

Modeling and Optimizing Photonic Bandgap (PBG) Structures

No Boundaries workshop

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Synopsis I

- Statement of Problem and Possible Applications
 - PBG Definition and Types
 - Applications
- Pertinent HFSS/Optimetrics Features
- Modeling Methodologies
 - Direct Transmission Method
 - ◆ Model Setup
 - ◆ Results Obtained
 - ◆ Example Project and Results
Square-rod dielectric lattice
 - Dispersion Diagram Method
 - ◆ Model Setup - Nominal
 - ◆ Model Setup - Optimetrics™
 - ◆ Example Projects, with Results
Square-pad PBG Surface
UC-PBG Surface
Square-rod dielectric lattice

Synopsis II

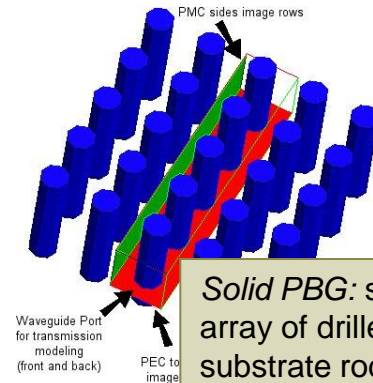
- Reflection-Phase Analysis Method
 - ◆ Model Setup - Nominal
 - ◆ Model Setup - Optimetrics™
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Hexagonal pad PBG surface
- Optimization Analysis with PBGs
 - General Considerations and Suggestions
 - Case Study 1: Direct Transmission Method
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 - ◆ Generating an overlapping Bluetooth Hexagonal pad PBG Surface
- References

What is a PBG?

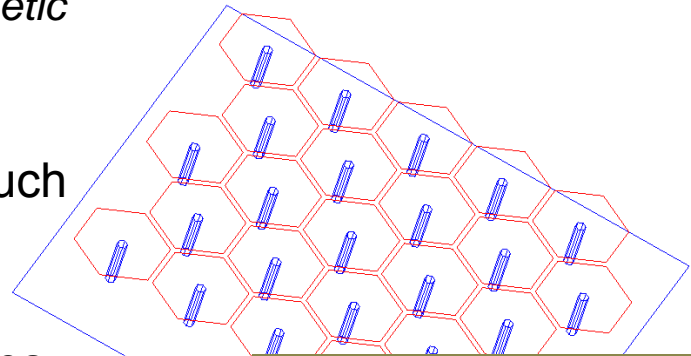
- ▶ A Photonic Bandgap (PBG) structure, or electromagnetic crystal, is a repeating construction which exhibits useful band rejection behavior for microwave or millimeter wave engineering.
 - ▶ Behavior is analogous to the characteristics of atomic crystal structures in Optical and Solid-State physics, and therefore generally discussed using similar terms.
- ▶ PBGs may occur in bulk form (substrates) or surface form (circuits with or without ground planes)
- ▶ Characteristics of useful PBG constructs include:
 - ▶ Inability to carry a propagating electromagnetic wave within its forbidden frequency band (bulk and surface)
 - ▶ DC conductance often maintained (surfaces w/ ground planes)
 - ▶ Reflects incident waves in-phase rather than imaged (surfaces)

What is a PBG?

- ▶ A Photonic Bandgap (PBG) structure is a repeating construction which exhibits useful behavior for microwave or millimeter wave engineering.
 - ◆ Behavior is analogous to the characteristics of atomic crystal structures in Solid-State physics, and therefore discussed using similar terms. Also sometimes called *electromagnetic crystals*.
- ▶ Physical Characteristics: repeating features ('array' symmetry), often much smaller than wavelength of interest
- ▶ Electrical Characteristics: Does not carry EM waves at certain frequencies (the *forbidden frequency range* or *band gap*).



Solid PBG: substrate with array of drilled holes, or substrate rods in air



Surface PBG: array of repeating circuit elements, with or without vias and ground layer. Sometimes also called *metallo-dielectric PBGs*.

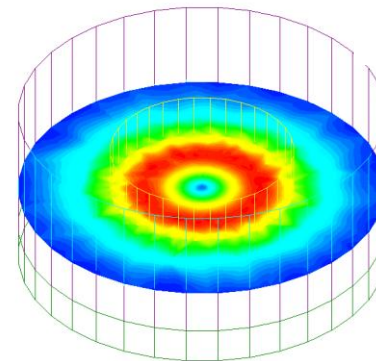
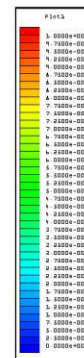
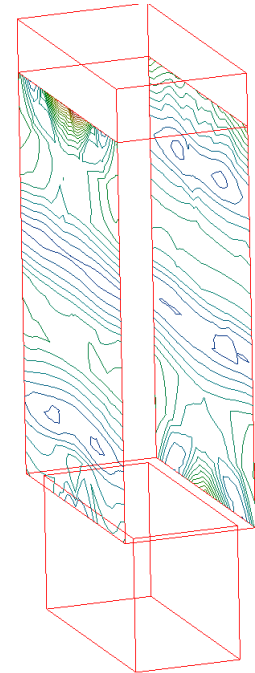
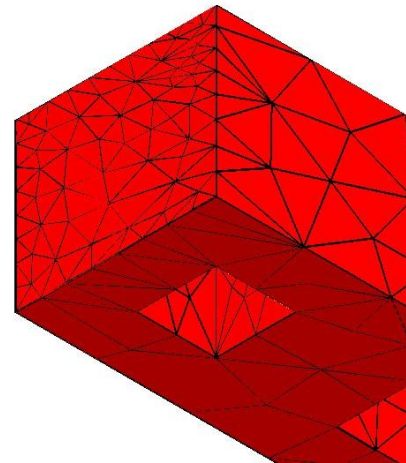
Potential Applications of PBGs

- Array design applications could include:
 - Novel TEM Mode waveguides for feed structures (Reference [A])
 - Reduced-loss antenna substrate materials (Reference [B])
 - Dielectric-filled waveguide feeds with built-in band rejection filtering
 - Non-imaging ground planes which improve element performance (References [D], [E])

NOTE: Included references are not offered as the seminal or original works discussing each application, but contain the specific designs used as examples for this presentation.

HFSS Features Pertinent to PBG Analysis

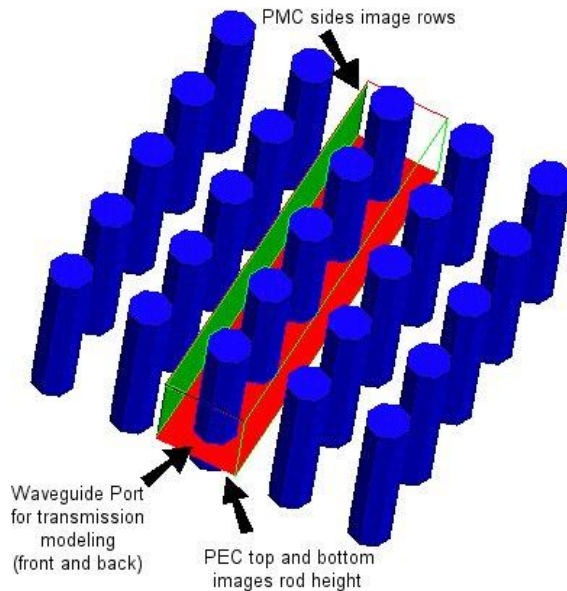
- ▶ Full-featured FEA Solver
 - ◆ Robust Meshing, Convergence
 - ◆ ALPS Fast-Frequency Sweep
- ▶ Linked Boundary Conditions
 - ◆ Unit-cell modeling of infinitely repeating structure
 - ◆ Unlimited master/slave wall pairs and orientations
- ▶ Eigenmode Solver
 - ◆ Direct eigenmode extraction without excitation
- ▶ PML automation via macros
 - ◆ Permits “open” termination for eigenmode solutions
- ▶ Field Calculator
 - ◆ Complex, algebraic and calculus operations on **any** output field quantity
- ▶ Optimetrics™ Interface for parametric variable sweeps



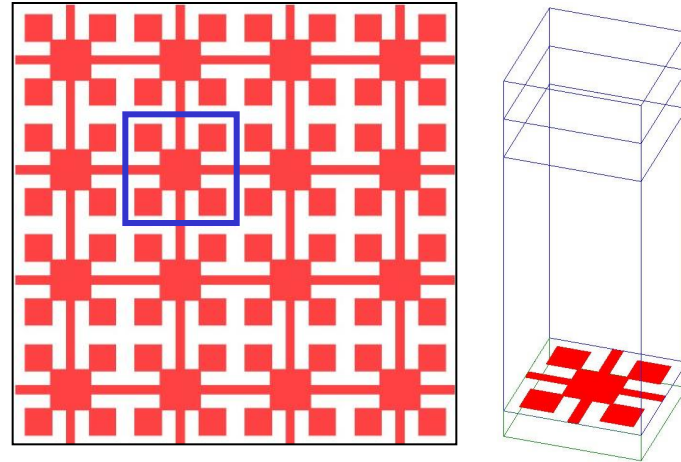
PBG Modeling Methodologies in HFSS

- ▶ Direct-Transmission Method: (HFSS)
 - ▶ “Waveguide Simulation” approach with finite number of periods
 - ▶ Suitable for 3D PBGs (substrates)
 - ▶ Transmission obtained directly from S-parameters
- ▶ Dispersion Diagram Method (HFSS+Optimetrics™)
 - ▶ Optimetrics-managed Eigensolution sweep with infinite array unit cell
 - ▶ Suitable for surface PBG circuitry as well as substrates
 - ▶ Dispersion diagram plotted from unified HFSS results
- ▶ Reflection-Phase Analysis Method (HFSS+Optimetrics™)
 - ▶ Optimetrics-managed incident wave frequency sweep with post-processor calculations, on infinite array unit cell
 - ▶ Suitable for surface PBG circuitry as well as substrates
 - ▶ Reflection-phase plotted from unified HFSS results

Basic PBG Modeling Methodologies in HFSS



Waveguide Simulator Approach: Uses HFSS only, provides only transmission vs. frequency data. Valid only for some symmetry cases and for finite periods in propagation direction. This basic approach is possible in other FEA/FDTD packages



Unit Cell Approaches (2 types): Uses HFSS and Optimetrics™ both. Applicable for all symmetry cases and infinite arrays.

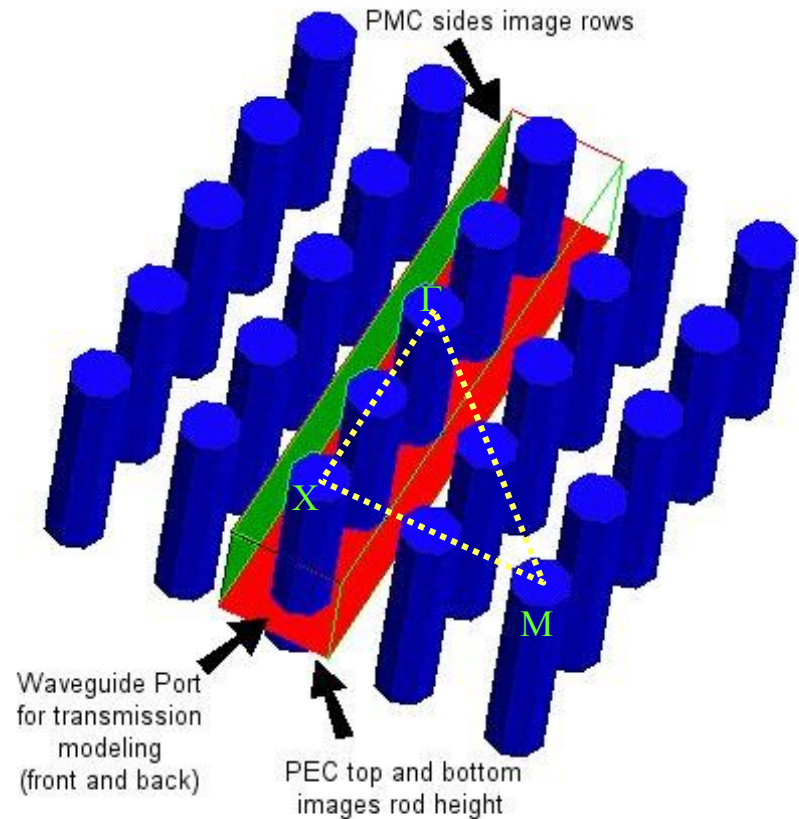
Type 1: Dispersion Method solves Eigenmode problem for a variety of boundary conditions, provides *dispersion diagram* data identifying band gap.

Type 2: Reflection-Phase Method solves reflected phase vs. frequency of an Optimetrics-managed sweep which also identifies band gap.

ONLY **ANSOFT** HFSS has the right feature set to perform these solution techniques

Direct-Transmission Method: Model Setup

- ▶ Image substrate/structure *height* with Perfect E faces
- ▶ Image repeated rows in *width* with Perfect H faces
- ▶ Excite model with ports on remaining 2 faces of rectangular modeled volume
 - ▶ Boundary conditions force ideal “parallel plate” or free-space plane wave excitation
 - ▶ Only a finite PBG length can be modeled!
- ▶ Choose appropriate “row” for model for desired transmission direction (dashed lines)

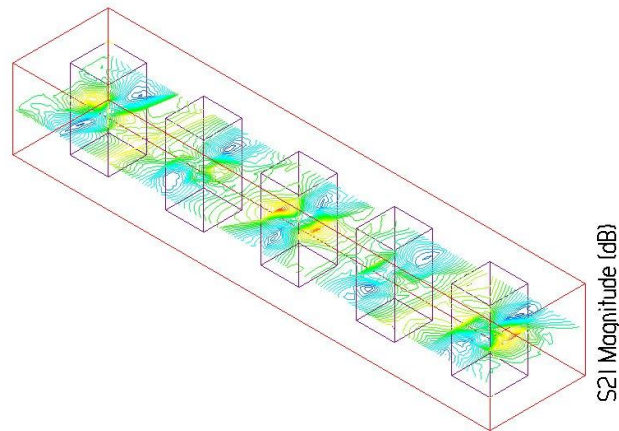


Direct-Transmission Method: Results Obtained

- ▶ View S-Matrix Data to obtain PBG “forbidden band”
 - ▶ Transmission through the PBG crystal is directly modeled as S_{21}
 - ▶ Frequency response obtainable using an ALPS fast sweep or discrete sweep
- ▶ Considerations regarding Data Results:
 - ▶ Port excitation is potentially very close to discontinuity in guide
 - ▶ Transmission parameters provided accurate only for direction of propagation modeled
 - ▶ Propagation in other (e.g. diagonal to structure) direction must be modeled with separate geometry
 - ▶ Transmission parameters provided accurate only for number of periods in direction of propagation modeled
 - ▶ Additional periods sharpen the response
 - ▶ Conceivably circuit-tool cascading of S-parameter black boxes could supplement HFSS results

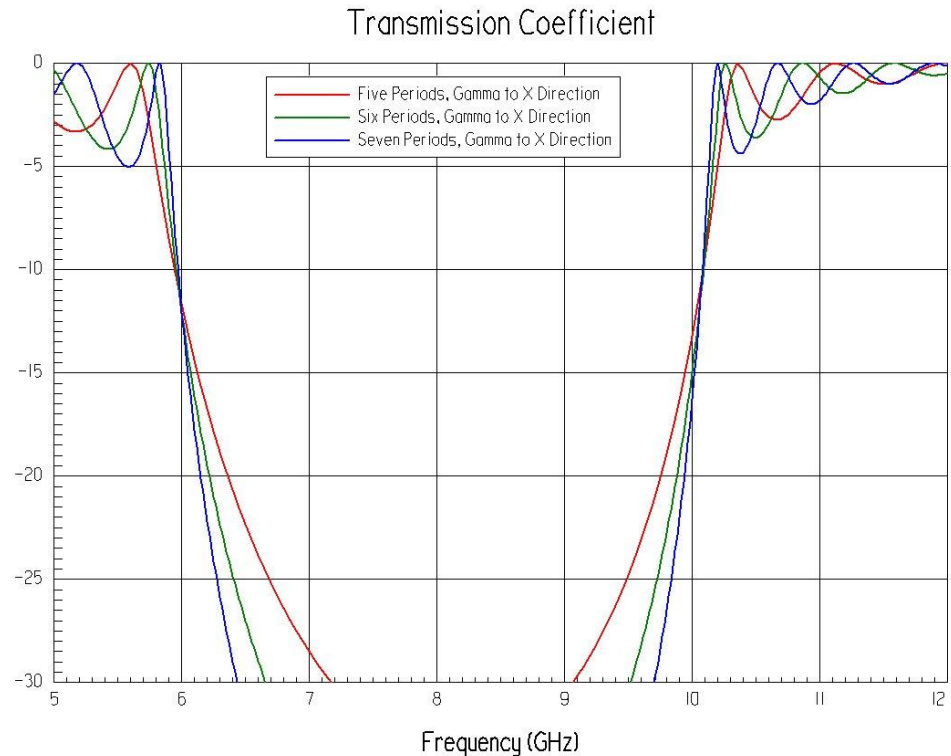
Direct Transmission Method

Example: Dielectric Rod PBG Substrate



Regular Array of Square Dielectric Rods in Air,
Design obtained from Reference [B]

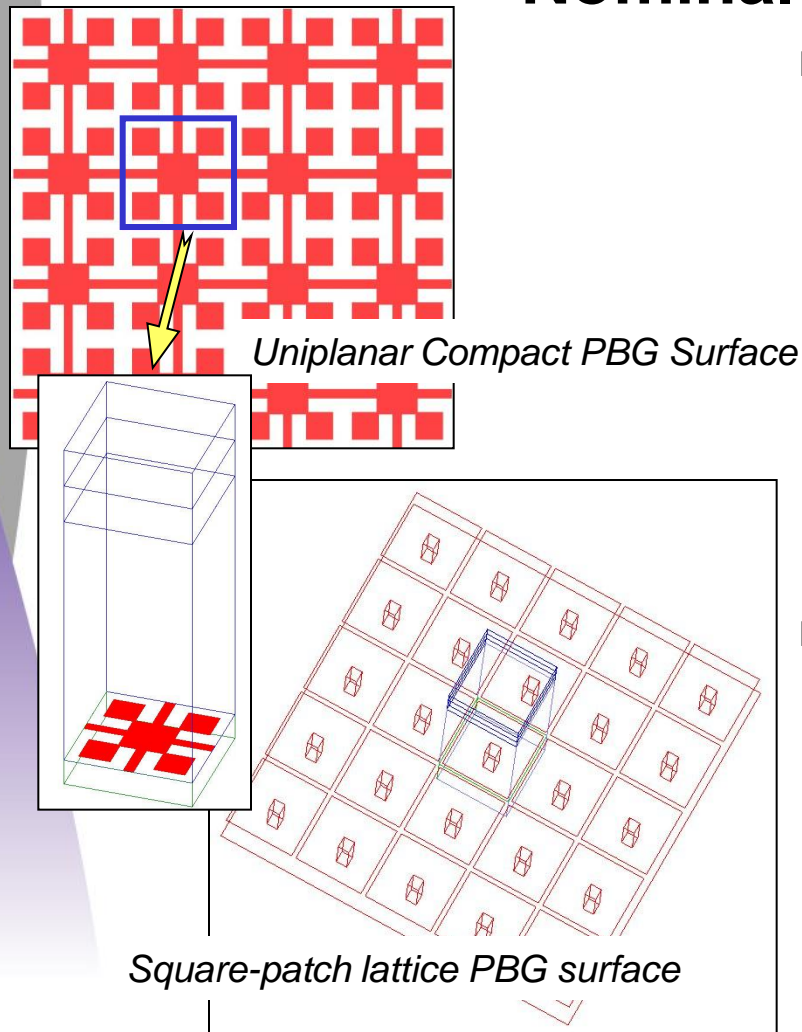
- 0.48 cm (square) cross-section
- Lattice Period 1.2 cm (width), 1 cm of height modeled [arbitrary selection, 15 GHz ceiling]
- Dielectric Constant $\epsilon_r = 10.2$
- Five periods in $\Gamma - X$ direction shown, with Complex-Magnitude E field superimposed at 11.95 GHz



Ansoft HFSS V7 Transmission Spectra for 5, 6, and 7 Periods of the Waveguide Simulator Structure shown at Left

[Solution parameters: 20 minutes exactly for 7 Period case, including all adaptive passes and 420 frequency-point fast sweep, performed on a Pentium II 350 MHz system]

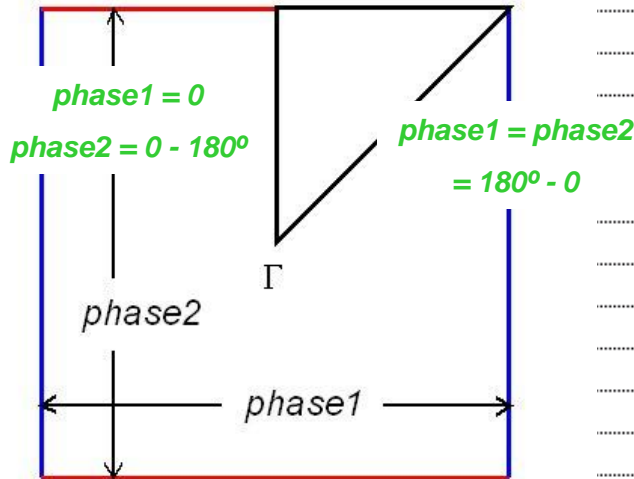
Dispersion Diagram Method: Nominal Project Setup



- ▶ HFSS nominal project is a unit cell of the repeating PBG circuit or structure, imaged with linked boundaries on each side
 - ◆ The phase relationship between each master/slave pair is set as a “function” (variable) in the HFSS interface
 - ◆ The “top” of the computation space is terminated with a *perfectly matched layer* construction (see Reference [C])
- ▶ The nominal project is to be analyzed with the new *eigensolver* in HFSS V7, and therefore has no “port” or other excitation
 - ◆ PML construction must be sufficiently broad-banded to cover eigensolution range

Dispersion Diagram Method: Optimetrics Project Setup

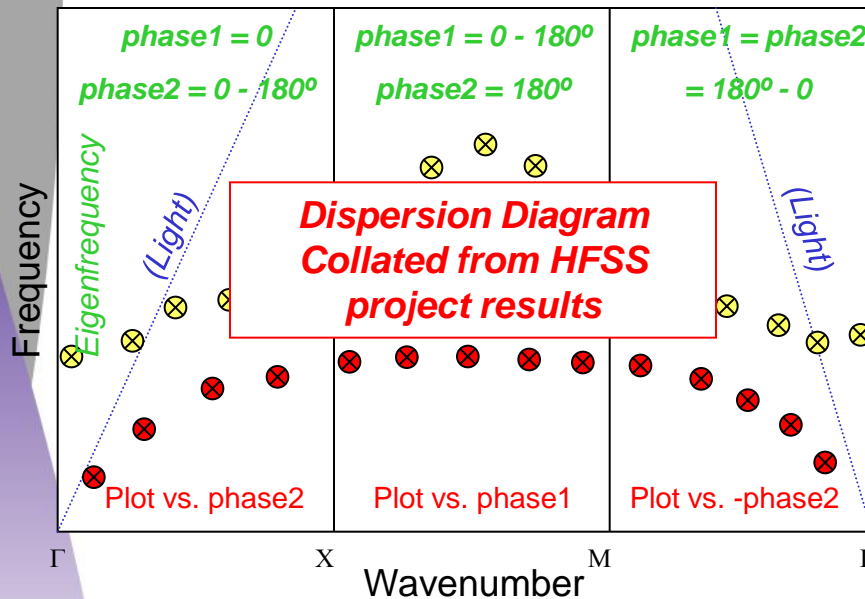
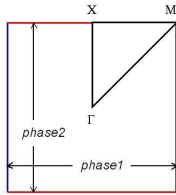
| Setup | phase1 | phase2 | Solved | Save Fields | Solve |
|---------|--------|--------------------------|--------|-------------|-------|
| setup1 | 0 | $phase1 = 0 - 180^\circ$ | N | N | N |
| setup2 | 10 | $phase2 = 180^\circ$ | N | N | N |
| setup3 | 20 | | N | N | N |
| setup4 | | X | | | N |
| setup5 | | M | | | N |
| setup6 | | | | | N |
| setup7 | | | | | N |
| setup8 | | | | | N |
| setup9 | | | | | N |
| setup10 | | | | | N |
| setup11 | | | | | N |
| setup12 | | | | | N |
| setup13 | | | | | N |
| setup14 | | | | | N |
| setup15 | | | | | N |
| setup16 | | | | | N |
| setup17 | 160 | 0 | N | N | Y |
| setup18 | 170 | 0 | N | N | Y |
| setup19 | 180 | 0 | N | N | Y |
| setup20 | 180 | 10 | N | N | Y |
| setup21 | 180 | 20 | N | N | Y |



► Ansoft Optimetrics™ is used to generate a parametric sweep using the HFSS nominal project

- ◆ For a square lattice, swept variables are *phase1* and *phase2*
- ◆ Project “setups” generated with phase combinations to solve for permissible solution modes along the Γ -X-M triangle
- ◆ For 10 degree phase steps, with repeat entries eliminated, requires 54 total “setups”

Dispersion Diagram Method: Optimetrics Project Output

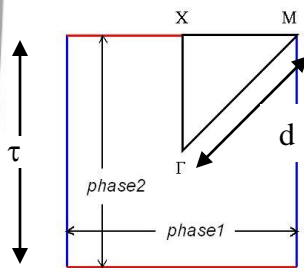


| Name | Value | Expression |
|-------|----------------|--|
| case1 | 0 | $p2 * 3e11 / (2.4 * 360)$ |
| case2 | 0 | $p2 * 3e11 / (.5 * 3.394 * 360)$ |
| f1 | 1.1419465E+010 | 1.1419465088.679 |
| f2 | 1.1715937E+010 | 1.1715937007.7225 |
| f3 | 2.4965044E+010 | 2.4965043690.9206 |
| light | 0 | $\text{if}(p1=0 \& p2!=0, \text{case1}, \text{if}(p1!=0 \& p1=p2, \text{case2}, 0))$ |
| neg_p | 0 | -p2 |
| p1 | 0 | 0 |
| p2 | 0 | 0 |

- Each third of the overall dispersion curve can be reproduced by plotting found eigensolutions vs. the appropriate input variable in Optimetrics™
- Results are plotted as permitted eigenmodes vs. boundary condition phases, analogous to plotting vs. wave number in a true dispersion diagram
 - Only appropriate setups plotted for each section and horizontal axis
 - “Light” line calculable from phase offset and cell dimensions as reference

Dispersion Diagram Method: The “Light Line”

- ▶ The “light line” represents the propagation of free radiation along the unit cell such that $c = f\lambda_o$
 - ◆ The Gamma point corresponds to “normal” radiation
 - ◆ The Chi point corresponds to “tangential” radiation parallel to the lattice
 - ◆ The Mu point corresponds to “tangential” radiation diagonal to the lattice
- ▶ For the ΓX leg of the triangle, the line falls along $\text{phase2} \cdot c / (\tau \cdot 360)$, while for the $M\Gamma$ leg it falls along $\text{phase2} \cdot c / (d \cdot 360)$.
 - ◆ A “conditional” statement can assign a single variable to either definition, for the appropriate segment of the parametric sweep.

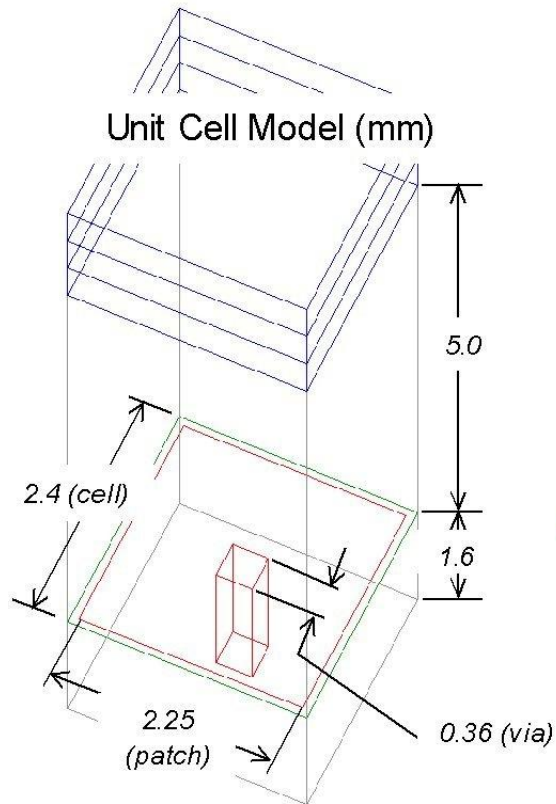


| Name | Value | Expression |
|-------|----------------|---|
| case1 | 0 | $p2 \cdot 3e11 / (2.4 \cdot 360)$ |
| case2 | 0 | $p2 \cdot 3e11 / (.5 \cdot 3.394 \cdot 360)$ |
| f1 | 1.1419485E+010 | 11419485088.879 |
| f2 | 1.1715937E+010 | 11715937007.7225 |
| f3 | 2.4965044E+010 | 24965043690.9206 |
| light | 0 | $\text{if}(p1==0 \& p2!=0, \text{case1}, \text{if}(p1!=0 \& p2==0, \text{case2}, 0))$ |
| neg_p | 0 | -p2 |
| p1 | 0 | 0 |
| p2 | 0 | 0 |

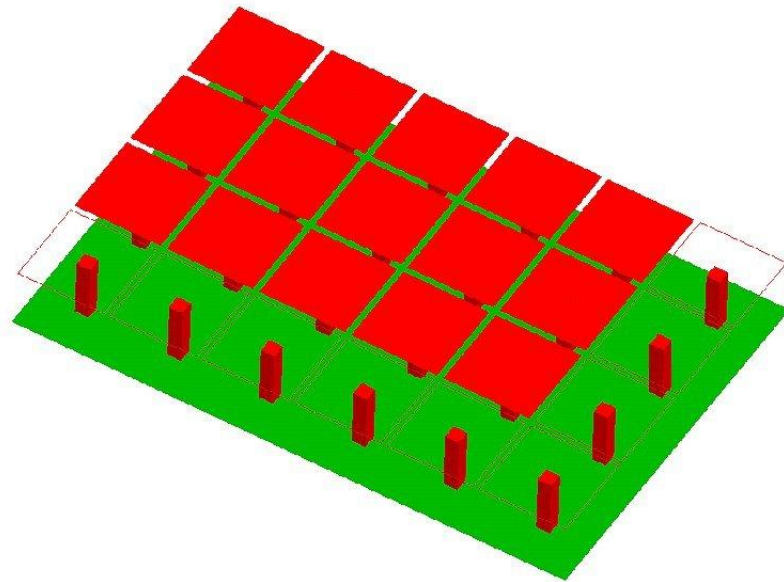
Dispersion Diagram Method: Output Considerations

- ▶ PML bandwidth may limit range of available eigenmodes for solution
 - ▶ Very low frequency eigensolutions difficult to find
 - ▶ Higher frequency eigensolutions may be 'clipped' by PML maximum absorption frequency range
 - ▶ Simple workaround: search for fewer modes, alter starting search frequency to find second, third band gaps
- ▶ Master/Slave boundary phase relationships more difficult to calculate for non-rectangular lattices
 - ▶ Analysis still possible, merely requires more algebraic entry by the user to set correct phase variables

Dispersion Diagram Method: Example Project 1

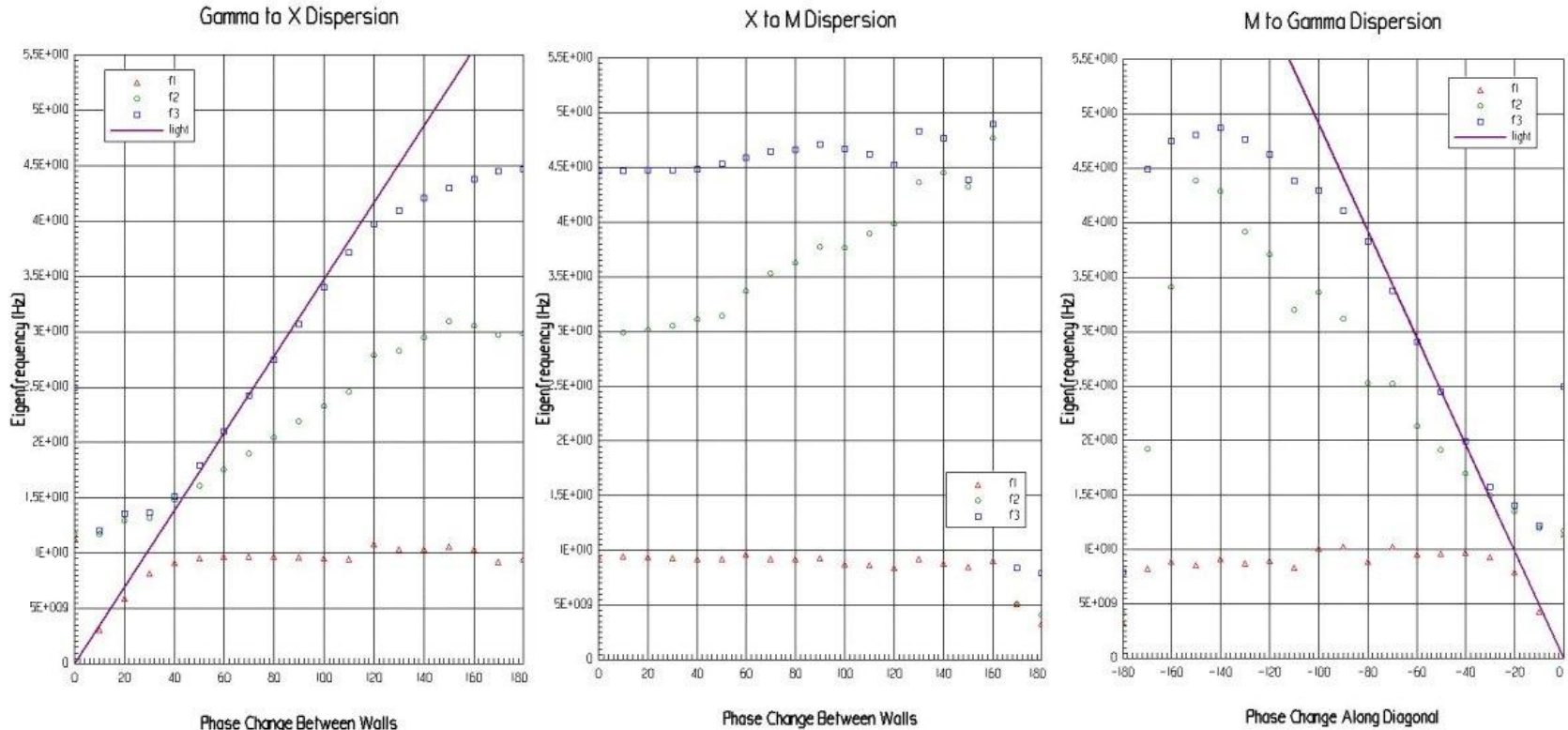


High-Impedance PBG Lattice
(some patches shown in wireframe for clarity)



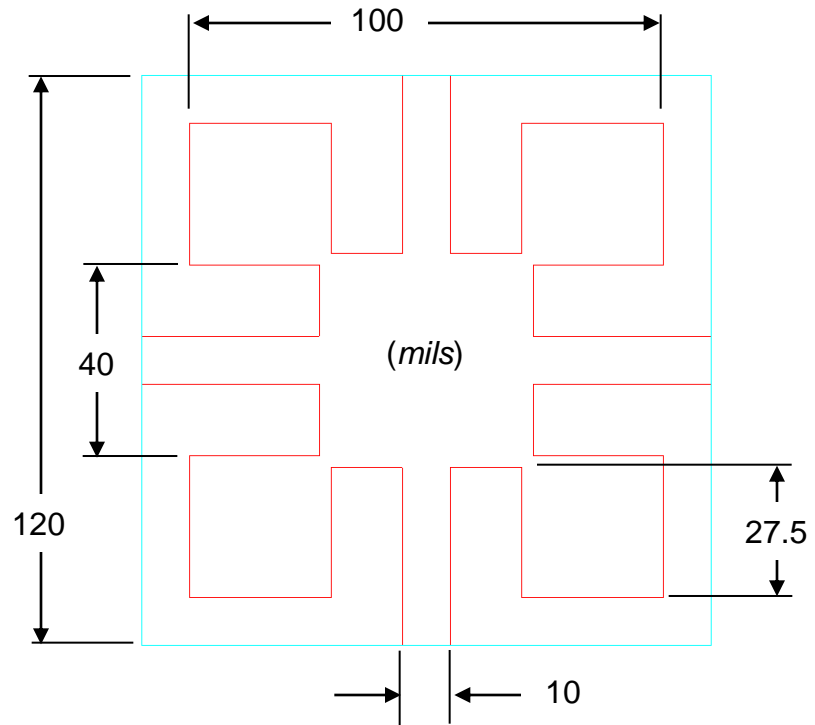
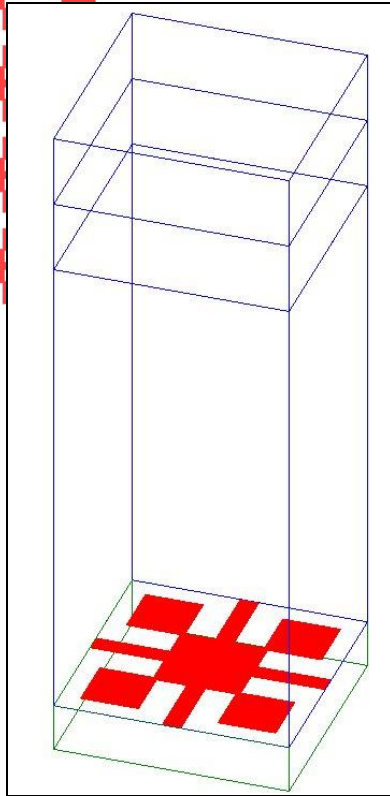
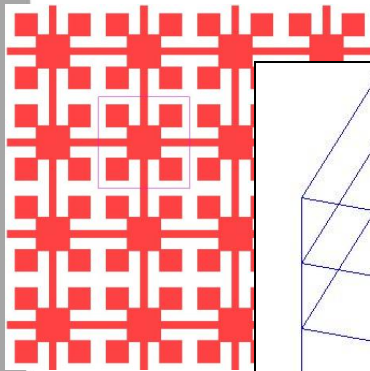
Unit cell at left constructed in HFSS as Nominal project, with 2 pairs of linked boundaries (sides) and a 3-layer PML on the top surface. Model geometry consists of a square patch with central via to an underlying ground plane, etched on a dielectric substrate of $\epsilon_r = 2.2$. Dimensions and material design per Reference [D].

Dispersion Diagram Method: Example 1 Results



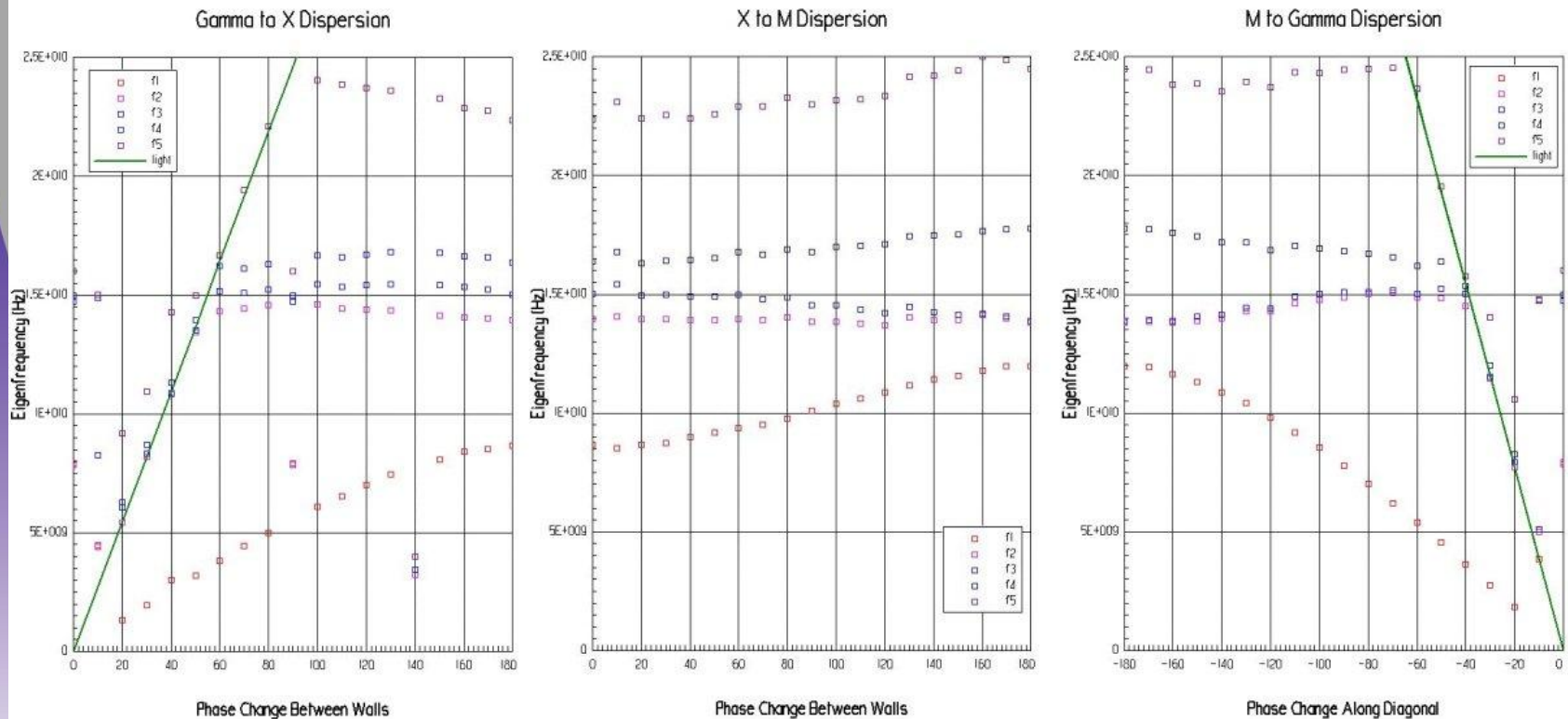
Results show forbidden band of approximately 10 - 15 GHz, which agrees closely with those published in Reference [D], Figure 10, from a non-commercial solver. Solution was obtained on a Pentium III (laptop), 450 MHz, 256 MB RAM, in 4 hrs 7 minutes, to 0.5% eigenfrequency convergence on each of 54 sequential HFSS projects. 3 eigenmodes per project were obtained.

Dispersion Diagram Method: Example Project 2



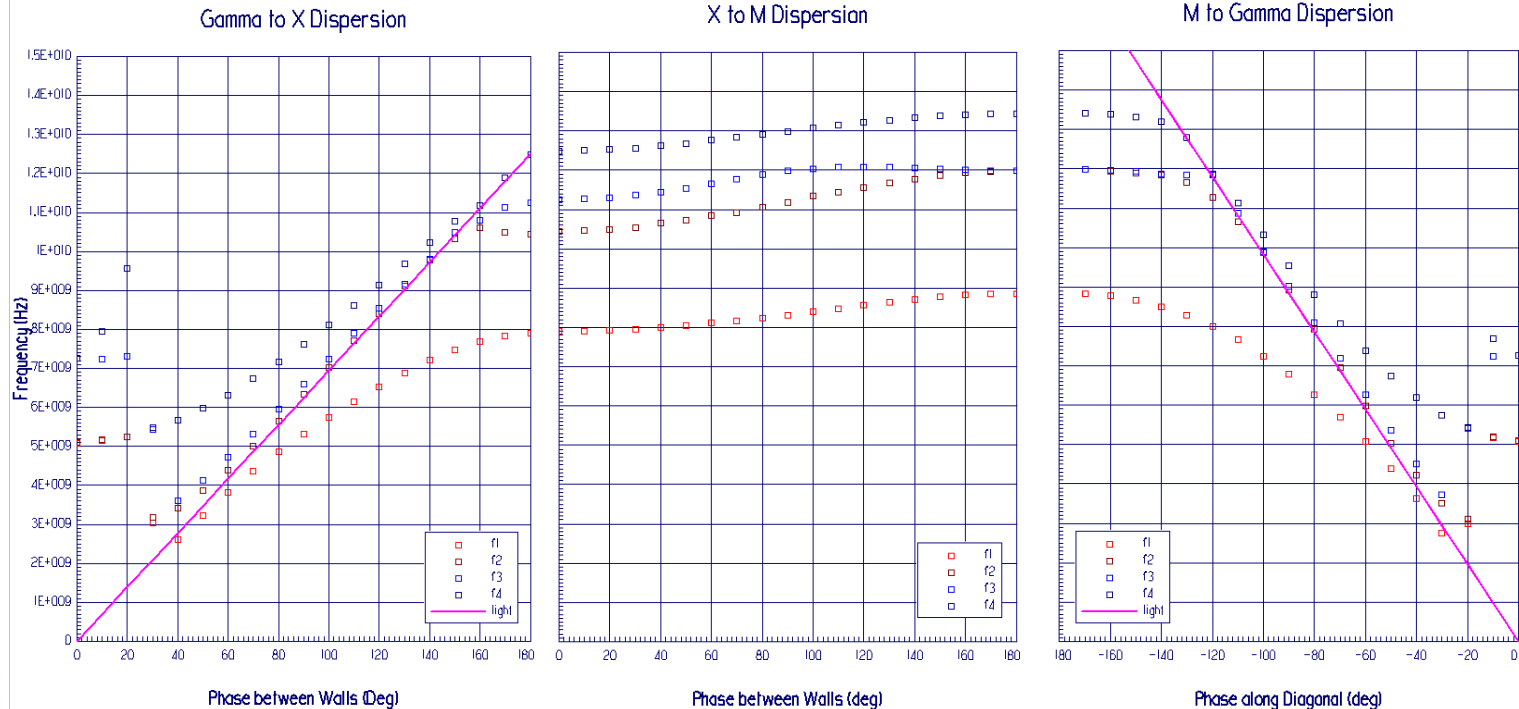
Unit cell UC-PBG at left constructed in HFSS as Nominal project, with 2 pairs of linked boundaries (sides) and a 2-layer PML on the top surface. Model geometry consists of a planar metal circuit above an underlying ground plane, etched on a dielectric substrate of $\epsilon_r = 10.2$ and height 25 mils. Dimensions (reproduced above right) and material design per Reference [E].

Dispersion Diagram Method: Example 2 Results



Results illustrating forbidden band at approximately 11.9 - 13.8 GHz, which corresponds reasonably with the results published in Reference [E]. Solution was performed on a Pentium III (laptop) 450 MHz system, 256 MB RAM, in 10 hrs 17 minutes to 1% eigenfrequency convergence on each of 54 sequential HFSS projects. 5 eigenmodes per project were obtained.

Dispersion Diagram Method: Example Project 3

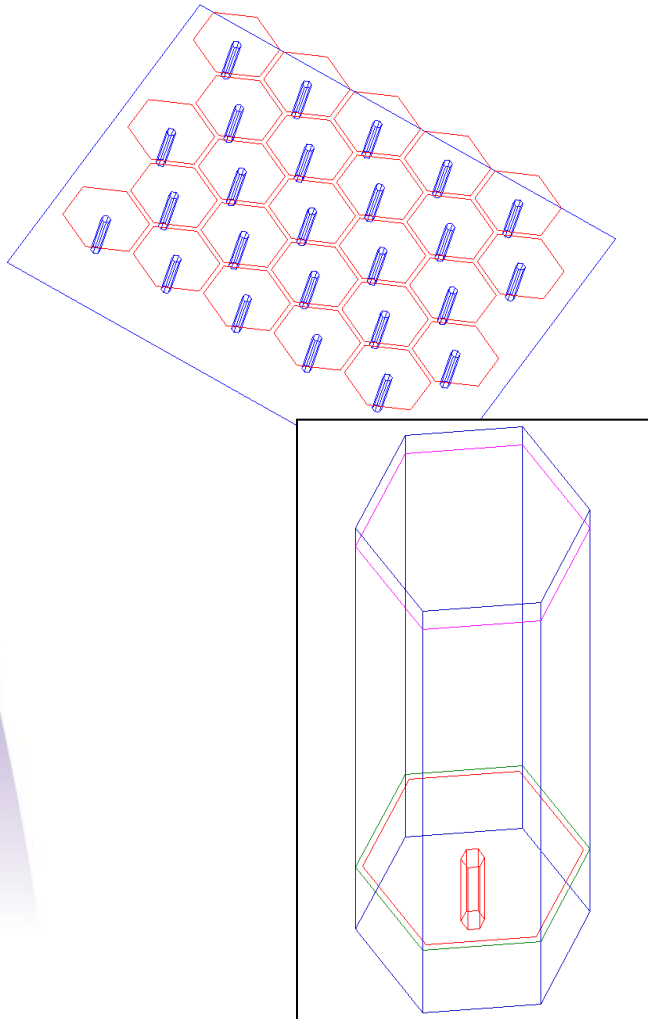


Results of a unit cell analysis of the square-rod dielectric model from the direct-transmission example shown previously, showing the dispersion diagram from that structure for all directions. Note that for the ΓX leg the band gap is a little narrower for the infinite case than for the 7-period model (8 - 10.5 GHz), and we now have information for the XM leg showing that for other propagation directions the band gap may be even more limited (9 - 10.5 GHz overall).

Dispersion Diagram Method: Notes for Consideration

- ▶ Entire dispersion plot may not be necessary
 - ▶ Square-grid dielectric only structures will have gap top and bottom defined by either the Γ , X, or M points on the Brillouin triangle
 - ▶ Other lattices and/or metallo-dielectric structures cannot be reduced to only 3 points
- ▶ Since band-gap information is 'spread' over multiple individual HFSS setups, optimization via this technique may be tricky
 - ▶ The gap-defining phase conditions may be different for different geometries, preventing selection of a single phase combination as your optimization 'nominal'
 - ▶ So how do you define a single project which will permit centering of a bandgap?...

Reflection Phase Analysis Method: Nominal Project Setup



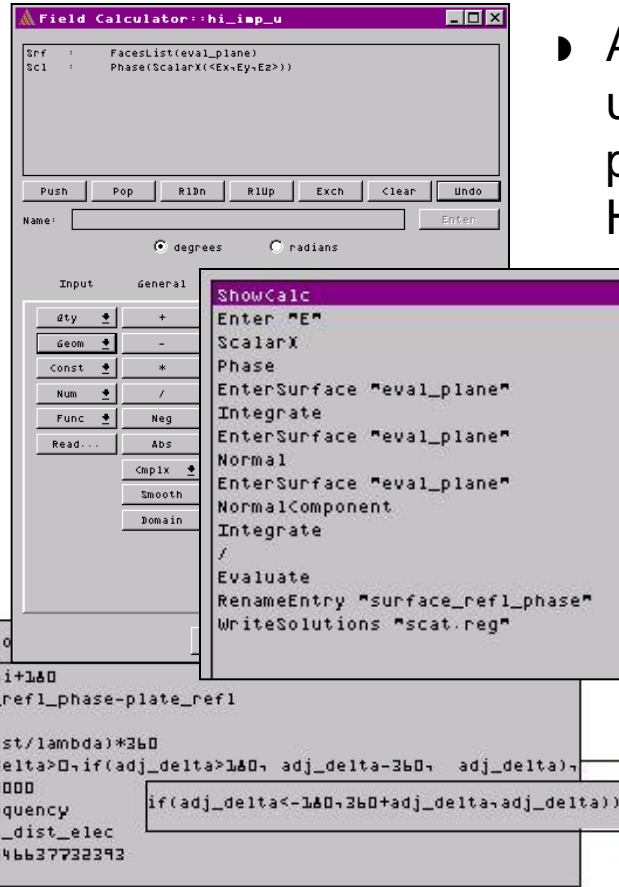
- ▶ HFSS nominal project is a unit cell of the repeating PBG circuit or structure, imaged with linked boundaries on each side
 - ◆ The phase relationship between each master/slave pair is set to *zero* to correspond with normal incidence
 - ◆ The “top” of the computation space is terminated with a standard radiation boundary
- ▶ An *incident plane wave* excitation is used, directed toward the PBG surface
- ▶ An additional integration plane is identified internal to the radiation boundary face to use for phase data extraction

Reflection-Phase Analysis Method: Optimetrics Project Setup

$$\phi_{PBG} = \frac{\int_S \text{Phase}(E_{\text{scattered}}) \cdot ds}{\int_S \hat{s} \cdot ds}$$

$$\phi_{\text{plate}} = 180 - \frac{d}{\lambda} \cdot 360$$

$$\Delta\phi = (\phi_{PBG} - \phi_{\text{plate}}) + 180$$



▶ Ansoft Optimetrics™ is used to generate a parametric sweep using the HFSS nominal project

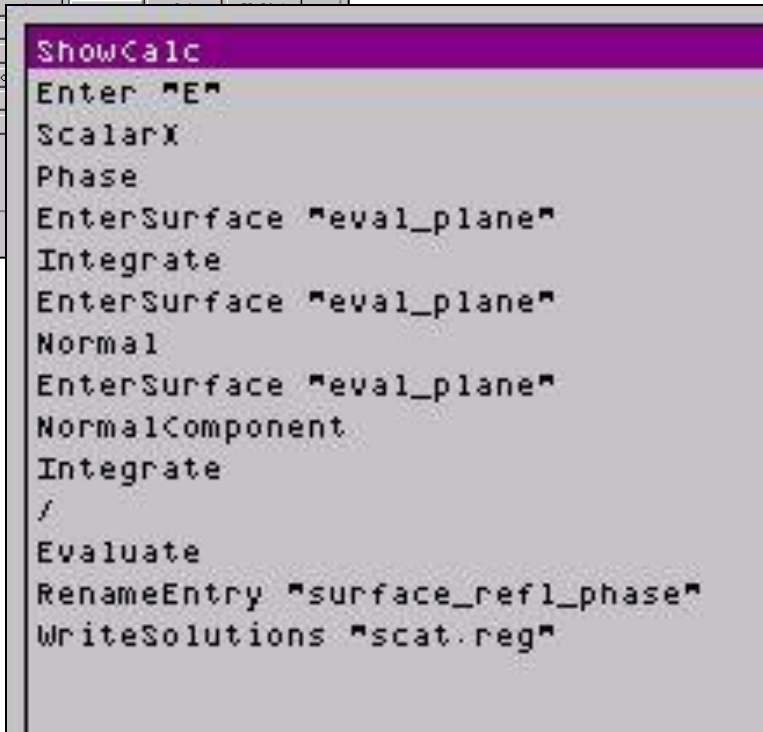
- ◆ The swept variable is the solution frequency
- ◆ For each project “setup”, the reflection phase of the PBG surface vs. that of an ideal metal plate at the same location is automatically calculated from the field results, using a user-recorded macro.
- ◆ No “calibration” project is required, since the reference perfect reflector phase can be calculated

Reflection-Phase Analysis Method: Detailed Post-Processor Macro



$$\phi_{PBG} = \frac{\int_S \text{Phase}(E_{scattered}) \cdot ds}{\int_S \hat{s} \cdot ds}$$

- ▶ Post-processing operations performed on “scattered” field solution (default)
 - ◆ Load E field into calculator stack
 - ◆ Take the Component along the E-field polarization
 - ◆ Take the Phase only of the resulting Complex Scalar data
 - ◆ Integrate over the Evaluation Plane surface
 - ◆ Integrate a Normal to the Evaluation surface dotted with the surface (to get surface area)
 - ◆ Divide the Phase integration by surface area to get Averaged Reflection Phase from the HFSS Model



Reflection-Phase Analysis Method: Optimetrics Output Functions

| Name | Value | Expression |
|--------------------|------------|---|
| adj_delta | 315.54664 | delta_phi+180 |
| delta_phi | 135.54664 | surface_refl_phase-plate_refl |
| eval_dist | 8 | 8 |
| eval_dist_elec | 144 | (eval_dist/lambda)*360 |
| final_refl_phi | -44.453362 | if(adj_delta>0,if(adj_delta>180, adj_delta-360, adj_delta), |
| frequency | 1.5E+010 | 15000000000 |
| lambda | 20 | 3e11/frequency |
| plate_refl | 36 | 180-eval_dist_elec |
| surface_refl_phase | 171.54664 | 171.546637732393 |

- An ideal metal plate would reflect an incident wave with a 180 phase shift. At a distance d this phase will be:

$$\phi_{plate} = 180 - \frac{d}{\lambda} \cdot 360$$

- Comparing this to the HFSS results, with an adjustment factor of 180 degrees to center the “ideal” result on zero, gives:

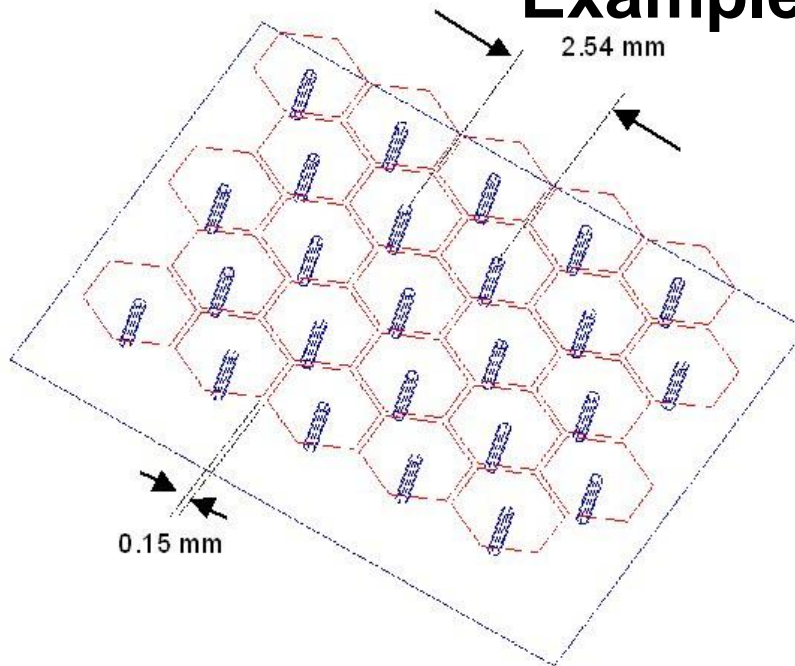
$$\Delta\phi = (\phi_{PBG} - \phi_{plate}) + 180$$

- Note the use of conditionals to assure the answer is in the desired quadrant of the polar chart

Reflection-Phase Analysis Method: Output Considerations

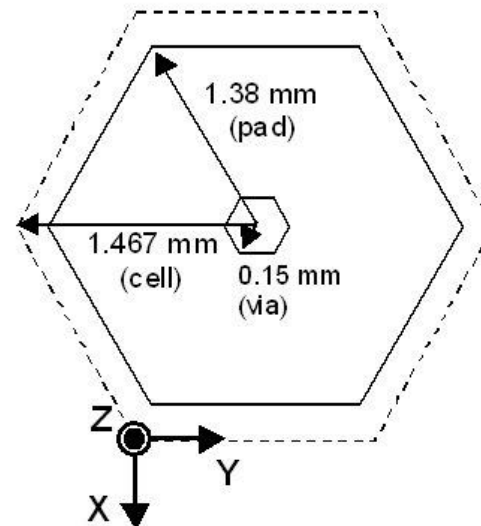
- ▶ Linked Boundary Master/Slave Phase must be appropriate to incident wave direction
 - ▶ Multiple polarizations with identical Poynting vectors could be realized for each frequency setup
 - ▶ Multiple incidence angles could also be solved for, tying master/slave phase variables to incidence angle variables and solving a larger parametric table
- ▶ Output results are calculated directly from field data, requiring fine convergence
 - ▶ Up-front “manual” or seeded meshing can improve starting and ending mesh overall and on evaluation surfaces
 - ▶ Ansoft adaptive meshing and convergence permit well-defined field data
- ▶ User must pre-solve nominal problem to record field calculation macro for use in all subsequent setups

Reflection Phase Analysis Method: Example Project



Hexagonal pads in uniform
triangular array (dielectric solid
not shown for clarity)

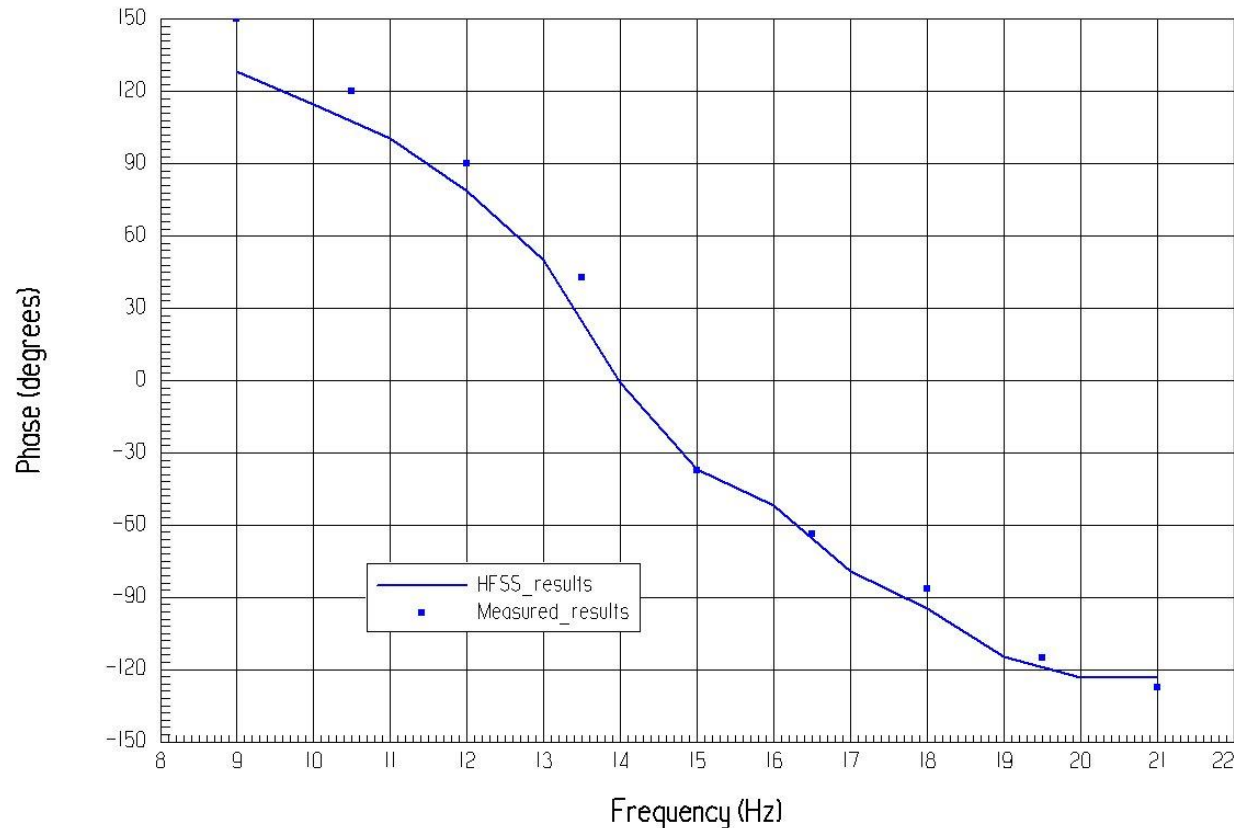
UNIT CELL DIMENSIONS
(Dielectric Height: 1.55 mm,
Air Volume Height: 8.45 mm
[above dielectric])



HFSS Nominal Project dimensions for hexagonal PBG surface consisting of patches with central vias. Patches etched atop a substrate with $\epsilon_r = 2.2$. Surface design (except via dimension which was not provided) per Reference [D].

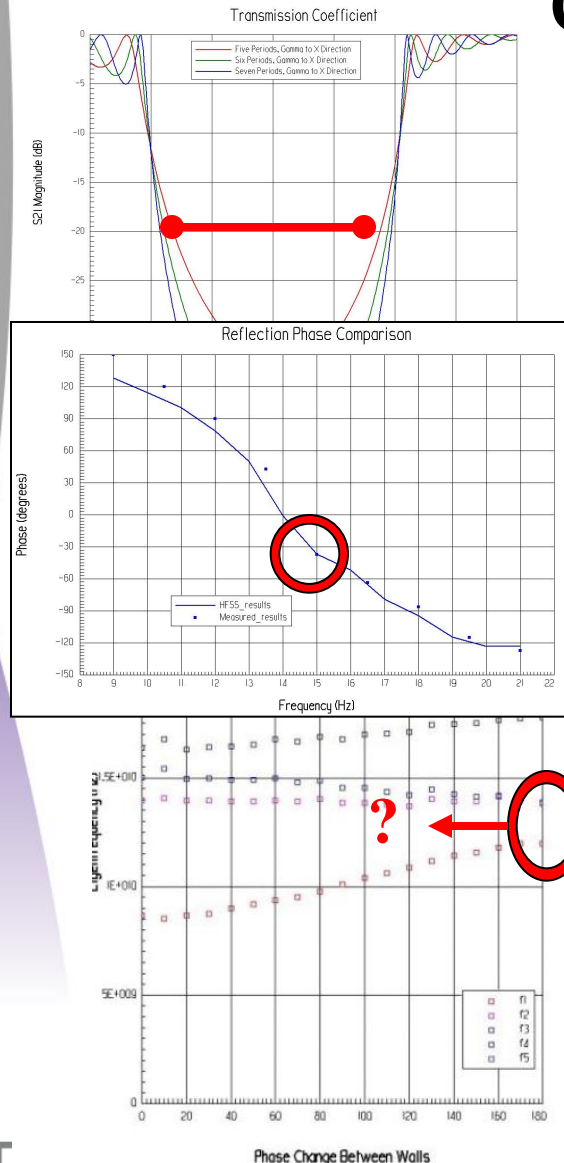
Reflection Phase Analysis Method: Example Results

Reflection Phase Comparison



HFSS delta phase results calculated from field data, plotted opposite those published in Reference [D], showing very good agreement. Computation was performed on a Pentium II 350 MHz system with 512 MB RAM in 5 hrs, 47 minutes for 13 sequential HFSS projects and automated macro phase extraction. Each project individually converged to a Delta-E criterion of 0.005.

Optimization Analysis of PBGs: Choice of Methods

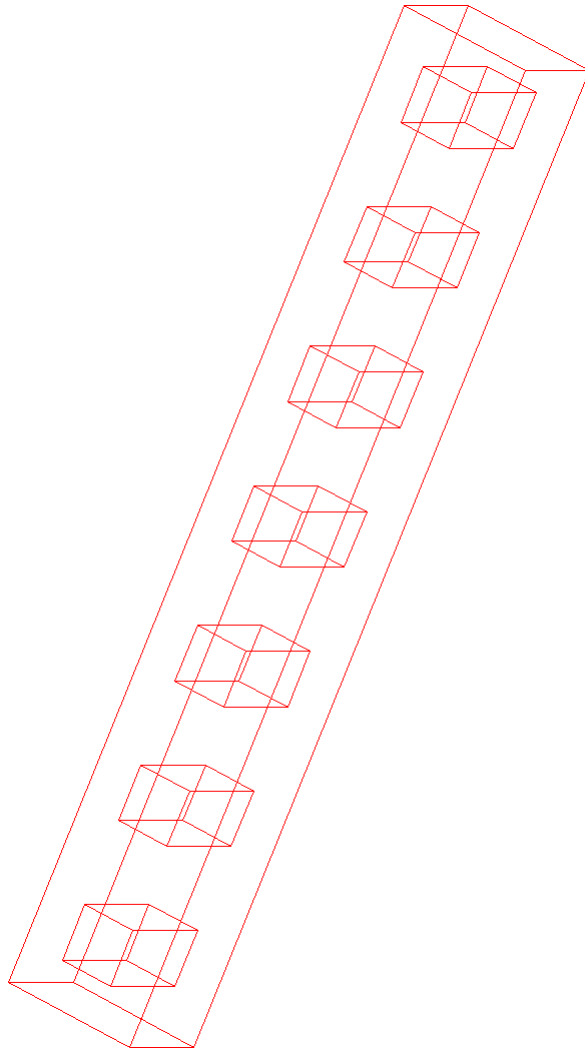


- ▶ Optimization of a PBG to a desired frequency band requires that all data appropriate to finding the optimum be available in a *single* HFSS project
 - ◆ Use “Filter Cost Function” to define desired forbidden band for Direct-Transmission method
 - ◆ Optimize final post-processed phase value to zero at desired band center for Reflection Phase method (does not assure bandwidth!)
- ▶ Dispersion Curve method may not be usable
 - ◆ Requires full dispersion analysis of ‘nominal’ design as its own parametric series of HFSS projects to pick the critical M/S phase combination defining the band gap
 - ◆ However, geometric alterations may place the point of closest approach between modes at a different combination of phase conditions!

Optimization Analysis of PBGs: Suggestions

- Stick to simplest solution possible
 - ◆ Don't use Reflection method if Direct Transmission will suffice
- Obtain a good starting design
 - ◆ Use transmission model or parametric sweeps to verify band gap of nominal design before trying to optimize
- Don't use too many variables at once
 - ◆ PBG behavior is associated with LC type characteristics, which can vary wildly if too many geometric features are varying
- Converge!!!
 - ◆ PBG devices are resonant, therefore their behavior is better captured by a well-adapted mesh
 - ◆ Less 'noise' in the solutions will allow the optimization a better comparison and improve the likelihood of success
- Verify results on finished design
 - ◆ Run parametric sweep of eigensolutions or incident wave problem to obtain dispersion or reflection phase data
 - ◆ Run sensitivity studies altering geometry, materials, etc. to verify manufacturability

Optimization Analysis of PBGs: Case Study 1: Direct Transmission



- ▶ GOAL: Alter the forbidden band of the structure evaluated in the first example from 6.5 - 9.5 GHz to 8 - 11 GHz, using Geometric variables only (7 period case)
- ▶ Input variable options:
 - ◆ Period (nominal: 1.2 cm)
 - ◆ Rod size (nominal: 0.48 cm)
 - ◆ Fill ratio: (rod size / period)
- ▶ PLAN: Try optimization with first two variables (independent) or with third variable (associated)
- ▶ Filter cost function defined between goal frequencies of 8 and 11 GHz, requiring $|S_{21}| > -30$ dB (0.03 linear)

Optimization Analysis of PBGs: Case Study 1: Optimetrics Setup

| Setup | period | rod |
|--------|--------|------|
| setup1 | 1.1 | 0.36 |
| setup2 | 1.1 | 0.48 |
| setup3 | 1.1 | 0.6 |
| setup4 | 1.2 | 0.36 |
| setup5 | 1.2 | 0.48 |
| setup6 | 1.2 | 0.6 |
| setup7 | 1.3 | 0.36 |
| setup8 | 1.3 | 0.48 |
| setup9 | 1.3 | 0.6 |

The screenshot shows the 'Filter Cost Function' dialog box. It has a title bar with a red background and a close button. Inside, there is a 'Reference curve' section with a checkbox 'Specify values in dB' which is unchecked. Below this, there are two rows of input fields: 'Start freq. (GHz)' with a value of '8' and 'End freq. (GHz)' with a value of '11'. To the right of these are 'Value' fields, both set to '0.03'. Below the frequency fields, there is a 'Desired band characteristics' section with a dropdown menu set to 'Below' and a 'reference curve' label. At the bottom, there is a 'Saturation Interval' field set to '0'. A note at the bottom states: 'NOTE: You can create any number of filter cost functions and weigh them appropriately in Optimetrics.' At the very bottom are 'OK', 'Cancel', and 'Help' buttons.

- Define a small set of parametric variations about the nominal problem for evaluation
 - Let period vary between 1.1 and 1.3 cm by 3 steps
 - Let rod size vary between 0.36 and 0.6 by 3 steps
- Set Optimization to seek goal “filter bandwidth” after performing Parametric sweep
 - Note: Multiple similar functions could be weighted as final cost function

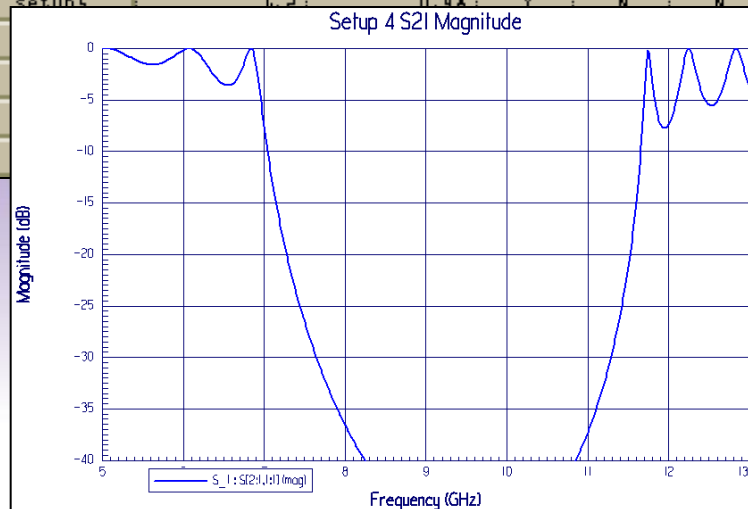
Optimization Analysis of PBGs:

Case Study 1: Results

(Success ruined my plan!)

- Unexpectedly, the cost function was met by one of the parametric variations!

| Setup | period | rod | Solved | Save Fields | Solve | band_gap |
|--------|--------|------|--------|-------------|-------|--------------|
| setup1 | 1.1 | 0.36 | Y | N | N | 6.95343E-007 |
| setup2 | 1.1 | 0.48 | Y | N | N | 0.141533 |
| setup3 | 1.1 | 0.6 | Y | N | N | 0.70429 |
| setup4 | 1.2 | 0.36 | Y | N | N | 0 |
| setup5 | 1.2 | 0.48 | Y | N | N | 0.184343 |
| | | | | | | 0.726147 |
| | | | | | | 0.00121549 |
| | | | | | | 0.243132 |
| | | | | | | 0.725273 |

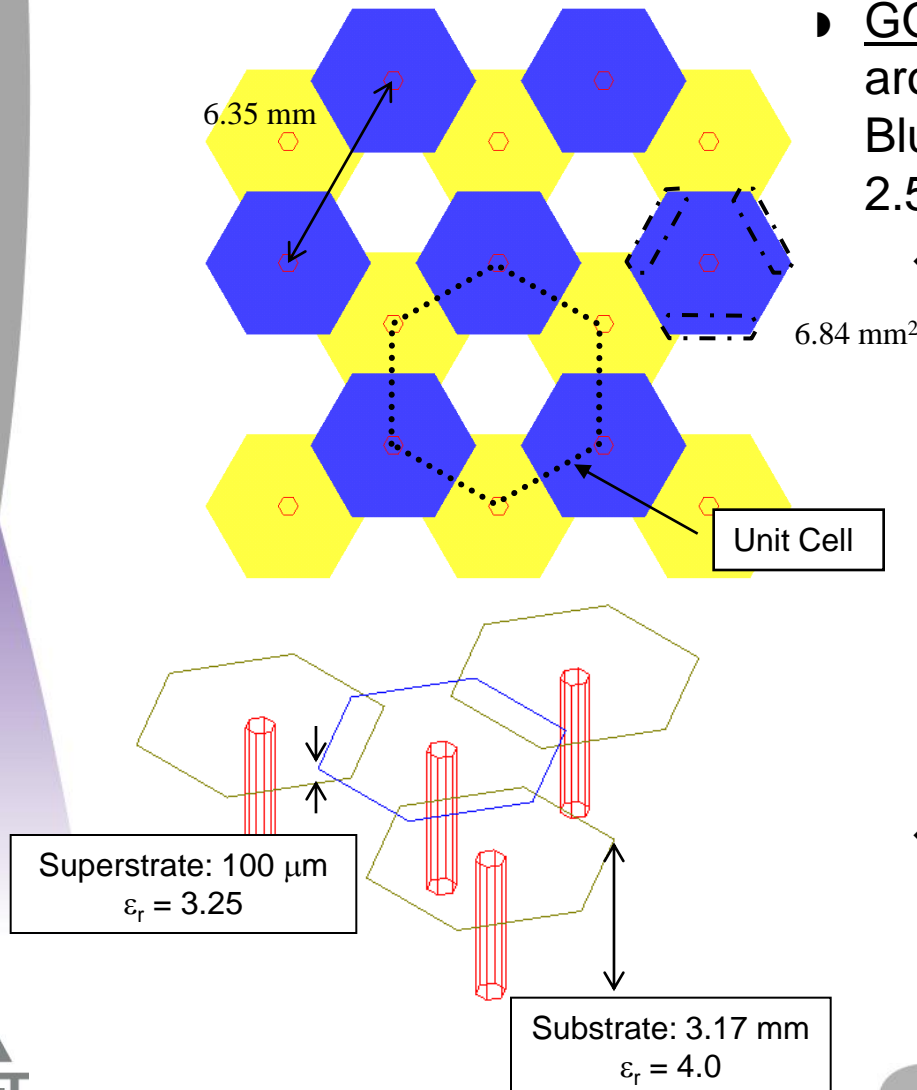


- No Optimization run was necessary
- No need to attempt Parametric or Optimization with single (fill ratio) geometry variable
- HOWEVER:** Recall that dispersion solution for this structure will likely show smaller gap width

- Demonstrates importance of sampling the solution space *before* just optimizing

Optimization Analysis of PBGs:

Case Study 2: Refl. Phase Analysis



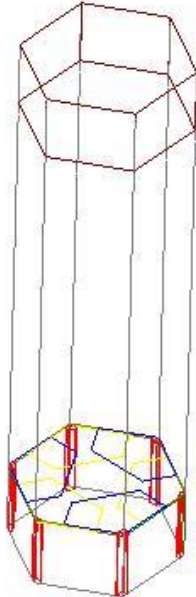
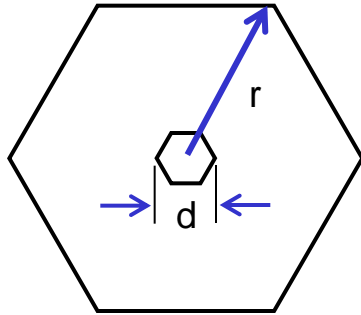
- ▶ GOAL: Design a PBG for use around a planar antenna in the Bluetooth frequency range of 2.4 to 2.5 GHz
 - ◆ Starting design was selected from vague dimensions provided in Reference [D], which demonstrated a three-layer construction with a measured bandgap centered near 2.375 GHz.¹ Dimensioning provided was:
“...a hexagonal lattice with a period of 6.35 mm, and an overlap area between adjacent metal plates of 6.84 mm². ”²
 - ◆ Sub- and superstrate dimensions and properties shown at left.

¹Reference [D], Figure 15

²Reference [D], page 2068

Optimization Analysis of PBGs:

Case Study 2: Refl. Phase Analysis, cont.

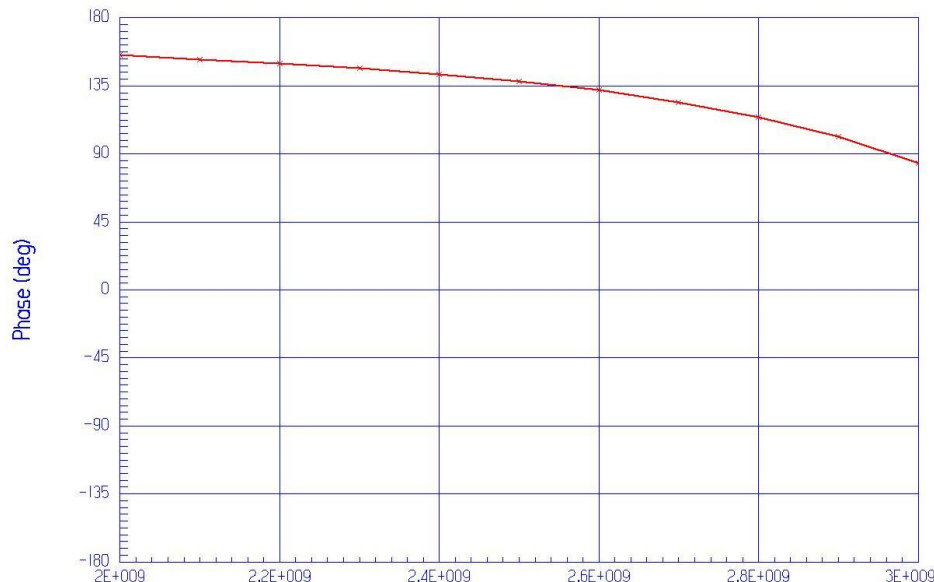


- ▶ PLAN Step 1: Construct unit cell with estimated dimensions from reference
 - ◆ Period, superstrate, and substrate as provided
 - ◆ Via “d” = 0.60 mm
 - ◆ Let Patch “r” = 2.5 mm
 - ◆ Terminate with PML atop air volume.
- ▶ Run Direct Reflection frequency sweep on nominal design using Optimetrics to see if estimated dimensions are close enough to try to tune design for desired band gap center
- ▶ PLAN Step 2: If acceptable, run a few Parametric variations and then Optimize at desired center of gap (2.45 GHz), altering Patch “r” to tune Reflection Phase difference to 180° off of ground plane reflection.
- ▶ PLAN Step 3: Confirm any resulting optimized geometry with another frequency sweep to display extend of usable band gap

Optimization Analysis of PBGs: Case Study 2: Initial Results

| Setup | frequency | patch | Solved | Save Fields | Solve | final_phase | plate_refl | refl_phase |
|---------|-----------|-------|--------|-------------|-------|-------------|------------|------------|
| setup1 | 2E+009 | 2.5 | Y | N | N | 155.255 | 135.84 | 111.095 |
| setup2 | 2.1E+009 | 2.5 | Y | N | N | 152.531 | 133.632 | 106.163 |
| setup3 | 2.2E+009 | 2.5 | Y | N | N | 150.014 | 131.424 | 101.438 |
| setup4 | 2.3E+009 | 2.5 | Y | N | N | 146.774 | 129.216 | 95.9899 |
| setup5 | 2.4E+009 | 2.5 | Y | N | N | 142.499 | 127.008 | 89.5069 |
| setup6 | 2.5E+009 | 2.5 | Y | N | N | 137.842 | 124.8 | 82.6417 |
| setup7 | 2.6E+009 | 2.5 | Y | N | N | 132.435 | 122.592 | 75.0271 |
| setup8 | 2.7E+009 | 2.5 | Y | N | N | 124.2 | 120.384 | 64.5843 |
| setup9 | 2.8E+009 | 2.5 | Y | N | N | 114.454 | 118.176 | 52.6297 |
| setup10 | 2.9E+009 | 2.5 | Y | N | N | 101.285 | 115.968 | 37.2531 |
| setup11 | 3E+009 | 2.5 | Y | N | N | 84.078 | 113.76 | 17.8288 |

Reflection Phase



- Parametric (frequency) sweep shows estimated nominal dimensions tune PBG band center to above 3 GHz
- Reference paper identifies critical feature to lowering bandwidth as capacitance between overlapping plates.
 - r probably must be greater than 2.5 mm
- Copy model for parametric and optimization sweep with r as input variable

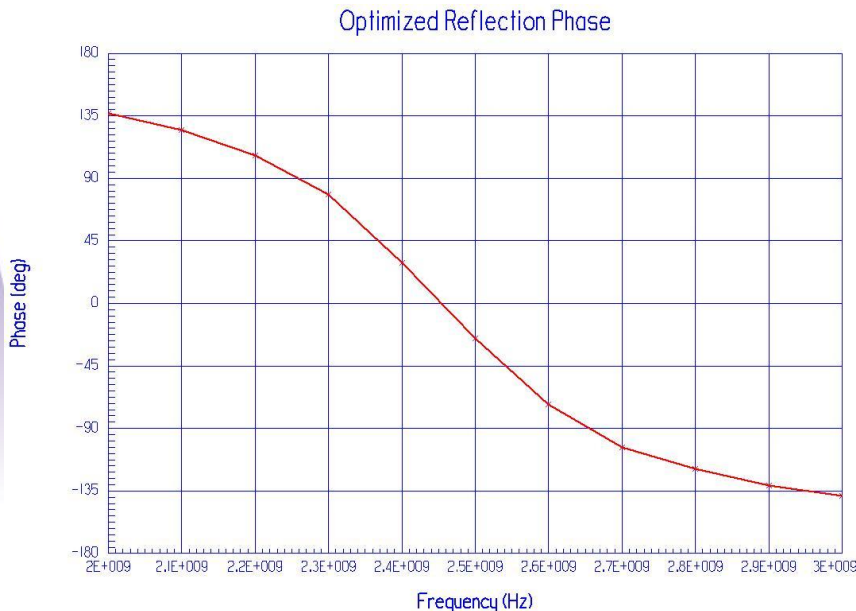
Optimization Analysis of PBGs: Case Study 2: Optimization Run

| Setup | patch | frequency | Solved | Save Fields | Solve | cost | final_phase |
|---------|---------|-----------|--------|-------------|-------|--------------|-------------|
| setup1 | 2 | 2.45E+009 | Y | N | N | 0.772567 | 158.212 |
| setup2 | 2.5 | 2.45E+009 | Y | N | N | 0.604232 | 139.918 |
| setup3 | 3 | 2.45E+009 | Y | N | N | 0.307244 | -99.7732 |
| setup4 | 3.17 | 2.45E+009 | Y | N | N | 0.636807 | -143.64 |
| setup5 | 3.01994 | 2.45E+009 | Y | N | N | 0.340099 | -104.972 |
| setup6 | 3.117 | 2.45E+009 | Y | N | N | 0.541123 | -132.41 |
| setup7 | 2.96352 | 2.45E+009 | Y | N | N | 0.185644 | -77.5556 |
| setup8 | 2.82653 | 2.45E+009 | Y | N | N | 0.0529025 | 41.401 |
| setup9 | 2.84297 | 2.45E+009 | Y | N | N | 0.0213994 | 26.3314 |
| setup10 | 2.89392 | 2.45E+009 | Y | N | N | 0.00975609 | -17.7791 |
| setup11 | 2.90246 | 2.45E+009 | Y | N | N | 0.0145455 | -21.7088 |
| setup12 | 2.88538 | 2.45E+009 | Y | N | N | 0.000459865 | -3.86 |
| setup13 | 2.88057 | 2.45E+009 | Y | N | N | 0.00114013 | -6.07784 |
| setup14 | 2.86775 | 2.45E+009 | Y | N | N | 5.59021E-005 | 1.34582 |
| setup15 | 2.87637 | 2.45E+009 | Y | N | N | 0.000310154 | 3.17002 |
| setup16 | 2.86976 | 2.45E+009 | Y | N | N | 0.00171578 | 7.45596 |
| setup17 | 2.8123 | 2.45E+009 | Y | N | N | 0.096582 | 55.9398 |
| setup18 | 2.85883 | 2.45E+009 | Y | N | N | 0.00794203 | 16.0413 |
| setup19 | 2.86574 | 2.45E+009 | Y | N | N | 0.00266656 | 9.29497 |
| setup20 | 2.86798 | 2.45E+009 | Y | N | N | 3.30816E-006 | -0.32739 |
| setup21 | 2.8682 | 2.45E+009 | Y | N | N | 0.000152838 | 2.2253 |
| setup22 | 2.86834 | 2.45E+009 | Y | N | N | 0.00183785 | 7.71663 |
| setup23 | 2.86776 | 2.45E+009 | Y | N | N | 0.004405 | -11.9466 |
| setup24 | 2.86795 | 2.45E+009 | Y | N | N | 0.00010456 | 1.84058 |
| setup25 | 2.86762 | 2.45E+009 | Y | N | N | 2.44286E-005 | 0.889656 |
| setup26 | 2.8678 | 2.45E+009 | Y | N | N | 0.00217465 | 8.39396 |
| setup27 | 2.86796 | 2.45E+009 | Y | N | N | 0.00268969 | 9.3352 |

- Cost function defined to center gap at 2.45 GHz
 - $cost = (final_phase/180)^2$
- 3 Parametric runs executed before beginning optimization
 - r permitted to vary from 2.0 to 3.17 mm
- Optimization did not achieve ideal goal of $cost = 0$, but did define several very good candidates
 - $r = 2.87$ mm picked as a likely value between good cost results
- Final parametric (frequency) sweep executed with selected value to verify gap

Optimization Analysis of PBGs: Case Study 2: Final Results

| Setup | patch | frequency | Solved | Save Fields | Solve | cost | final_phase | plate_refl | refl_phase |
|---------|-------|-----------|--------|-------------|-------|-----------|-------------|------------|------------|
| setup28 | 2.87 | 2E+009 | Y | N | N | 0.575632 | 136.567 | 135.84 | 92.4067 |
| setup29 | 2.87 | 2.1E+009 | Y | N | N | 0.482088 | 124.979 | 133.632 | 78.6306 |
| setup30 | 2.87 | 2.2E+009 | Y | N | N | 0.350487 | 106.564 | 131.424 | 57.9875 |
| setup31 | 2.87 | 2.3E+009 | Y | N | N | 0.190383 | 78.5392 | 129.236 | 27.7552 |
| setup32 | 2.87 | 2.4E+009 | Y | N | N | 0.0262084 | 29.1402 | 127.008 | -23.8518 |
| setup33 | 2.87 | 2.5E+009 | Y | N | N | 0.0399333 | -25.4323 | 124.8 | -80.6323 |
| setup34 | 2.87 | 2.6E+009 | Y | N | N | 0.163643 | -72.815 | 122.592 | -130.223 |
| setup35 | 2.87 | 2.7E+009 | Y | N | N | 0.33091 | -103.545 | 120.384 | -163.163 |
| setup36 | 2.87 | 2.8E+009 | Y | N | N | 0.436089 | -118.867 | 118.176 | -179.309 |
| setup37 | 2.87 | 2.9E+009 | Y | N | N | 0.52942 | -130.97 | 115.968 | -164.998 |
| setup38 | 2.87 | 3E+009 | Y | N | N | 0.591293 | -138.4 | 113.76 | -155.36 |



- Parametric (frequency) sweep of $r = 2.87$ mm case verifies band gap centered where desired
 - Useable constructive phase shift over range of at least 2.3 - 2.6 GHz
- Using either HFSS or Ensemble, a patch antenna could now be modeled with and without a few surrounding periods of this surface to evaluate improvements to antenna patterns
 - Ensemble 7 “SVD Fastsolve” permits in excess of 10,000 unknowns for a MoM solution!

Final Words

- ▶ Photonic bandgap constructions offer new design opportunities to the microwave, millimeter wave, and wireless industry
- ▶ Ansoft HFSS has been shown effective in modeling and designing these constructions, due to certain unique features and capabilities
 - ▶ Eigensolver
 - ▶ Linked (master/slave) boundary conditions
 - ▶ Field Calculator
 - ▶ Optimetrics™ parametric and optimization sweep engine
- ▶ With the ability to solve these problems without requiring customized software development, PBG constructs can be used in mainstream design applications.

References

- [A] Fen-Ran Yang, Kuang-Ping Ma, Yongxi Qian, and Tatsuo Itoh, "A Novel TEM Waveguide Using Uniplanar Compact Photonic-Bandgap (UC-PBG) Structure," *IEEE Transactions on Microwave Theory and Techniques*, Vol 47, Number 11, November 1999, pp. 2092 – 2098.

- [B] John D. Shumpert, William J. Chappell, and Linda P. B. Katehi, "Parallel-Plate Mode Reduction in Conductor-Backed Slots Using Electromagnetic Bandgap Substrates," *IEEE Transactions on Microwave Theory and Techniques*, Vol 47, Number 11, November 1999, pp. 2099-2104

- [C] Istvan Bardi and Zoltan Cendes, "New Directions in HFSS for Designing Microwave Devices," *Microwave Journal*, Vol 41, Number 8, August 1998, pp. 22-36

- [D] D. Sievenpiper, L. Zhang, R. F. J. Broas, N. G. Alexópolous, and E. Yablanovitch, "High-Impedance Electromagnetic Surfaces with a Forbidden Frequency Band," *IEEE Transactions on Microwave Theory and Techniques*, Vol 47, Number 11, November 1999, pp. 2059-2074.

- [E] Roberto Coccioli, Fei-Ran Yang, Kuang-Ping Ma, and Tatsuo Itoh, "Aperture-Coupled Patch Antenna on UC-PBG Substrate," *IEEE Transactions on Microwave Theory and Techniques*, Vol 47, Number 11, November 1999, pp. 2123-2130.