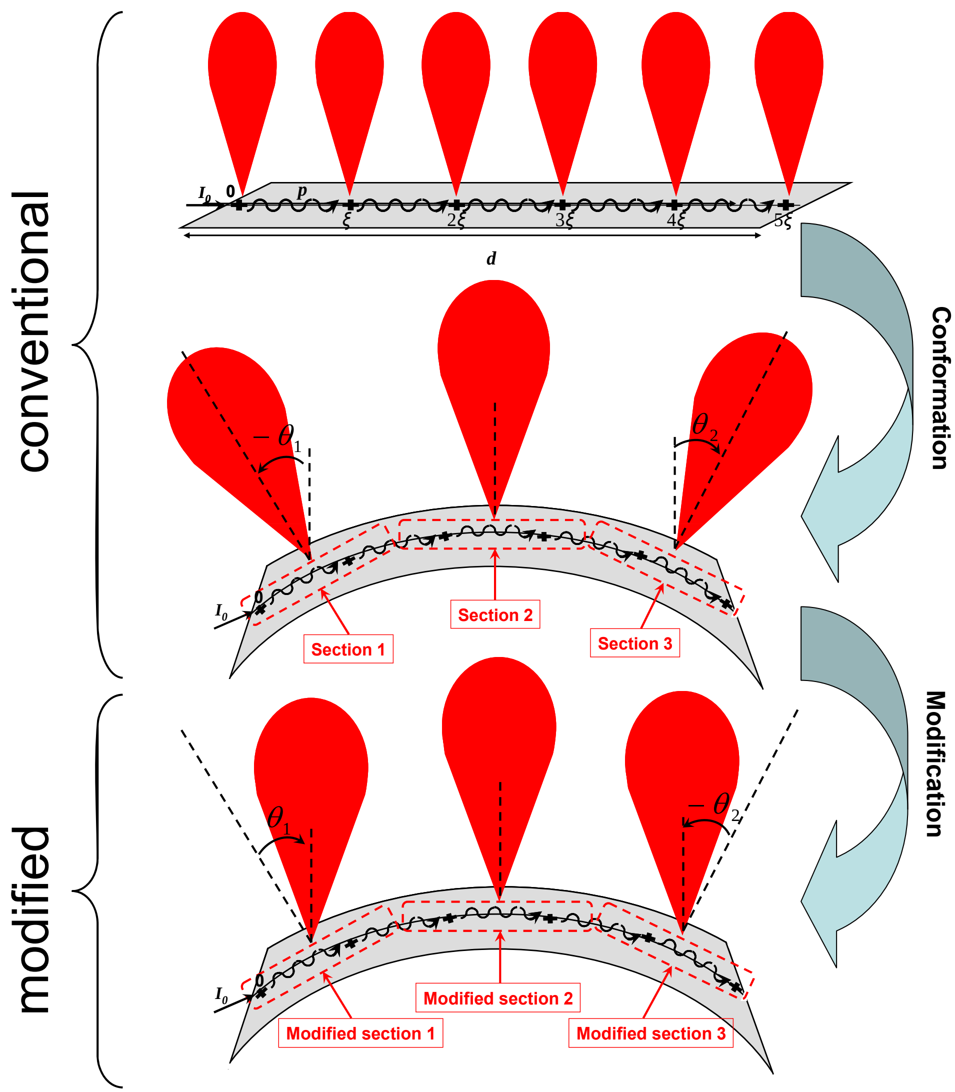
Beamwidth Control Capability: Principle



- Uniformly biased periodic TL
  - ➔ Each unit cell radiates toward the same angle
  - ➔ High directivity

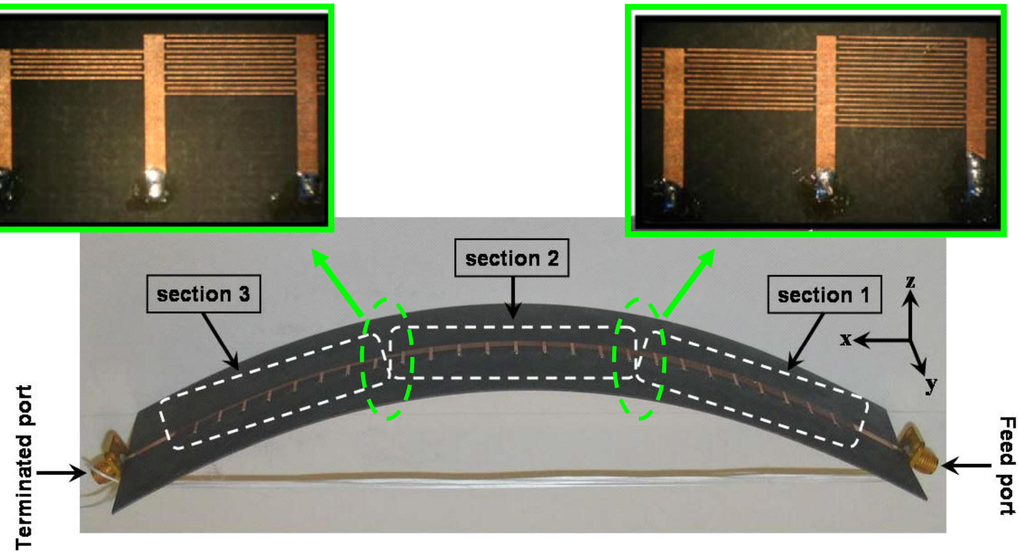
- Non-Uniformly biased periodic TL
  - ➔ Each unit cell radiates toward different angles
  - ➔ Beamwidth is determined by the superposition of each cell
  - ➔ Broader beamwidth

Conformal Leaky-Wave Metamaterial Antenna:



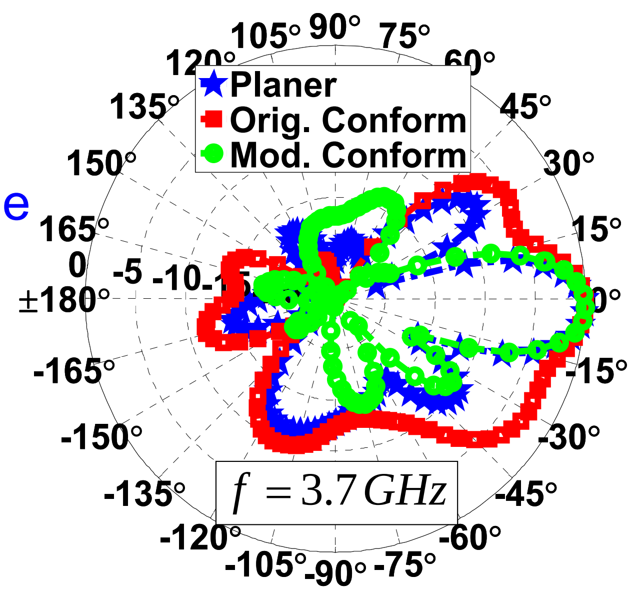
- Conforming a conventional planar LWA results in radiated beam dispersion and decreased gain
- CRLH metamaterial unit-cells can be adjusted to compensate radiation (beam dispersion)
- Implemented static solution for broadside beam (3 sections)

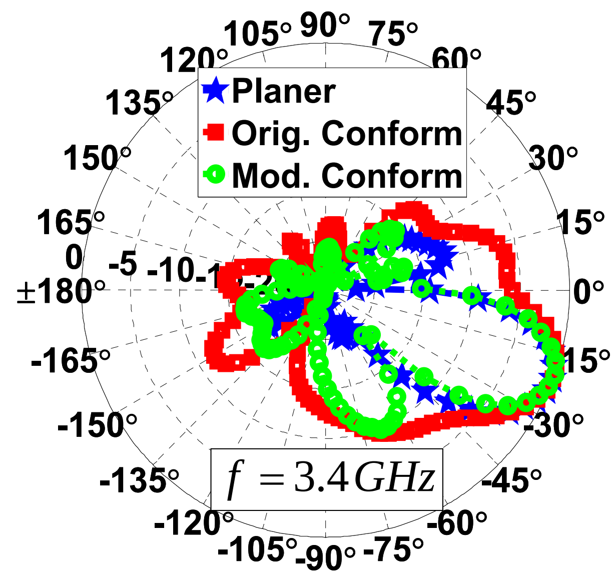
Static 3-section conformal prototype implementation:



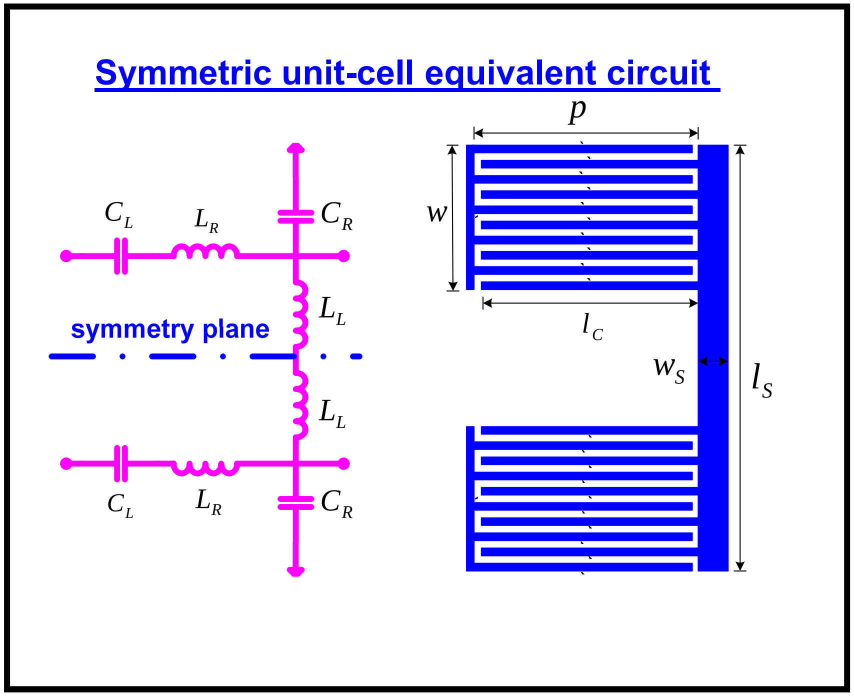
• Similar concept can be implemented in dynamic fashion with tunable components (varactors, etc.)

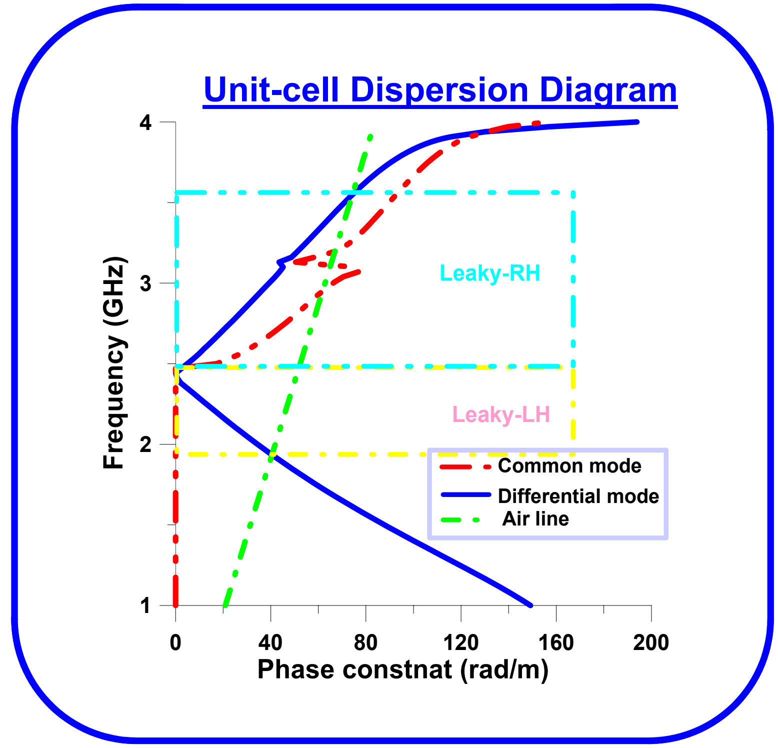
• Modified beamwidth due to 3-section design is narrow, comparable to non-conformal antenna





Balanced symmetric unit-cell implementation:

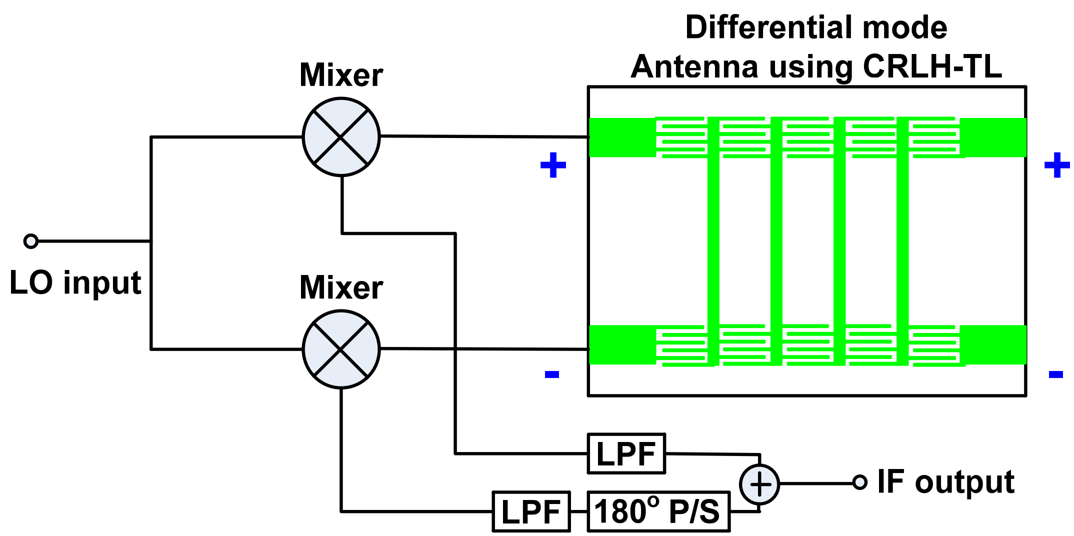




- Differential mode operation due to symmetric unit-cell
- Even mode suppression in LH region
- Balanced CRLH-based leaky-wave antenna provides continuous scanning

30-cell differential mode CRLH antenna

Metamaterial-based Antenna System Application:

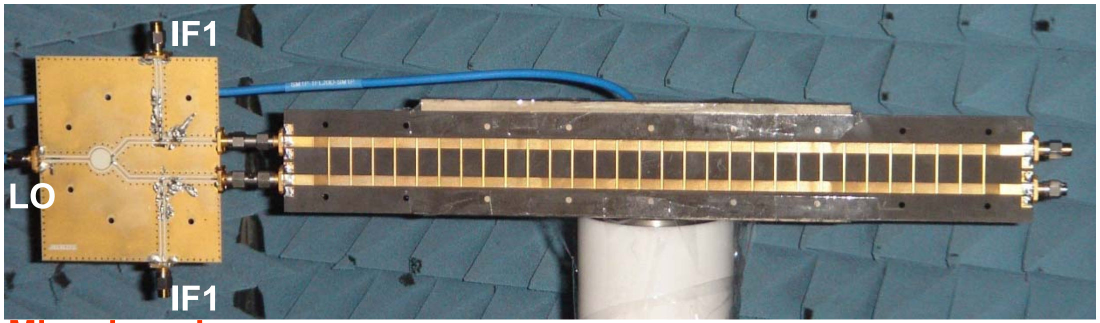


Integrated mixer system schematic

Balanced mixer integrated with CRLH differential mode antenna:

- Differential mode leaky-wave operation
- Even mode suppression – low LO leakage
- Balanced CRLH-based leaky-wave antenna provides continuous scanning
- High RF-LO isolation

Measured Results:

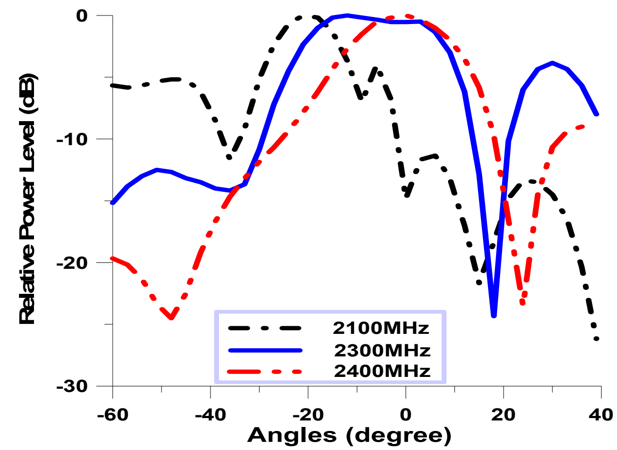


Mixer board

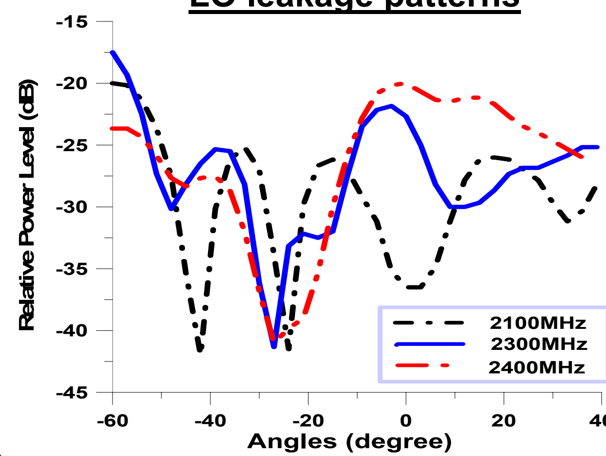
Integrated system hardware:

- 1.96 GHz – 2.40 GHz operation
- 21 dB avg. conversion loss
- -21° – 0° scanning in LH region

Radiated patterns

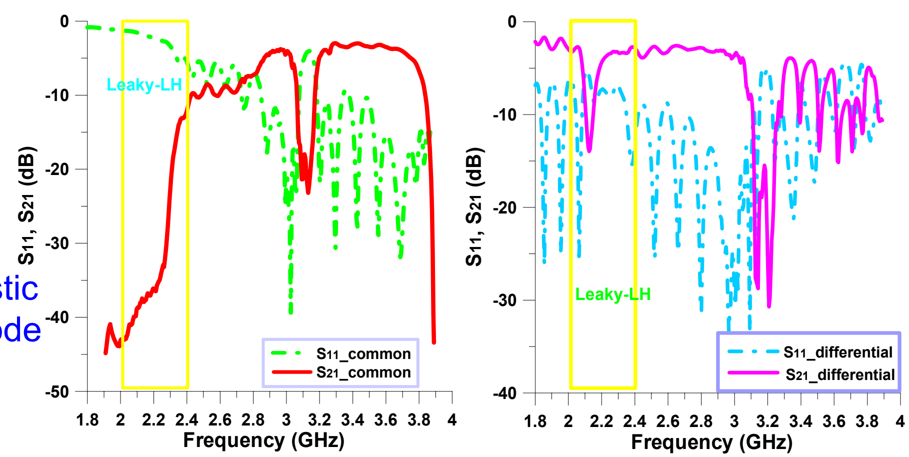


LO leakage patterns

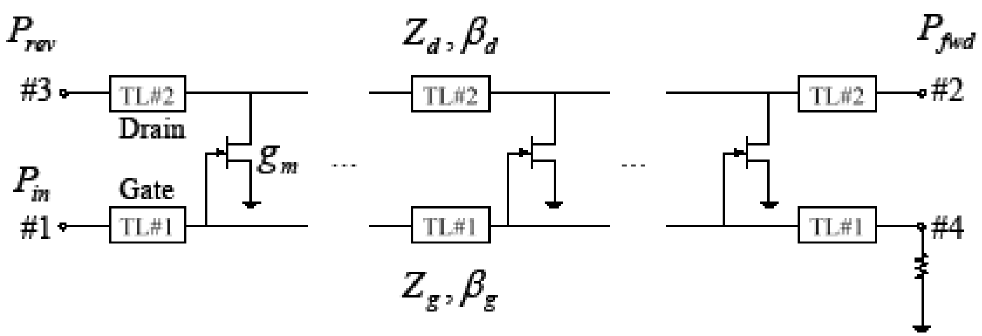


Measured S-parameters:

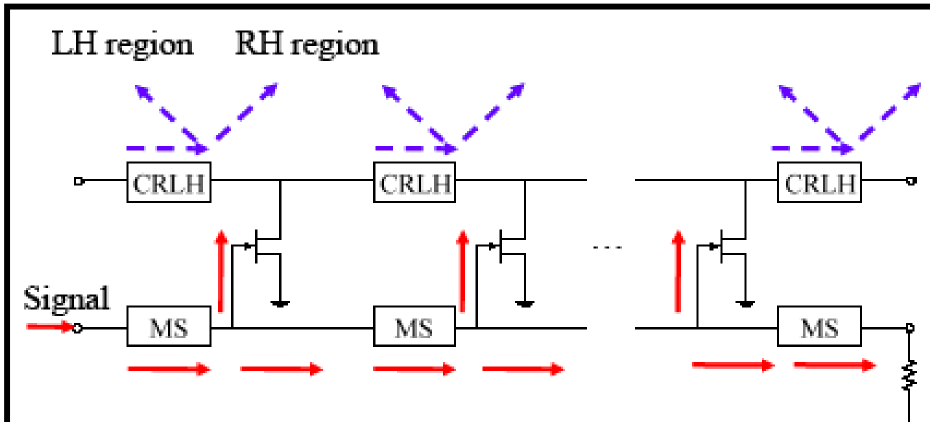
Stop band characteristic in even mode excitation



Distributed Amplifier with CRLH-TL LWA

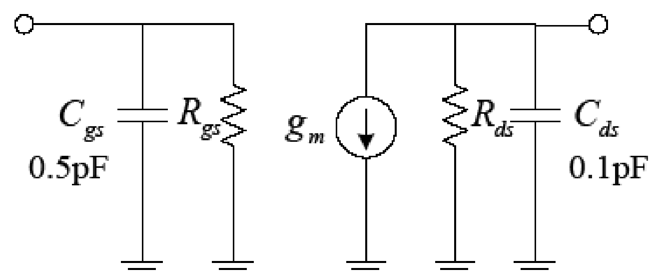


Conventional DA with FET

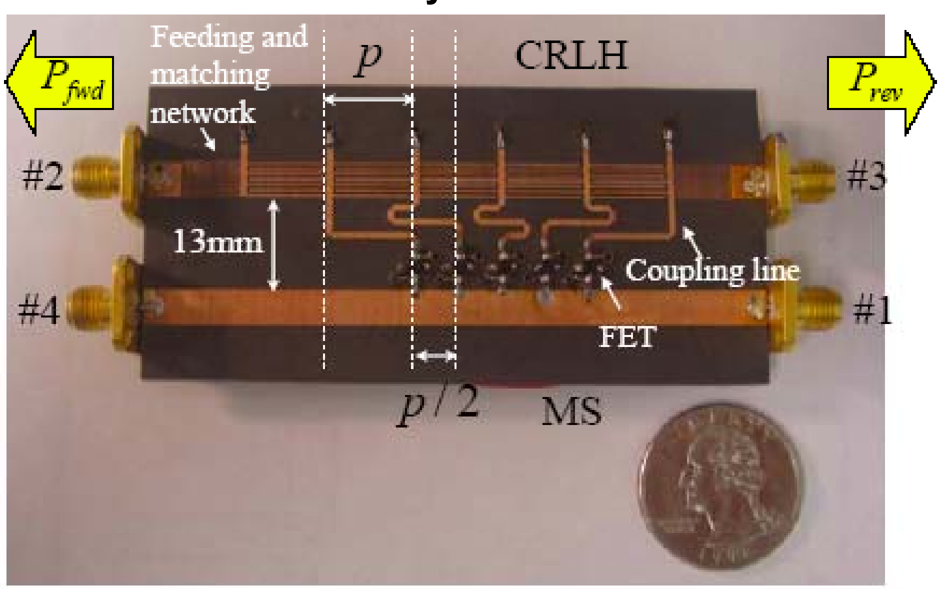


DA using CRLH and MS TLs

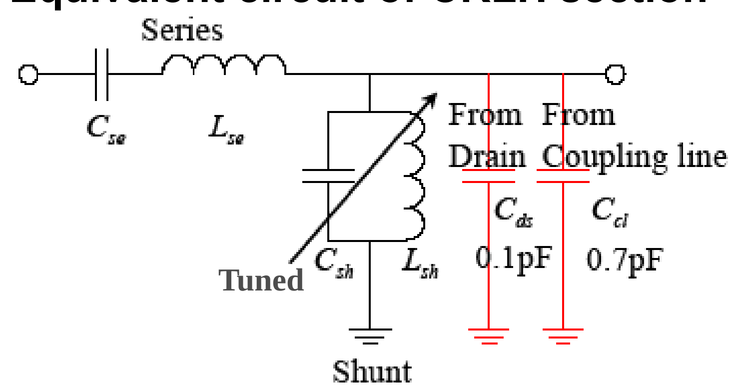
Equivalent circuit of FET



A 5 unit-cell distributed amplifier with MS-TL and CRLH-TL leaky wave antenna.



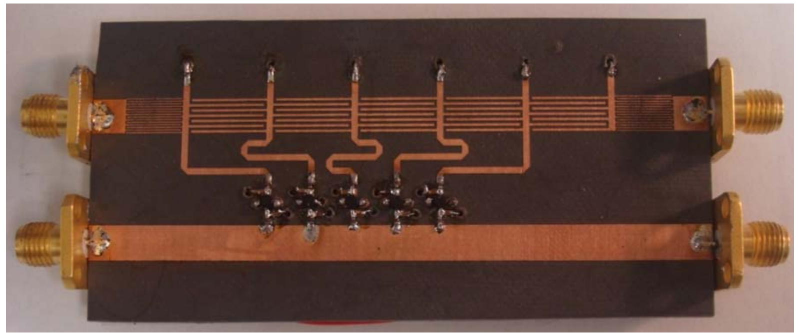
Equivalent circuit of CRLH section

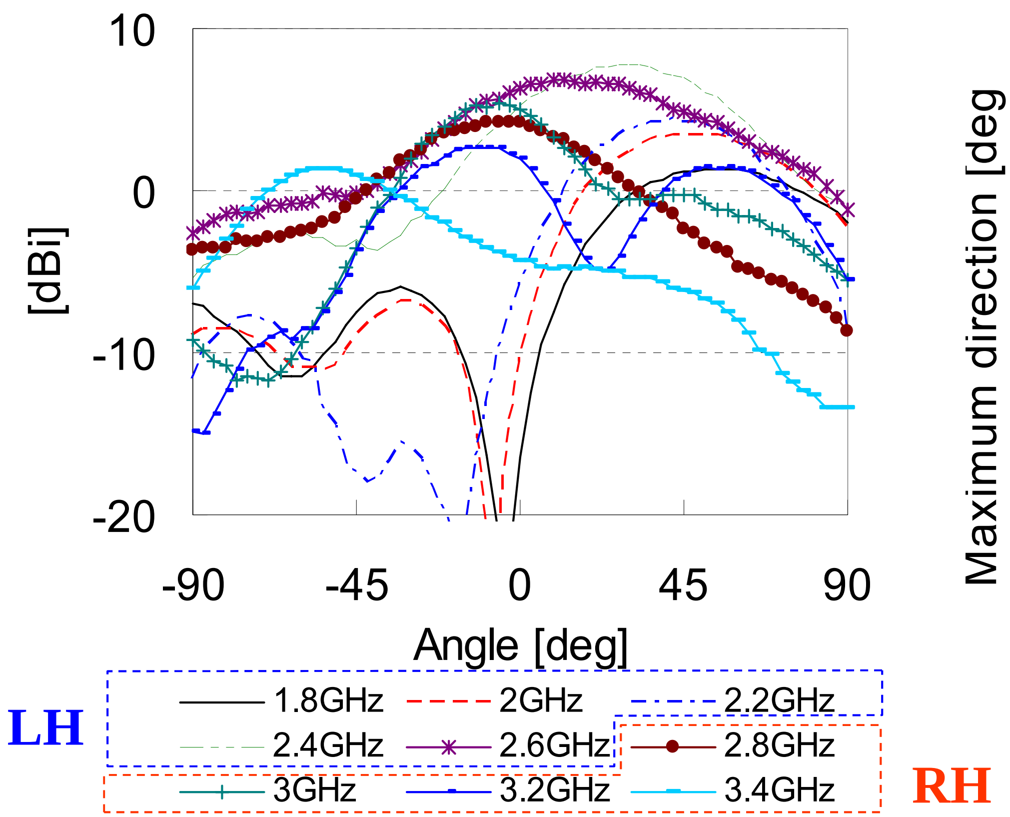


[6] K. Mori and T. Itoh, "Distributed Amplifier with CRLH-Transmission Line Leaky Wave Antenna," European Microwave Conference, Amsterdam, October 2008.

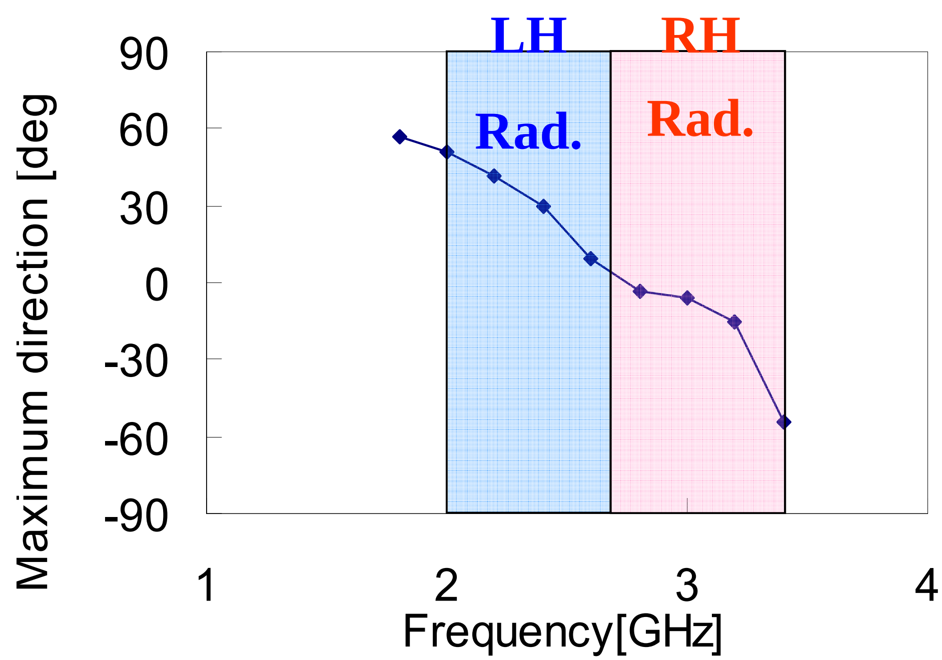
Radiation Pattern

P_{in} →





Measured radiation pattern

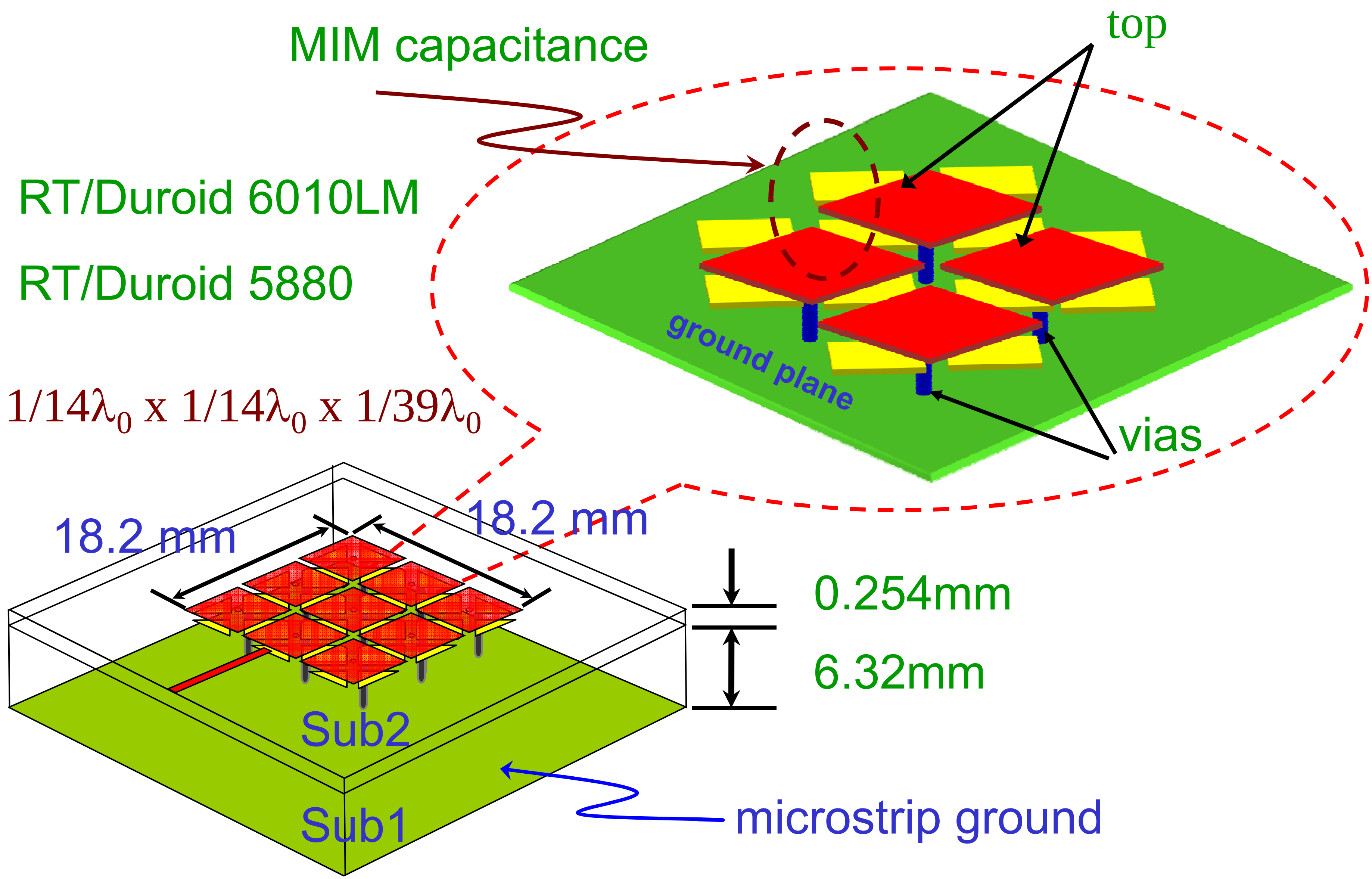


Maximum direction

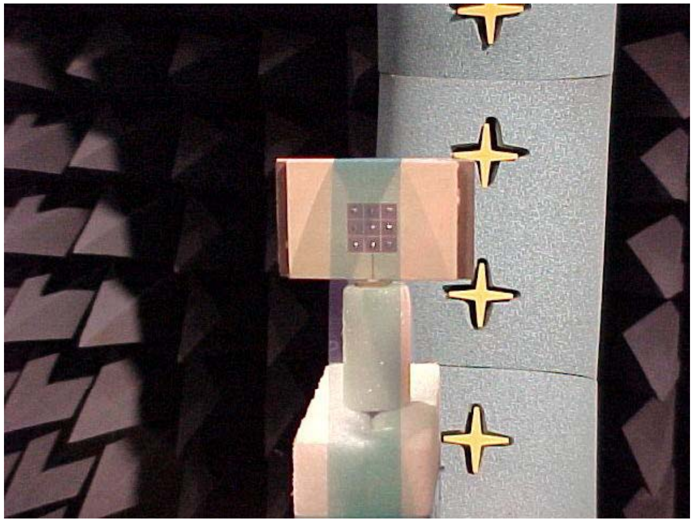
4. Antenna Applications

4b. Resonant Antennas

Small Antenna – Mushroom Type



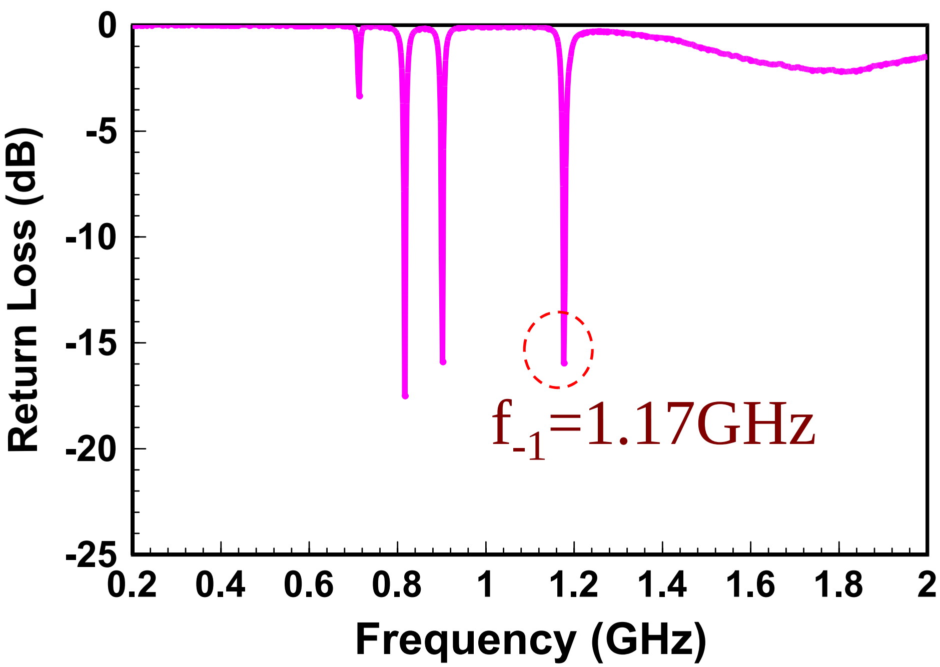
Small Antenna – Mushroom Type (Exp. Results)

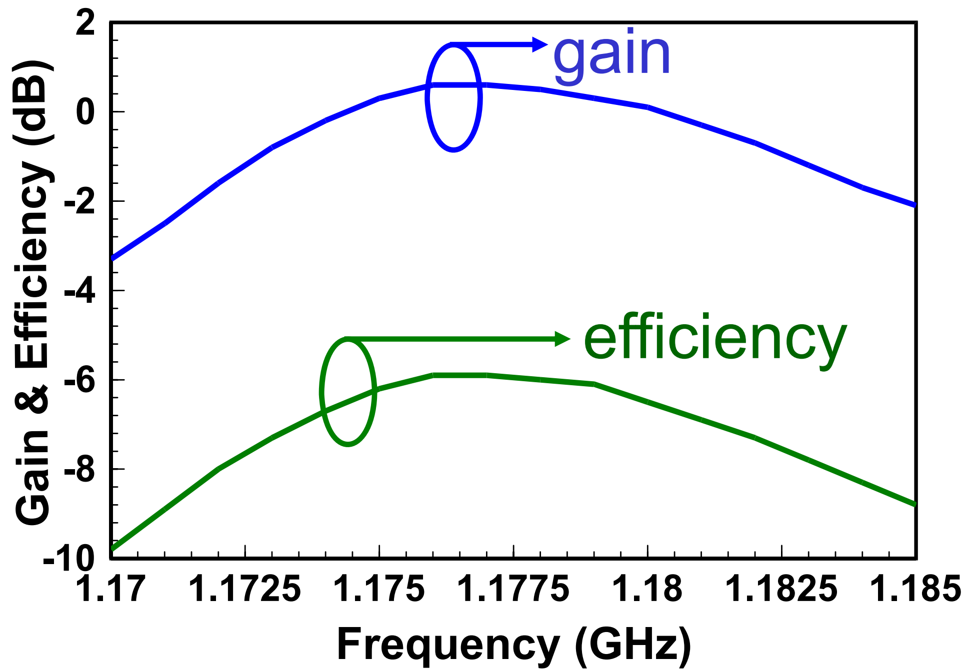


Max gain : 0.6dBi

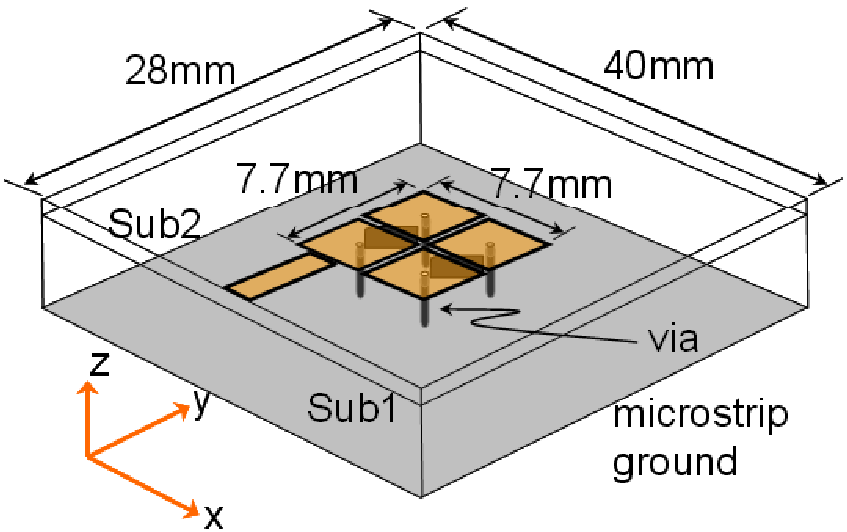
Highest efficiency:

5.9dB ~ 26 %

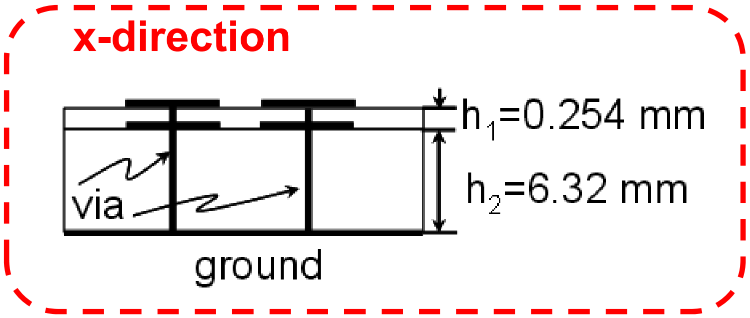


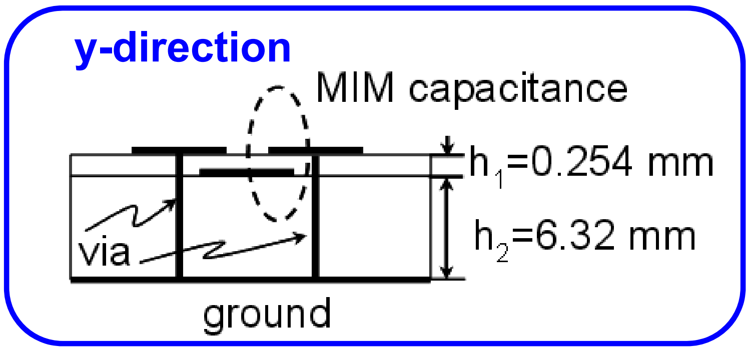


Compact Dual-Band Antenna (PCS/Bluetooth)

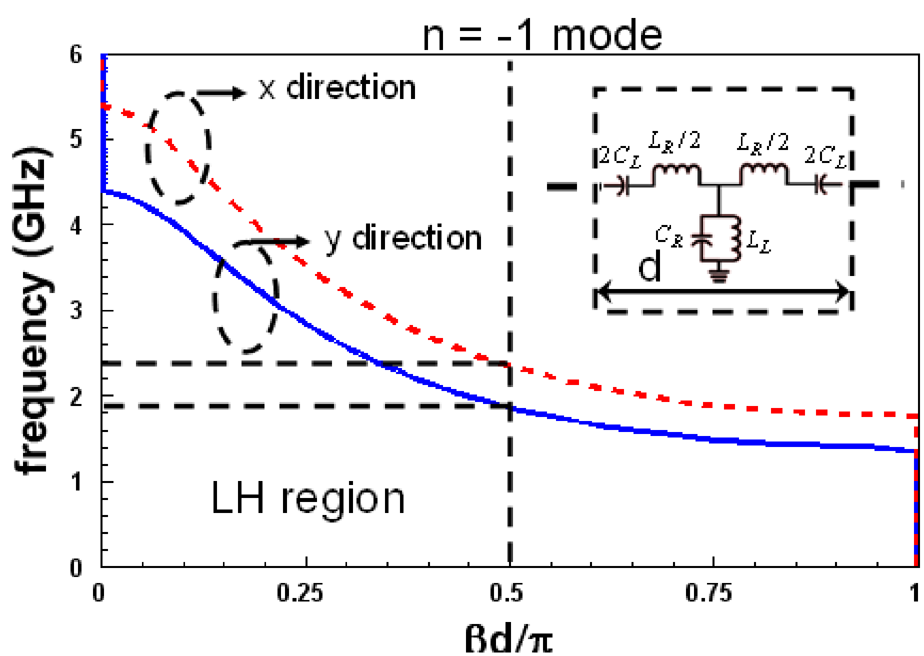


- **Based on anisotropic metamaterial.**
- **Half-wavelength distribution.**
- **96% size reduction.**

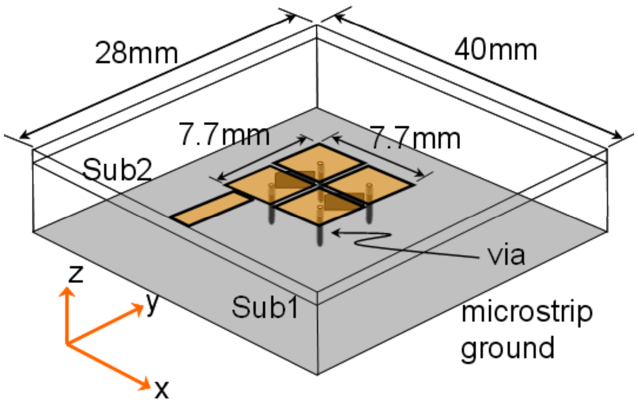




Dispersion Diagram

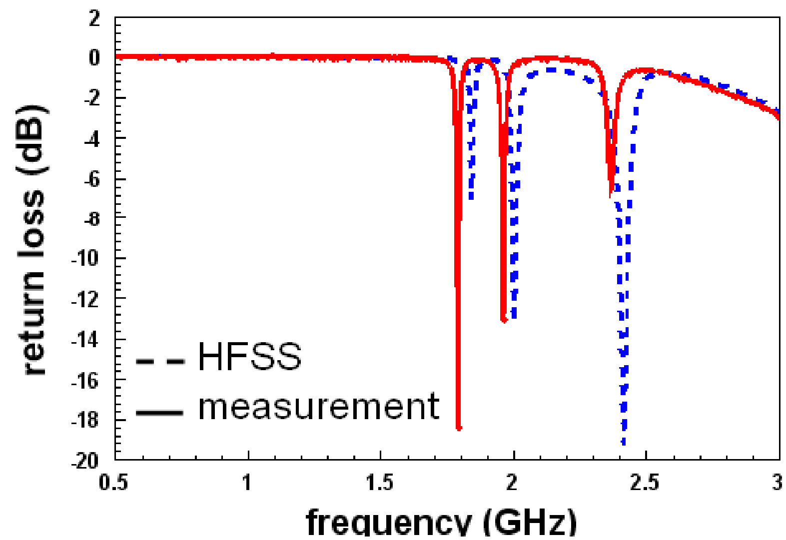


Compact Dual-Band Antenna (PCS/Bluetooth)



$1/17\lambda_o \times 1/17\lambda_o \times 1/19\lambda_o$ @ 2.37 GHz

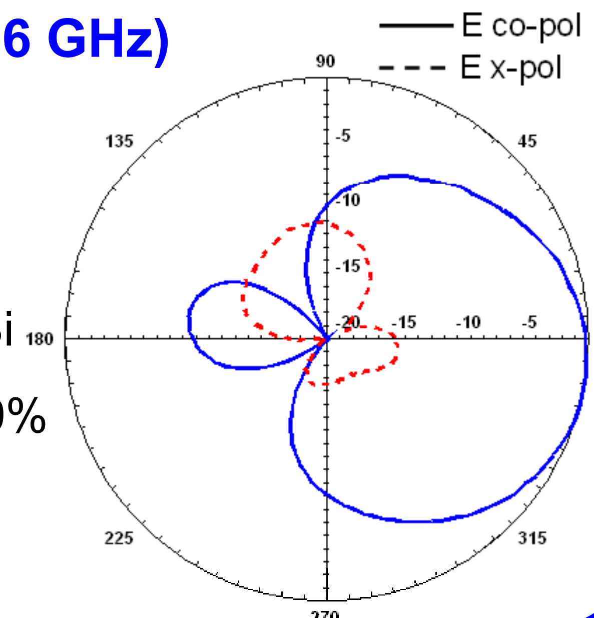
~ 96% size reduction



PCS (1.96 GHz)

Gain: -3.0 dBi

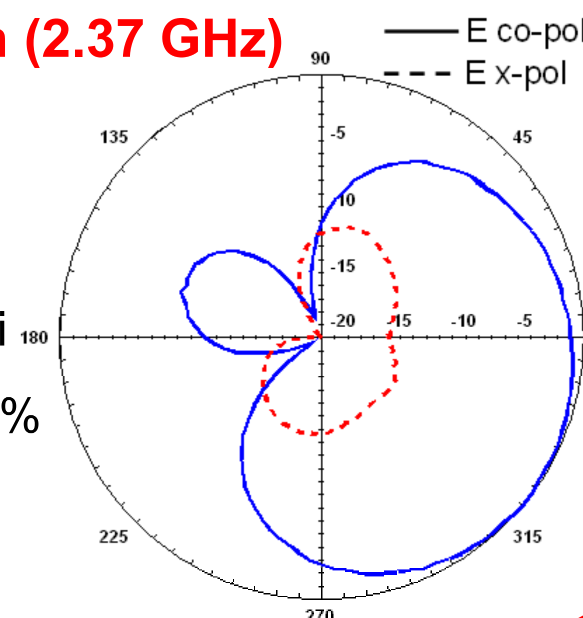
Efficiency: 29%



Bluetooth (2.37 GHz)

Gain: -2.3 dBi

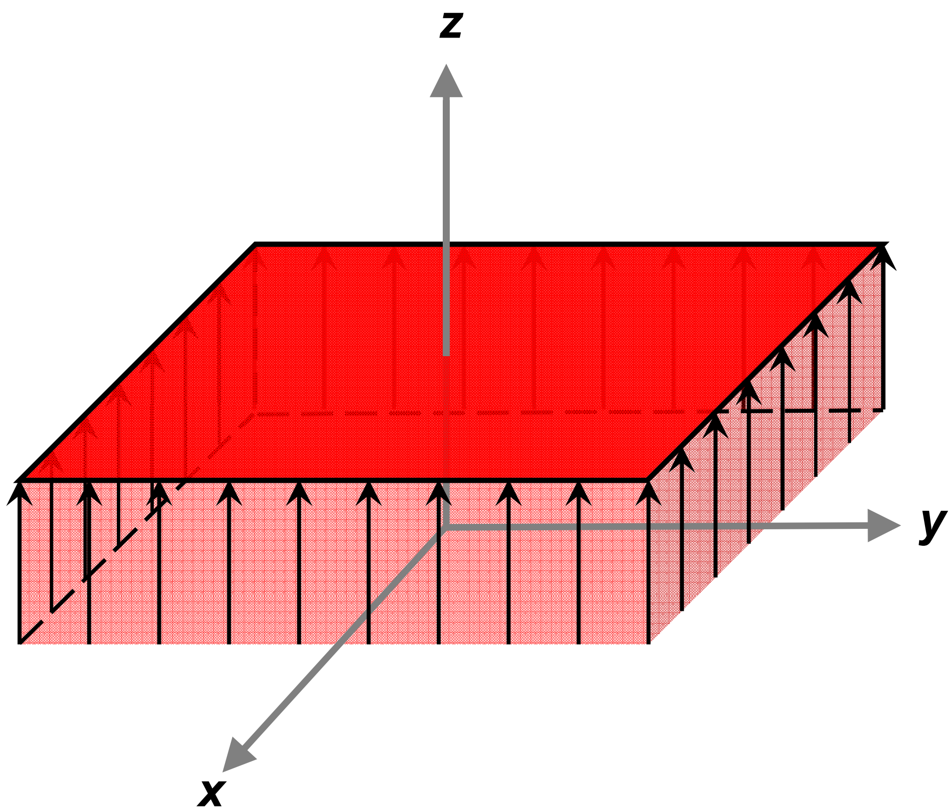
Efficiency: 25%



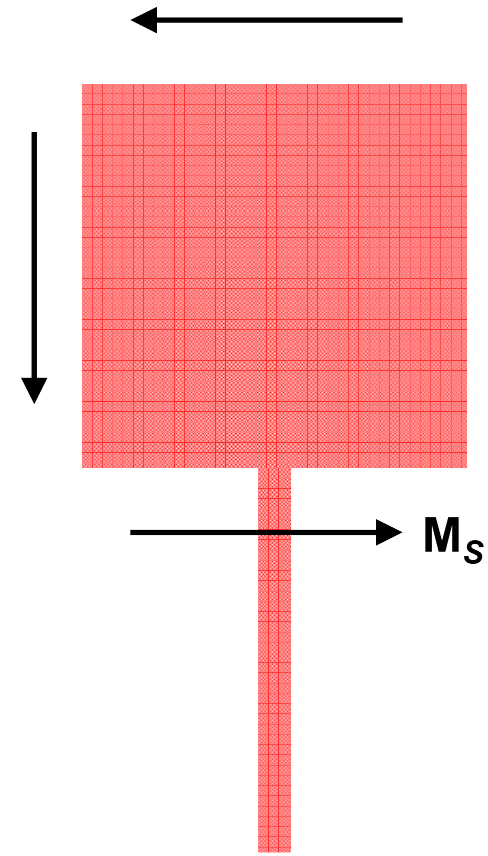
CRLH Infinite Wavelength Patch Antenna

Constant Field Distribution for Monopolar Radiation

- Similar to TM_{01} mode of circular patch antenna.
- Monopolar radiation pattern is achieved.
- Size of patch can be arbitrary.

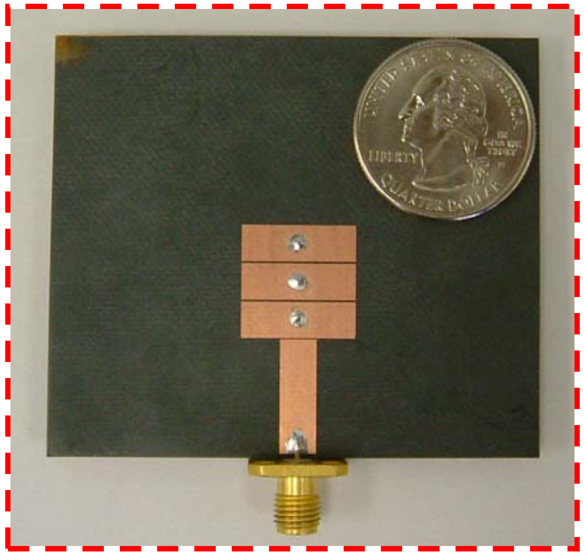


CRLH Square Patch Antenna (infinite wavelength)

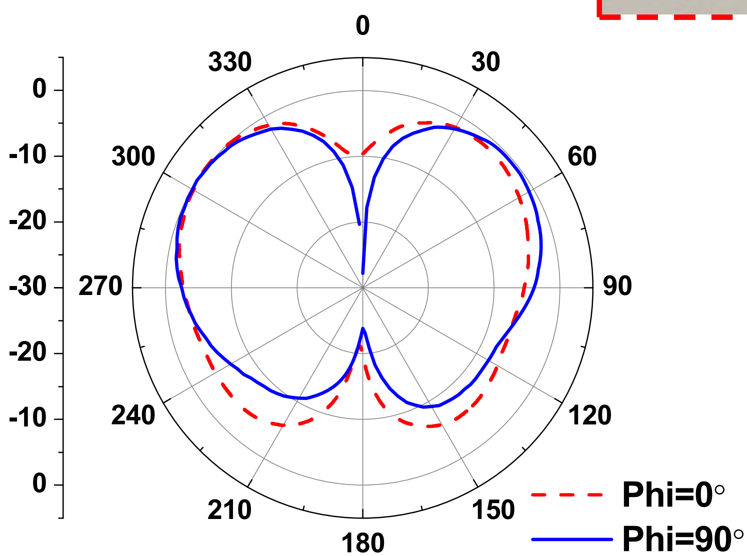


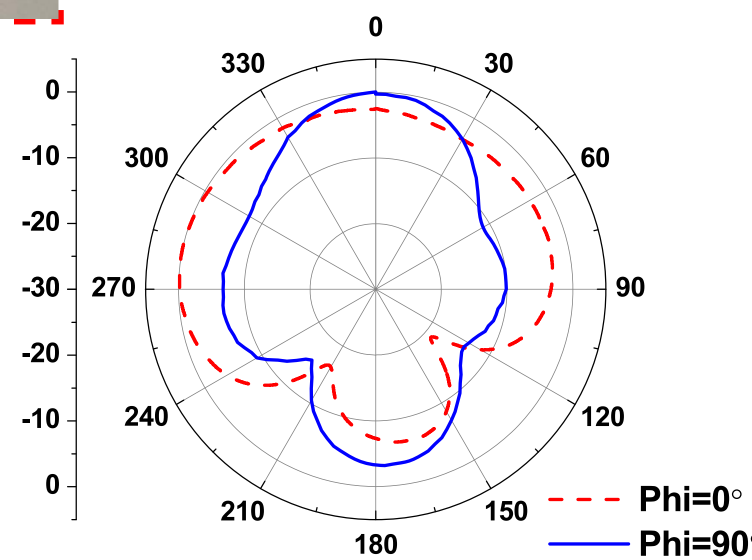
Backward Wave Dual-Mode Antenna (APMC 2005)

f_0=4.015 GHz
gain=2.3 dBi
efficiency=75.0%
size: $\lambda_o/5 \times \lambda_o/5 \times \lambda_o/50$



f_{-1} =3.560 GHz
gain=-2.5 dBi
efficiency=22.5%
size: $\lambda_o/5.7 \times \lambda_o/5.7 \times \lambda_o/54$

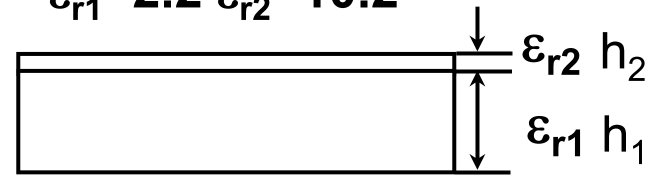


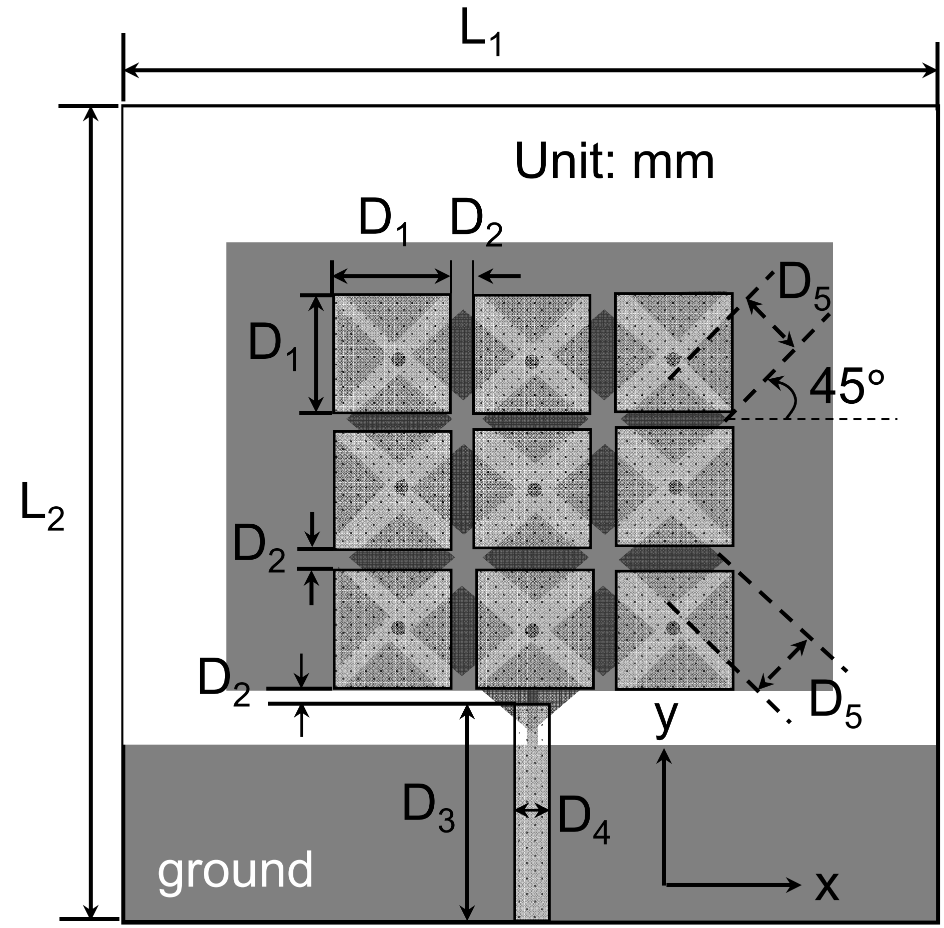


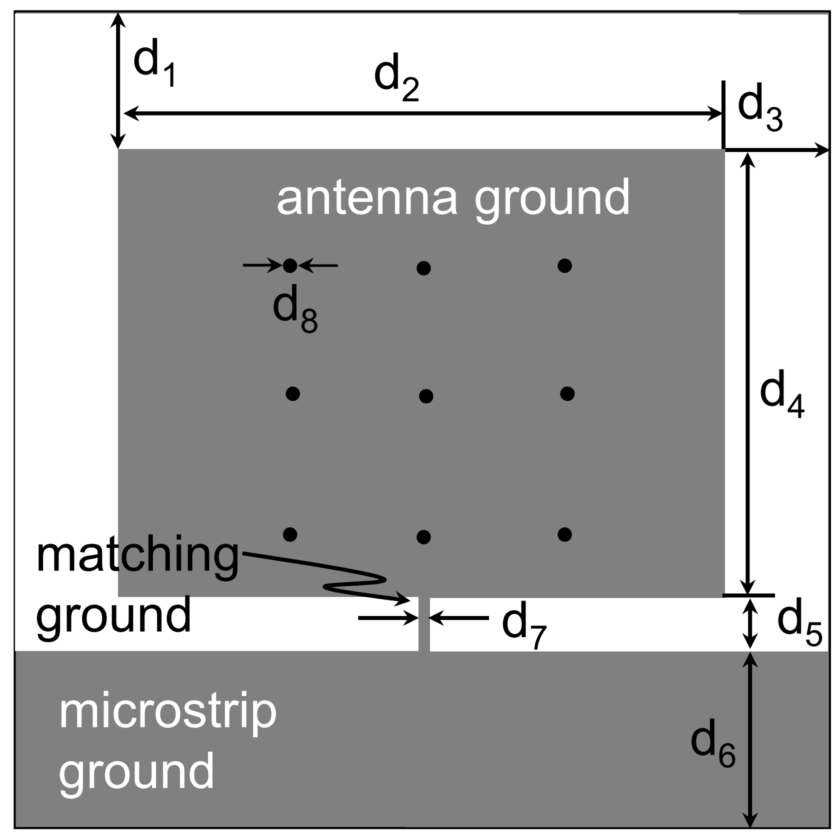
Broadband Small Antenna

h_1=3.16, h_2=0.254, L_1=L_2=40, D_1=4, D_2=0.1, D_3=14, D_4=1.2, D_5=1.75. d_1=7.8, d_2=24, d_3=8, d_4=18.1, d_5=2, d_6=12.1, d_7=0.2, d_8=0.24,

ε_{r1}=2.2 ε_{r2}=10.2

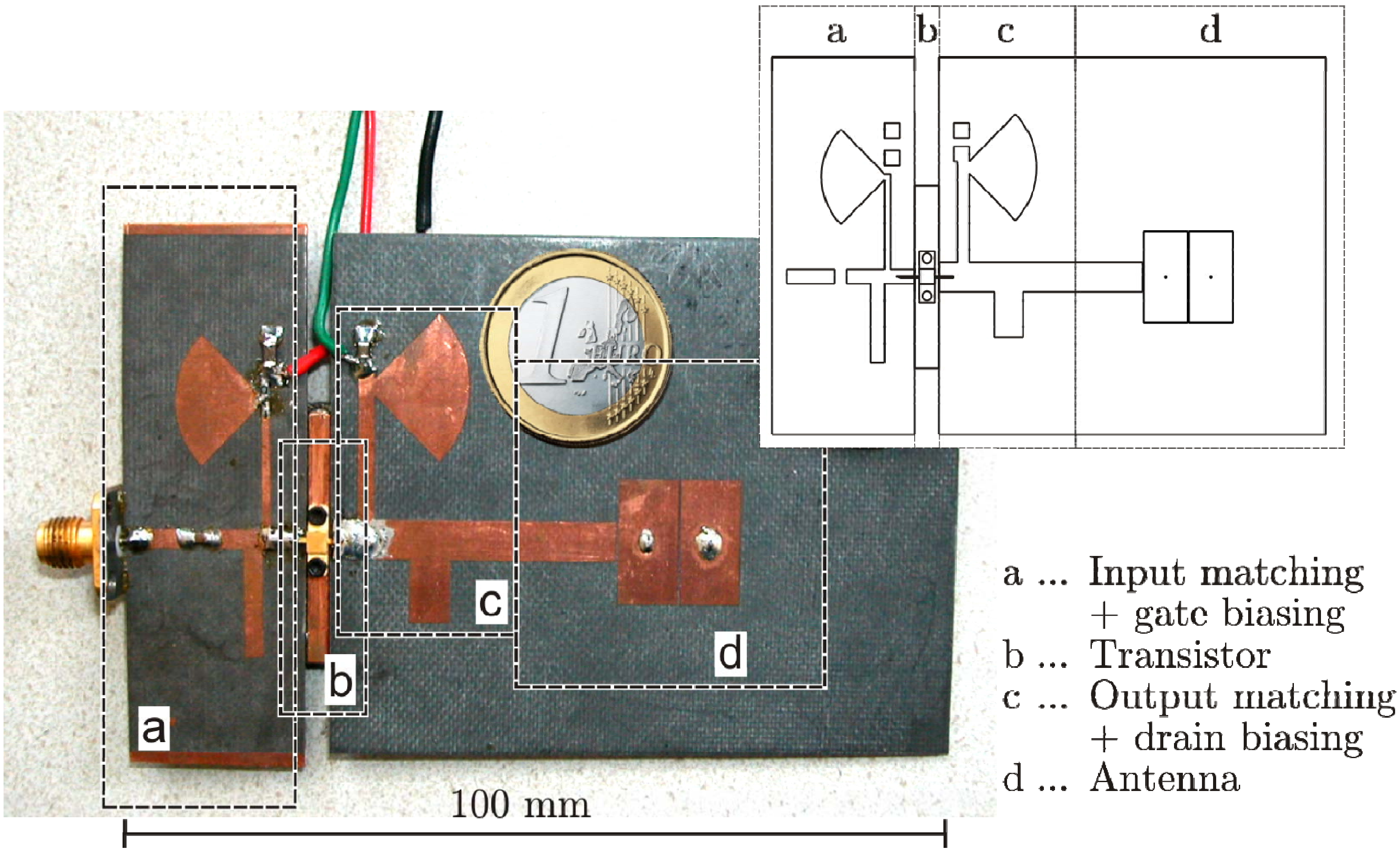






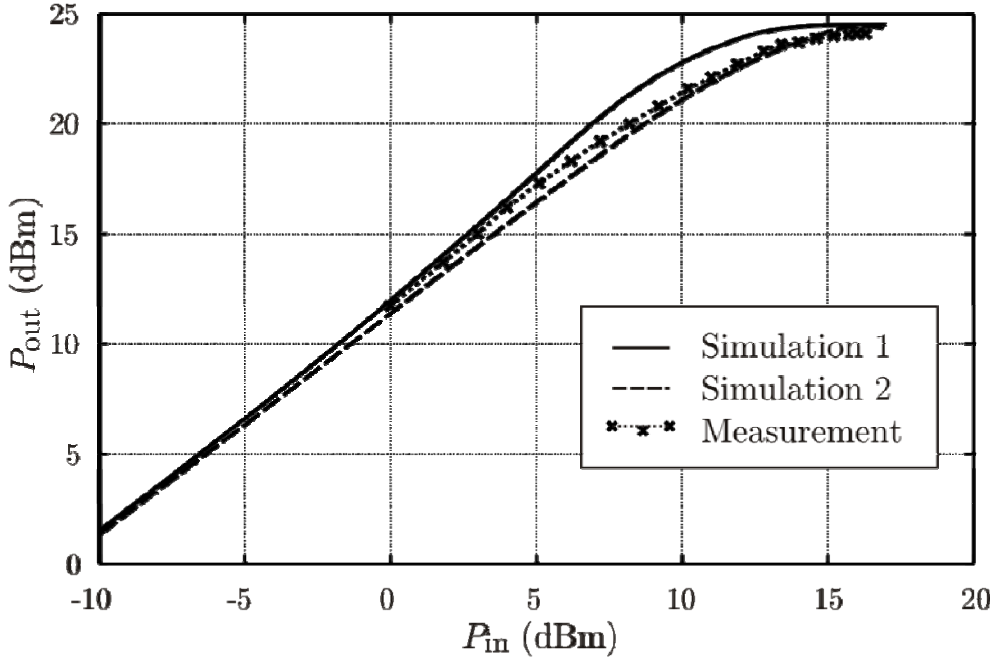
A Power Amplifier Integrated with a CRLH MM Antenn

Implementation



"A power amplifier integrated with a composite right/left-handed metamaterial antenna," Asia-Pacific Microwave Conference 2009, December 7 -10, 2009, Singapore, Paper TU4F-4, (C. M. Schmid, T. Itoh and A. Stelzer).

Measurements



Gain:

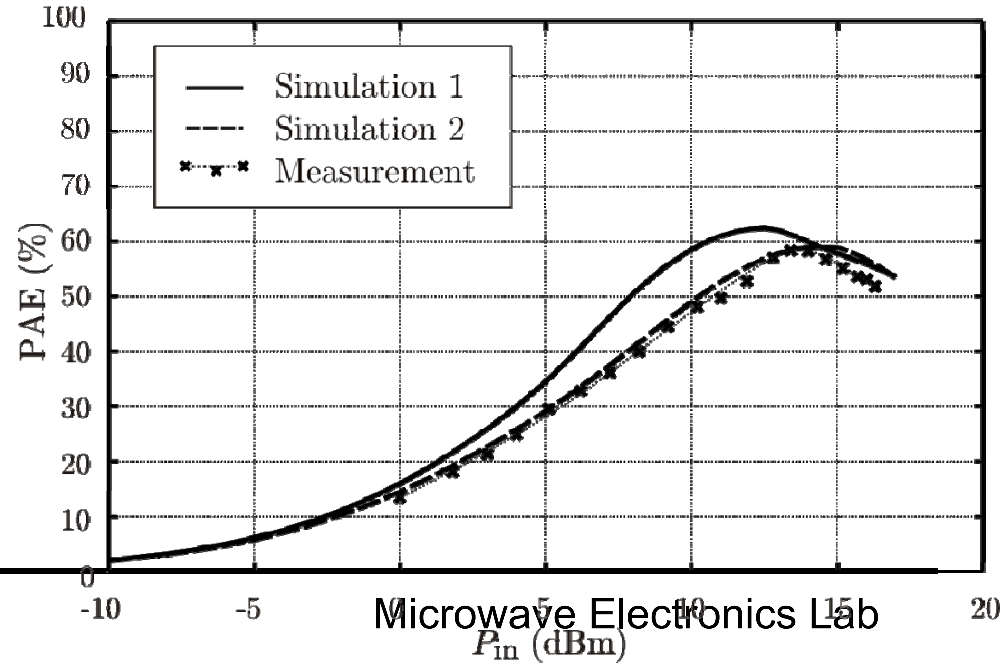
Simulation: 10.4 dB

Measurement: 10.2 dB

Power added efficiency (PAE):

Simulation: 62 %

Measurement: 58 %



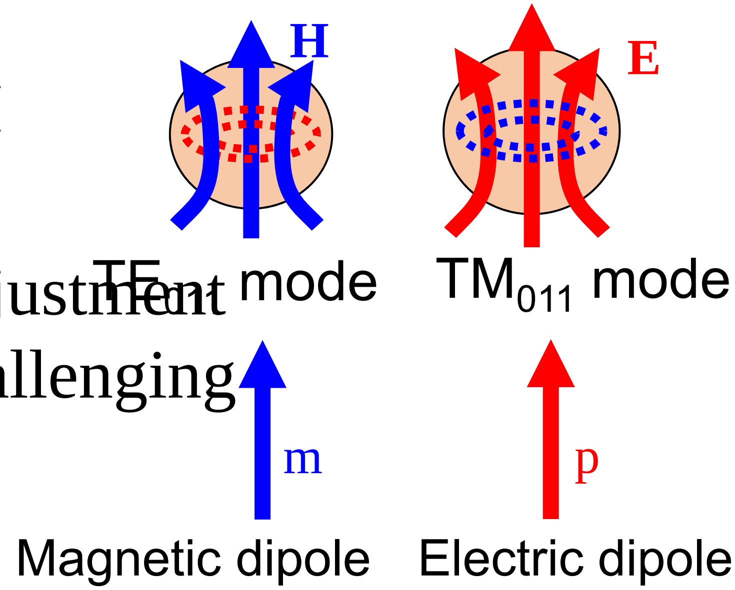
5. Dielectric Resonator Based LHM

LHM Structures Using DRs

1) Two-DR scheme

- **Configuration:** Combination of TE & TM resonances of DRs
- **Features**: Operational bands is narrow Adjustment of DR resonant frequencies may be challenging

[1] *C. L. Holloway et al., IEEE Trans. Antennas Propat., 51, 2596, 2003*



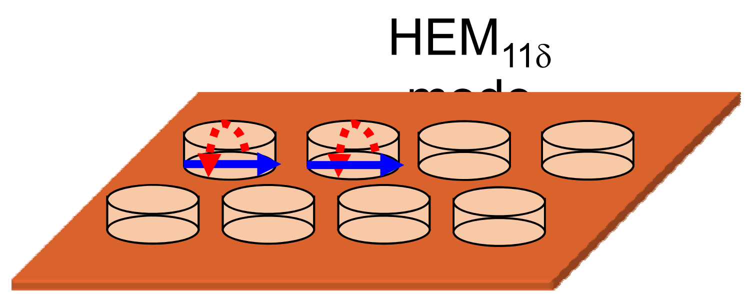
2) One-DR scheme

- **Configuration:** Mutual coupling
- **Features:**

  a) Wide operational band, compared to two-DR scheme

  b) The operation is sensitive to the arrangement of DRs .

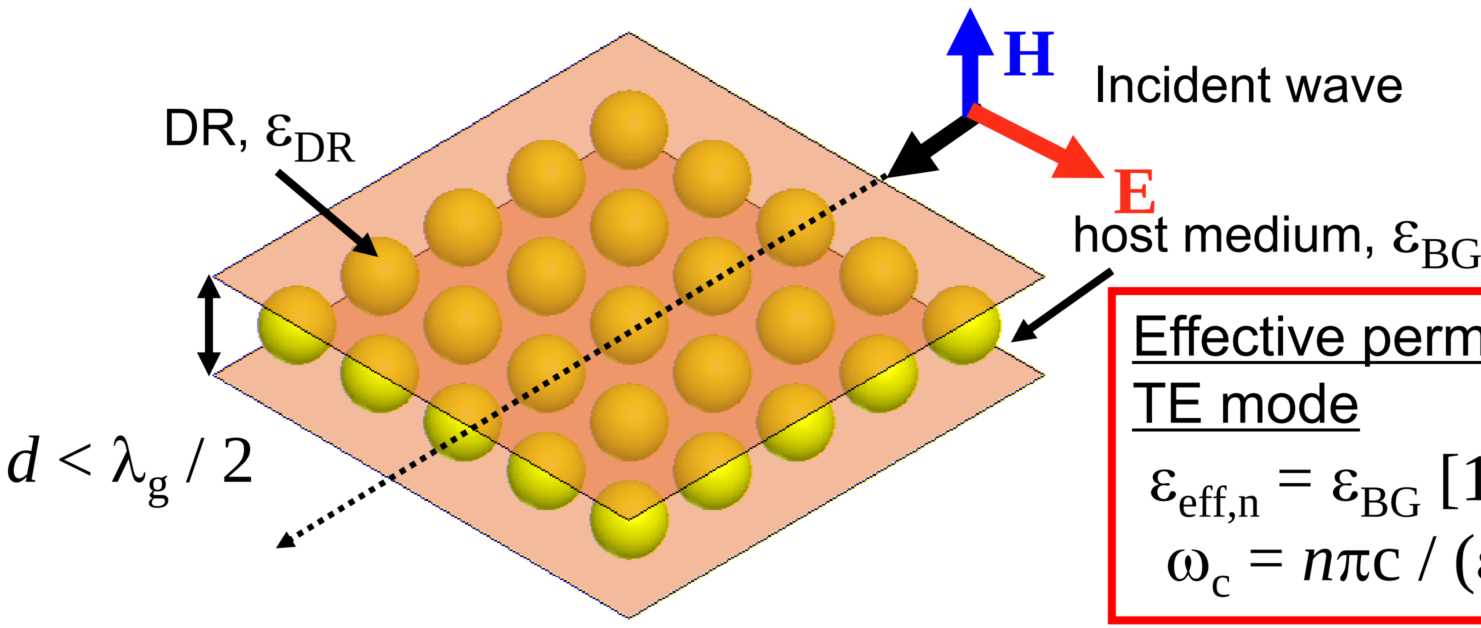
[2] *E. A. Semouchkina et al., IEEE Trans. MTT,53, 1477, 2005.*



3) One-DR Scheme in Cut-Off Background

- **Configuration:** Combination of TE-resonant DRs and negative epsilon background composed of cut-off parallel-plate waveguide
- **Features:**
  a) Fabrication tolerance is large compared to two-DR scheme
  b) Effective epsilon and mu can be designed separately.

[3] T. Ueda et al, *36th European Microwave Conference 2006, 435, 2006*

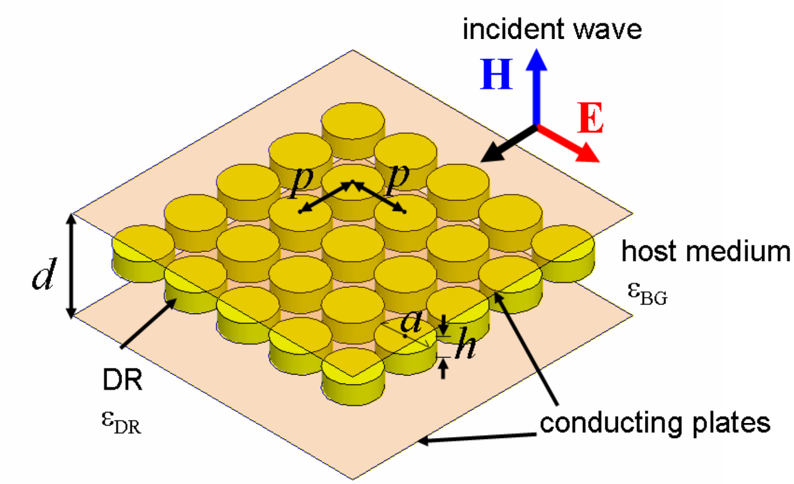


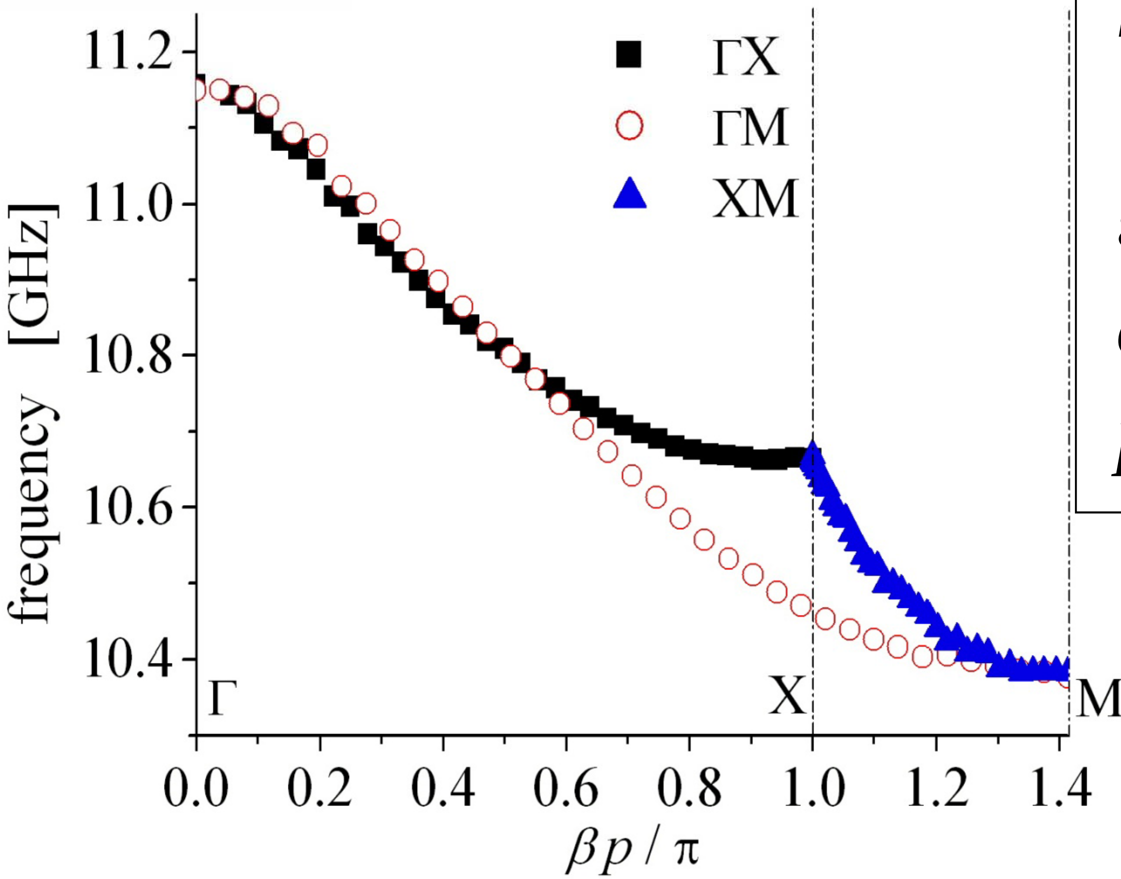
Effective permittivity of PPWG TE mode

$$\varepsilon_{eff,n} = \varepsilon_{BG}\,[1-(\omega_c/\omega)^2\,] < 0$$

$$\omega_c = n\pi c \,/\, (\varepsilon_{BG})^{1/2}\, d$$

Dispersion of 2D DR Array in Cutoff Waveguide





DR disc

$\varepsilon_{DR} = 38$

$a = 5.10$ mm

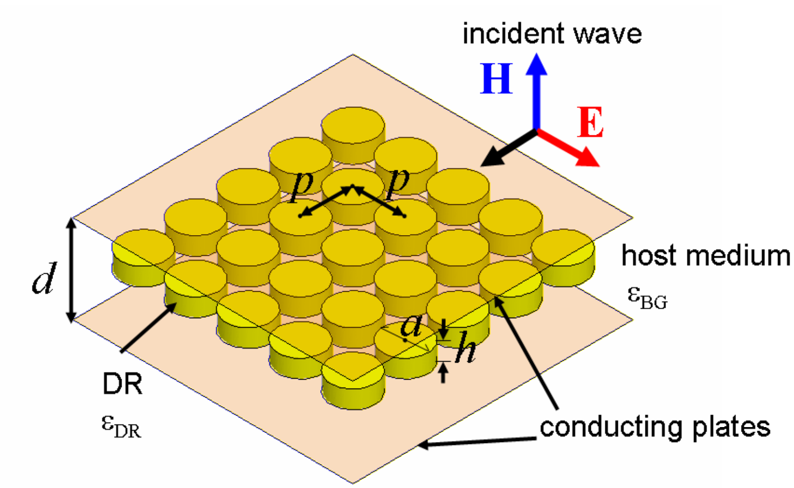
$h = 2.03$ mm

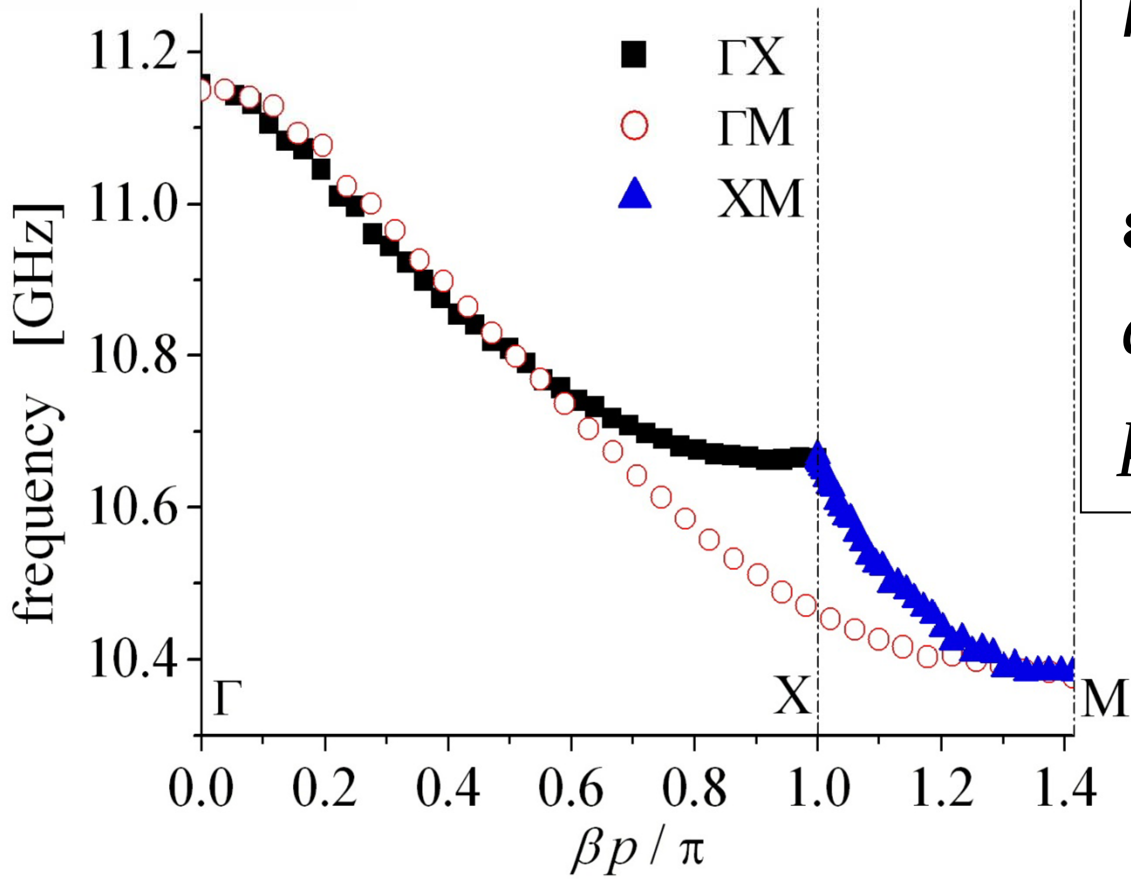
$\varepsilon_{BG} = 2.2$

$d = 5.00$ mm

$p = 6.00$ mm

Dispersion of 2D DR Array in Cutoff Waveguide





DR disc

$\varepsilon_{DR} = 38$

$a = 5.10$ mm

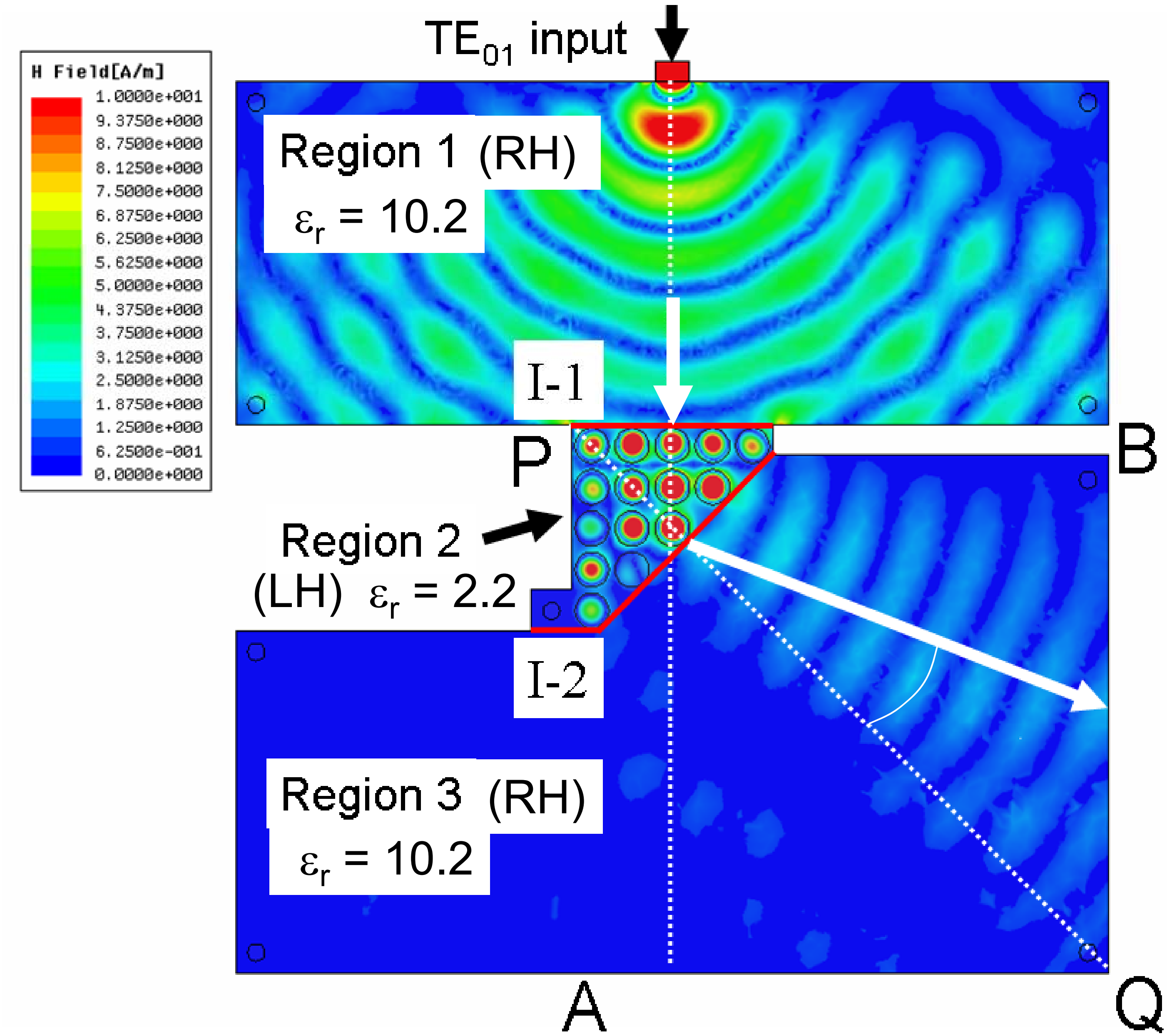
$h = 2.03$ mm

$\varepsilon_{BG} = 2.2$

$d = 5.00$ mm

$p = 6.00$ mm

Numerical Verification of Negative Refraction in 2-D RH-LH-RH structure



In Region 2, there are 15 DRs. Beam propagation along ΓX

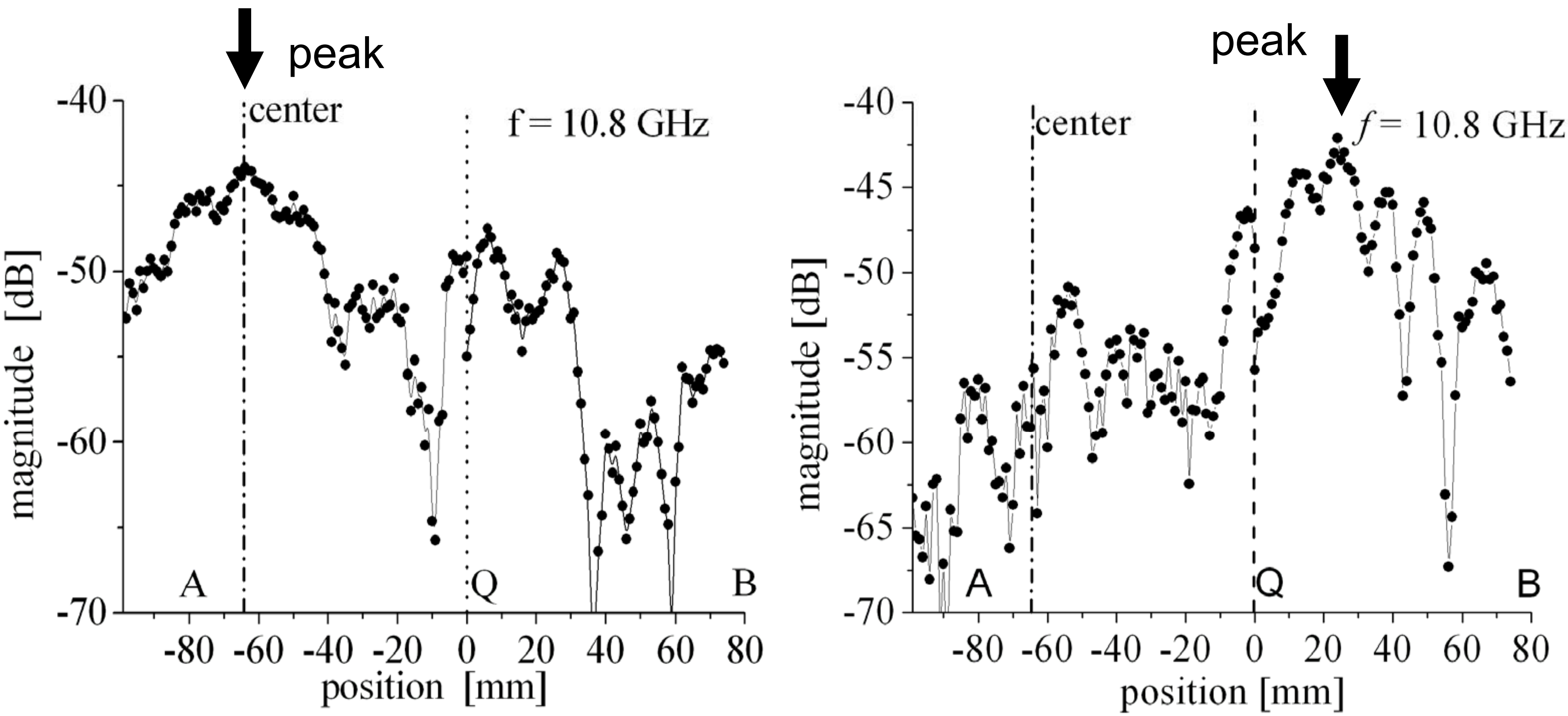
Incident angle $\theta_{LH} = 45$ deg

Transmitted angle $\theta_{LH} = -25$ deg

at $f = 10.8$ GHz

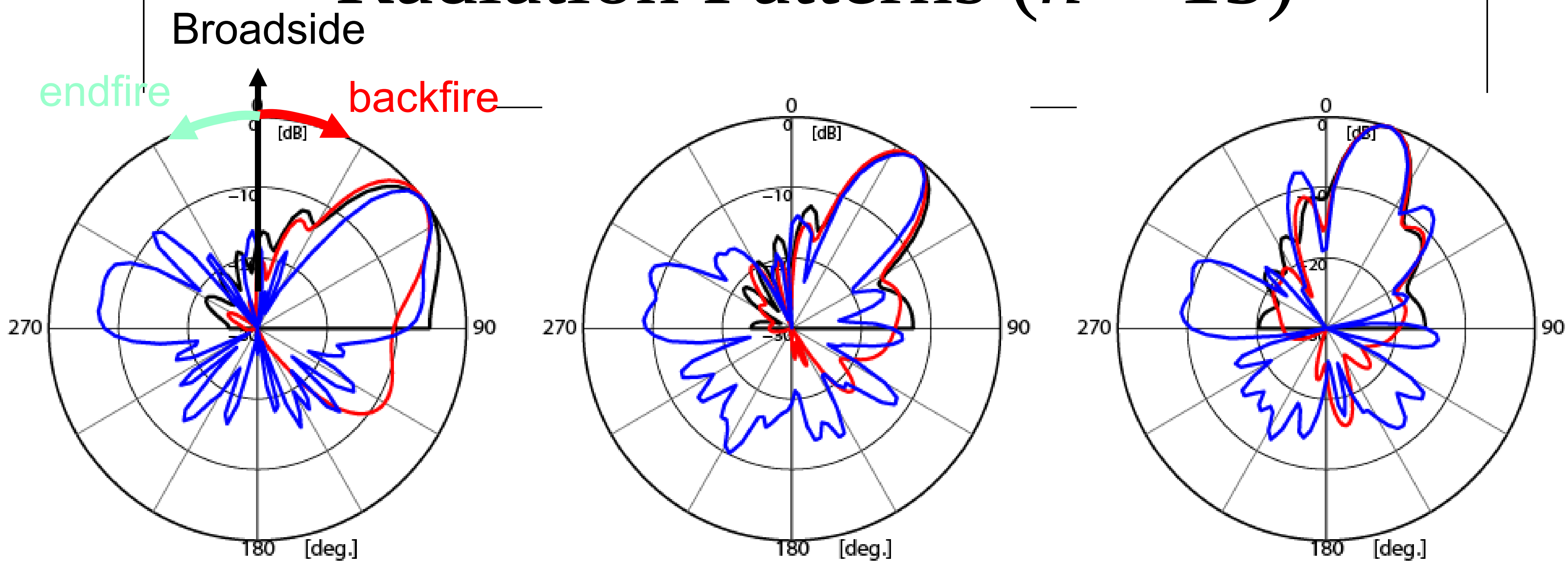
Measured Field Profiles

Fields were measured by a loop antenna as a magnetic probe at positions outside 5mm away from edge lines AQ and QB



RH prism inserted in Region 2   LH prism inserted in Region 2

Radiation Patterns (*n* = 15)



f = 10.9GHz

f = 11.0GHz

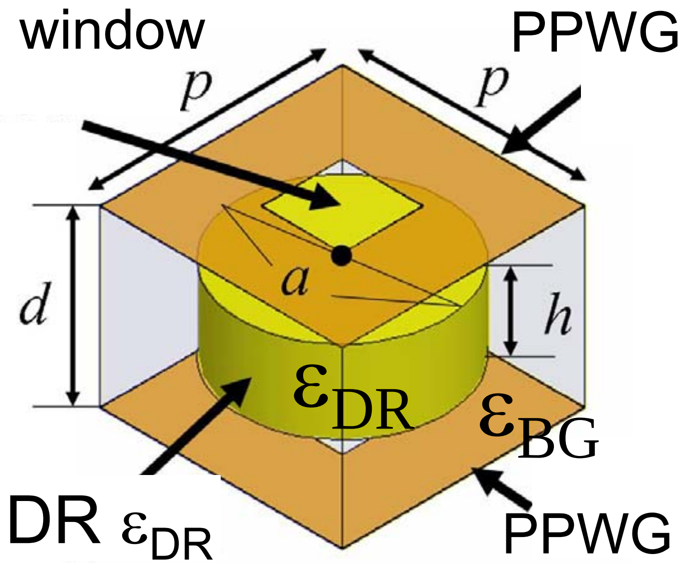
f = 11.1GHz

Array factor using damping constant α

Full-wave analysis

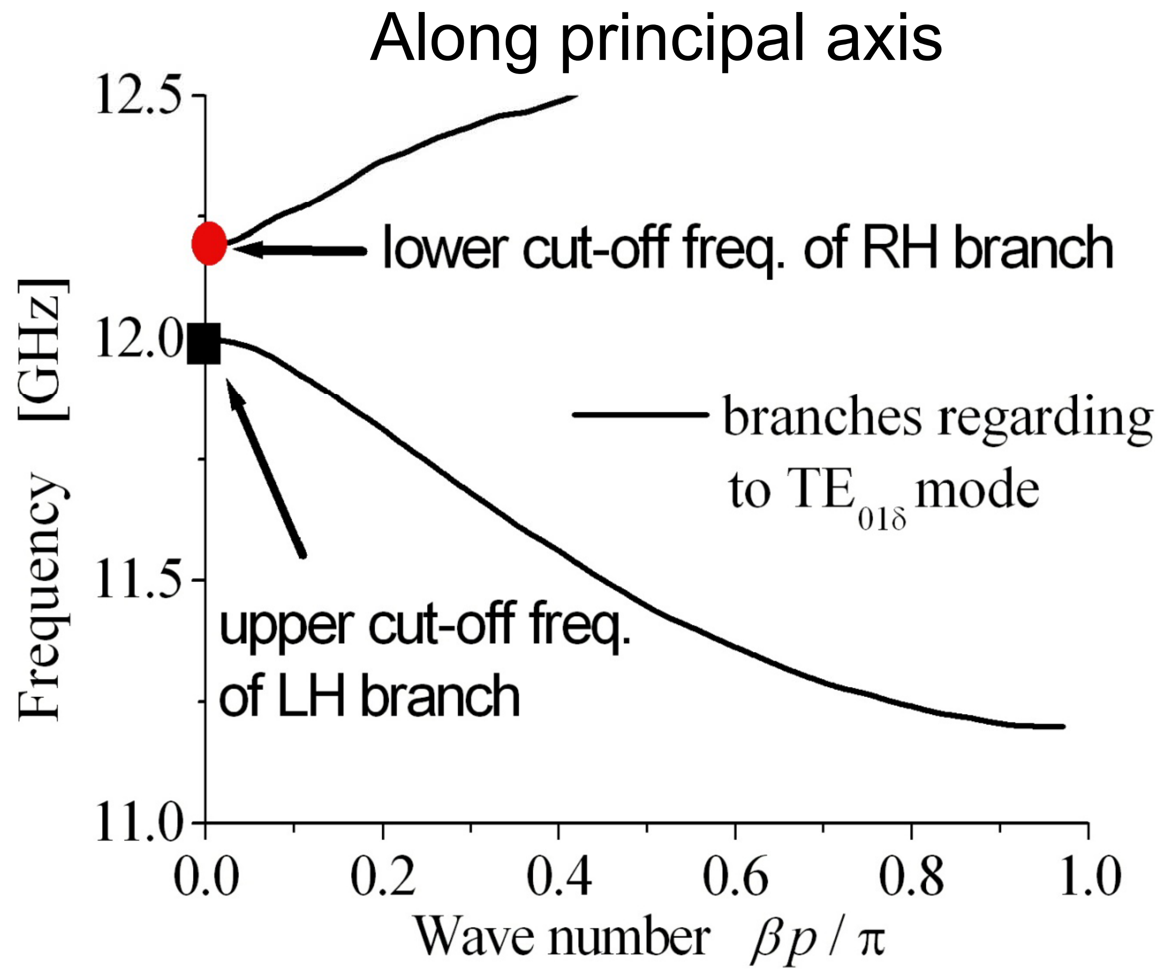
Measurement

Dispersion Diagram under Periodic Condition



ε_{DR} = 38
***a* = 5.10 mm**
***h* = 2.03 mm**
ε_{BG} = 2.2
***d* = 4.00 mm**
***p* = 6.00 mm**

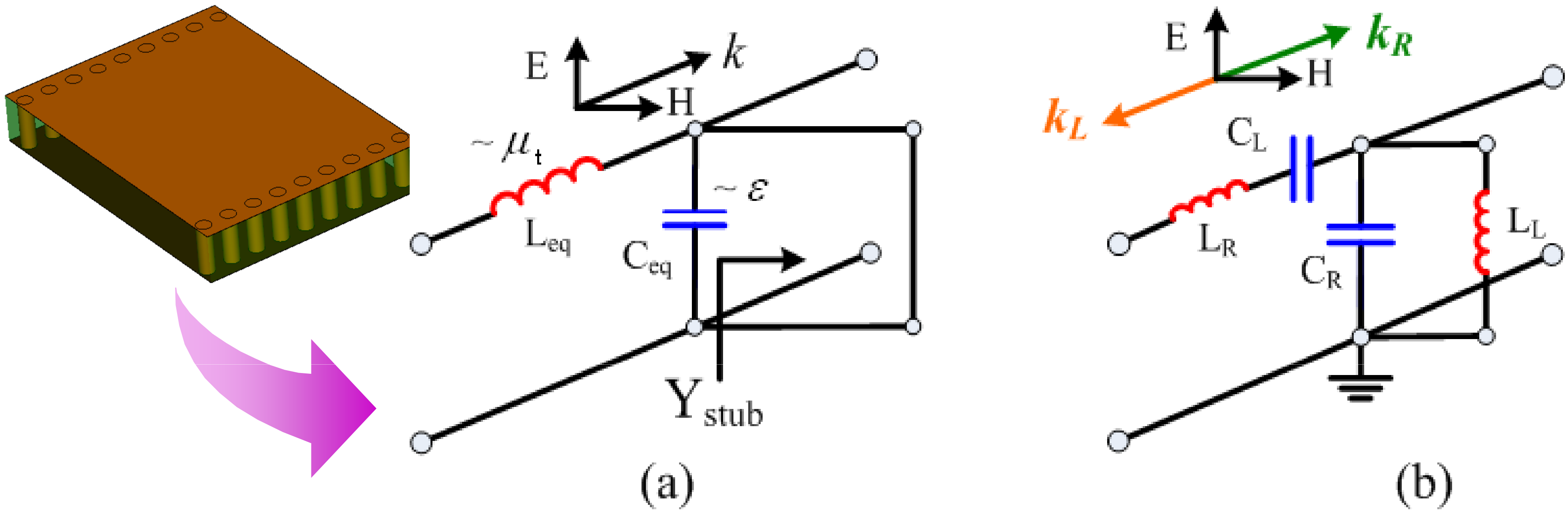
Open window: 2mm x 2mm



Unbalanced case

6. SIW CRLH

Unit Cell Design and Analysis

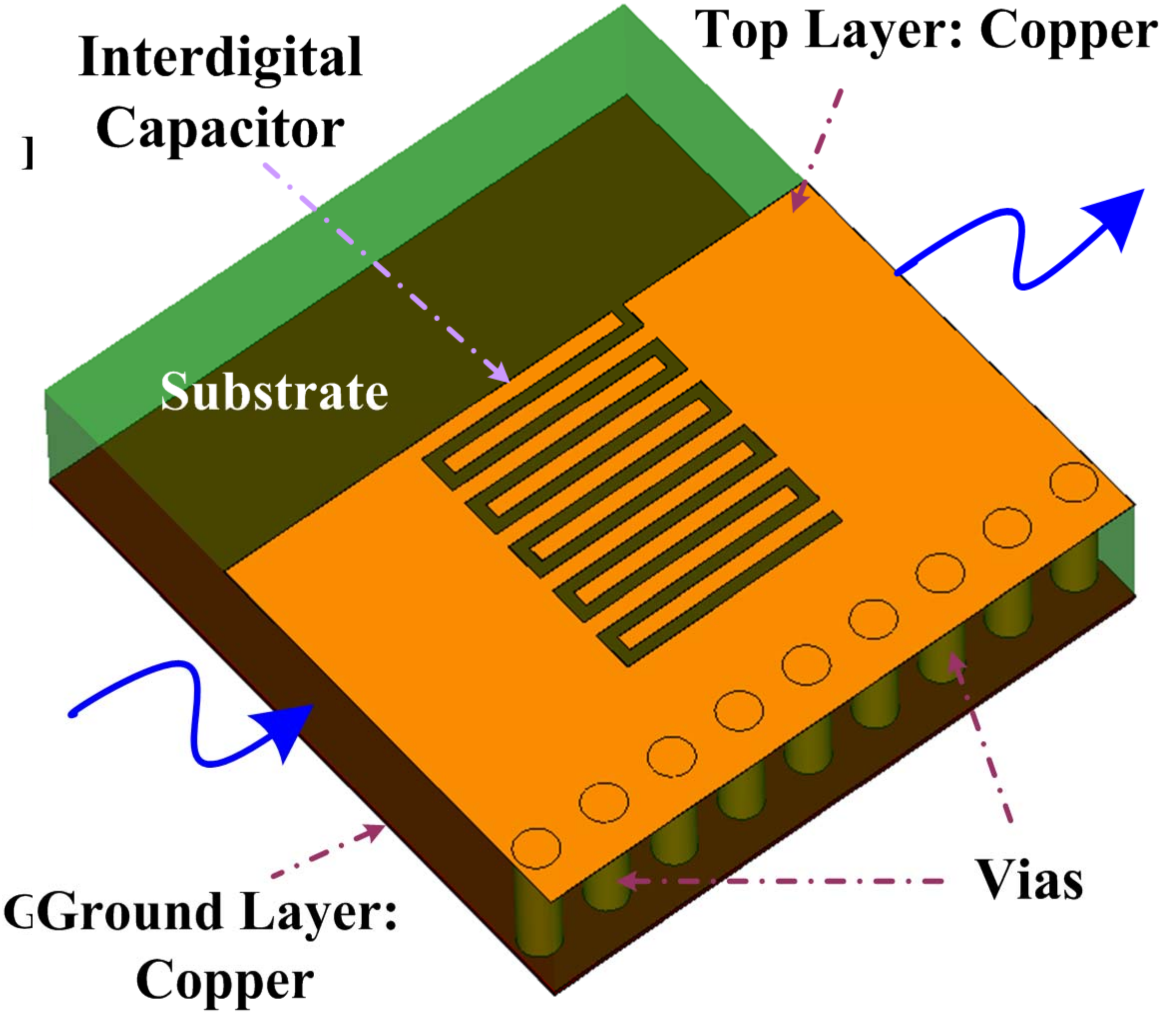


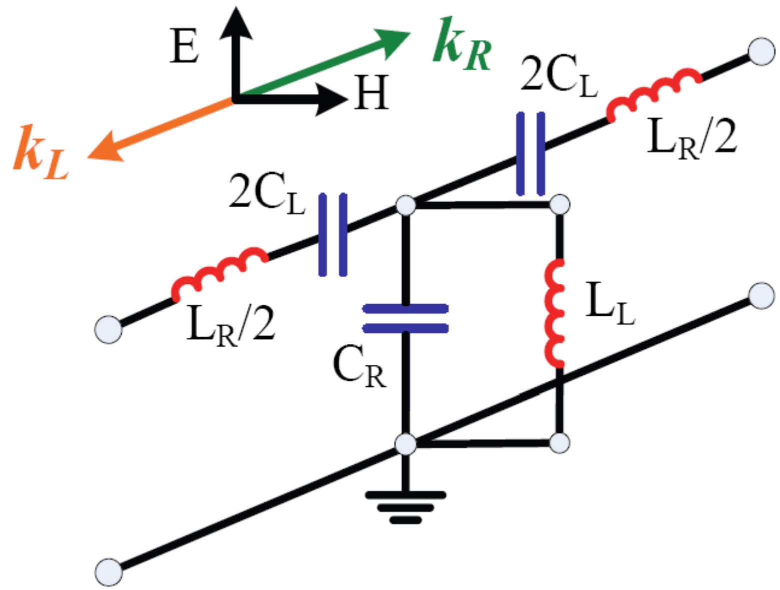
(a) Equivalent circuit model for the SIW and HMSIW Transmission Lines

(b) Circuit model for CRLH Transmission Lines

Only the series capacitor is missing and needs to be introduced !

Unit Cell Design and Analysis





Proposed CRLH-based SIW or HMSIW Unit Cell Design

C_L: Interdigital Capacitor

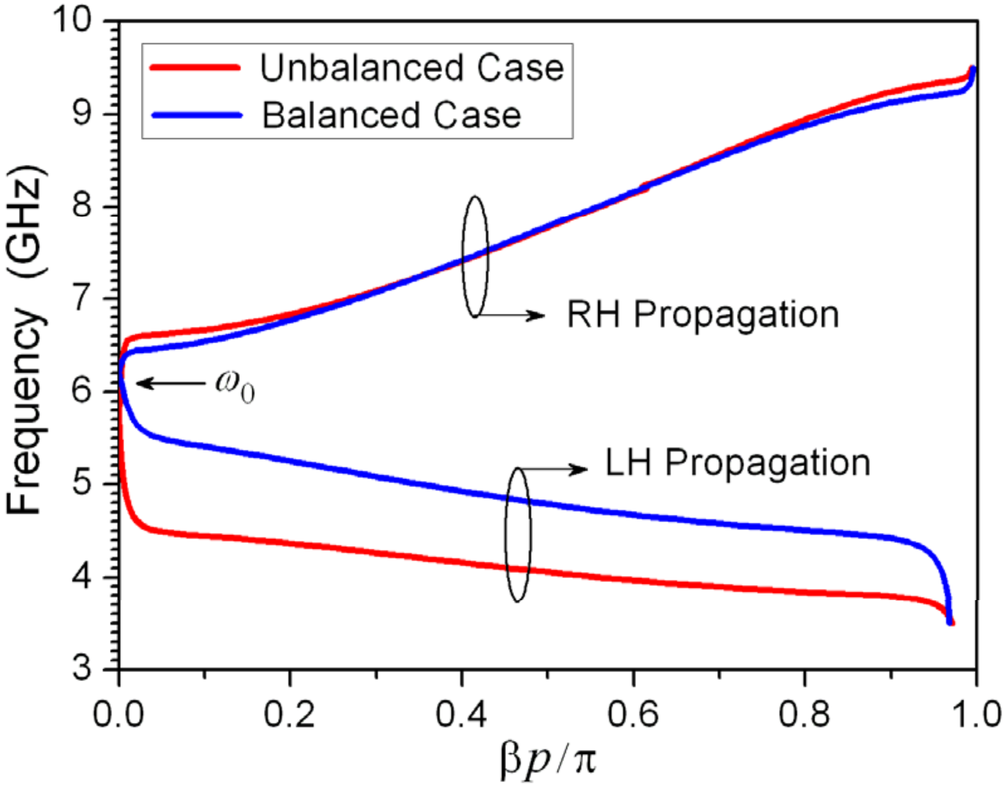
L_L: From Via-walls

C_R: Shunt Capacitance

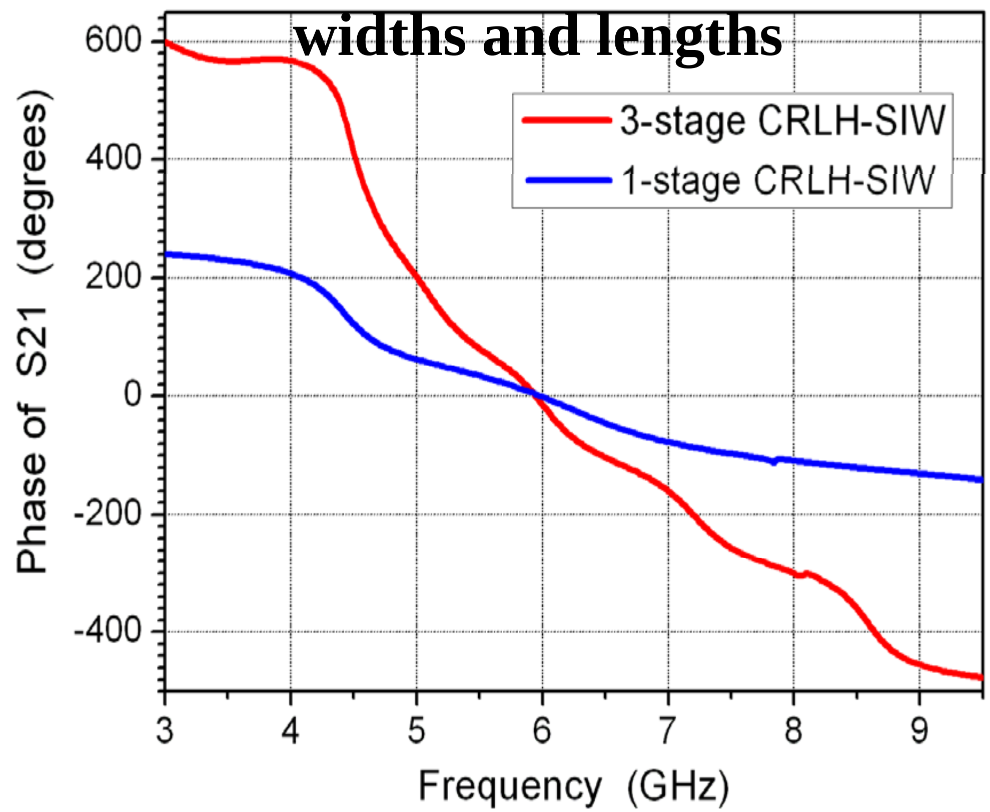
L_R: Series Inductance

- ☑ **Simple Implementation !**
- ☑ **The series capacitor (C_L) can be easily controlled.**

Unit Cell Design and Analysis



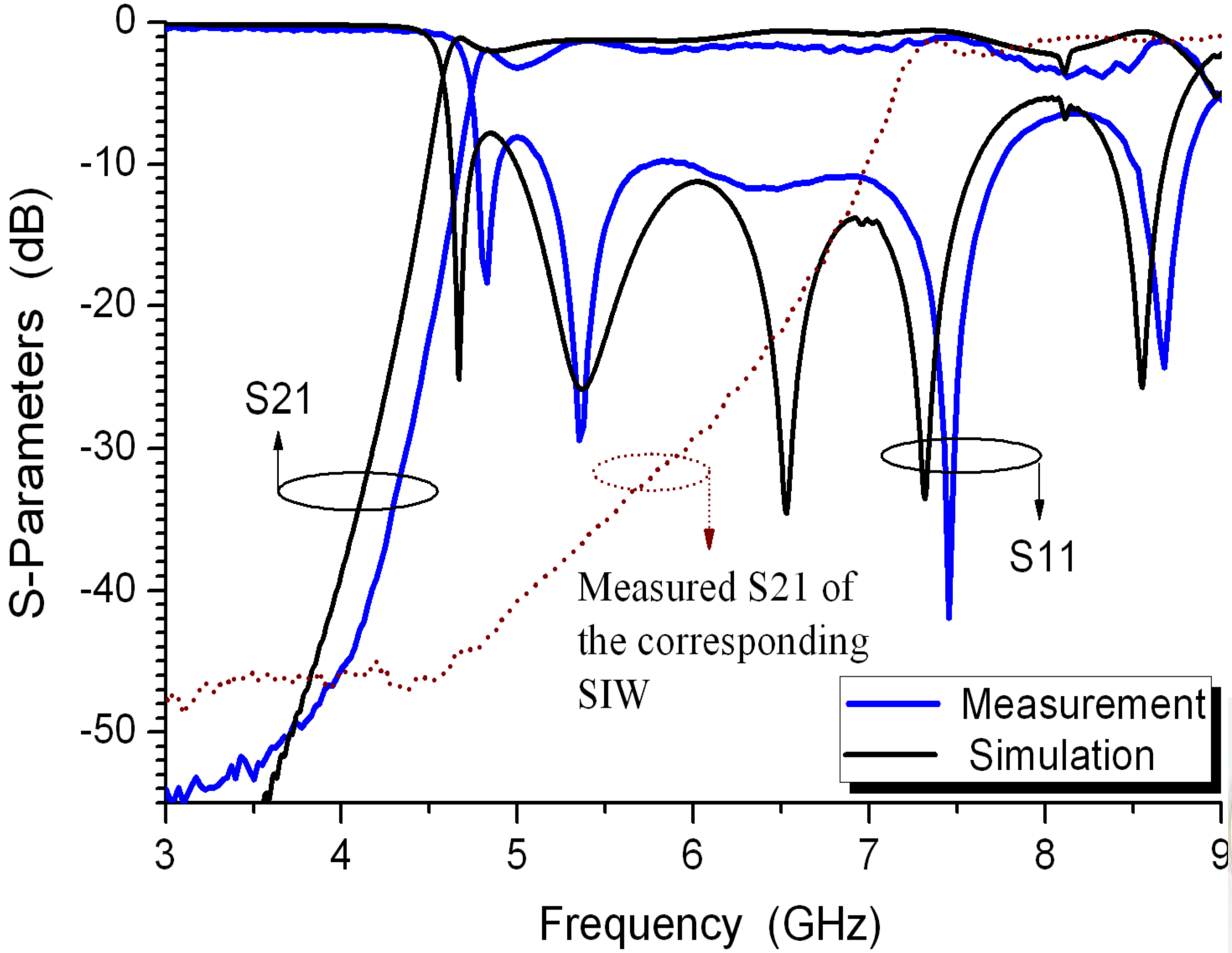
Dispersion diagram of the CRLH SIW unit cells: Balanced case and Unbalanced case are realized by choosing different slot widths and lengths



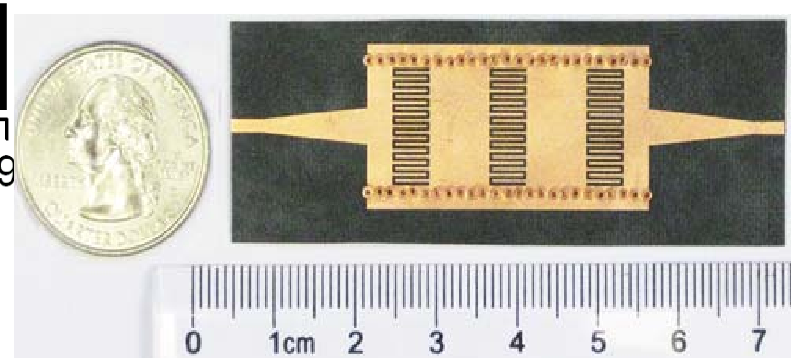
Unwrapped S_{21} phase for the corresponding one- and three-stage balanced CRLH SIW unit cells

Backward Wave

CRLH SIW and HMSIW TLs



- **Measured and Simulated S-Parameters for the fabricated SIW and CRLH-SIW TLs**



- **Without changing the waveguide**
- **size, the passband has been extended to a lower frequency! (from 7.4 GHz to 4.8 GHz)**

7. Conclusions

Conclusions

- Transmission line approach of metamaterials
- Nonresonant structures

  with low losses and broad bandwidth
- Concept of composite right/left-handed (CRLH) material
- Dispersion engineering capability
- Passive components and antennas with unique features
- DR based and SIW based CRLH