Student Paper Finalist

We1E-2

Ultra-fast Simulation and Inverse Design of Metallic Antennas

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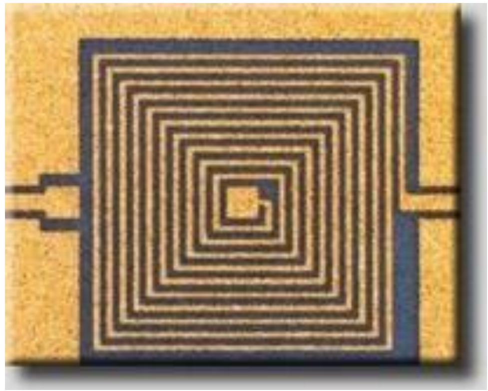
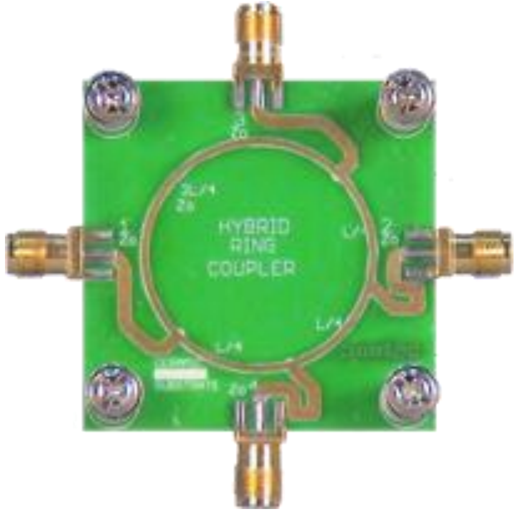
Background:
Electromagnetic Device Optimization

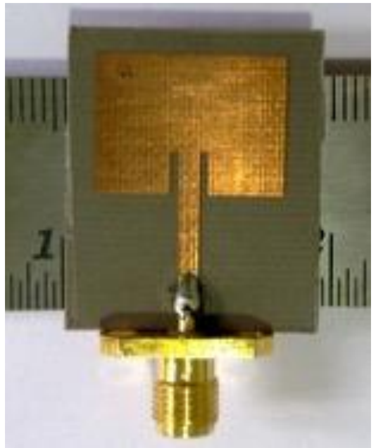
- EM devices are ubiquitous in our society, present in everything from cellular phones to biomedical devices and industrial systems



Antenna



Waveguide coupler



Passive

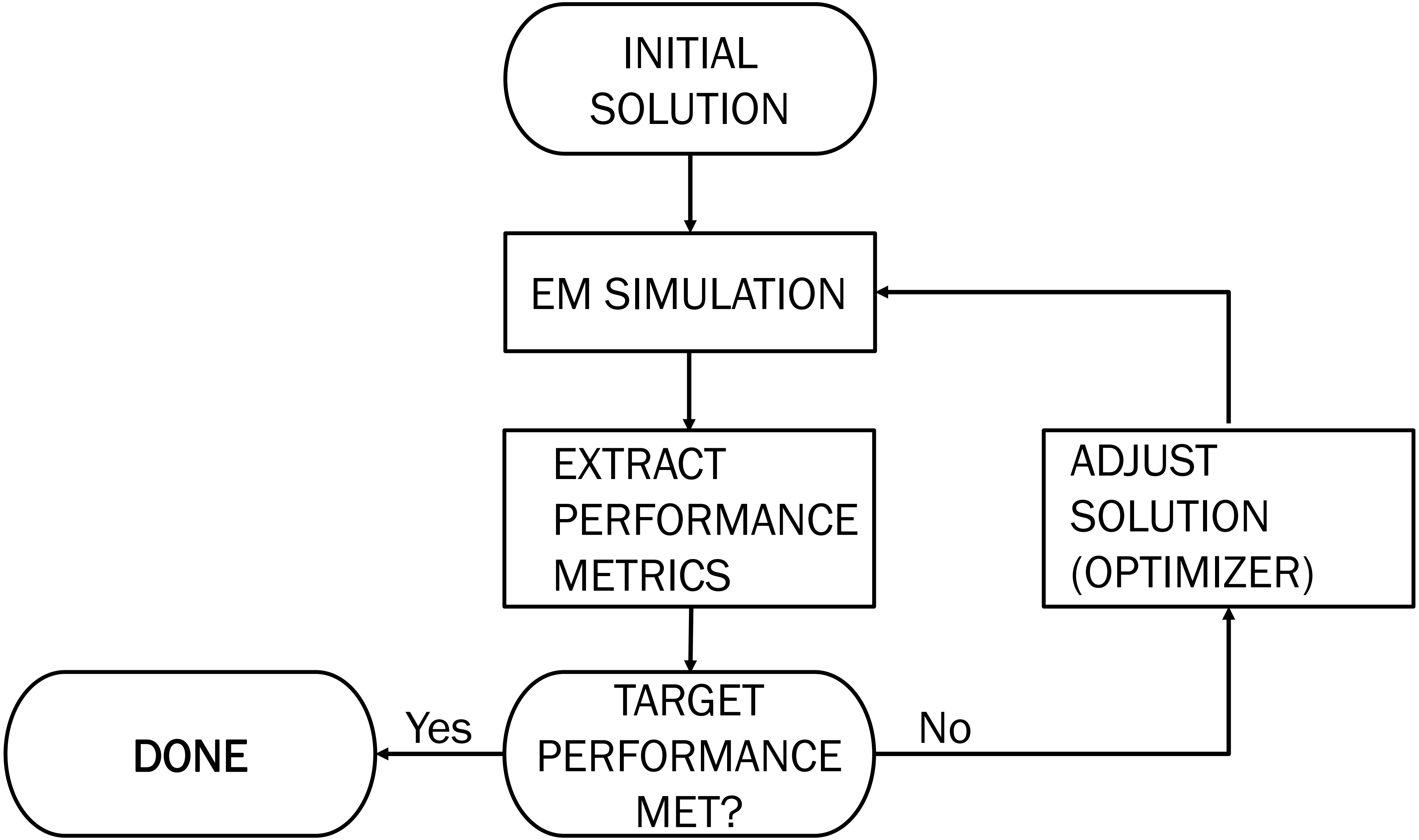
- Increasing technological performance demands necessitate high performance, compact EM device designs

Inverse Design

- Computers can be more effective at designing complicated electromagnetic structures than humans:

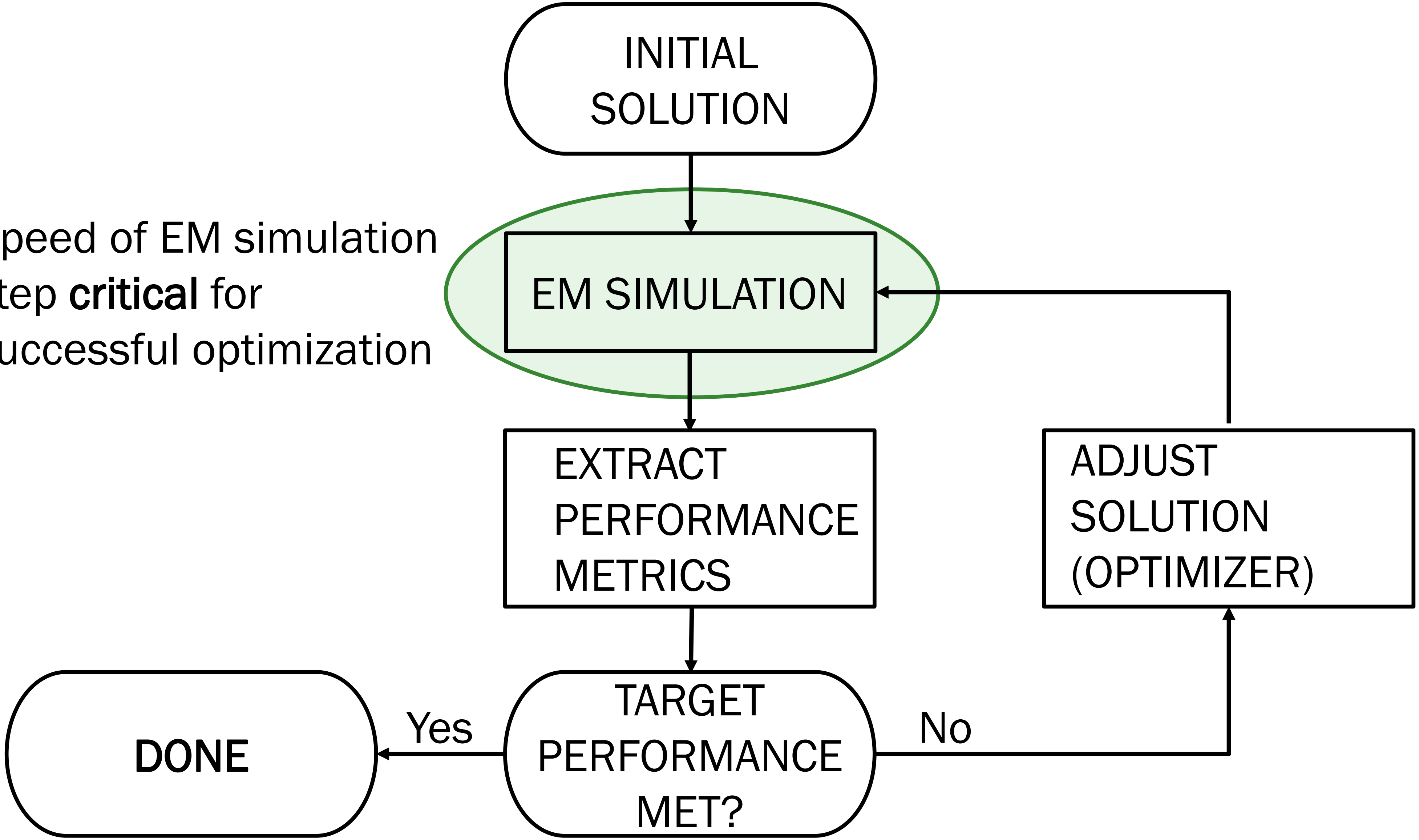
- Tremendous increase in computational power and numerical methods in recent decade
- Machines can use similar heuristic-based approaches as humans for design

Traditional Electromagnetic Optimization

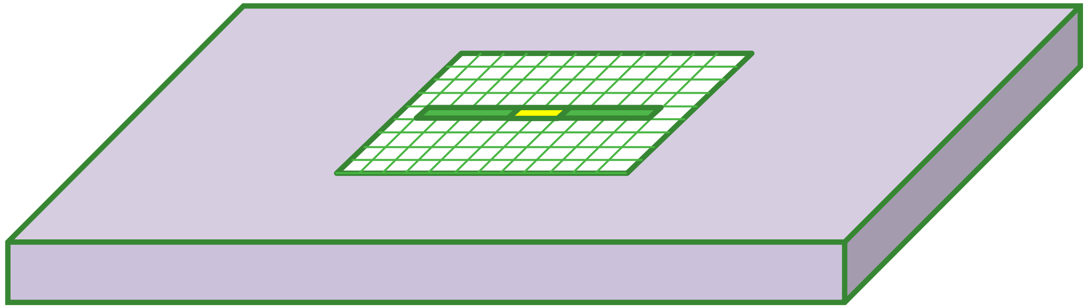


Traditional Electromagnetic Optimization

Speed of EM simulation step **critical** for successful optimization



Setting the Scene: Simple Design Example



- Radiating planar, metal antenna to be designed on lossy dielectric substrate
- *Example:* cells filled to design dipole antenna

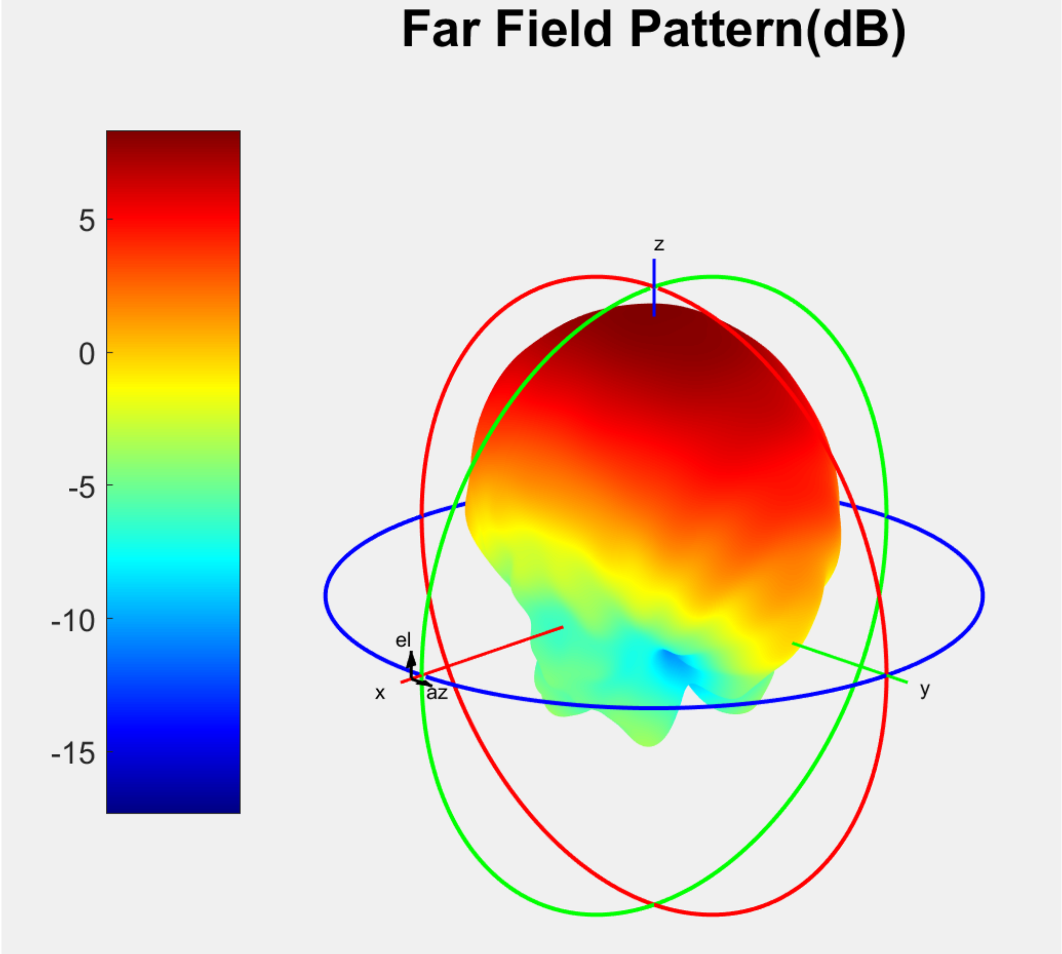
Setting the Scene: Simple Design Example

- Goal: Optimize Antenna Gain at Specific Solid Angle (θ, ϕ)

$$Gain(\theta, \phi) = \frac{U(\theta, \phi)}{Pin}$$

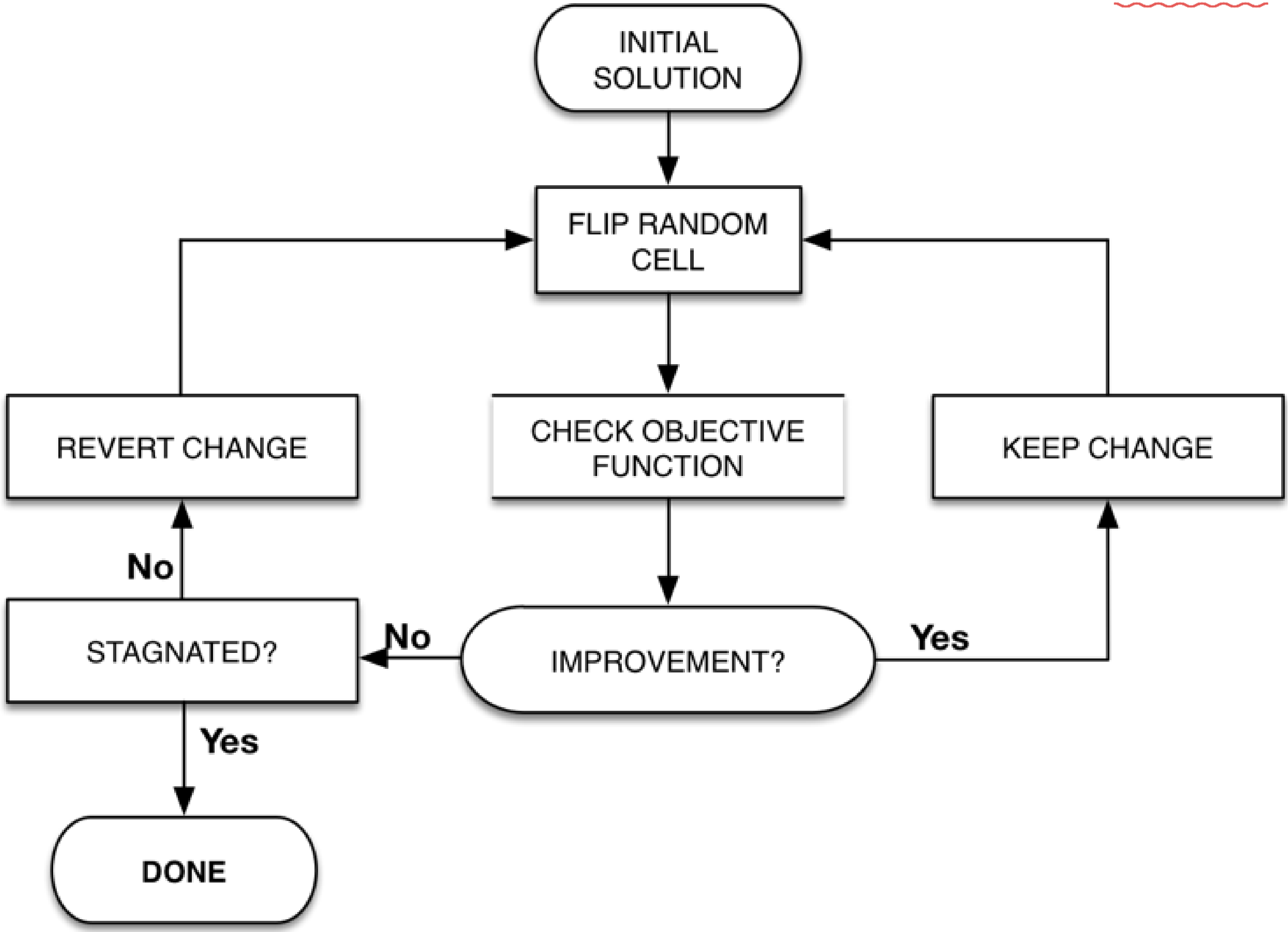
$$U(\theta, \phi) = \text{Radiation Intensity at } (\theta, \phi)$$

$$max \frac{U(\theta, \phi)}{Pin}$$



Direct Binary Search (DBS)

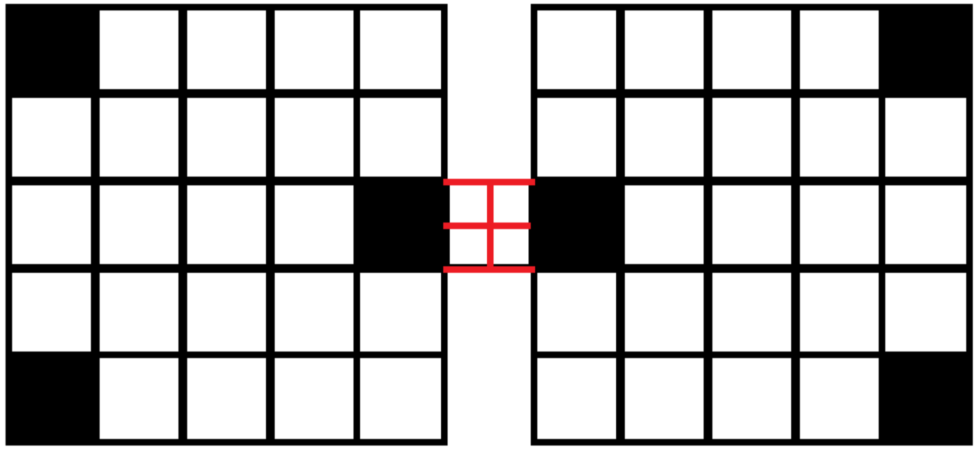
- Volumetric gradient-based optimization of conductivity on surface does not work well for metals.
- Direct Binary Search effective → Needs many iterations to converge.
- Can forward solve (EM simulation) be accelerated?



Direct Binary Search

A simple graphical representation

1. Start with a random initial design

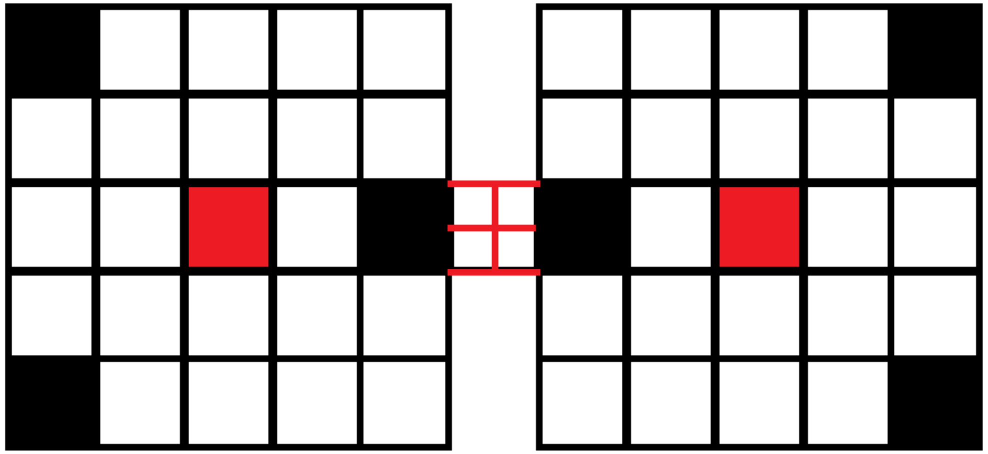


Note: We choose to enforce left/right mirror symmetry in this example.

Design algorithm:

A simple graphical representation

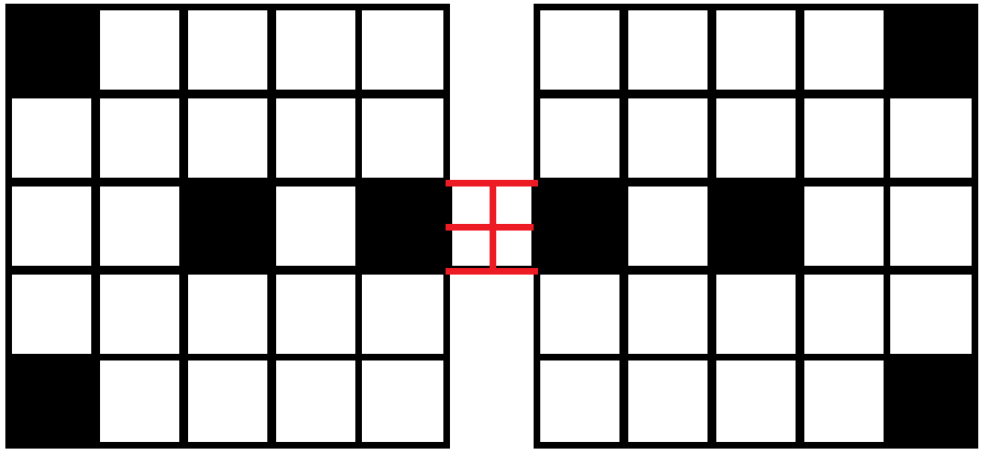
2. Flip a random tile and check objective function:



Design algorithm:

A simple graphical representation

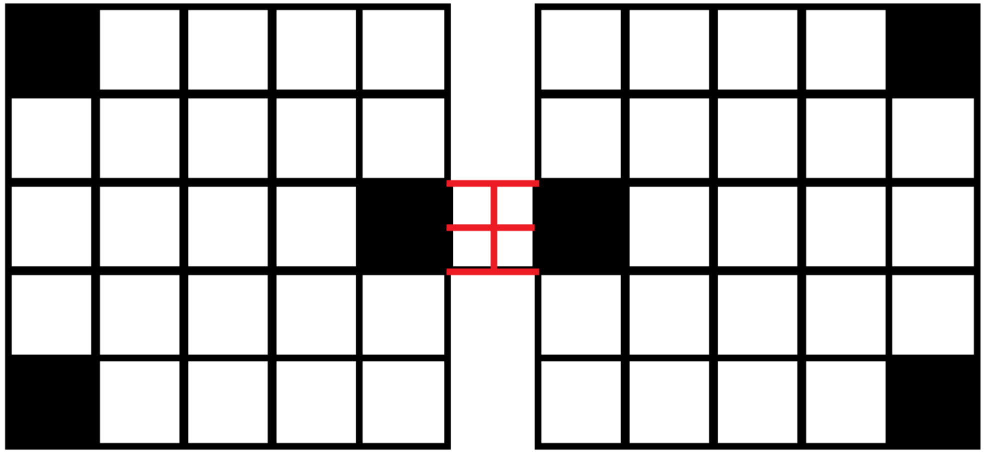
3. If objective function improves, keep the change and return to the previous step (step 2):



Design algorithm:

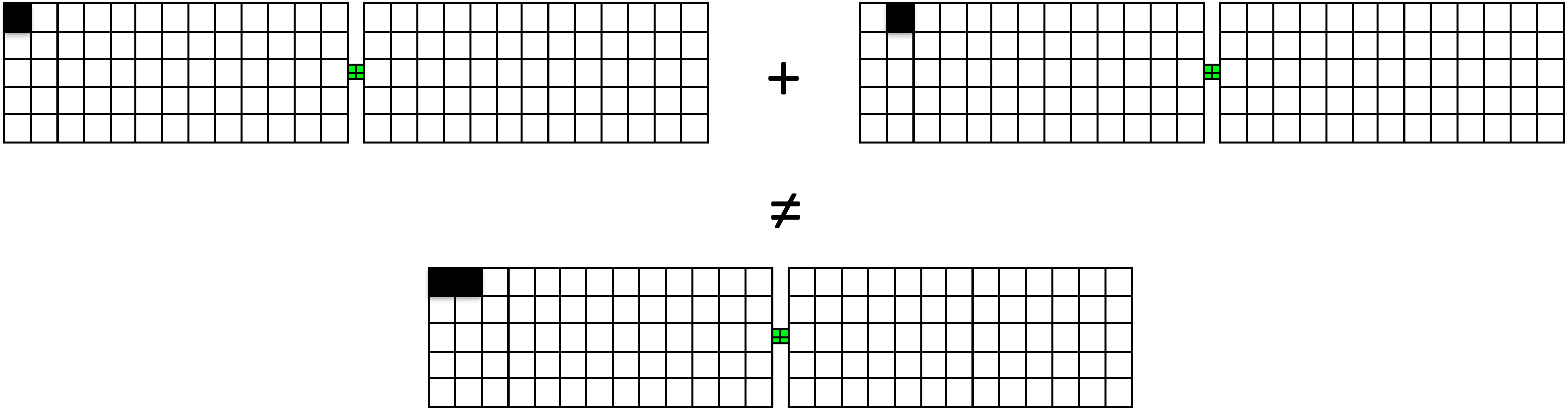
A simple graphical representation

4. Otherwise, revert the change:



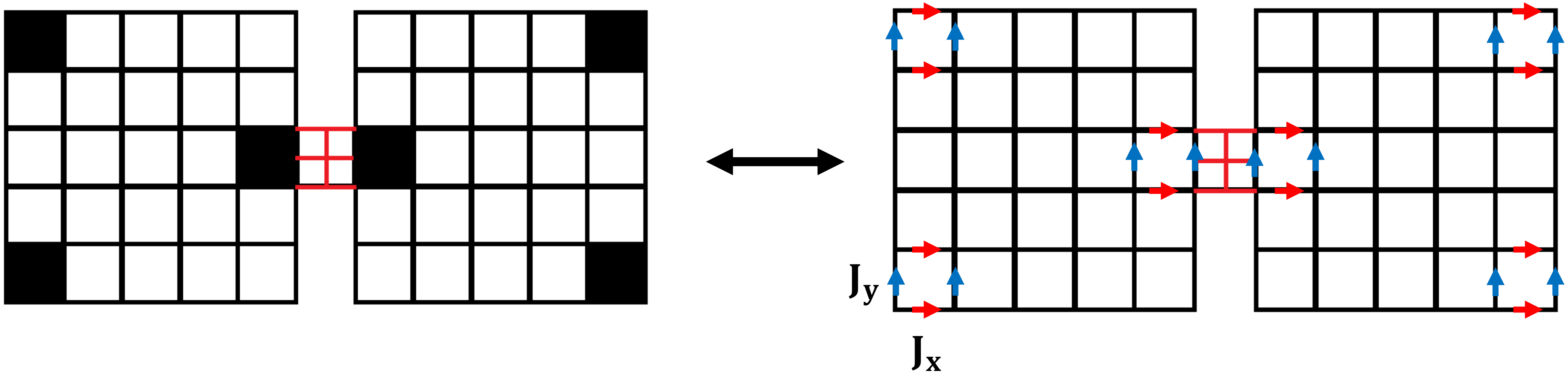
5. Continue step 2 if more tiles can be tried, otherwise the optimization has converged.

Superposition fails for metals



- Current sources (J) in Maxwell's equations → linear
  - Source J_A results in fields $\mathbf{E}_A$, source J_B results in fields $\mathbf{E}_B$
  - $a*J_A + b*J_B \rightarrow a*\mathbf{E}_A + b*\mathbf{E}_B$
- Dielectrics (and metals) field solutions **CANNOT** be superimposed (multiple scattering)

Current Equivalence Theorem



Perfect Electrical Conductors (PEC) boundary condition can be enforced by enforcing zero tangential E-fields:

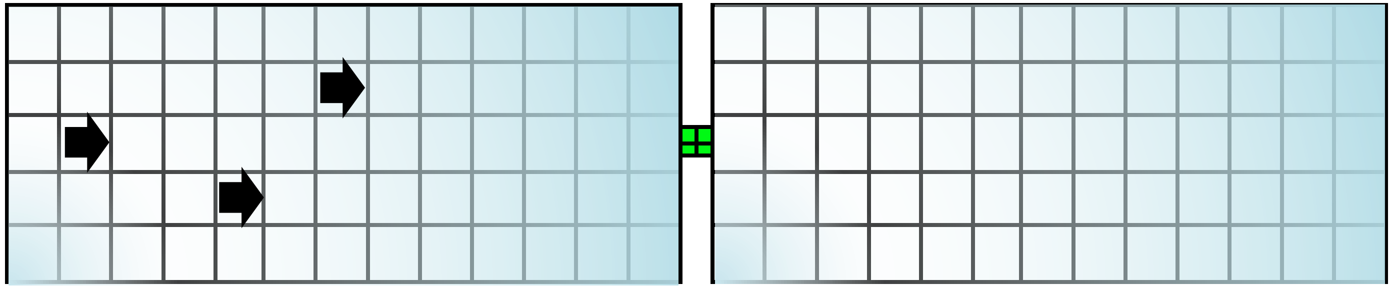
$$\boldsymbol{E\ fields}: \ \boldsymbol{E_x = E_y = 0}$$

Alternatively, corresponding J_x and J_y current densities can be found, which produce E-fields that combined with those of the center driven port excitation, also result in:

$$\boldsymbol{E_x = E_y = 0}$$

Leveraging Current Equivalence

- Choose values for J_{pec}'s to enforce $E_{tan} = 0$ over desired PEC region:

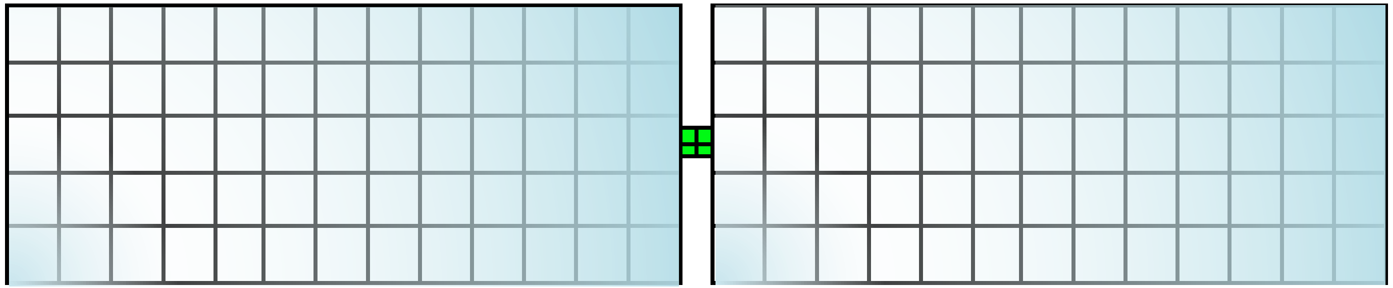


- Numerical Green's Function data: Z: $J_{surf} \rightarrow E_{tan}$ (EM simulations)
- Use NGFs to solve small linear system: $\boldsymbol{J_{pec}} = -[G^T Z G]^{-1} G^T \boldsymbol{E_{src}}$
- Store fields required to compute objective function produced by each J_{surf}: $\boldsymbol{EH_{obj}} = M\boldsymbol{J_{surf}}$

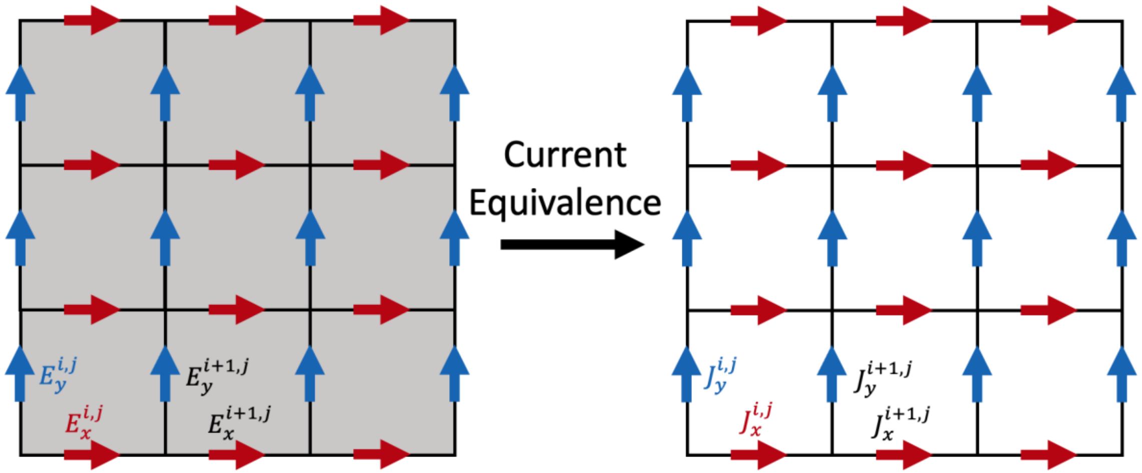
- G: Tall 0-1 selection matrix selecting cells to be set to PEC boundary condition.
- Z: An "impedance" matrix mapping surface J to the surface E fields on the same grid
- $\boldsymbol{E_{src}}$: Fields produced over design region by lumped port source excitation.
- M: Mapping matrix for all E/H components needed by computing objective function
- $\boldsymbol{EH}_{obj}$: Target E/H fields required by objective function
- **Approach ultra-fast: Millisecond to second time-scale on personal computer**

Leveraging Current Equivalence

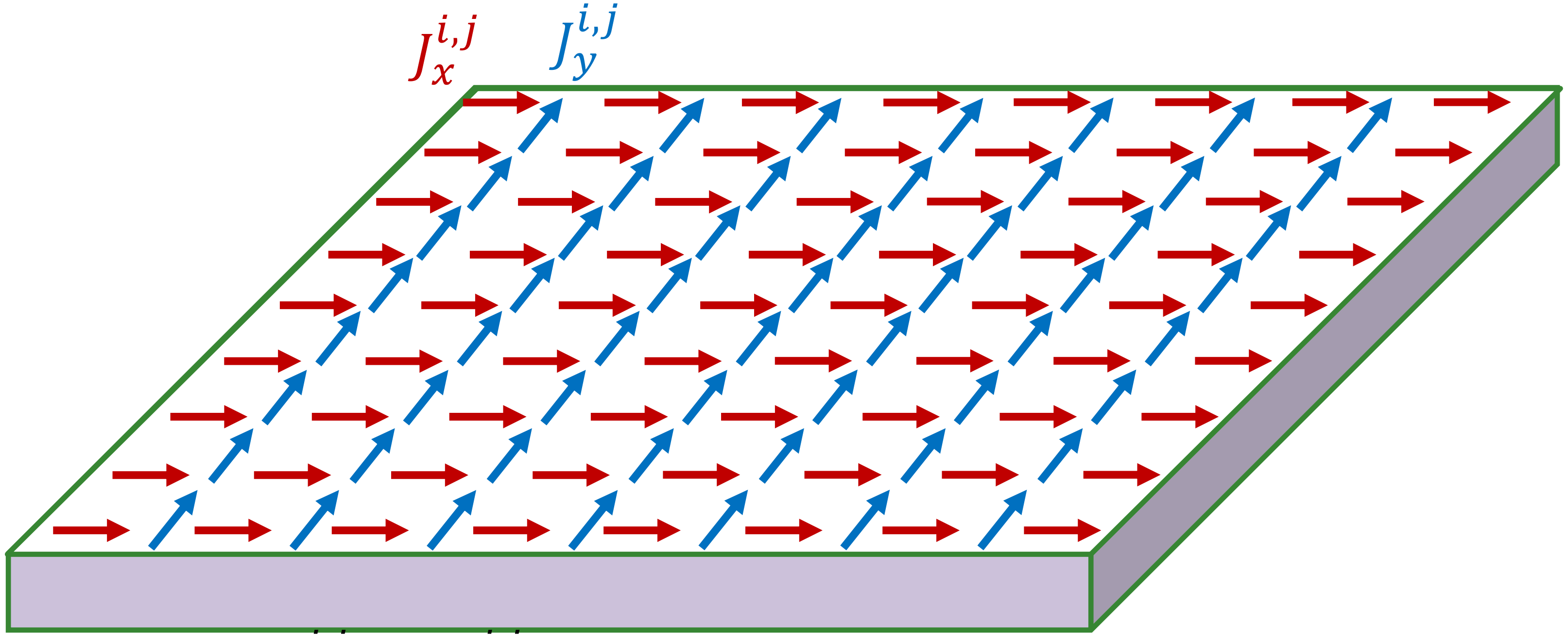
- Source Current Generates non-zero tangential E-field on design surface:



- Instead of explicitly setting PEC boundary condition, can find surface J's which satisfy it:



Precomputations: GPU Accelerated FDTD

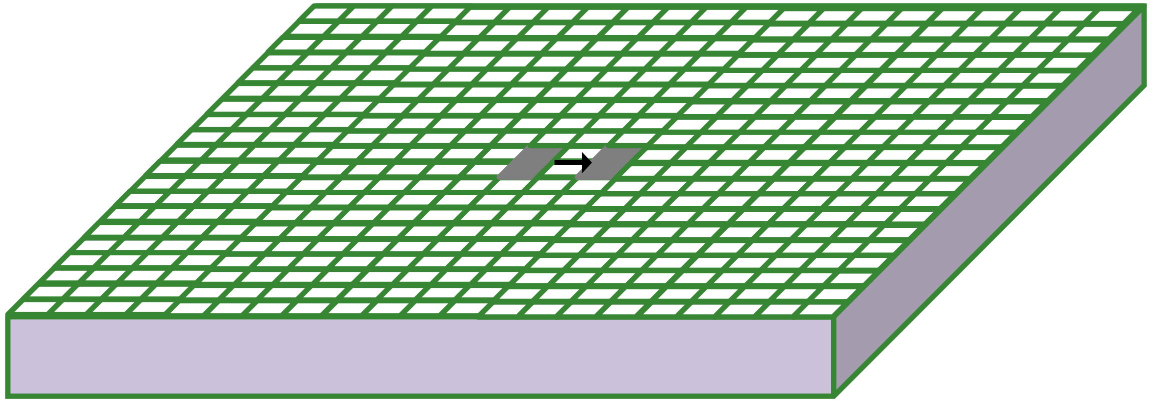


- Need to solve system for all $J_x^{i,j}$ and $J_y^{i,j}$ source excitations in design region and record collocated tangential $E_x^{i,j}$ and $E_y^{i,j}$ fields and EH_{obj} fields needed for computing objective function at each frequency of interest. **completely parallelized**
- **Can be** : Each precomputation independent of the rest.
- GPU accelerated FDTD solver: Enables solving for all frequencies using a single simulation per source by using broadband excitation.
- Typically, 30 seconds per simulation on Titan V GPU and 15 on newer A100 GPU.

Results:

Ultra-broadband substrate antenna optimization

- 1.36mm thick, 10.5 x 10.5mm Rogers RO3035 ($\varepsilon_r = 3.5$) dielectric substrate with metal ground plane ($\sim\lambda \times \lambda \times \frac{\lambda}{4}$ at 30GHz inside dielectric).
- 50-ohm X-directed lumped port source at center of top surface.
- 21x20 tiles over design region (tiles adjacent to lumped port are fixed to metal and those above and below lumped port are kept empty).
- **Goal:** Maximum S11 10-dB impedance bandwidth and far-field gain in broadside direction($\theta = 0, \phi = 0$).



Results:

Nonlinear objective function

- **Goal**: Maximum S11 10-dB impedance bandwidth and far-field gain in broadside direction($\theta = 0, \phi = 0$).
- Strategy: Use the following nonlinear multi-objective function:

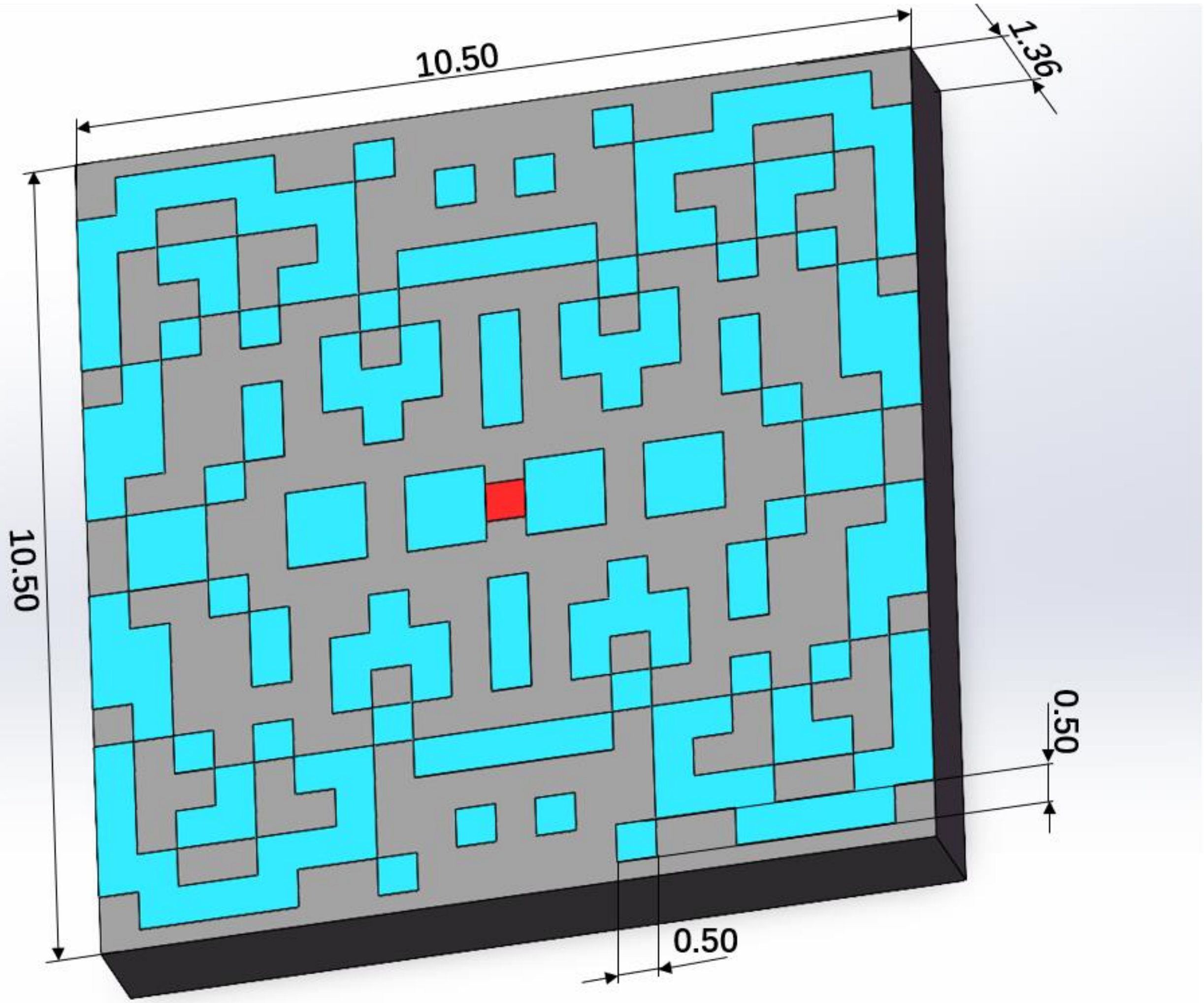
$$f_n = \frac{|S11_n|}{1 + e^{(3 - D_n(0,0))}} + \frac{5D_n(0,0)}{1 + e^{(10 - |S11_n|)}}$$

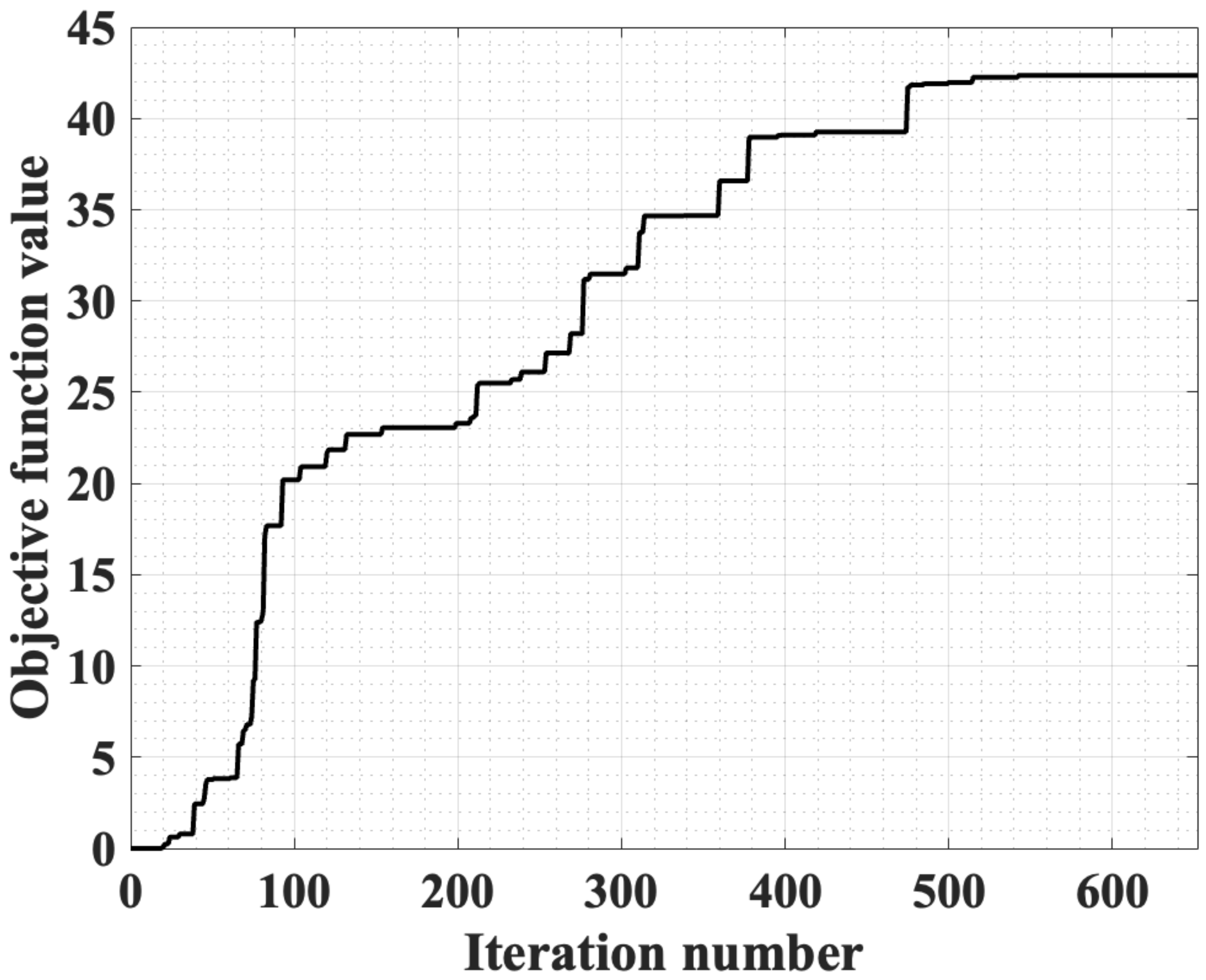
- Multiple f_n at five frequencies $n = 25, 27.5, 30, 32.5, 35\ GHz$ are combined together for wide bandwidth optimization:

$$f_{obj} = \frac{1}{\frac{1}{f_1} + \frac{1}{f_2} + \frac{1}{f_3} + \frac{1}{f_4} + \frac{1}{f_5}}$$

Results:

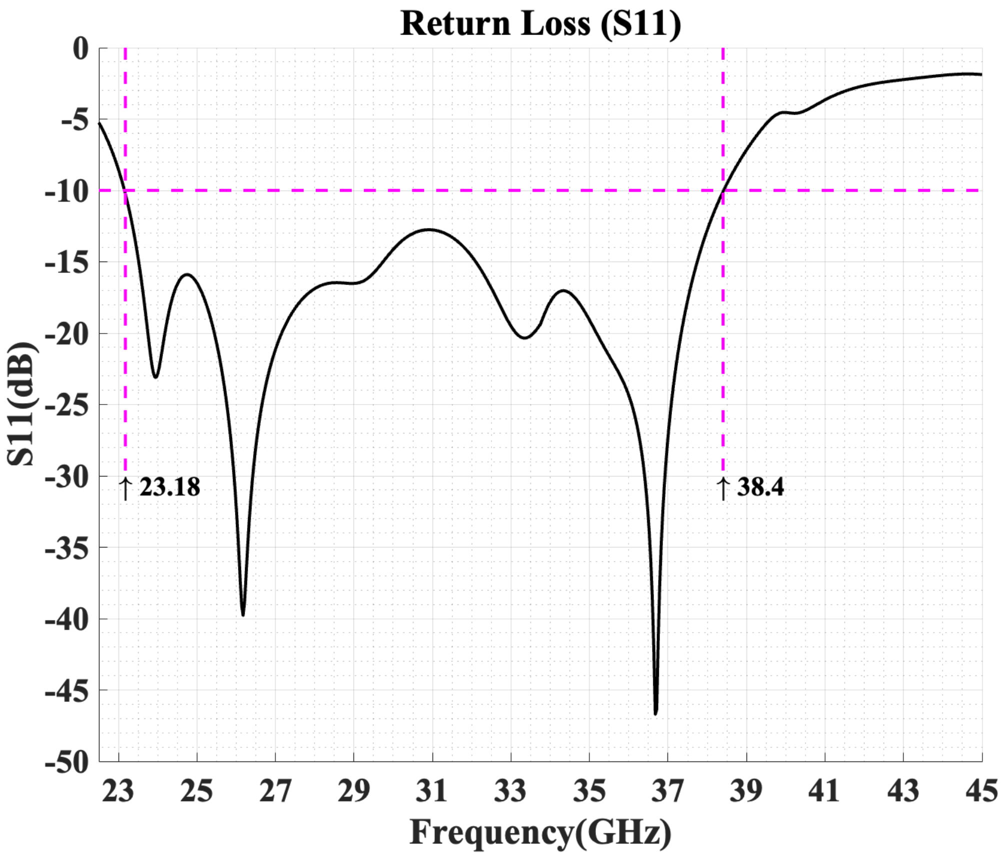
Optimized design structure

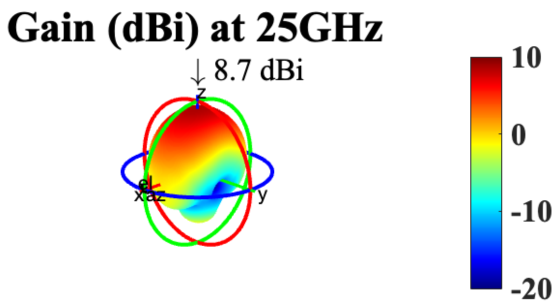


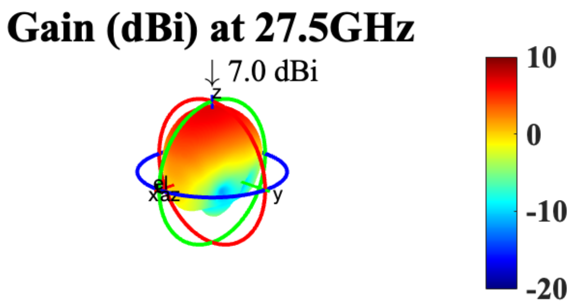


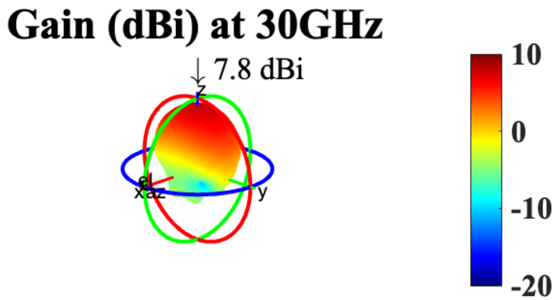
Results:

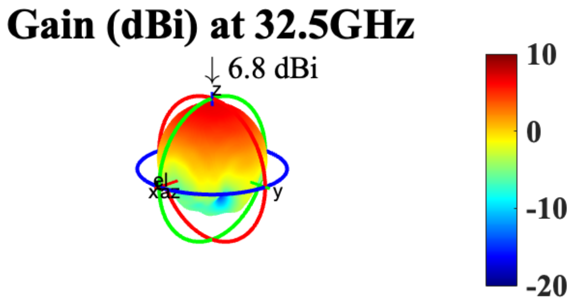
Antenna performance

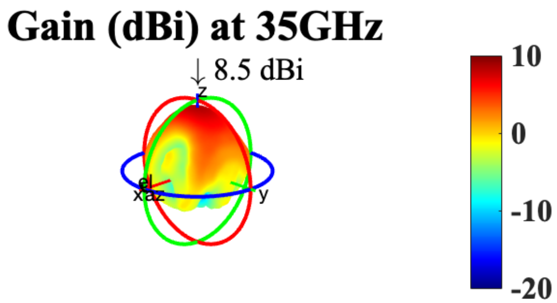






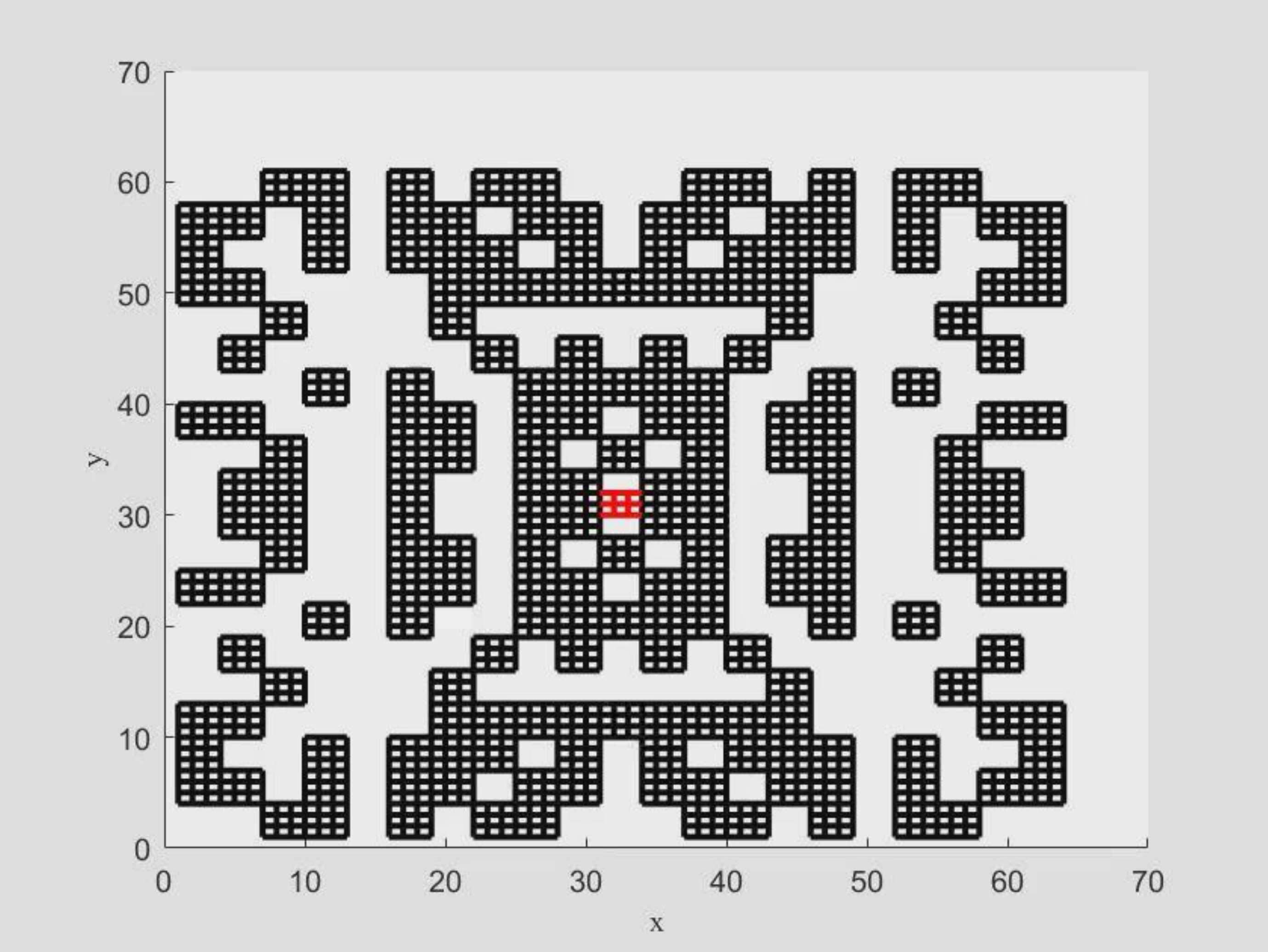






Results:

Optimization History



Conclusions

The method is **fast:**

- Each precomputation simulation takes 30 seconds using GPU accelerated FDTD solver.
- Precomputations can be completely parallelized due to being independent of each other.
- Each candidate design takes 1 sec/frequency to evaluate: 5 secs per iteration for 5 frequencies
  - (Note: This can also be parallelized in future work.)
- DBS algorithm converged with 650 iterations, requiring total optimization time of 54 minutes.

And can achieve **high-quality designs** from completely random starting points:

- Example inverse designed metallic substrate antenna achieves 50% S11 fractional bandwidth and greater than 6.8dB broadside gain across the whole bandwidth.