Improved RF Metamaterial Band-Pass Filter Design Using CSRR Structures on LCP Substrate

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Introduction

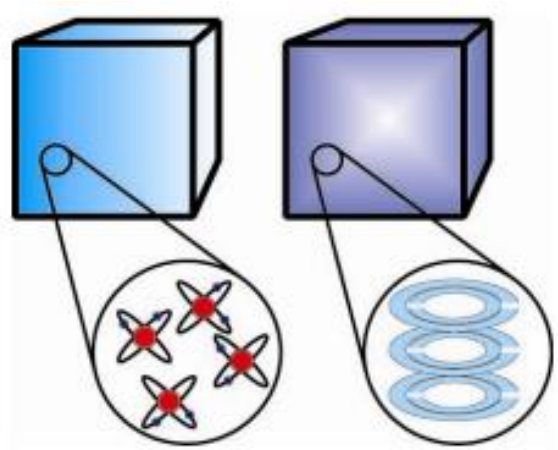
- Metamaterial filters present many advantages
  - Compact size
  - Simple design
  - Low fabrication cost
- The problem with band-pass filters
  - Upper band smoothing effect
  - Asymmetric frequency response
- How to improve the frequency response?

Metamaterial Background

- V. Veselago foundational work (1967)
  - Negative index of refraction
  - Negative parameters yield unusual materials
- J. Pendry
  - Theoretical basis for negative ε and μ
  - Superlens (2000)
- D. Smith
  - First realization of a negative index of refraction
- Electromagnetic implications

What is a Metamaterial?

- Periodic structures
  - Artificially created
  - Sub-λ size
  - Cascading “unit cells”
- Resonators like atoms
  - Structure vs. composition
  - Physical dimensions
  - Resonator shapes



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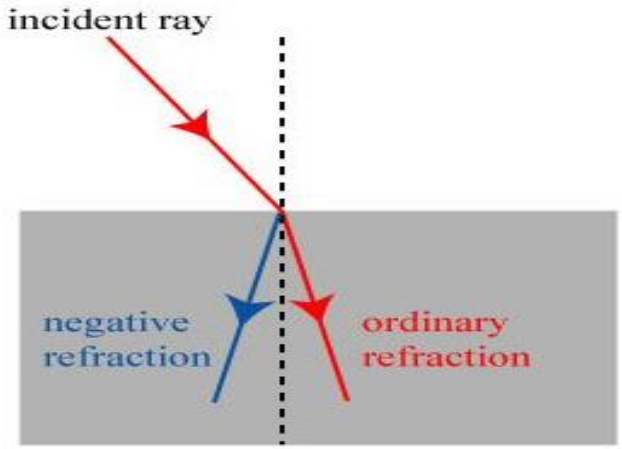
What is a Metamaterial?

- Negative ε and μ
  - Reverse Snell's Law
    - ($n^2=\varepsilon\mu$)
  - Inverse Doppler Effect
- Maxwell's Equations
  - D = εE, B = μH
    - "Left-handed" medium
    - Poynting vector opposite of k
  - Boundary conditions
    - Negative normal components



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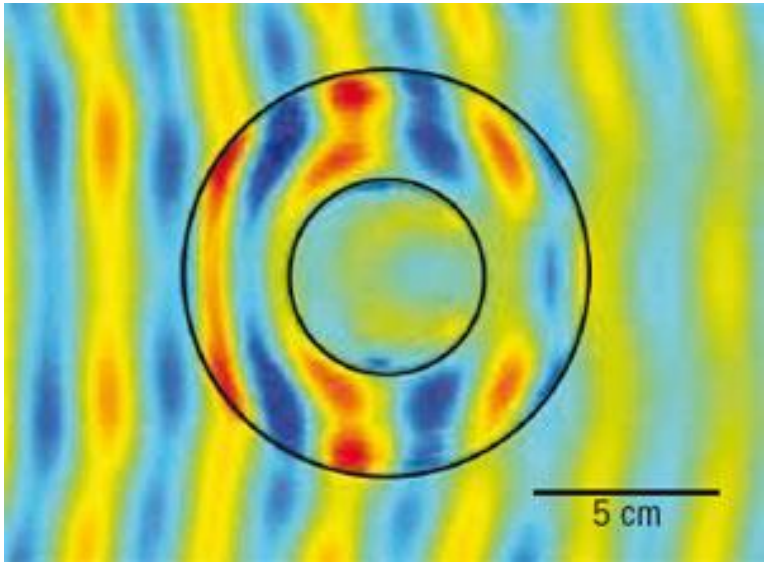
Metamaterial Applications

- Electronic
  - Filters
  - Antennas
  - Oscillators
- Optical
  - Lenses
  - Invisibility cloak
- Acoustic
  - Seismic cloak

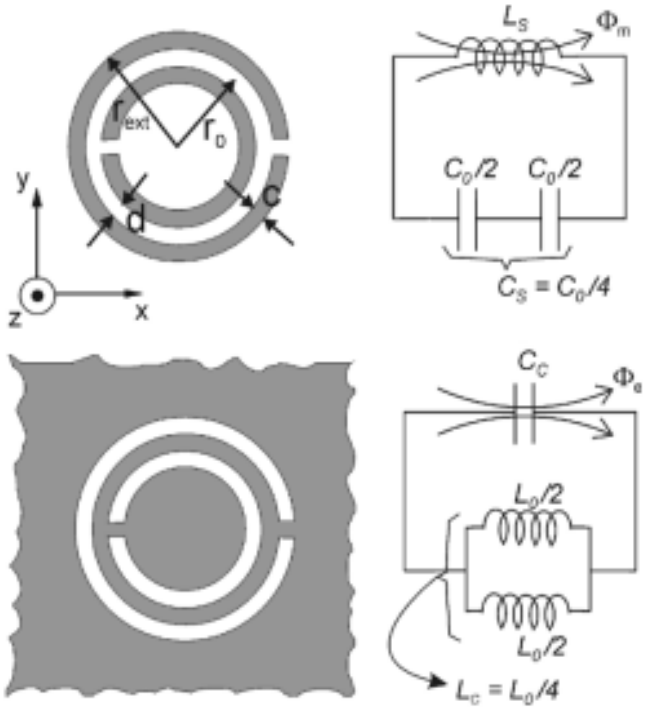


Resonating Structures

- Split-ring resonator (SRR)
  - External magnetic flux
  - Incorporated into signal line
- Complementary split-ring resonator (CSRR)
  - External electric field
  - Etched into ground plane
- Other shapes are possible
  - Square, H-shaped, spiral

Resonating Structures

- Circuit models
  - LC resonator
- Dimensions
  - Spacing
  - Gaps
  - Radius
- Duality
  - CSRR > negative image of SRR
  - “Roughly” duals



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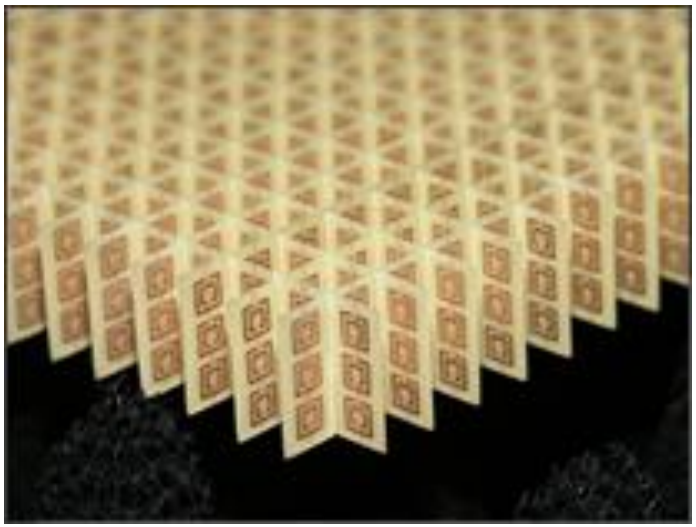
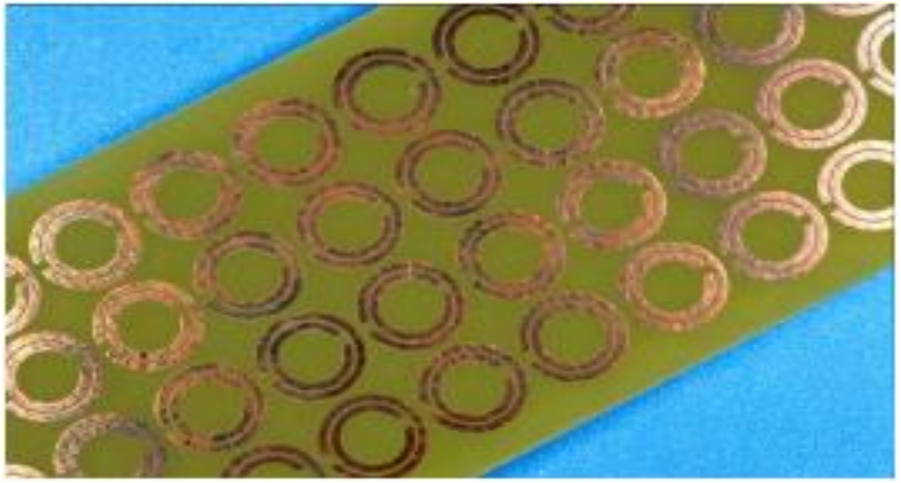
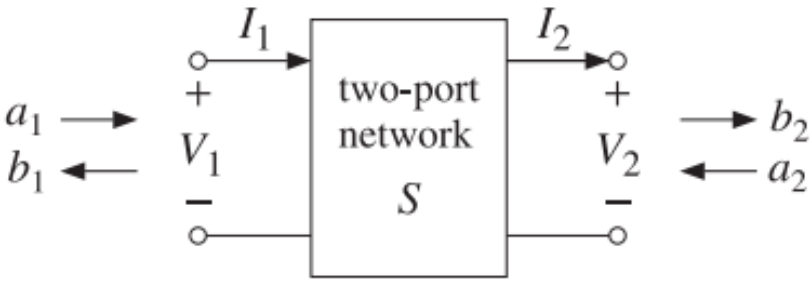
Resonating Structures





Microwave Filters Review

- S-Parameters
  - Two-port network
  - Insertion loss
    - S11
  - Return loss
    - S21
  - Graph of magnitude (dB) vs frequency (Hz)



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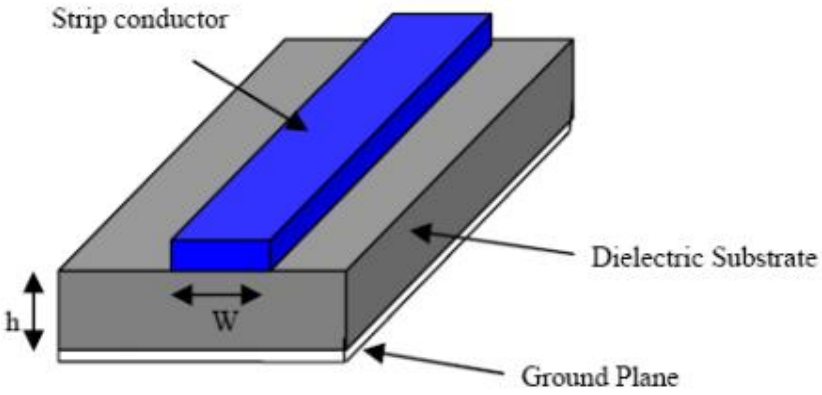
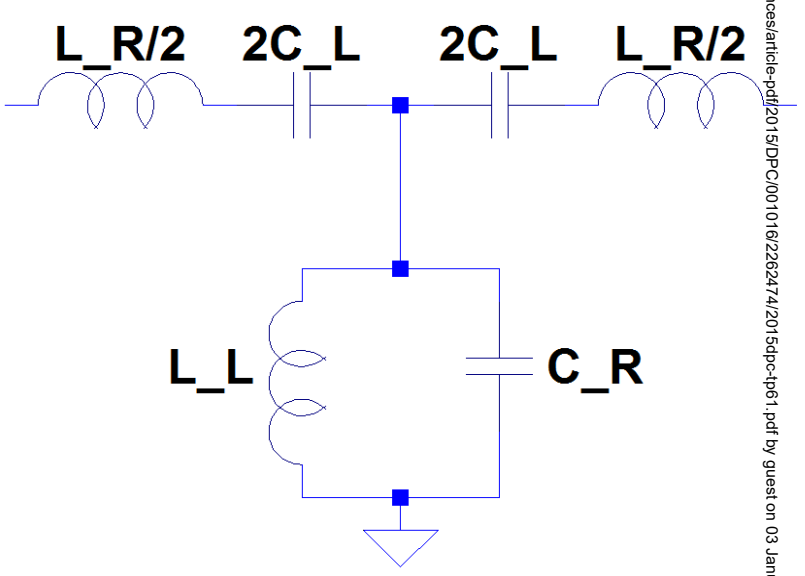
Microwave Filters Review

- Microstrip
  - Conducting metal sheet
  - Dielectric substrate
  - Ground plane
  - Models L and C
- Transmission line
  - Lumped elements



Metamaterial Filters

- Metamaterial T-Line model
  - Backward waves
  - CRLH behavior
    - Low *f* > reactive elements
    - High *f* > line elements
  - Negative parameters
    - $\varepsilon_{eff} = \frac{C_R}{l} - \frac{1}{\omega^2 L_L l}$
    - $\mu_{eff} = \frac{L_R}{l} - \frac{1}{\omega^2 C_L l}$



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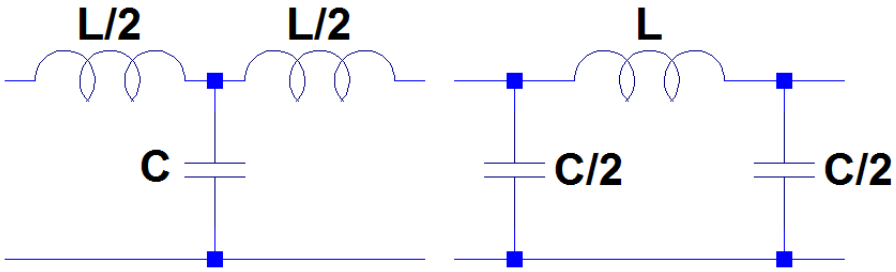
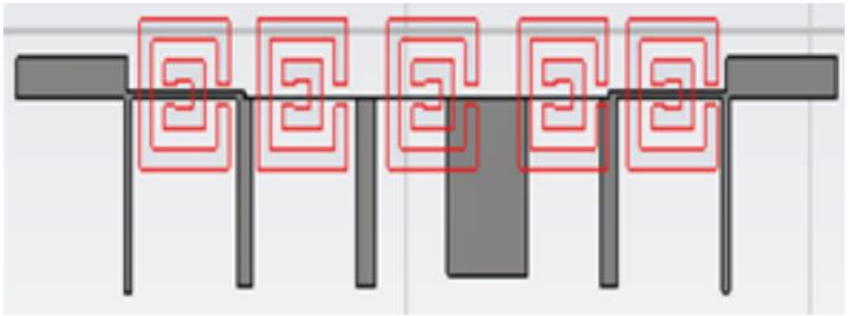
Metamaterial Filters

- Low-pass filter
  - Series inductance
  - Shunt capacitance
- Metamaterial LPF
  - Shunt stubs
  - Inductance
  - No etched line gaps





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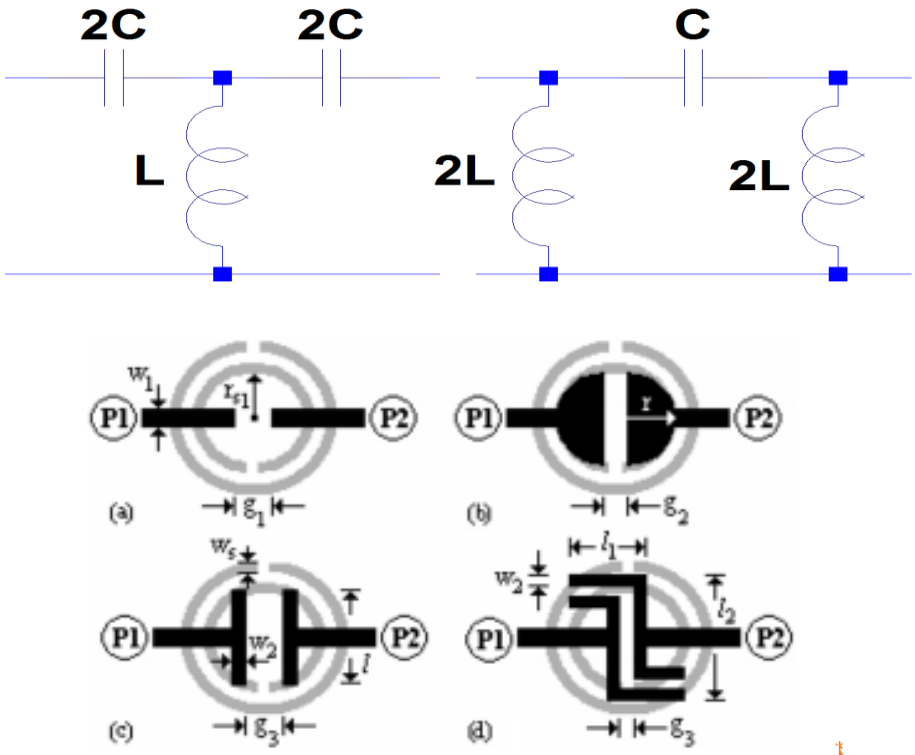
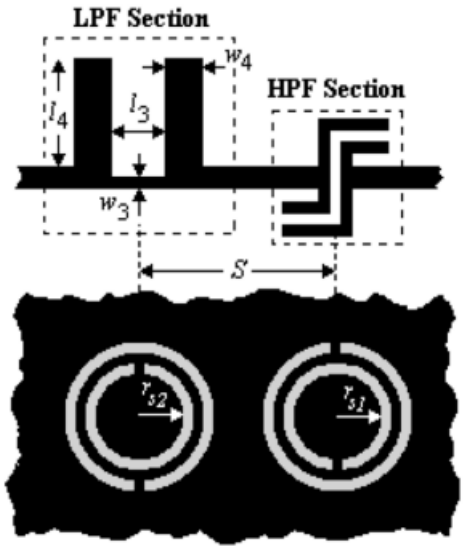
Metamaterial Filters

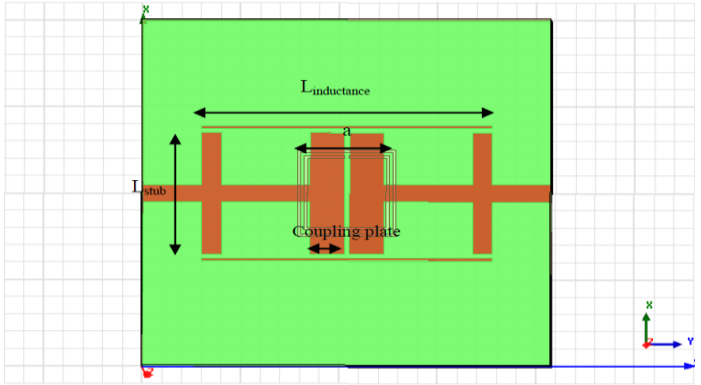
- High-pass filter
  - Shunt inductance
  - Series capacitance
- Metamaterial HPF
  - Series etched gaps
  - Capacitance
  - No line shunt stubs



Metamaterial Filters



- Metamaterial BPF
  - Shunt stubs
  - Series gaps
  - Capacitance and inductance
- Three approaches
  - Alternating elements
  - Series gap
  - Single element



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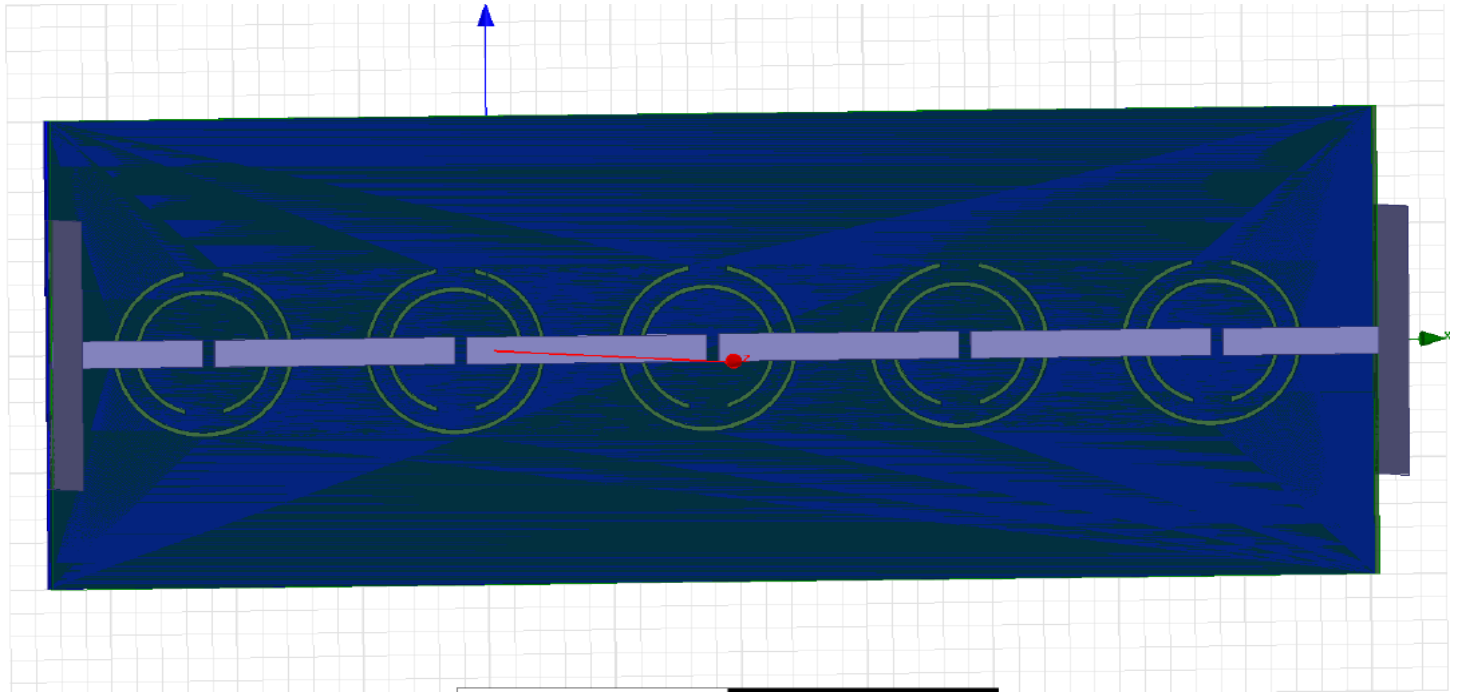
Previous BPF Design

- Filter
  - Series gaps
  - No shunt stubs
- Frequency response
  - ~-16dB S21 at f_c
  - Smoothing effect in the upper band
  - Sharp dropoff in the low band
    - Transmission zero
  - Common problem with BPFs and BSFs

Previous BPF Design



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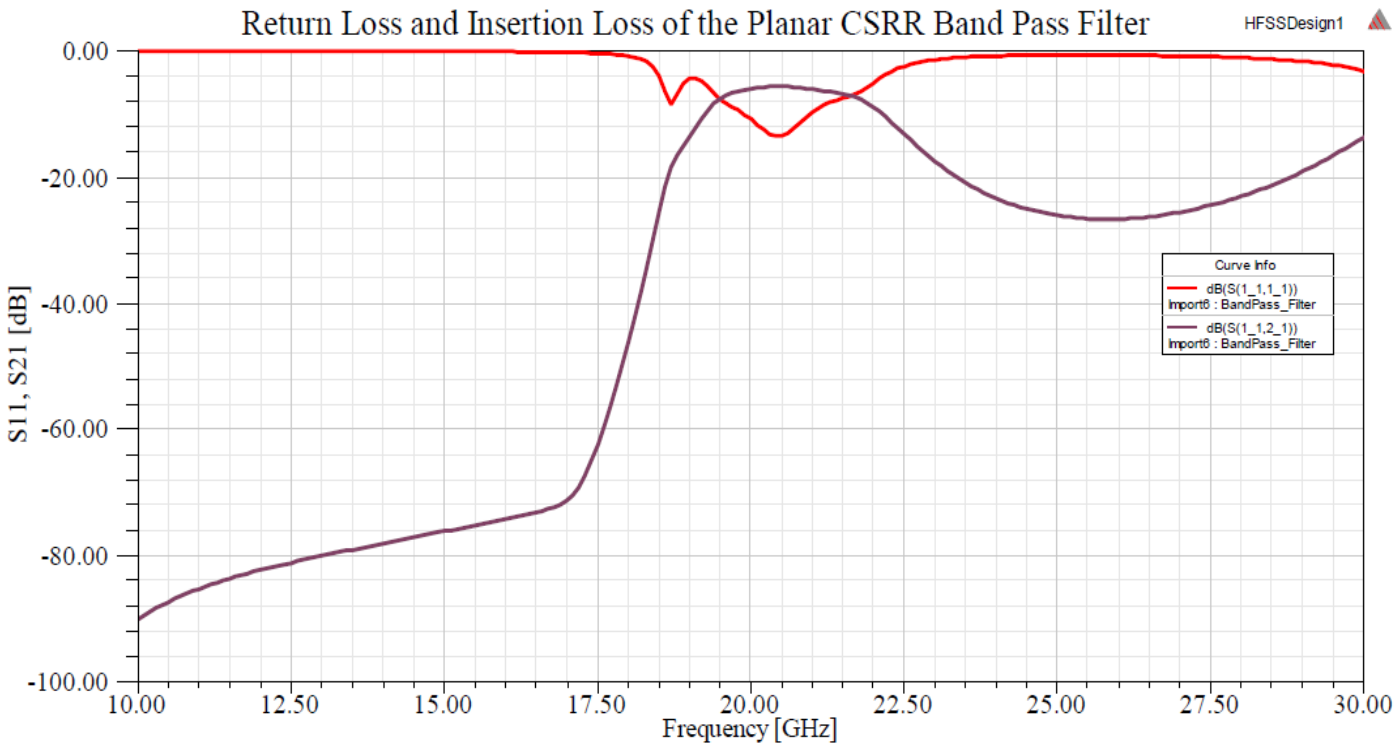
Previous BPF Design



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Previous BPF Design

- Improvement goals
  - Improve passband S11
  - Remove S21 smoothing in upper band
- Method
  - Single element design
    - Combination of LPF and HPF
  - HFSS modeling and simulation
  - Unit cell approach

Single Element Design

- Saves space
  - Filters ~1/2 the length
  - High-order filters
- Increased complexity
  - More tuning required
  - More sensitive to dimensions
- Relatively new approach

HFSS

- Commercial EM field solver
  - FEM
  - Filters, antennas, packaging, etc.
- 3D modeling
  - Material definitions
  - Variable dimensions
- Simulation
  - Specify parameters
  - Software creates the mesh

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Liquid Crystal Polymer (LCP)

- Environmental resistance
  - Extreme temperatures
  - Chemicals, radiation, fire
- RF properties
  - Relatively low ε (~ 3)
  - Low loss tangent (~0.004)
- Flexible substrate
  - Small effect on filter performance
- Micromachinable

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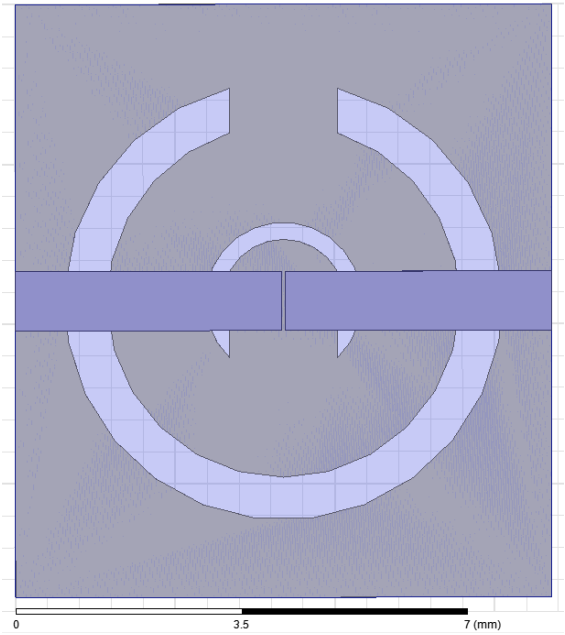
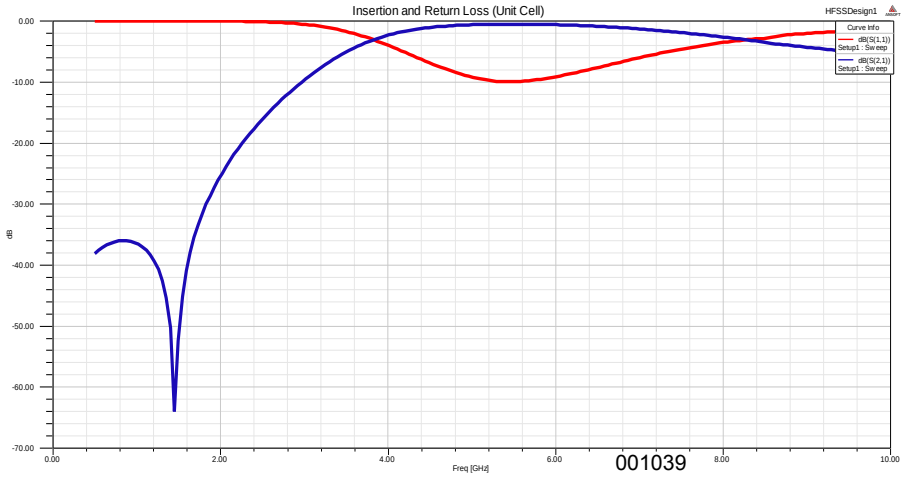
Simulation Setup

- Frequency Sweep
  - HFSS
  - 1 to 10 GHz
  - 201 points
  - Solution frequency 4.2GHz
- S-Parameter plot
  - S11 (insertion loss) in red
  - S21 (transmission loss) in blue

Improved BPF Design

- Initial Design
  - Copper line
  - Copper ground
  - LCP substrate





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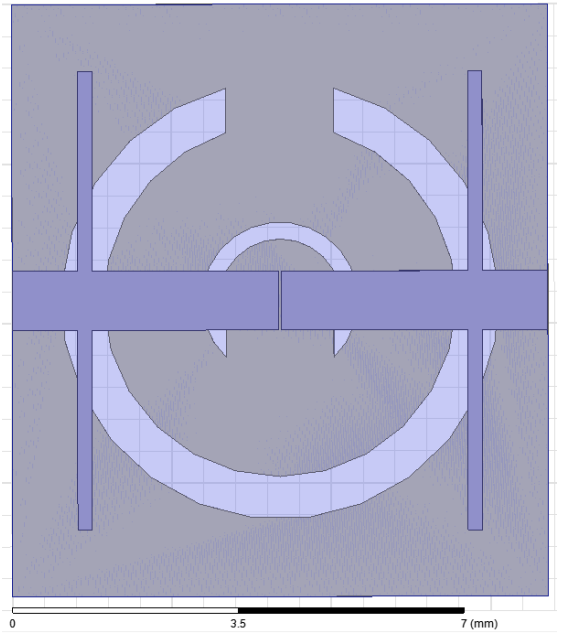
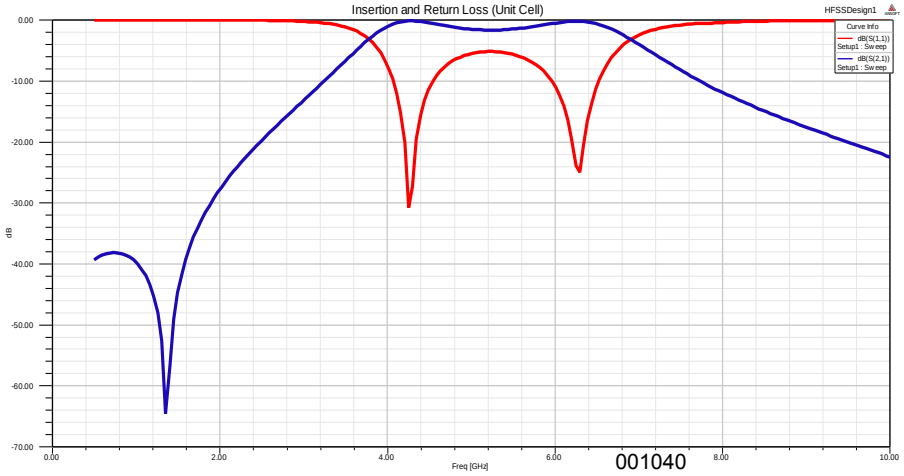
Improved BPF Design

- Shunt stubs added
  - Increased low-pass component
  - Two resonant frequencies
  - Less smoothing





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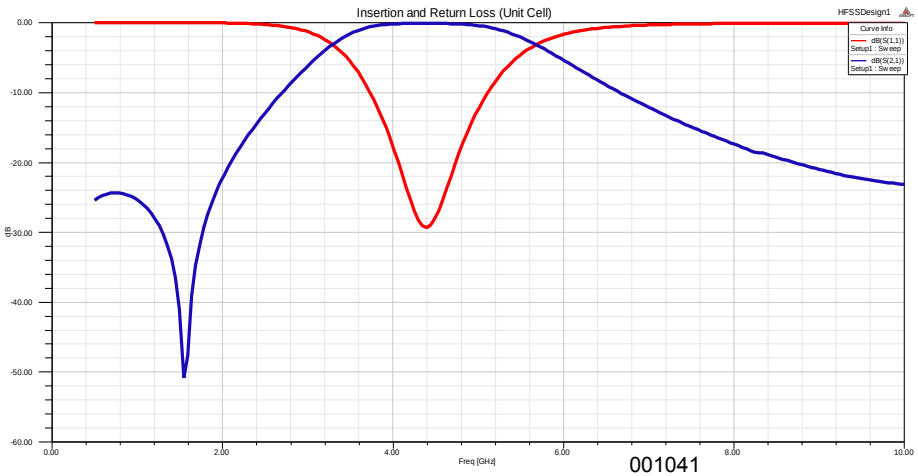
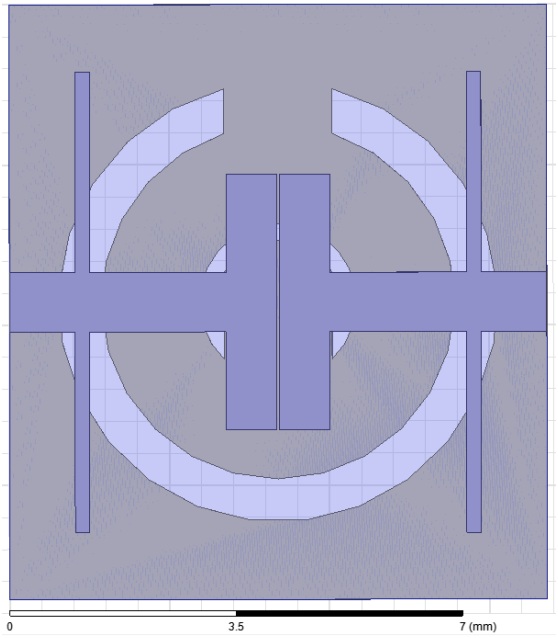
Improved BPF Design

- Stubs at the gap added
  - High-pass component
  - Second resonance removed
  - Band-pass behavior





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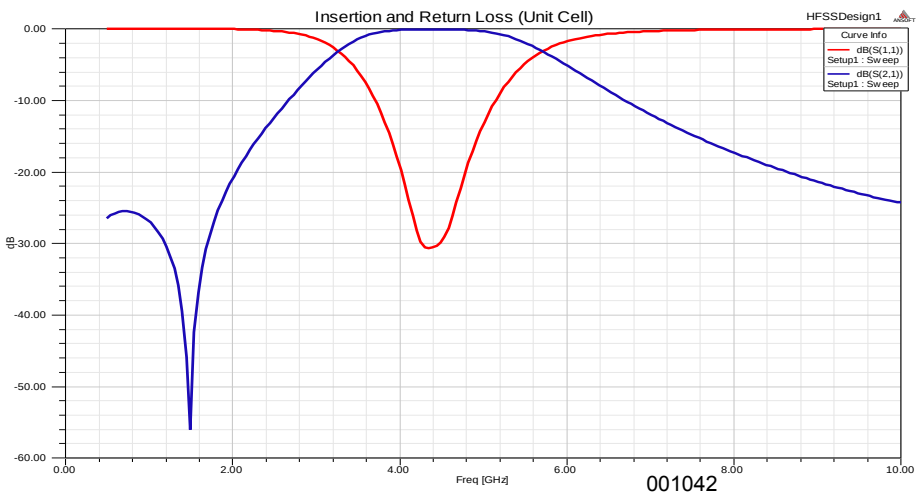
Improved BPF Design

- Inductive lines added
  - Slight increase in performance
  - -30dB S21 at f_c



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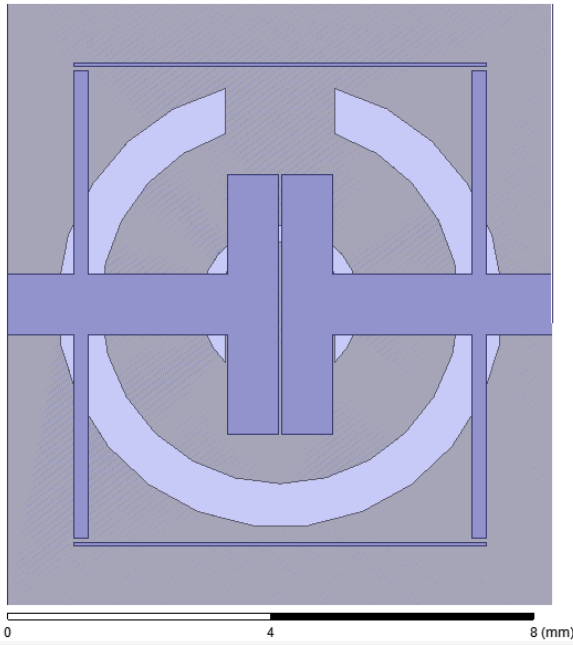

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Future Work

- Fabricate model for physical testing
- Use unit cell to make a high-order filter
  - Impedance matching between cells
- Model curved structure
  - LCP flexibility
  - Previous work—effect on frequency response
- Test more element combinations

Conclusions

- Metamaterial band-pass filter design has a unique challenge
  - Smoothing effect in the upper band
- Additional design considerations can help improve upper band performance
- Combining low-pass and high-pass metamaterial design concepts can help
- Example filter modeled and simulated

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Questions?

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