ELECTROMAGNETIC DESIGN OPTIMIZATION

Application to Patch Antenna Reflection Loss
on a Textured Material ("Metamaterial") Substrate

April 22, 2005

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Doctoral Committee:
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Overview

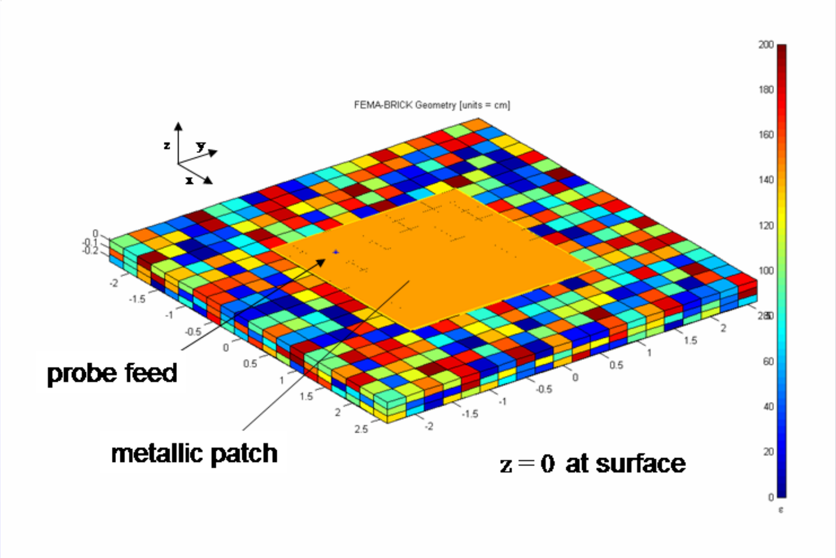
- Introduction of Research Focus
  - textured substrates for wideband design
  - past work; code and measurement validation
  - development approach
- Linear System Development
  - FEMA-BRICK FE-BI system
    - decomposition
    - narrowband optimizations
  - wideband approximation and eigendecomposition
  - relating eigenvalues to material texture
- Optimization Examples
  - patch and square spiral geometries
- Conclusions and Future Work

Applications

- Rapidly growing wireless, automotive and biomedical industry
  - driving need for increasingly miniaturized antenna designs
  - leverages a large body of work in high-dielectric ceramics
- Need for multifunctional, miniaturized advanced devices
  - bandwidth, efficiency, isolation
  - ease of use, low cost
  - power-handling
  - complexity

Metamaterial Antenna Design

- Combine dielectrics in a texture (structured lattice) at sub-wavelength granularity
  - fixed antenna geometry
- Integrate EM tools with matrix system optimization to design textured materials
  - Metamaterials
- Design context assumes full control over [ε] combinations
  - focus on optimization problem
  - combining materials in geometry only limited by EM tool



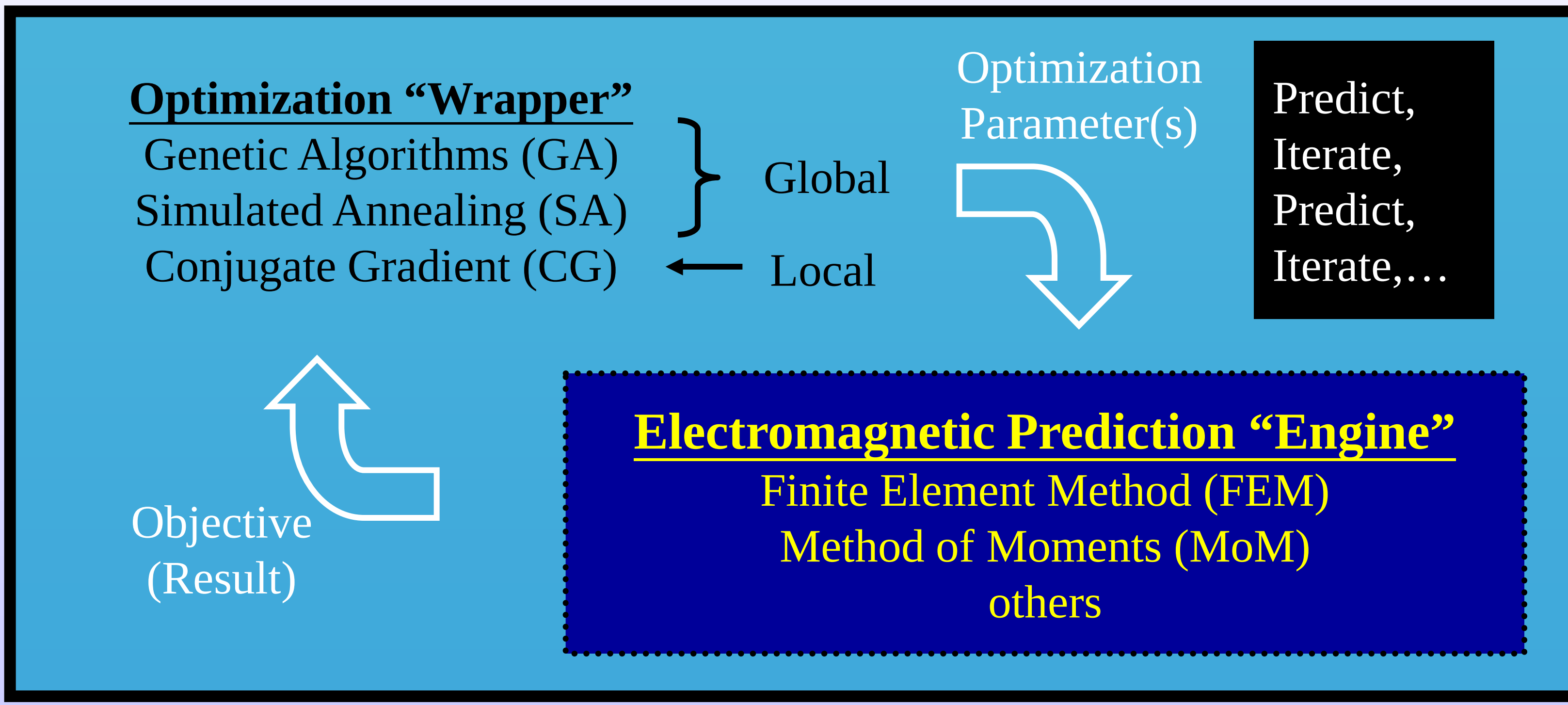
Design space of textured dielectrics to optimize reflection loss (reflection coefficient) over a band

Why Focus on EM Optimization?

- Great deal of EM community interest
  - advances in high-dielectric antenna materials
  - advances in speed and accuracy of prediction codes
    - optimization of designs is one key driver
- Need for more direct optimization approaches
  - multi-modal optimization problem
    - antenna designs part of a large and sensitive search-space
    - genetic algorithms a dominant area of research
      - general class of statistical “gradient-free” approaches
    - “fractal design” offered as a new way to improve antennas
  - most approaches are general-purpose applications
    - not dependent on a particular prediction code per se

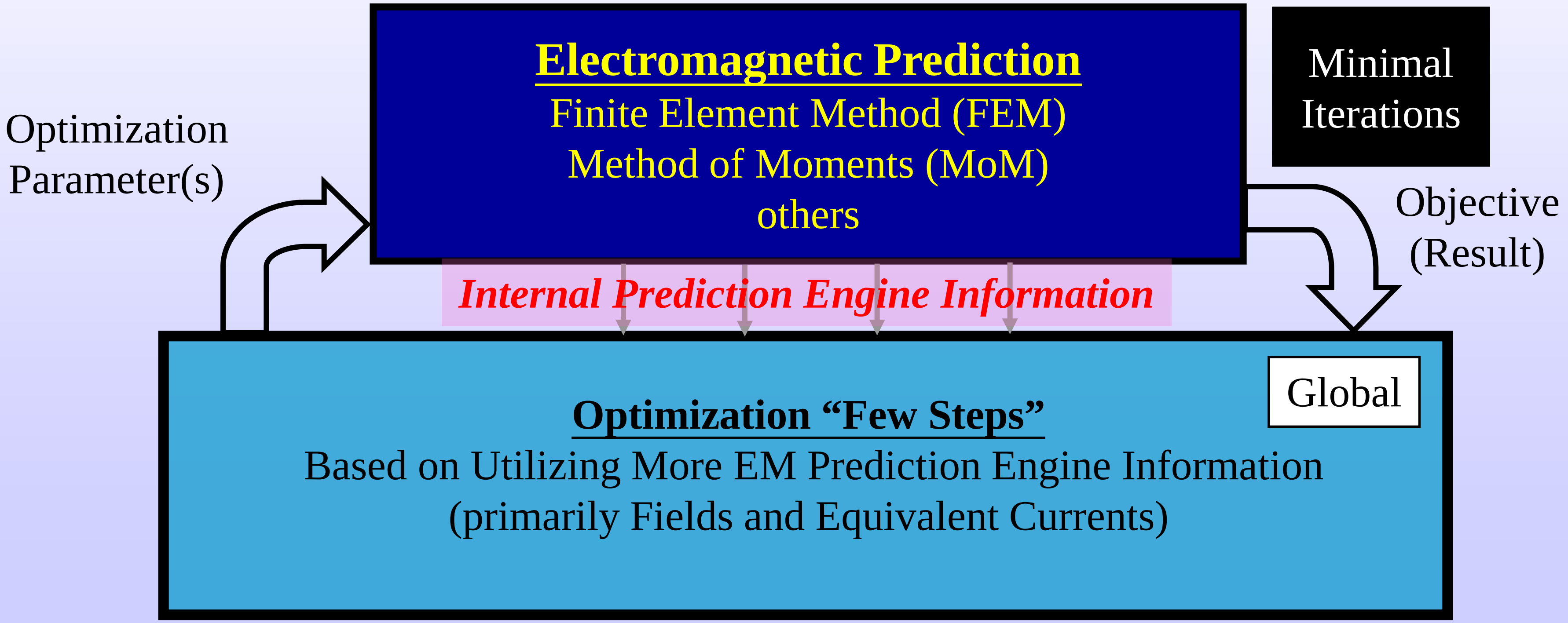
Research Focus[1]

- **Standard Approach to Electromagnetic Optimization**:
  - Can be very time-intensive (1000's of iterations, several minutes per iteration)



Research Focus²

- **Proposed Approach to Electromagnetic Optimization**:
  - Remove the "wrapper"

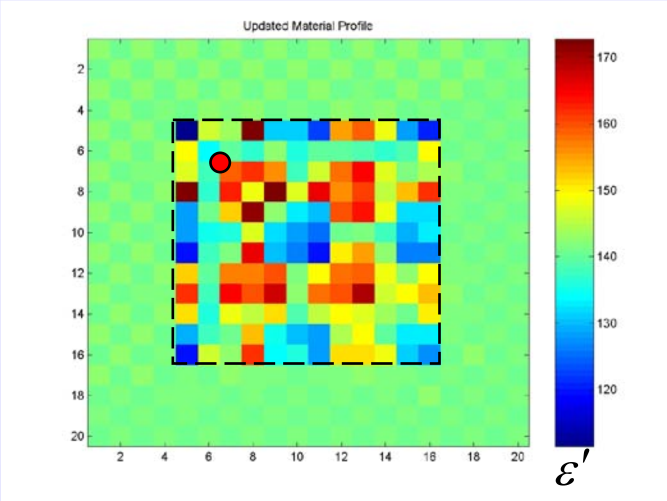


Objective Function for this Work

- Optimize reflection loss over a bandwidth
  - over all frequencies contained in some band, F
  - commensurate with radiation performance
  - computed via Z-directed field at probe location

$$J\left(\boldsymbol{\varepsilon}\right) = \left\| s_{11}(\boldsymbol{\varepsilon}) \right\|_{f_i}^{\infty}, \quad f_i \in \mathbf{F}$$

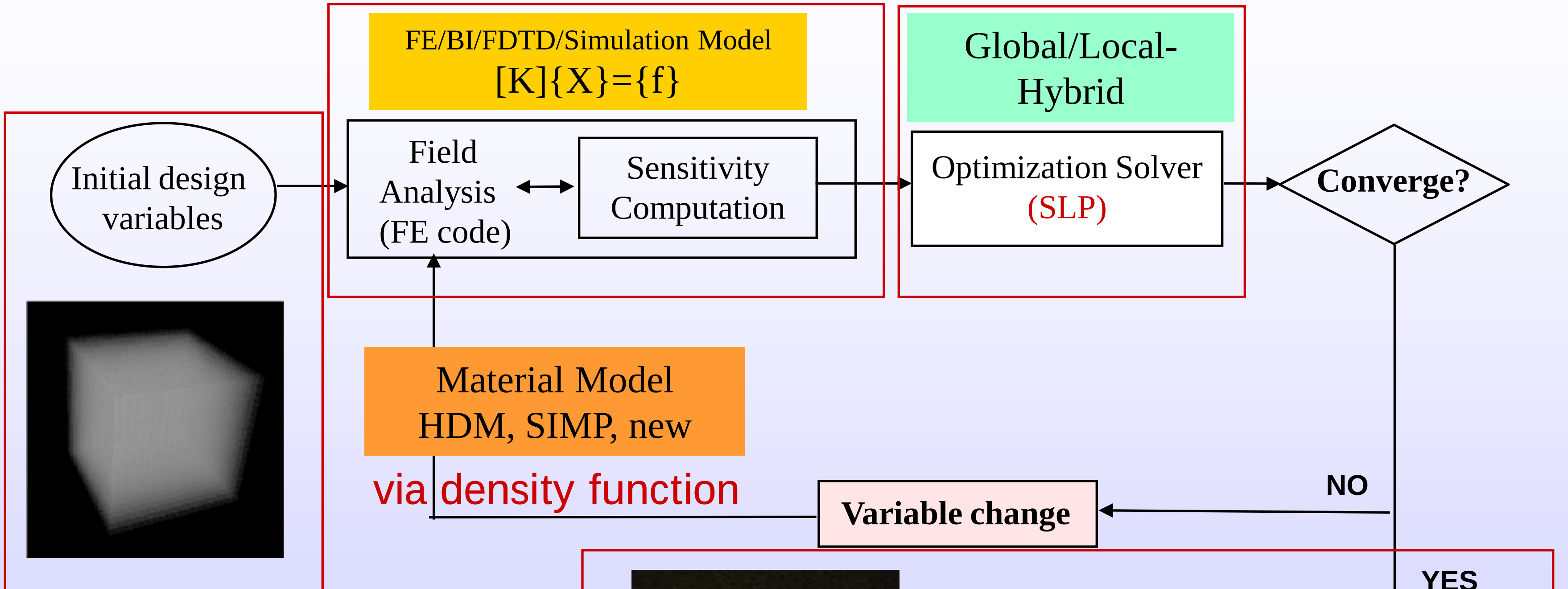
$\boldsymbol{\varepsilon} \equiv$ matrix of brick permittivity values

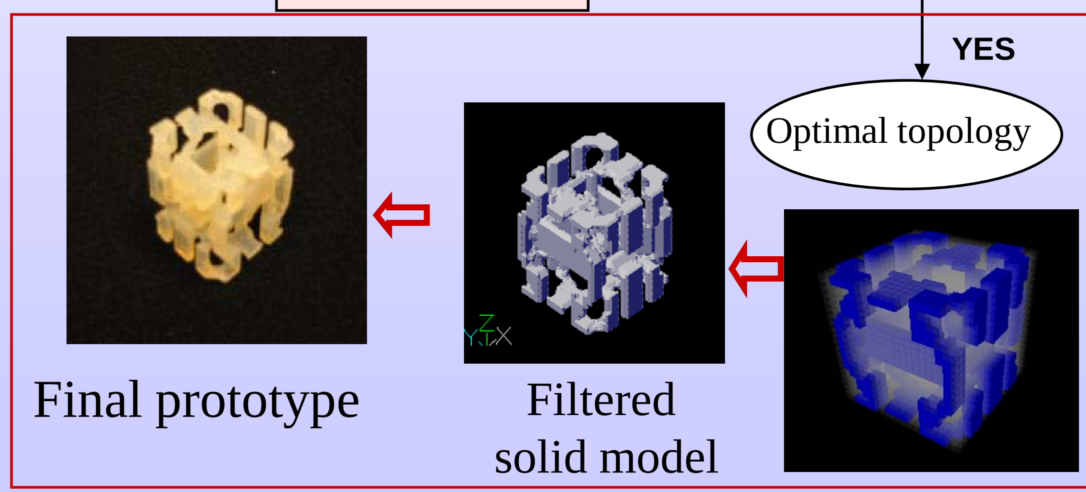


$$\boldsymbol{\varepsilon}_{opt} = \underset{\boldsymbol{\varepsilon}}{\operatorname{argmin}}\left[J(\boldsymbol{\varepsilon}) \right]$$

Example Optimized Material Profile

Recent Optimization Approach (SLP)



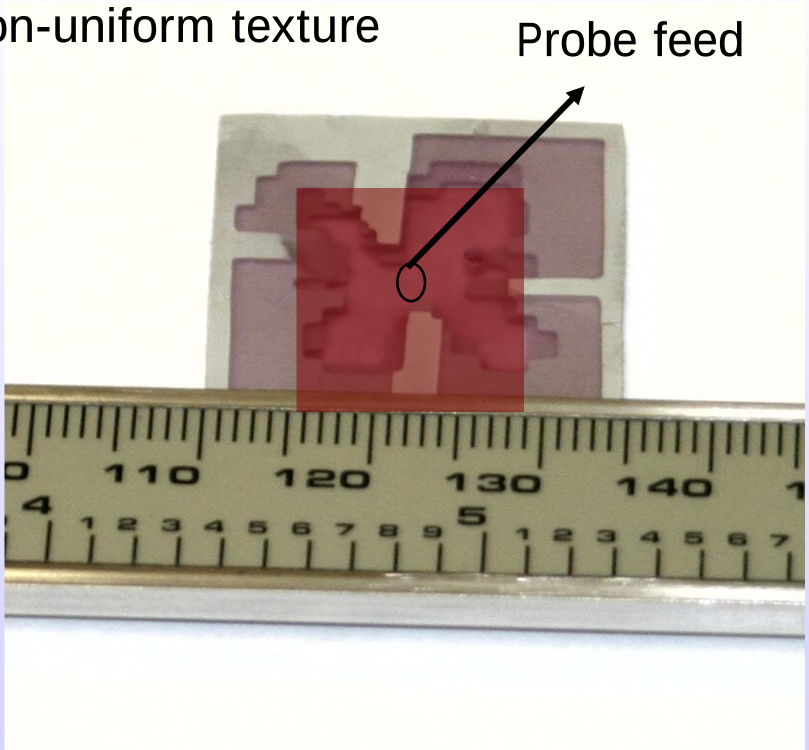


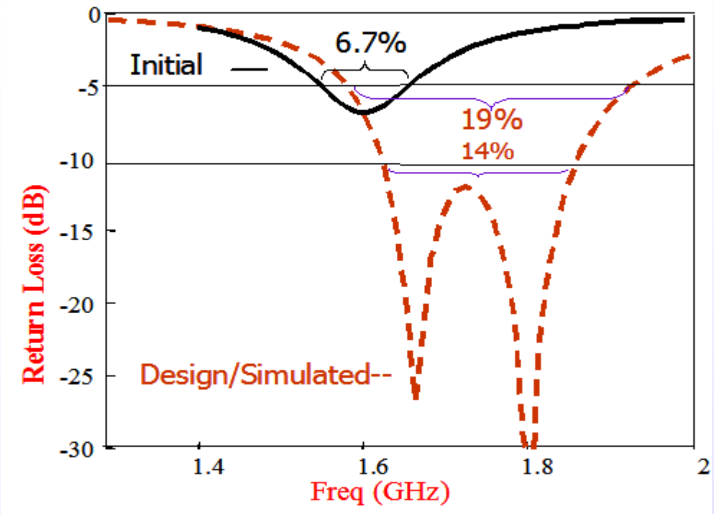
E-field sensitivity is used to determine optimal material perturbation regions – a "smoothness" constraint is used to minimize high-contrast materials and speed convergence

Measurement Validation

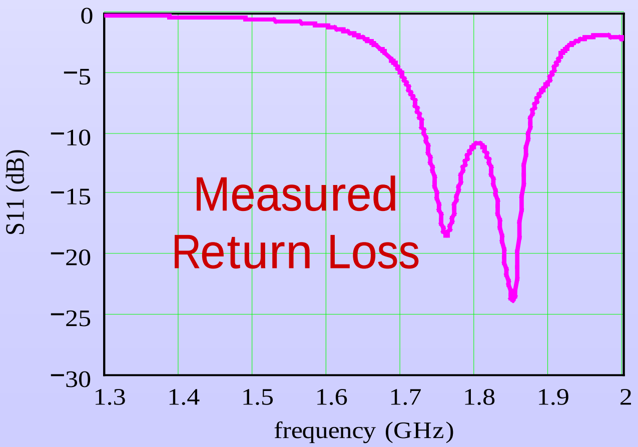
Measured patch
on non-uniform texture

Probe feed



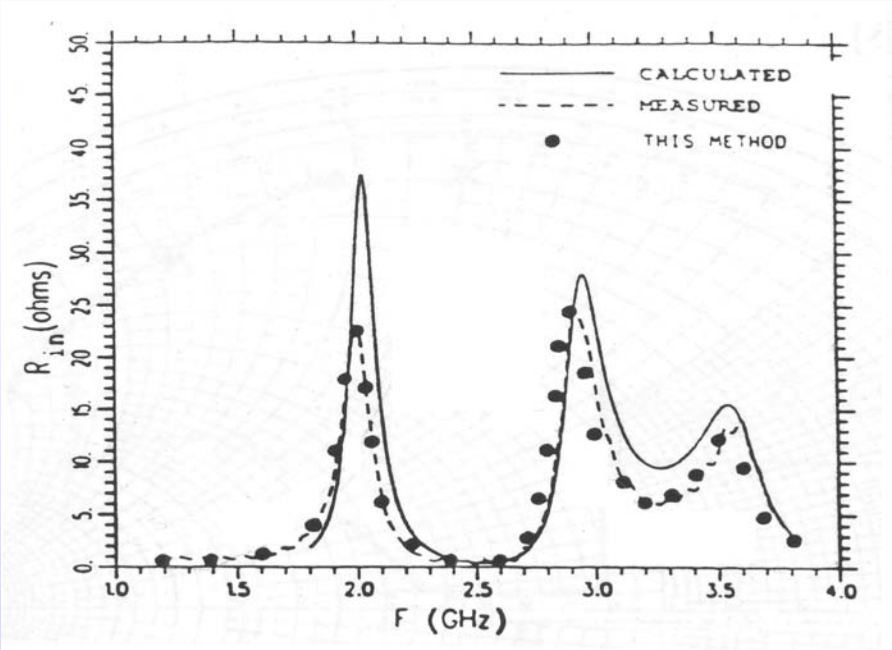


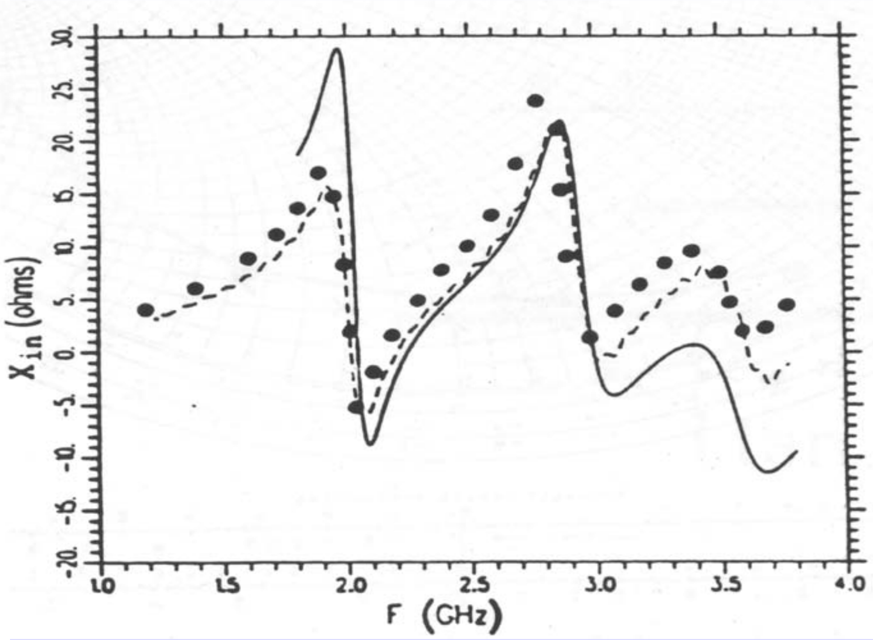
Measured data shifted by 100MHz;
Bandwidth and nulls are as simulated.



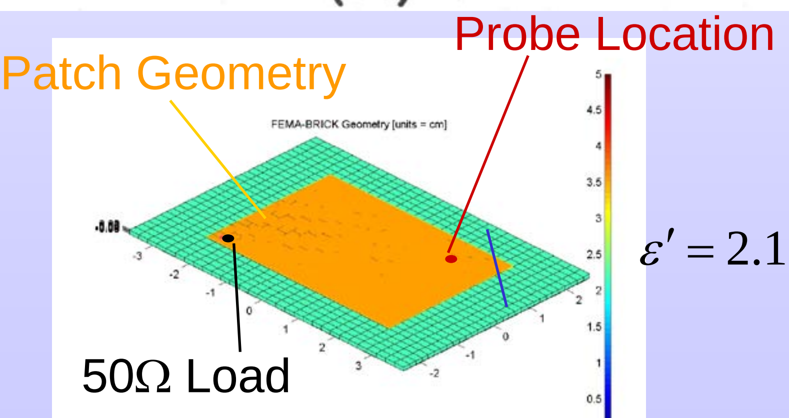
- G. Kiziltas, D. Psychoudakis, J.L. Volakis and N. Kikuchi *APT,* Vol. 51, Oct. 2003, pp. 2732-2743.
- G. Kiziltas, Y. Koh, J.L. Volakis, N. Kikuchi and J. Halloran, 2003 IEEE APS Symposium digest, pp. 485-488, Vol. 1, Columbus, OH.

Validated Code : FEMA-BRICK





- Jin, Jian-Ming; Volakis, J.L.; Alexanian, A.; "Electromagnetic Scattering and Radiation from Microstrip Patch Antennas and Arrays Residing in a Cavity", Project Report and User's Guide for FEMA-BRICK, 1991.



$\varepsilon' = 2.17$

7.5 x 5.1 x 0.08779 (thick) cm geometry

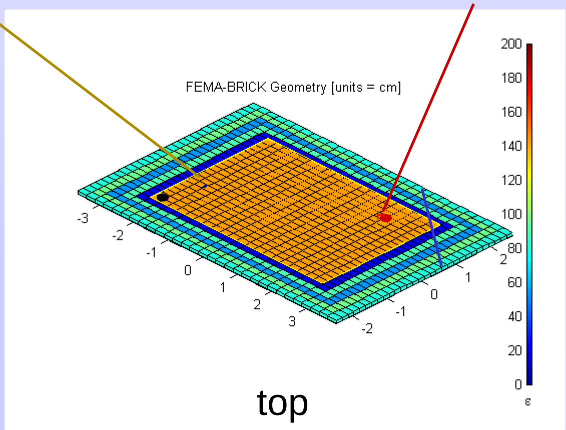
FEMA-BRICK Movie

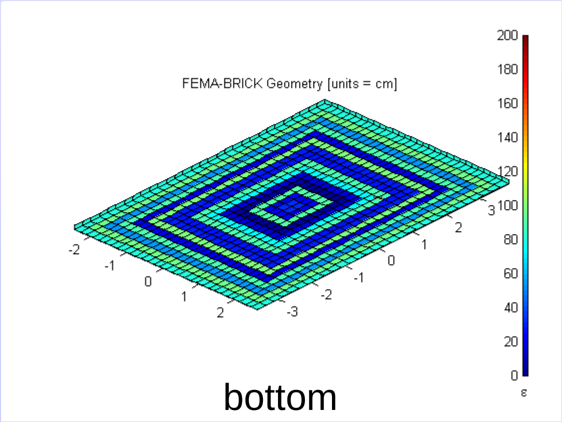
Parametric Constraints

- Standard optimization requires reasonable constraints
  - number of possible material choices
  - regions of optimization
    - e.g., concentric rings or “wavelet-like” sub-regions
- Goal is for “non-parametric” solutions
  - individual bricks are not constrained
    - only exception is that final solution must be well-conditioned
  - find best brick values and combinations

Patch Geometry

Probe Location





Material Constraints

- Available materials

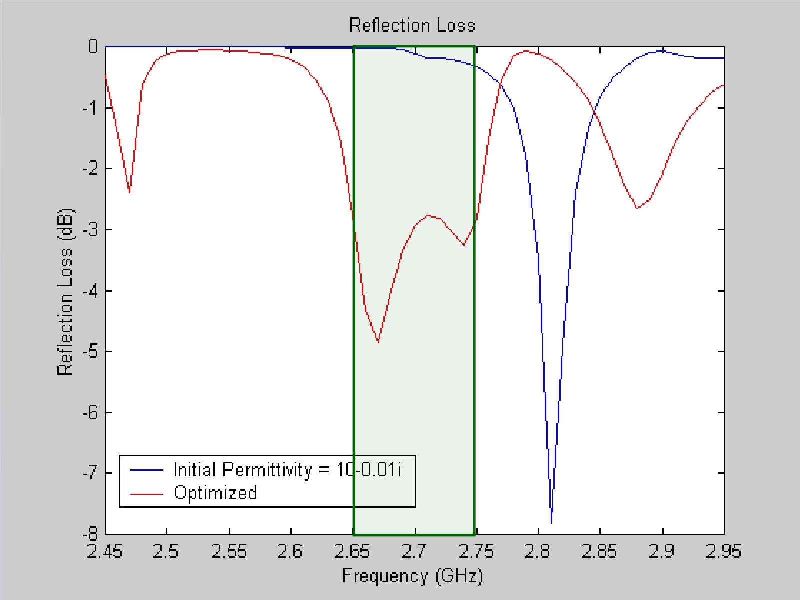
Material Name	Permittivity	Composition (Hardened)
Air / Vacuum	1	
See FEMA-BRICK Manual	2.17 – j 0.0033	
Stycast*	3.3 – j 0.004	Epoxy Resin
Ferro ULF100†	10 – j 0.01	$CaMgSi_2O_6$
Ferro ULF280†	30 – j 0.045	$BaTiO_3$
Ferro ULF101†	100 – j 0.15	Bi – Ba – Nd – Titanate

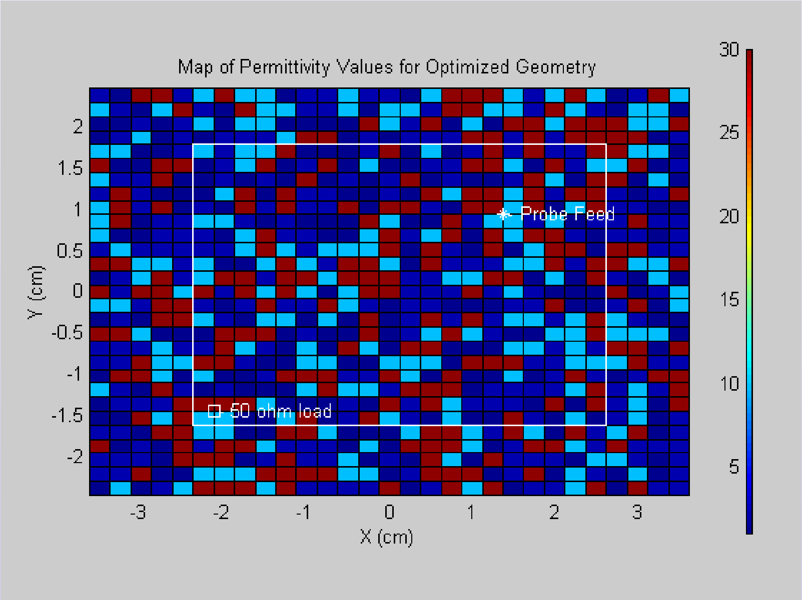
*** Stycast : from Emerson & Cuming Co.**
† LTCC: from Ferro Corp.

Preliminary Attempt via GA

- Genetic algorithms require judicious use
  - computation times prohibitive for this problem

Optimization Region (2.65-2.75 GHz)

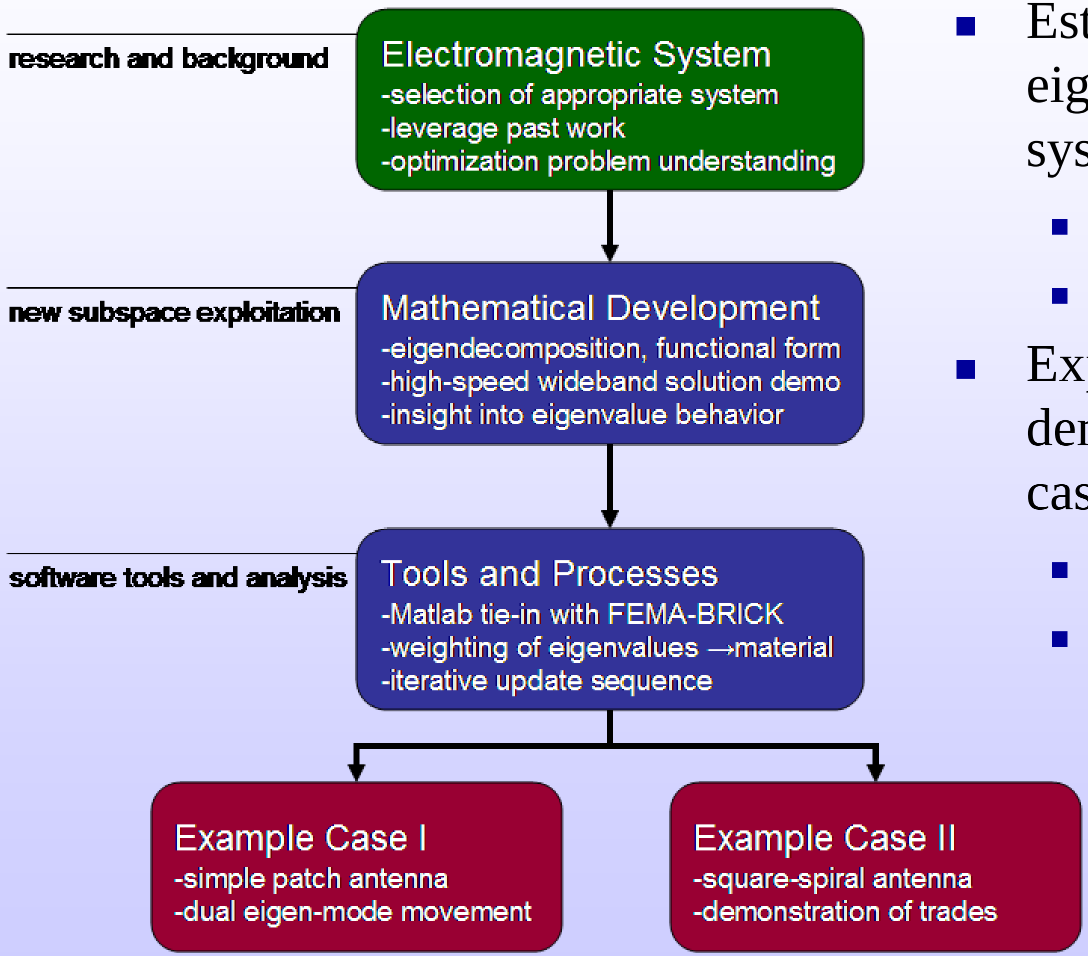




Reflection Loss (dB)

Final Material Texture, Re{ε}
(constrained to real permittivity $\varepsilon \in [1, 2.17, 10, 30]$*)*

Development Approach



- Establish relationship between eigen-decomposition of FE-BI system and textured substrate
  - broadband application
  - intuitive optimization
- Exploit relationship to demonstrate two representative cases
  - varying eigen-decompositions
  - limits in optimization potential

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FEMA-BRICK Setup

- FEMA-BRICK† code solves the FE-BI‡ system using a fast approach to obtain

$$\overline{\overline{G}}_{e2} = 2\overline{\overline{G}}_0 = -\left(\overline{\overline{I}} + \frac{\nabla\nabla}{k^2}\right)\left[\frac{e^{-jkR}}{2\pi R}\right]$$

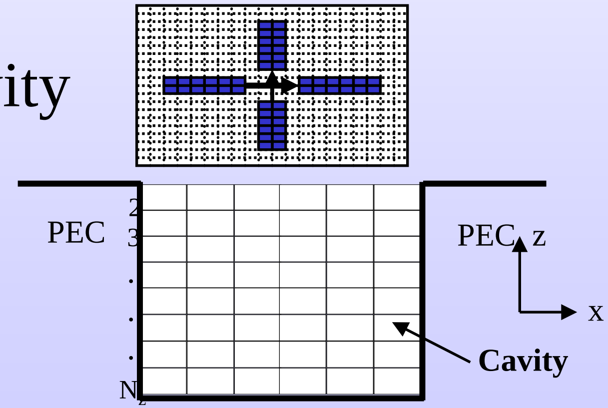
Finite Element (FE)

$$\sum_{j=1}^{N} E_j \left\{ \int_V \left[\frac{\nabla \times \mathbf{W}_i \cdot \nabla \times \mathbf{W}_j}{\mu_r} - k^2\, \varepsilon_r \mathbf{W}_i \cdot \mathbf{W}_j \right] dV - k^2 \int_S \int_{S'} \left[\mathbf{W}_i \cdot \hat{\mathbf{z}} \times \overline{\overline{G}}_{e2} \times \hat{\mathbf{z}} \cdot \mathbf{W}_j \right] dS' dS \right\}$$

$$= f_i^{\text{int}} + \tilde{f}_i^{\text{ext}}, \quad i = 1, 2, 3, \ldots, N$$

Boundary Integral (BI)

- develops brick mesh (volumetric) in a cavity
  - aperture embedded in an infinite ground plane
- matches volumetric and surface terms
- probe feed (good for thin substrate)



†Jin, J.-M.; Volakis, J.L.; "A Finite-Element-Boundary-Integral Formulation for Scattering by Three-Dimensional Cavity-Backed Apertures", *IEEE Transactions on Antennas and Propagation,* Vol: 39, Issue: 1, Jan. 1991.

‡ Finite Element – Boundary Integral (FE-BI)

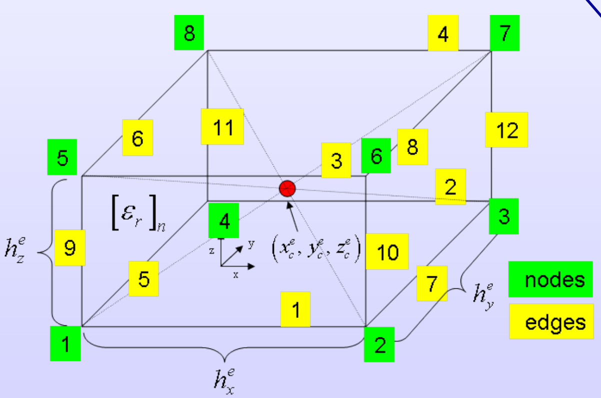
System Solution

Finite Element (FE) | Boundary Integral (BI)

$$\sum_{j=1}^{N} E_j \left\{ \int_V \left[\frac{\nabla \times \mathbf{W}_i \cdot \nabla \times \mathbf{W}_j}{\mu_r} - k^2 \varepsilon_r \mathbf{W}_i \cdot \mathbf{W}_j \right] dV - k^2 \int_S \int_{S'} \left[\mathbf{W}_i \cdot \hat{\mathbf{z}} \times \overline{\overline{G}}_{e2} \times \hat{\mathbf{z}} \cdot \mathbf{W}_j \right] dS' dS \right\}$$

$$= f_i^{\text{int}} + \tilde{f}_i^{\text{ext}}, \quad i = 1, 2, 3, \ldots, N$$

$$\overline{\overline{G}}_{e2} = 2\overline{\overline{G}}_0 = -\left(\overline{\overline{I}} + \frac{\nabla\nabla}{k_0^2} \right) \left[\frac{e^{-jkR}}{2\pi R} \right]$$



Finite Element (FE) | Boundary Integral (BI)

$$\underbrace{\left(\mathbf{A}^{(1)}(\mu) + \mathbf{A}^{(2)}(\varepsilon) + \begin{bmatrix} \mathbf{G}^{(1)} + \mathbf{G}^{(2)} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \right)}_{\mathbf{R}} \underbrace{\begin{bmatrix} \mathbf{E}^{bi} \\ \mathbf{E}^{fe} \end{bmatrix}}_{\mathbf{E}} = \underbrace{\begin{bmatrix} \tilde{\mathbf{f}}^{ext} \\ \mathbf{f}^{int} \end{bmatrix}}_{\mathbf{F}}$$

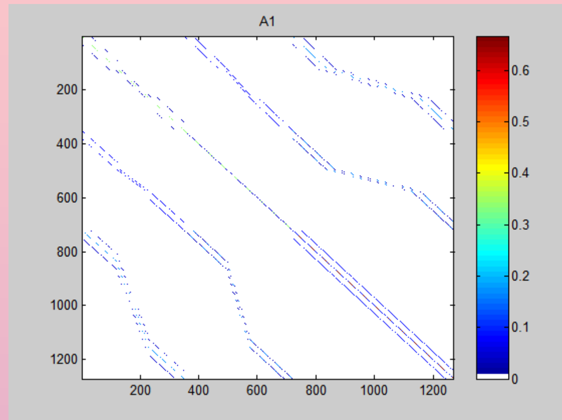
$$\mathbf{E} = \mathbf{R}^{-1}\mathbf{F}$$

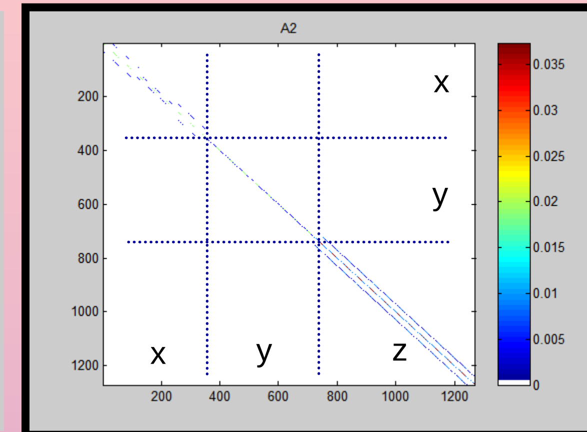
Solved via BiCG in FEMA-BRICK on a Per-Frequency Basis

Sparse FE and Dense BI Structure

Finite Element Matrices

$A^{(1)}(\mu)$

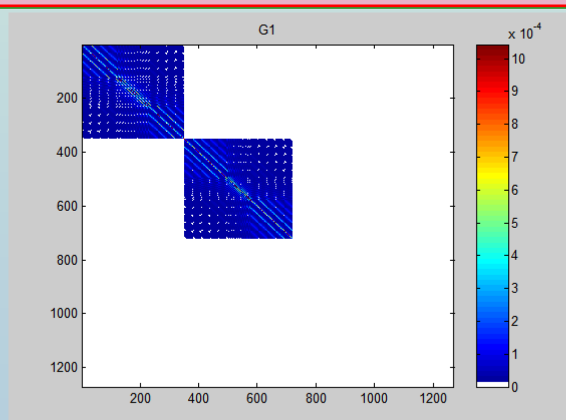


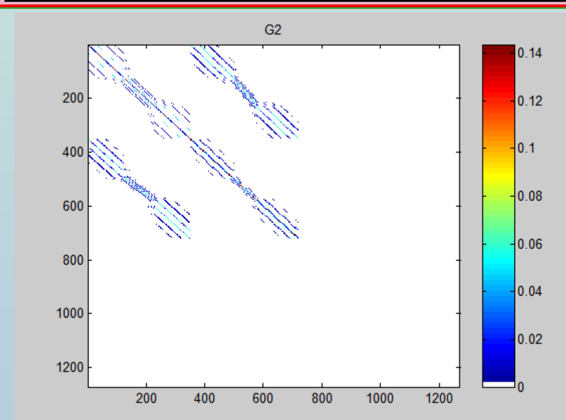


$A^{(2)}(\varepsilon)$

"Control" Matrix

$G^{(1)}$





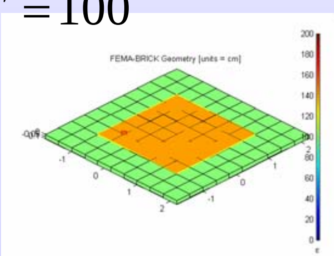
$G^{(2)}$

Boundary Integral Matrices

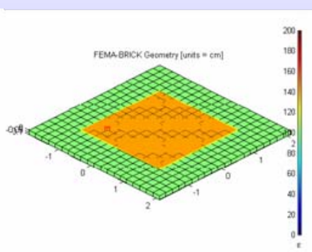
System Condition

- Valid E-field solutions are dependent on proper sampling, expansion functions and system development
  - segmentation (check for convergence)
  - alternate bases (field edge-based expansion function)
  - cross-code validation
    - important to ensure the code is "appropriately disparate"

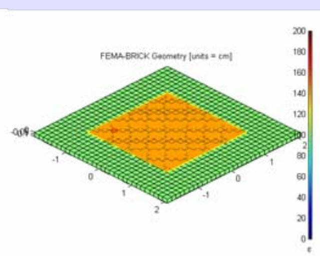
$\varepsilon' = 100$



10×10

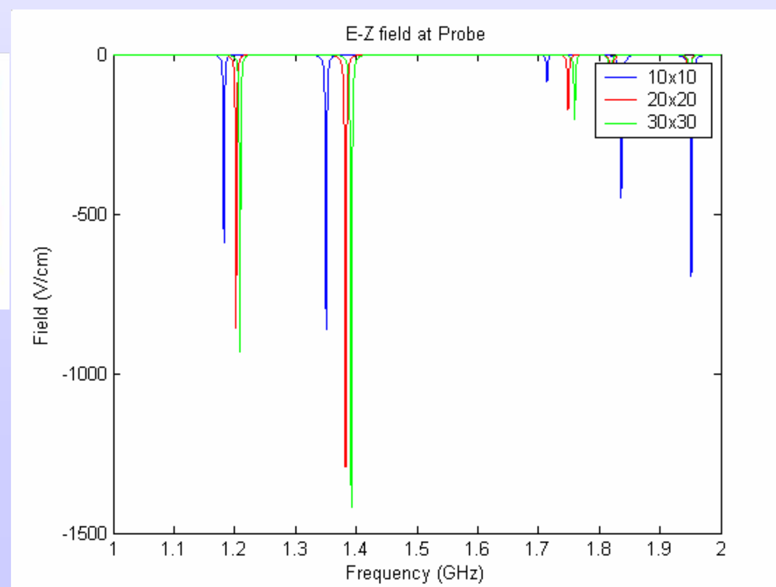


20×20



30×30

FEMA-BRICK Movie



Narrowband Optimization via TLS

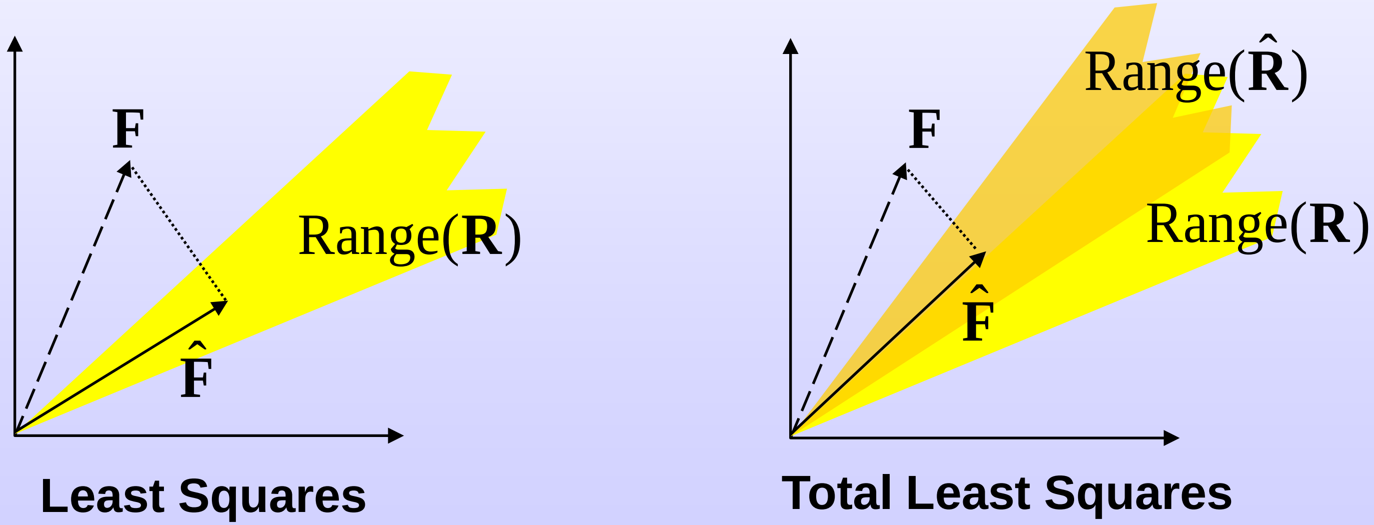
- Constrain the field at the probe location to the desired objective value (corresponding to desired input impedance)
  - solve remaining system via TLS
  - simple weighted update for material texture

$$\left(\mathbf{A}^{(1)}(\mu) + \mathbf{A}^{(2)}(\varepsilon) + \begin{bmatrix} \mathbf{G}^{(1)}+\mathbf{G}^{(2)} & \mathbf{0} \\ \mathbf{0} & \mathbf{0}\end{bmatrix}\right)\begin{bmatrix} e_1 \\ \vdots \\ e_{n-1} \\ \hline e_n \\ \hline e_{n+1} \\ \vdots \\ e_N \end{bmatrix} = \begin{bmatrix} \tilde{\mathbf{f}}^{ext} \\ \mathbf{f}^{int} \end{bmatrix}$$

constrained to objective at feed location

TLS Solution Space

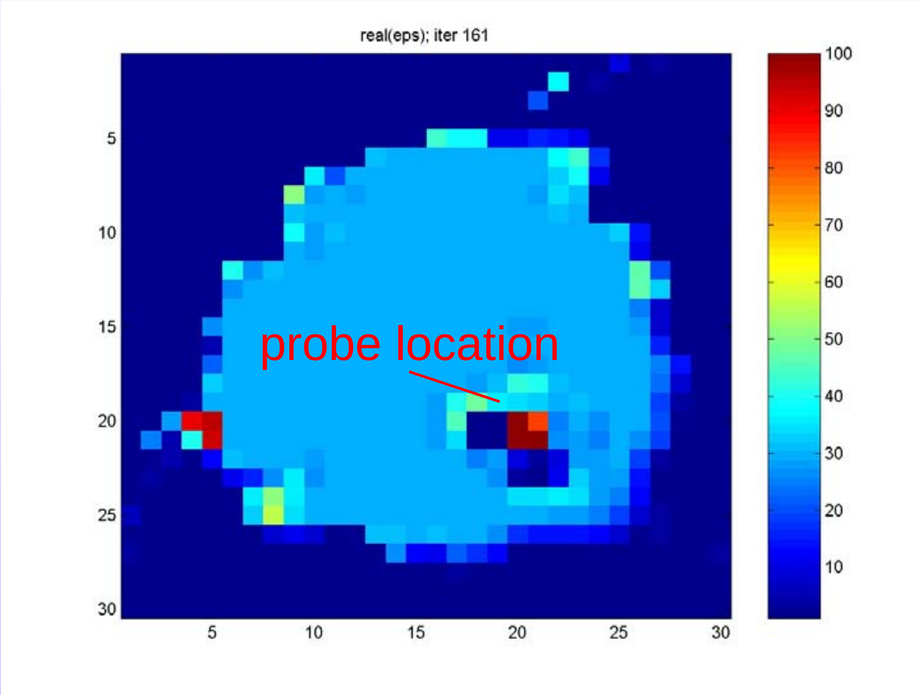
- Total Least Squares (TLS) finds a unique solution by assuming error may equivalently exist in the observation (**F**) as well as the range of the data matrix (**R**) for the system **RE≈F**
  - contrasted with Least Squares (LS) where error is assume to exist only in **F**



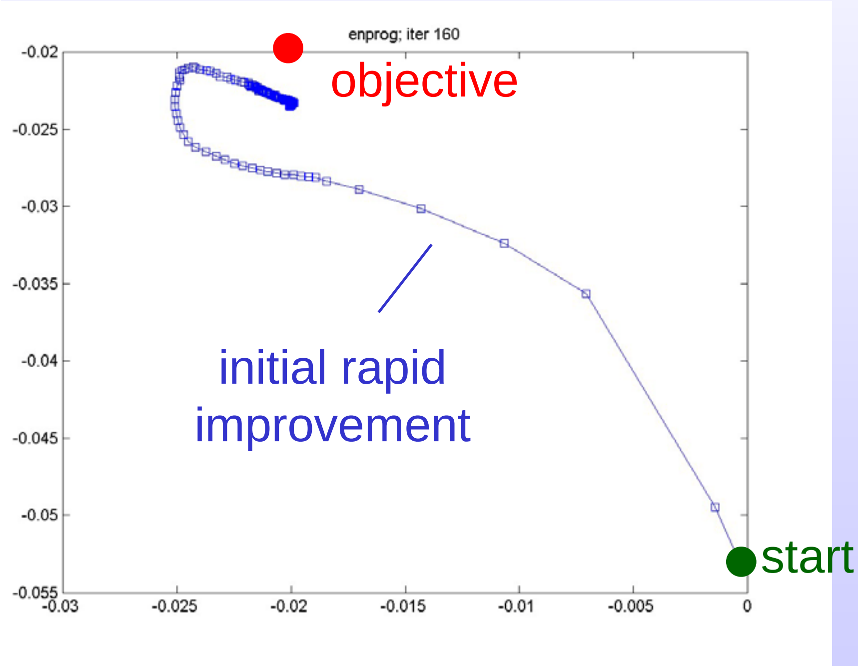
†Golub, Gene H.; VanLoan Charles F.; *Matrix Computations*, 3rd Edition, The Johns Hopkins University Press, 1996.
†Van Huffel, Sabine; Vandewalle, Joos; The Total Least Squares Problem – Computational Aspects and Analysis, SIAM Publications, 1991.

Example TLS Results (2 GHz)

- Iterative improvement overall, with some deviation (imperfect solution)



Final Material Texture, Re{ε}
[constrained to real permittivity 1 < ε < 100]



Complex E-field at Probe Feed Location

Issues Highlighted by TLS

- Slow convergence
  - updates guided by smallest singular values
- Incomplete convergence
  - updates quickly driven to material specification limits

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Complete Eigendecomposition

- Narrowband initially
  - solve inversion problem in straightforward fashion
    - material decomposed into bases to relate to eigen-space
  - similar solutions involving eigen-mode computation and evaluation are very popular for some applications†

$$\left(\mathbf{A}\mu^{(1)}(\;) + \mathbf{A}\varepsilon^{(2)}(\;) + \begin{bmatrix} \mathbf{G}^{(1)}+\mathbf{G}^{(2)} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}\right)\mathbf{R} = \mathbf{X}\Lambda\mathbf{X}^{-1}$$

chosen material bases

† Chan, C.-H.; Pantic-Tanner, Z.; Mittra, R.; "Field Behaviour Near a Conducting Edge Embedded in an Inhomogeneous Anisotropic Medium", *Electronics Letters*, Volume 24, Issue 6, 17 March 1988.

† Sarabandi, K.; "A Technique for Dielectric Measurement of Cylindrical Objects in a Rectangular Waveguide", *IEEE Transactions on Instrumentation and Measurement*, Vol: 43, Issue: 6, Dec 1994.

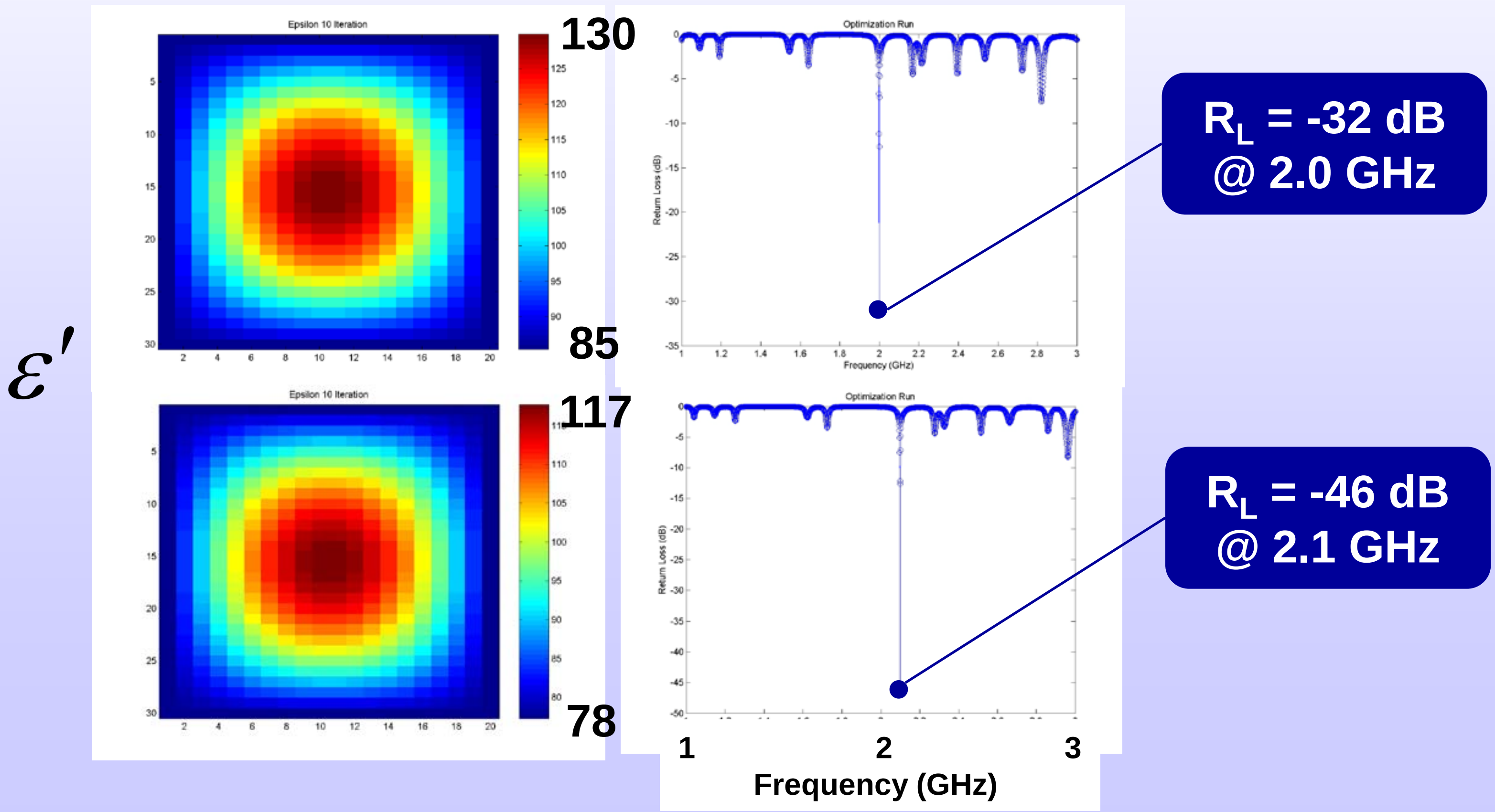
† Kiang, J.; "Microstrip Lines on Substrates with Segmented or Continuous Permittivity Profiles", *IEEE Transactions on Microwave Theory and Techniques*, Vol: 45, Issue: 2, Feb 1997.

† Yatsuk, L.; Lyakhovsky, A.; "Longitudinal Slots in a Rectangular Waveguide Loaded with a Layered Dielectric", *Mathematical Methods in Electromagnetic Theory*, 2000 MMET International Conference, Volume 2, 12-15 Sept 2000.

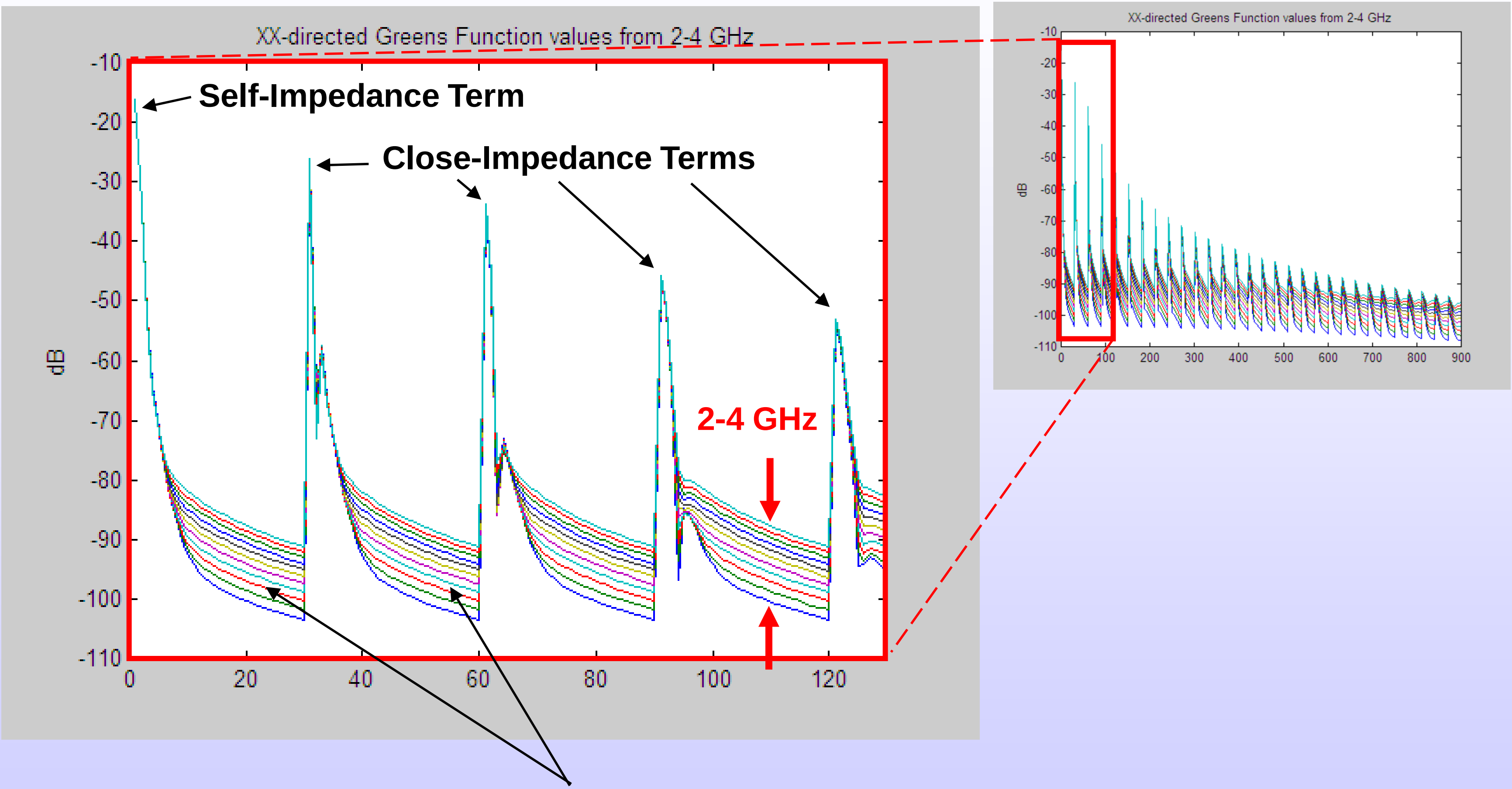
† Yatsyk, V.V.; "About Self-organization and Dispersion of Eigen Fields of a Nonlinear Dielectric Layer", *Direct and Inverse Problems of Electromagnetic and Acoustic Wave Theory*, 2002 Proceedings of the 7th International Seminar/Workshop on DIPED, 10-13 Oct 2002.

Narrowband Results

- Achieved very good results with only two material bases
  - constant and rooftop sinusoidal
  - could select frequency to optimize *almost* at will



Wideband BI Coefficients



Principle Differences are Near the "Zeros" (increasing *R*) of the BI Matrix Terms

Expansion of free space Green's function kernel →

$$e^{-jkR} \approx e^{-jk_0R}\left(1 + j(k-k_0)R - \frac{1}{2}(k-k_0)^2 R^2 + \ldots\right)$$

Approximate Wideband System

Use First Term Only

$$e^{-jkR} \approx e^{-jk_0 R}$$

Finite Element (FE) | Boundary Integral (BI)

$$\underbrace{\left(\mathbf{A}_{\mu}^{(1)}(k) + \mathbf{A}_{\varepsilon}^{(2)}(k) + \begin{bmatrix} \mathbf{G}^{(1)} + \mathbf{G}^{(2)} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}\right)}_{\mathbf{R}} \underbrace{\begin{bmatrix} \mathbf{E}^{bi} \\ \mathbf{E}^{fe} \end{bmatrix}}_{\mathbf{E}} = \underbrace{\begin{bmatrix} \tilde{\mathbf{f}}^{ext} \\ \mathbf{f}^{int} \end{bmatrix}}_{\mathbf{F}}$$

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$$= f_i^{\text{int}} + \tilde{f}_i^{\text{ext}}, \quad i = 1, 2, 3, \ldots, N$$

Boundary Integral (BI)

$$\tilde{k} = k / k_0$$

Normalized Frequency

$$\mathbf{A}_{\mu}^{(1)}(k;\mu) = \mathbf{A}_{\mu}^{(1)}(k_0;\mu)$$

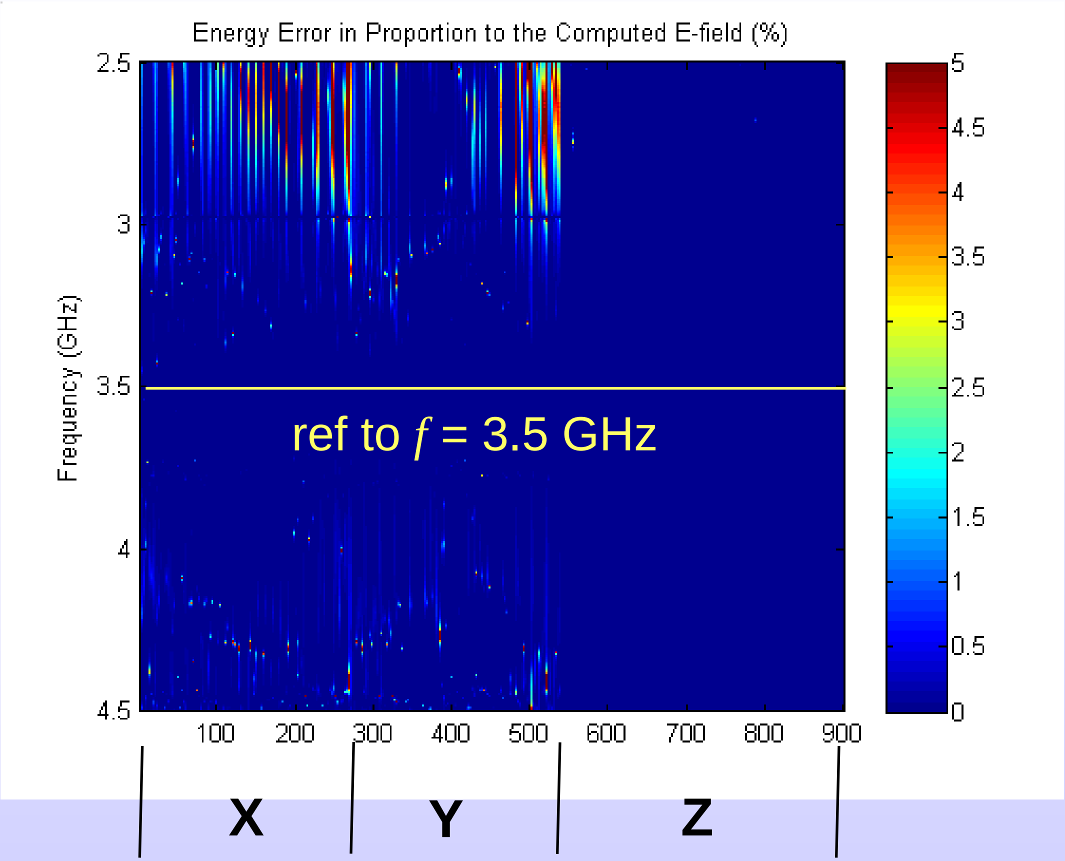
$$\mathbf{A}_{\varepsilon}^{(2)}(k;\varepsilon) = \tilde{k}^2 \mathbf{A}_{\varepsilon}^{(2)}(k_0;\varepsilon)$$

$$\mathbf{G}^{(1)}(k) \approx \tilde{k}^2 \mathbf{G}^{(1)}(k_0)$$

$$\mathbf{G}^{(2)}(k) \approx \mathbf{G}^{(2)}(k_0)$$

← **Key Approximation**

Wideband Approximant Accuracy[1]

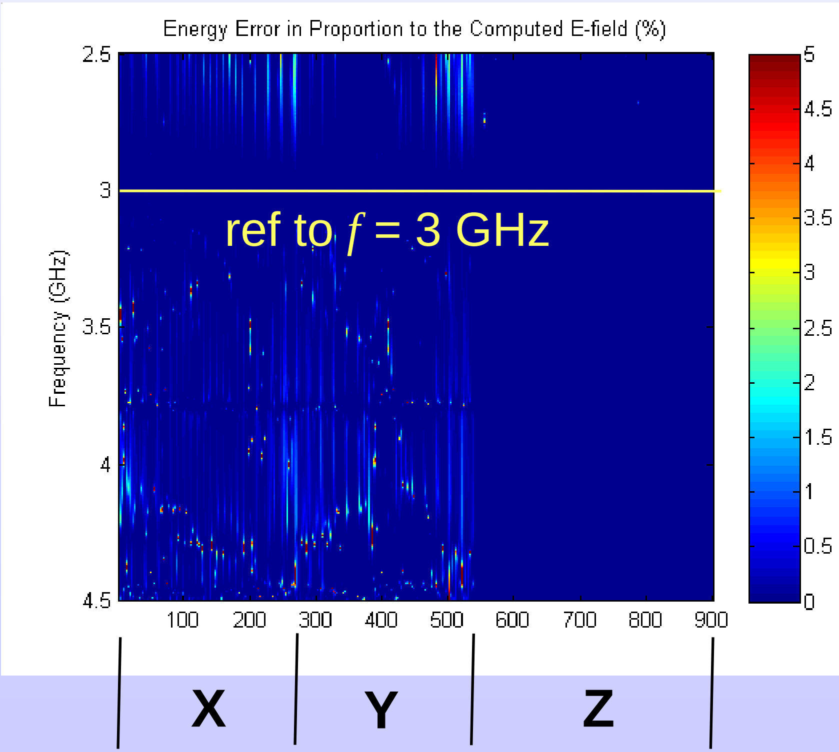


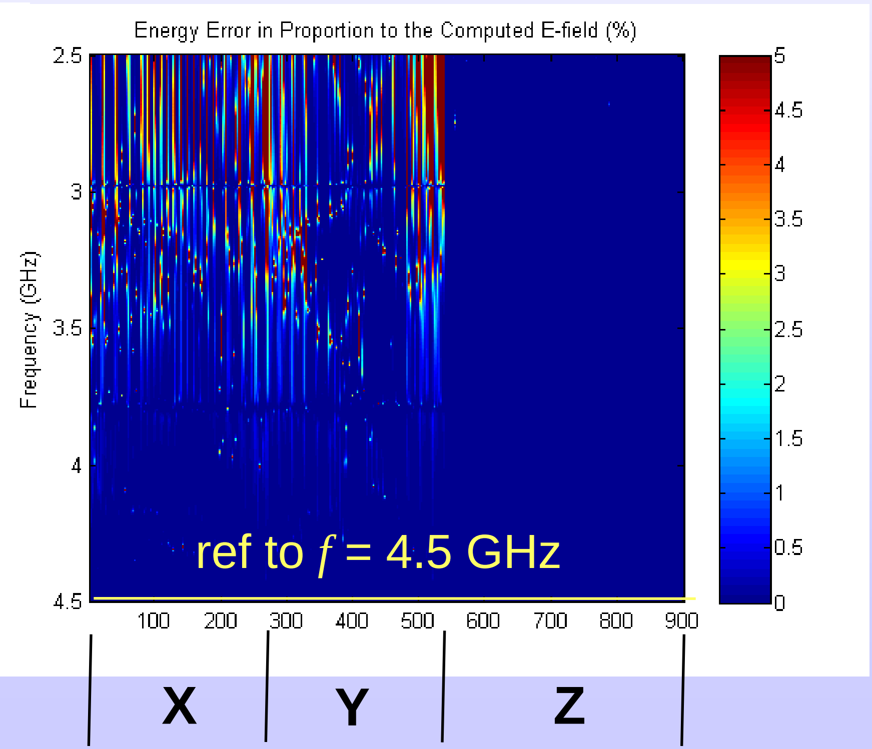
- Approximation exact at center frequency
- Graceful degradation away from center frequency
  - reasonably wide fractional bandwidth
  - appropriate for fast computation

$$\mathbf{error} = \frac{\left|\left(\mathbf{A}^{(2)} + \mathbf{G}^{(1)}\right)\mathbf{E}\,\mathbf{K}^2 + \left(\mathbf{A}^{(1)} + \mathbf{G}^{(2)}\right)\mathbf{E} - \mathbf{F}\right|^2}{\left|\mathbf{E}\right|^2} \times 100\%$$

Wideband Approximant Accuracy^2

- Reasonably robust approximation
  - fractional BW on order of 30%
  - often this limit could be pushed even further





Wideband Eigendecomposition

- Fast inversion of quadratic approximate system
  - setup begins with a specific eigendecomposition

$$\mathbf{X}\mathbf{\Lambda}\mathbf{X}^{-1} = \left\{\mathbf{A}^{(2)}\left(k_0\right)+\mathbf{G}^{(1)}\left(k_0\right)\right\}^{-1}\left\{\mathbf{A}^{(1)}\left(k_0\right)+\mathbf{G}^{(2)}\left(k_0\right)\right\}$$

  - results in a functional eigenvalue form as is typical of similar eigendecompositions

$$\mathbf{E}\left(k\right) \approx \left(\tilde{k}^2\mathbf{I} + \mathbf{X}\mathbf{\Lambda}\mathbf{X}^{-1}\right)^{-1}\left\{\mathbf{A}^{(2)}\left(k_0\right)+\mathbf{G}^{(1)}\left(k_0\right)\right\}^{-1}\mathbf{F}\left(k\right)$$

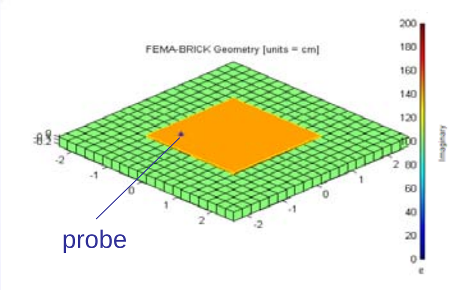
$$= \mathbf{X}\mathbf{\Lambda}_k^{-1}\mathbf{X}^{-1}\left\{\mathbf{A}^{(2)}\left(k_0\right)+\mathbf{G}^{(1)}\left(k_0\right)\right\}^{-1}\mathbf{F}\left(k\right)$$

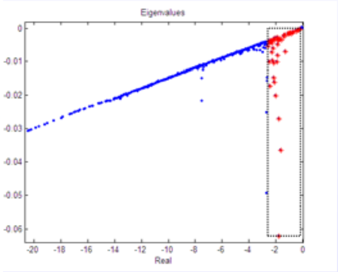
$$\mathbf{\Lambda}_k = \mathrm{diag}\left(\lambda_i + \tilde{k}^2\right)$$

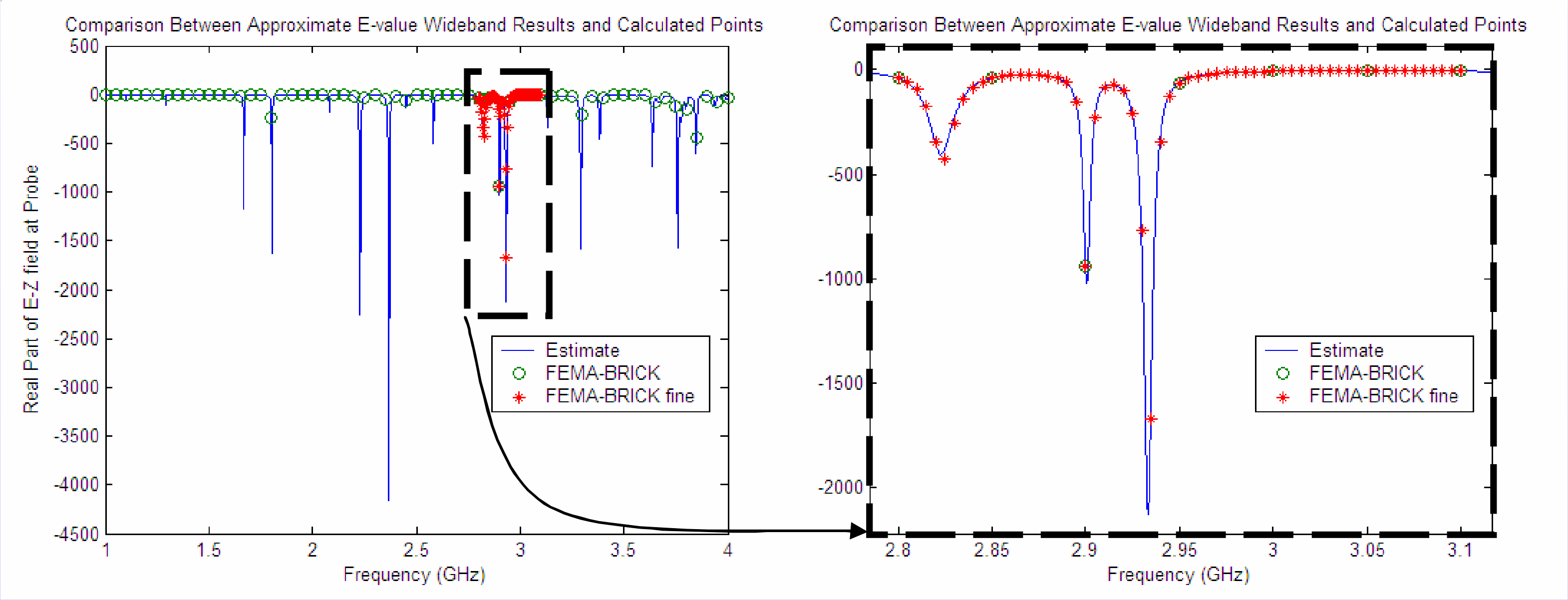
Key functional form

Approximation Accuracy

- Approximation reasonably predictive
  - eigen-term selection
  - excellent accuracy
  - physical meaning...

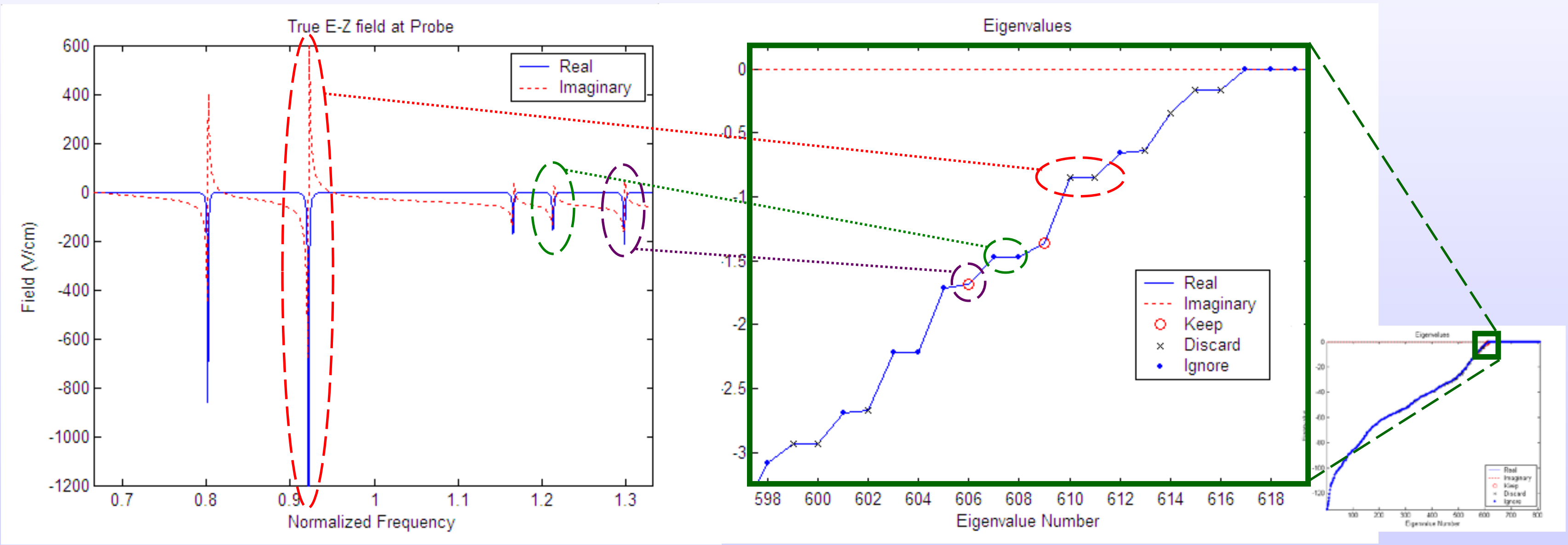






Eigen-mode Correspondence[1]

- Intuitive behavior in frequency location
  - location of resonances easily related to eigenvalues

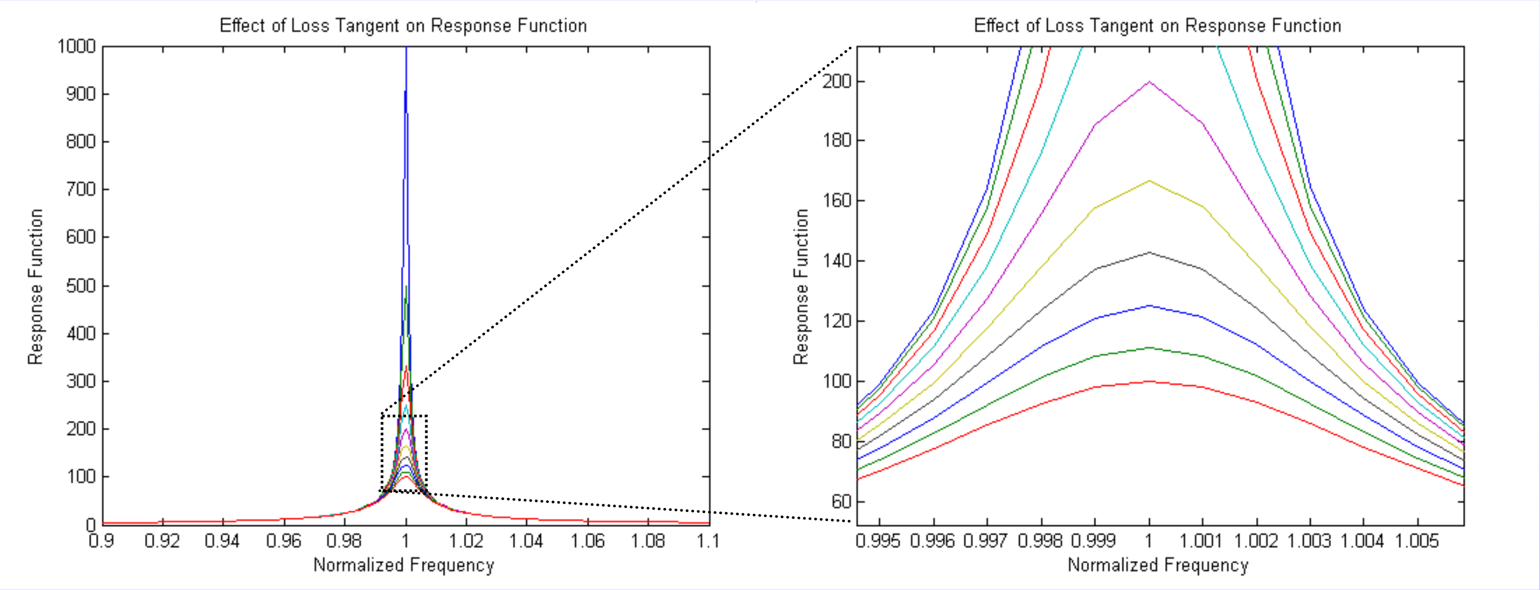


$$\Lambda_k^{-1} = \mathrm{diag}\left(\frac{1}{\lambda_i + \tilde{k}^2}\right) \Rightarrow \tilde{k}_i \approx \sqrt{-\mathrm{Re}\{\lambda_i\}}$$

Movement of location also affects amplitude

Eigen-mode Correspondence[2]

- Intuitive behavior in resonance amplitude
  - resonance amplitudes easily related to eigenvalues

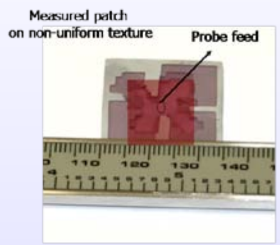


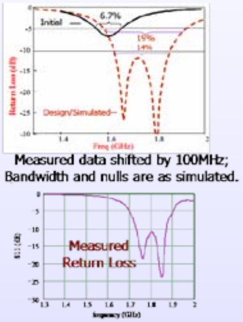
$$\Lambda_k^{-1} = \mathrm{diag}\left(\frac{1}{\lambda_i + \tilde{k}_i^2}\right) \Rightarrow e_{n,obj}\left(\tilde{k}_i\right) \propto \frac{1}{\mathrm{Im}\left\{\lambda_i\right\}}$$

Losses dampen eigen-term contribution ←

Optimization in Wideband

- Broadband designs leverage some ability to assimilate appropriate resonances in an organized fashion
  - must develop eigen-space desired result
    - determine which eigen-terms to use
    - “move” these terms in frequency-space
    - account for amplitude/location relation





- G. Kiziltas, D. Psychoudakis, J.L. Volakis and N. Kikuchi *APT*, Vol. 51, Oct. 2003, pp. 2732-2743.
- G. Kiziltas, Y. Koh, J.L. Volakis, N. Kikuchi and J. Halloran, 2003 IEEE APS Symposium digest, pp. 485-488, Vol. 1, Columbus, OH

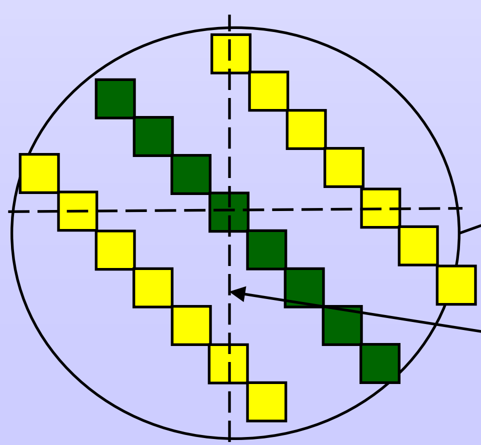
- Design success hinges on the ability to associate desired eigen-mode response with material texture
  - must work efficiently with only control matrix, $\mathbf{A}\left(\boldsymbol{\varepsilon}^{(2)}\right)$
  - manage updates via a weighting scheme
  - determine a way to minimize number of iterations necessary to achieve convergence toward the objective

Relating Eigenstructure to Material Texture

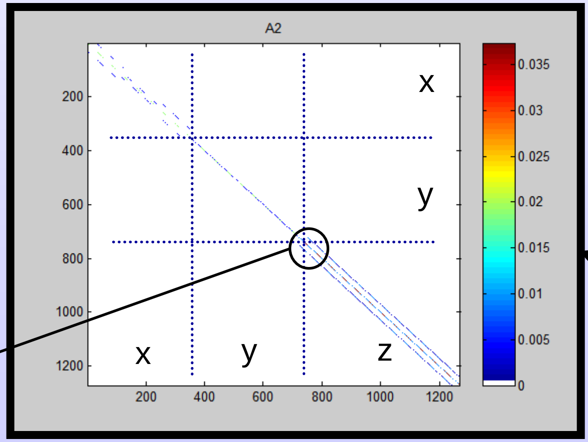
- Exploit symmetric matrix structure
  - decompose control matrix via LDL

$$\mathbf{A}^{(2)}(\boldsymbol{\varepsilon}) = \mathbf{L}\mathbf{D}\mathbf{L}^{T} \Rightarrow \mathbf{D} = \mathbf{D}(\boldsymbol{\varepsilon}) = \mathrm{diag}\left[\mathbf{d}(\boldsymbol{\varepsilon})\right]$$

Lower triangular (with unity diagonal) and predominantly a function of brick geometry → matrix structure



Elements associated with a particular dielectric brick

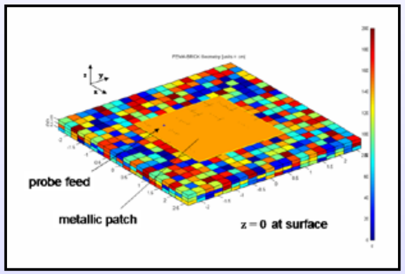


$\mathbf{A}^{(2)}(\boldsymbol{\varepsilon})$

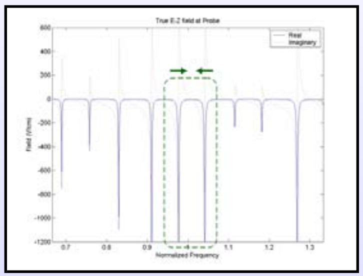
"Control" Matrix

Weighted Update

- Key to isolate material contributions to a diagonal
  - establishes a relationship between a weighting *desired* in eigen-space and the *required* textured weighting in material-space



$$\mathbf{W}_D \approx f\left(\mathbf{W}_\Lambda^{-1}\right)$$

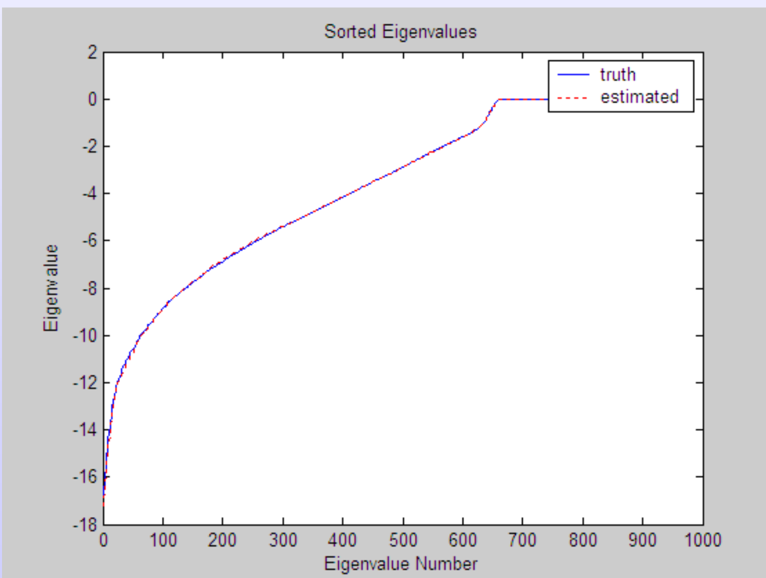


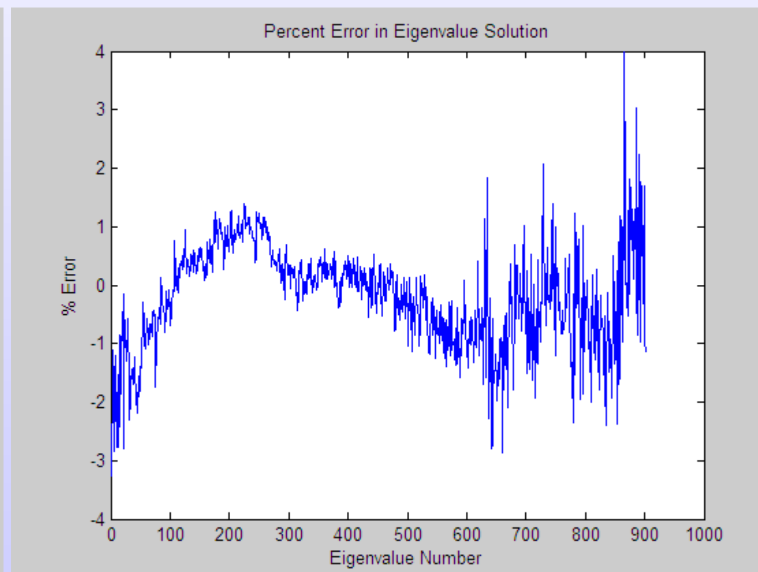
- Efficiencies in approximation dealt with by amplifying weights appropriately
  - emulates multiple iterations at the same proposed weighting

$$\mathbf{W}_D \rightarrow \mathbf{W}_D^{\alpha}$$

Test of LDL Decomposition

- Analyze effects of random material perturbations
  - compute eigen-terms assuming $(\mathbf{L}+\Delta\mathbf{L}) \rightarrow \mathbf{L}$
  - compare difference in eigenvalue computations
    - "estimated" results arise from assumption that **L** does not vary

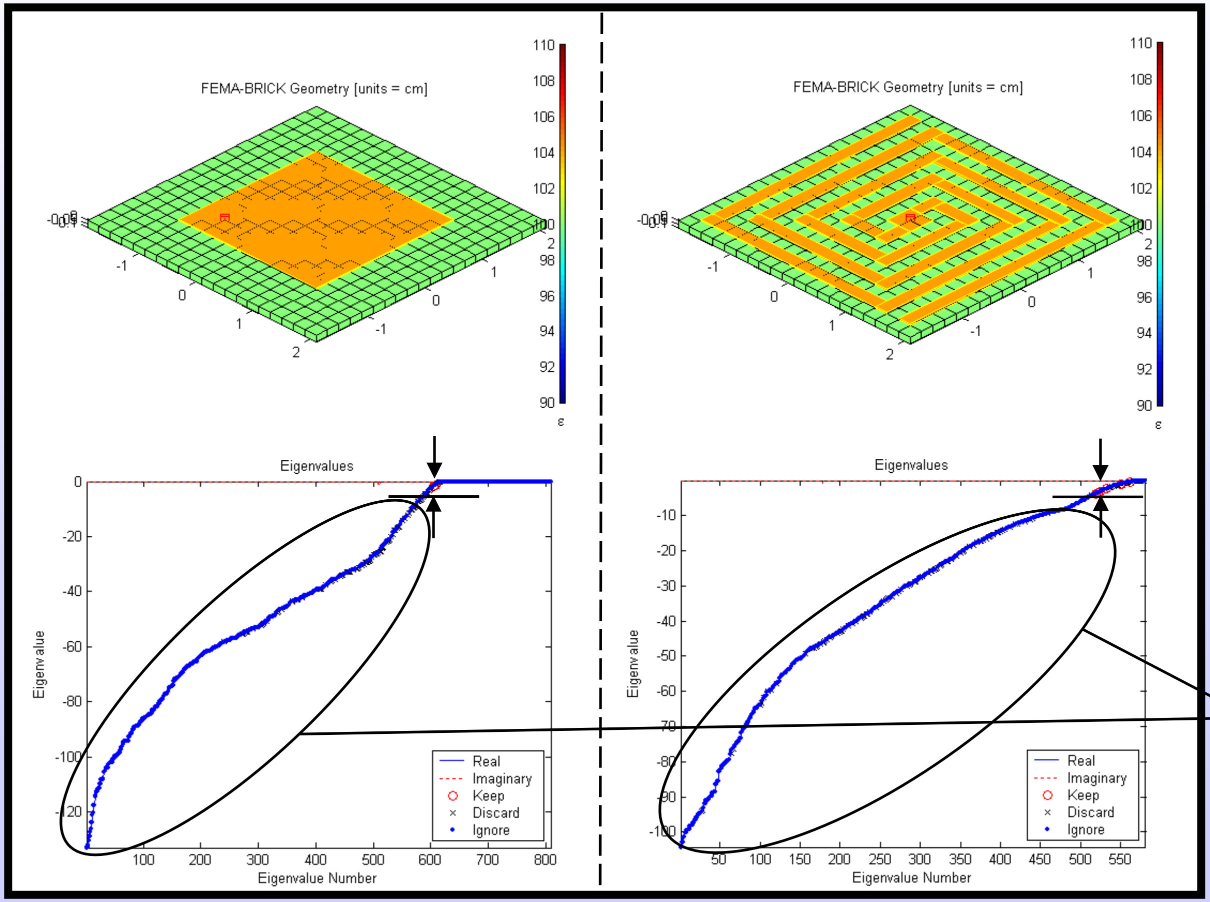




Results above for a "severe" random weighting over [0.5,1.5]

Geometry and Eigenvalues

- Eigenvalues depend on both geometry and material



Narrow region within which eigenvalues may be reasonably used; strong desire for more terms to be clustered near

$$\mathrm{Re}\left\{\lambda_i\right\} \approx -1$$

Many terms are extraneous to optimization

Overview

- Introduction of Research Focus
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- Linear System Development
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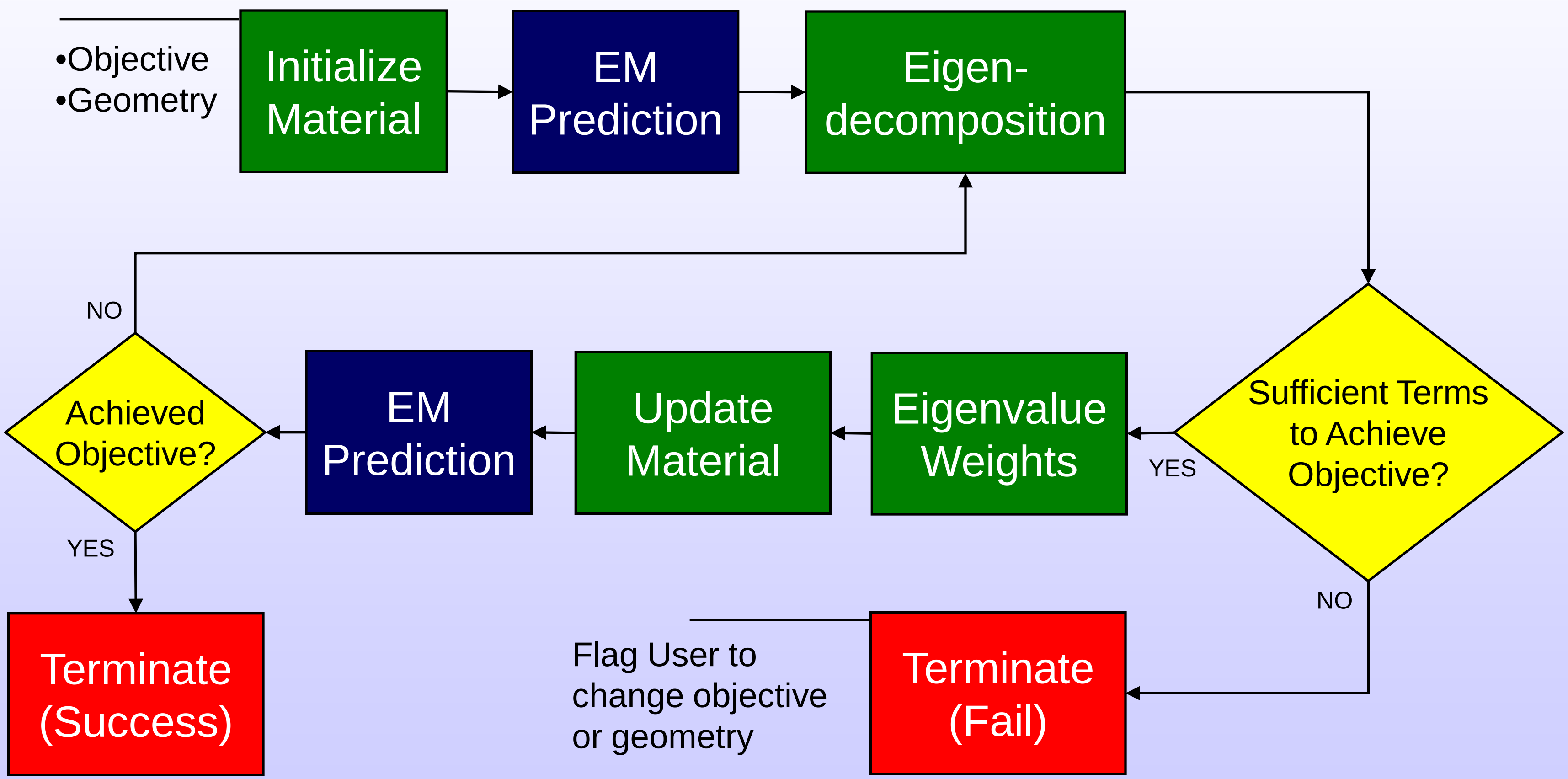
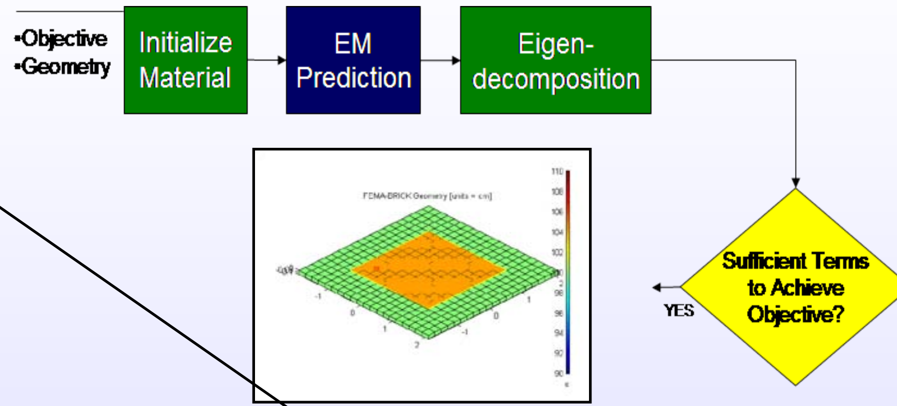
    - decomposition
    - narrowband optimizations
  - wideband approximation and eigendecomposition
  - relating eigenvalues to material texture
- Optimization Examples
  - patch and square spiral geometries
- Conclusions and Future Work

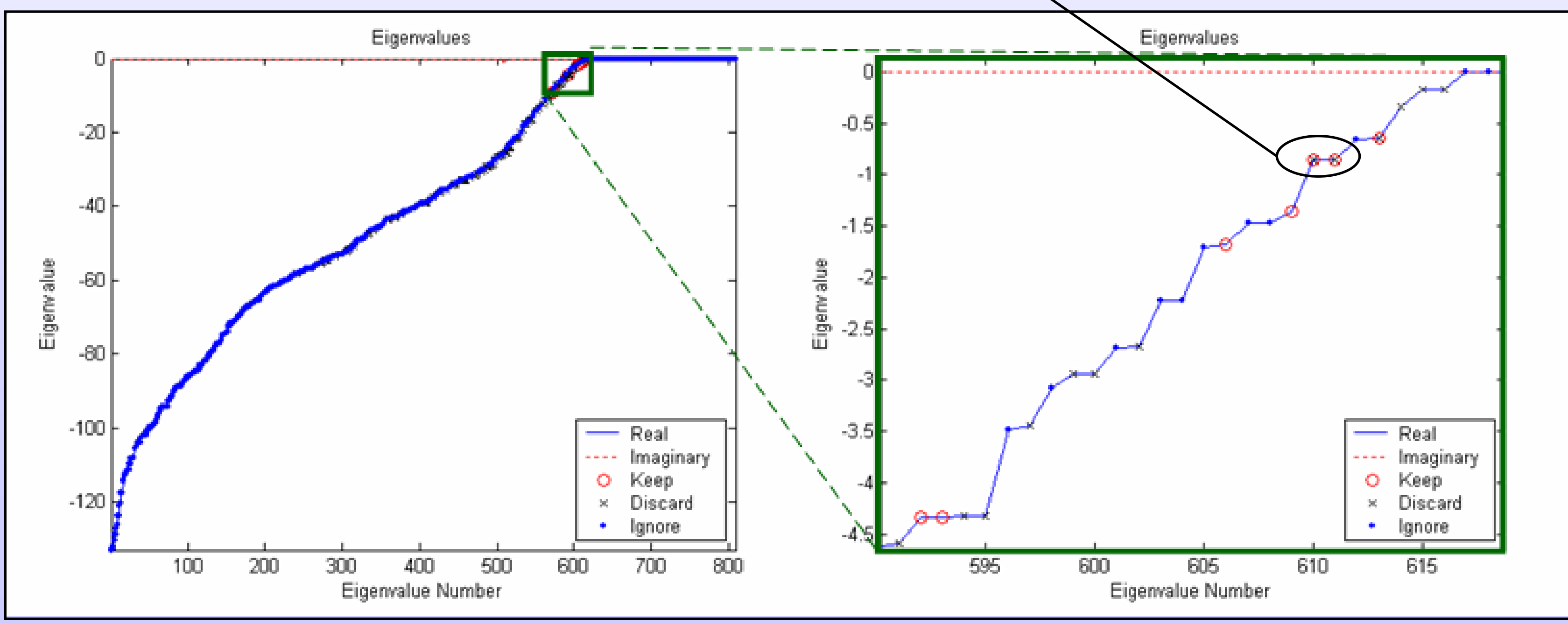
Basic Algorithm



Offset Feed Patch Antenna

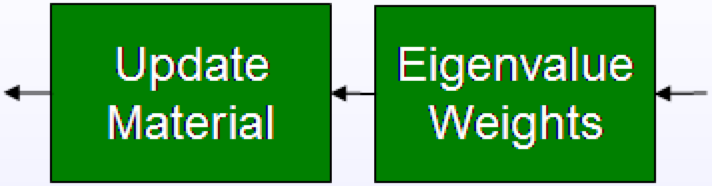
- Introduce basic geometry
  - choose eigenvalues to adjust as two identical eigenvalues
  - “twisted apart” through differential weighting

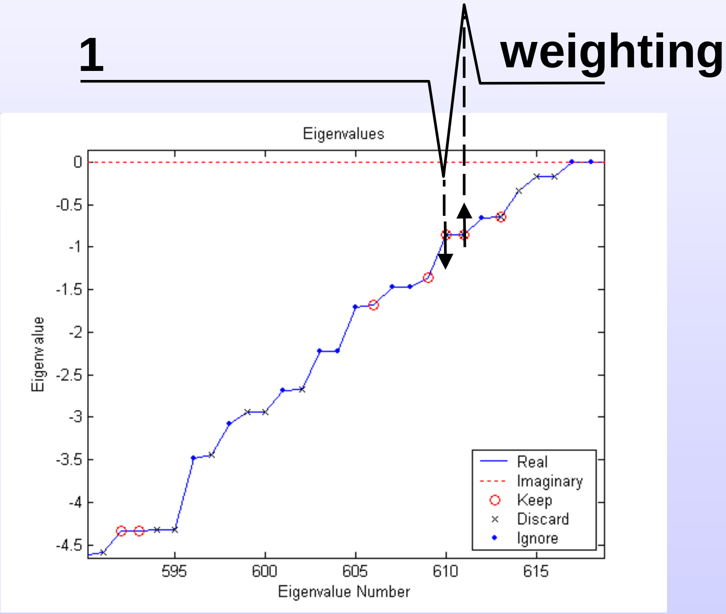


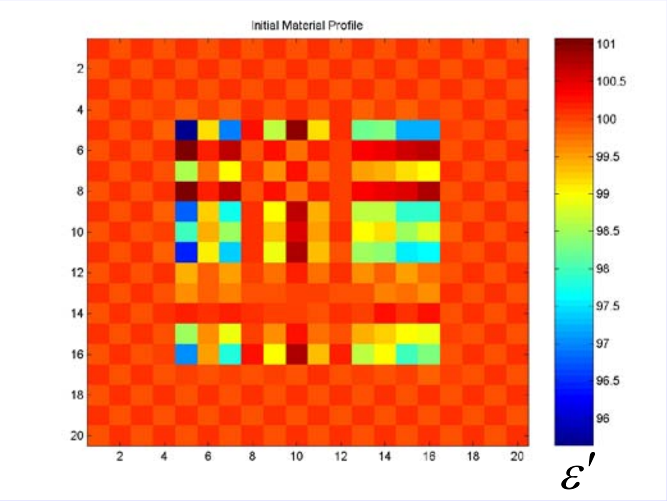


Eigenvalue Weight Translation

- Minimal perturbation
  - initialized at $\varepsilon' = 100$



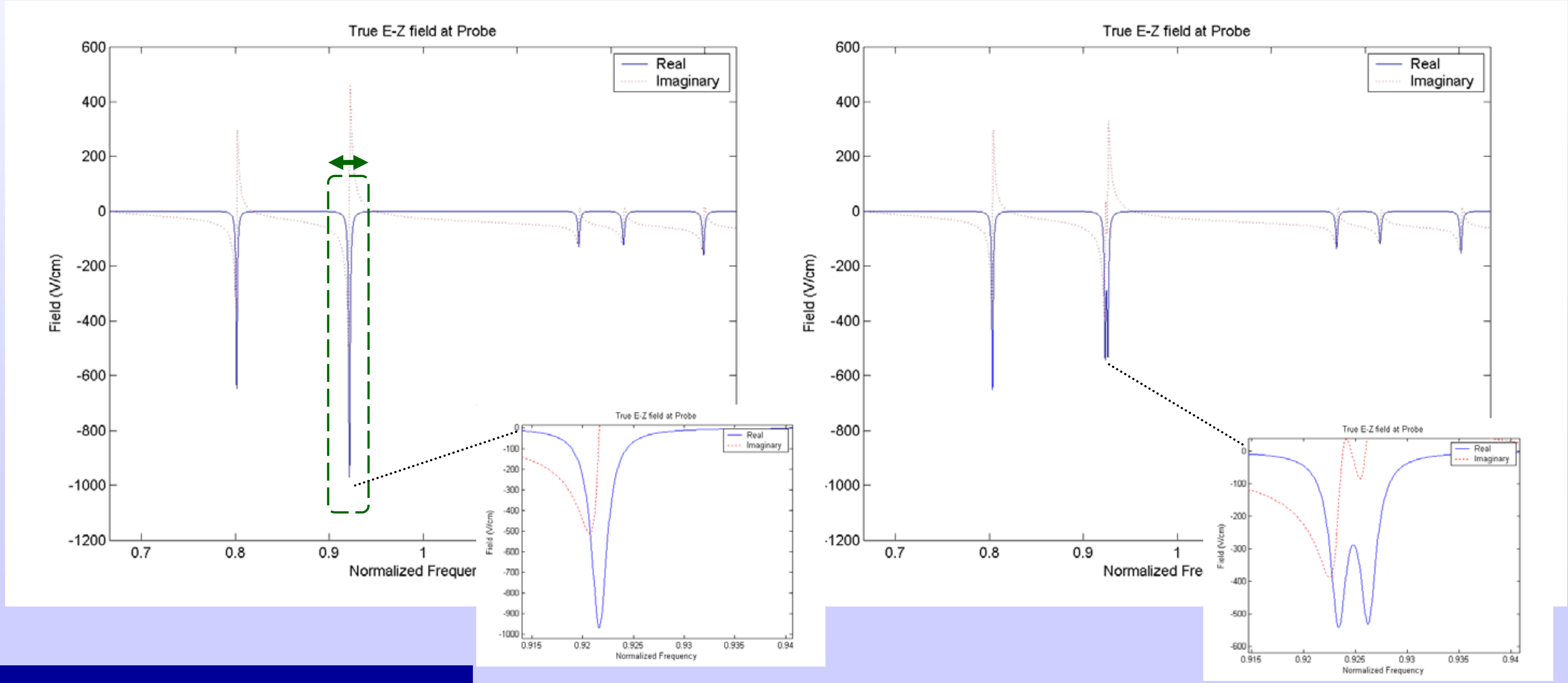




Texture contains small “channels” and “posts”

Eigen-mode Separation

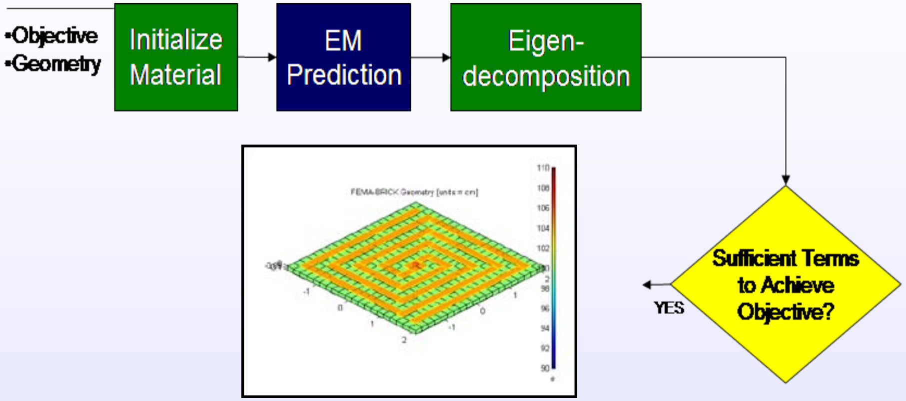
- Case utilized no iteration (i.e., direct)
  - other eigen-modes relatively unaffected

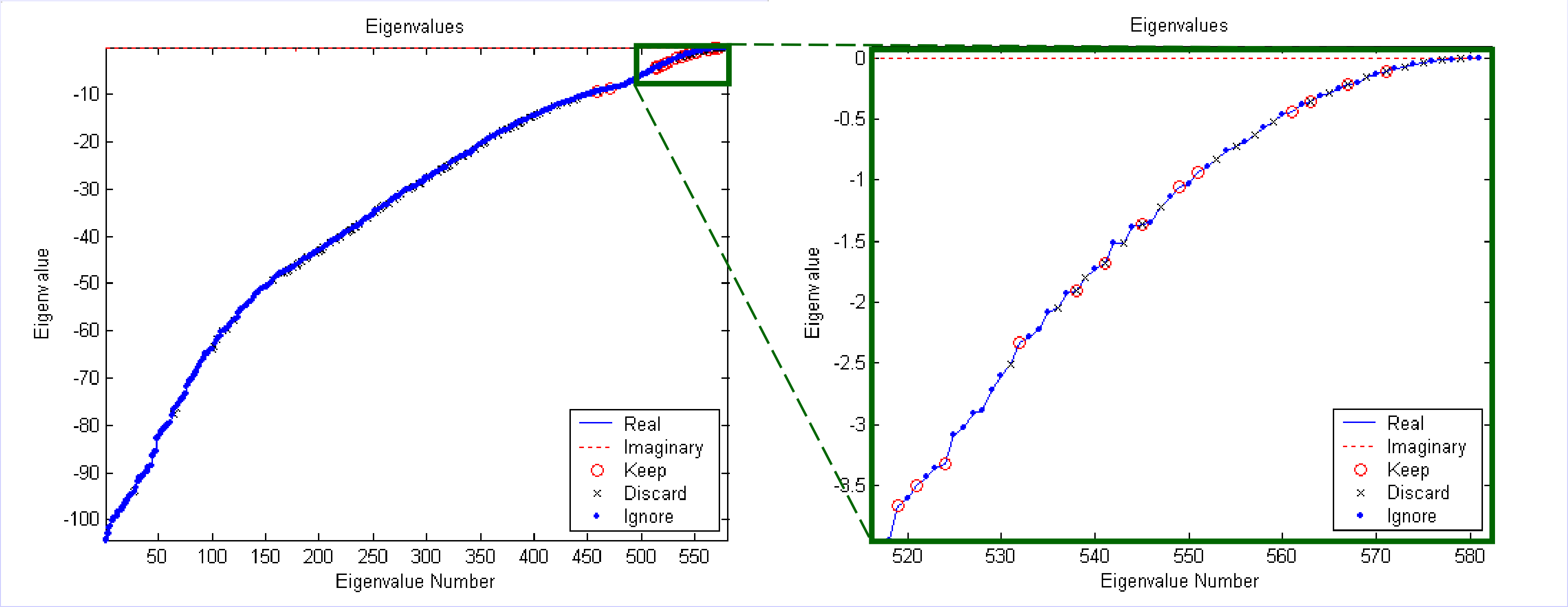


FEMA-BRICK Movie

Square-Spiral Antenna

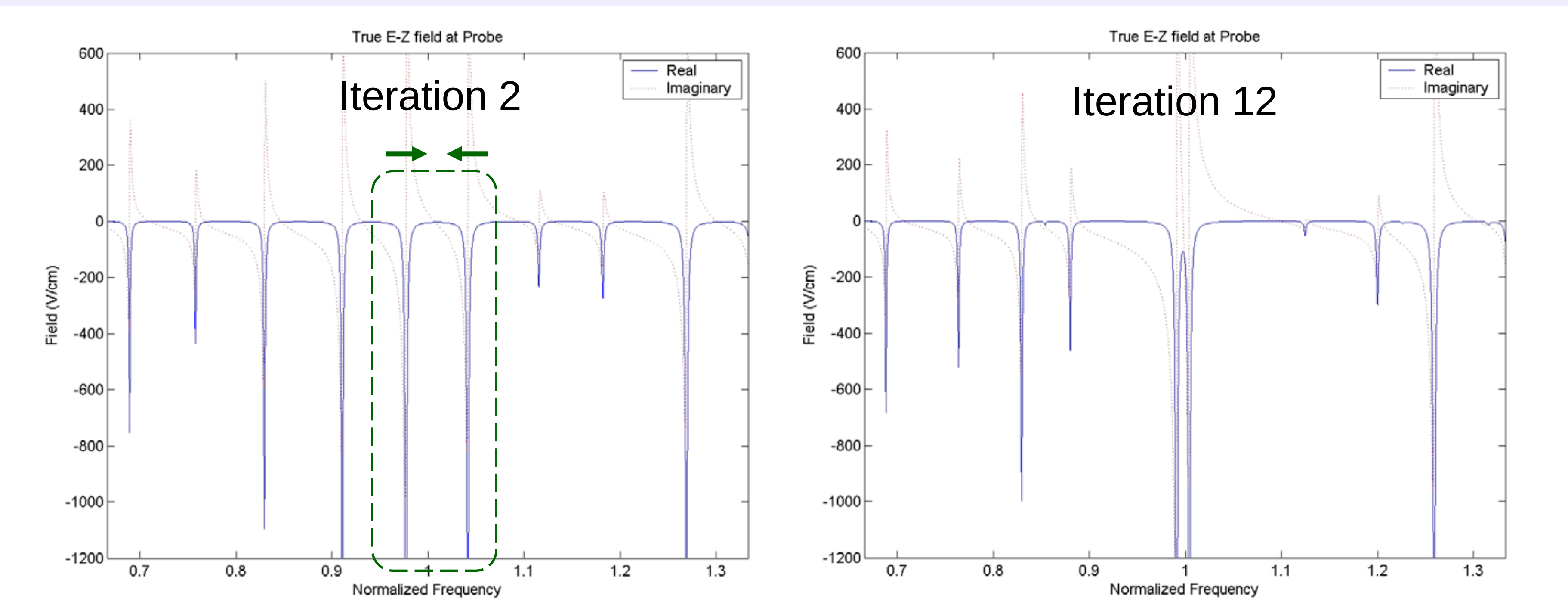
- Introduce basic geometry
  - choose eigenvalues to adjust as two separate eigenvalues
  - “drawn together” through weighting toward a central objective





Squeezing Eigen-modes Together

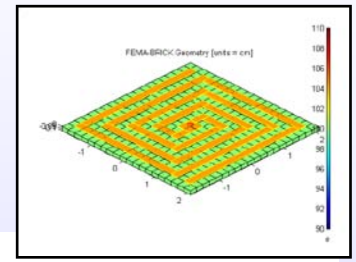
- First iteration shifts desired modes to center frequency via a constant material scaling
  - "squeezing" process managed in reasonable steps, but could be hastened with a more aggressive choice of α for $\mathbf{W}_D \rightarrow \mathbf{W}_D^{\alpha}$



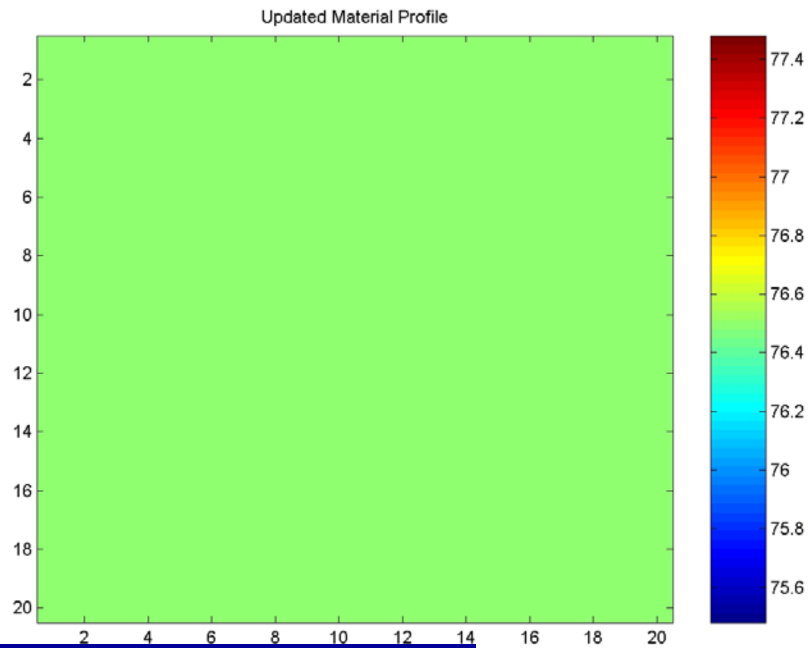
FEMA-BRICK Movie

Material Texturing for Square-Spiral

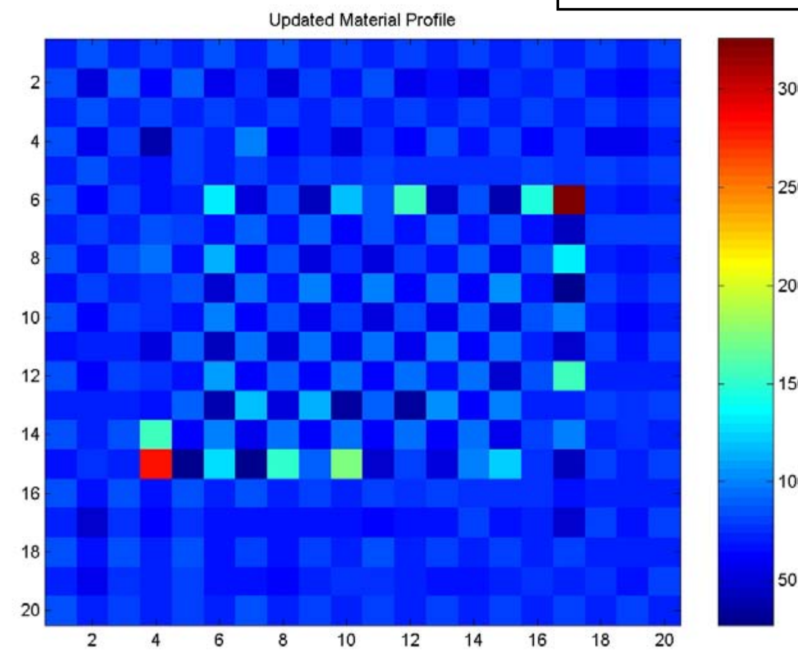
- Formation of high-dielectric "posts" in specified regions
  - directly under portion of metal spiral element
  - produces a clear mode disturbance



Iteration 2



Iteration 12



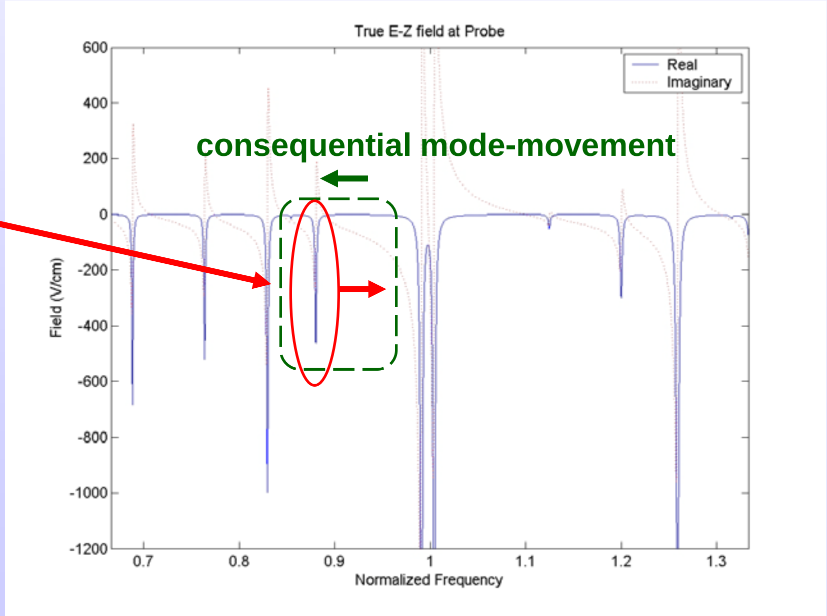
FEMA-BR

MOVIE PLANNED/NEEDED

“Capturing” of Additional Modes

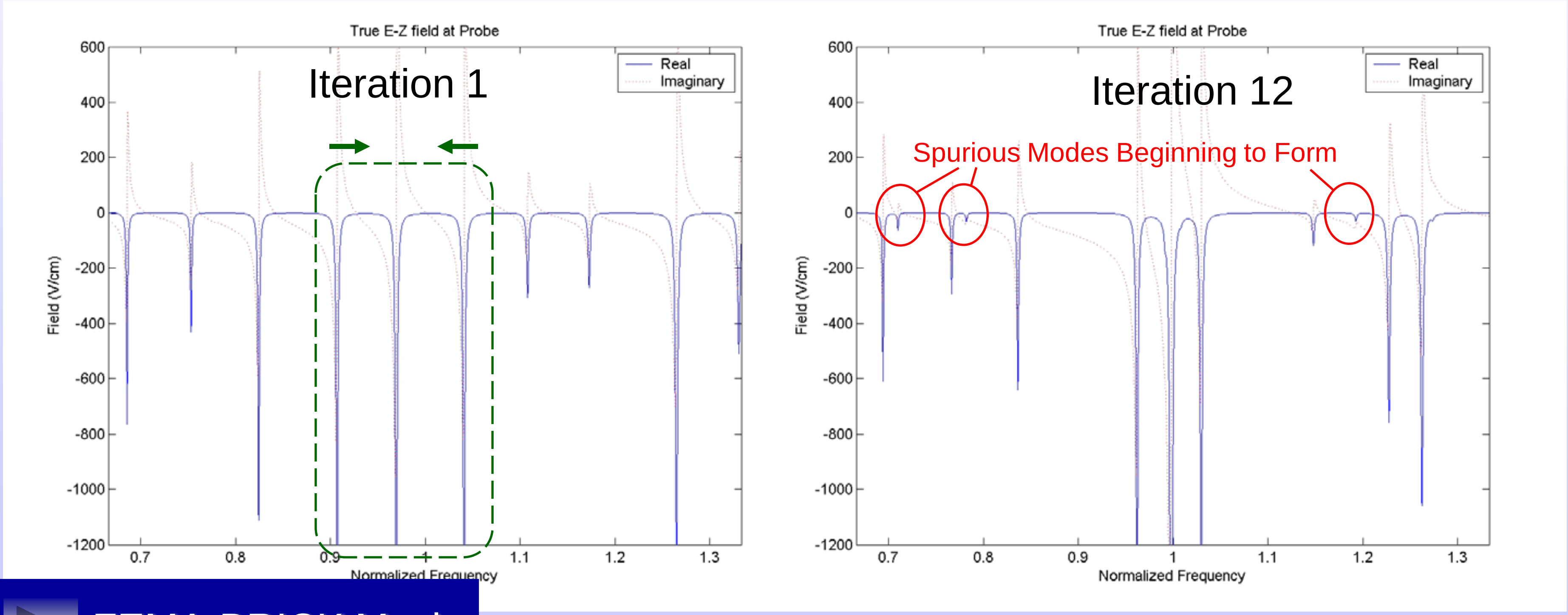
- Generally, all modes are disturbed as a result of texturing
  - as texturing increases away from initial conditions
  - modes that are not “targeted” for optimization are allowed to freely float
    - this minimizes the required amount of material texturing

A clear test of the validity of the material / eigen –weighting formulation is to force this additional mode to move inward toward the center frequency – did not naturally tend this way as a result of the first optimization.



Squeezing More Eigen-modes Together

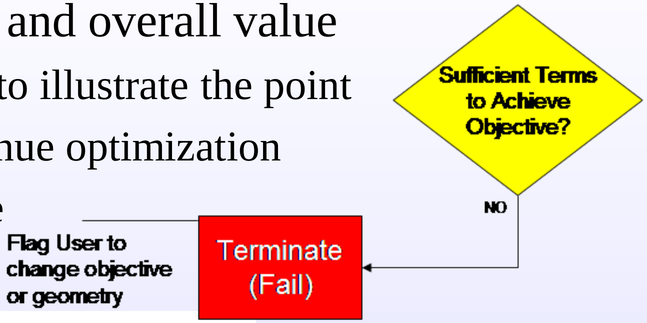
- First iteration shifts desired modes to center frequency via a constant material scaling
  - "squeezing" process managed in reasonable steps to understand a critical feature of "overreaching" in the design

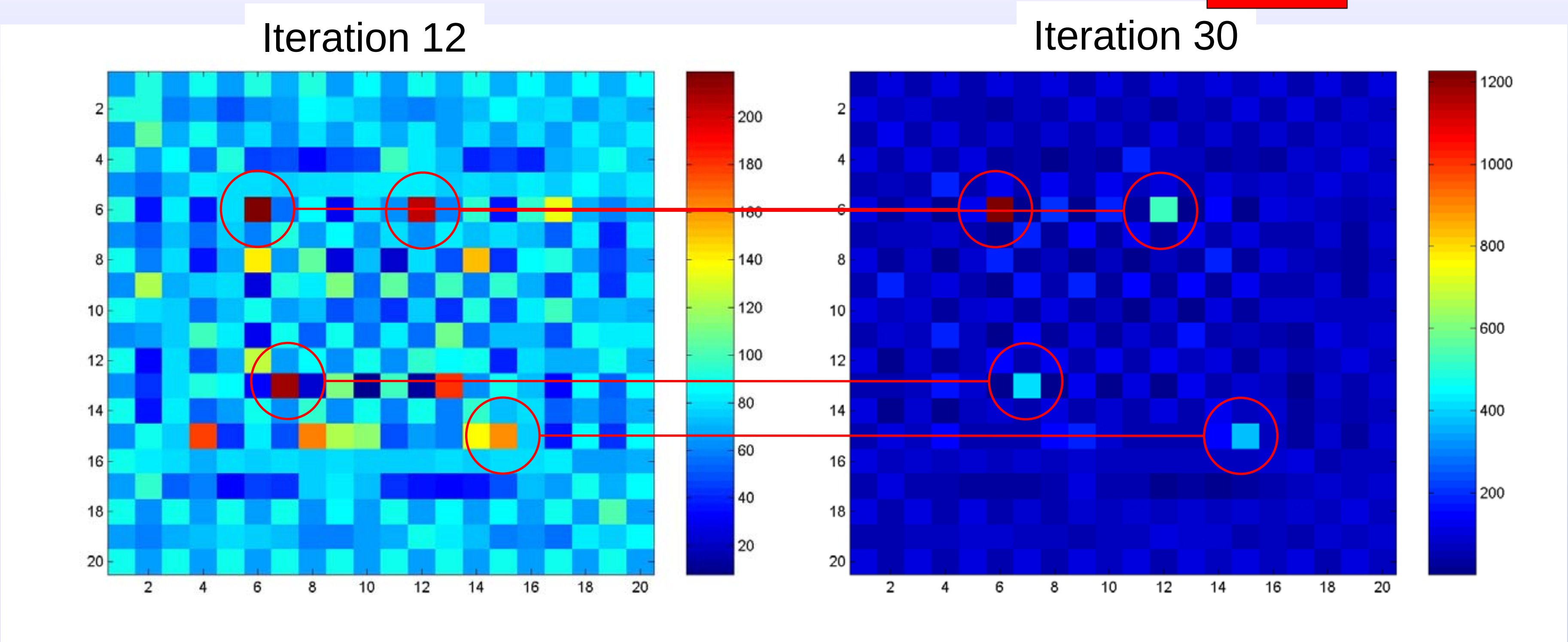


FEMA-BRICK Movie

Controlling Spurious Modes

- Must maintain an upper bound on dielectric contrast and overall value
  - previous example was allowed to continue weighting to illustrate the point
  - certain bricks/regions are consistently chosen to continue optimization
  - certain modes may not allow user to achieve objective





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Conclusions

- The electromagnetic optimization problem is closely coupled to the electromagnetic inversion problem
  - an operable electromagnetic (eigen-mode) subspace must be found
    - here determined for FE-BI
    - a (near) instantaneous wideband system solution arises
    - eigen-mode correspondence in frequency and amplitude enables physical insight for the optimization solution
- Mapping eigen-mode movement to physical material or geometry is the key requirement
  - modification of eigenvalues in the system subspace was shown to lead to textured material solutions
  - functionality of eigenvalues to include combined frequency-dependence and material-dependence was demonstrated

Future Work

- Optimization of geometry
  - relating noted eigen-mode behavior to geometric constraints or parameterization
- Constrained optimization of material
  - working within the bounds of material constraints to achieve optimal solutions that minimally disturb the initial material distribution
- Design of exotic materials
  - a great match between materials science disciplines and miniaturized antennas is already forming in industry
  - such optimization results can more efficiently drive key areas of advanced material prototypes
- Management of large systems
  - it may be possible to eliminate a large portion of the eigendecomposition computation requirements (few relevant eigenvalues)
  - direct computation of eigensystem may be possible
- Application of equivalent techniques to other electromagnetic problems
  - FE-BI is a somewhat general solution approach – seeking similar decomposition approaches for other prediction techniques (e.g., MoM) has already been done
  - apply similar decompositions to other interesting optimization problems
    - best suited to "parametrically challenging" situations

Acknowledgements

- Advisors
  - Profs Yagle and Volakis
- RadLab Metamaterials project team and ElectroScience Laboratories at OSU
  - Prof Volakis, Gullu Kiziltas, Dimitrius Psychoudakis, Students at OSU who commented on results last Fall (need names)
- Colleagues at General Dynamics AIS
  - Chris, Martin, Ivan, Tom, Dan, Dave and many others for moral support!
- General Dynamics
  - underwriting and supporting the entire effort

MY FAMILY!