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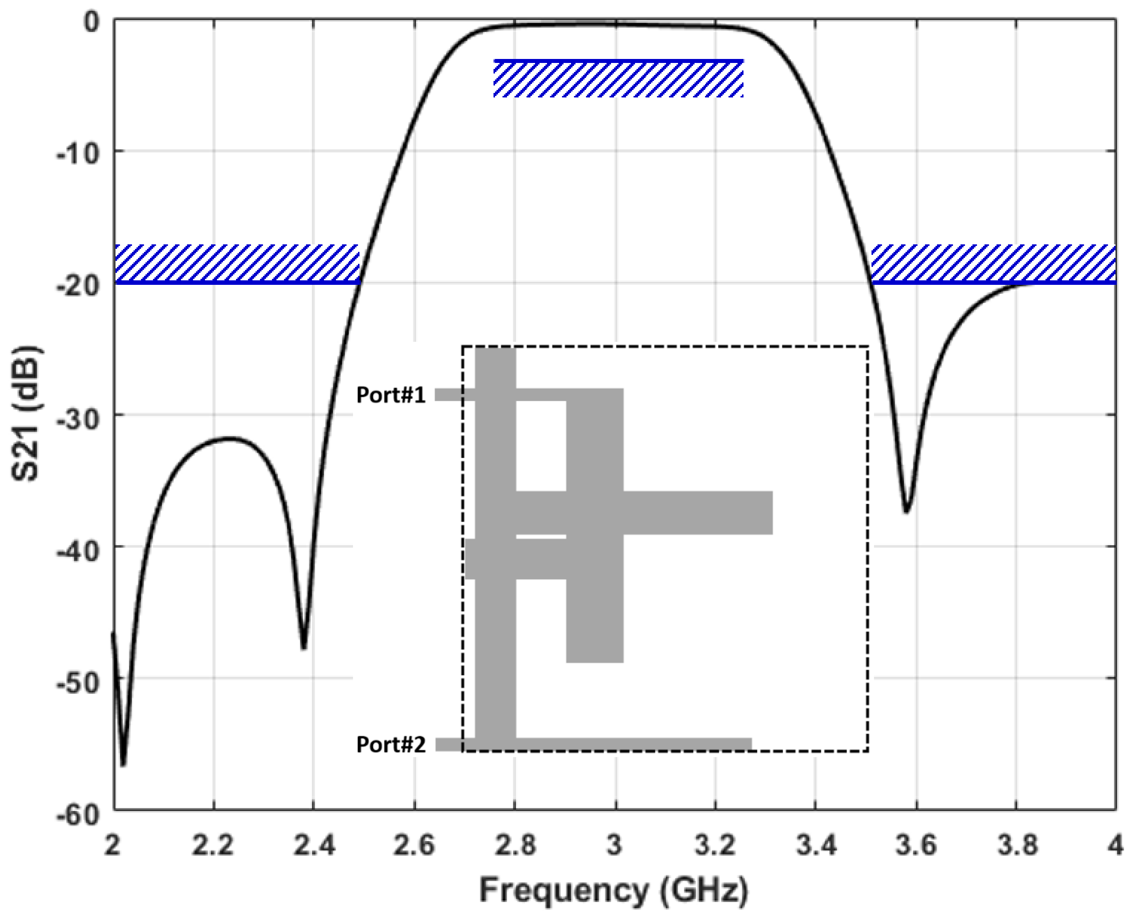
An *Additive* Approach to the Shape Synthesis of Microstrip Circuits and Antennas

Some Preliminary Masters Thesis Results

OVERVIEW AND PRESENTATION OUTLINE

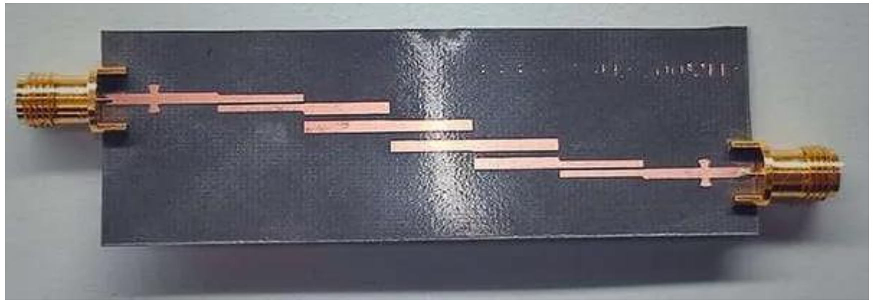
1. Motivation
2. Existing Shape Synthesis Methodologies
   - Discrete Pixelation Methods
   - Continuous Pixelation Methods
   - Subtractive Shape Synthesis Methodology
3. Proposed Additive Shape Synthesis
   - Essential Idea
   - Implementation Considerations
4. Bandpass Filter Example
5. Concluding Remarks

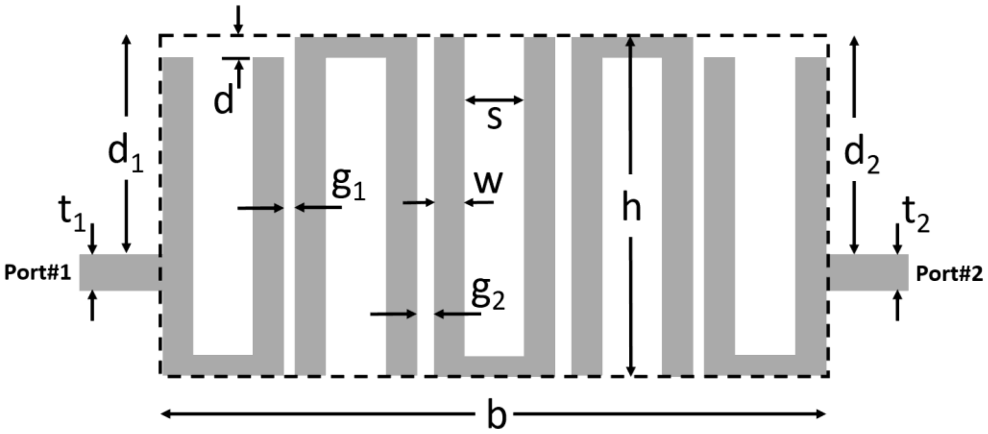


Presentation will "think" in terms of filters. This design approach works for matching networks, antennas and non-planar networks as well

I. MOTIVATION

Feature Optimization – The 'Conventional' Design Approach





- Cascade elementary configurations originating from a "design library"

- Full-wave computational electromagnetics (CEM) "forward" analysis can be used to compute the performance of the assembled circuit.

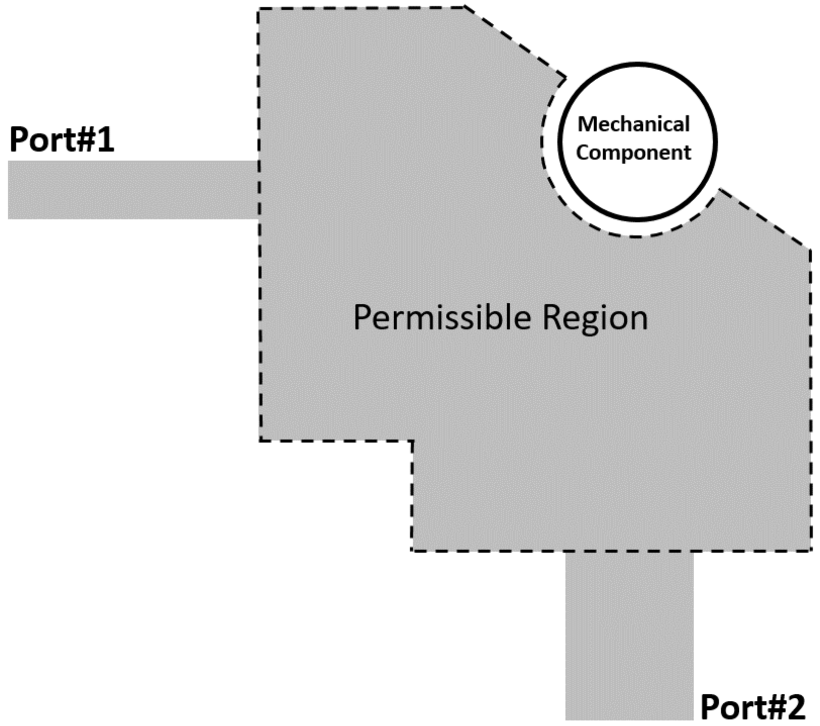
- Used in conjunction with some optimization algorithm to iteratively adjust the value of selected geometrical features – the design (optimization) variables – to obtain some required electrical performance.

- CEM forward analysis is computationally time-consuming, and so surrogate models can be trained using full-wave CEM forward modelling, are employed to reduce this burden in the design process.

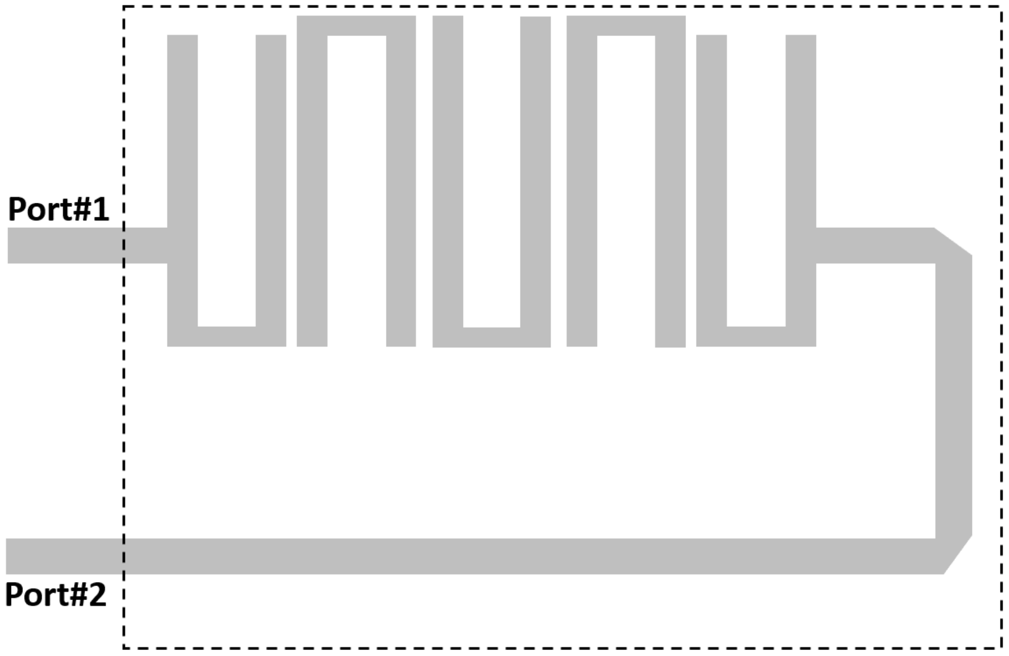
- Such feature-optimization based design is the standard and has been a widely-used and successful design route.

I. MOTIVATION

Layout & Other Fabrication Constraints



e.g. Overall board layout may only permit filter's conducting material inside dashed line.

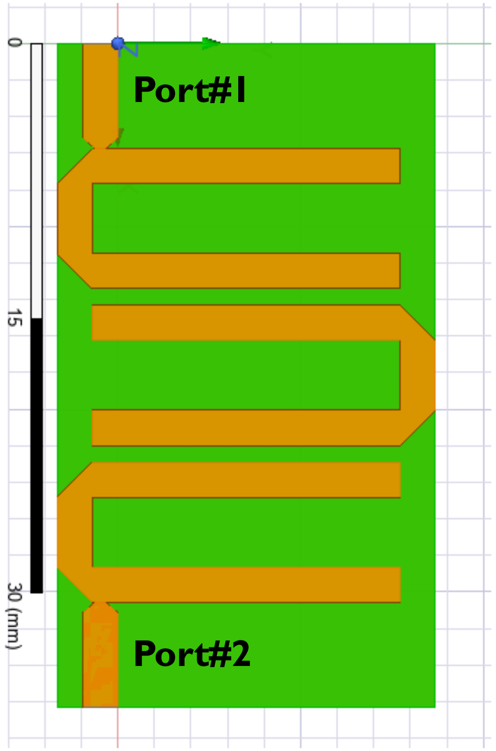


e.g. Desired port locations may not necessarily align with those of design library item.

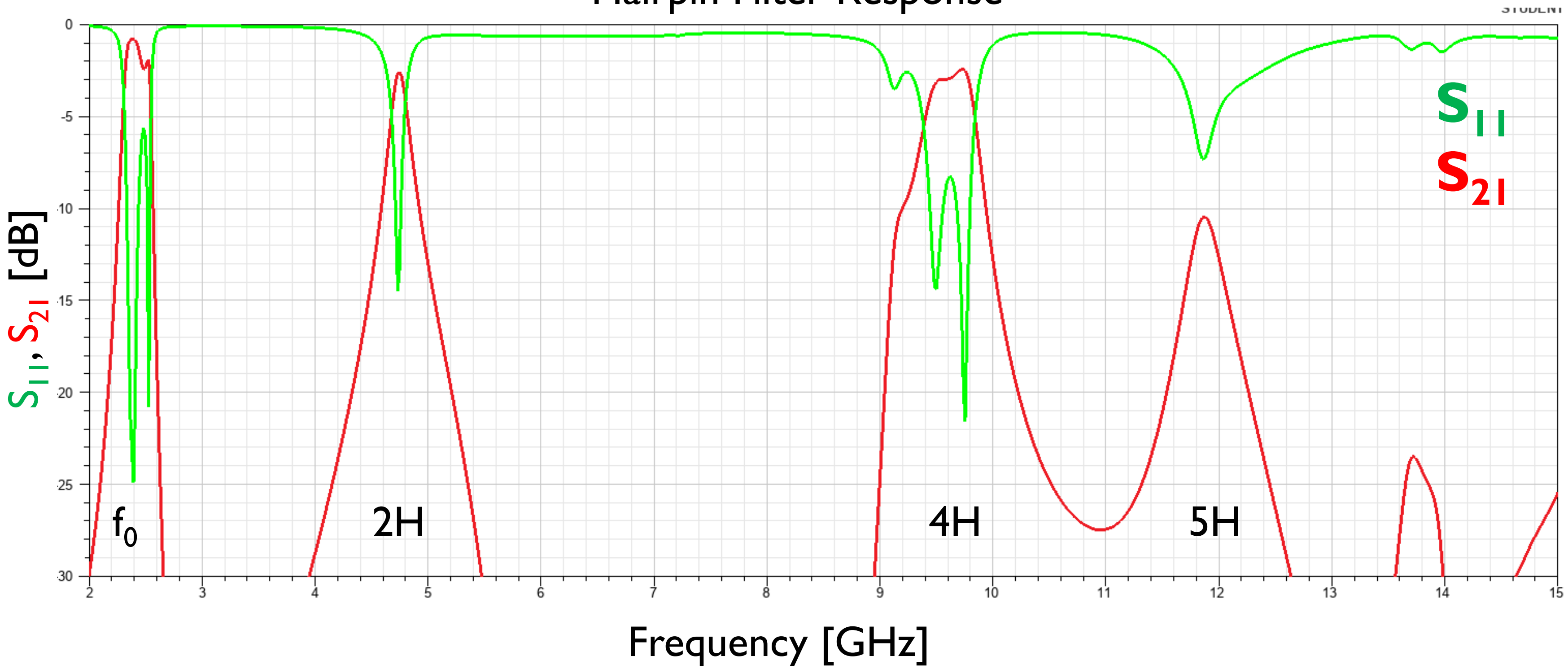
I. MOTIVATION

Harmonics

Hairpin Filter



Hairpin Filter Response



e.g. Structure might have undesirable harmonic rejection

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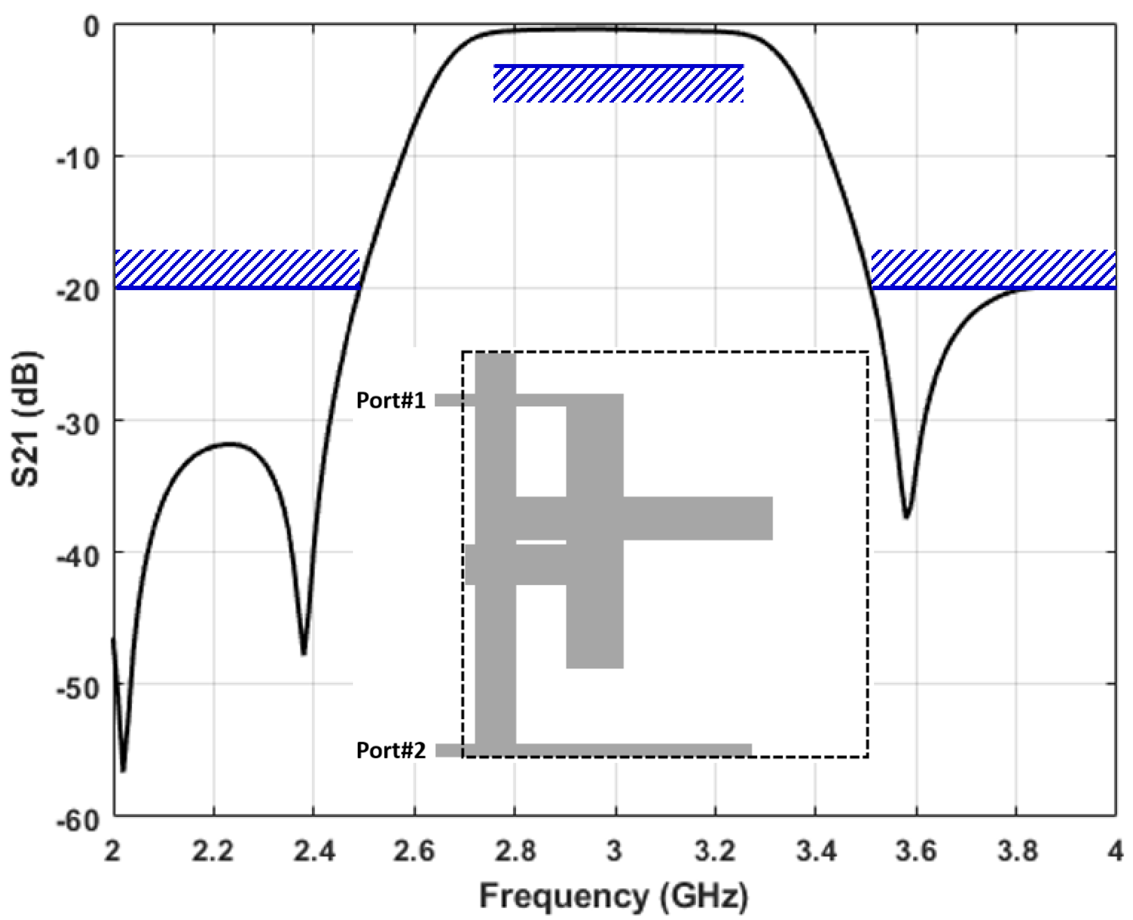

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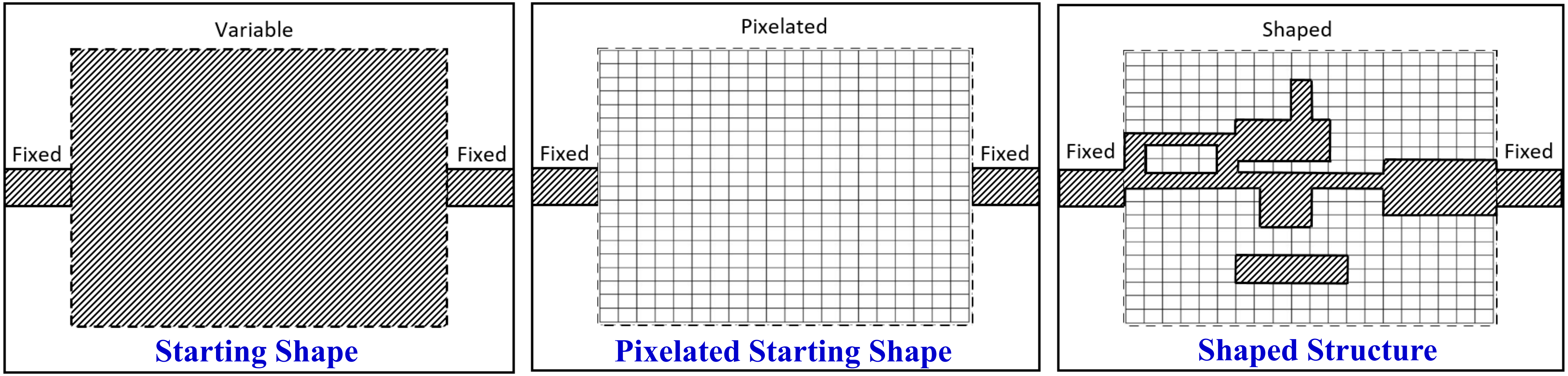
2. EXISTING SHAPE SYNTHESIS METHODOLOGIES

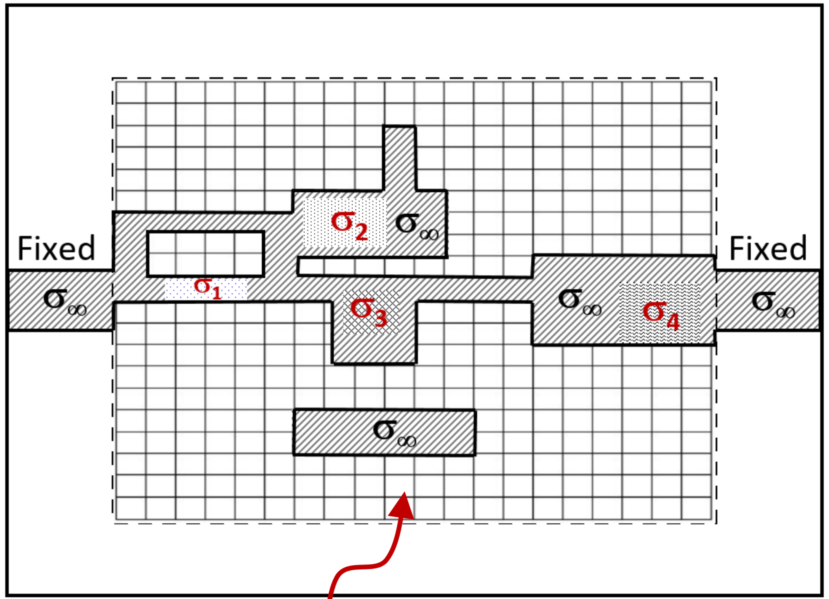
Pixelation-Based Methods (Discrete Case)



- Design (Optimization) Variables : Conductor (1) or No Conductor (0) in Individual Pixels
  ☞ Binary Optimization Variables.
- Need to Use Non-Gradient Based Optimizers (e.g. PSO, GA).
- Fine Geometrical Resolution Requires Very Many Pixels
  ☞ Enormous Number of Design Variables.
- Convergence Issues with Non-Gradient Optimizers.

2. EXISTING SHAPE SYNTHESIS METHODOLOGIES

Pixelation-Based Methods (Continuous Case – "Topology Optimization")



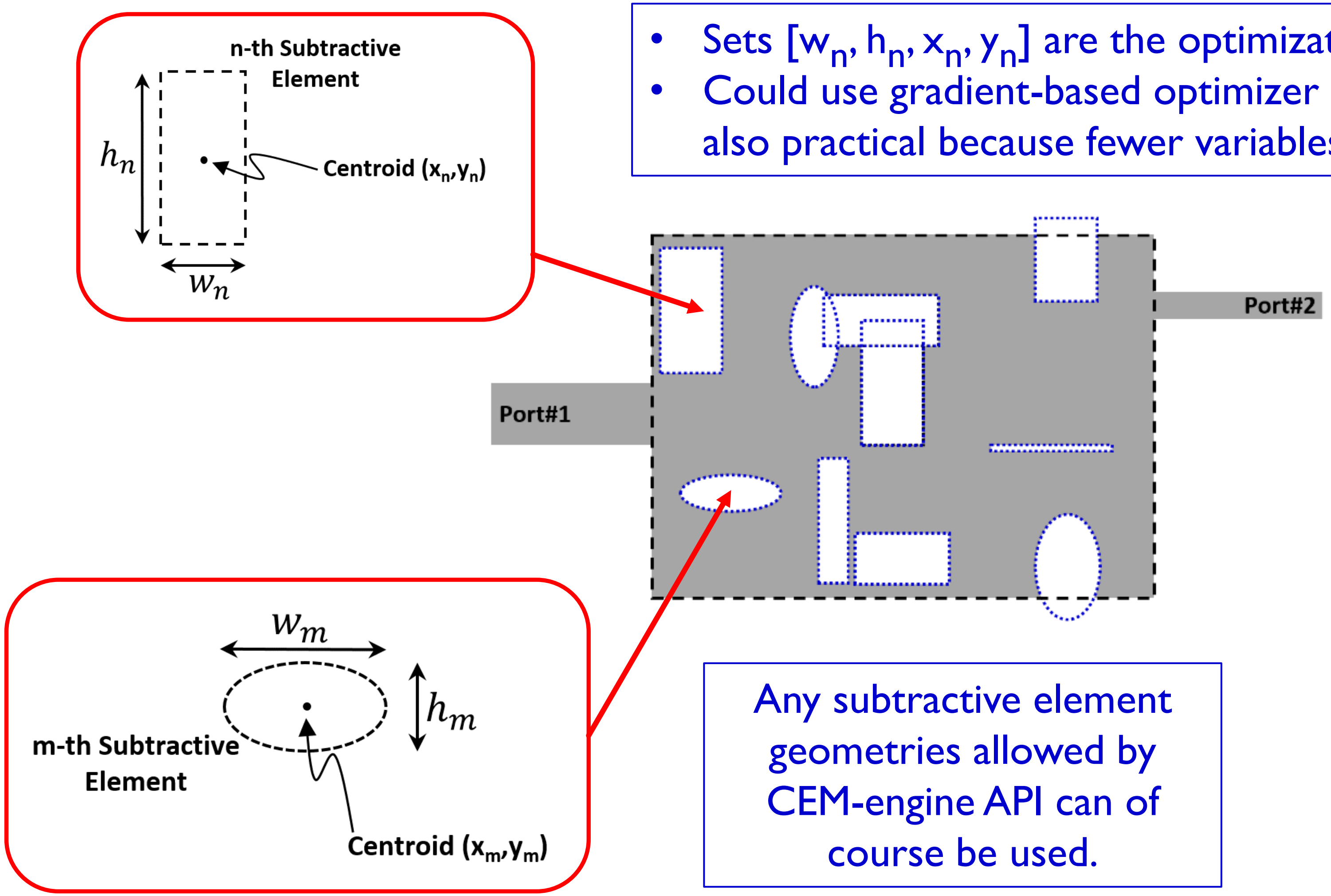
Range of Conductivity Values (Undesirable)

- Design (Optimization) Variables : Conductivity Value of Material in Individual Pixels
  - ☞ Continuous Optimization Variables.
  - ☞ Continuous Range of Conductivity Values.
- Can Use Gradient Based Optimizers to Handle the Enormous Number of Design Variables Required for Fine Geometrical Resolution.
- But Need to Use Techniques to "Nudge" Solution to Near-Binary One (And Then Do Final "Binarization" of Pixel Material).
- Disadvantages Mentioned by Many Authors When Shaping *Conducting* Material Structures.
- Need Computationally Rapid Way to Effectively Find Gradient Information. Not Necessarily Available for Complicated Objective Functions.

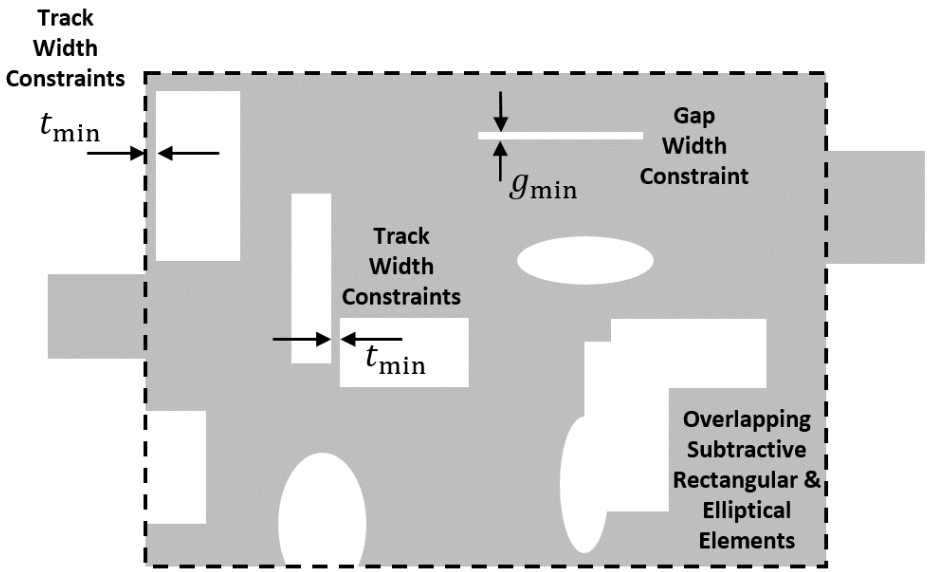
2. EXISTING SHAPE SYNTHESIS METHODOLOGIES

The Subtractive Method

- Sets [w_n, h_n, x_n, y_n] are the optimization variables.
- Could use gradient-based optimizer if gradients available, but non-gradient one also practical because fewer variables than with pixel-base approaches.



Any subtractive element geometries allowed by CEM-engine API can of course be used.

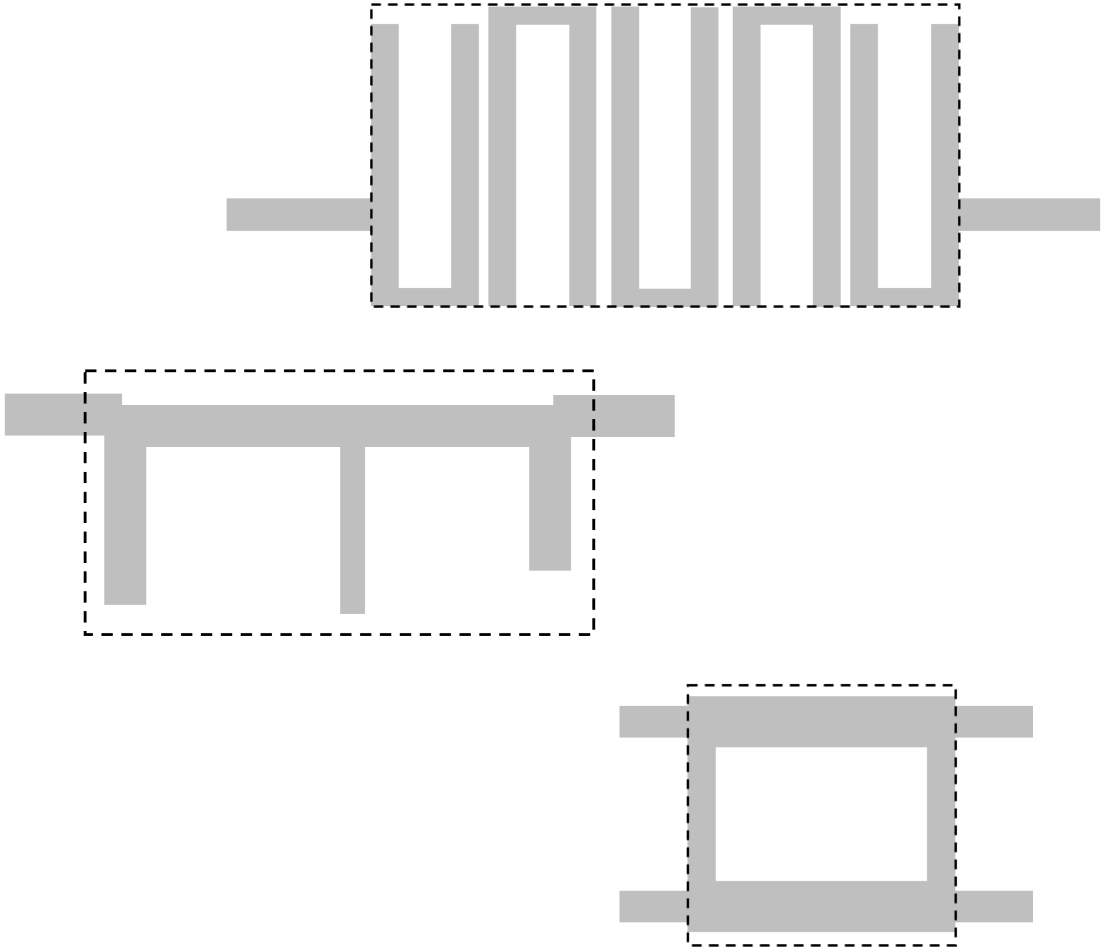


Subtractive Rectangular & Elliptical Elements Pierce Starting Shape Boundary

Fabrication-constrained design possible, as with other shape synthesis methods.

2. EXISTING SHAPE SYNTHESIS METHODOLOGIES

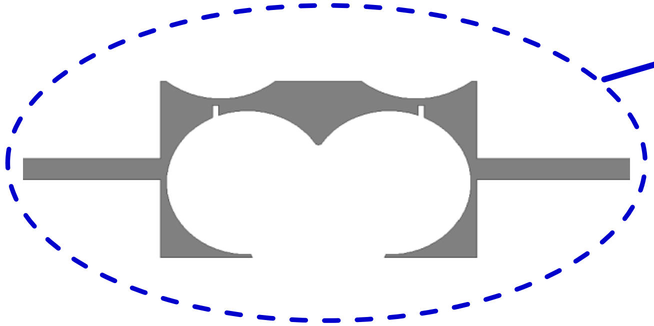
The Subtractive Method – Why?

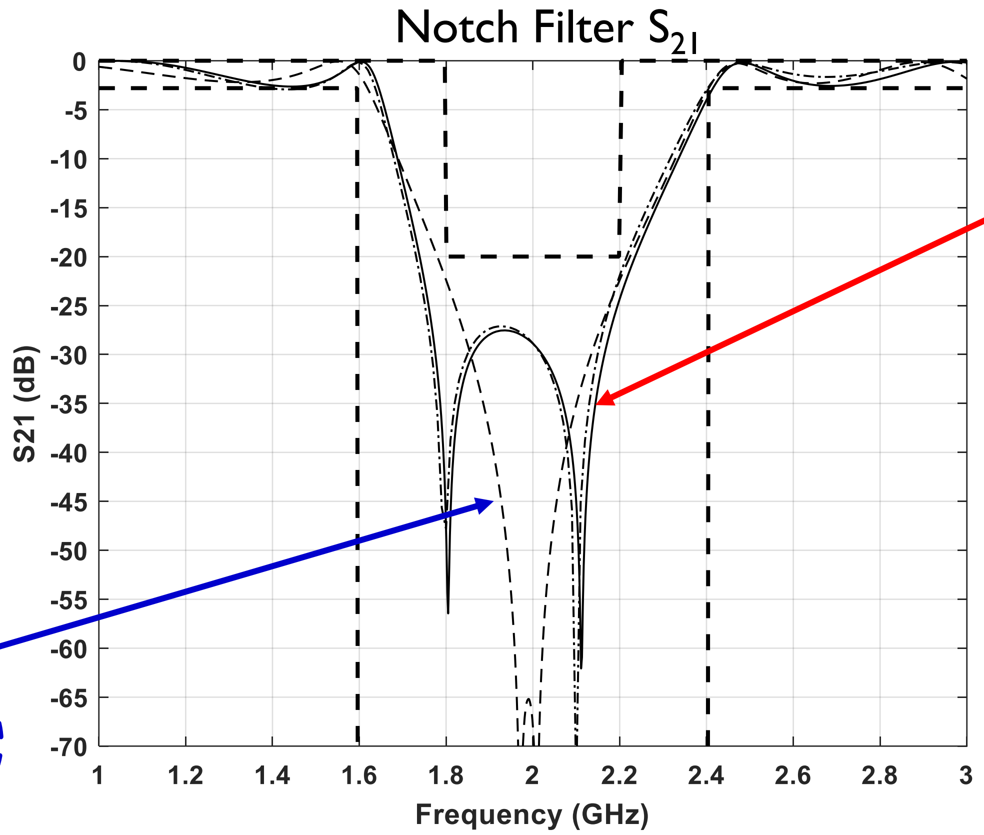


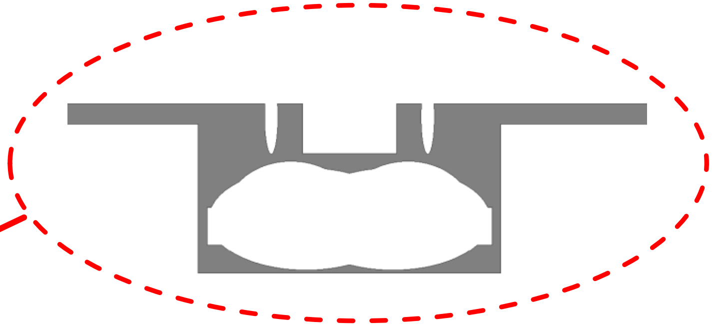
- Many conventional ‘library’ components, or even pixelation-based ones, can be viewed as a continuous conducting area from which *relatively few* pieces have been removed (‘subtracted’).
- Don’t know size and location of such “subtractive objects”, so make these the optimization variables.
- Need the geometrical resolution but not as large a number of degrees of freedom provided by the required pixelation.
- Not always trying to find fundamental limits. Just want to solve the particular design problem subject to some practical constraints.

2. EXISTING SHAPE SYNTHESIS METHODOLOGIES

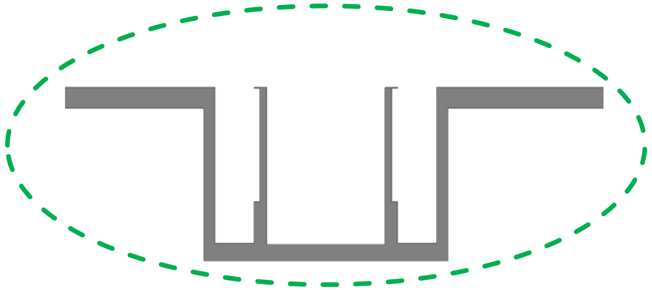
The Subtractive Method (Cont'd)







Similar S_{21}, but filter x dimension is 25% smaller



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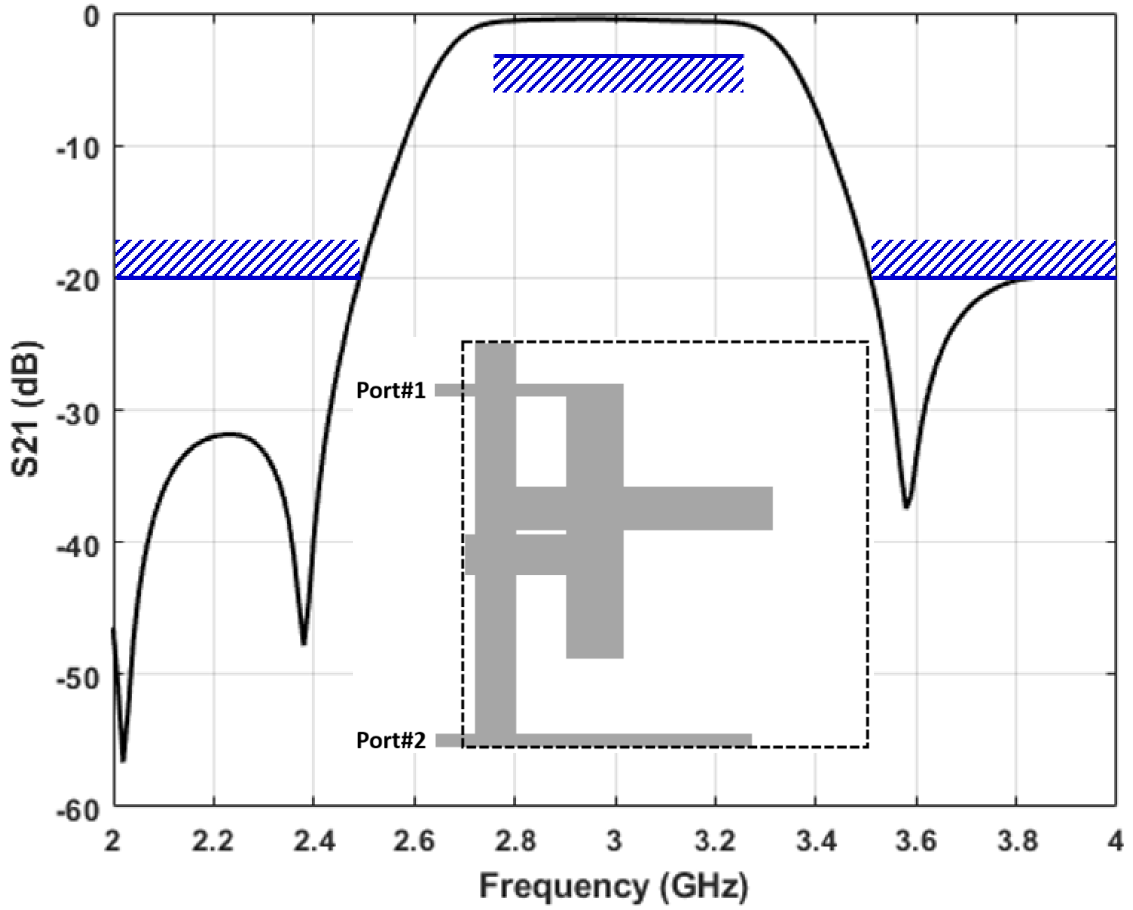

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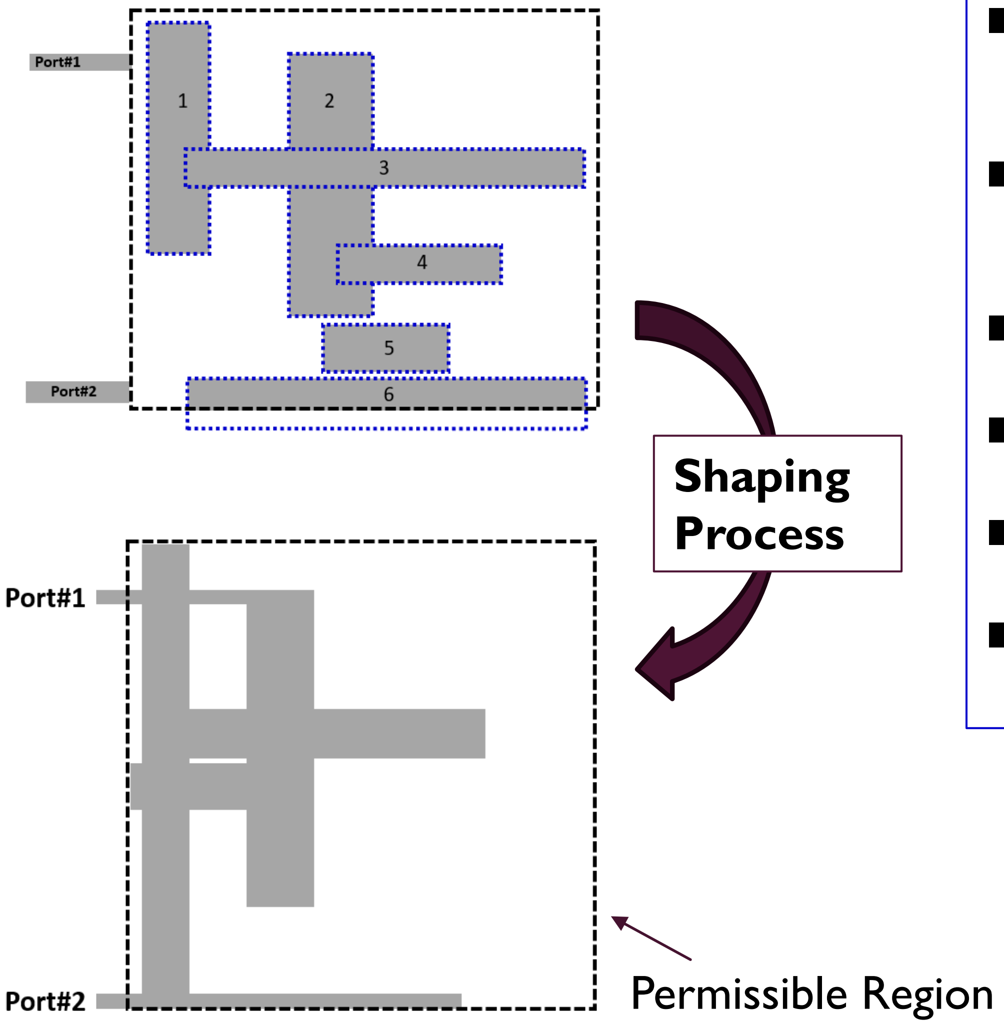
3. PROPOSED ADDITIVE SHAPE SYNTHESIS

The Essential Idea



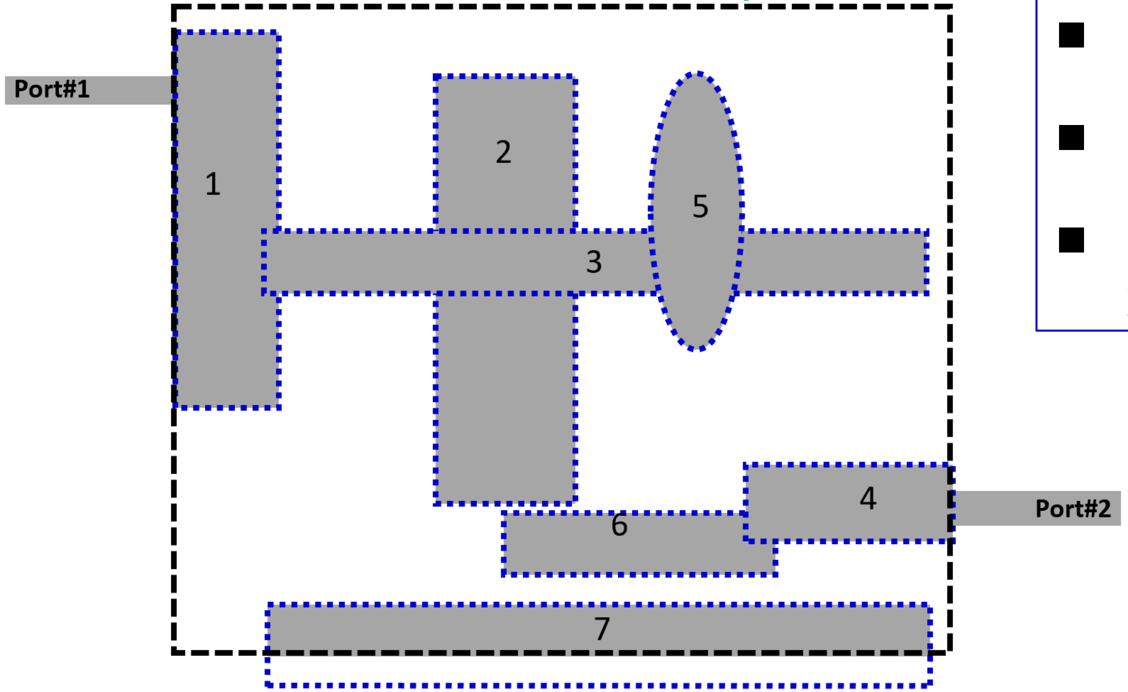
- Subtractive shape synthesis : Begin with *permissible region* entirely occupied by conductor, which is then shaped through adjustment of the size and location of selected subtractive geometrical objects.
- Proposed additive approach : Begin with *permissible region* (mostly) devoid of conductor and use the size and location of additive elements to populate the permissible region with conductor to realize the shaped circuit layout.
- Initial set of values for such geometrical parameters must be assigned at the commencement of any shape synthesis for it to get started.
- When additive elements overlap their union simply results in a more complex conductor shape.
- If any part of an element extends passed the boundary of the permissible region, that part is ignored.
- Fabrication constraints, existing intuition ("informed shaping"), can be embedded into the shaping algorithm via the controller script.

3. PROPOSED ADDITIVE SHAPE SYNTHESIS

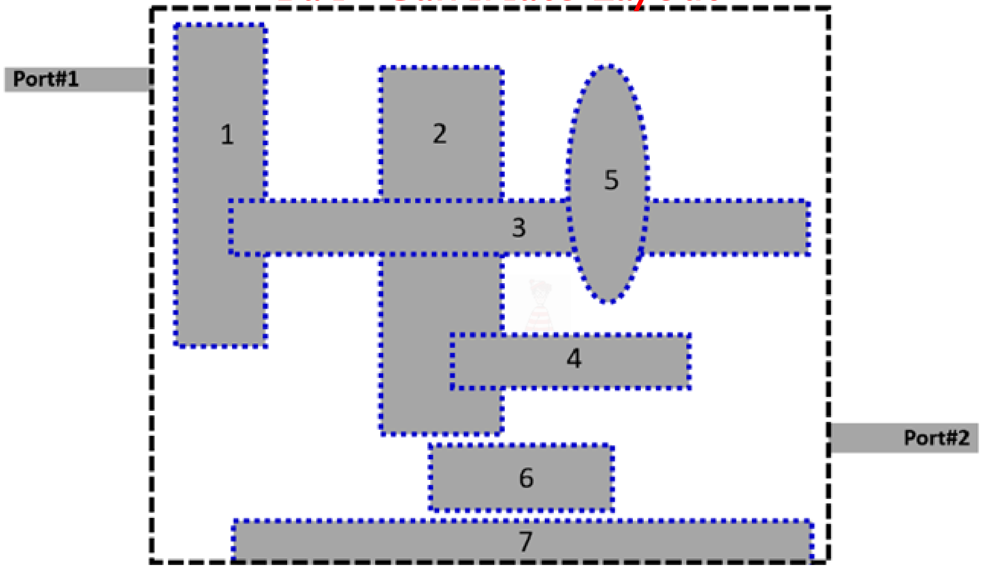
“Informed” vs “Blind” Shaping

- Blind shaping: where the only optimizer constraints are based on fabrication requirements. Every layout that the optimizer generates is simulated
- Informed shaping: where every layout that is to be simulated has a good chance of giving a favourable cost.
- The key difference is informed shaping aims to simulation efficiency (i.e. a larger fraction of the total simulations are of “good” layouts”)
- Example: stipulate that certain of the additive elements always be in physical contact with the fixed ports/ each other

“Good” Candidate Layout



“Bad” Candidate Layout



3. PROPOSED ADDITIVE SHAPE SYNTHESIS

Shaping Considerations

- Shaping (as in the shaping controller) can be done using an external script or inside of the CEM engine using the optimization feature
- Not all scripting tools interfaces are equal (in terms of quality, ease of use and documentation)
- Initially AWR and pyAWR were used. Have since moved on to HFSS and pyAEDT
- The cost landscape is large and complex. Non gradient optimizers *seem* to be more promising (PSO, Simplex, Bayesian, GA in particular)
- Optimizers are available in *Python, Mojo, Julia,* and *Matlab.*
- More then one optimizer can be used during shaping
- Initial simulations can be done with lossless materials, and courser meshes to speed up simulations
- There are many other ways to implement controller script and utilize existing optimizers of various kinds

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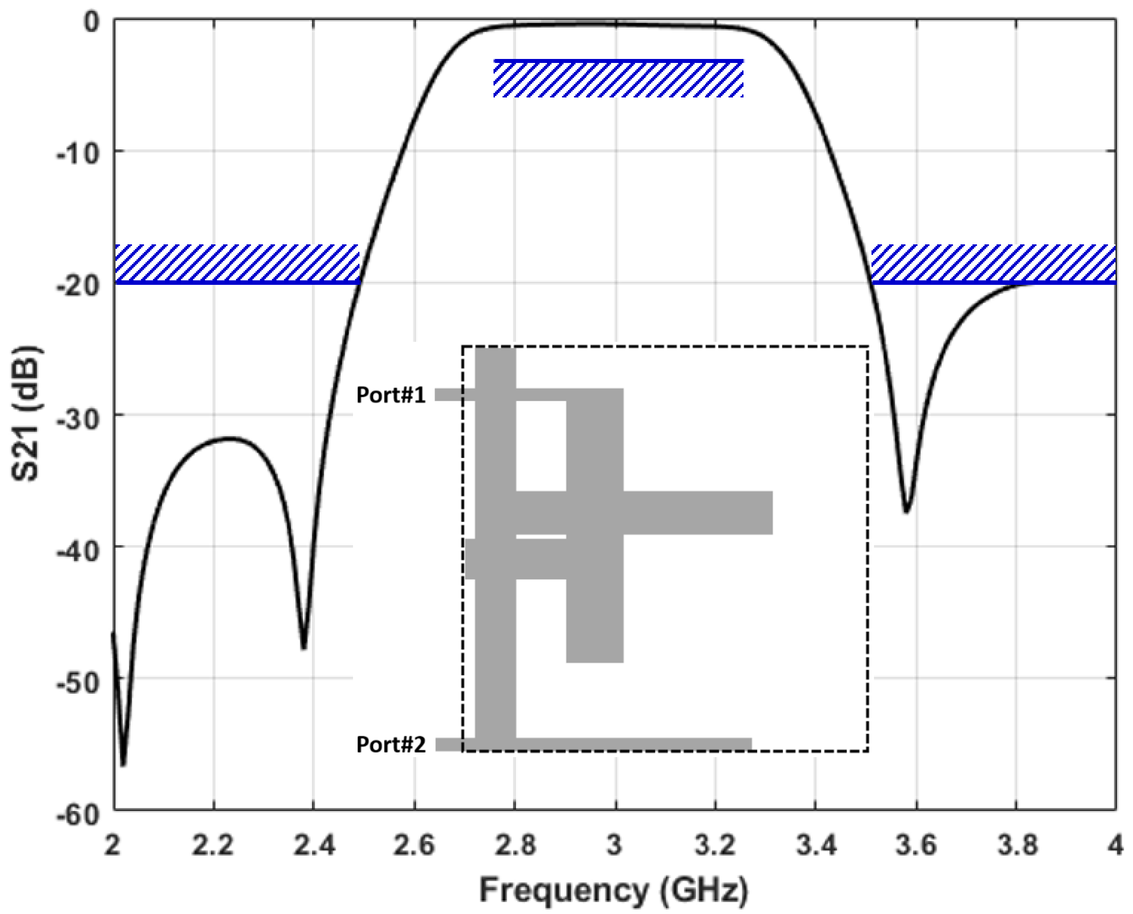

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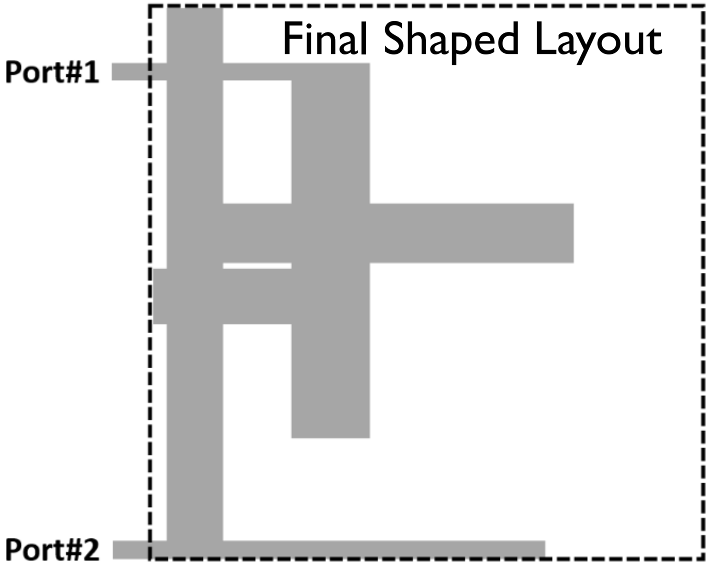
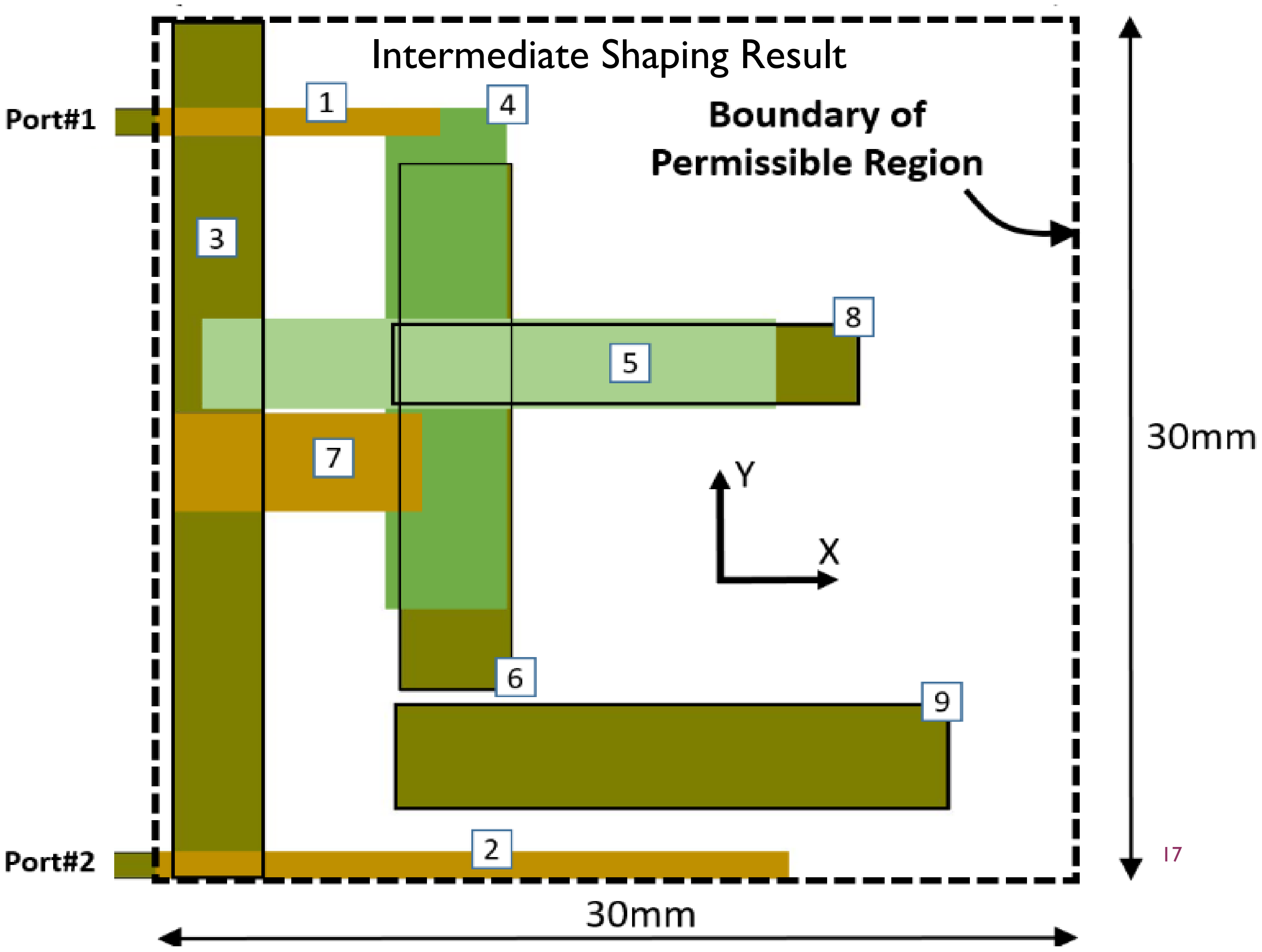
4. BANDPASS FILTER EXAMPLE

The Details

- *Cadence AWR* was used for simulations
- Used particle swarm optimizer (PSO).
- Shaping done entirely inside AWR using internal optimization functionality
- Optimization done in multiple steps

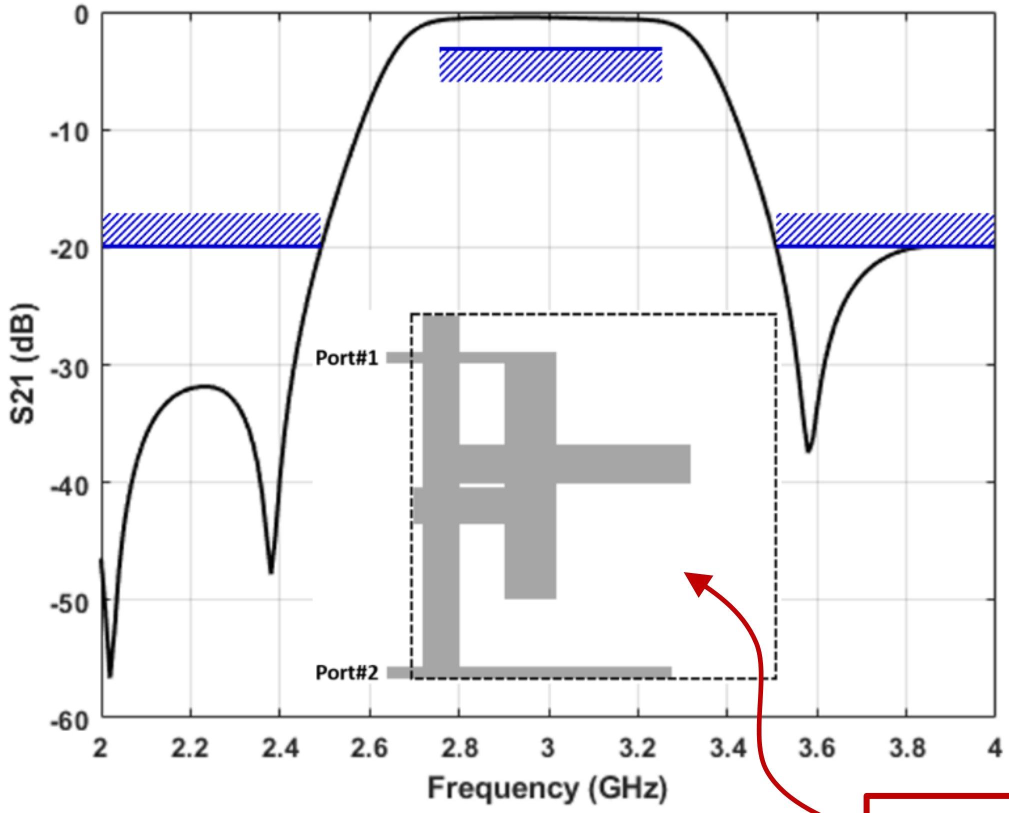




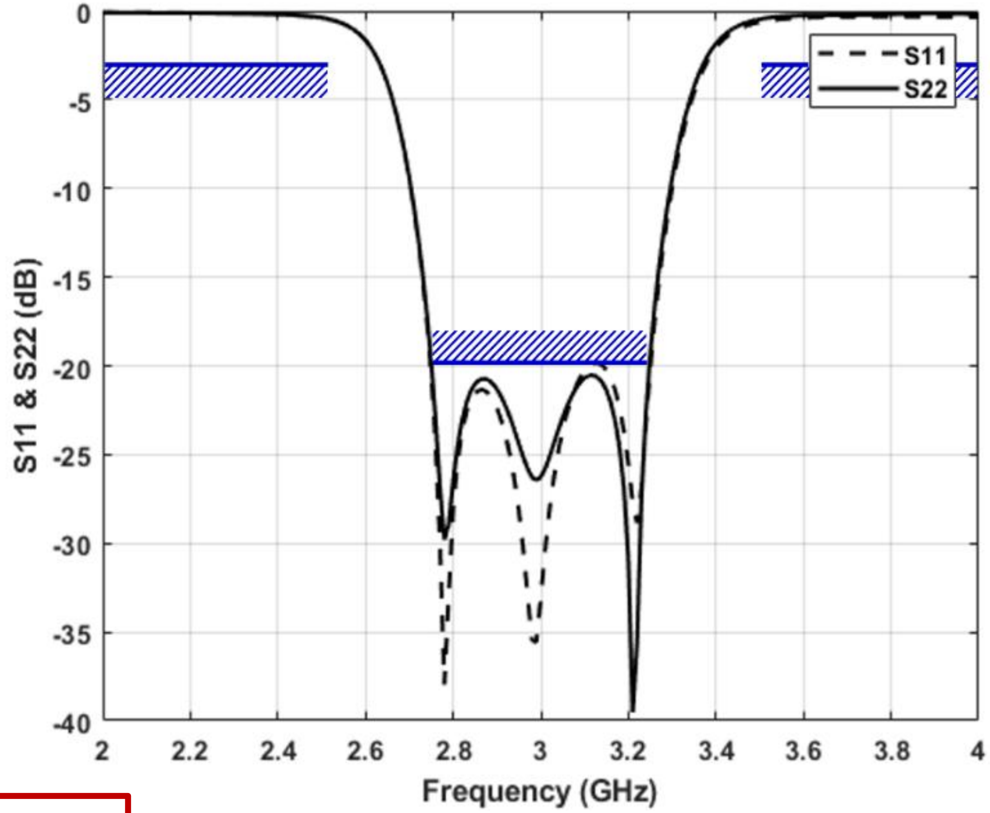
4. BANDPASS FILTER EXAMPLE

Shape & Computed Response of Synthesized Filter

Example Bandpass Filter S_{21}



Example Bandpass Filter S_{11}, S_{22}



Shaped Microstrip Filter Layout

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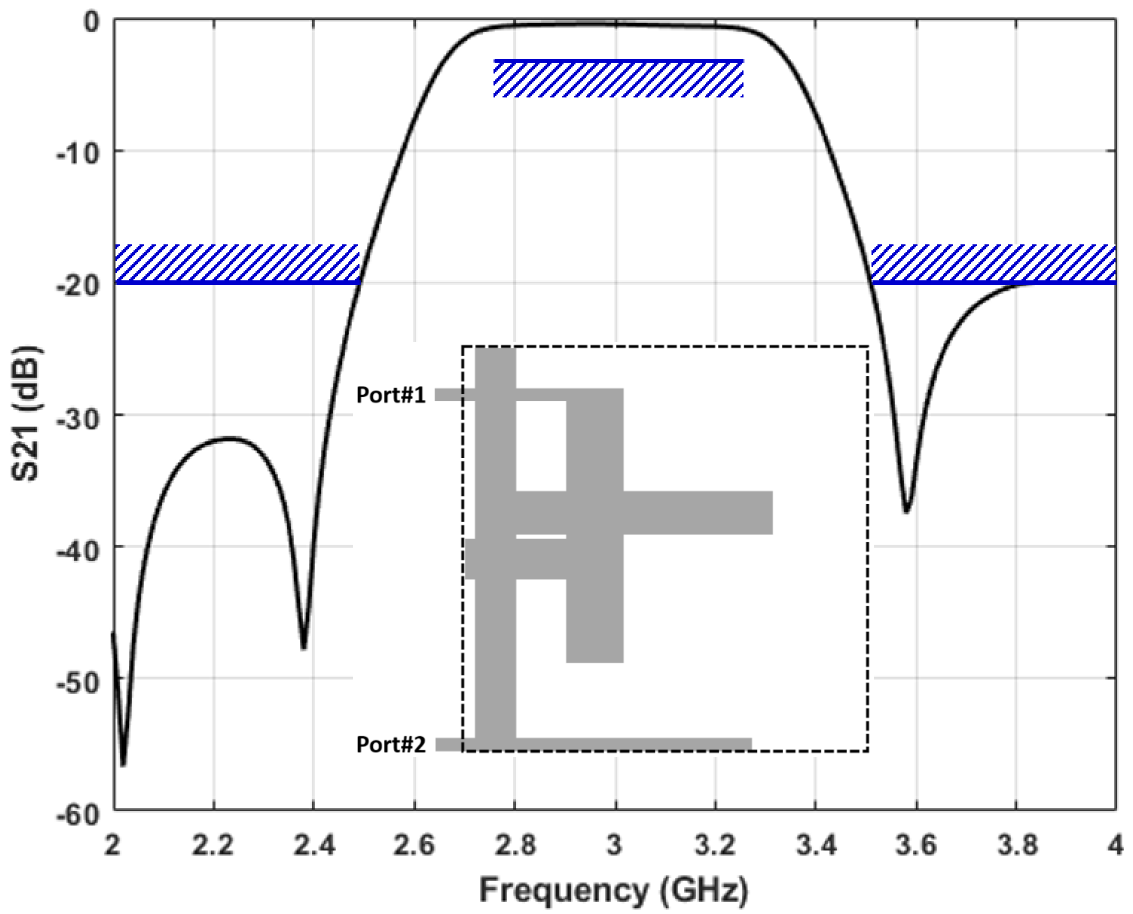

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5. CONCLUDING REMARKS

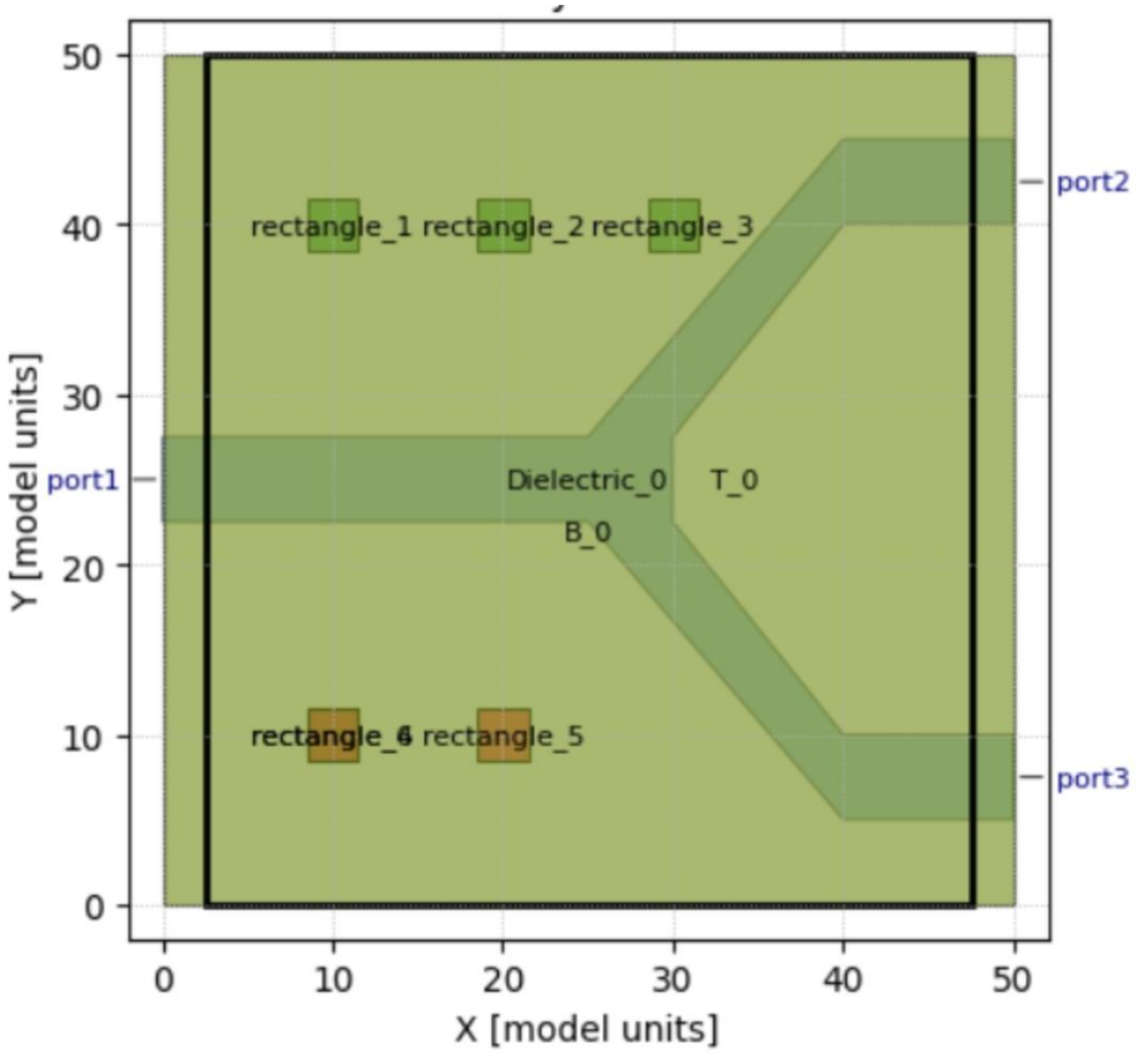
- An additive approach to the shape synthesis of microstrip circuits has been proposed and demonstrated by example.
- Differs from the methods adopted in other work on such shape synthesis.
- Contributes to on-going work (by us and others) on the topic of shape synthesis.
- Can be relatively easily incorporated with CEM packages that permit geometry, and other, control via an API.
- Shape synthesis has been shown by researchers to have many virtues, but there are still drawbacks (time to converge, sensitivity to part-to-part variation)
- Need to get to stage where it becomes convenient in design practice.

uOttawa

https://github.com/ncardamone10
cardamonen.ca

6. BACKUP: MIXED SHAPE SYNTHESIS

- ❑ Both additive and subtractive shapes
- ❑ multiple shaping layers
  e.g. 4, 6, 8, or 12 layer PCBs
- ❑ Multiport structures



6. BACKUP: OBJECTIVE FUNCTIONS

$$H_n(x_n) = sgn(x_n - a_n)$$
$$H_n(x_n) = w_n \cdot (x_n \pm k_n) \pm c \cdot e^{d \cdot (x_n - a_n)}$$
$$H_n(x_n) = w_n \cdot (x_n \pm k_n) \pm sgn(x_n - a_n).$$

$$F = \sum_{n=1}^{N} \left\{ \prod_{m \neq n}^{N} logsig(x_m - b_m) \right\} H_n(x_n)$$

$$\mathrm{Rad}_i = 1 - \sum_{n=1}^{N} |S_{n,i}|^2$$

M. R. Khan, C. L. Zekios, S. Bhardwaj, and S.V. Georgakopoulos,
"Multiobjective fitness functions with nonlinear switching for antenna optimizations,"
IEEE Open Journal of Antennas and Propagation, vol. 3, pp. 613–626, 2022,
doi: 10.1109/OJAP.2022.3178840.