Electromagnetic Band Gap Structures for Noise Mitigation in Printed Circuit Boards and Packages

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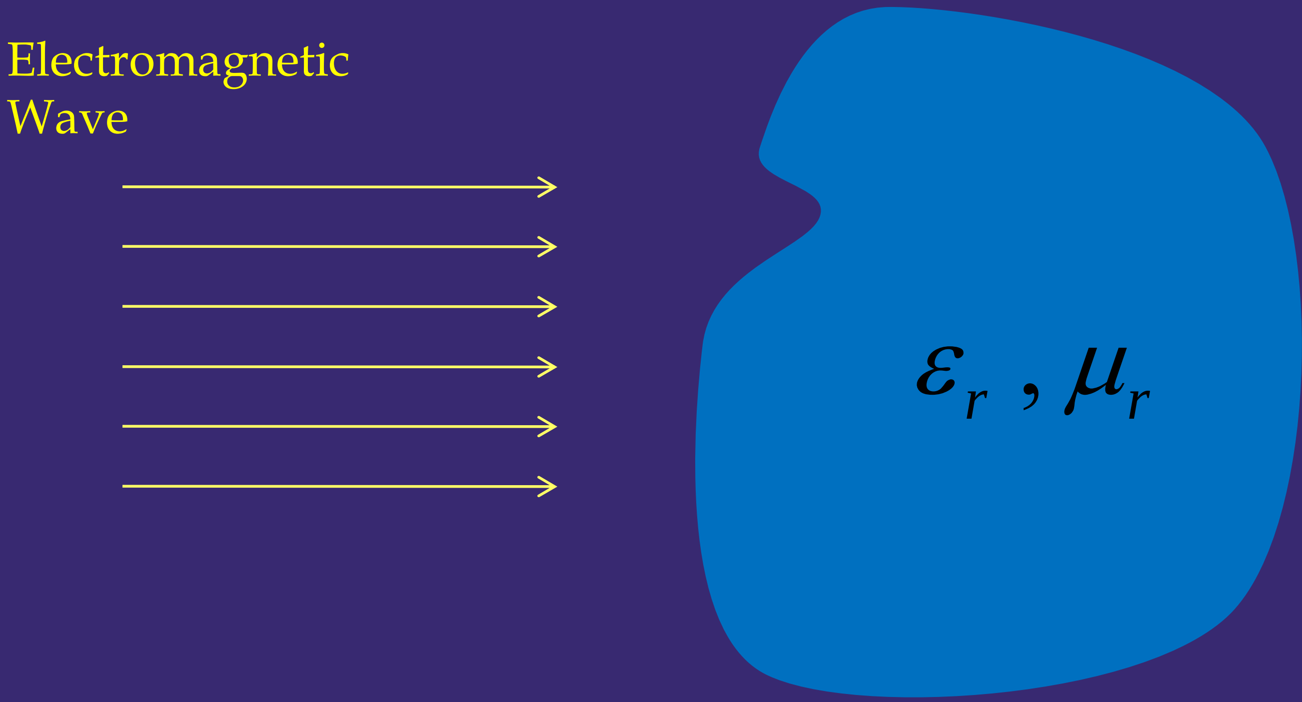
Omar M. Ramahi
University of Waterloo
Waterloo, Ontario, Canada

gratitude… to many wonderful colleagues, friends and brilliant graduate students who are too many to mention

…

but too good to never forget!

Traditional Material!!



The only properties an electromagnetic wave sees:

1. Electric permittivity, ε
2. Magnetic Permeability, μ

Metamaterial and Bandgap Structures!!

But what if

$$\varepsilon_r < 0, \mu_r < 0$$

or

$$\varepsilon_r > 0, \mu_r < 0$$

or

$$\varepsilon_r < 0, \mu_r > 0$$

or even if

$$\varepsilon_r \approx 0, \text{ or } \mu_r \approx 0$$

Negative Index or Double Negative Media

Maxwell Equations

$$\beta \times \mathrm{E} = \mu\, \mathrm{H}$$

$$\beta \times \mathrm{H} = -\varepsilon\, \mathrm{E}$$

$$\beta \times \mathrm{E} = -\mu\, \mathrm{H}$$

$$\beta \times \mathrm{H} = \varepsilon\, \mathrm{E}$$

Positive media
Or Right Handed

Negative media
Or Left Handed

Dispersion Relationship:

$$\omega^2 \varepsilon\mu = \beta_x^2 + \beta_y^2 \qquad \text{; positive media}$$

$$\omega^2 \varepsilon\mu = \beta_x^2 + \beta_y^2 \qquad \text{; negative media}$$

Index of Refraction:
Need Consistent Interpretation with ME

$$n^2 = \varepsilon \mu$$

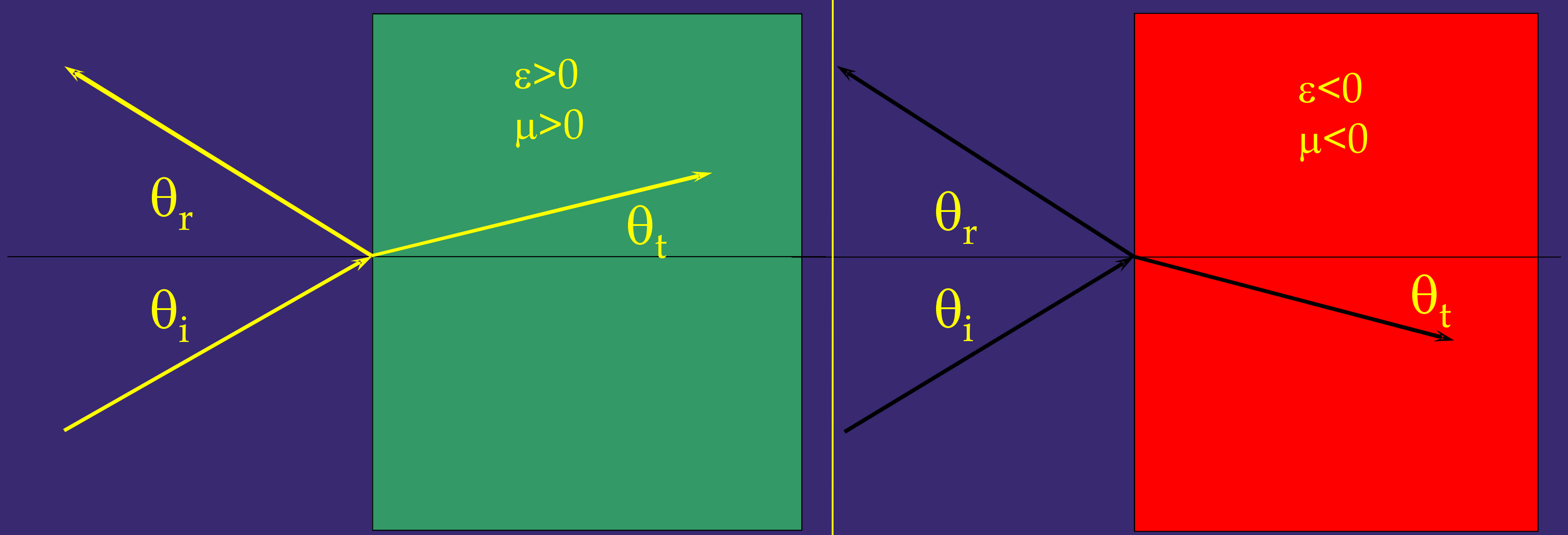
$n = \pm 1$

$n = +1;$ positive media

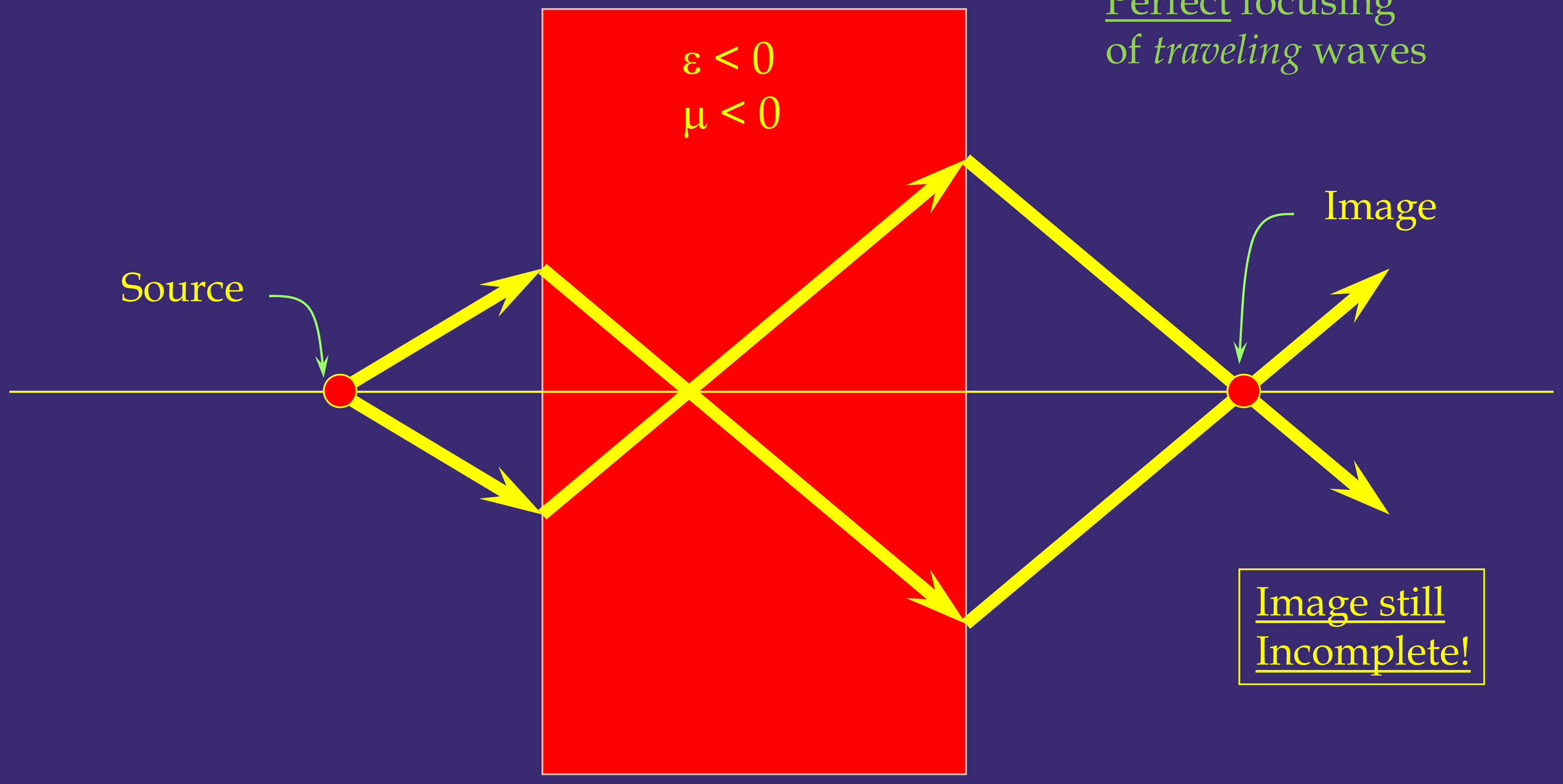
$n = -1;$ negative media

The case of μ , ε < 0

Positive Index Medium | Negative Index Medium



Flat Lens!
(without optical axis!)

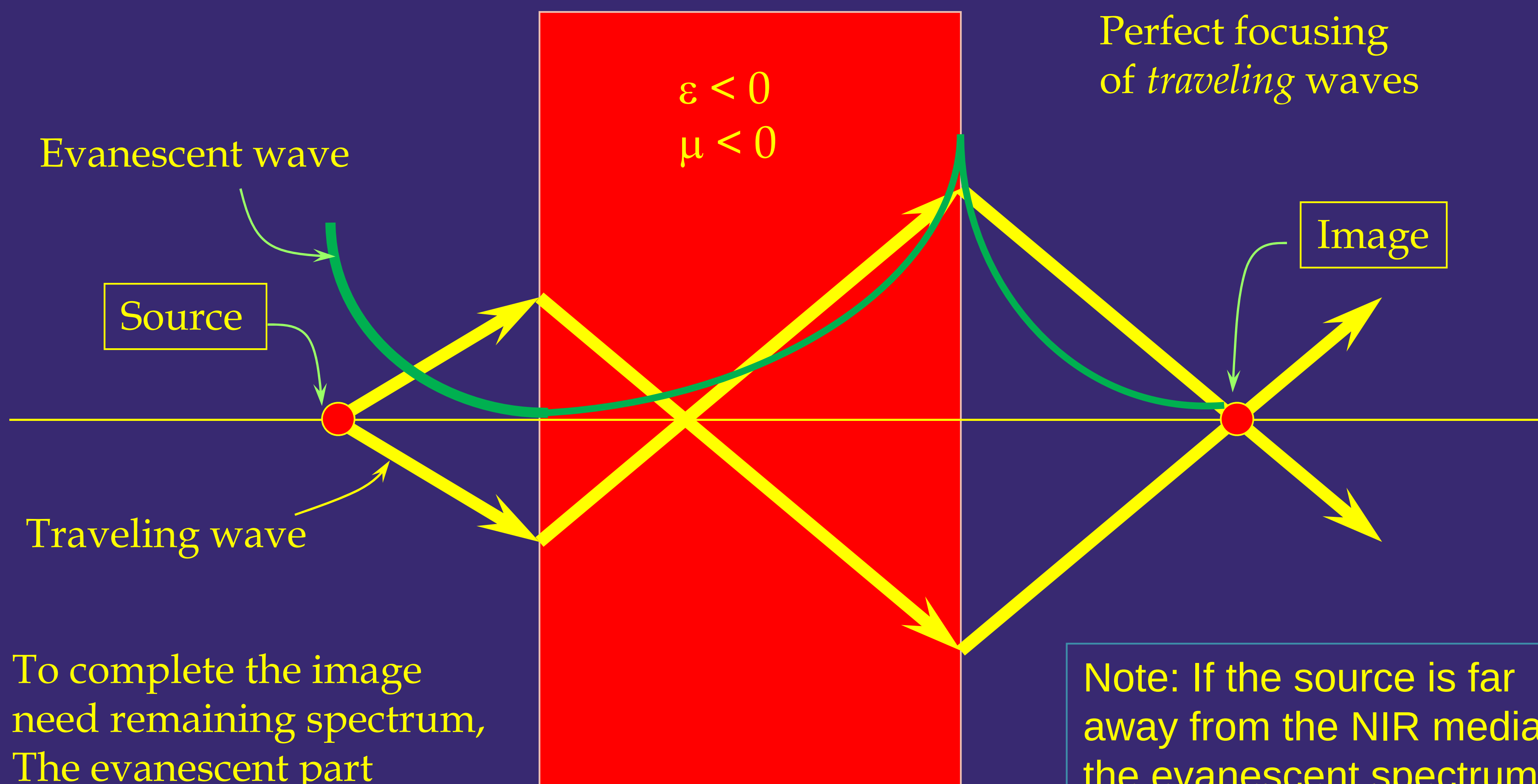


Perfect focusing of *traveling* waves

Image still Incomplete!

Flat Lens!

Perfect focusing
of *traveling* waves



To complete the image
need remaining spectrum,
The evanescent part

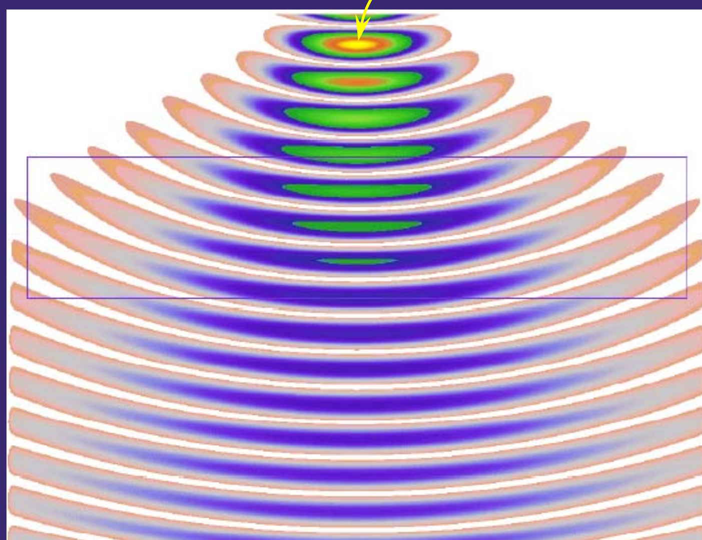
Note: If the source is far away from the NIR media, the evanescent spectrum will be lost forever.

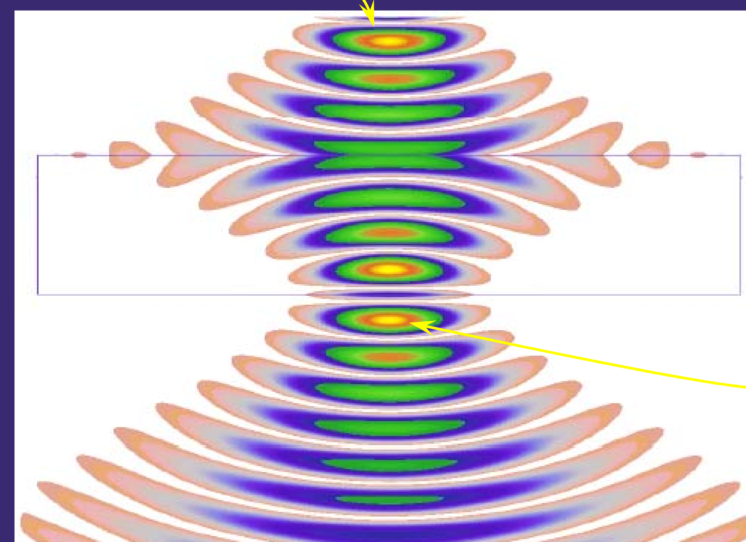
Time-Domain Simulation

Right Handed medium

Left Handed medium

Source

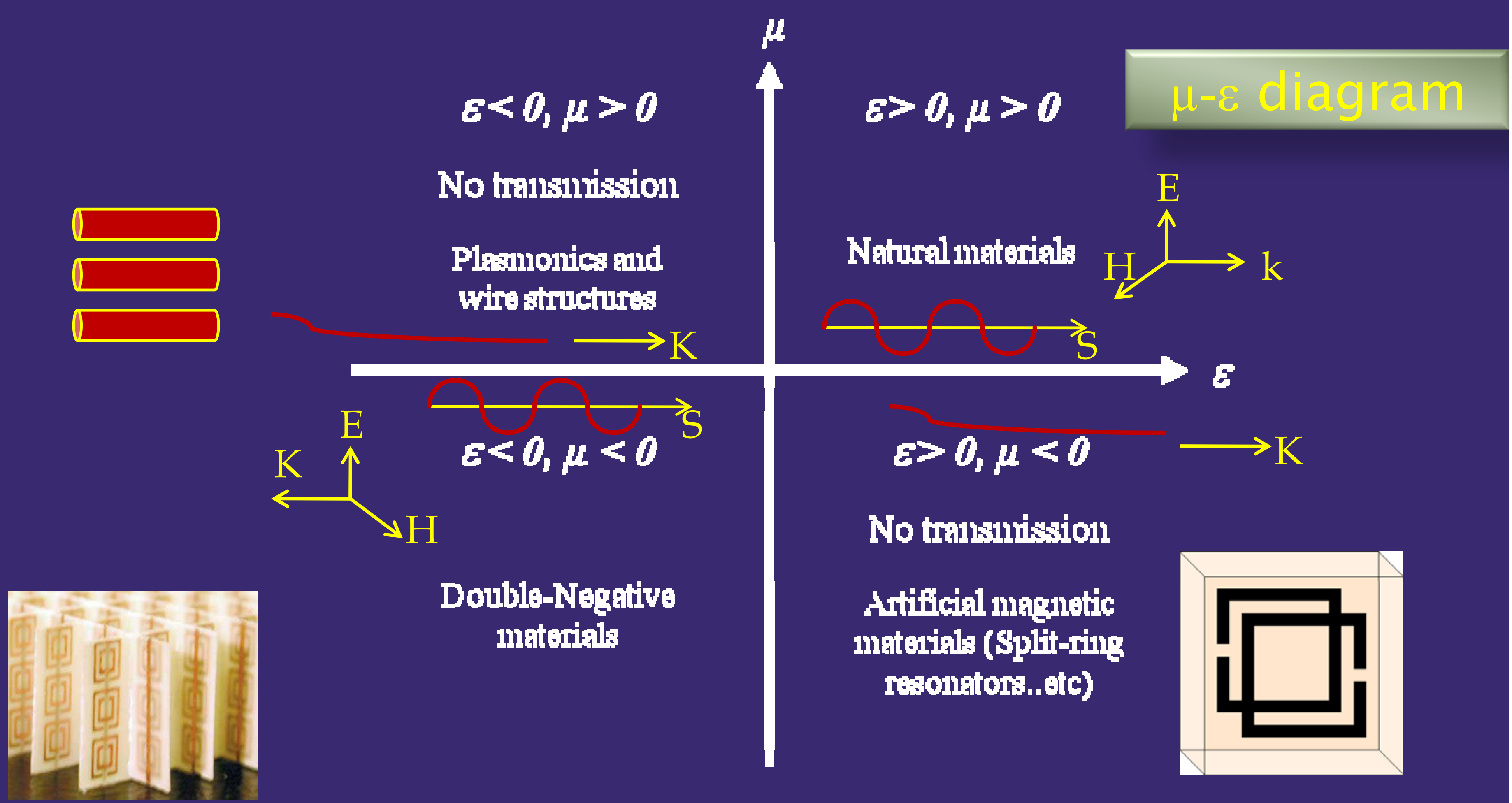




Image

Source: Zilkowski; Optics Express, April 2002

More possibilities



Epsilon near-zero materials!

Metamaterial!!

But what if

$$\varepsilon_r < 0, \mu_r < 0$$

or

$$\varepsilon_r > 0, \mu_r < 0$$

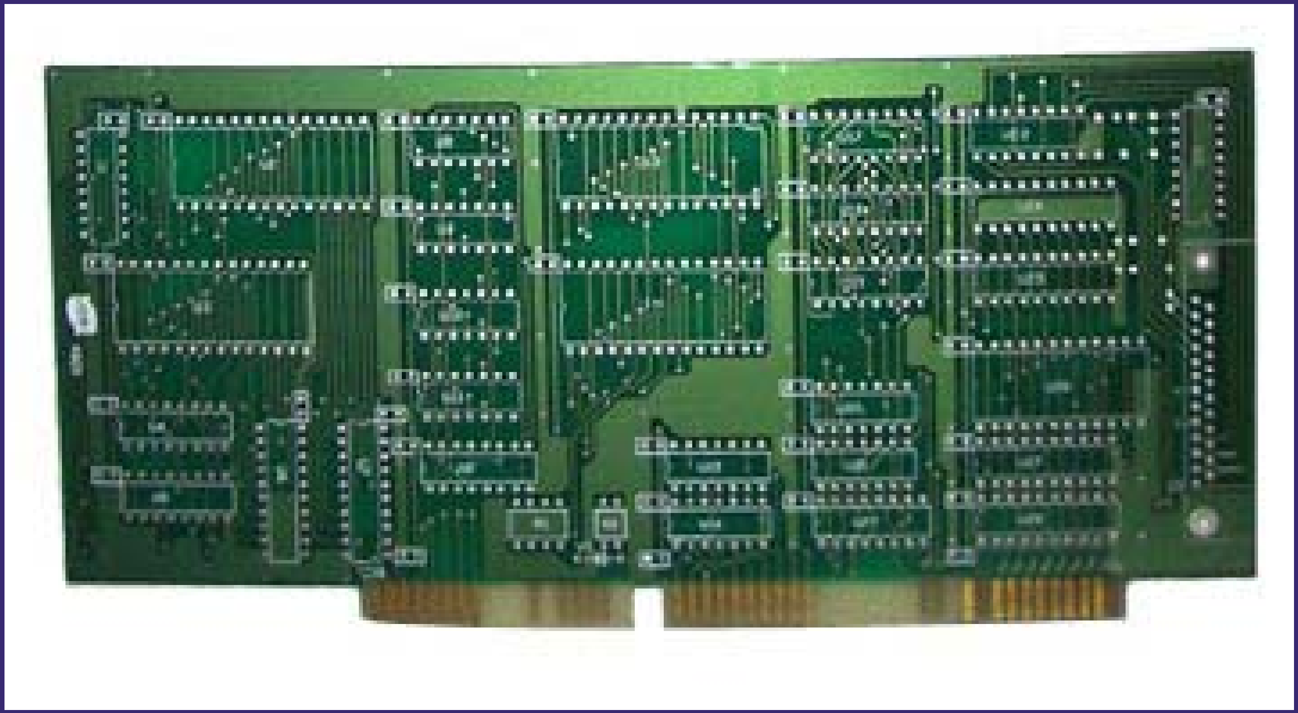
or

$$\varepsilon_r < 0, \mu_r > 0$$

or even if

$$\varepsilon_r \approx 0, \text{ or } \mu_r \approx 0$$

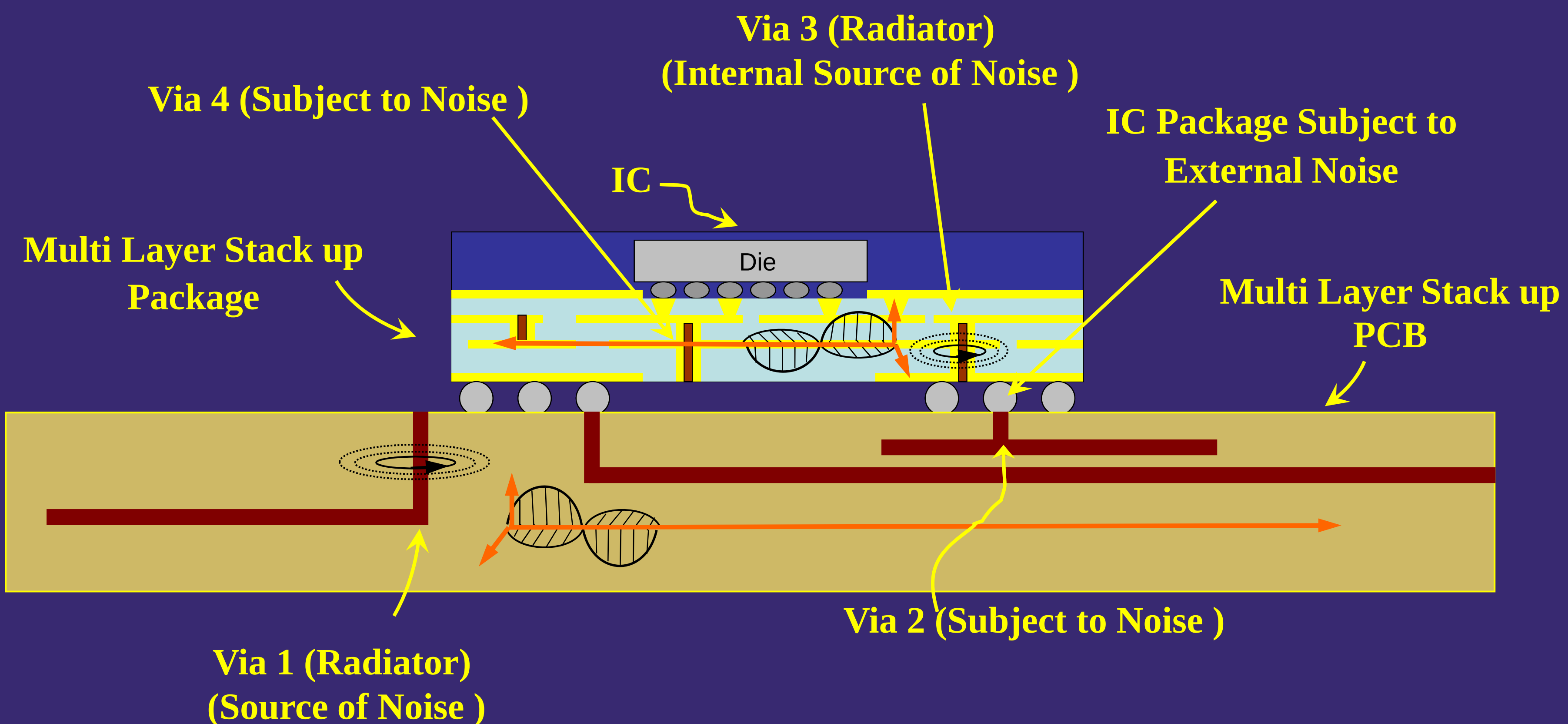
Electromagnetic Compatibility in PCBs and Packages



University of Waterloo

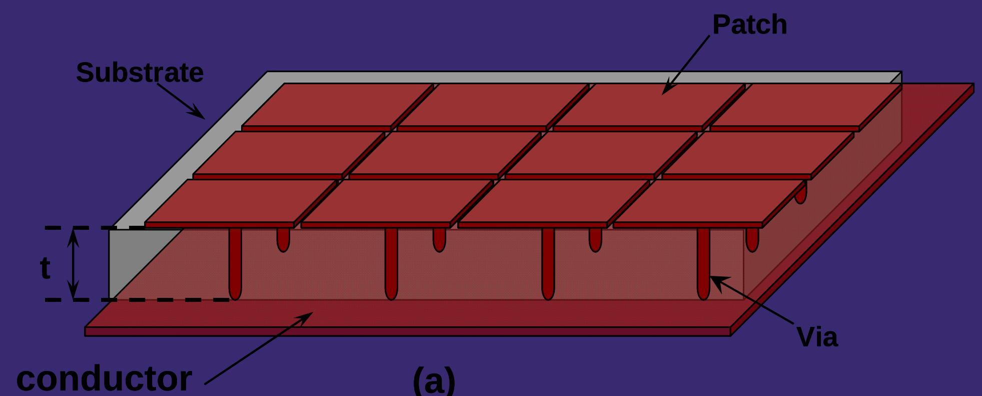
Noise… noise…noise …

IC subject to Internal and External Noise

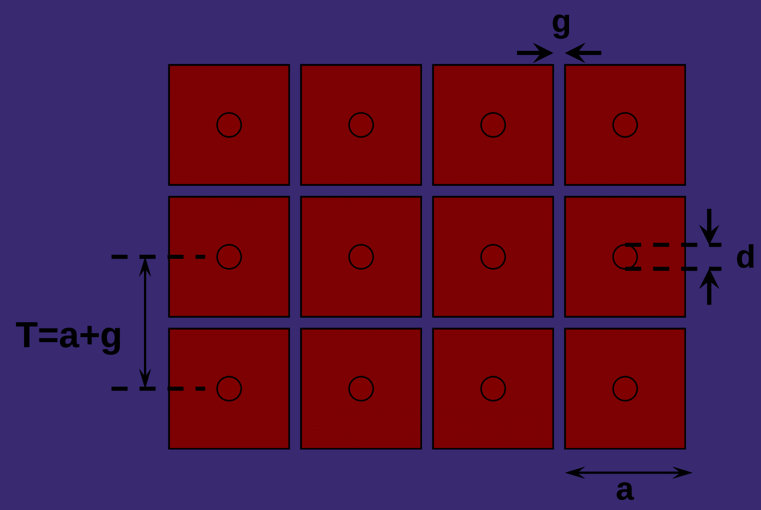


Electromagnetic Band Gap Structures
In reality, a single negative media …
or metamaterial!

EBGs Can Take Various Shapes

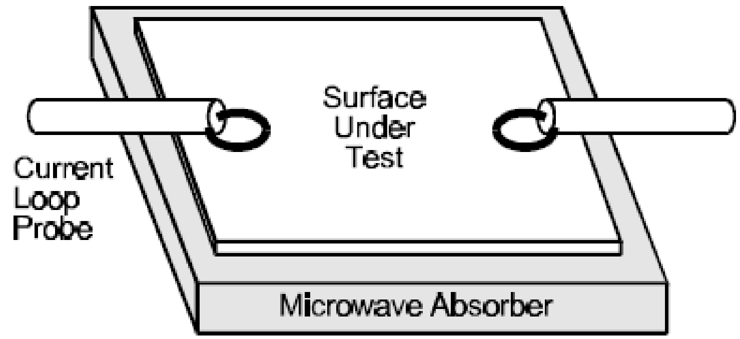


(a)

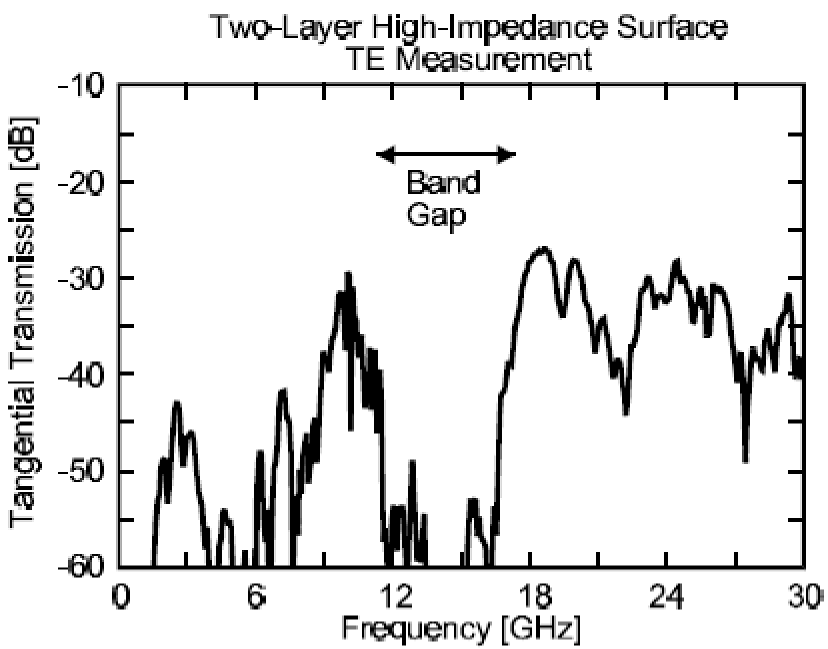


(b)

Textured (High Impedance) Surfaces Ideal for EMI/EMC Applications



2.2 TE surface wave measurement using small loop antennas



.3 TE surface wave transmission data on a textured surface

Source: D. Seivenpiper, High Impedance Electromagnetic Surfaces, PhD Thesis, UCLA, 1999

Textured (High Impedance) Surfaces Ideal for EMI/EMC Applications

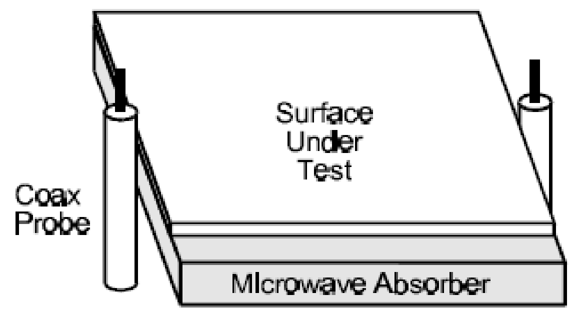


Figure 7.1.1 TM surface wave measurement using monopole probe antennas

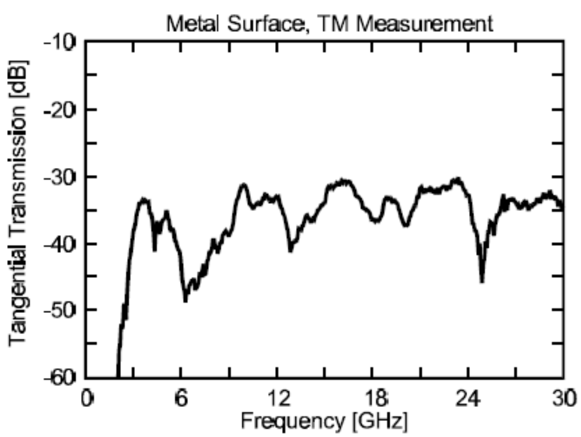


Figure 7.1.3 TM surface wave transmission data on a flat metal surface

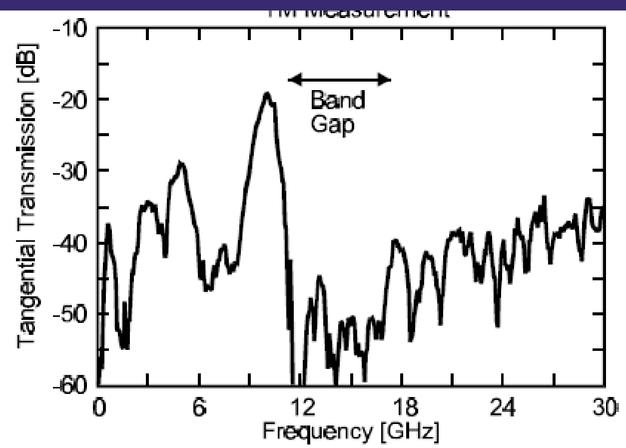
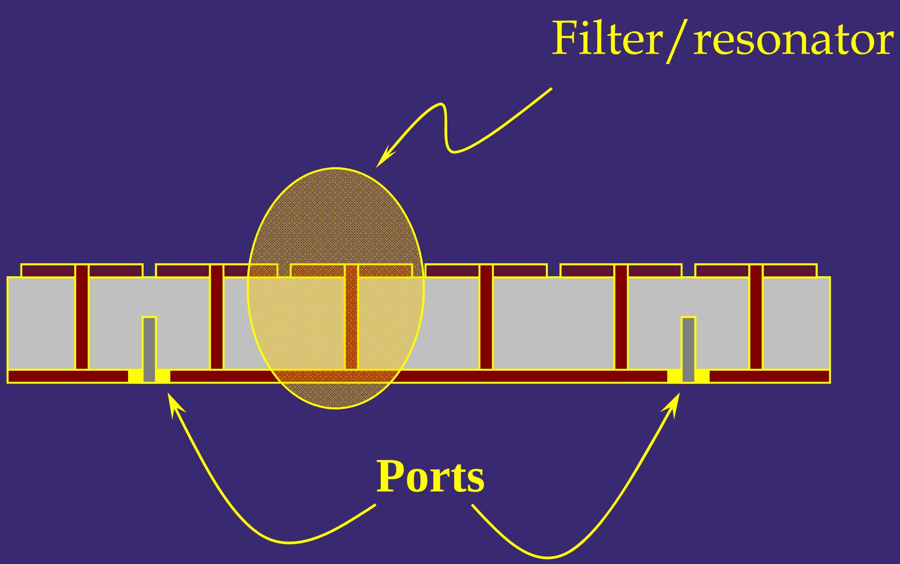
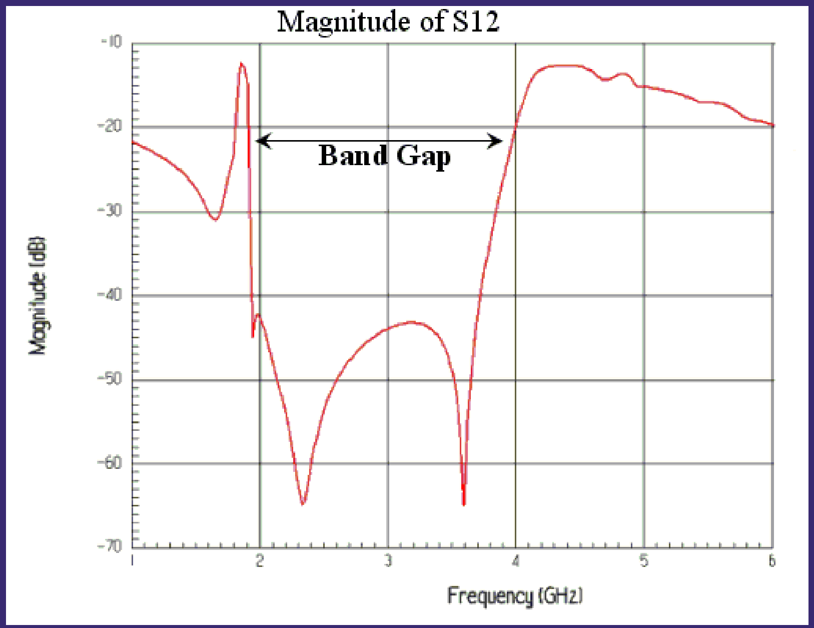


Figure 7.1.4 TM surface wave transmission data on a textured surface

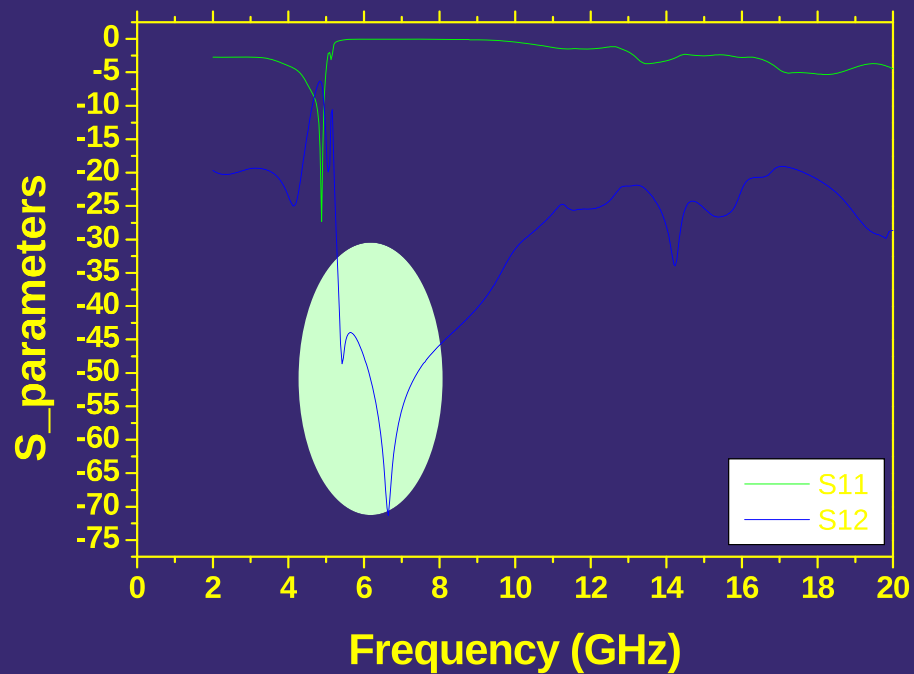
Source: D. Seivenpiper, High Impedance Electromagnetic Surfaces, PhD Thesis, UCLA, 1999

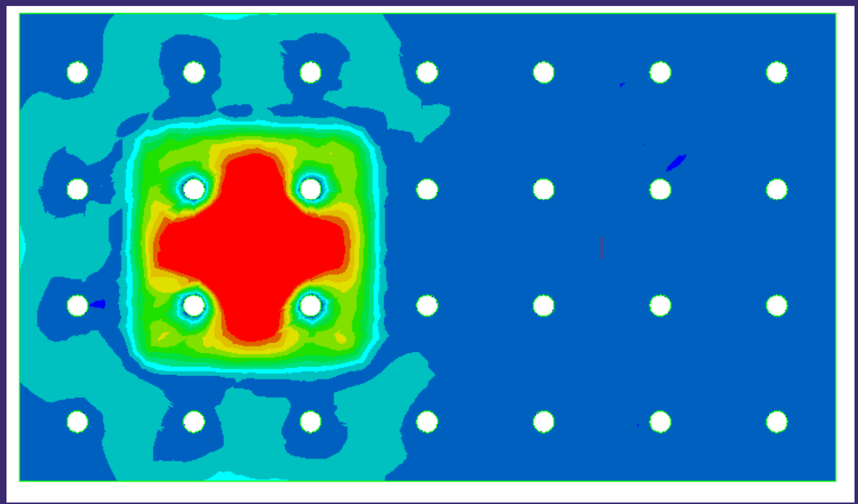
Design of EBG structure using S-parameters simulation



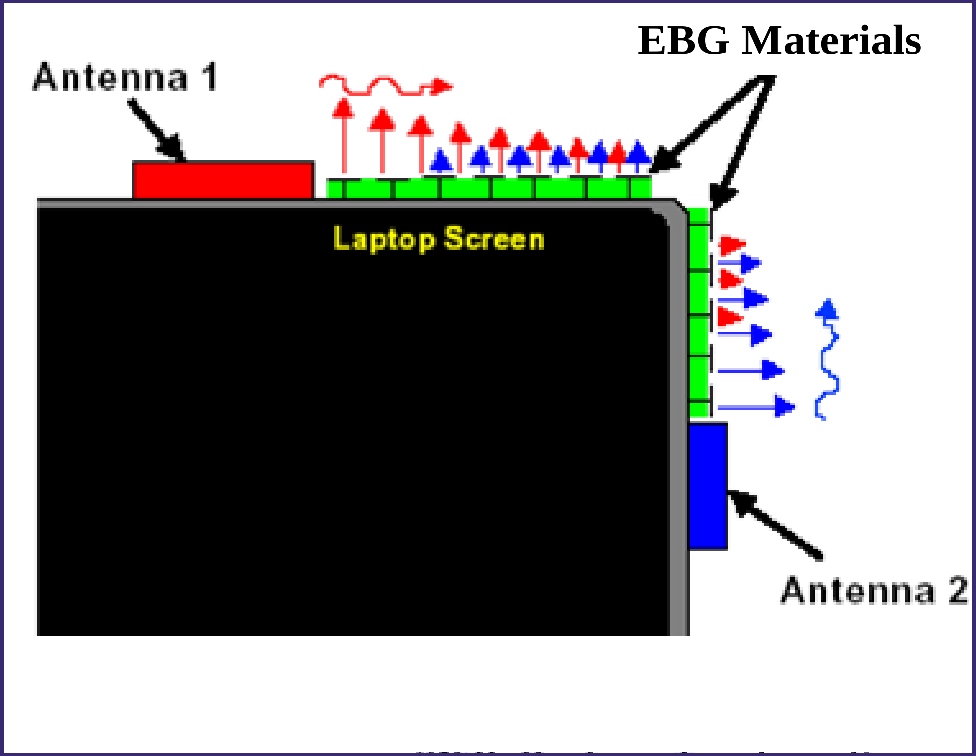


EBGs as an EM Wave Suppressor



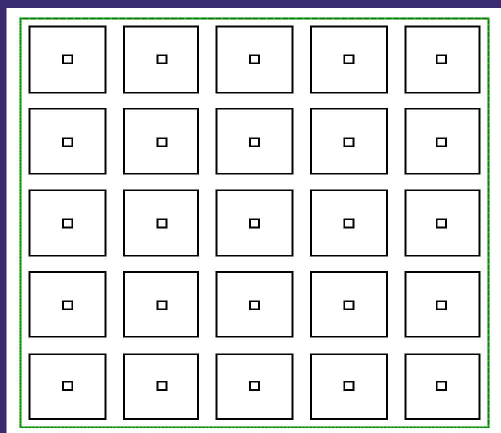


Surface Wave Mitigation using EBG Materials

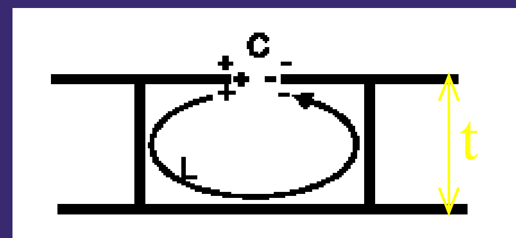


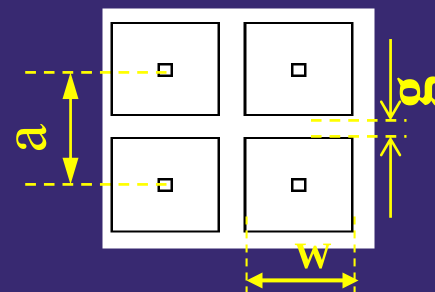
BUT… will the above work for any antenna?

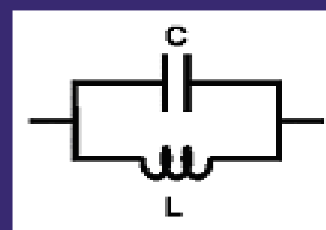
Interpretation and Analyses



Top view of HIS with square patches







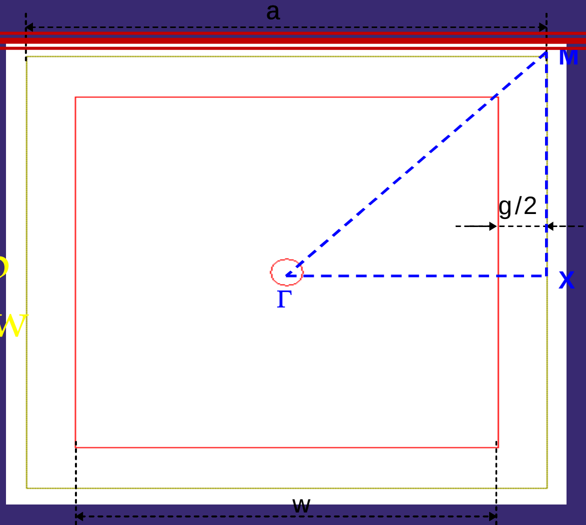
$$f_{res} = \frac{1}{2\pi\sqrt{LC}}$$

- Surface wave propagation
  - TM waves at low Freq.
  - No propagation around f_{res}
  - TE waves at high Freq.

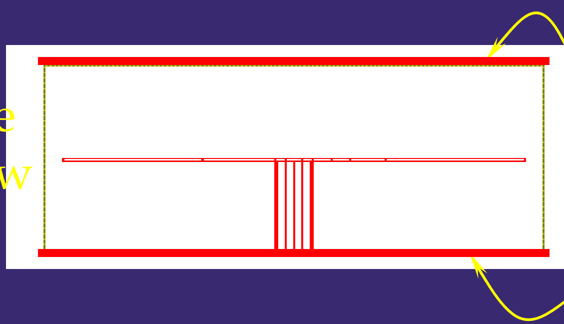
- Resonance comes from lumped behavior of vias and patches
- period must be much smaller than wavelength:

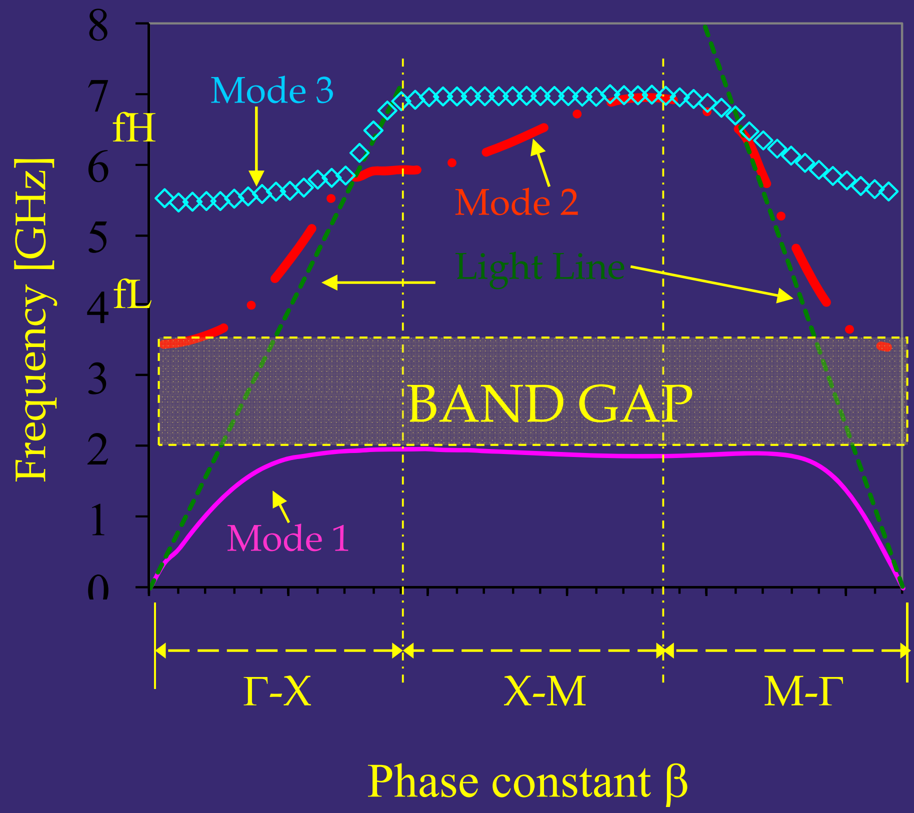
Characterization using Dispersion diagrams

Top view



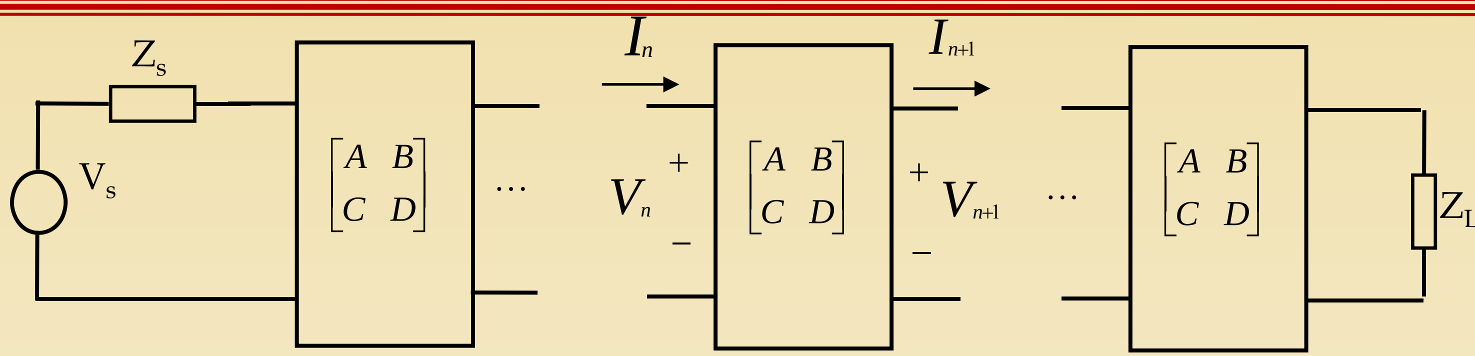
side view





Analysis of a unit cell provides eigenmode solutions for Maxwell's equations

Characterization using Dispersion Equations (approximate Analysis)



Floquet's theorem :

$$\begin{bmatrix} V_n \\ I_n \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{n+1} \\ I_{n+1} \end{bmatrix}$$

$$\begin{bmatrix} V_{n+1} \\ I_{n+1} \end{bmatrix} = e^{-\gamma d} \begin{bmatrix} V_n \\ I_n \end{bmatrix}$$

$$\gamma = \alpha_n + j\beta_n$$

In order to have a solution

$$\begin{vmatrix} A - e^{\gamma d} & B \\ C & A - e^{\gamma d} \end{vmatrix} = 0$$

$$\cosh(\gamma d) = \cos(\beta d) + j\frac{YZ_w}{2}\sin(\beta d)$$

Transmission Line and Periodic Structure Theory (TLPS) Modeling

$$\cosh(\gamma d) = \cos(\beta d) + j\frac{YZ_w}{2}\sin(\beta d)$$

- For the first cell:

$$\cosh(\alpha_1 d)\cos(\beta_1 d) + j\sinh(\alpha_1 d)\sin(\beta_1 d) = \cos(\beta d) + j\frac{YZ_w}{2}\sin(\beta d)$$

- Case 1, $\alpha_1 = 0$: (outside the gap, wave propagation)

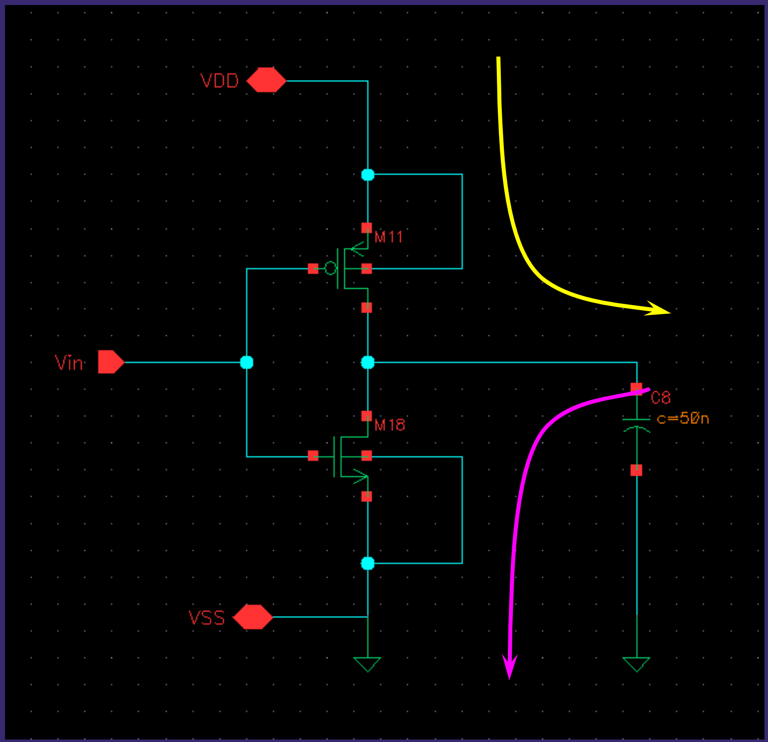
$$\cos(\beta_1 d) = \cos(\beta d) + j\frac{YZ_w}{2}\sin(\beta d)$$

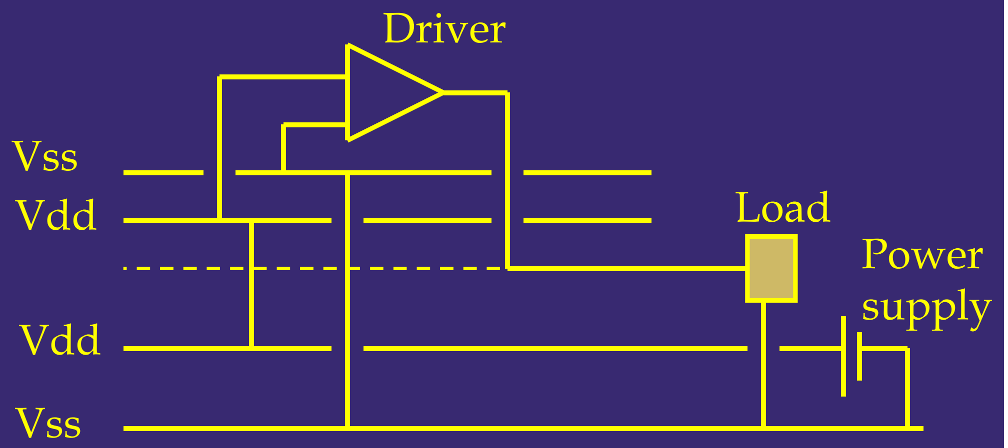
- Case 2, $\alpha_1 \neq 0$ and $\beta_1 = 0$ or π: (inside the gap, amplitude decay)

$$\cosh(\alpha_1 d)\cos(\beta_1 d) = \cos(\beta d) + j\frac{YZ_w}{2}\sin(\beta d)$$

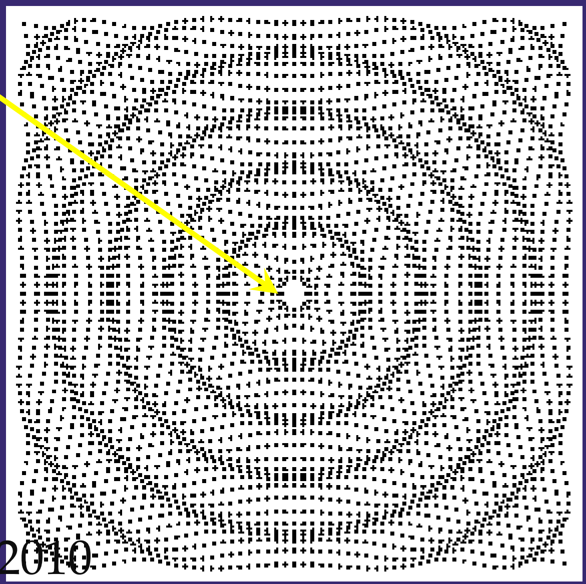
EBGs for Switching Noise Suppression

EBGs for Switching Noise Suppression

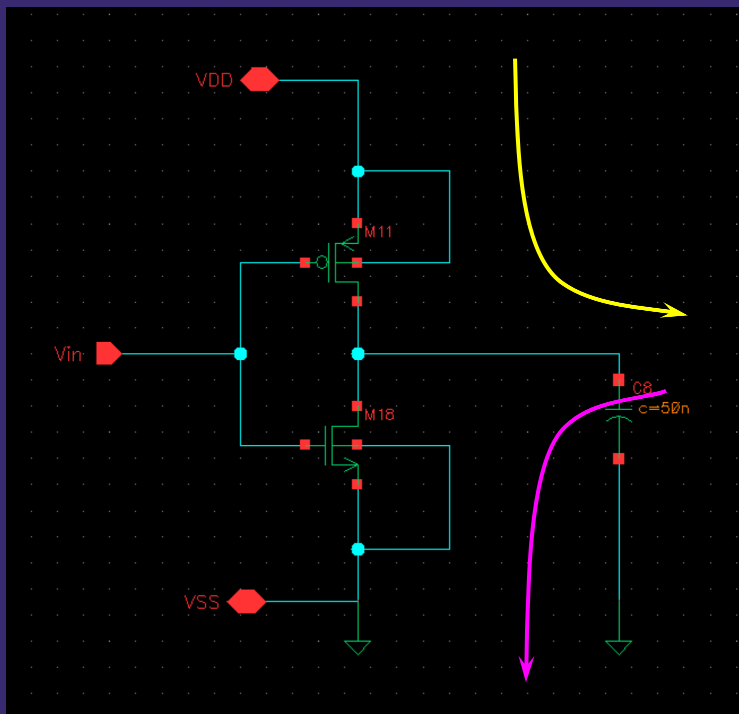


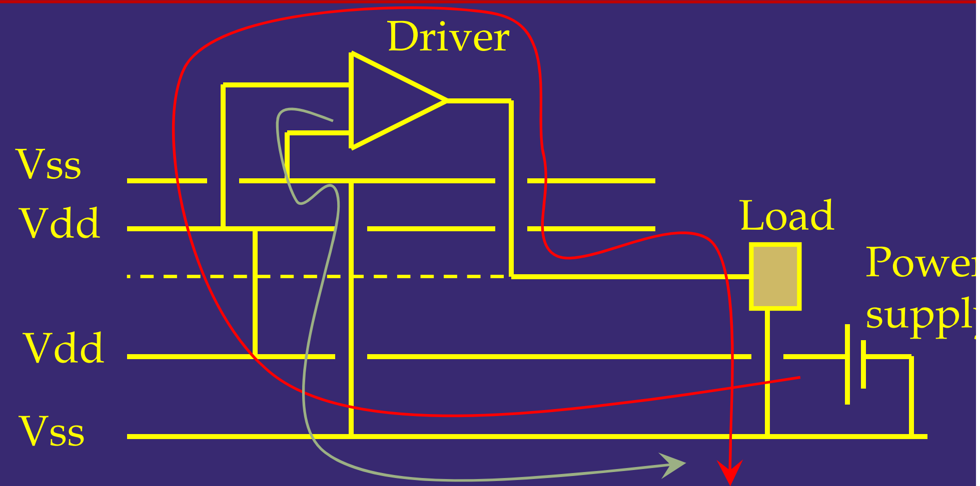


Switching noise source

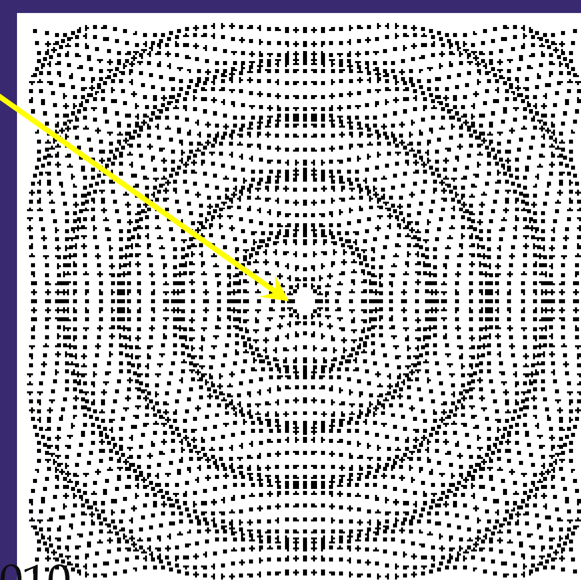


Switching and switching noise

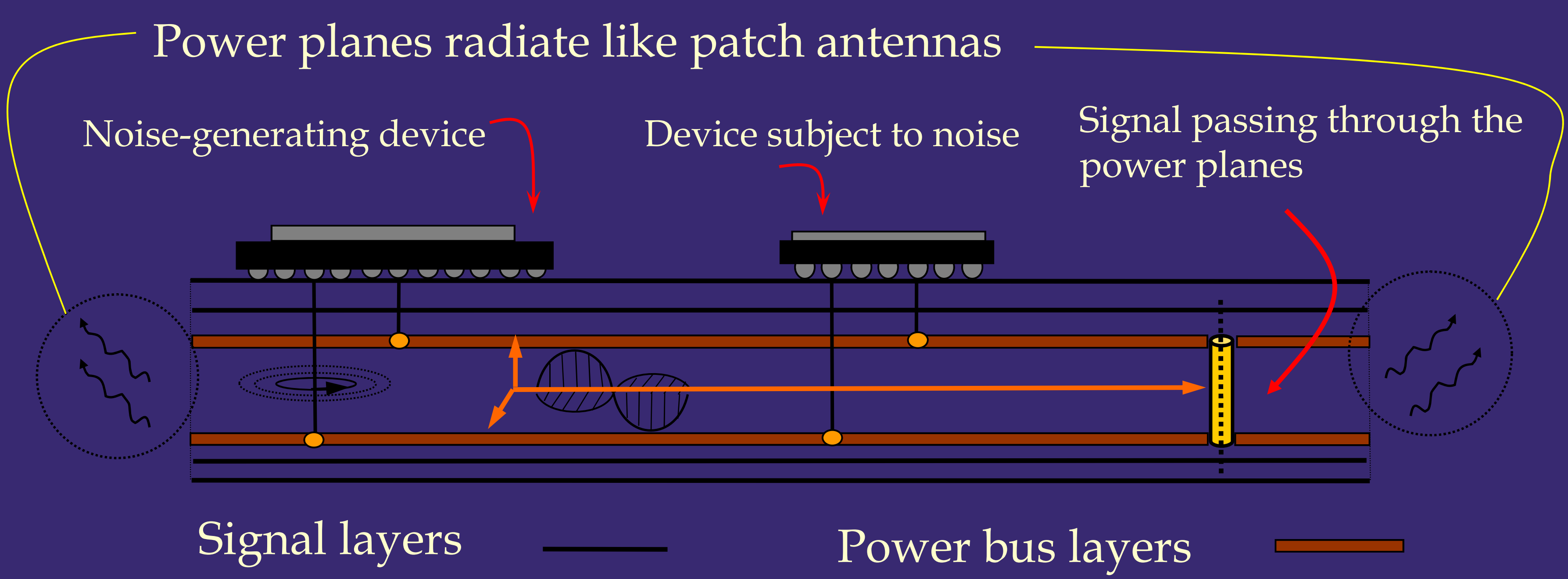




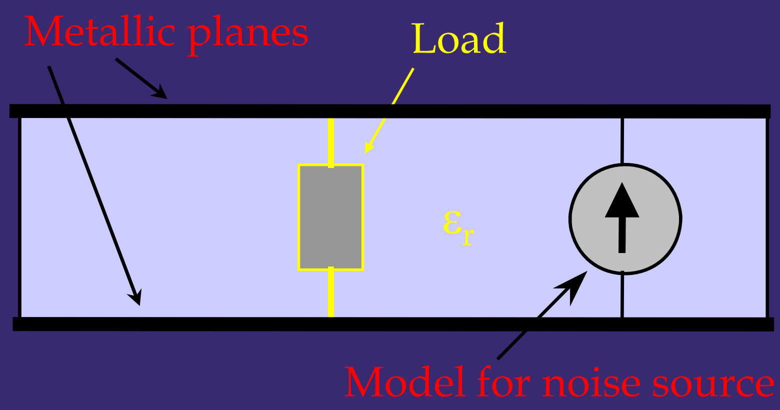
Switching noise source

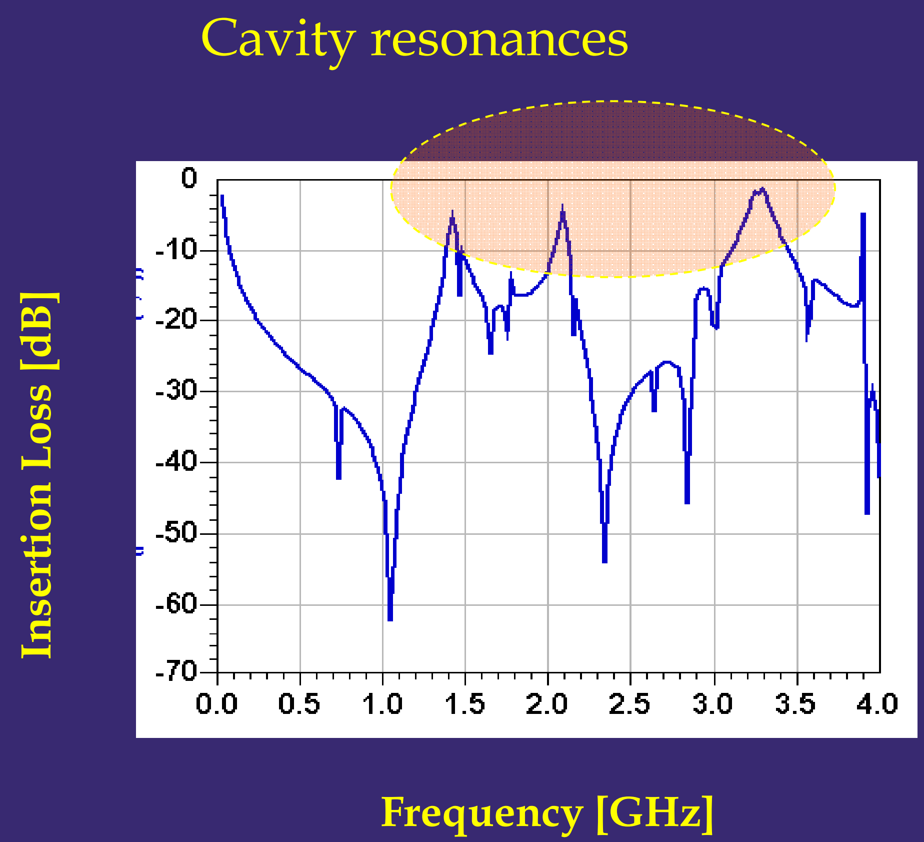


Switching noise: Propagation point of view

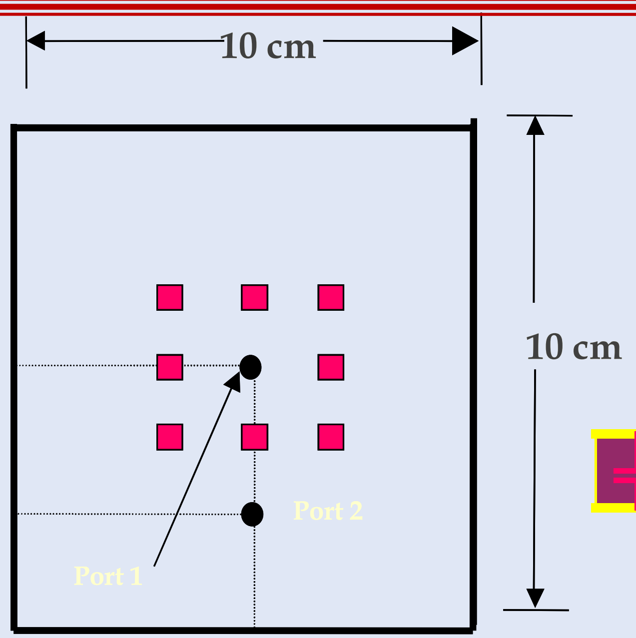


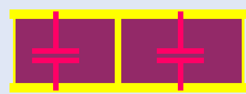
Model for Power Plane Analysis

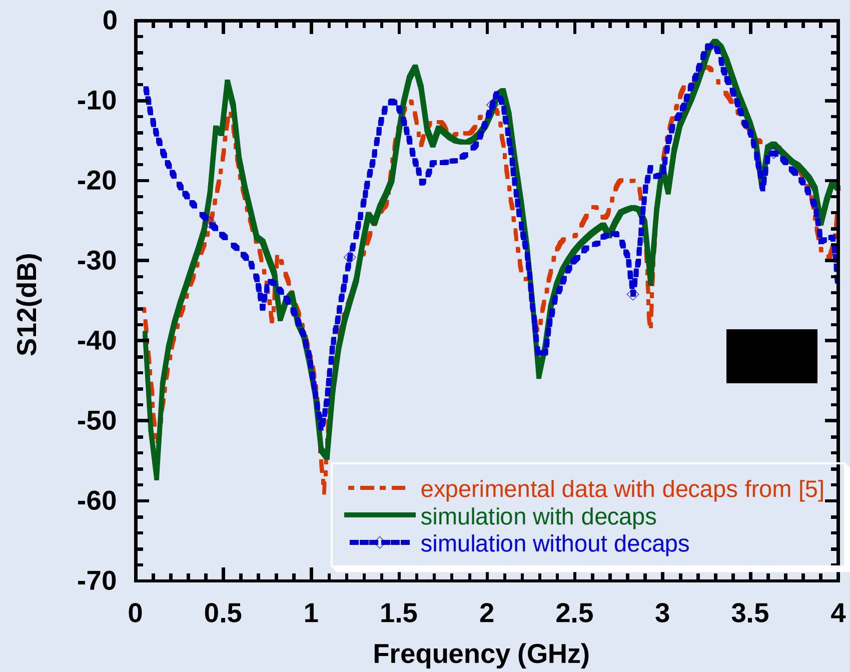




Noise mitigation with decoupling capacitors around noise source

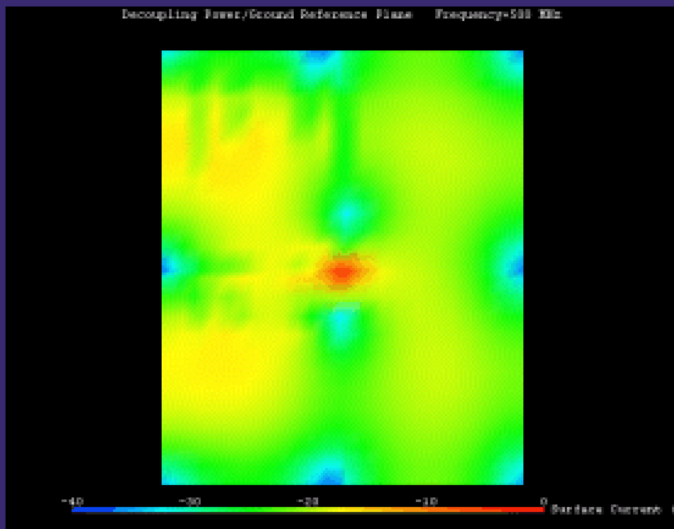




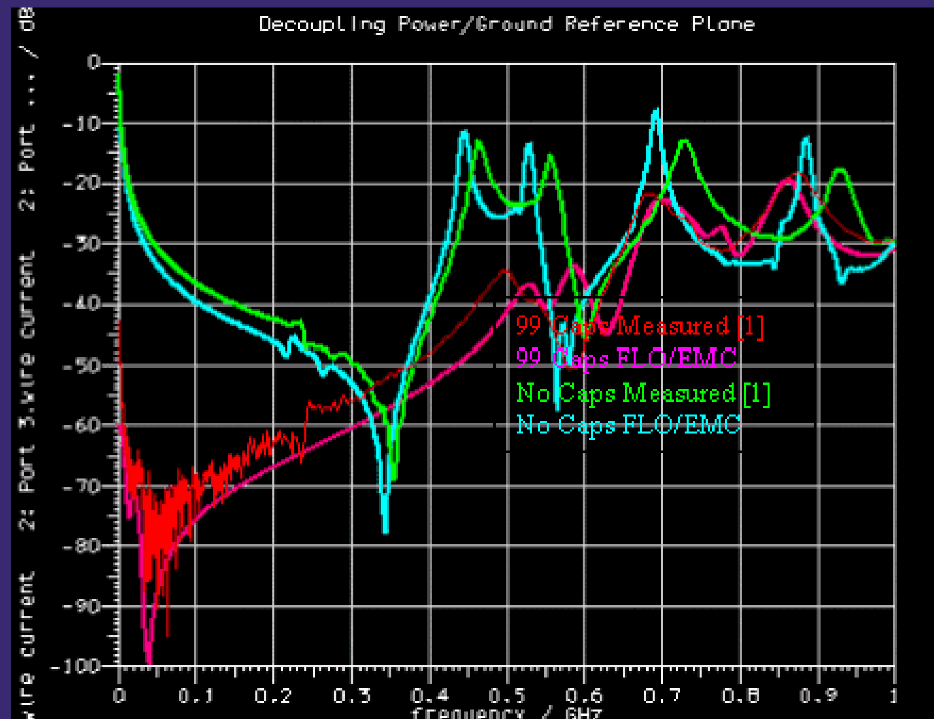


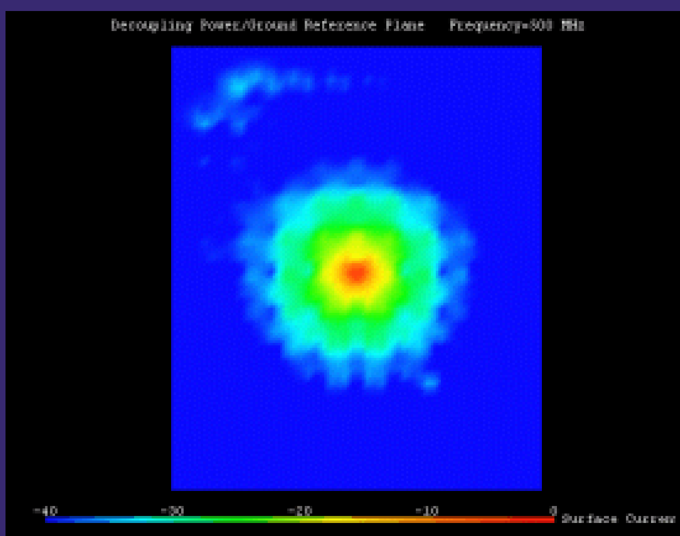
$$Z_{cap} = \frac{1}{j\omega C} + R + j\omega L$$

Noise mitigation with decoupling capacitors around noise source



Surface Current on Ground Plane (No Capacitors)



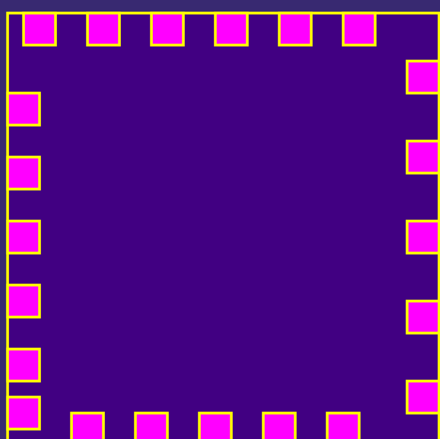


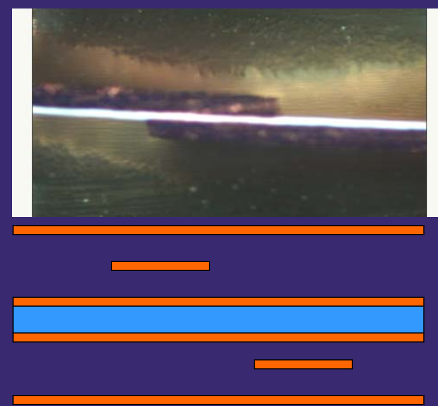
Surface Current on Ground Plane (99 Capacitors)

Previous work: Other SSN mitigation techniques

RC dissipative edge termination

- Mitigates low frequency
- Does not address parallel-plate resonance



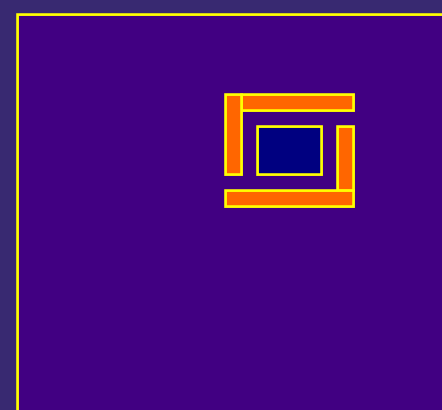


Embedded capacitance

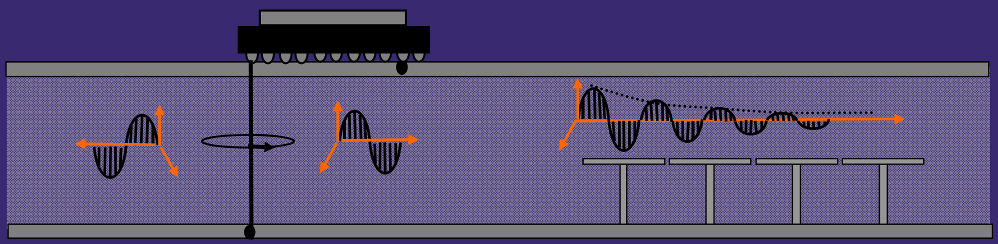
- Does not remove parallel-plate resonance
- Worsens reliability of board (fragile)

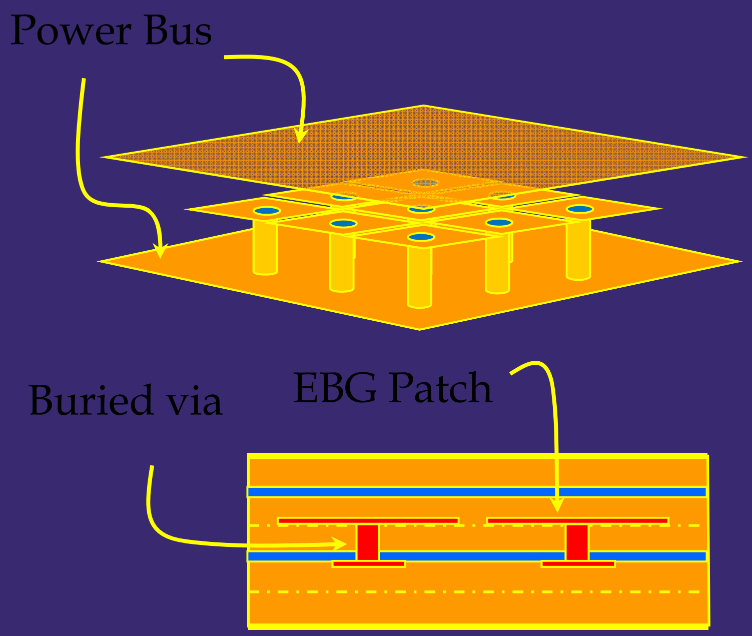
Separation of Vdd plane

- Stops parallel-plate propagation to and from sensitive devices
- localized solution

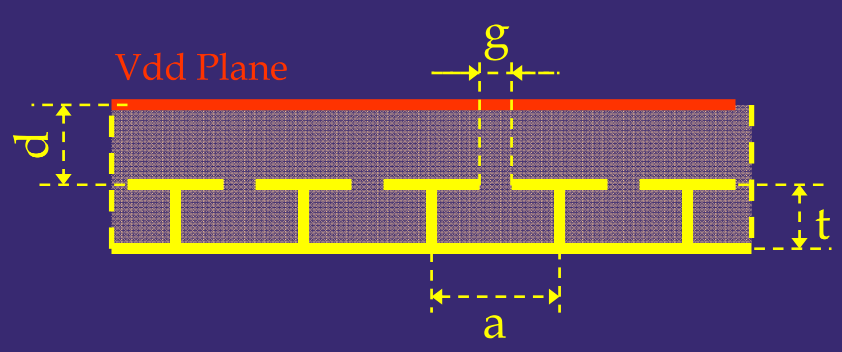


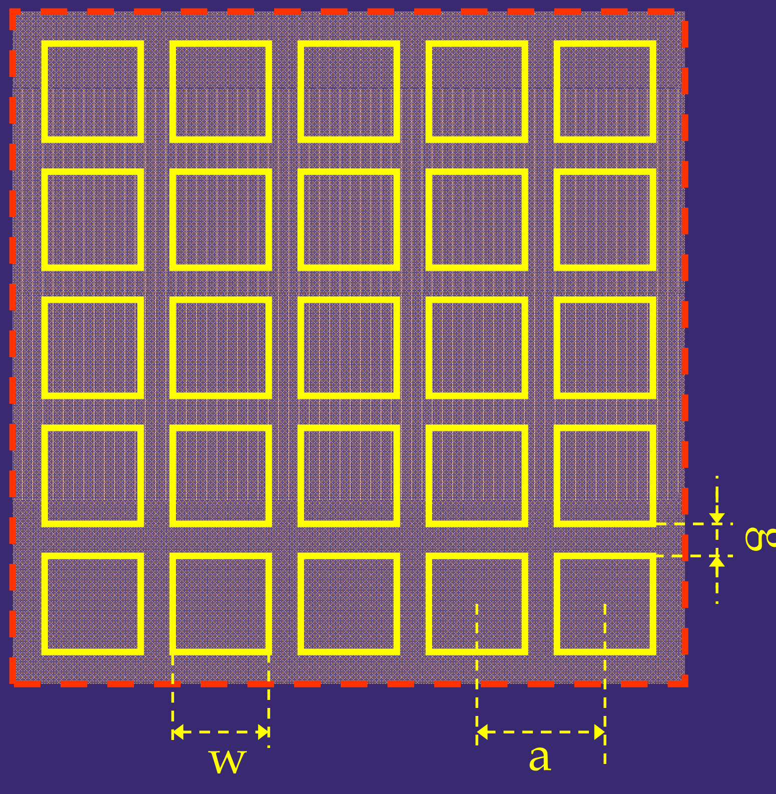
Switching noise suppression in the presence of EEBG structures



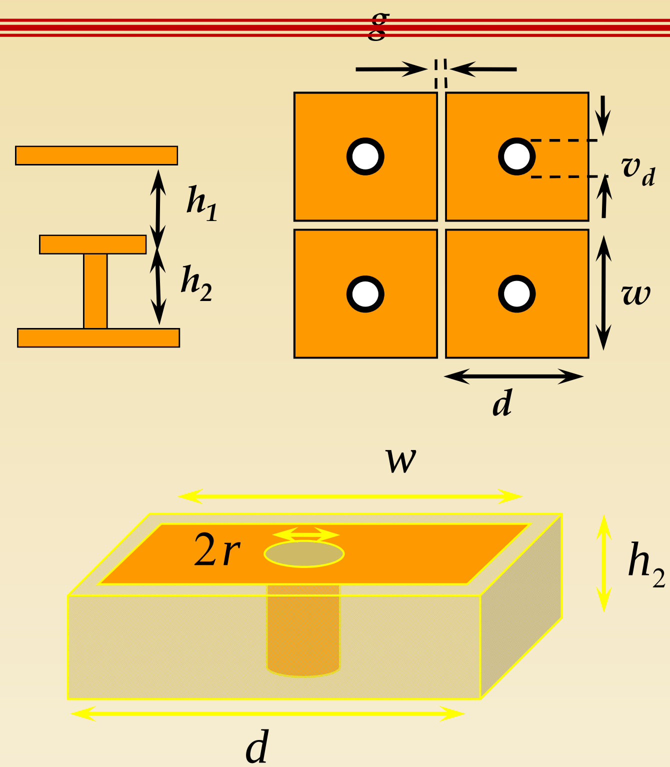


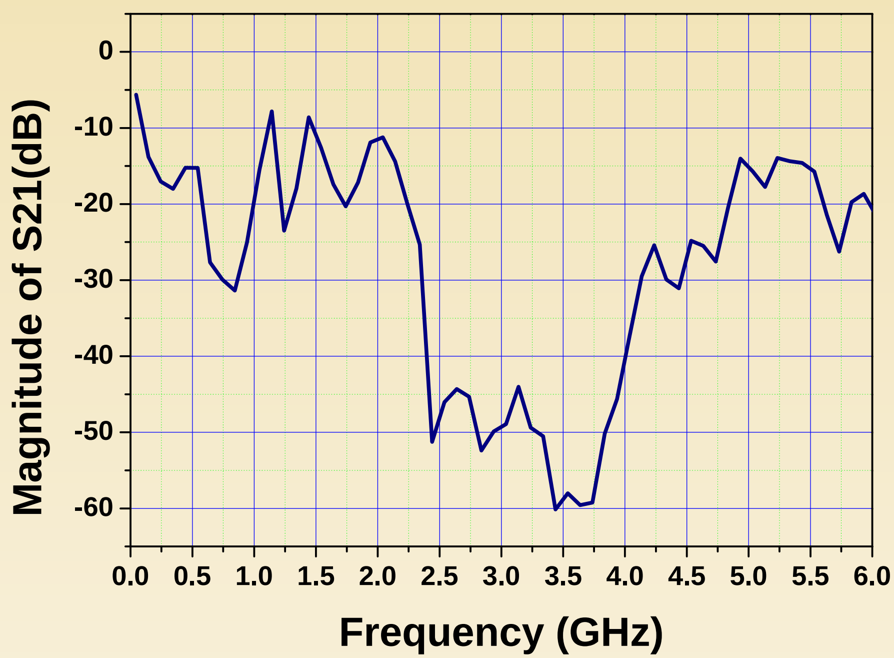
Power plane with EBGs



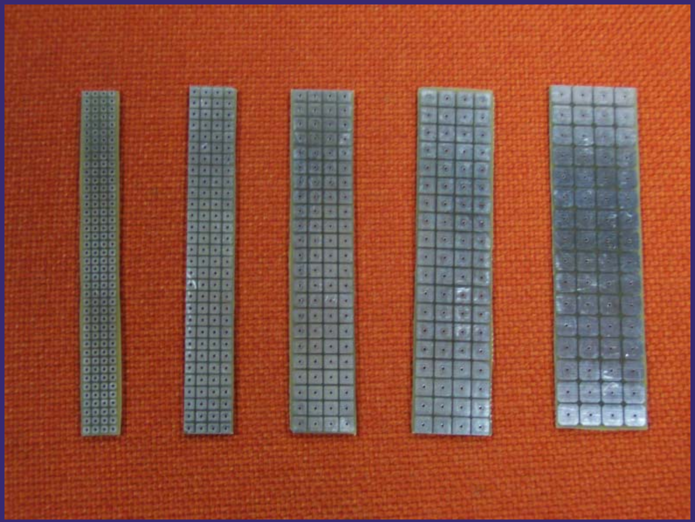


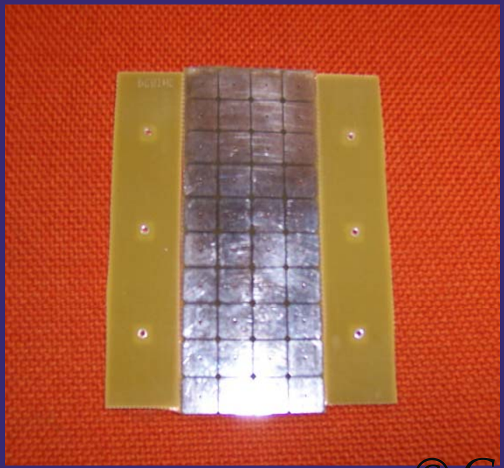
What is the result of using them?

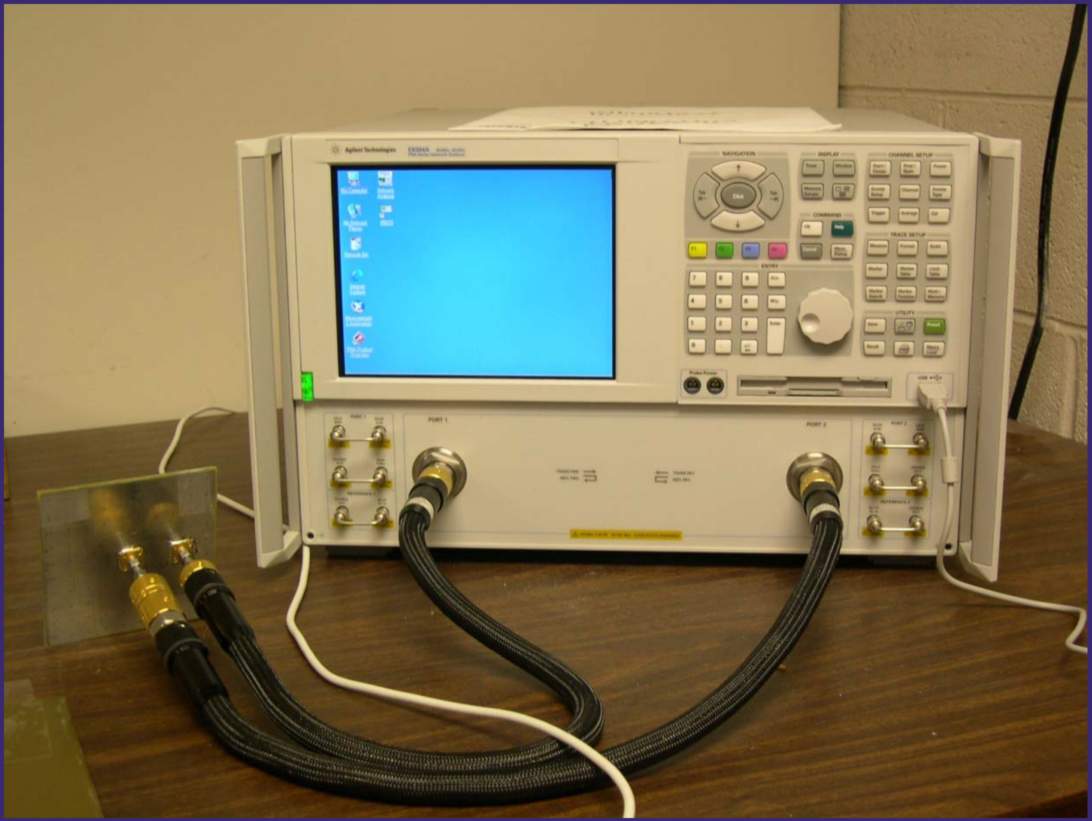




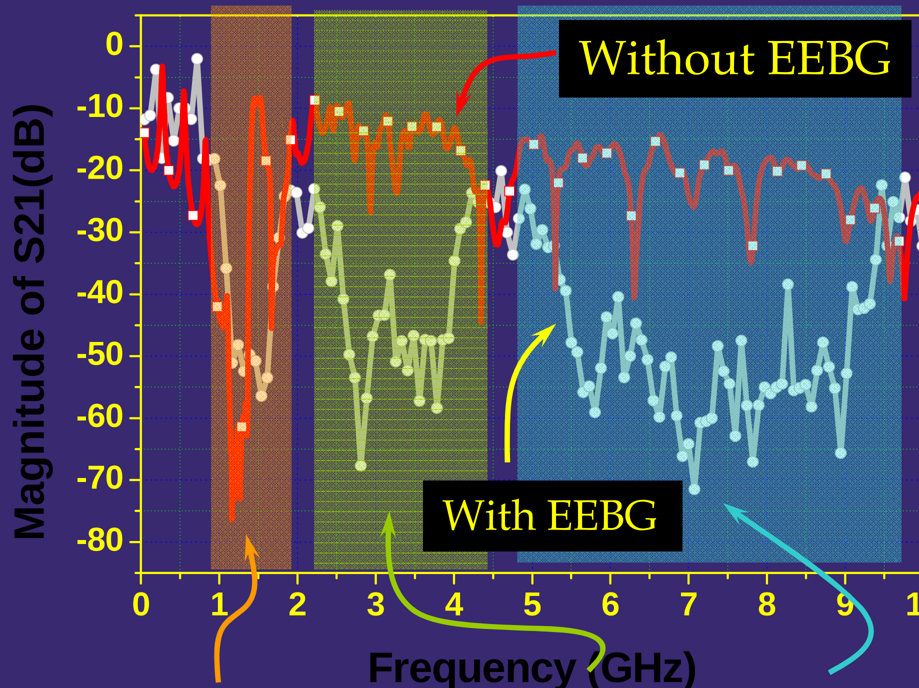
Experimental setup

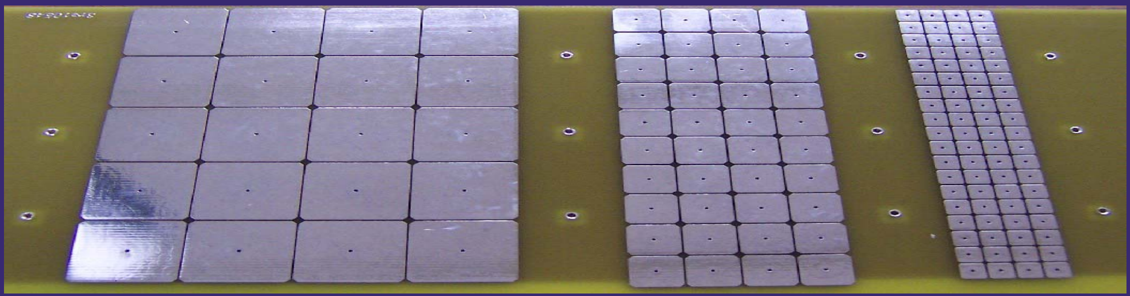






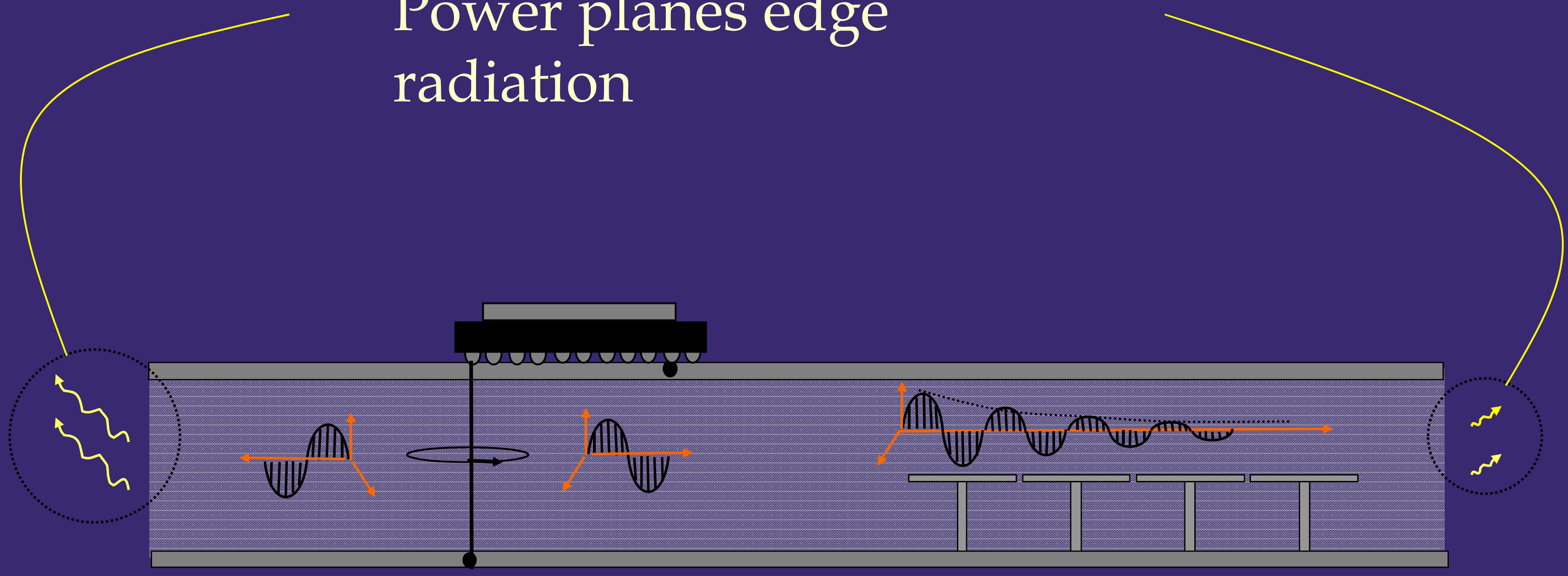
Wide Band Noise Mitigation





EMI suppression

Power planes edge radiation

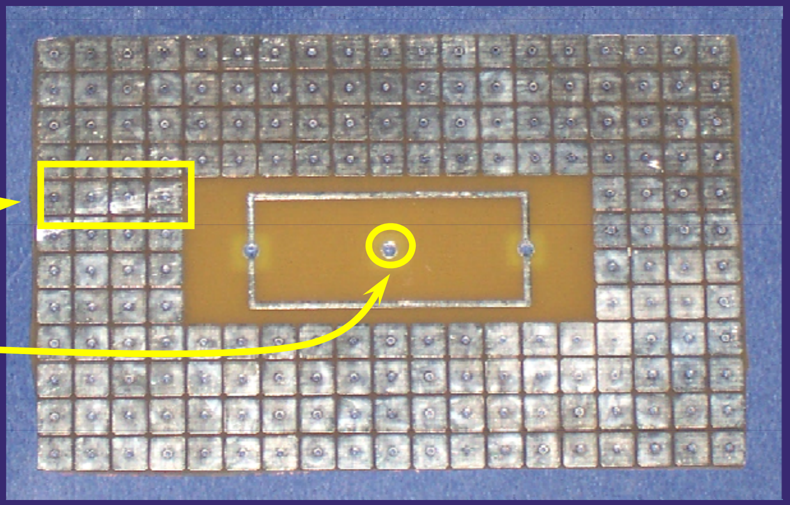


EMI reduction: Experiment setup

Board under test (6.5 cm x 10 cm) fabricated on commercial FR4.

Four Rows of 5mm EEBG

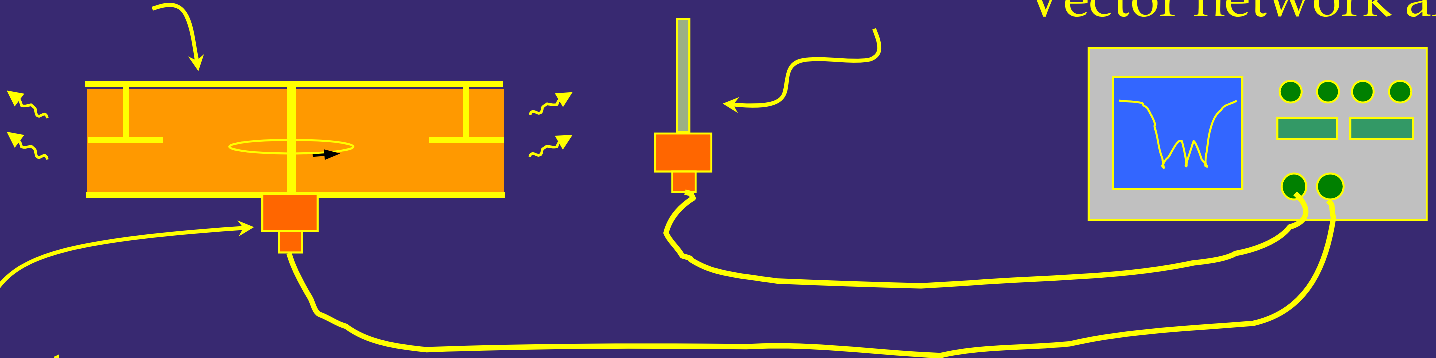
Excitation Point



Board under test

Monopole Antenna

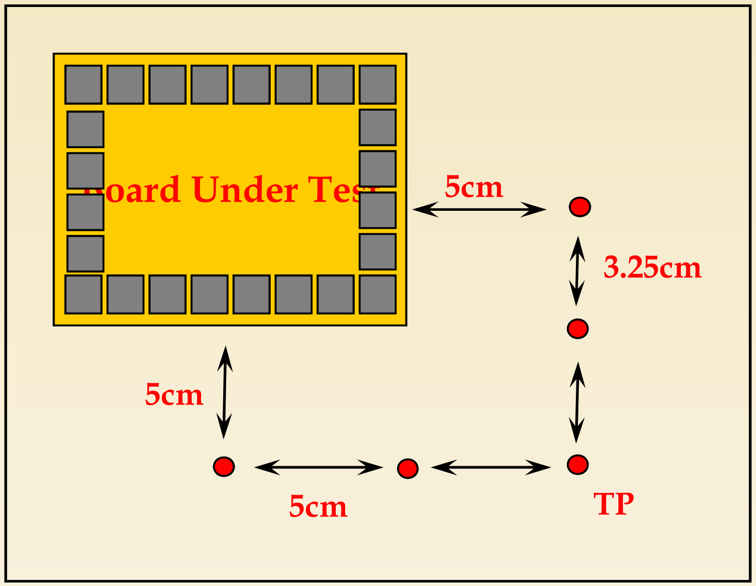
Vector network analyzer

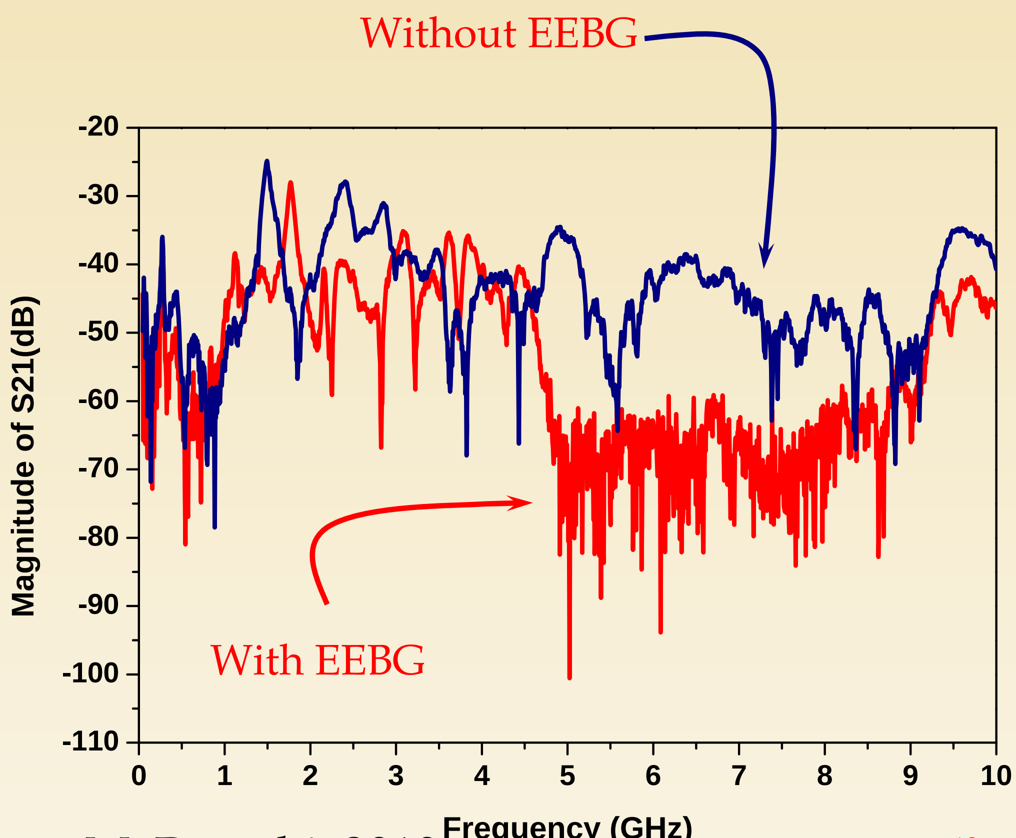


SMA connector

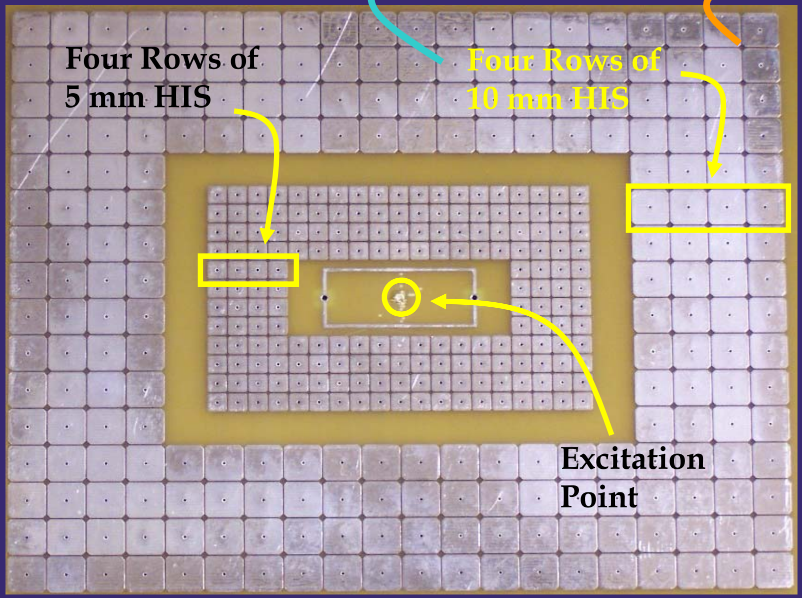
EMI reduction: Experiment results

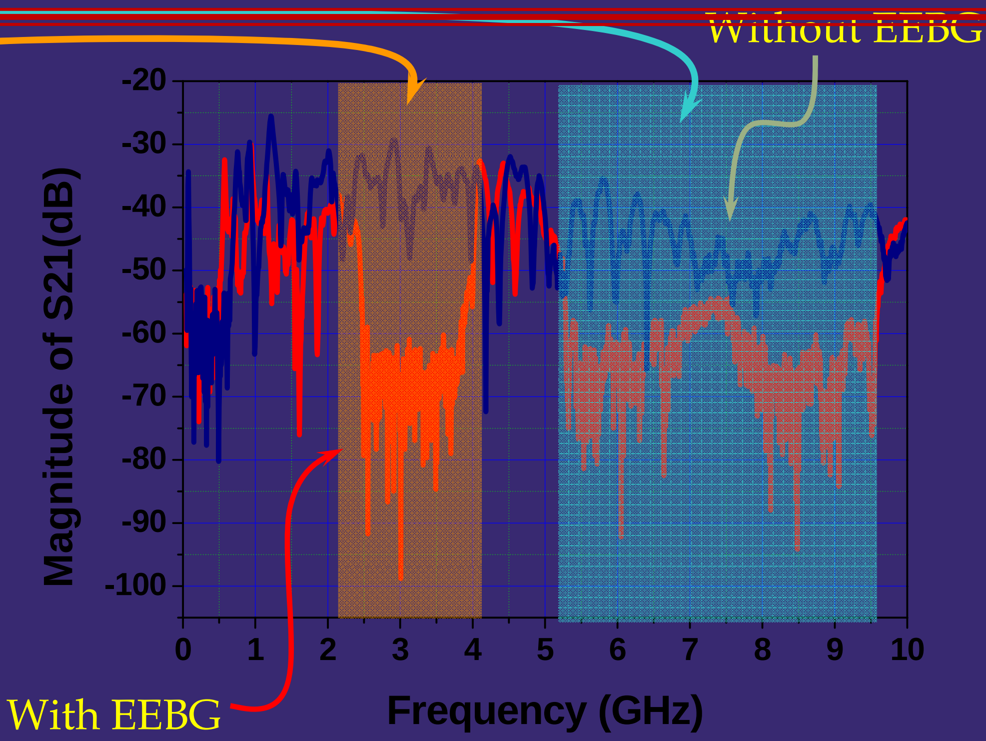
- EMI suppression is omni-directional
- Results at different test points are similar





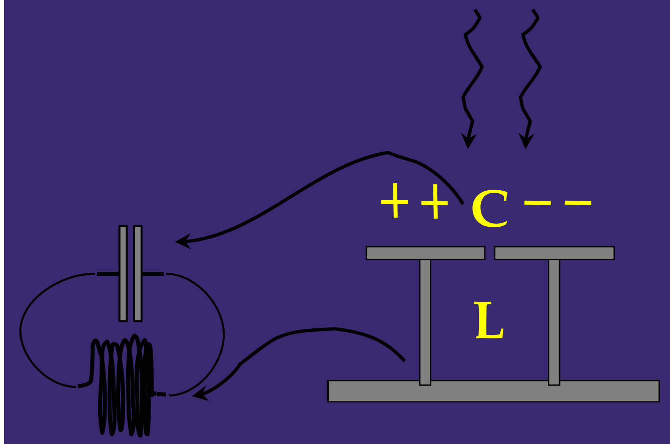
Ultra Wide-Band EMI Reduction

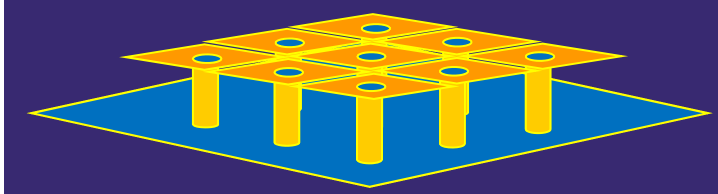


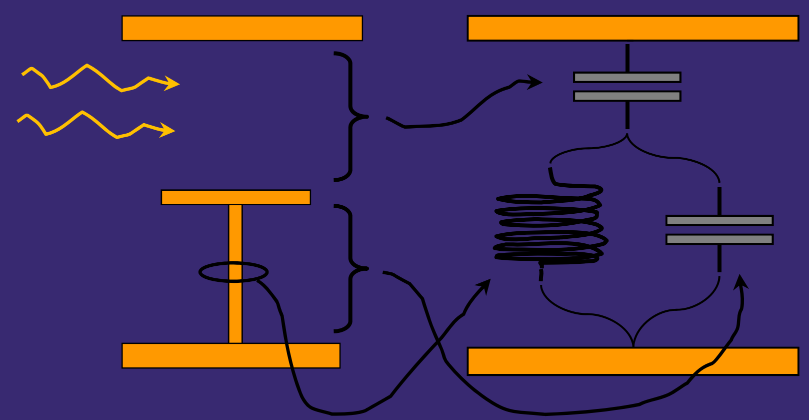


Developing methodologies for studying EEBG structures

The Challenge of Modeling





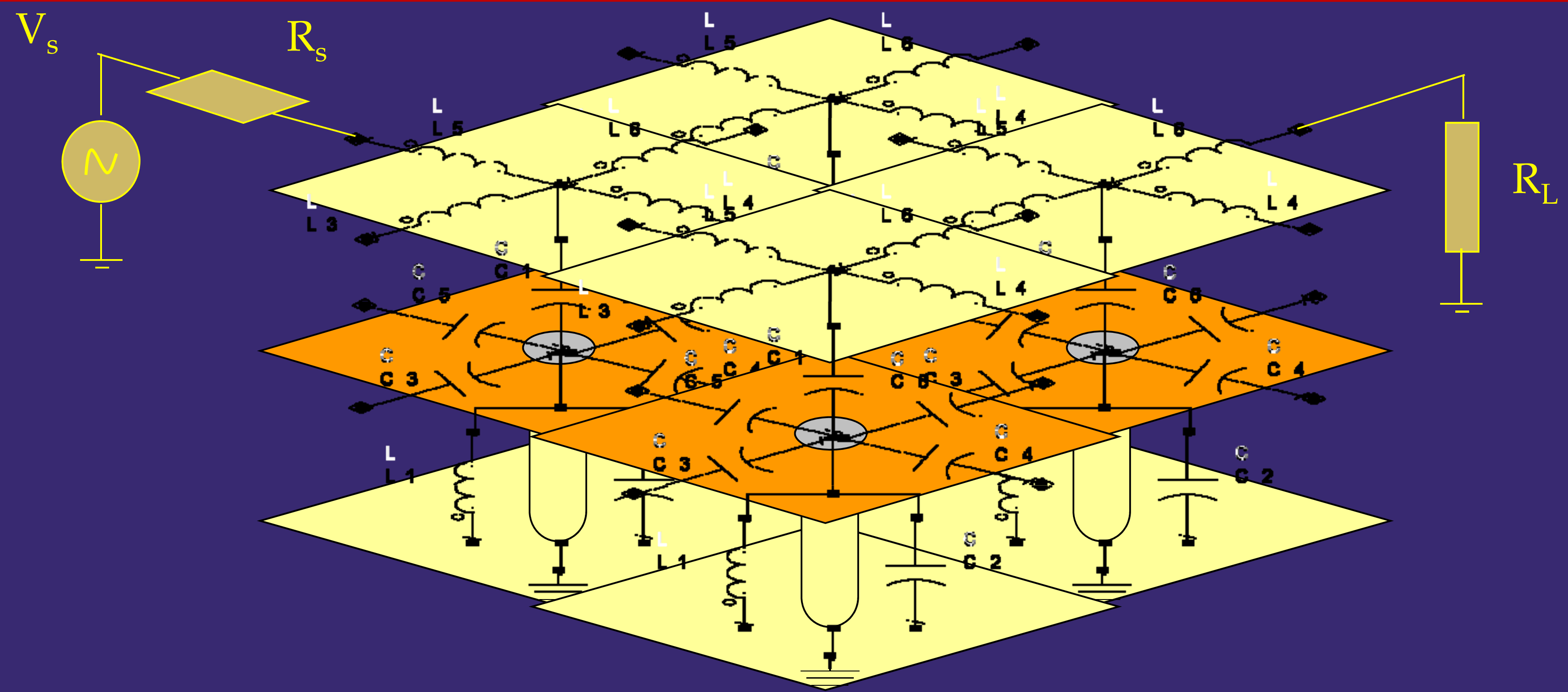


$$f_{res} = \frac{1}{2\pi\sqrt{L\ (C_1 + C_2)}}$$

$$Z_{LC} = \frac{jL\omega}{1 - LC\omega^2}$$

2D Model based on new unit cell

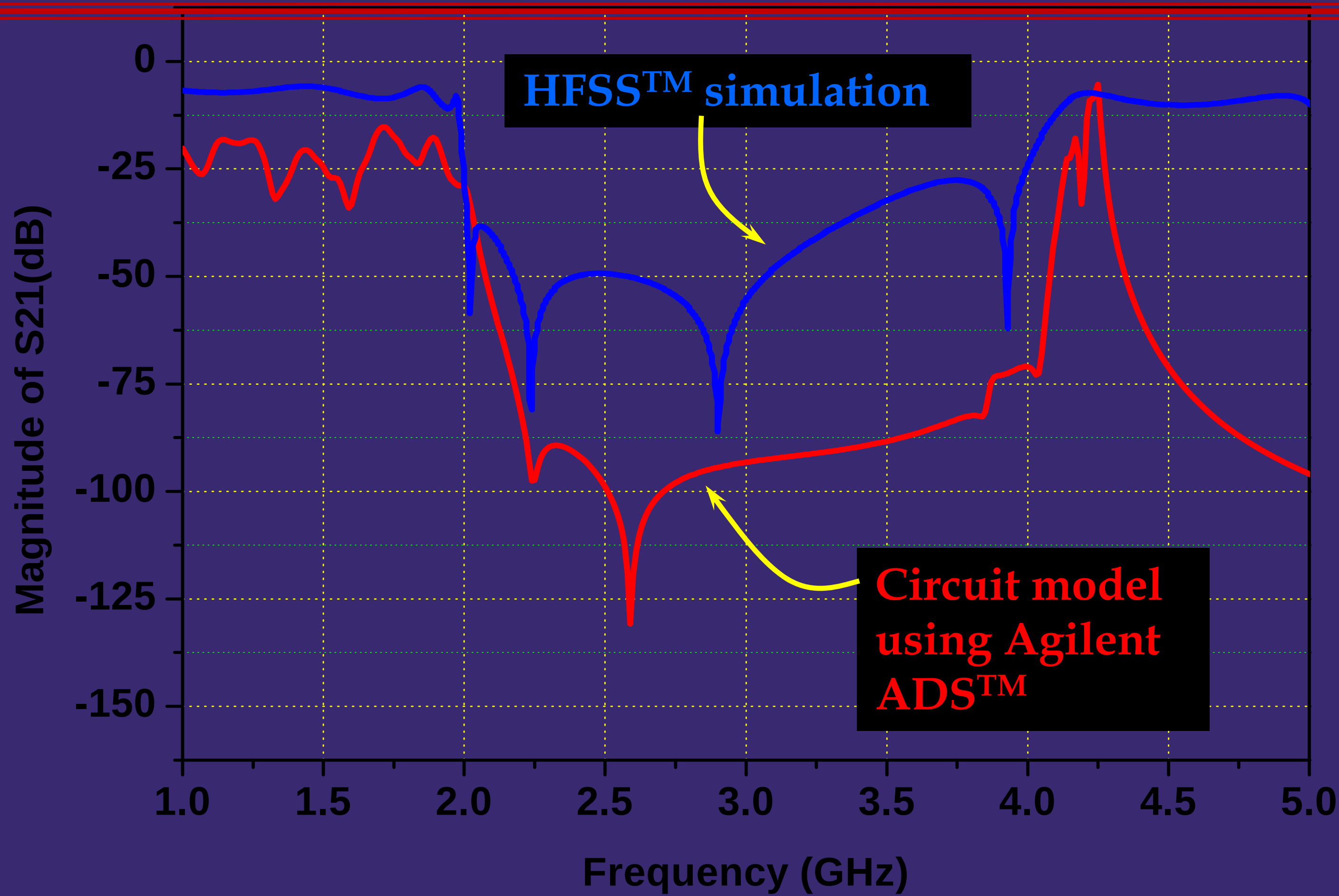
Model based on TEM-transmission-line model combined with the LIS model



$$C_{3-6} = 2\frac{w(\varepsilon_{r1}+\varepsilon_{r2})\varepsilon_0}{\pi}\cosh^{-1}(d/g)$$

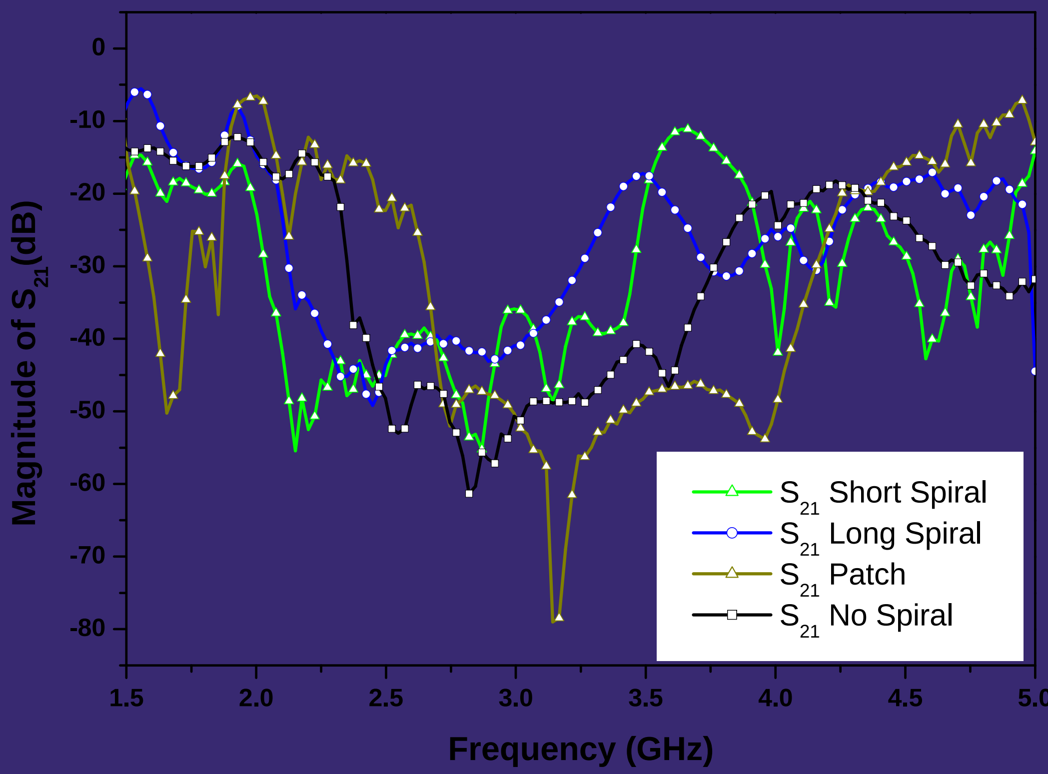
$$L_{3-6} = \frac{\mu_0}{2}h$$

2D Model based on new unit cell



Accuracy limited to low frequencies

Modeling Complex EBG Structures!

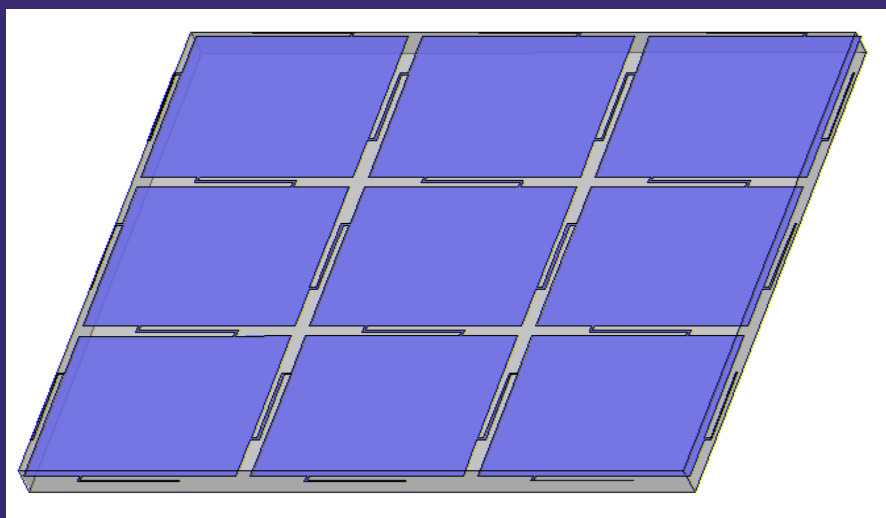


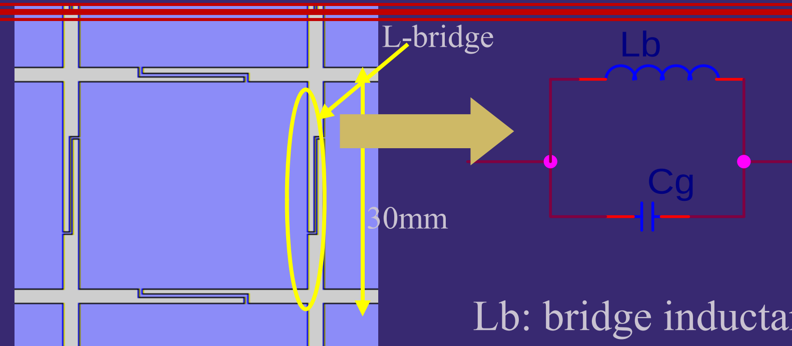
Planar EBG Structures

Patches of different shapes without vias!

University of Waterloo

Planar EBG Structure

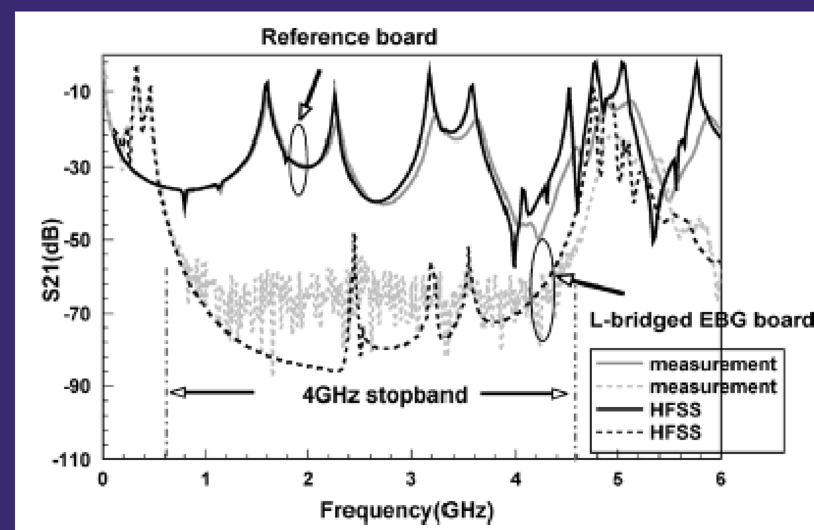




unit cell

Lb: bridge inductance

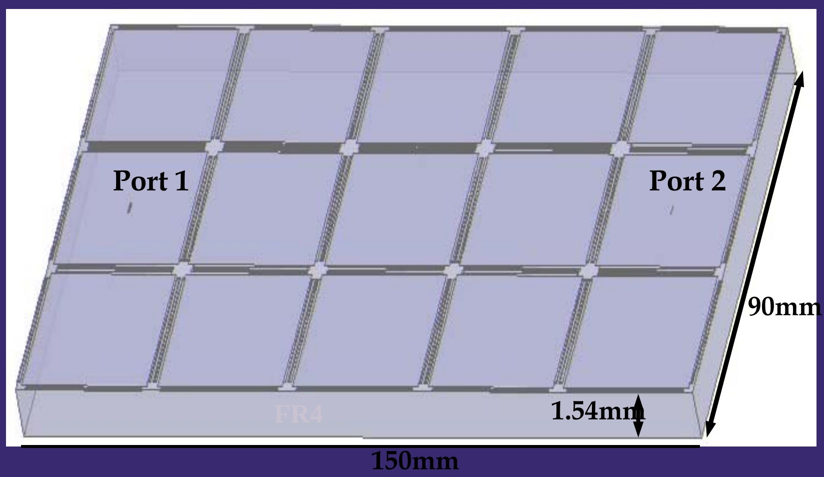
Cg: gap capacitance



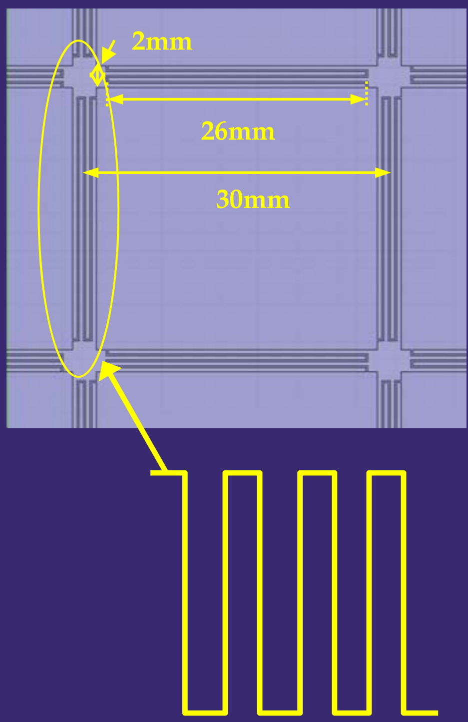
T. L. Wu, C. C. Yang, Y. H. Lin, et al. “A novel power plane with super-wideband elimination of ground bounce noise on high speed circuits” *IEEE Microwave and Wireless Components Letters*, Vol. 15 No.3, pp. 174-176, 2005

Meander Line EBG Structure

Top View



Unit Cell

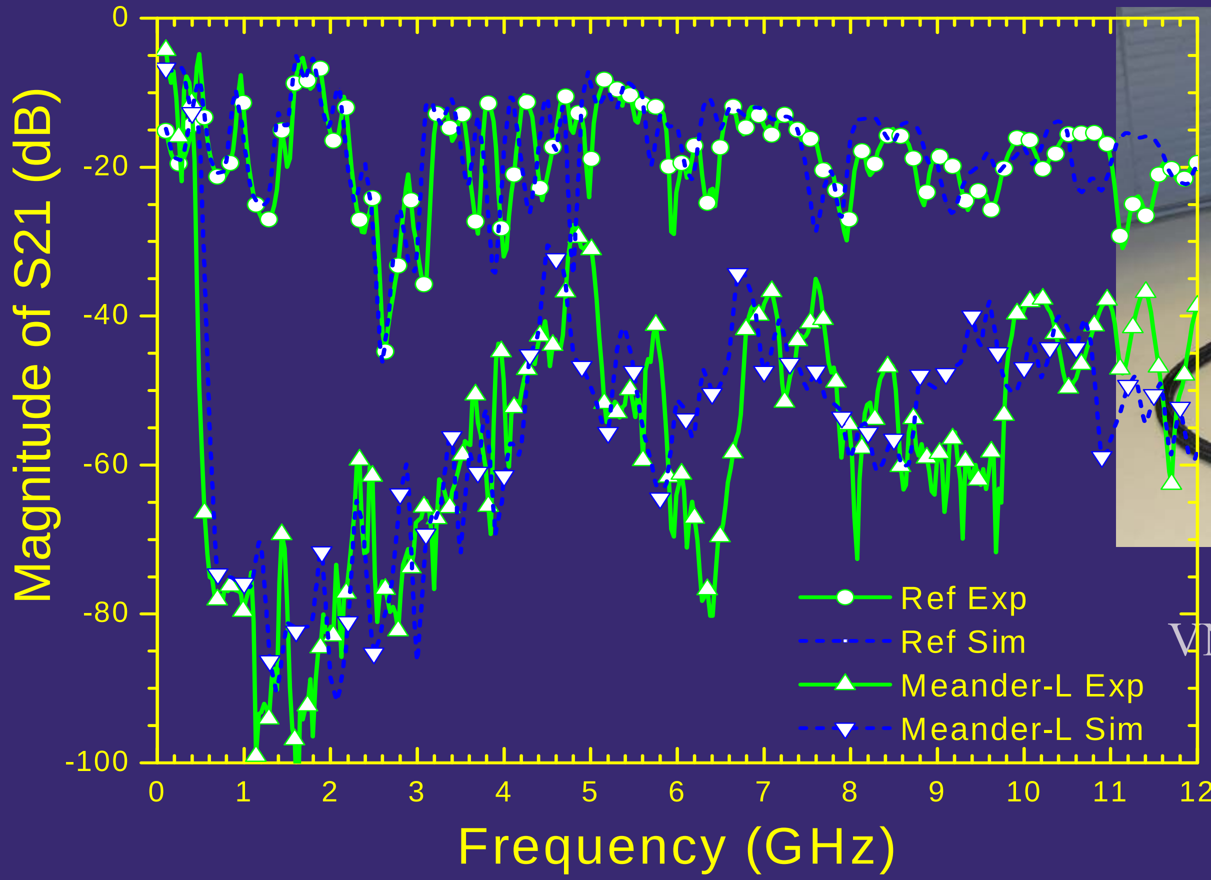


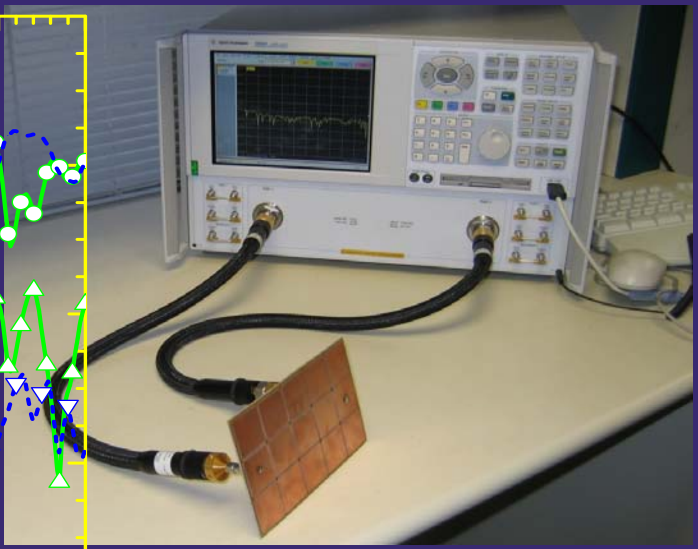
Fabrication and Test Board

LPKF ProtoMat C100/HF circuit plotter

Physical size of board: 3x5 unit cells (90x150mm)

Simulation and Measurement

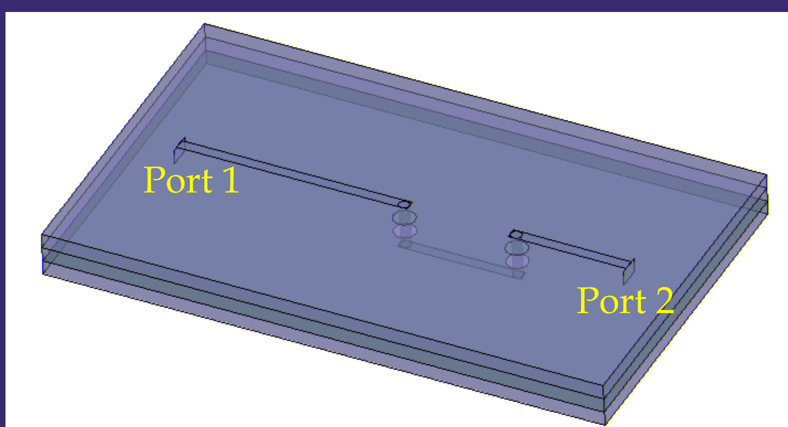




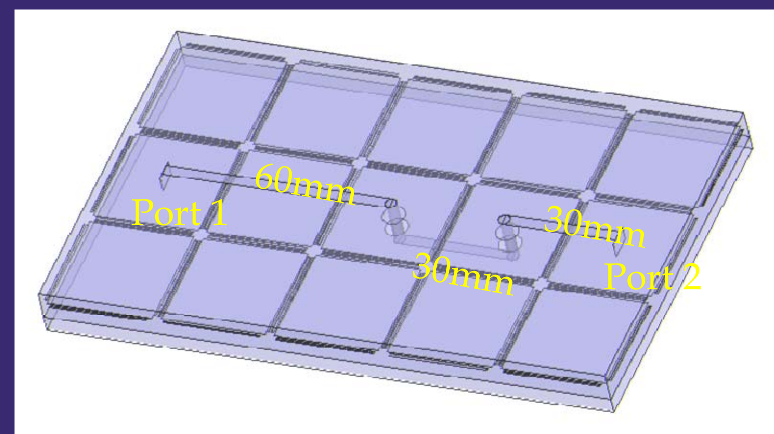
VNA measurement

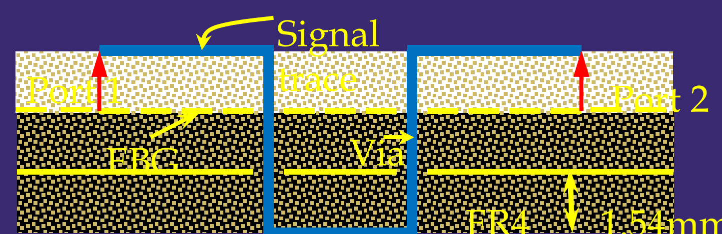
What about Signal Integrity?

Structure A:



Structure B:

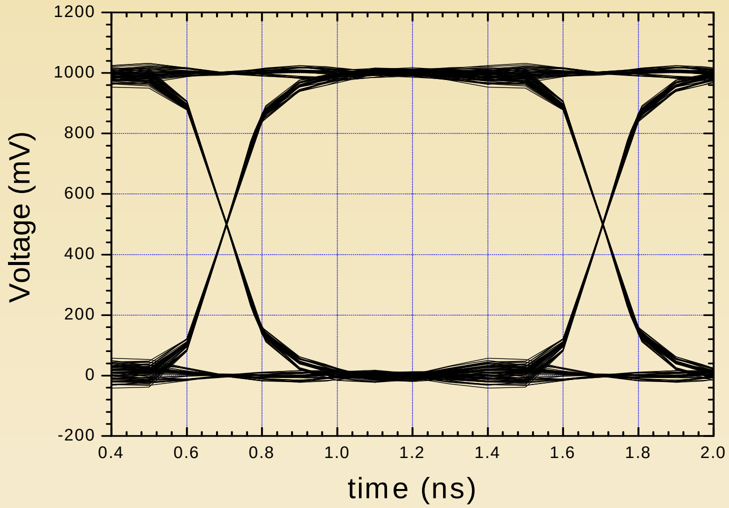




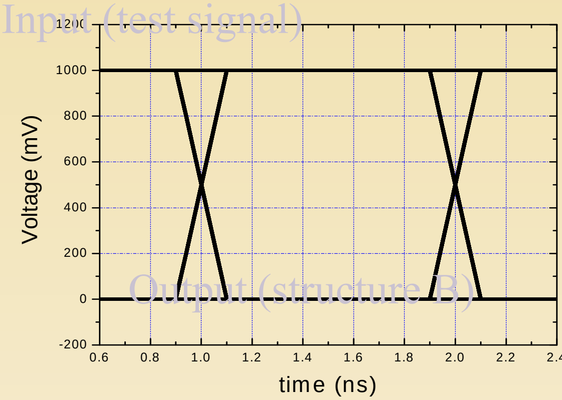
Side view

University of Waterloo

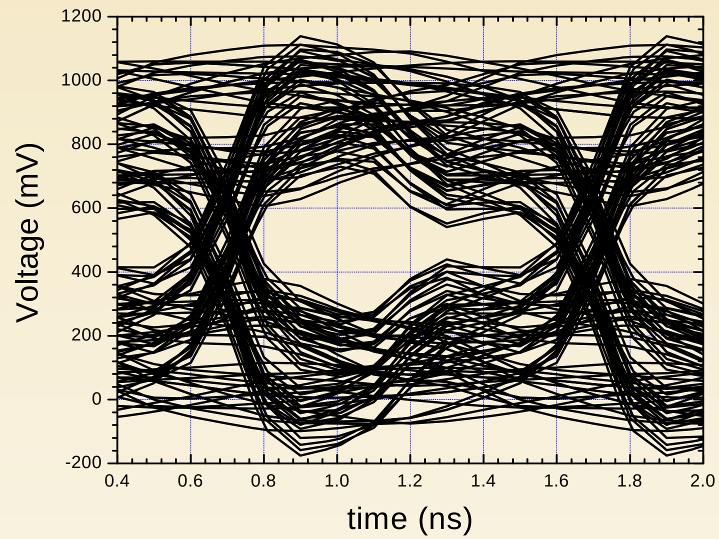
Eye Diagrams



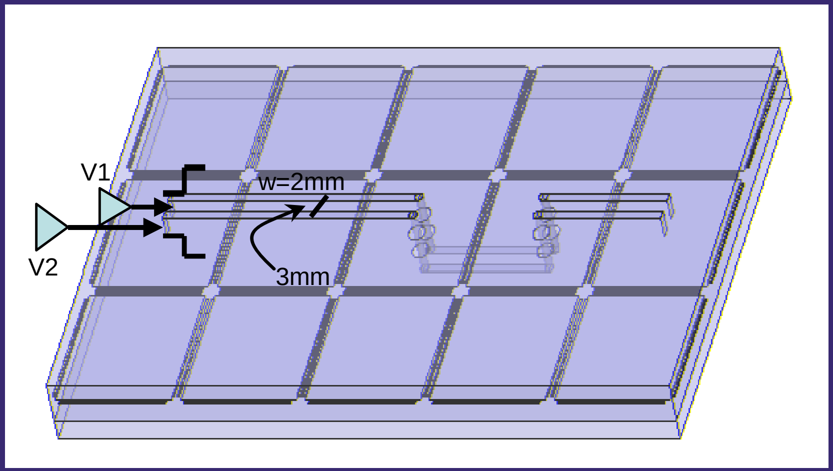
Input (test signal)

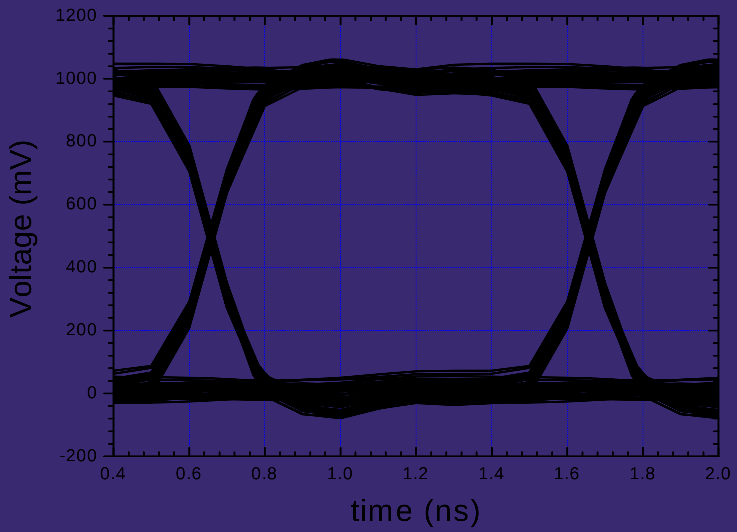


Output (structure B)

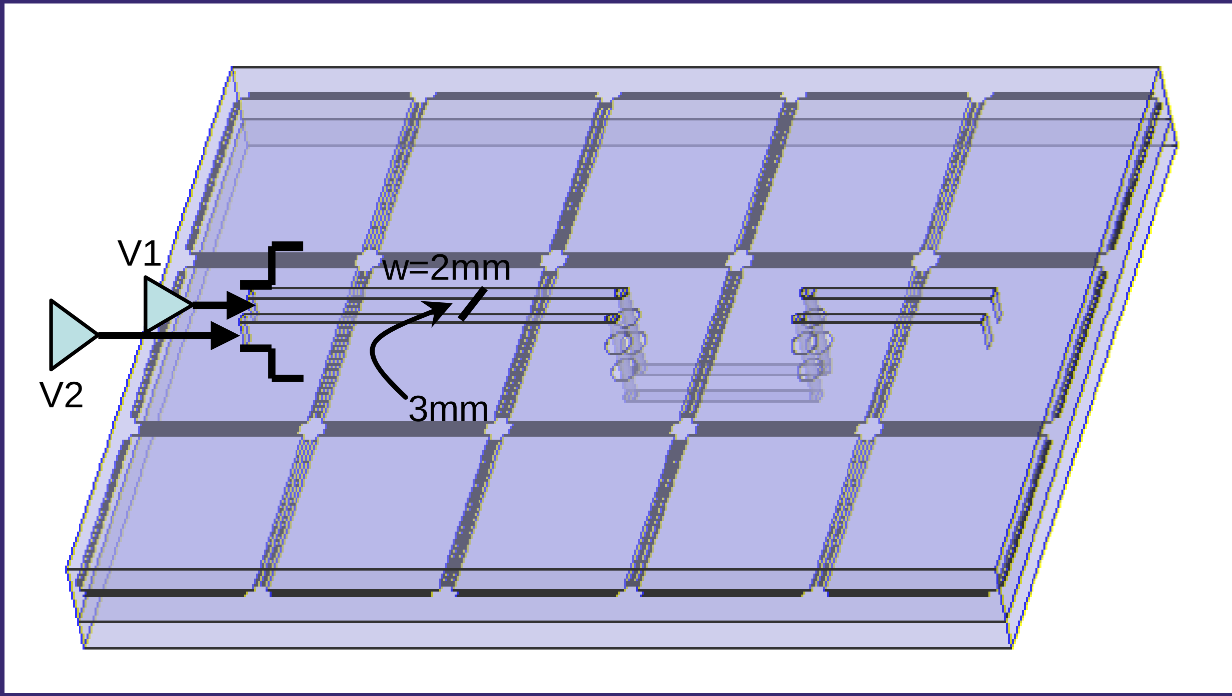


Differential Signaling





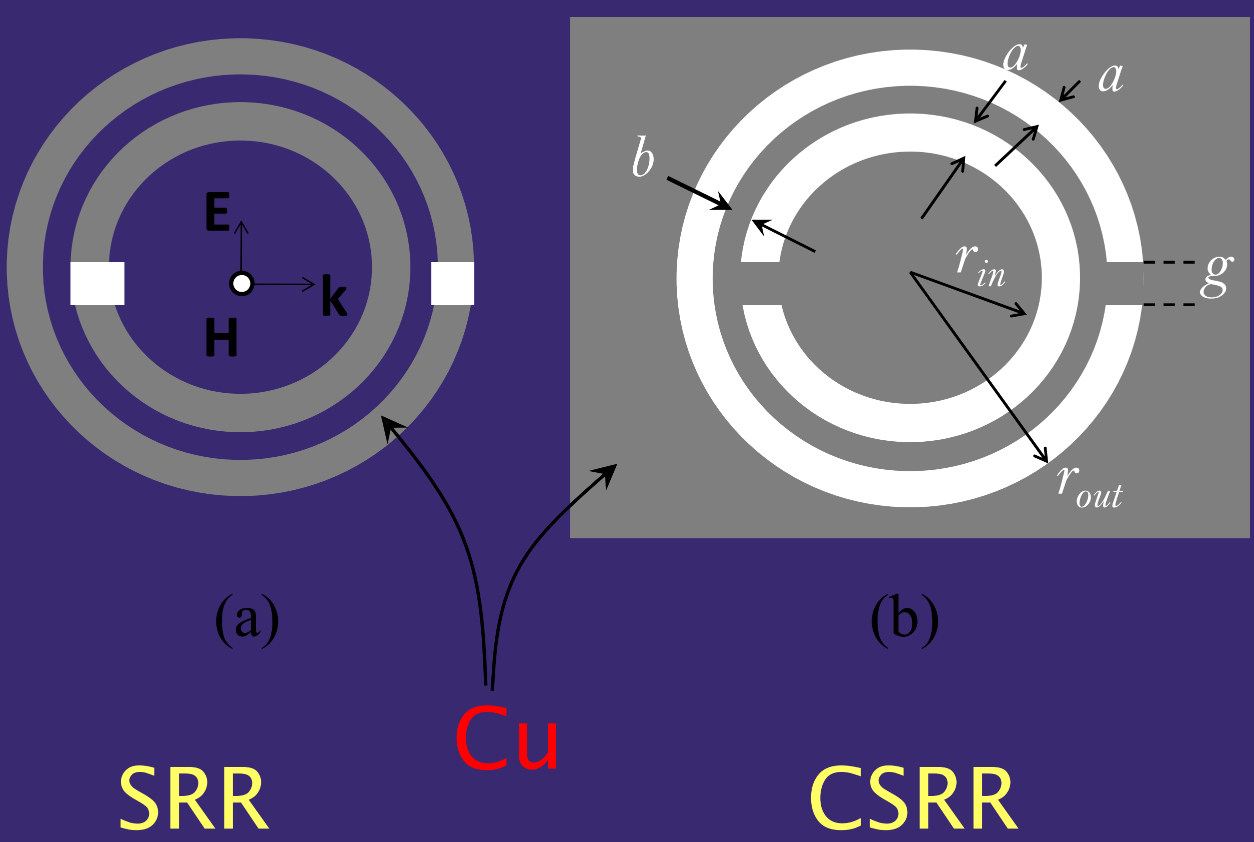
Filtering of Common Mode Currents!



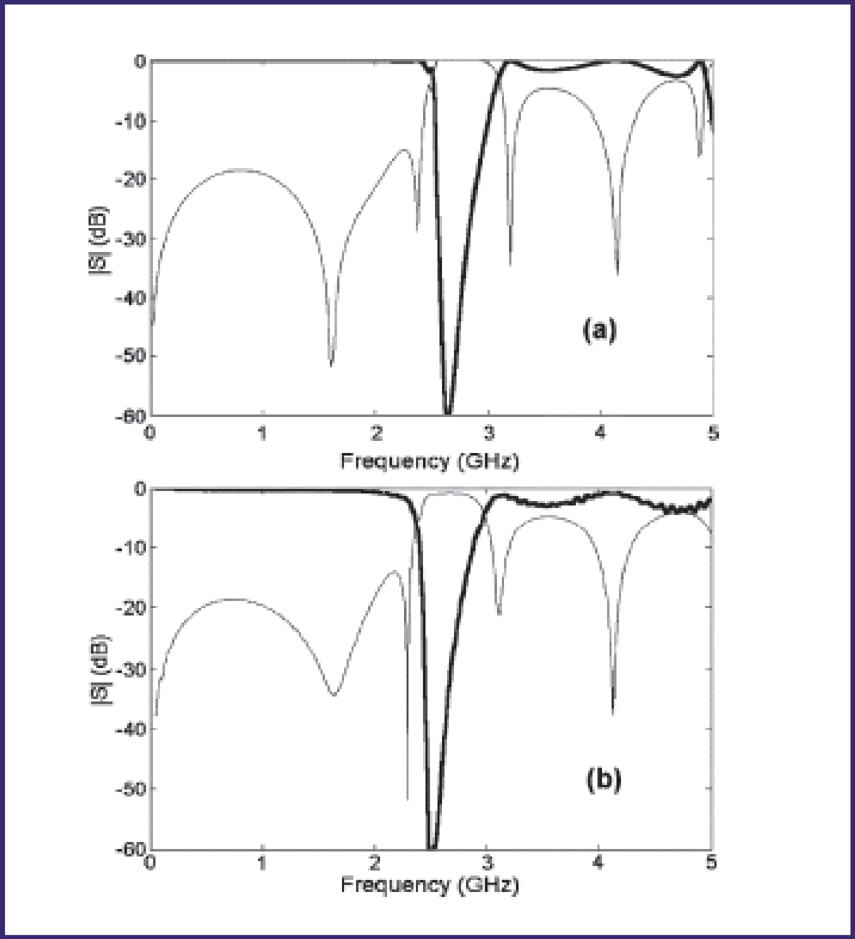
Different Varieties of Metamaterials

Complementary Structures!

Split-Ring Resonator and Complementary Split Ring Reson.

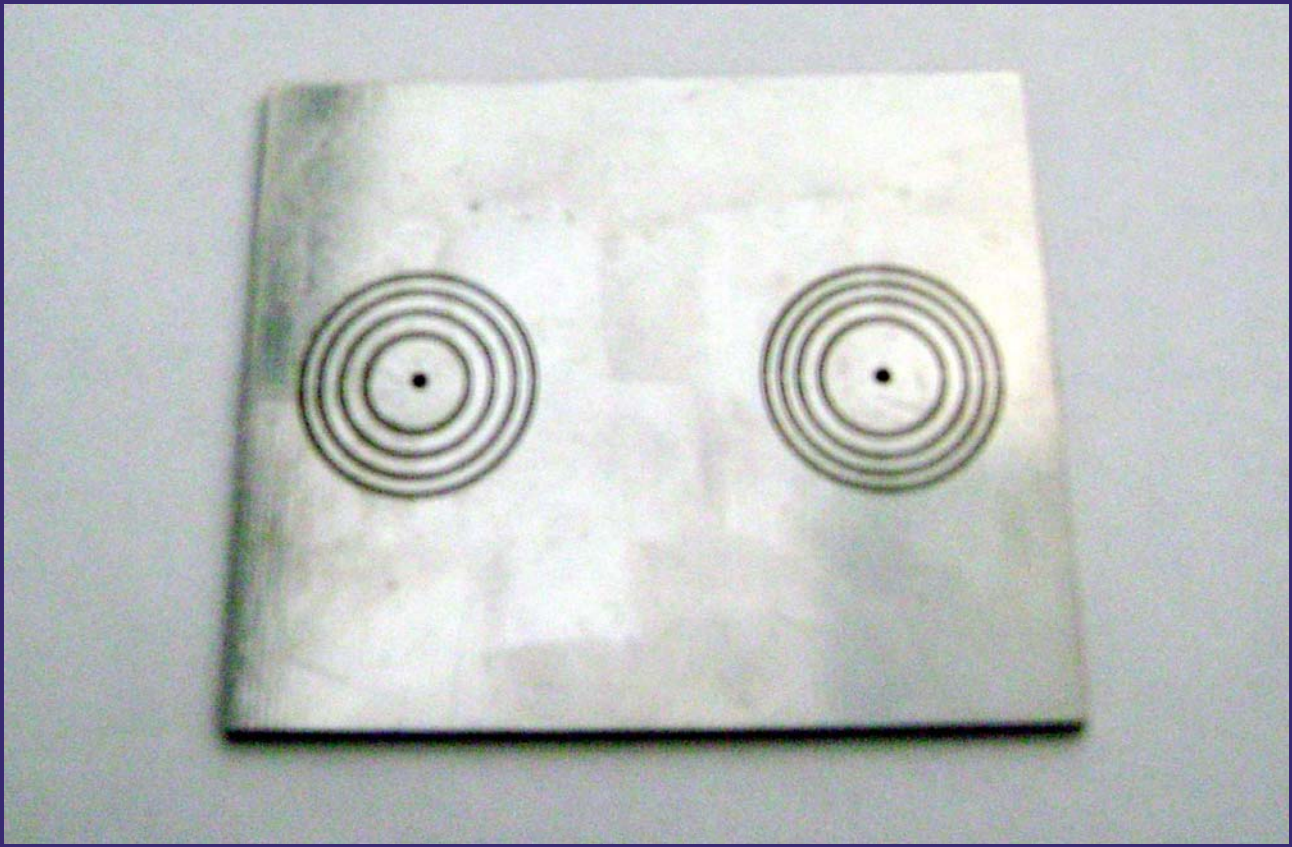


Excellent very small filter!

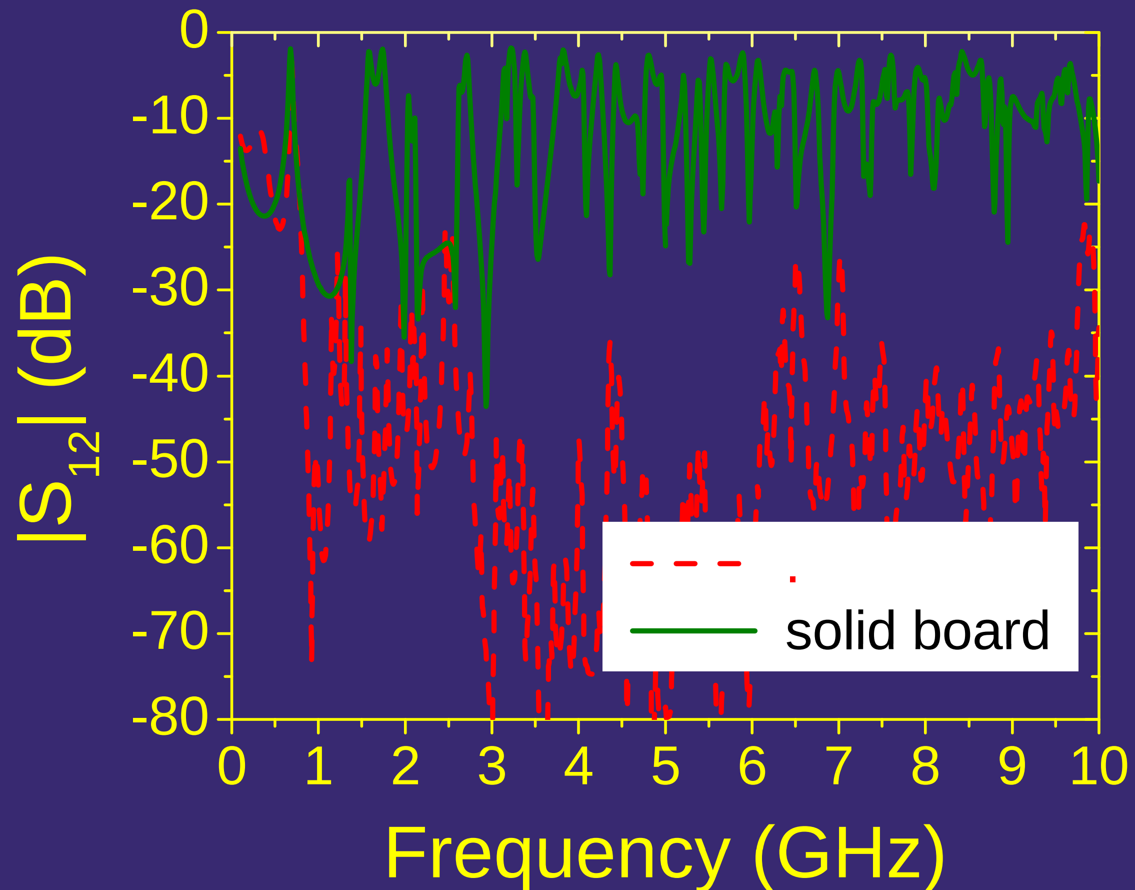


Falcone et al., IEEE MWCL, June 2004

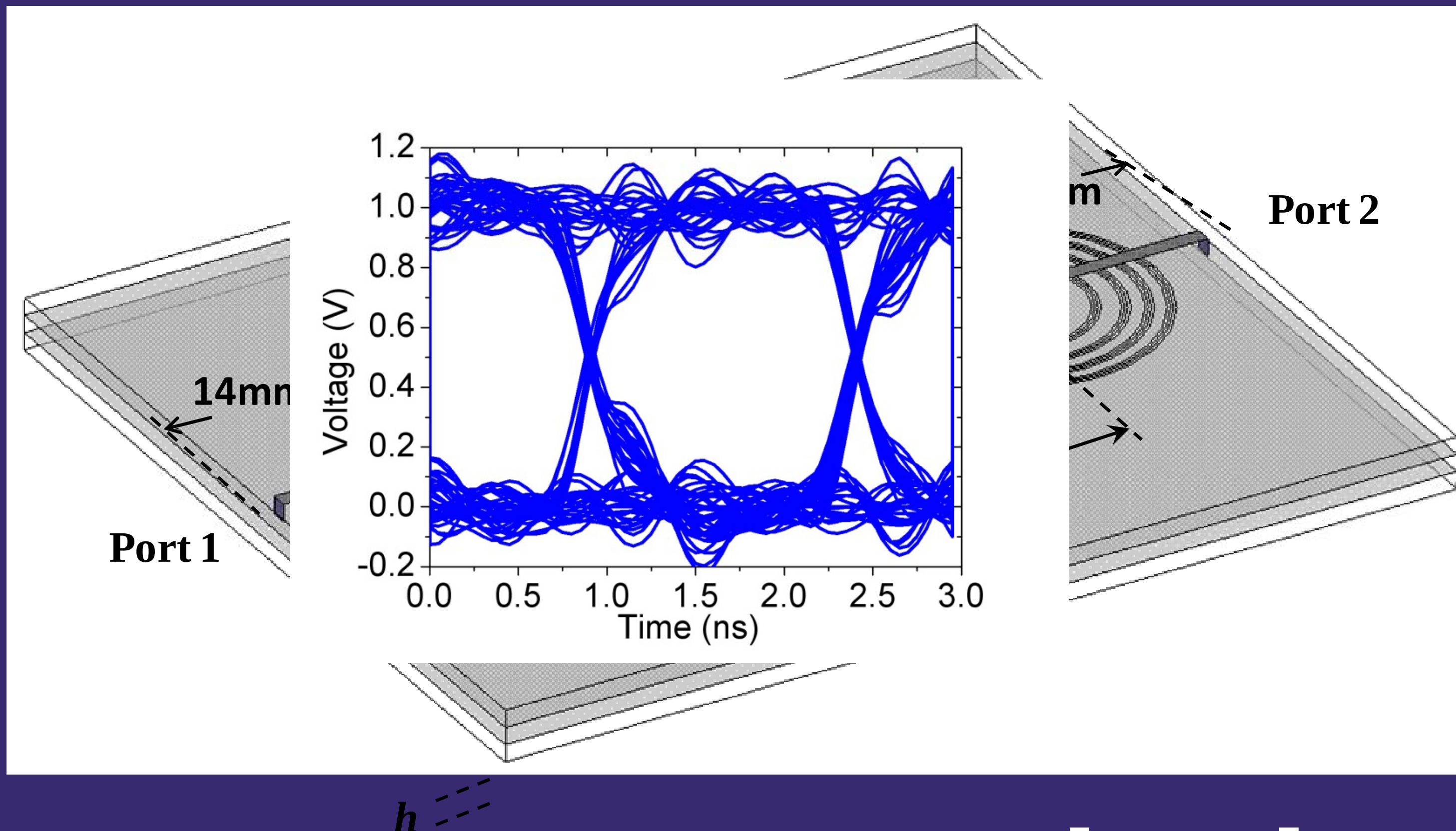
Design of PCBs using Split-Ring Resonators (Negative media)



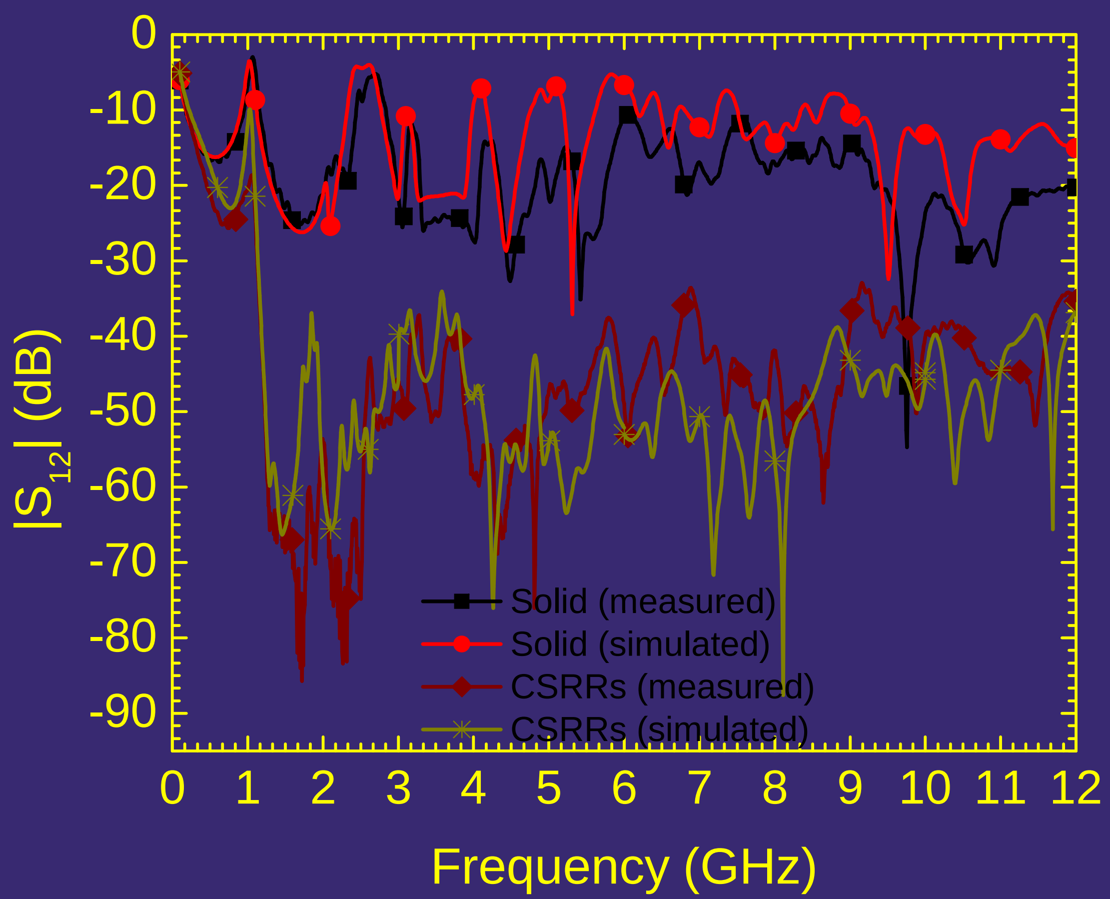
Experiment with Rogers Board



Split-Ring Resonator and Complementary Split Ring Reson.

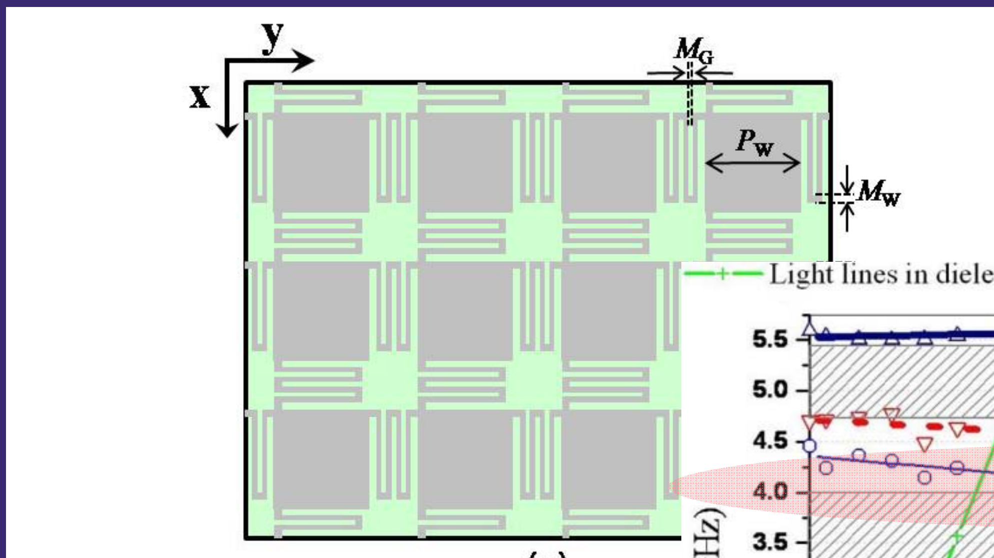


Experiment with FR4

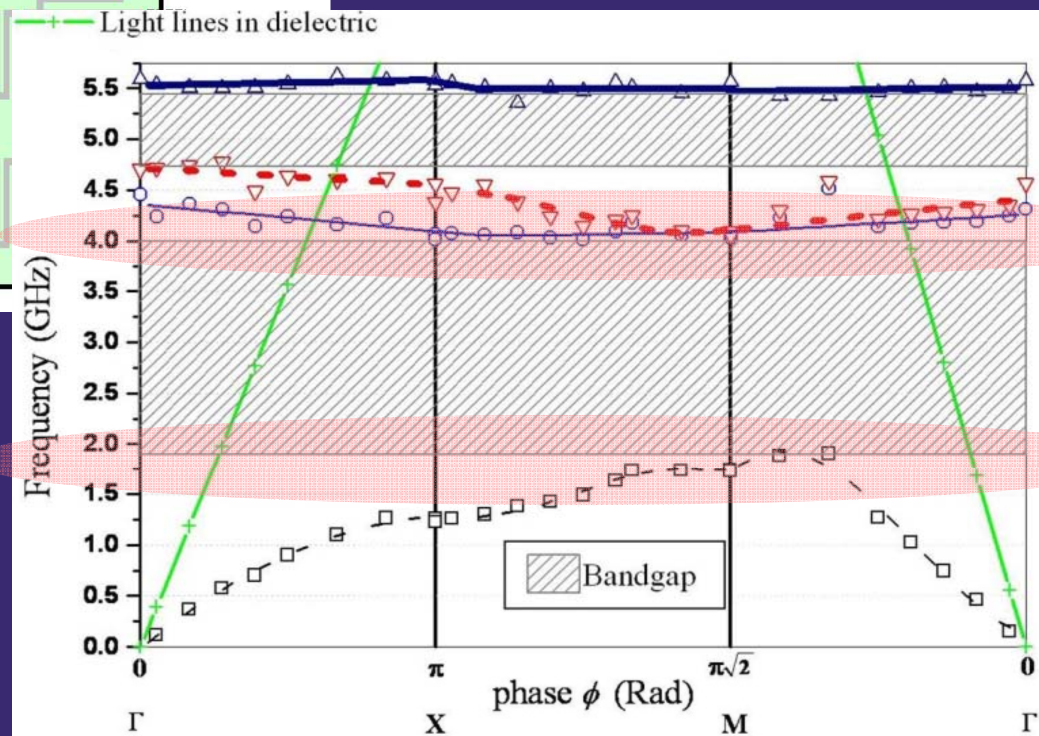


Next challenges:

EBG or ?

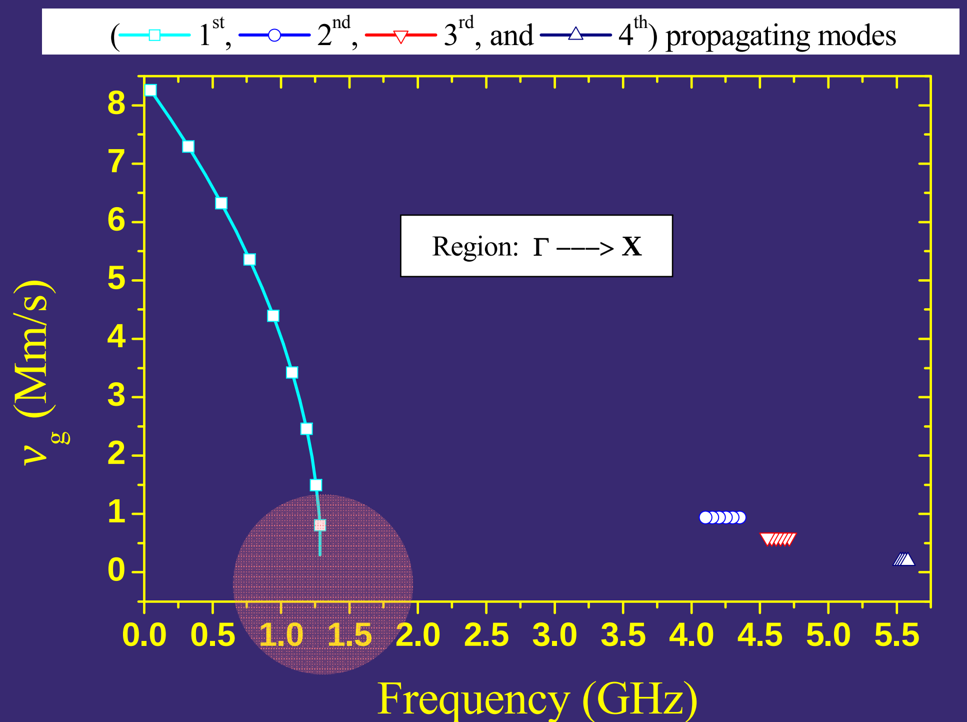


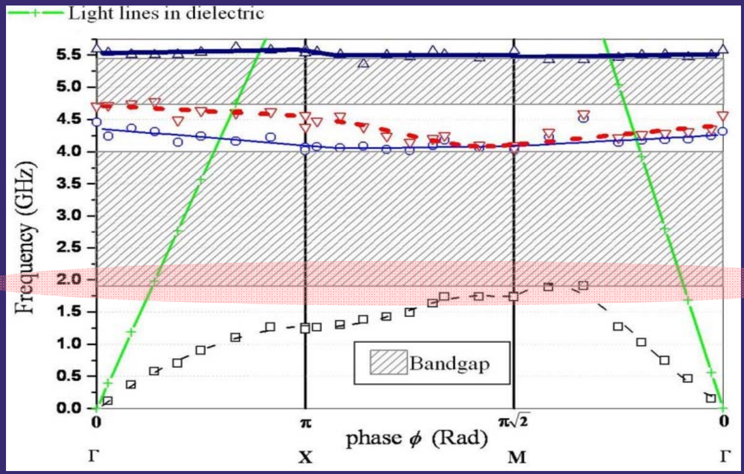
y
x
M_G
P_W
M_W



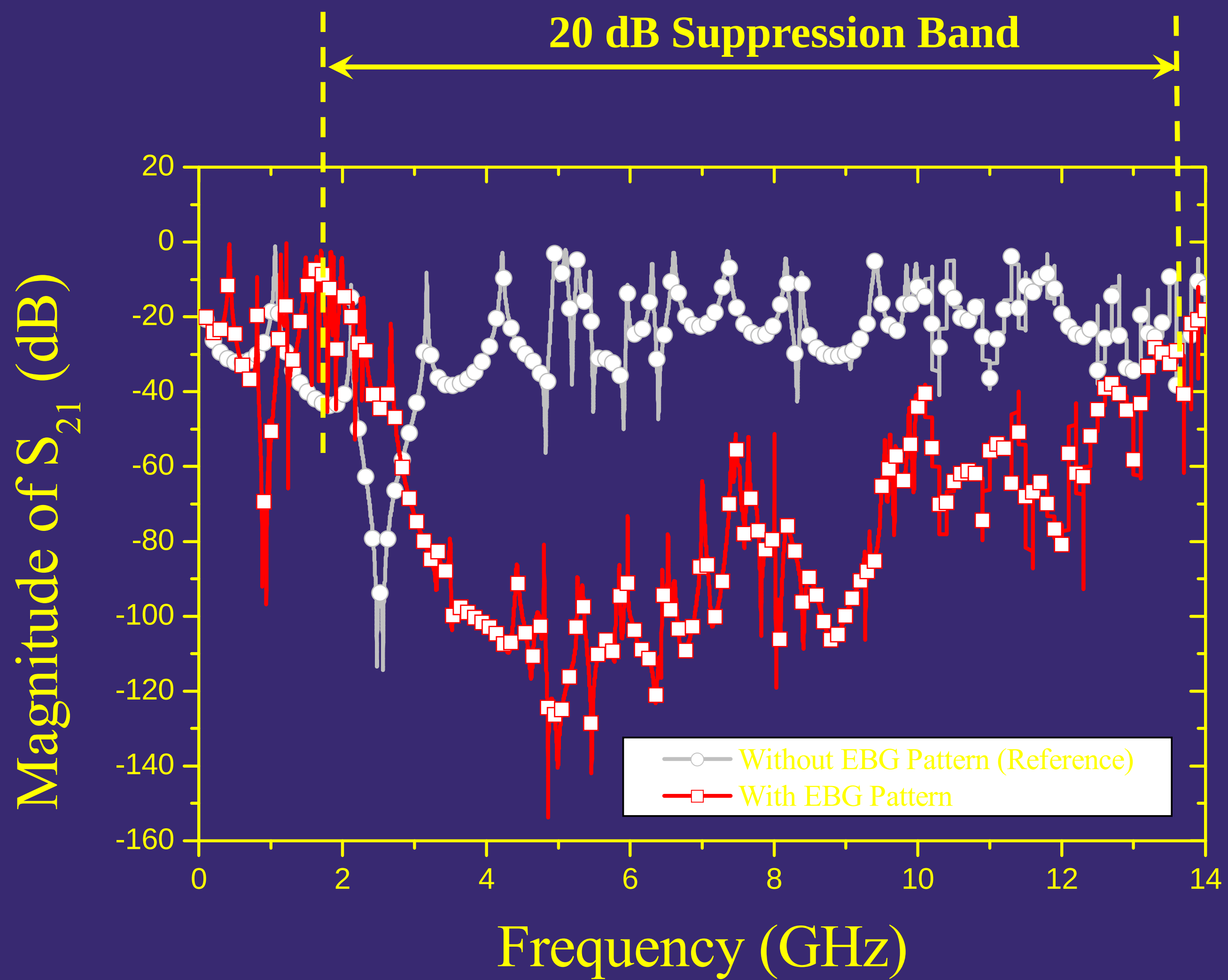
Light lines in dielectric
Frequency (GHz)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
π
π√2
0
phase φ (Rad)
Γ
X
M
Γ
Bandgap

Dispersion Diagram.. How important?

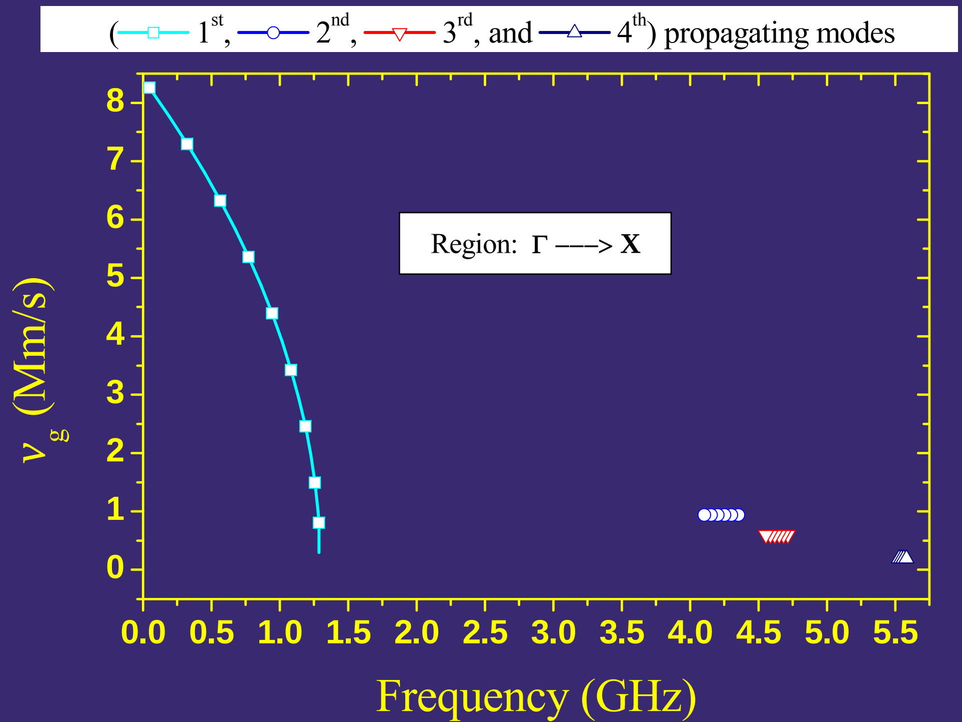


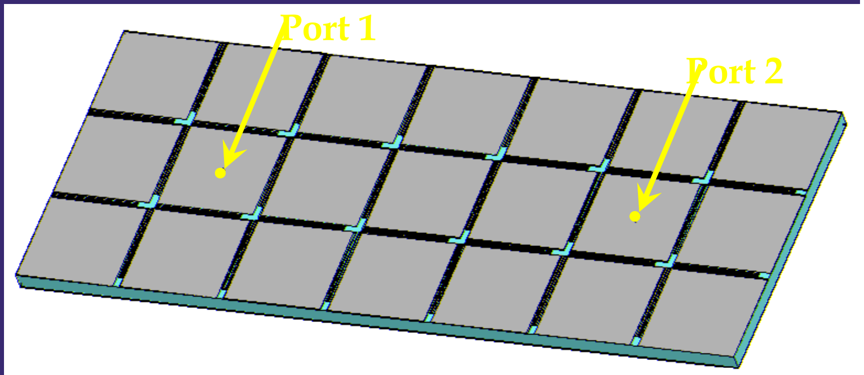


Suppression Bandwidth

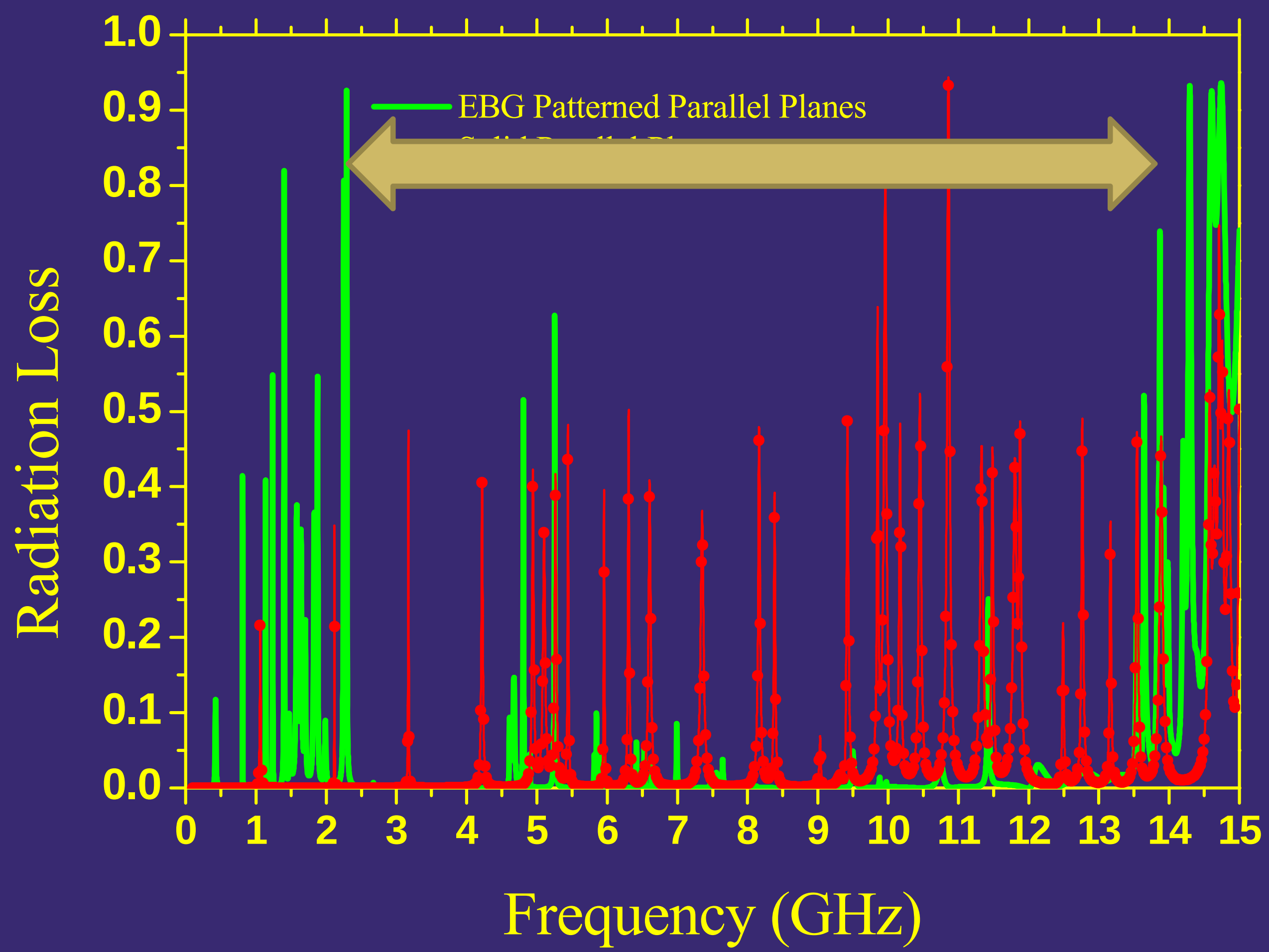


Suppression Bandwidth



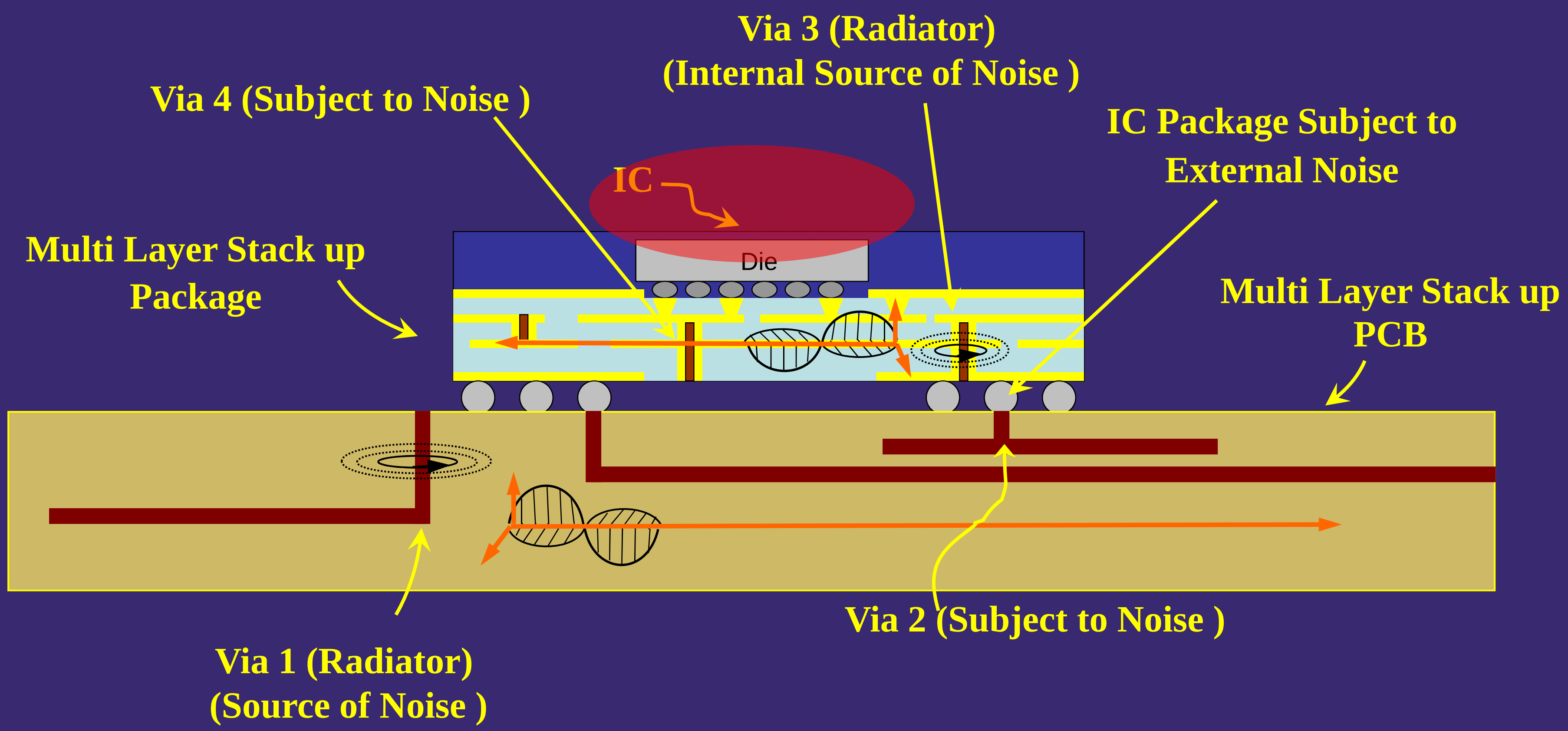


Suppression Bandwidth vs. Bandgap



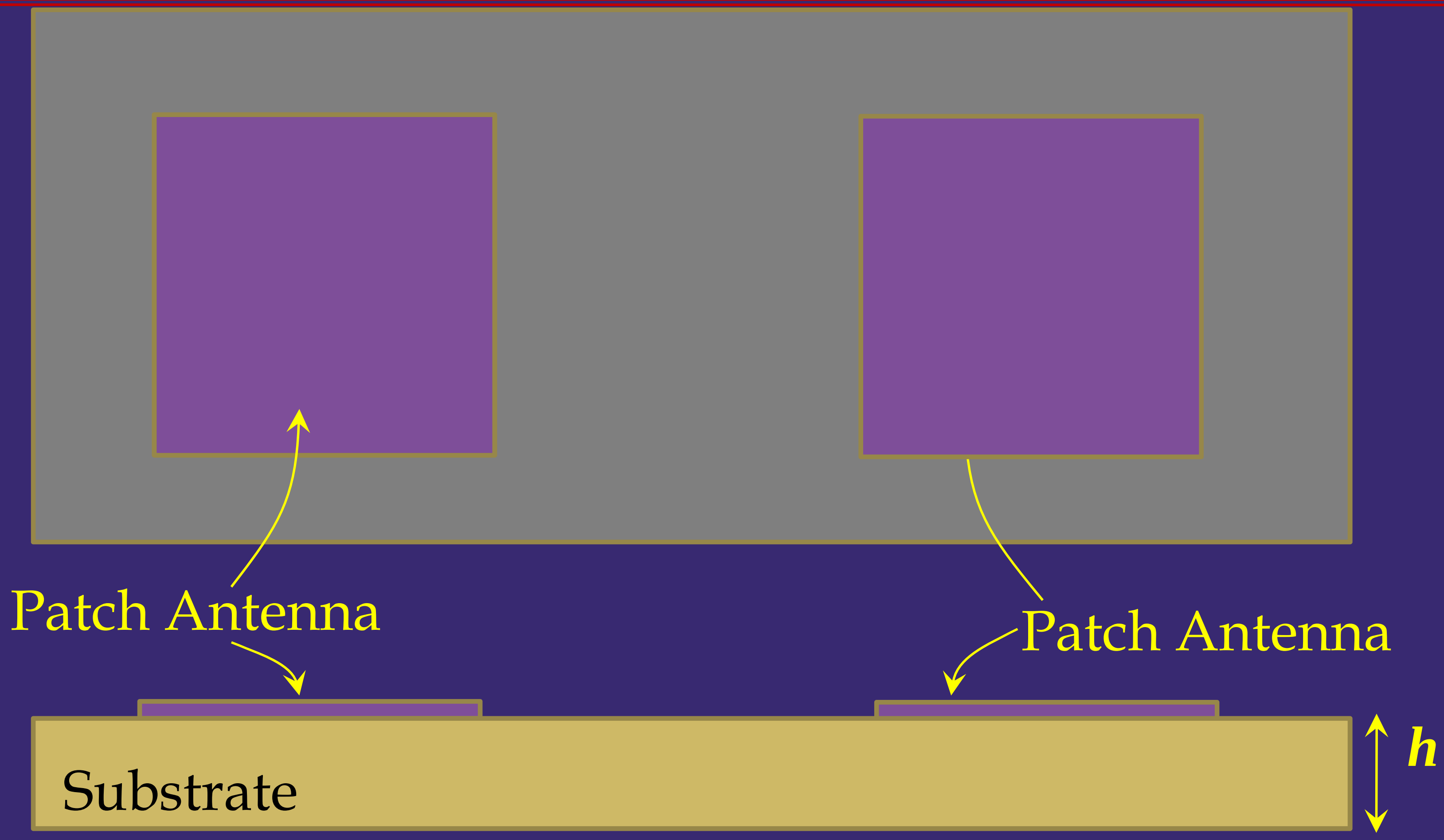
Noise… noise…noise …

IC subject to Internal and External Noise

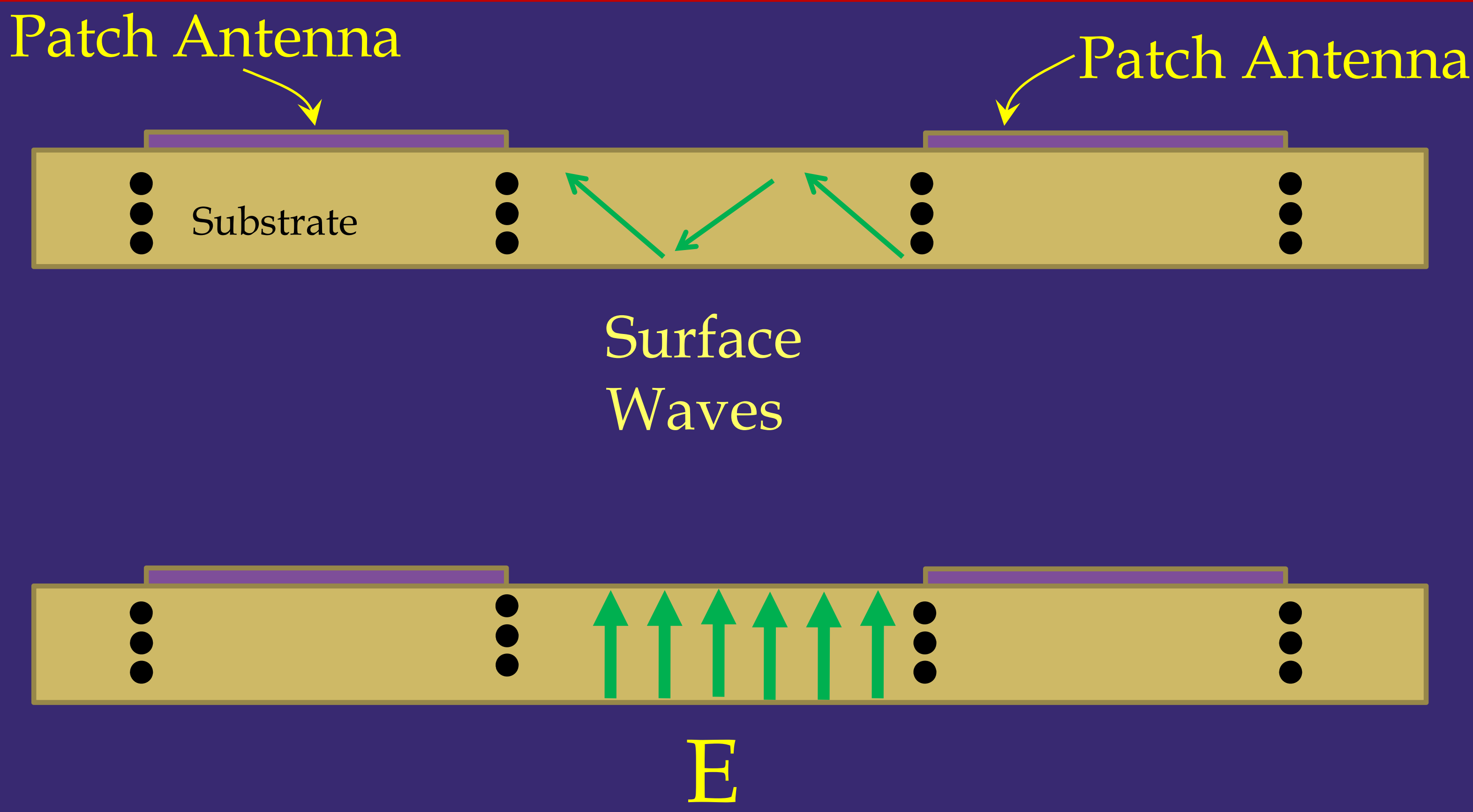


Reduction of Coupling between Patch antennas

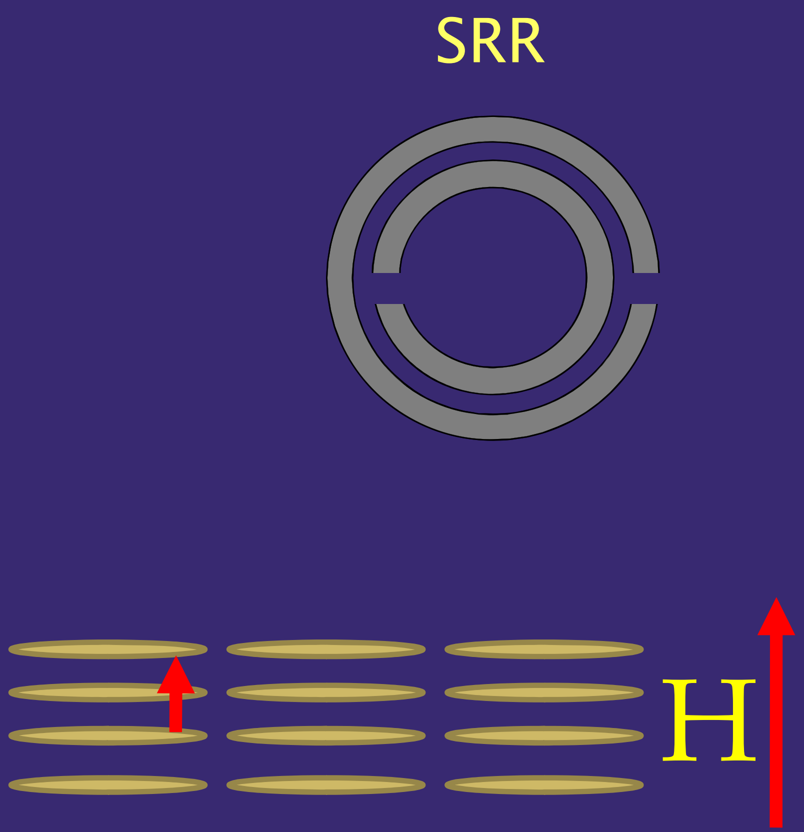
Reduction of Coupling between Patch antennas

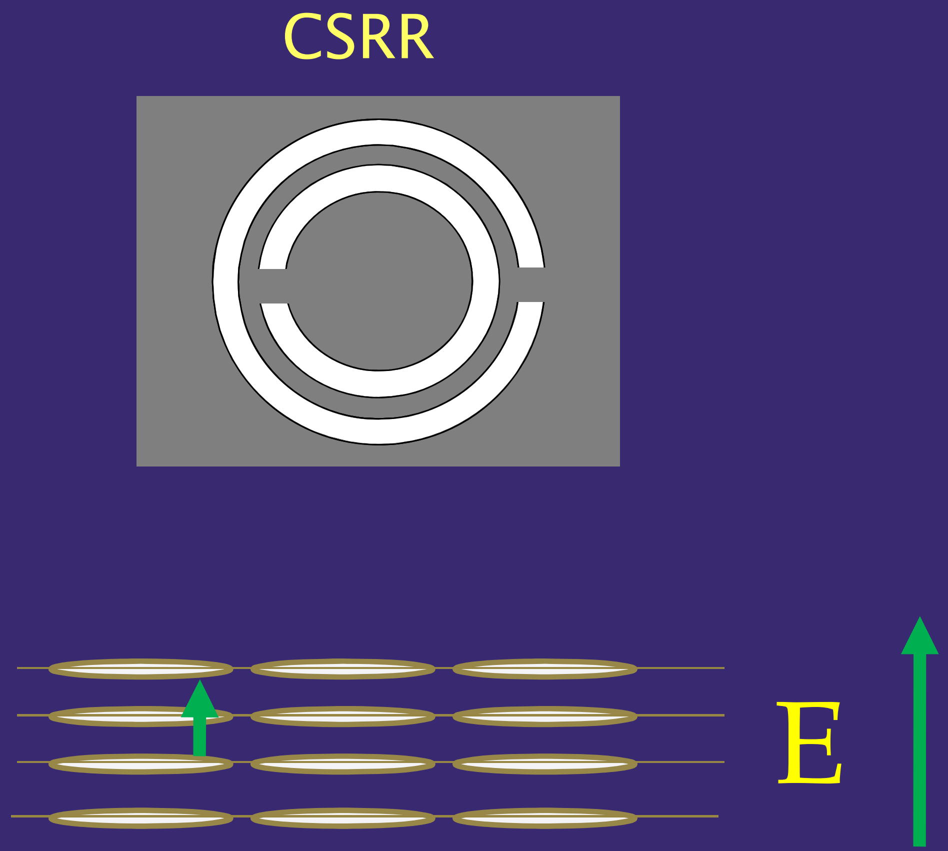


Reduction of Coupling between Patch antennas

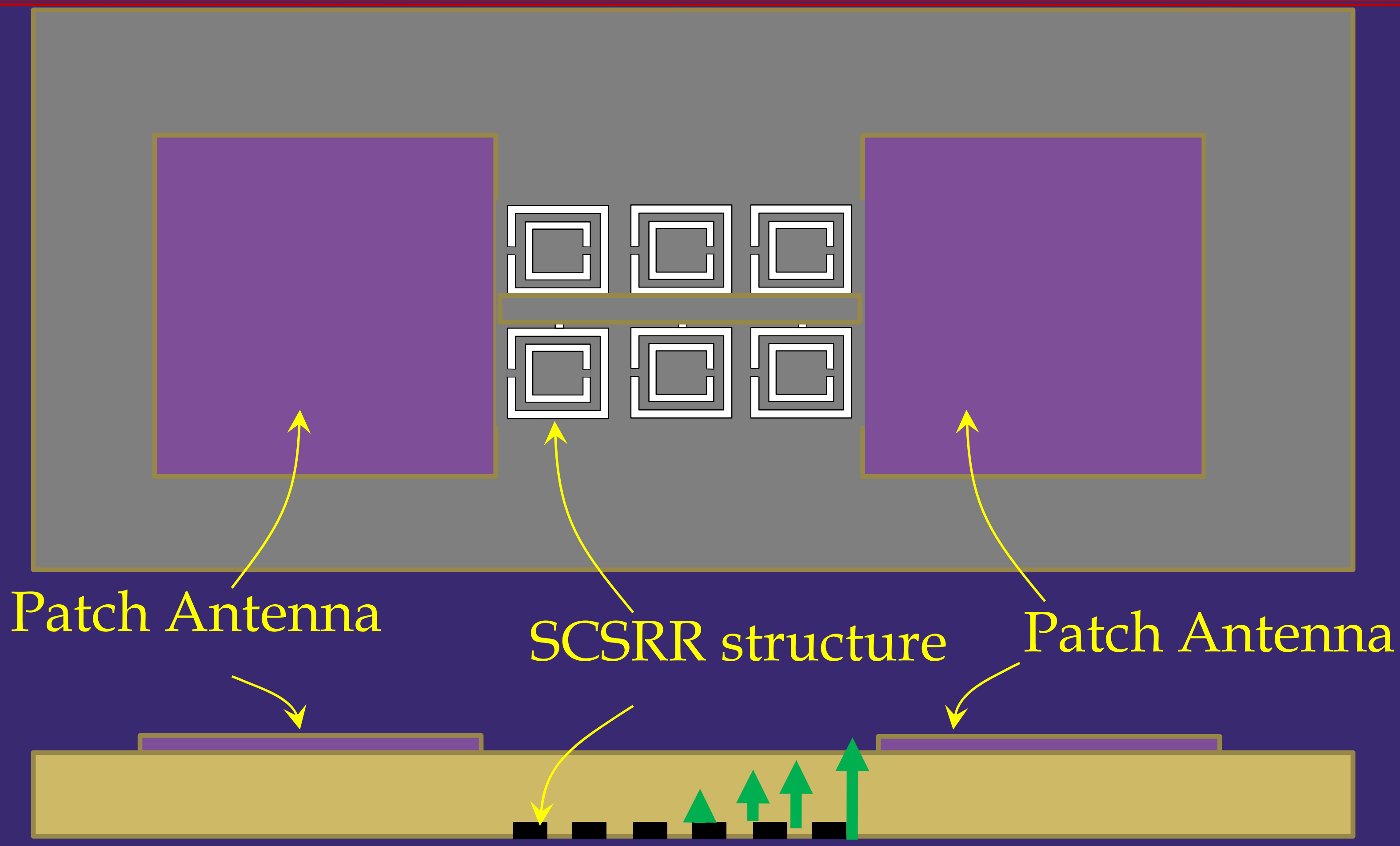


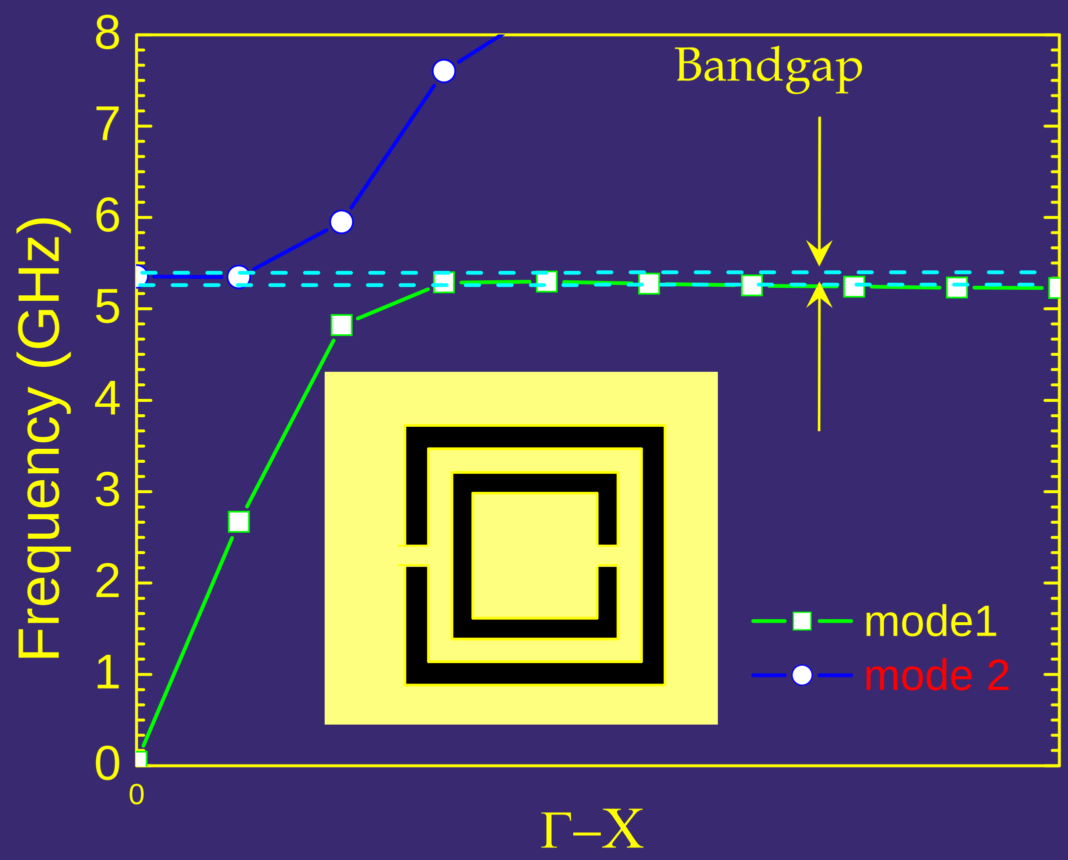
Complementary Split Ring Resonator



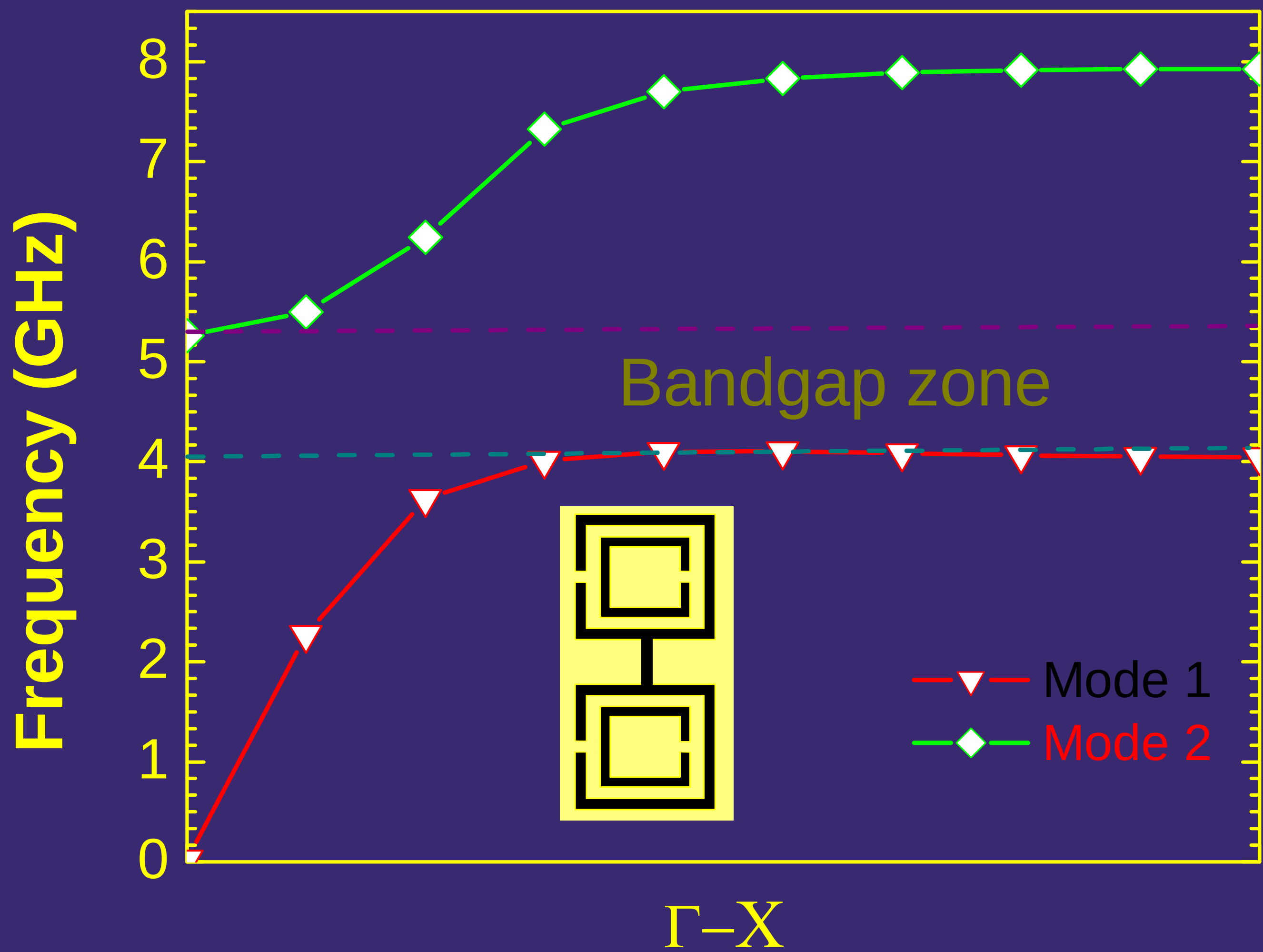


Design of PCBs using Complementary Split-Ring Resonators

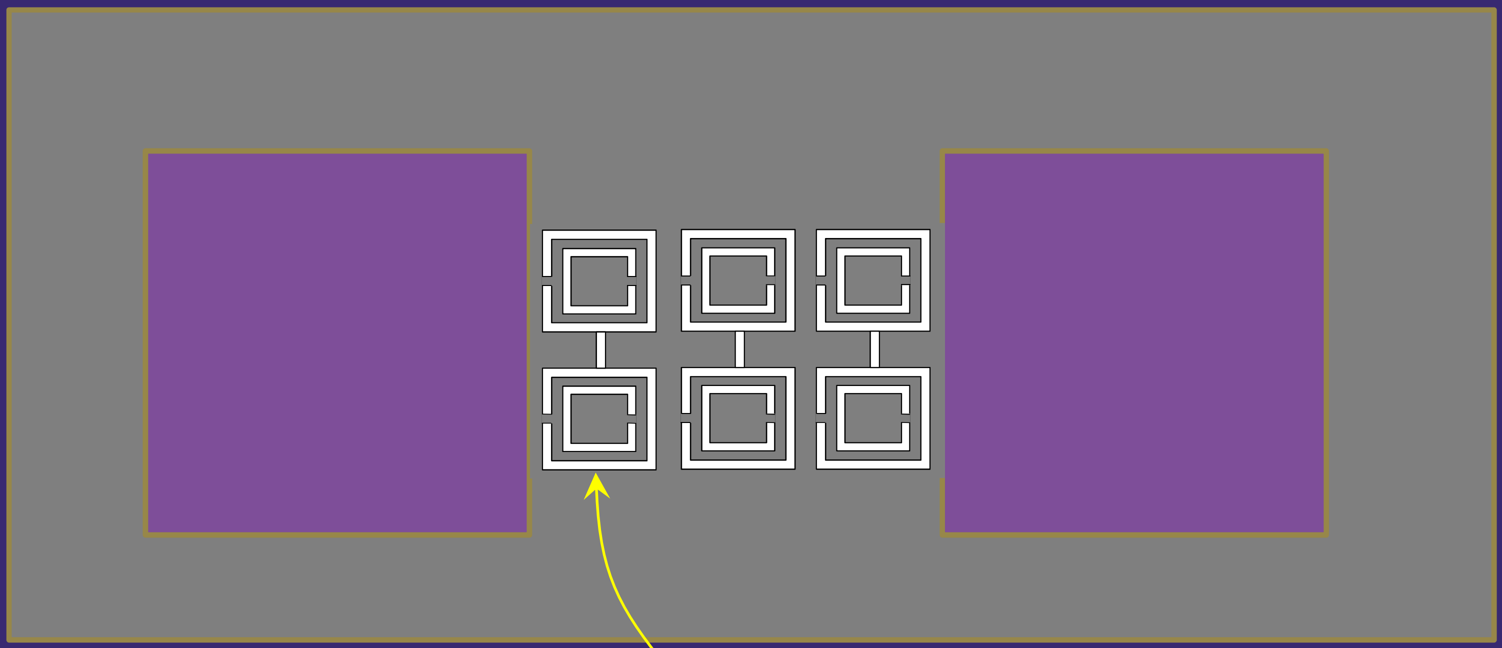




8
7
6
5
4
3
2
1
0
0
Frequency (GHz)
Γ–X
Bandgap
mode1
mode 2

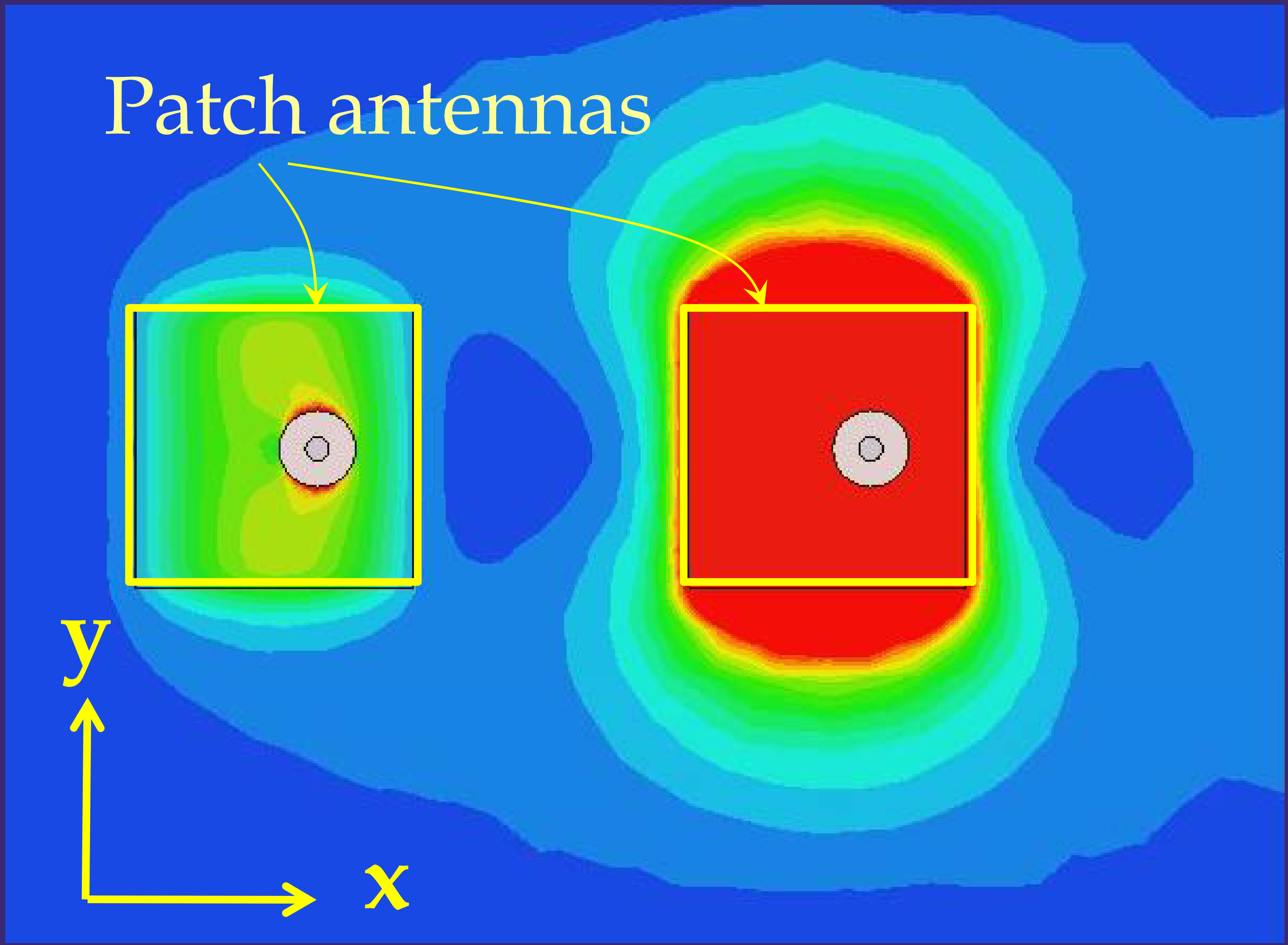

Frequency (GHz)
8
7
6
5
4
3
2
1
0
Bandgap zone
Mode 1
Mode 2
Γ–X

SCSRR

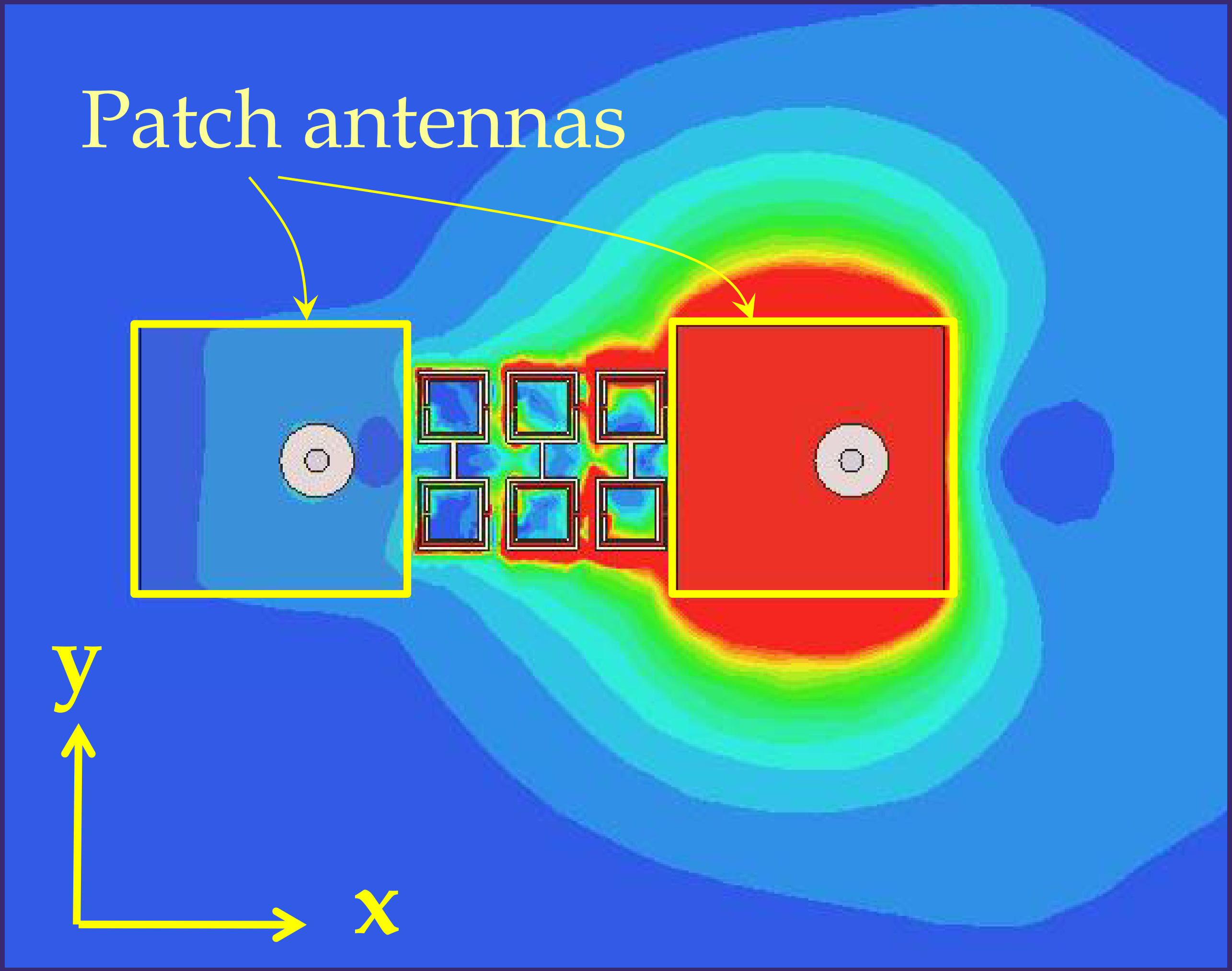


SCSRR structure

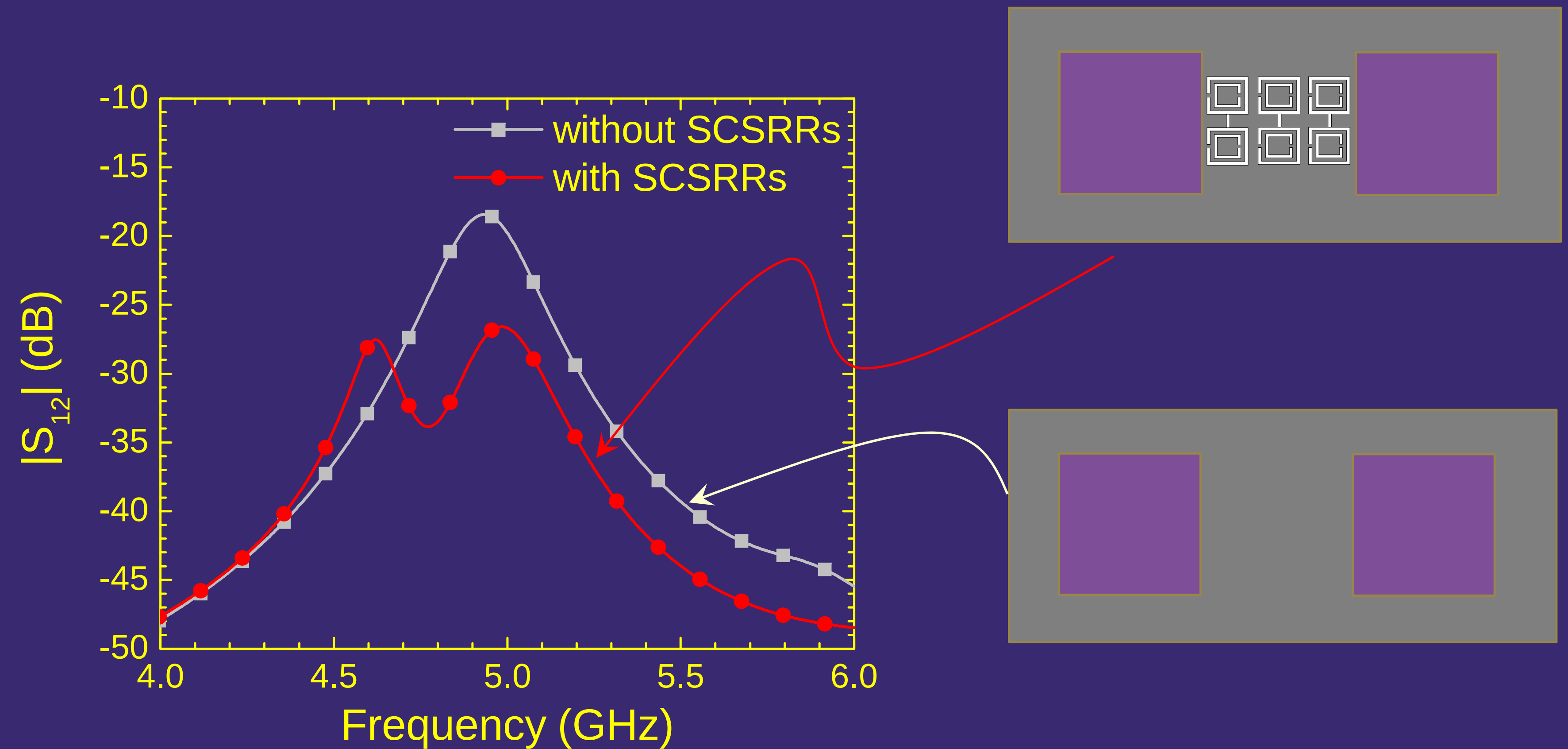
Surface Currents on Ground Plane



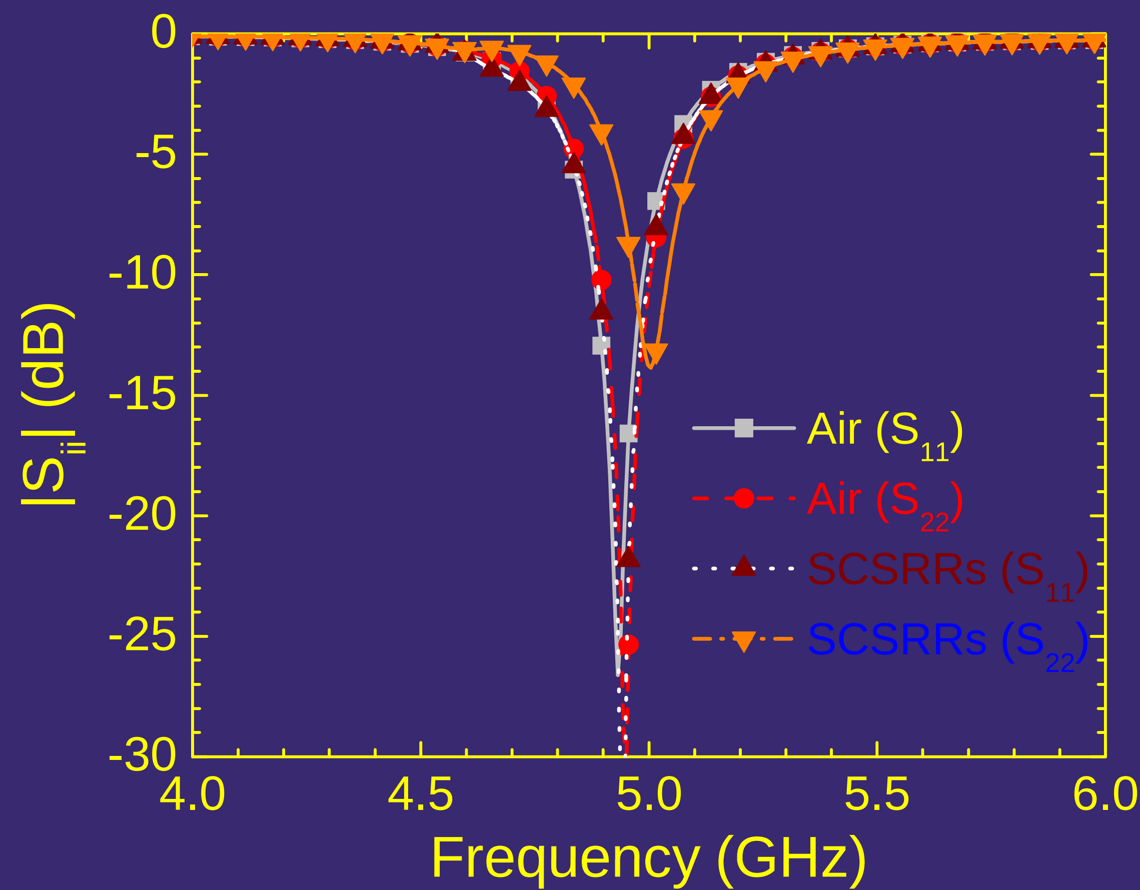
Surface Currents on Ground Plane



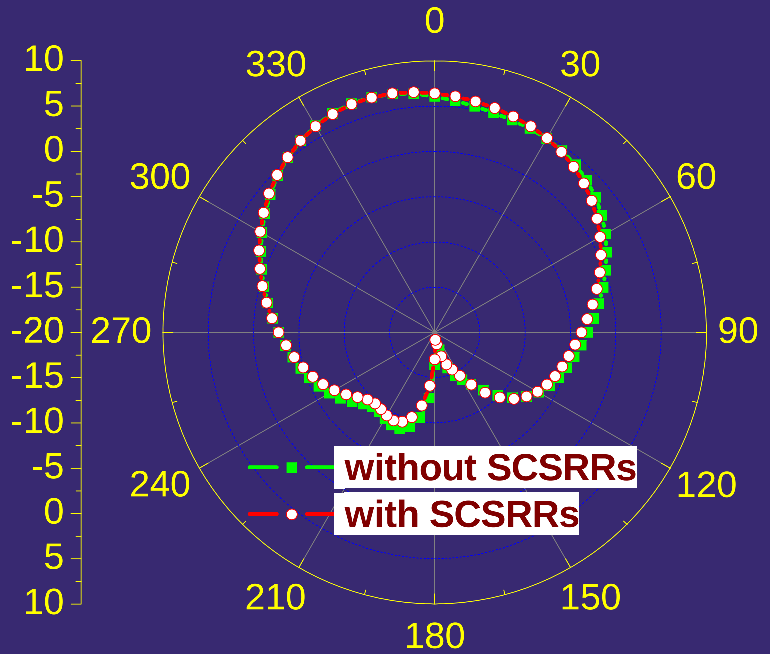
Performance of SCSRR



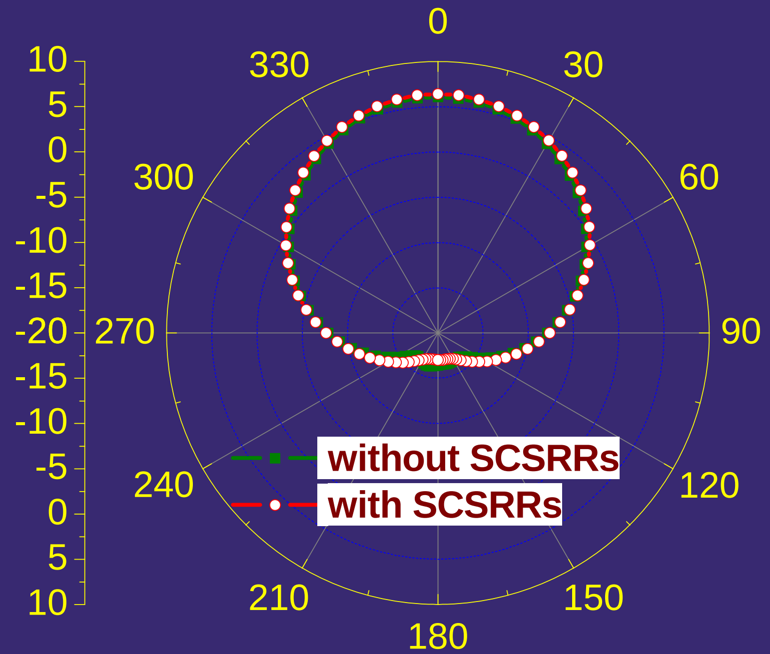
Antennas Matching Practically not affected!



Radiation Patterns



H-plane



E-plane

In summary …

EBGs…

Perhaps has the most important application in the field of EMI/EMC!!.