



Techniques for Analyzing Antenna Lattice Structures

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Wireless and Microwave Technology Conference
Tutorial Session RA-2
Thursday, April 07, 2005
Clearwater, FL



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Part One: Introduction and General Methods Overview

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Introduction – Rationale for Topic

- ◆ EVERYTHING IS GOING WIRELESS
 - ◆ From PDAs, to cellphones, to headsets, to NAS (network attached storage), printers and other peripherals, virtually every consumer electronics application is going *wireless*
 - ◆ With greater demands on wireless applications, greater need is placed on the requirements of the wireless data channel
 - ◆ At the same time, the desired wireless applications are becoming smaller, permitting less space for antenna architecture client-side
 - ◆ Antennas interfacing with single-chip RF systems becoming more common
 - ◆ The ULTRAWIDEBAND option intends to expand signals across a very wide spectral bandwidth, thus lowering signal power at any one frequency ,and reducing the need for ‘high gain’ antennas – or does it?
 - ◆ Traditional Wireless infrastructures (BLUETOOTH, 802.11a/b/g/n, etc.) utilize controlled bandwidth, implying ‘good’ antennas for lower power amplifiers, etc.
 - ◆ Increasing demand for cross-platform usability (like the newest tri-band cell phones) will continue to require more and more multipurpose antennas
 - ◆ Client-side AND infrastructure-side implications for multifunctionality

Introduction – Antenna Definitions

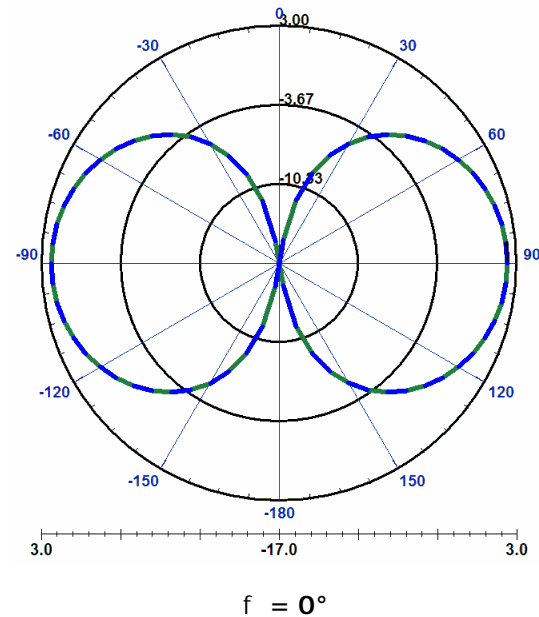
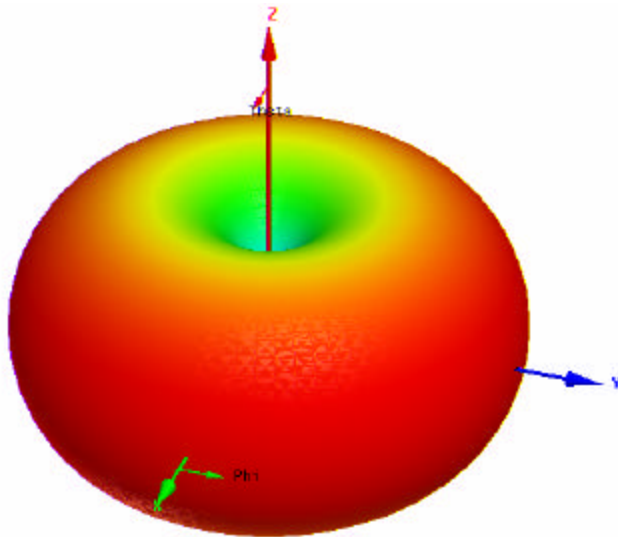
- ♦ What is an Antenna?
 - ♦ *“An antenna is a transition device, or transducer, between a guided wave and a free space wave, or vice versa.”* Kraus, “Antennas”, 2nd edition, p. 18. [1]
 - ♦ In other words, an antenna can act as a matching device between a “guided wave” transmitted along, for example, a 50 Ω coaxial cable to a “free-space wave” transmitted through the 377 Ω ether of free space.
- ♦ Important Antenna Parameters
 - ♦ Input Impedance, Z_{in}
 - ♦ Radiation Resistance, R_r
 - ♦ Efficiency, e
 - ♦ Far Field Pattern
 - ♦ Polarization
 - ♦ Radiation Intensity, U
 - ♦ Directivity, D
 - ♦ Gain, G

Introduction – Antenna Parameters

- ♦ Antenna Parameters
 - ♦ **Input Impedance:** The input impedance, Z_{in} , of an antenna is the impedance that the antenna, effectively a two terminal circuit element, presents to a transmission line. Z_{in} can be complex, $R + jX$.
 - ♦ Example: $\lambda/2$ dipole, $Z_{in} = 73 + j42.5 \Omega$
 - ♦ **Radiation Resistance:** Since an antenna radiates, it “loses” energy to a free space wave. This loss can be effectively considered a resistance term.
 - ♦ Example: $\lambda/2$ dipole, $R_r = 73 \Omega = \text{re}Z_{in}$.
 - ♦ **Efficiency:** In addition to radiation loss, R_r , an antenna can have conduction and/or dielectric loss. This “ohmic” loss, R_l , is additive to the antenna’s $Z_{in} = R_r + R_l + jX$. Thus one can define an efficiency for an antenna:
 - ♦ $e = R_r / (R_r + R_l)$. This denotes the percentage of power that radiates to the far field.

Introduction – Parameters, cont.

- ♦ Antenna Parameters, cont.
 - ♦ **Far Field Patterns:** An antenna cannot have a spherically uniform radiation pattern. The pattern that an antenna radiates depends on its geometry.
 - ♦ Example: z-axis oriented, 0.47λ resonant dipole. Radiates uniformly in φ but has a strong dependence in θ. A “donut” of energy around its principle axis.



Introduction – Parameters, cont.

- ♦ Antenna Parameters, cont.
 - ♦ **Polarization:** A complete understanding of an antenna's far field pattern has to include information on the polarization and relative phase of the radiated field. It describes the orientation of the electric field vector in the far field and can depend on θ and f .
 - ♦ Example: z-axis oriented, 0.47 λ resonant dipole. Since radiation develops from acceleration of charges (i.e. electrons) and for such an antenna electron flow is along the z-axis, it is natural to assume, and correct, that a dipole's polarization is in the θ direction. (e.g. in the xy plane the polarization is in the z-direction.)
 - ♦ **Radiation Intensity:** Power radiated per unit solid angle.
 - ♦ Example: z-axis oriented, 0.47 λ resonant dipole. Radiation intensity $U(\theta, f)$ peaks in the $\theta = 90^\circ$ plane (i.e. XY plane).
 - ♦ **Directivity:** $D(\theta, f) = U(\theta, f)_{max} / U(\theta, f)_{ave}$
 - ♦ Example: isotropic radiator. $D(\theta, f) = 1$, for all θ and f (by definition).
 - ♦ Example: z-axis oriented, 0.47 λ resonant dipole. $D_{max} = 1.64$ @ $\theta = 90^\circ$
 - Note, in general D is dependent on θ and f however as a shorthand when presented as a single number it is understood to represent the peak directivity D_{max} .

Introduction – Parameters, cont.

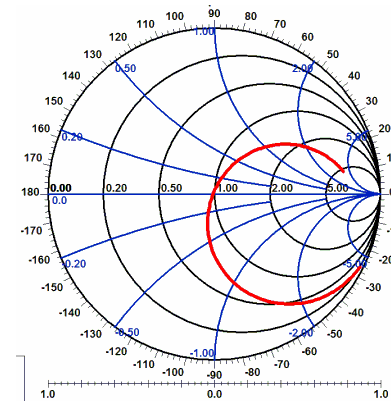
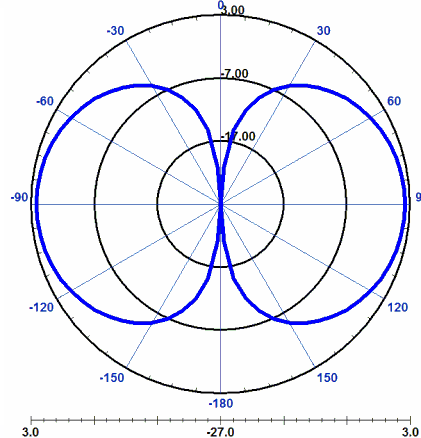
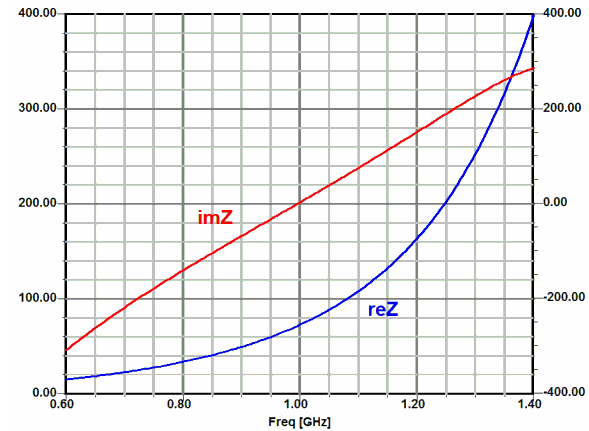
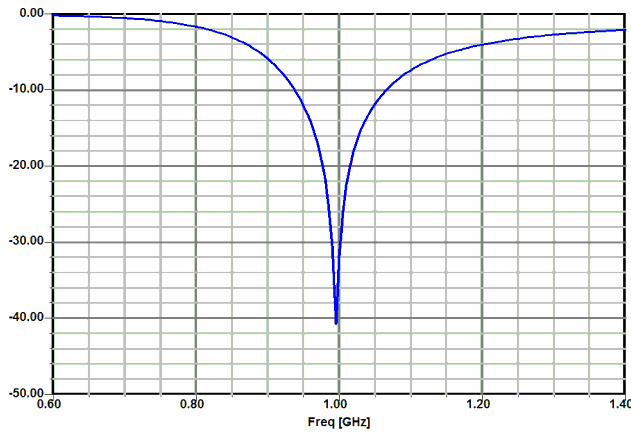
- ♦ Antenna Parameters, cont.
 - ♦ **Gain:** $G = eD$.
 - ♦ For a lossless antenna the gain and directivity are identical.
 - ♦ Note this does not include source mismatch!! However in practice most antenna ranges measure 'gain' that includes the effect of VSWR mismatch or input reflection losses
- ♦ General comments on antennas and antenna parameters:
 - ♦ **Units:** Gain and Directivity are often expressed in decibels.
 - ♦ $D \gg 10 \log_{10} D \gg$ Dipole $D = 10 \log_{10} 1.64 = 2.15$ dBi. (i stands for isotropic)
 - ♦ There is no such thing as an isotropic antenna with dual polarization and 10 dB of gain!
 - ♦ Antenna patterns can be isotropic about an axis (dipole) or directional (horn). The more directional the pattern the higher the directivity. A useful analogy is squeezing a balloon.
 - ♦ In general, the smaller the antenna, the **smaller** $\text{re}Z_{\text{in}}$ and the **larger** $\text{im}Z_{\text{in}}$
 - ♦ Antennas, as radiators, coupling strongly to their surroundings. An antenna design will always require integration to its platform. It can **never** be consider an isolated component. Coupling distance to be considered is related to wavelength, not aperture size

Introduction – Dipole Example

- ♦ **An Ansoft HFSS example:** $L = 0.47\lambda$, $L/2r = 100$, resonant dipole
 - ♦ To develop confidence in the HFSS solution process, simulate a known antenna structure and compare simulation results to theoretical.
 - ♦ An infinitely thin, $\lambda/2$ dipole is not resonant ($Z_{in} = 73 + j42.5 \Omega$). It is inductive at its terminals. Making it slightly shorter and/or adding thickness, $2r$, makes it resonant ($Z_{in} \sim 72 + j0 \Omega$). Its far field parameters are close to those of a $\lambda/2$ dipole.
 - ♦ To simulate an antenna in HFSS: (The Antenna Cookbook)
 - ♦ Space radiation boundaries at least $\lambda/4$ away from the dipole
 - ♦ Use PMLs (Perfectly Matched Layers) for the radiation boundary.
 - ♦ Seed surfaces of the radiation walls with $\lambda/8$ tet elements.
 - ♦ Set “Max Delta S Per Pass” = 0.01.
 - ♦ Set “Refinement Per Pass” = 15%
 - ♦ Set “Minimum Converged Passes” = 2

Introduction – Dipole Results

- ◆ **HFSS Results:** $L = 0.47\lambda$, $L/2r = 100$, resonant dipole at 1GHz
 - ◆ $D = 1.6392$
 - ◆ $Z_{in} = 73 + j0 \Omega$

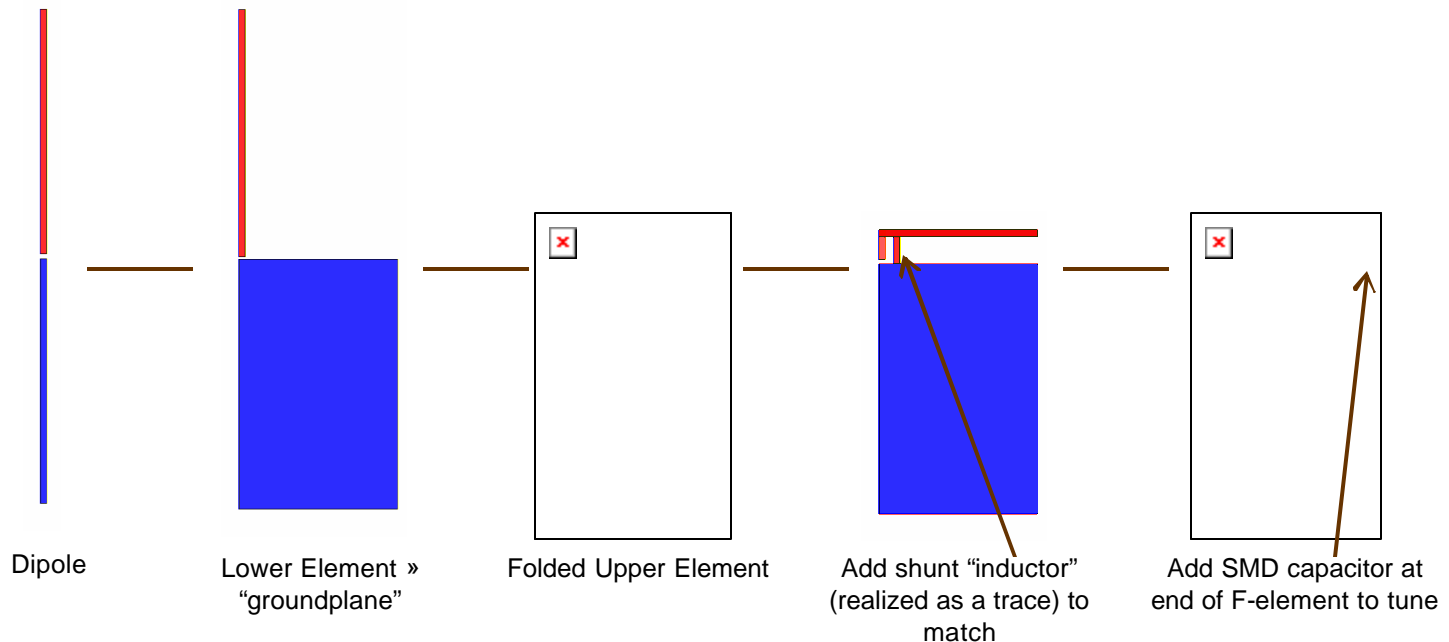


Introduction – Reducing the Dipole

- ♦ A “Real World” Wireless Client Device antenna. The inverted-F
 - ♦ At 900 MHz the large size of a $\lambda/2$ dipole (~83mm) would tend to make it unsuitable for many RFID applications. There are an infinite variety of techniques to reduce an antenna’s size. A few are:
 - ♦ Add dielectric.
 - ♦ Meander the element. e.g. helix or spiral.
 - ♦ Load antenna elements with capacitance.
 - ♦ In general, any change that reduces an antennas size will result in:
 - ♦ Reduced bandwidth (typically not an issue with RFID applications)
 - ♦ Reduced efficiency and therefore reduced gain. (An important indicator of an antenna’s performance).
 - ♦ A useful “reduced” size antenna is the inverted-F. This antenna can be easily implemented on many platforms. It can utilize the groundplane of a device (e.g. PDA) as one half of the radiating element.

Introduction – Evolution of IFA

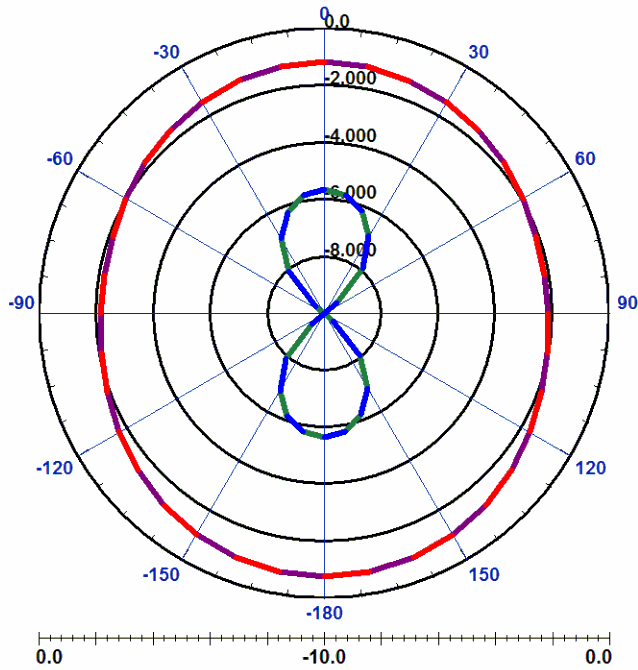
- ♦ Evolution of the end loaded, inverted-F



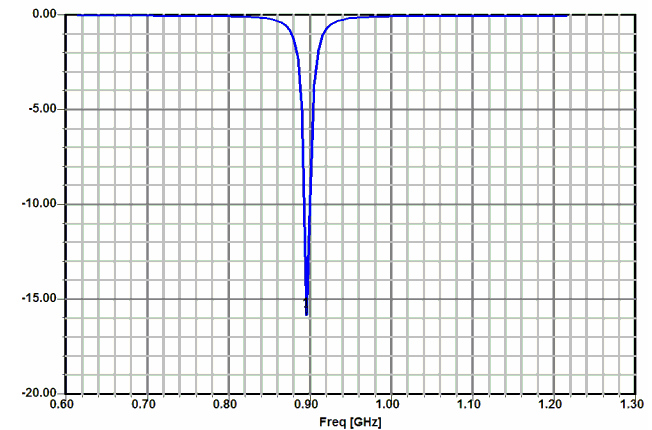
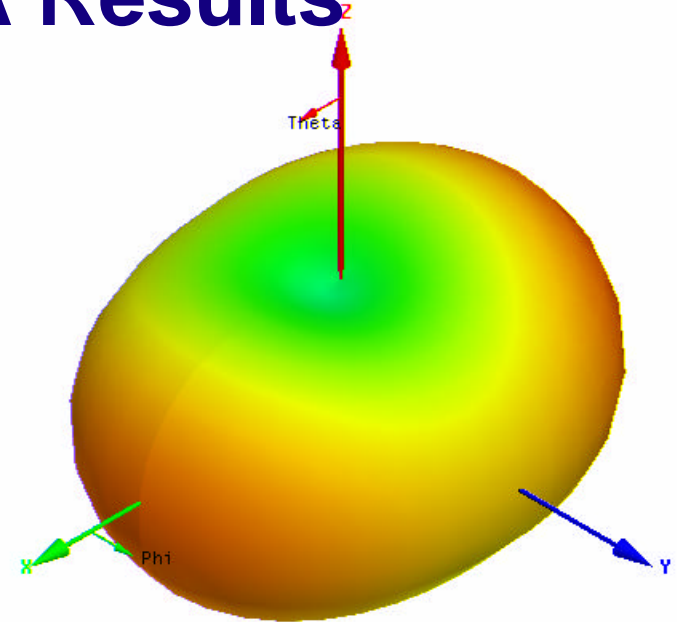
- ♦ Adding shunt "inductance" is a common "trick" for matching small antennas.
- ♦ The end of the F-element can be loaded with a SMD capacitor for tuning.
- ♦ Depending on size restrictions, additional meandering of the F-element may be required to achieve resonance.
- ♦ But in the end, the antenna must still have some reasonable 'size' w.r.t. wavelength to operate
- ♦ Further optimization can only be achieved by other means of boosting efficiency

Introduction – IFA Results

- ◆ **HFSS Results:** end loaded, inverted-F
 - ◆ Copper conductor with lossy FR4 substrate

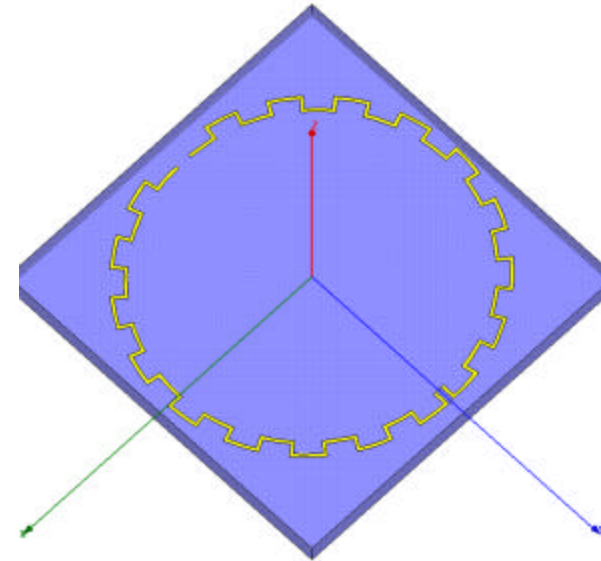


- ◆ G (dBi), ? polarization at $\theta = 0$ and 90° .
Very narrow banded! Efficiency only 55%!
Lots of work to do.



Introduction – Closing Comments

- ♦ Wireless applications growing in complexity, but shrinking in size
- ♦ Antenna size reduction comes with consequences
 - ♦ In general, any change that reduces an antenna's size will result in:
 - ♦ Reduced bandwidth (typically not an issue outside of UWB applications)
 - ♦ Reduced efficiency and therefore reduced gain. (An important indicator of an antenna's performance).
- ♦ Therefore, engineers must use any and all 'tools' at their disposal for achieving higher performance from smaller antennas, including
 - ♦ Load tuning – element specific
 - ♦ Folding/Meandering Antenna Topology – element specific
 - ♦ Smart Diversity (Communication System Techniques)
 - ♦ **Arraying individually substandard antennas to provide appropriate coverage**
 - ♦ **Efficiency improvements by dielectric or other material loss reduction (dielectric laticing)**
 - ♦ **Filtering/tuning with FSS**
 - ♦ **PBG applications for reduction of unwanted imaging currents**
- ♦ The remainder of this presentation will focus on simulation techniques specific to those applications which involve repeated lattice structures and which could be of interest to the Wireless antenna community.

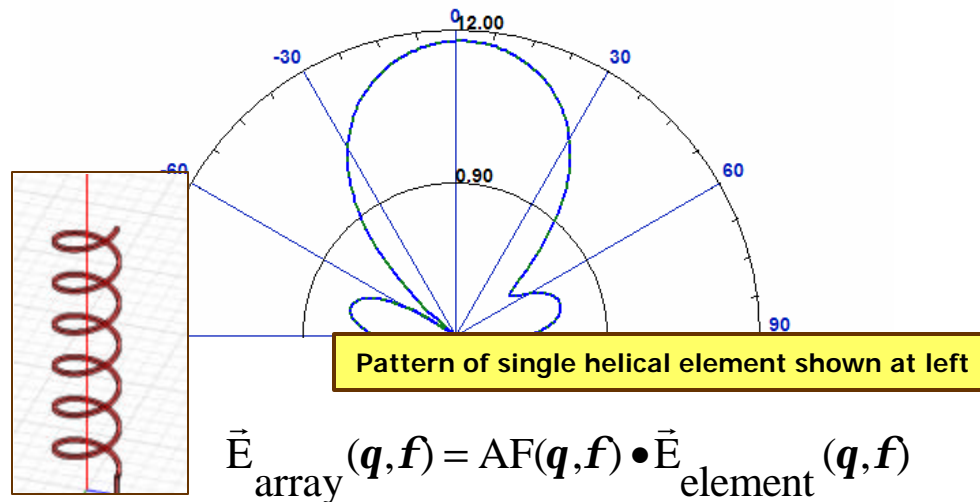


Outline

- ◆ Overview of Simulation Approaches for Latticed Structures
 - ◆ Single/Analytical, Brute, E/H Walls, WG Sim, Linked Boundaries, DomainDecomp
- ◆ Overview of Free-space Termination Options
 - ◆ Surface impedance, 'Radiation', PMLs, Floquet Mode Port
- ◆ Simulation Techniques for Electromagnetic Bandgap (EBG) Applications
 - ◆ Unit cell approaches
 - ◆ Dispersion and Reflection Analysis
 - ◆ Metallodielectric (FEM/MOM) and Dielectric (FEM)
- ◆ Simulation Techniques for FSS Applications
 - ◆ Unit Cell Approaches
 - ◆ Excitation Definitions
 - ◆ FEM and MOM Ramifications (current continuation, etc.)
- ◆ Simulation Techniques for Array Applications
 - ◆ Unit Cell Approaches
 - ◆ "Active S11" and Scan Blindness
 - ◆ "Active Element Pattern" extraction methods

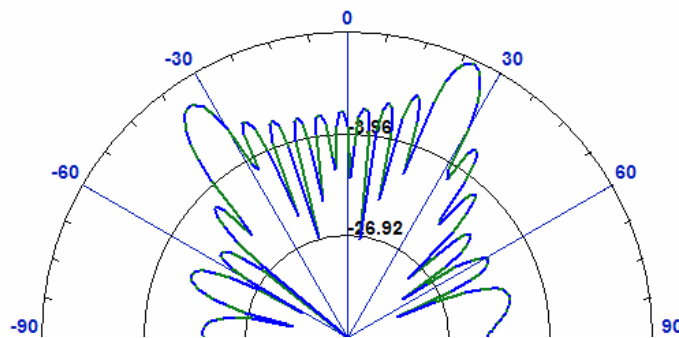


Simulation Overview: Analytical



$$\vec{E}_{\text{array}}(\mathbf{q}, \mathbf{f}) = \text{AF}(\mathbf{q}, \mathbf{f}) \bullet \vec{E}_{\text{element}}(\mathbf{q}, \mathbf{f})$$

$$\text{AF}(\mathbf{f}, \mathbf{q}) = \sum_{n=1}^N W_n e^{jk \vec{r}_n \cdot \vec{r}}$$



Ideal pattern of linear array (10 elements, 1l spacing, 25° scan angle)

- ♦ Analytic array solutions
 - ♦ Perform isolated single-element experiment
 - ♦ Apply mathematical array factor
- ♦ PROS:
 - ♦ Simple, not computationally intensive
 - ♦ Single-element solution can take advantage of symmetry
 - ♦ Can be postprocessing step following any single-element simulation
 - ♦ Easily modified by editing single-element or array factor
 - ♦ Can include amplitude and phase variations per element in array factor
- ♦ CONS: *Idealized Array Results only*
 - ♦ Neglects Edge Effects (significant in smaller arrays)
 - ♦ Neglects mutual coupling effects (significant in **most** useful arrays)
 - ♦ Cannot predict scan blindness, active element pattern, active S11

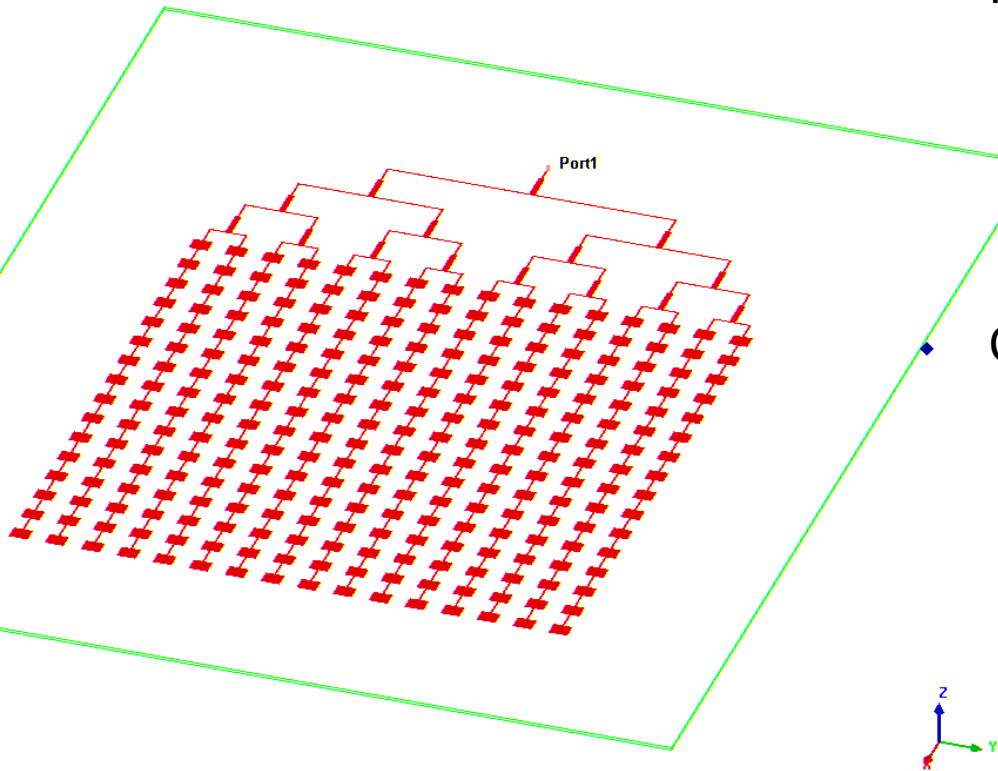
Simulation Overview: Brute Force

- ◆ Solve entire array in simulation
- ◆ PROS:

- ◆ Permits any phase/amplitude tapers desired
- ◆ Works even for 'defected' arrays
- ◆ Neglects Nothing

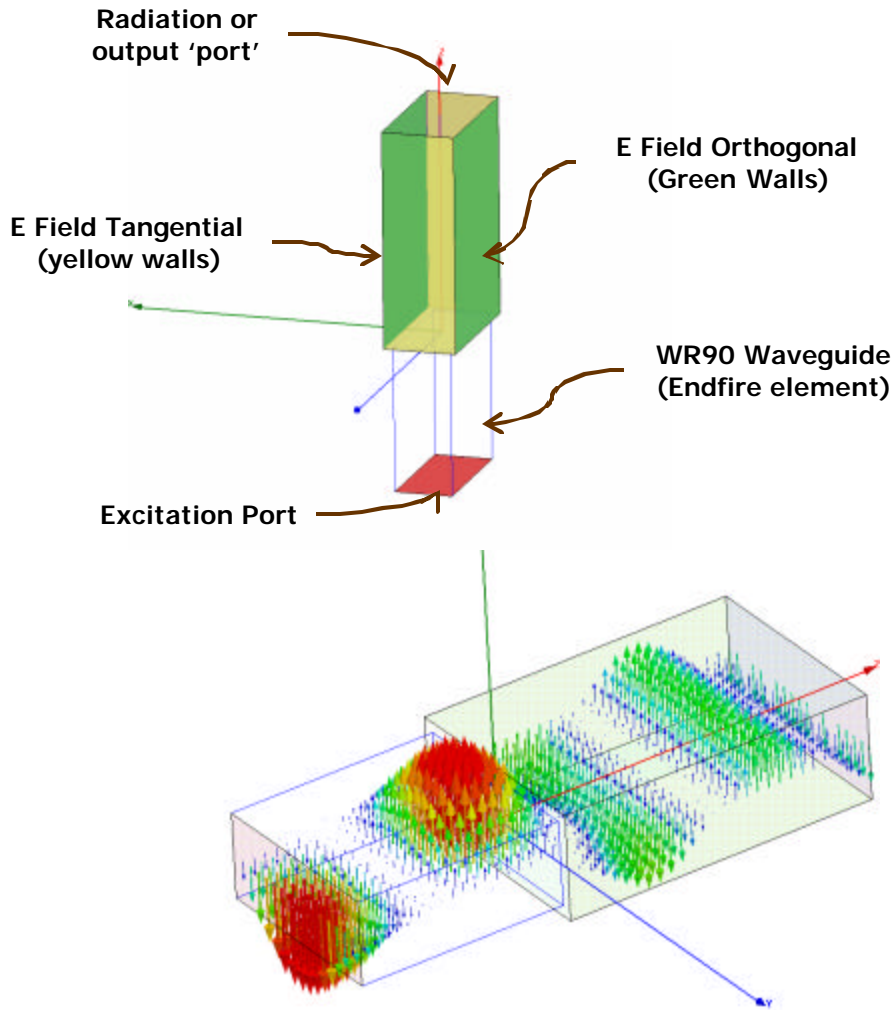
CONS:

- ◆ Computationally very intensive
- ◆ Requires setting all sources independently
 - ◆ Unless feed network included in array geometry
- ◆ Impractical for physically or 'geometrically' very large arrays



Linear-phase fed 16 x 16 patch antenna array. Solvable in Ansoft Designer PlanarEM (MoM) simulation

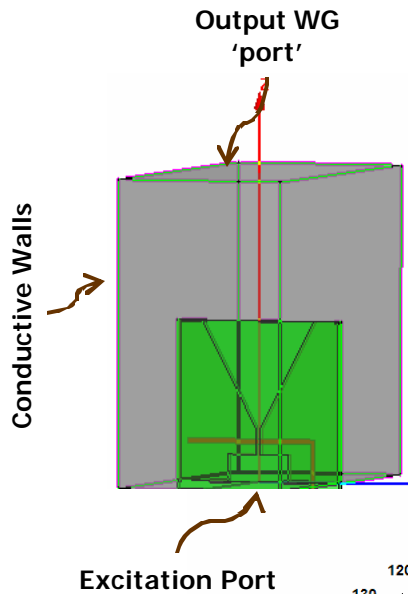
Simulation Overview: E/H Walls



- ♦ Solve one unit of the array with E and H conductor sidewalls
 - ♦ Most basic of the 'waveguide simulator' approaches.
 - ♦ E and H boundaries permit plane wave travel – simulate effect of infinite repetition of such cells
- ♦ PROS:
 - ♦ Much more efficient than brute force
 - ♦ Can capture mutual coupling effect for circumstances where its use is valid
- ♦ CONS:
 - ♦ Only valid for limited set of circumstances
 - ♦ TE modes, rectangular grids, identical excitation
 - ♦ Only provides for 'boresight' or all elements in phase behavior
 - ♦ Therefore no scan blindness, active S11 vs. scan, etc.

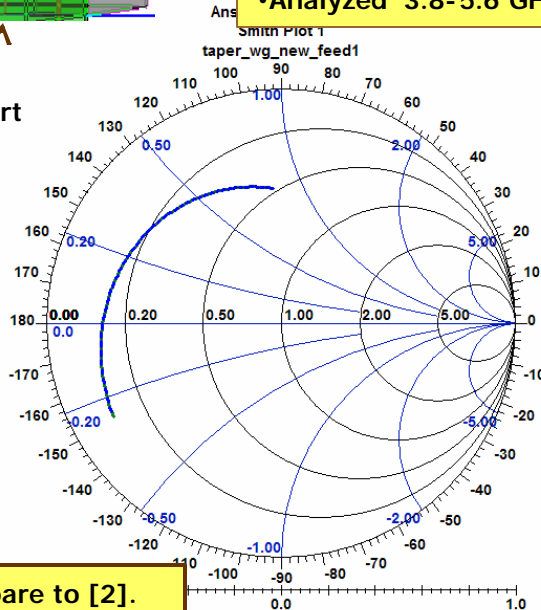
Vector E Field Animation showing TE₁₀ mode in Waveguide, 'plane' wave in air block portion above array

Simulation Overview: “Waveguide Simulator”



Example linearly taper slot antenna :

- Length = 1.38 cm
- Opening = 1.52 cm
- Substrate
 - Thickness = 0.1cm
 - $\epsilon_r = 2.2$
- Unit cell: 2.215cm x 4.78cm
- Analyzed 3.8-5.6 GHz.

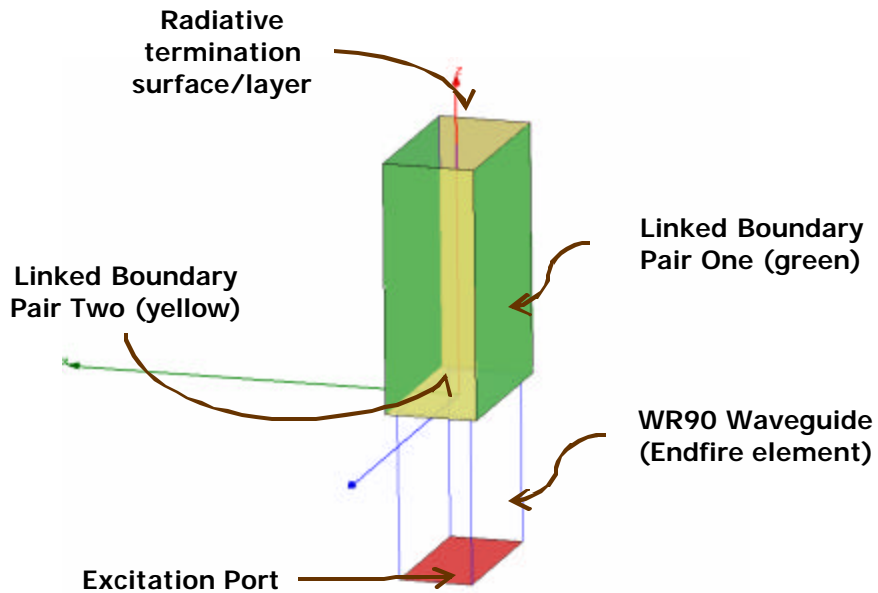


Results Compare to [2].
Further Details on WG
Simulation in [3]

- Solve one unit of the array with various combinations of E and H conductor sidewalls ('waveguide')
 - Solve many 'modes' of excitation for the output port.
 - Each 'mode' coincides with a specific angle of incidence, e.g. scan angle out of the array
- PROS:
 - Much more efficient than brute force
 - Can capture mutual coupling effect over specific discrete scan angles
- CONS:
 - Only valid for discrete scan angles and modes
 - User must compute modal to angle relationships
 - Relative to array spacing, etc.
 - No continuous scan blindness, active S11 vs scan angle.
 - Pattern computation from results difficult (output is S-parameters)



Simulation Overview: LBCs



$$E_S = e^{jy} E_M$$

Y can be a single fixed value for each master/slave pair, or computed from an intended scan angle in spherical coordinates (θ, ϕ) , from the vector relationship between the master and slave walls, and their normal vectors or orientation in the spherical coordinate system.

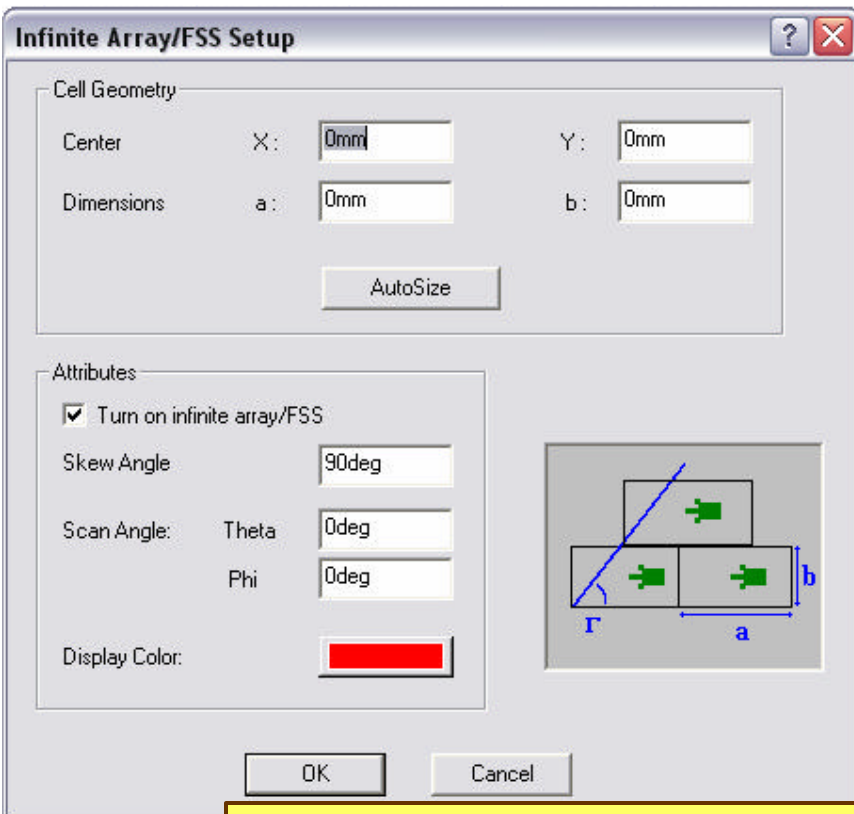
Fixed values imply frequency scanning or periodic waveguiding structures (e.g. corrugated waveguide with Master and Slave on Input and Output faces).

Ansoft HFSS™ permits both assignment techniques.

- ♦ Solve a true unit cell surrounded by *linked* (or periodic) *boundary conditions* (LBCs) [4]
 - ♦ Boundaries constrain phase relationship between walls, not E vector orientation
 - ♦ User defines local coordinate systems relating 'master' to 'slave' wall of pair
 - ♦ Relative phase can be absolute per pair or computed relative to an effective array scan angle
- ♦ PROS:
 - ♦ Solution efficiency
 - ♦ Most general Unit Cell Approach
 - ♦ Computes true active S11 and scan blindness
 - ♦ Computes true single element pattern with mutual coupling terms
 - ♦ Multiply by array factor to get array pattern
 - ♦ Can compute 'active element' pattern
- ♦ CONS:
 - ♦ Still neglects edge effects – all elements have same mutual behavior to kin
 - ♦ While including effects of phase excitation differences, assumes uniform amplitude excitation – no tapering
 - ♦ Iterative solution: one solution per scan angle or LBC phase criteria set.

Simulation Overview: PMM

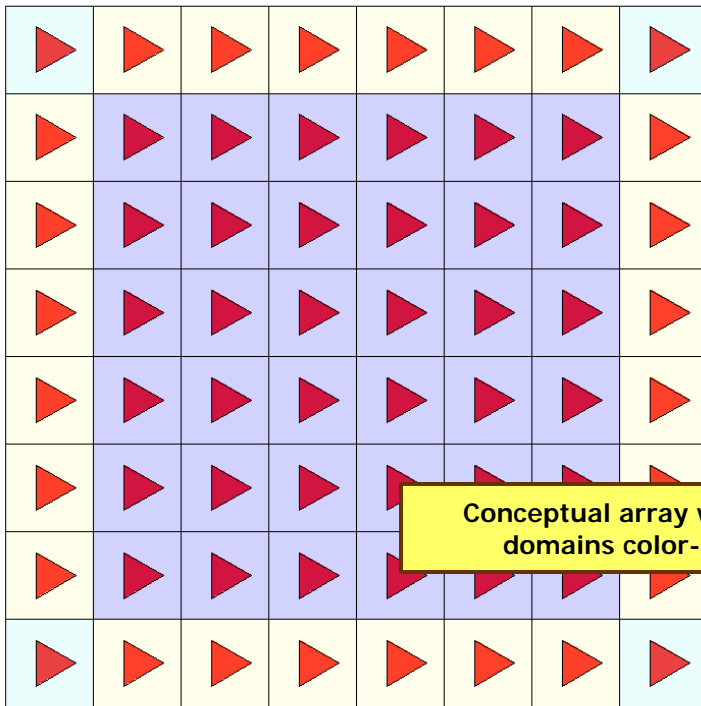
- Specific to surface-type codes, the *periodic moment method* (PMM) permits current imaging on lattice structures (e.g. for planar arrays)
 - User defined lattice spacing, generally as height, width, and skew angle α type parameters
 - Excitation assumed to be uniform in amplitude with scan angle relations similar to LBC technique in 3D simulation
 - May also be plane wave, not local 'ported' excitation
- PROS:
 - For planar circuits, much more efficient than brute force
 - Can compute active S11 and mutual coupling effects w.r.t. scan angle.
 - Can compute active element pattern, array pattern.
- CONS
 - Edge effects neglected (all mutual coupling terms identical)
 - Amplitude variations still missing
 - Implementations may not allow for 'current continuation' between cells (not limitation of method)



Ansoft Designer Planar EM Array Setup

Detailed Description of the Periodic Moment Method can be found in [5].

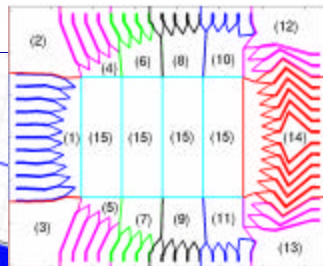
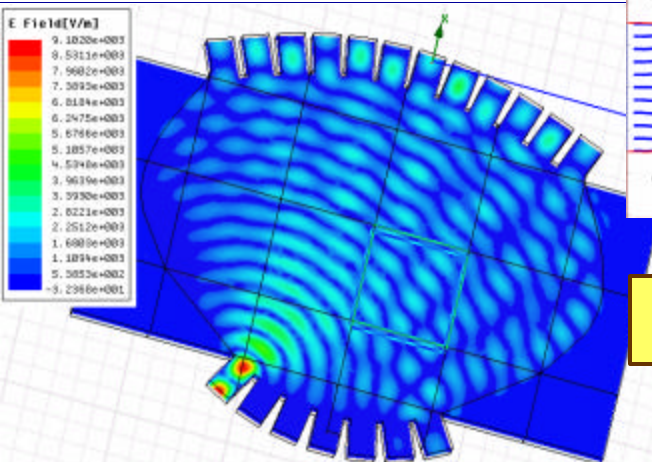
Simulation Overview: Domain Decomposition



Conceptual array with subdomains color-coded.

- Subdivide model into 'subdomains' of unique behavior, and solve each iteratively to determine interaction between subdomain boundaries
 - Domains can be identical geometry in non-identical placements, e.g. array corner, edge, and center elements
- PROs:
 - Solution efficiency better than brute force
 - Computes true active S11 and scan blindness
 - Compute **all** array behavior including scan blindness, active S11, active element pattern, and array pattern including both mutual coupling AND **edge effects**
 - Useful for other large-structure applications besides periodic geometries (see bottom)
 - Can set excitations for amplitude as well as phase offsets (Taylor taper, etc.)

- CONs
 - Iteration between subdomains reduces efficiency slightly below that of LBC approach
 - Excitations now individually managed
 - No known commercial software currently has this technique**

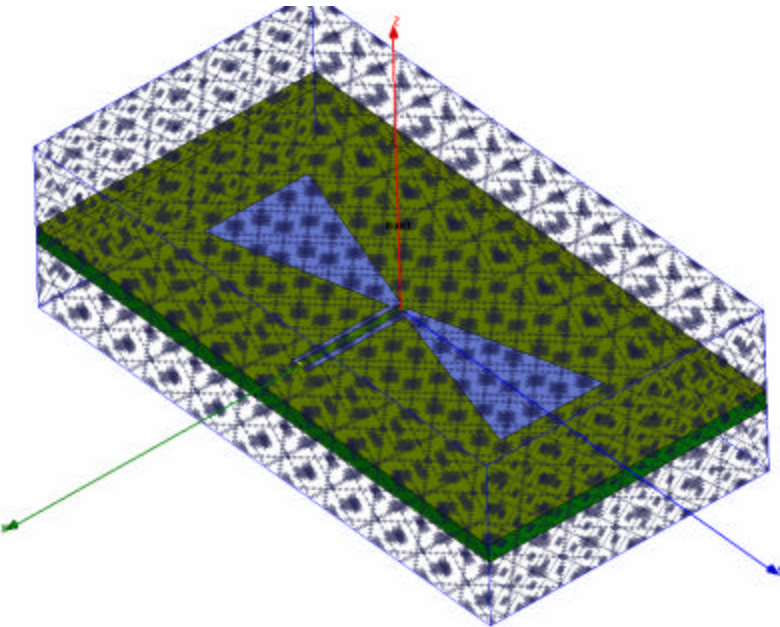


Rothman Lens (Ansoft, under development)

Simulation Overview: Final Words

- ◆ As discussed, each method has its benefits and drawbacks
- ◆ As a general rule, the fewer the drawbacks, the more usage-intensive a technique will become
 - ◆ E.g. LBC's requiring local coordinates, PMM requiring lattice definitions, Domain Decomposition requiring segregation of subdomains.
 - ◆ Misuse (incorrect sizing of unit cell as compared to array factor to be applied later) will result in nonphysical results
- ◆ For different applications, different methods may prove more useful than others
 - ◆ E.g. PMM for planar geometries vs. LBCs for more volumetric ones
- ◆ Remainder of course will apply a subset of these methods for specific applications
 - ◆ Use of **Periodic Moment Method** will be illustrated for FSS and PBG applications using Ansoft Designer (Planar EM level solver)
 - ◆ Use of **Linked Boundary Condition** method will be illustrated for FSS, PBG, and array applications using Ansoft HFSS

Free-space Terminations: First Words



- ♦ All antenna analysis of a computational nature requires some handling of the 'free space' into which the antenna is to radiate
 - ♦ Ray tracing methods simply assume infinite open space outside drawn geometry
 - ♦ Finite Element and Finite Difference Time-Domain methods generally assume fields cannot exist outside user defined region
 - ♦ User defines an 'air volume' surrounding radiator
 - ♦ Method of Moments can have closed formulation (assumes cavity dimension surrounds currents being solved) or open formulation (assumes single imaging ground plane only)
 - ♦ Proper definition of the cavity and/or plane can influence results
- ♦ Therefore, proper treatment of the boundary where the computational domain ends but real 'free space' around the antenna continues is of paramount importance
- ♦ Following slides will outline some methods in use today.

Free-space Terminations: 377W

- ♦ Intrinsic impedance of free space is given as

$$h_o = \sqrt{\frac{\mu_o}{\epsilon_o}} = 376.73031 \approx 377\Omega$$

- ♦ Therefore, the 'simplest' way to terminate a volume with the implication of further free space outside it is with a 377 $\Omega/?$ surface impedance
 - ♦ " $\Omega/?$ " denotes "ohms per square" which is generalized sheet resistance, not to be mistaken as having any 'unit' (such as meters²) implications
 - ♦ For conversion, imagine a thin film resistor, l long (direction of current flow) by w wide. Lumped resistance is related to sheet resistance by

$$R_L = \frac{w}{l} R_S$$

- ♦ For a coaxial resistor (annular surface area with inner radius a and outer b) the relation would be:

$$R_L = \ln\left(\frac{b}{a}\right) R_S$$

(derivation left to the student ☺)

- ♦ PROS: Simple to assign; single-value entry; works for eigensolutions too
- ♦ CONS: What about terminating volumes other than vacuum? Boundaries between volumes?

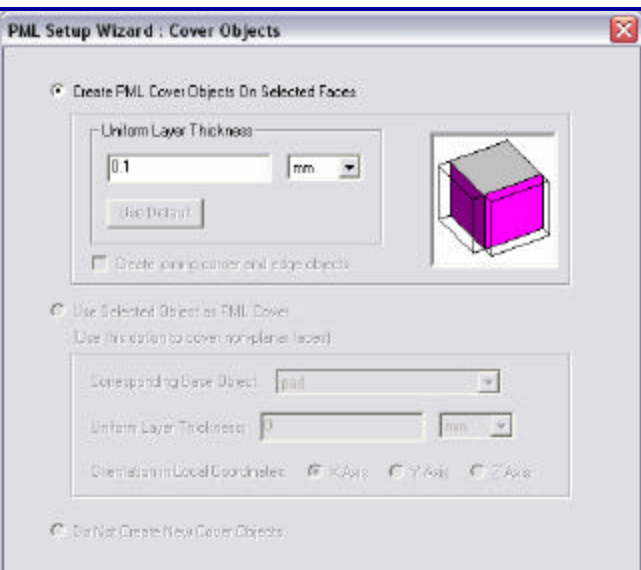
Free-space Terminations: “Radiation Boundary”

- Most 3D simulation software uses a second-order impedance surface termed a “radiation boundary”
- Unlike simple 377Ω , a radiation boundary is computed for each material touching the surface and is frequency dependent

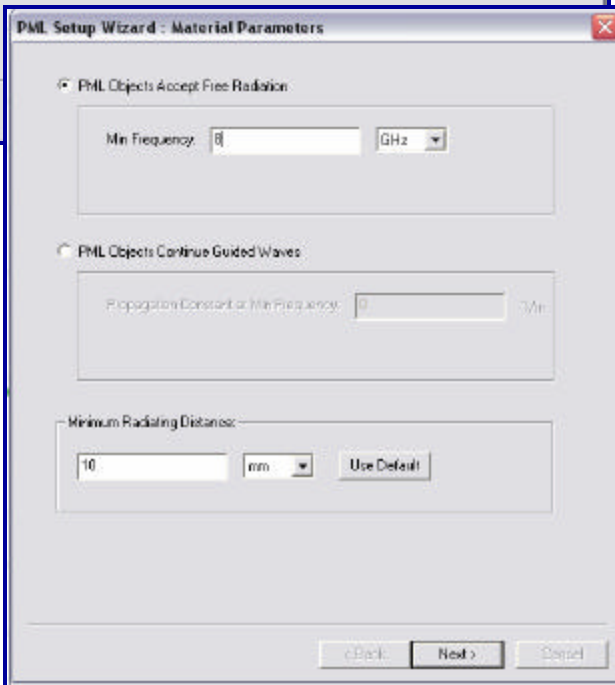
$$(\nabla \times E)_{\text{tan}} = jk_o E_{\text{tan}} - \frac{j}{k_o} \nabla_{\text{tan}} \times (\nabla_{\text{tan}} \times E_{\text{tan}}) + \frac{j}{k_o} \nabla_{\text{tan}} (\nabla_{\text{tan}} \cdot E_{\text{tan}})$$

- PROS:
 - Superior absorption to single-valued impedance boundary, especially with nonhomogeneous volumes
 - Reasonably absorptive with reflections exceeding 80 dB isolation possible
 - Transparent user setup (ease of use)
- CONS:
 - As a *surface termination* only, sensitive to angle of incidence and distance from radiator
 - Loses some absorption over broad solution frequency ranges using numerical sweep techniques (e.g. AWE, ALPS)
 - Not functional for eigensolution due to frequency dependence! (k_o is wavenumber $\omega\sqrt{\mu\epsilon}$)

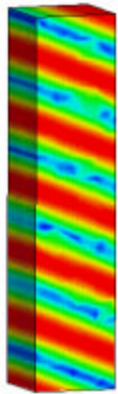
Free-space Terminations: PMLs



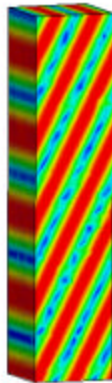
- ◆ Perfectly Matched Layers (PMLs) are slab absorbers which can also terminate an interior volume
 - ◆ Berenger-type PMLs are used for time-domain codes [6], while bianisotropic materials are used for frequency-domain codes [5]
 - ◆ Use Snell's law to refract incoming radiation deeper into the material for absorption
 - ◆ Material parameters computed based on frequency of use, distance from radiator, and PML slab thickness
- ◆ PROS:
 - ◆ Superior absorption vs. surface impedance possible.
 - ◆ Can be closer to radiator, reducing overall modeled volume
 - ◆ Refractive nature makes them far less sensitive to angle of incidence
- ◆ CONS:
 - ◆ Generally have a frequency bandwidth of acceptable operation
 - ◆ Adds 'wavelength volume' by higher dielectric constant
 - ◆ More setup requirements
 - ◆ Still cannot absorb 'grazing' incidence rays



Free-space Terminations: Floquet Mode Boundary



Steered TE00



TE10,
Propagating



TE10, Cutoff
(surface wave)

- The modeled space is terminated with analytic 'port' at which fields must satisfy the condition of a superposition of Floquet free-space modes, per:

$$\iint_{port} \mathbf{W}_p \cdot \left(\mathbf{E}(x, y) - \sum_{q=1}^N x_q \mathbf{W}_q \right) da = 0 \quad p = 1, \dots, N$$

$$A \mathbf{x}_m = \mathbf{b}_m \quad m = 1, \dots, M$$

- PROS:
 - Best termination possible assuming sufficient modes computed, up to and including grazing/surface wave
 - Automatic segregation of radiative incidence angles into different modes
 - Useful for isolating specular vs. grating lobe type effects
- CONS:
 - For use on single face, not entire model periphery (e.g. in array unit cell not isolated antenna)

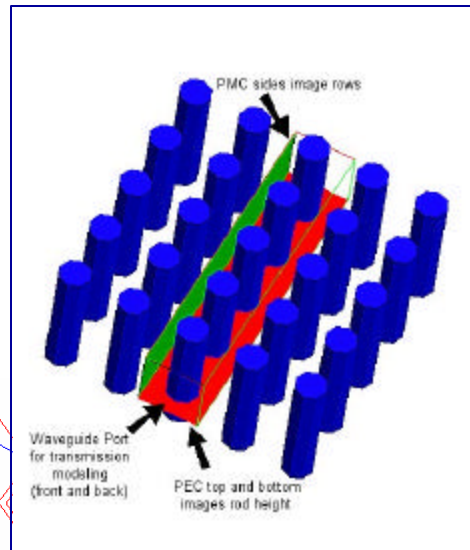
Terminations: Final Words

- ◆ As discussed, each method has its benefits and drawbacks
- ◆ As a general rule, the fewer the drawbacks, the more usage-intensive a technique will become
 - ◆ PMLs require additional setup yet provide superior absorption
 - ◆ Floquet boundaries require additional computational requirements
 - ◆ Additional setup *may be* made transparent to users with commercial software advances
 - ◆ But ‘assumptions’ made should always be understood by educated users!!
- ◆ For different applications, different methods may prove more useful than others
 - ◆ E.g. Floquet mode terminations not generally usable for non-arrayed element analysis
 - ◆ Sometimes ‘easiest method’ is ‘enough’
- ◆ Remainder of course will apply a subset of these methods for specific applications
 - ◆ Use of **Radiation Boundary**, 377 ohm Impedance, or **PMLs** will be illustrated as applicable for examples from Ansoft HFSS™
 - ◆ Examples shown from Ansoft Designer™ Planar EM solver use ‘open’ formulation Method of Moments (MoM)

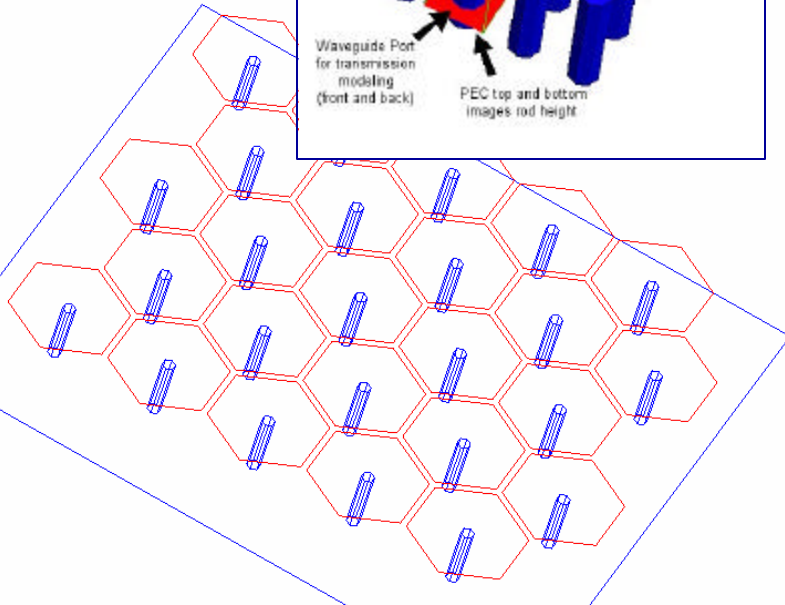
Part Two: Specific Application Techniques for EBGs

Wireless and Microwave Technology Conference
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Thursday, April 07, 2005
Clearwater, FL

Electromagnetic Bandgaps (EBGs): Description



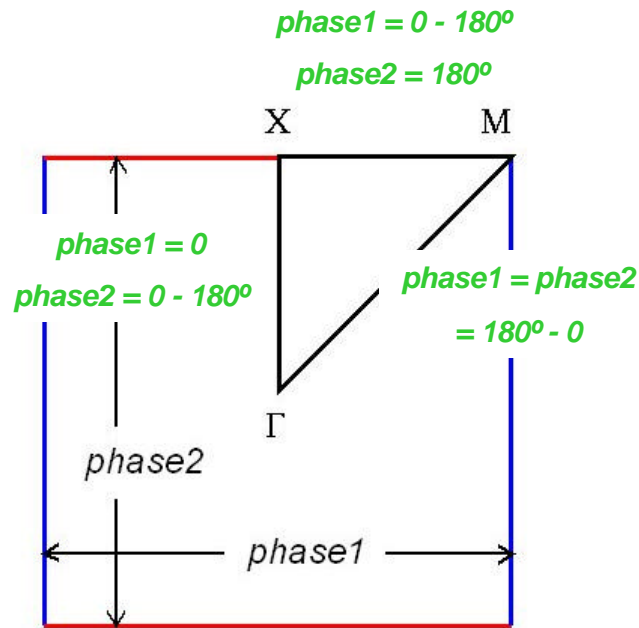
- ♦ Electromagnetic Bandgaps (EBGs) formerly called Photonic Bandgaps (PBGs) are an interesting new technique for surface wave reduction in antenna applications
 - ♦ A periodic metal pattern or dielectric change provides a tuned circuit effect with a 'forbidden band', preventing surface wave transmission
 - ♦ At the tuned frequency, the surface has a 'high impedance' effect [7]
 - ♦ Therefore, unlike a ground plane, it reflects incoming waves *in phase* rather than 180° out of phase
- ♦ Implication:
 - ♦ Ground plane imaging currents will not be destructively interfering with desired antenna behavior
 - ♦ Balanced elements can be made much closer to such a surface without efficiency penalties, rather than requiring cavities or voids beneath
 - ♦ NOT for use 'beneath' patch-like antennas



Dielectric rod EBG (top) and Sievenpiper hexagonal plates with via (bottom, [7])



EBGs: Characteristics for Analysis



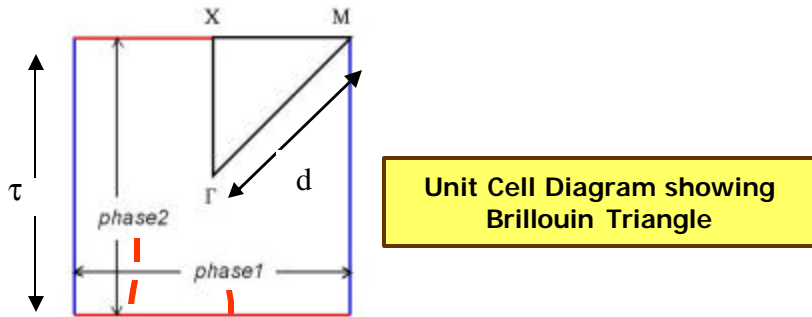
$$f_{PBG} = \frac{\int_s \text{Phase}(E_{\text{scattered}}) \cdot ds}{\int_s \hat{s} \cdot ds}$$

$$f_{\text{plate}} = 180 - \frac{d}{l} \cdot 360$$

$$\Delta f = (f_{PBG} - f_{\text{plate}}) + 180$$

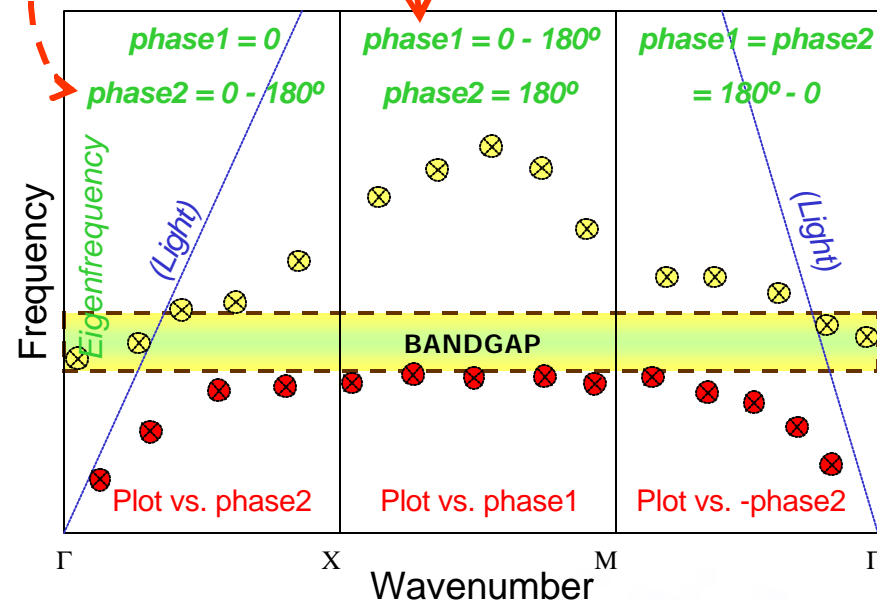
- The features of an EBG construction of interest to antenna designers are:
 - *Dispersion Diagram* – wave propagation vs. frequency, also known as the ‘band diagram’
 - Will show the frequency band(s) over which the EBG forbids surface wave travel
 - *Reflection Phase Analysis* clarifies the subset of the band gap where the surface reflection is constructive ($\pm 90^\circ$ phase range)
 - Both behaviors are an array or lattice phenomenon, and will not show up for a single or even small number of elements
- Useful EBGs will have feature size much smaller than wavelength
 - Otherwise they’re too large to assist with a small antenna design
- Therefore, solving a ‘brute force’ array of such features would become computationally demanding
 - “Geometrically Dense” – much discretization
 - Perfect application for the Unit Cell Techniques discussed so far

EBGs: Dispersion Analysis



Unit Cell Diagram showing Brillouin Triangle

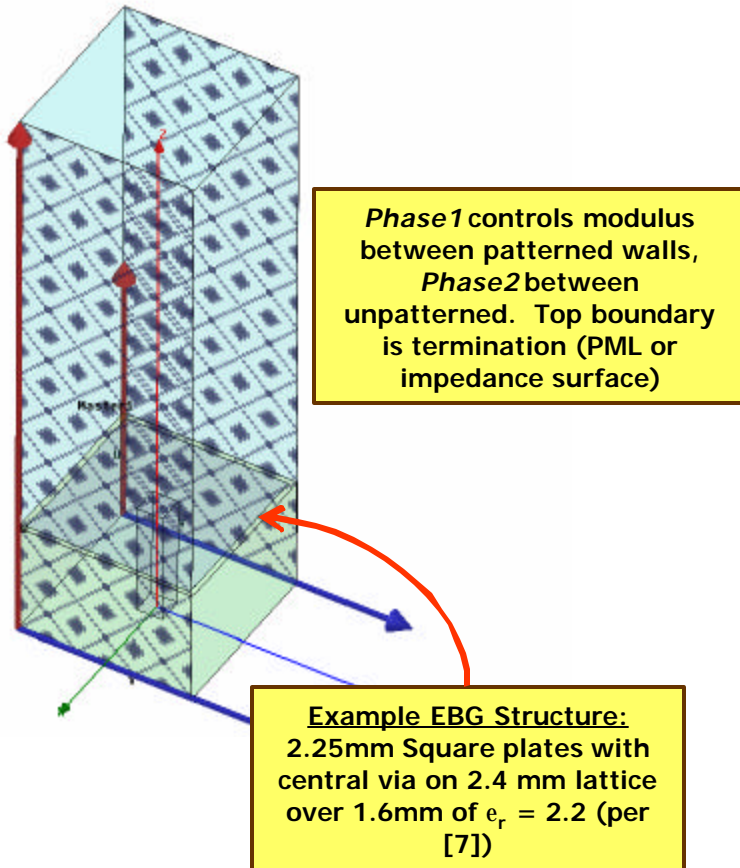
- Dispersion Analysis can be performed with an LBC Unit Cell approach
- Eigensolution is performed over range of possible phase differences between the lattice wall sets
 - Phase difference between Master and Slave wall analogous to an *angle of incidence*, therefore a *wave number* across the cell
 - Resonant frequencies are plotted with respect to the phase difference and arranged to replicate a Brillouin Triangle dispersion curve set
 - Three subsweeps as shown at left, each corresponding to one 'leg' of the triangle
 - Solve for a number of modes (TE, TM, etc)
 - Detailed directions in [8]
 - The "light line" may also be plotted to show the free space propagation relation ($c=f\lambda$)
- Band Gap is identified by frequencies where there are no possible eigensolutions of any mode between the light lines



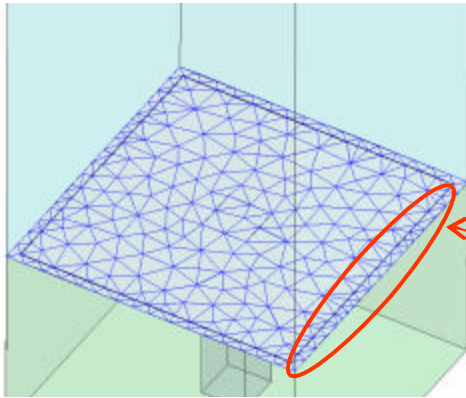
EBGs: Dispersion Analysis Setup

- ♦ Geometry Setup:

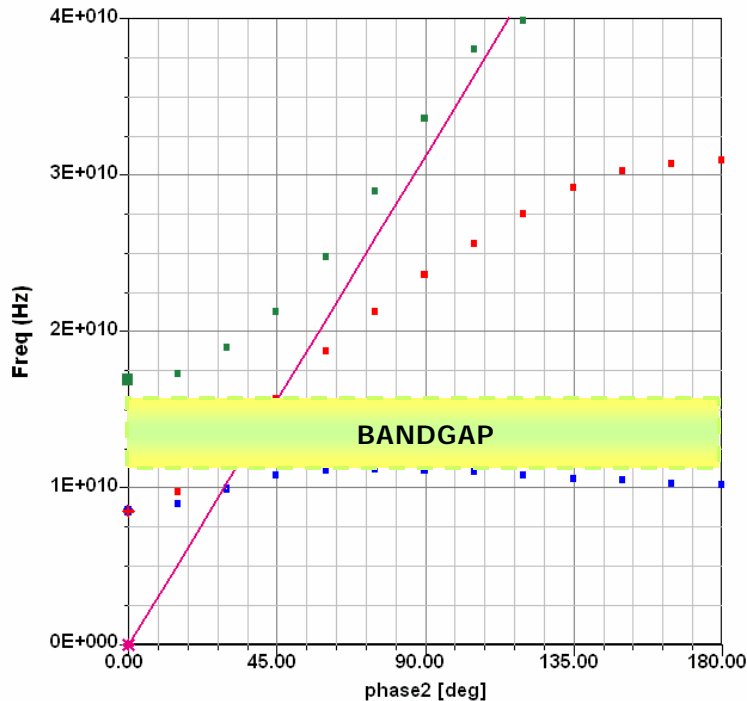
- ♦ Unit cell must include 'air height' above the surface under test reasonable to assume tipping a phase-front plane to a relatively high angle (e.g. 60° or so)
 - ♦ Cross-section dimension of unit cell model matches lattice repetition
 - ♦ Distance to absorbing boundary not 'wavelength related' as unit cell size often much smaller than wavelength. Plus simulation bandwidth for eigensolutions will be considerable (10+ GHz range)
 - ♦ Resonance effect of the lattice will be proportional to geometric loading features (capacitance between plates, etc)
 - ♦ Use PML or impedance boundary to terminate top of air volume (not shown)
- ♦ Define sides of model as LBC Master/Slave pairs
 - ♦ Parameterize the phase modulus between them as *Phase1* and *Phase2*. These are the input variables to a parametric sweep'
 - ♦ LBC should cover side faces of PML if present as well



EBGs: Dispersion Analysis Outputs



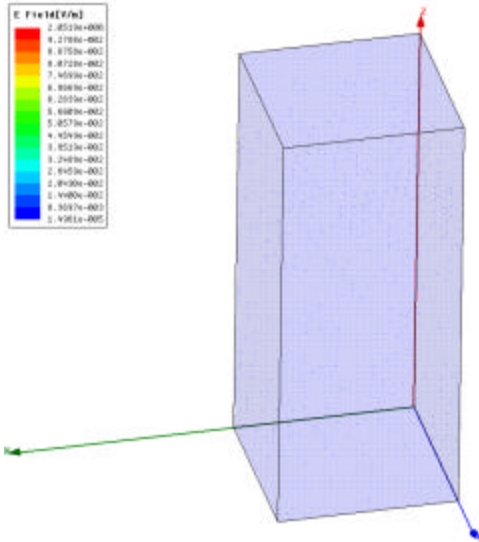
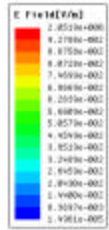
Note denser mesh at cell periphery (gap between plates)



- ◆ Solution Techniques:
 - ◆ Simulation convergence can be aided with the use of *mesh operations* or user-assisted instructions
 - ◆ Adaptive mesh techniques will converge on proper fields regardless. But if user has insight into expected behavior, such as importance of the narrow gap between plates from cell to cell, providing instruction to pre-condition the mesh can speed the solution process.
- ◆ Results:
 - ◆ After simulation, results can be plotted as data table or as graphical form
 - ◆ Eigenmodes fall into curves, between which will be the band gap
 - ◆ Analytical values such as the light line can be superposed on the same axes using Output Variable capability.
 - ◆ Results from one leg of the Brillouin Triangle are shown at right, indicating an expected bandgap
 - ◆ Gap of ~11-17 GHz agrees with Ref [7] paper

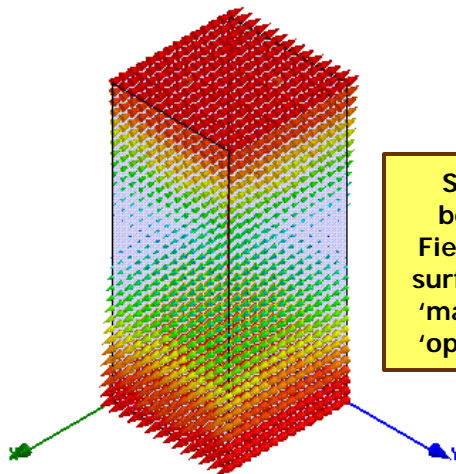
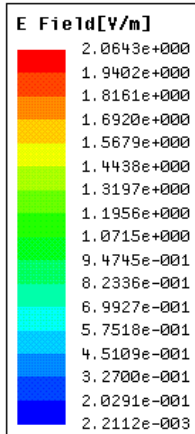


EBGs: Reflection Phase Analysis



Unit cell of air with radiation at top, LBC sides, and PEC bottom. Note Total E Field is strongest 1/4 above surface since metal reflects *out of phase*.

- ◆ Construct a unit cell of the lattice structure as before (options described in following pages)
- ◆ A scattering solution of response to a normal plane wave excitation is computed
- ◆ Phase of the reflected wave w.r.t. a metal plate reflection is extracted
- ◆ Band Gap identified by frequencies where the reflection is not $\pm 180^\circ$
 - ◆ Procedure defines most useful subset of bandgap ($\pm 90^\circ$ range)

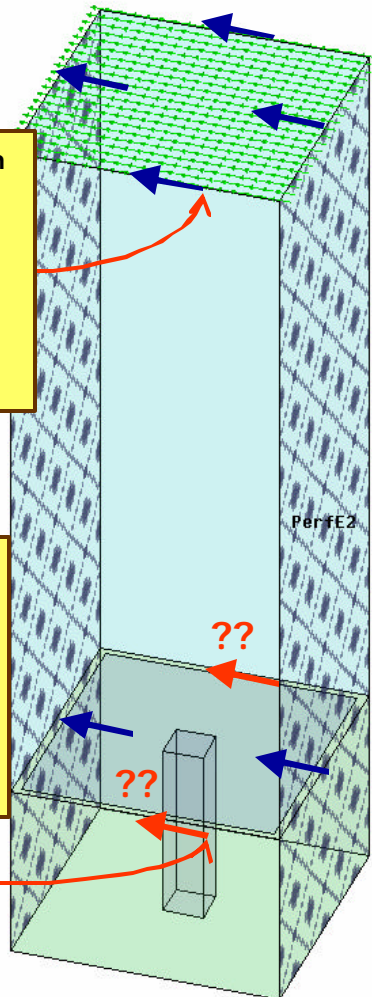


Same cell, with PMC bottom face. Total E Field is strongest at the surface because an ideal 'magnetic conductor' or 'open' reflects *in phase*.



EBGs: Reflection Phase Setup 1

- Method One
 - For unit cells which do not constitute simply 'planar' geometries in stratified dielectric media, volumetric solution is required.
 - E.g. Dielectric woodpile or rod lattice
 - If lattice is square or rectangular, the E/H wall "waveguide simulator" may be sufficient
 - **CAUTION:** Although E/H walls are appropriate for plane wave symmetry, response of the circuit may not be E/H symmetric!!
 - See example at left
 - May limit polarization cases for this method
- Construct unit cell with reasonable height above surface to be evaluated
 - $\lambda/10$ minimum at lowest frequency to be tested, or 3-4 times the unit cell cross-section dimension is sufficient, whichever is smaller
- Define two parallel sidewalls as Perfect E conductor, two as Perfect H conductor
- Define a port excitation at the top of the model. The boundary conditions will enforce a plane-wave type wave distribution
- Extract results from S11 phase.
 - "De-embed" to top of surface



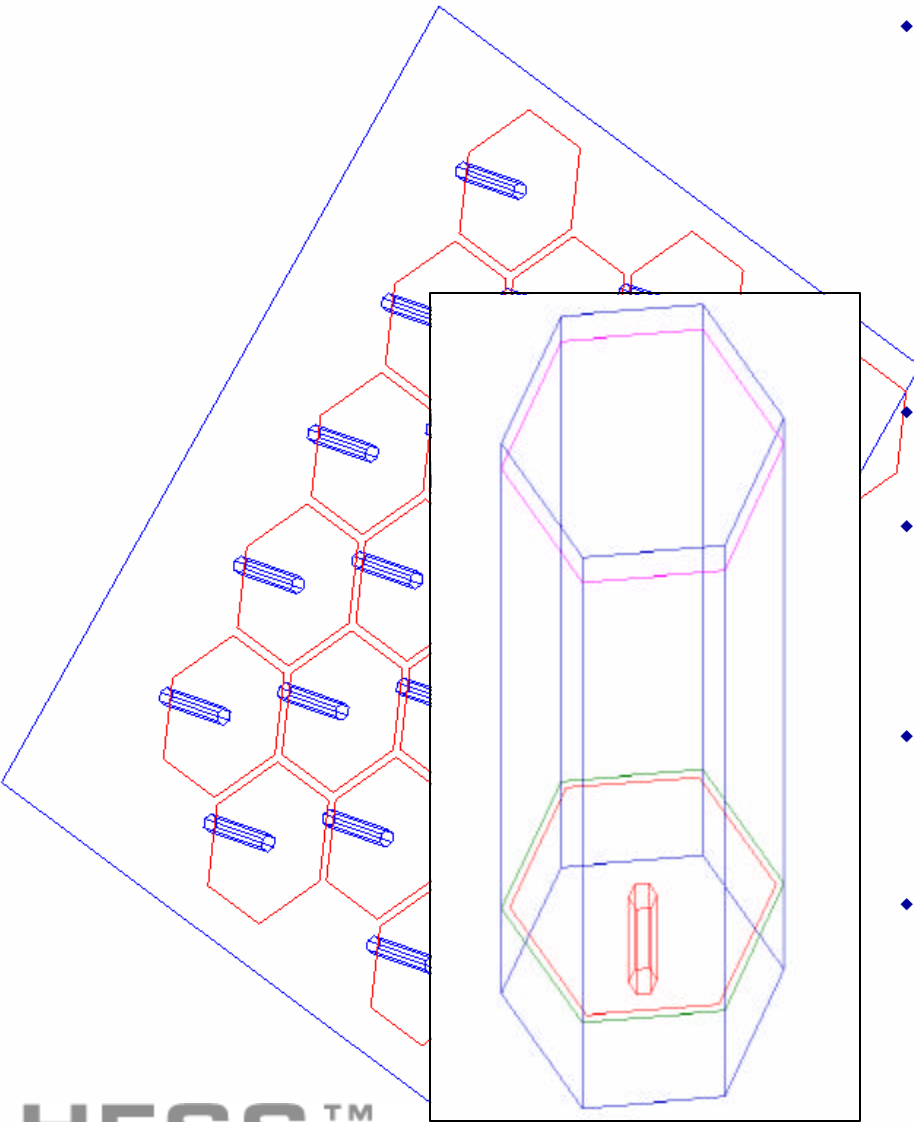
Consider the same patch array shown before.

Patterned sides force E orthogonal, plain sides force E parallel.
Generates TEM port excitation.

...but would fields be 'parallel' to narrow channels between plates on two sides vs. the other two? **NO.** Yet approximation might be acceptable for single polarization assumption.

EBGs: Reflection Phase Setup 2

- ♦ Method Two
 - ♦ If lattice is nonrectangular, and structure still requires 3D solution, use Unit Cell with LBCs
 - ♦ Or rectangular, with field behavior of lattice not permitting E/H wall pairs
 - ♦ LBC sets can define many nonorthogonal lattices as shown at left. Example below is of hexagonal patch lattice per Sievenpiper [5]
- ♦ Unit cell dimensional requirements are the same as for Method One
- ♦ Add a radiation boundary condition to the top face
 - ♦ PML not necessary for normal incidence/reflection
- ♦ Excite model with plane wave input and compute scattering response
 - ♦ Normal incidence plane wave
- ♦ Post-process reflection phase by evaluation of the local field solution
 - ♦ E.g. in HFSS™ by using the supplied Vector Field Calculator

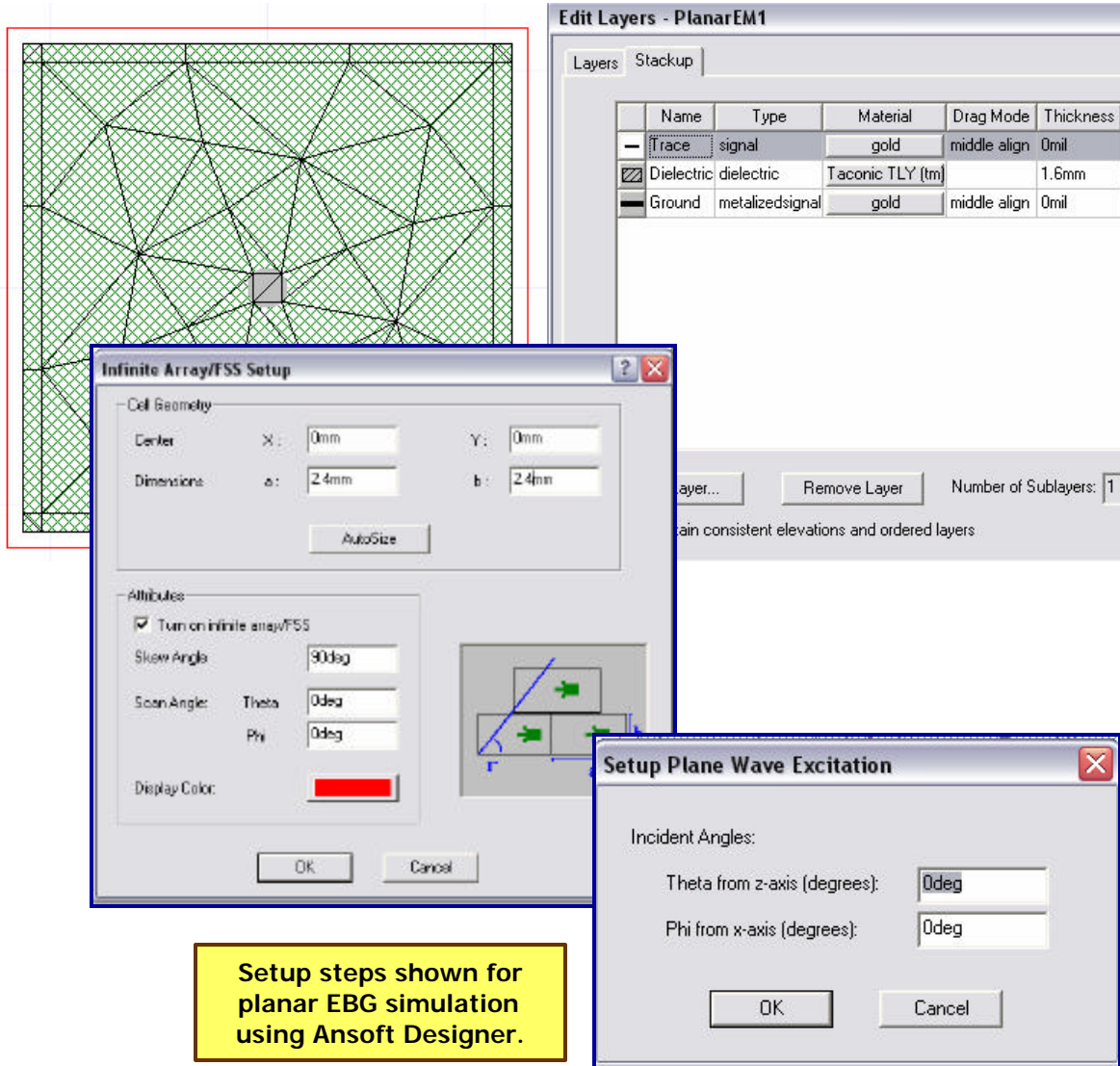


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EBGs: Reflection Phase Setup 3



Setup steps shown for planar EBG simulation using Ansoft Designer.

- For 'planar' circuit, can take advantage of method of moments and solve unit cell in PMM
- Draw single unit metal pattern in layout
 - Depending on treatment of *current continuation* in your code of choice, consider if pattern cell should be connected or not
- Define lattice constants for array
- Specify plane wave excitation and frequencies of solution.
 - Normal direction only
 - Multiple polarizations if desired

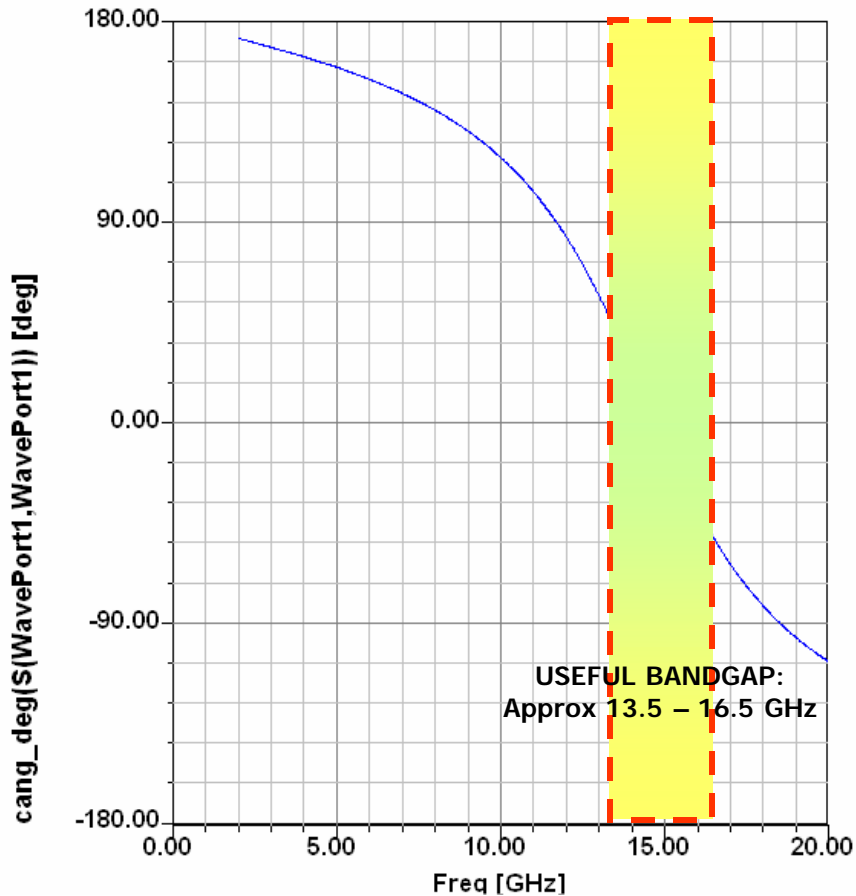


EBGs: Reflection Phase Results

30 Mar 2005

Ansoft Corporation
XY Plot 1
reflection phase 1

14:36:37



- ◆ A scattering solution of response to a normal plane wave excitation is computed
- ◆ Phase of the reflected wave w.r.t. a metal plate reflection is extracted
- ◆ Band Gap identified by frequencies where the reflection is not $\pm 180^\circ$
 - ◆ Procedure defines most useful subset of bandgap ($\pm 45^\circ$ range)
- ◆ Results at left from HFSS E/H wall technique; Designer solution for same structure is identical.
 - ◆ Compare to [7]
 - ◆ For polarization case where E field lies parallel to lattice orientation, E/H wall assumptions are sufficient
 - ◆ Would not work on other polarization, hexagonal lattice, etc.

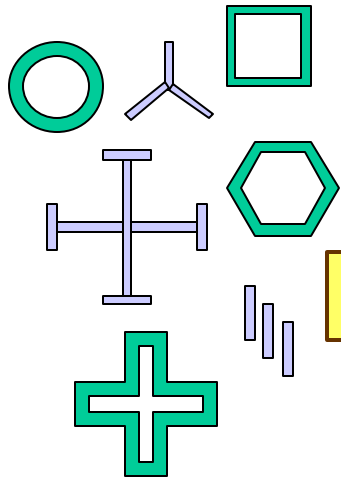
HFSS™

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Part Three: Specific Application Techniques for FSSs

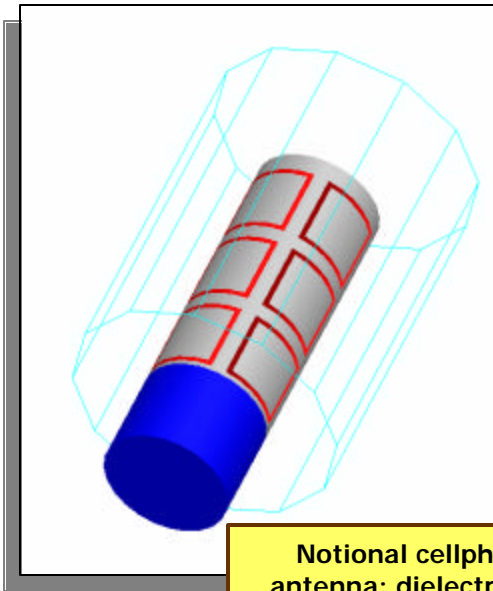
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Thursday, April 07, 2005
Clearwater, FL

Frequency Selective Surface (FSS): Description



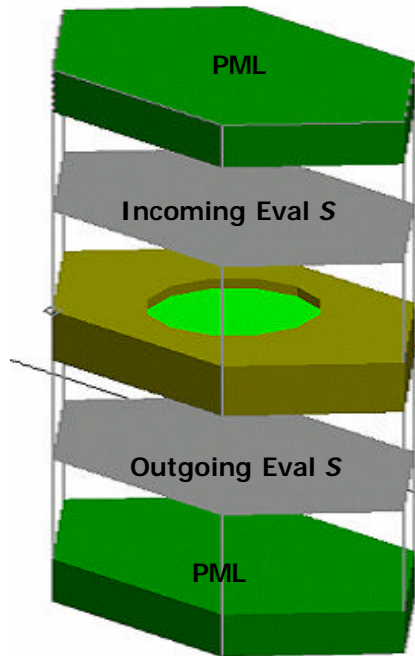
Different FSS element types [5]

- A *frequency selective surface* is essentially a ‘filter’ for plane waves in space
- It intends to provide either a passband or stopband at certain frequencies
 - Reduce out-of-band noise; limit bandwidth of a broader-band, lower-Q antenna, provide frequency-domain ‘splitter’ reflector (dichroic surface)
 - For military applications, FSS provide for ‘stealthing’ of the antenna at out-of-band frequencies
 - Novel applications of frequency-selective behavior (see left)
- Construction:
 - Generally constructed of a lattice of repeating metal patterns or nonmetal apertures on a layer.
 - Often accompanied by different dielectric layers for matching
 - Sometimes 3D dielectric structures
- Important Parameters of an FSS:
 - Bandwidth – the band of any desired stop or passband behavior
 - Measured by measuring the FSS’s transmission and reflection characteristics over frequency and angle of incidence.
 - Insertion Loss – the attenuation in the band of interest
 - Polarization – the polarizations for which it is useful
 - Refraction/Grating – for more detailed ‘radome’ designs, the effects of beam squinting, spreading, or lobing as they pass through an FSS structure become important



Notional cellphone antenna: dielectric rod with FSS pattern on sides modifying beam shape and tuning. [9]

FSS: Nonplanar Cell Analysis 1

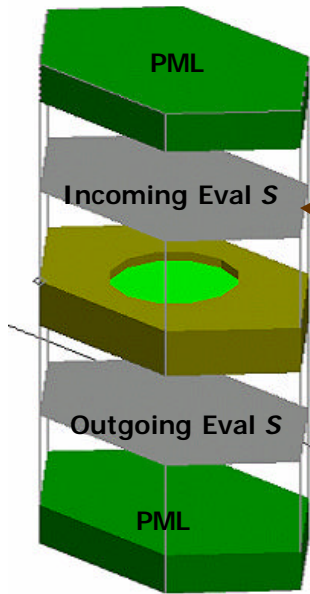


Non-rectangular lattice of incompletely dielectric-filled holes in thick metal plate. This type of FSS is used in some avionics applications due to high structural strength.

More details of FSS analysis using HFSS can be found in [10].

- Using a volumetric code like HFSS™, set up unit cell model with *linked boundary conditions*
 - E/H walls also useable for limited cases (normal incidence only, rectangular lattice)
- Source excitation is plane wave at angle (ϕ, θ)
 - Can be varied in parametric fashion for analysis w.r.t. incidence angle
- LBC boundary setup uses “scan angle” of $(\phi+180^\circ, \theta)$
 - Boundary condition reinforces ‘specular’ reflection direction
- FSS is a *transmissive* surface so unit cell requires radiation termination of some form on both top *and* bottom of modeled cell!
 - Radiation boundaries or even simple 377Ω sufficient for normal incidence case
 - But FSS analysis implies angle of incidence range as well as frequency range of interest. Therefore more robust absorption offered by PML and/or Floquet ports are preferred

FSS: Nonplanar Cell Analysis 2



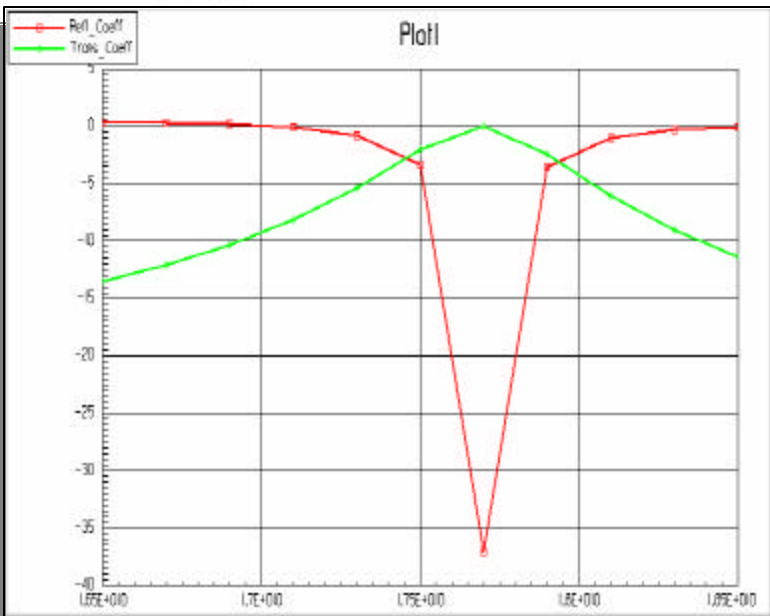
Evaluation planes for integration of power flux (unnecessary in HFSS™v10)

- Results extracted from scattered and total field data
 - Integration surfaces drawn into model (inner face of PML or interior to 'air' height between PML and FSS)
 - Integrate Poynting vector flux on evaluation surfaces

$$P_t = \int_s |E_{tot} \times H_{tot}^*| \cdot ds$$

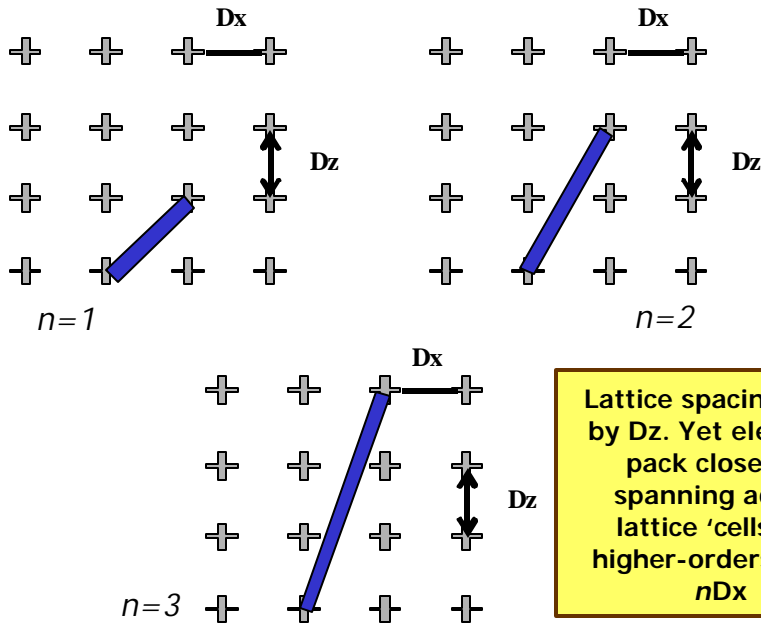
$$P_i = \int_s |E_{inc} \times H_{inc}^*| \cdot ds$$

$$T = 10 \log \left(\frac{P_t}{P_i} \right)$$

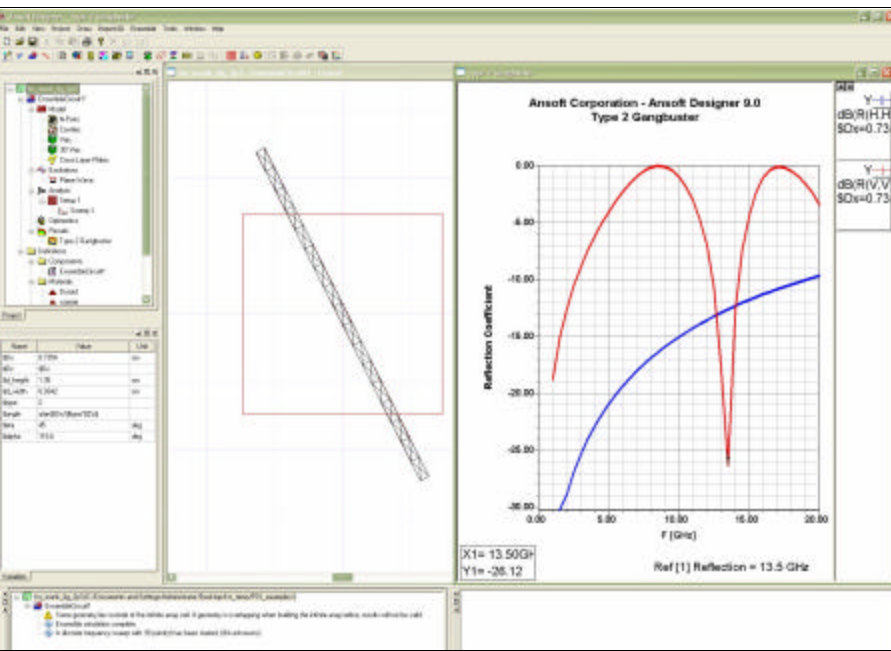


- Integration of *Total* fields on outgoing side provides *Transmitted* power.
- Integration of *Scattered* fields on incoming side provides *Reflected* power.
- Integration of *Incident* fields on either plane provides *Incident* power.
- Ratios of above provide transmission and reflection coefficients
- HFSS™v10 has automated these post-processing routines as if they are S-parameters

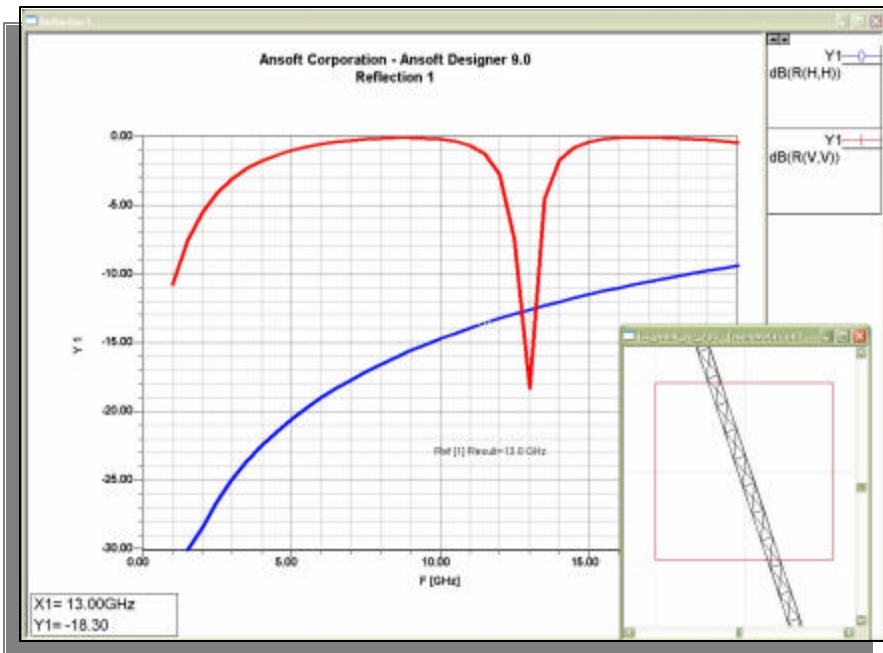
FSS: Planar Analysis 1



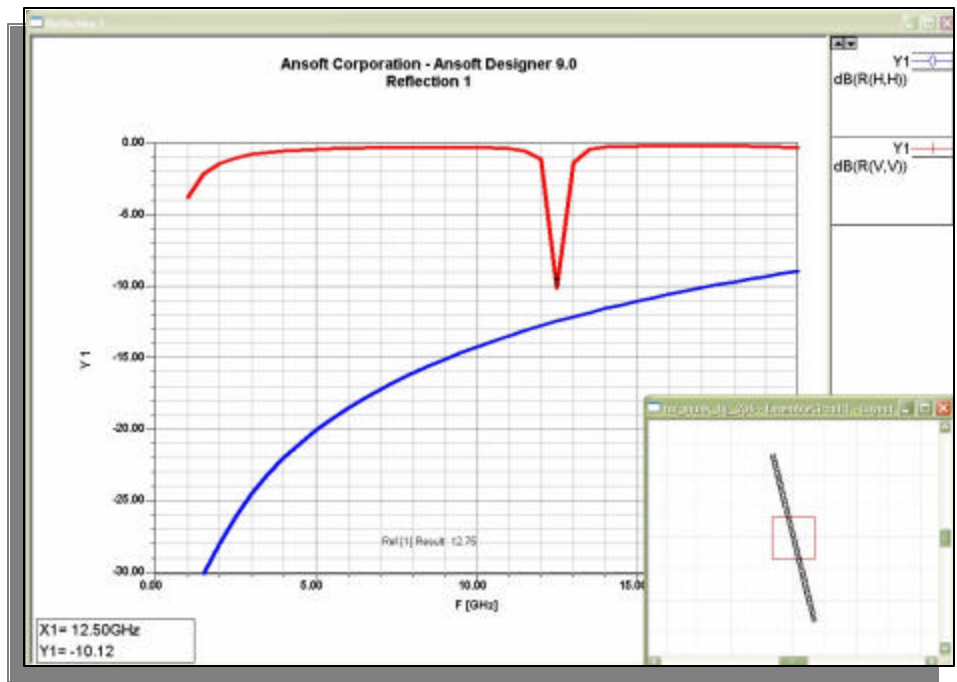
- As with planar EBGs, planar FSS structures are most efficiently solved with the PMM method
 - Define array lattice
 - Define incident wave orientation and frequency
 - Draw unit cell pattern
 - Setup identical to EBG, just no solid ground surface
- Unit cell geometry CAN exceed 'cell size' for some array types
 - E.g. "Gangbuster" array shown at left [5]
 - Parameterizing the geometry (vertex points of rectangle) based on rules of Gangbuster order can permit variation of design state as well.
- Results post-processed from near fields
 - Ansoft Designer™ performs automated results extraction for user



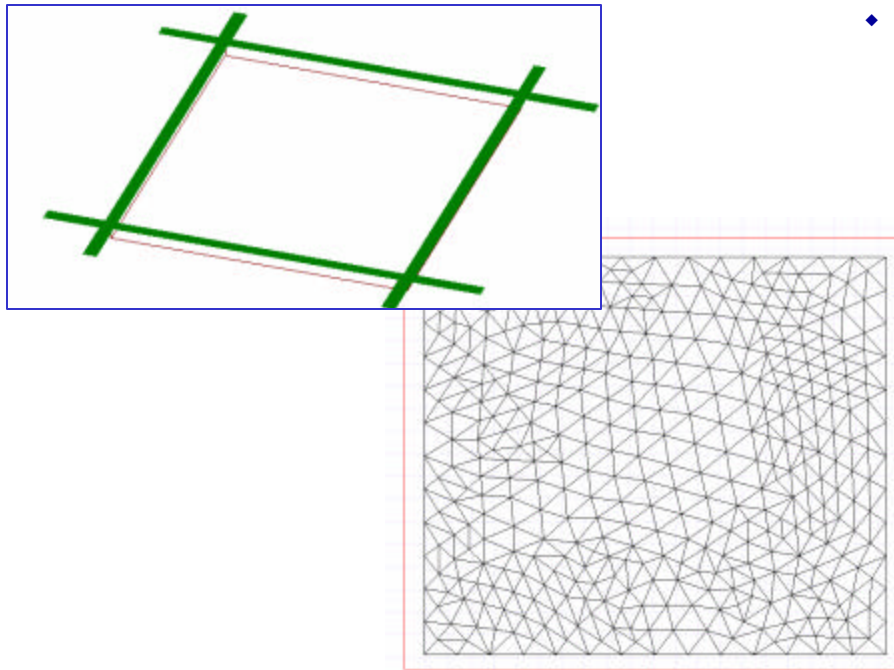
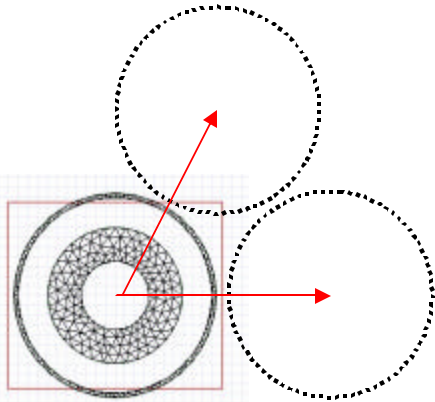
FSS: Planar Analysis 2 – Gangbusters, cont.



Example results of additional Gangbuster Arrays. Higher order results in flatter reflection coefficient out of band, slight reduction in resonant frequency. Per [5]



FSS: Planar Analysis 3 – Current Continuation

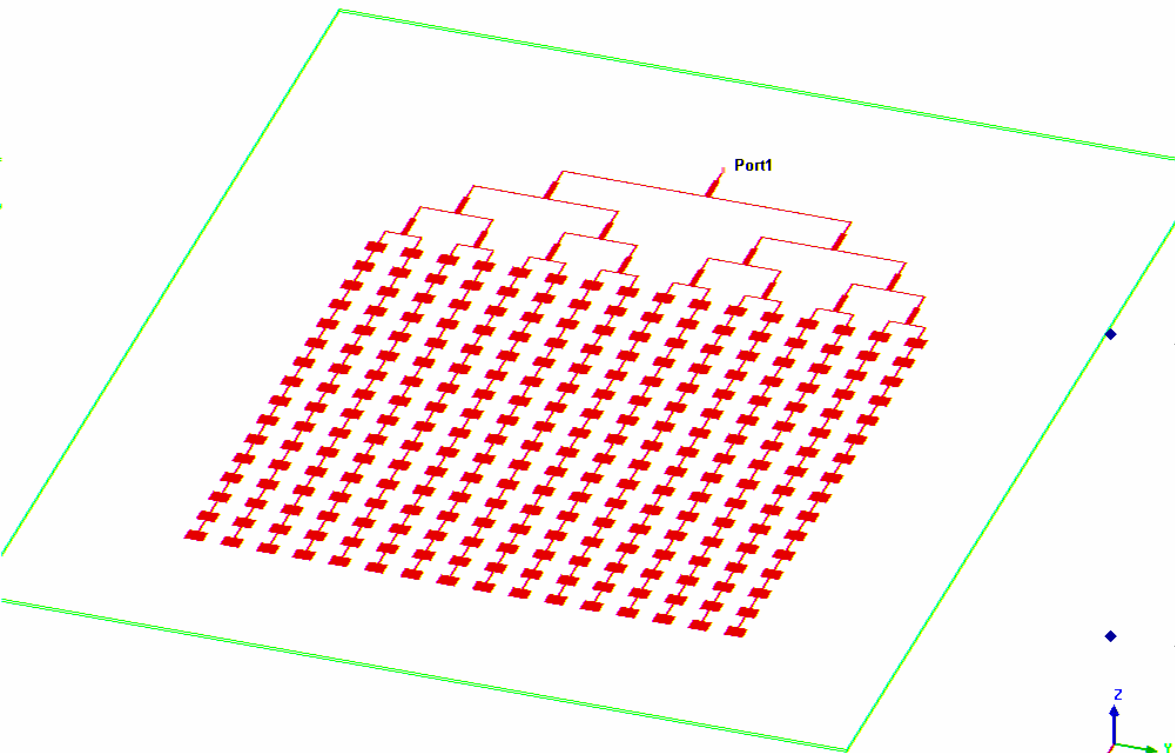


- While unit cell 'geometry' can extend beyond lattice, metal may not be permitted to 'connect' between cells
 - PMM method implementation may or may not include the effects of 'current continuation' between cells
 - Example at left – ring array does not touch. Inductive grid screen, however, does.
- In MoM simulators which permit *magnetic current* modeling, drawing cell pattern as 'negative' on a 'ground plane' layer provides easy workaround
 - Rather than drawing the inductive grid on a 'trace' layer, draw the holes in the grid on a 'plane' layer
 - Magnetic current in each cell is confined and does not continue

Part Four: Specific Application Techniques for Antenna Arrays

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Antenna Arrays: Characteristics for Analysis



- ♦ Geometric Characteristics of Array:
 - ♦ Element type
 - ♦ Element size
 - ♦ Array lattice spacing
 - ♦ Array feed type (e.g. fixed per left, or variable as in a switched or phased array)

- ♦ Array characteristics for analysis:
 - ♦ *Active S11*
 - ♦ *Scan Blindness*
 - ♦ *Active Element Pattern*
 - ♦ *Array Pattern*

- ♦ Array Patterns have several contributors:



- ♦ Single element pattern
- ♦ Mutual Coupling between elements
- ♦ Array Factor (Lattice spacing)
- ♦ Feed weightings (mag and phase)



Antenna Arrays: Definition of Active S11

$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$

$$S_{11} \equiv \left. \frac{b_1}{a_1} \right|_{a_2=0}$$

$$S_{12} \equiv \left. \frac{b_1}{a_2} \right|_{a_1=0}$$

$$S_{22} \equiv \left. \frac{b_2}{a_2} \right|_{a_1=0}$$

$$S_{21} \equiv \left. \frac{b_2}{a_1} \right|_{a_2=0}$$

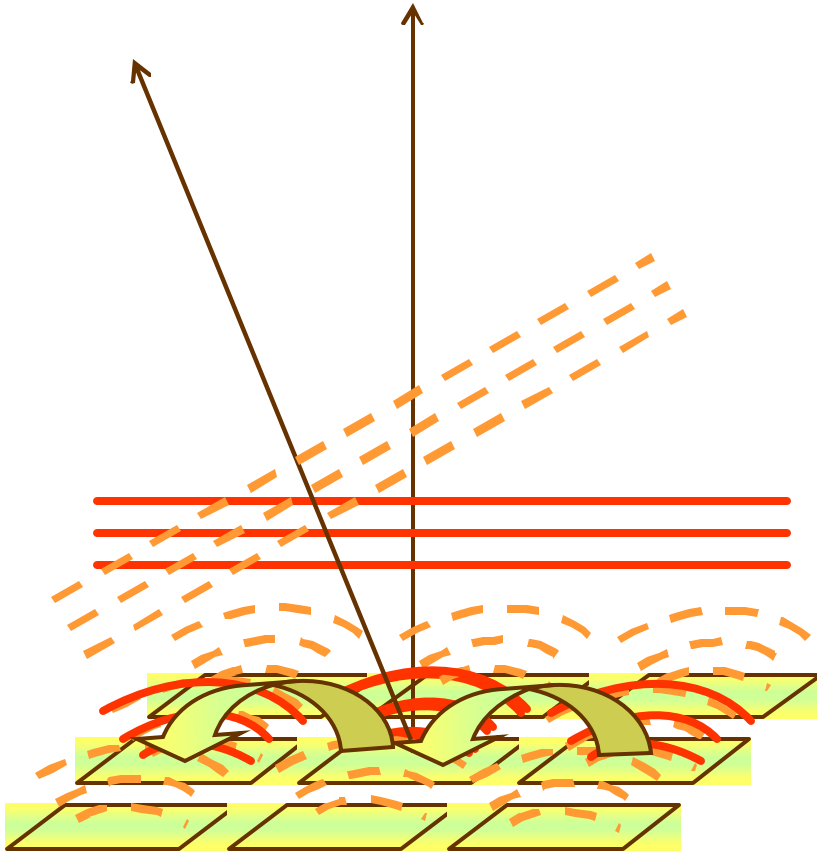
$$\text{Active } S_{11} = \frac{b_1 - S_{12}a_2}{a_1}$$

$$\text{Active } S_{11} = S_{11} - \left(\frac{a_2}{a_1} \right) S_{12}$$

- *S-parameters* assume no excitation except at each port being measured. They are therefore excitation-independent after derivation
 - The insertion loss between 2 ports of a 4-port coupler does not vary with respect to excitation on the other 2 ports, for example
- In an array environment however, mutual coupling effects can't generally be measured for an $N \times N$ matrix.
 - Would require alternately loading all other ports to measure in pairs on 2-port VNA – tedious and time consuming
- However, measuring response from an active port when all others are active is easier.
 - “Reflection” measured at tested port is really composed of both true reflection from the excitation at that port and energy from mutual coupling from other excited ports
 - This is **Active S11**
- In general, Active S-parameters are the passive S-parameters multiplied by an excitation weighting vector set describing the inputs to all ports
 - 2-port derivation at left

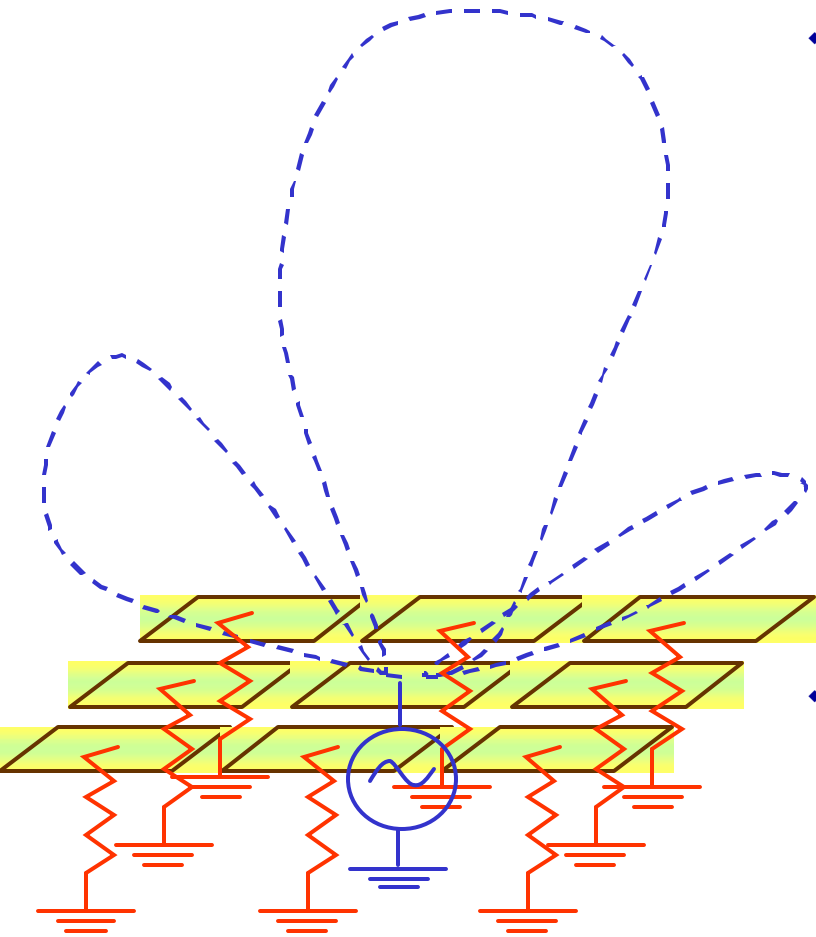


Antenna Arrays: Definition of Scan Blindness



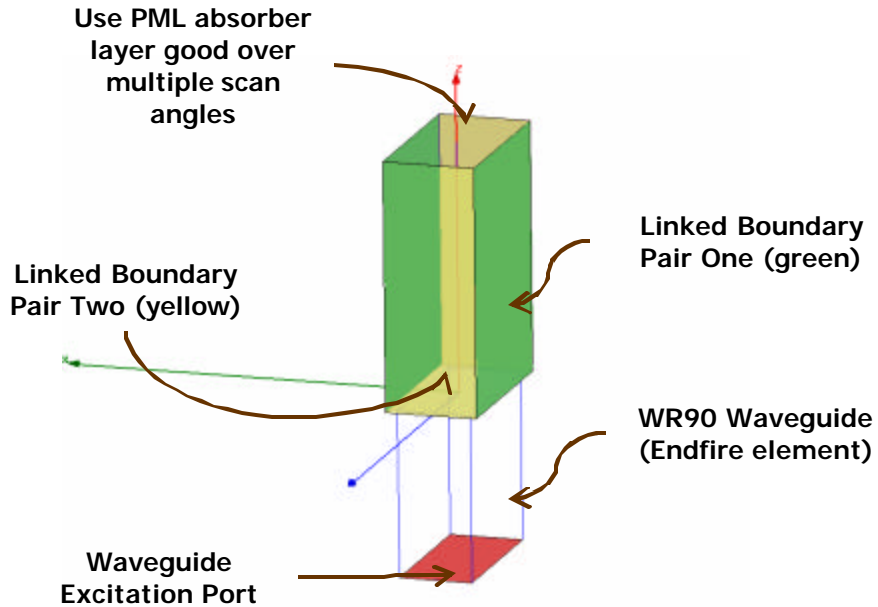
- ◆ As an array beam is scanned to greater and greater angles from boresight, mutual coupling will eventually generate so much “reflection” cross-fed into adjacent elements that the array is no longer usable
 - ◆ Effect is not simply gradual degradation off boresight but may have strong interaction at specific angles
- ◆ This characteristic is obviously related to *Active S11*
 - ◆ As Active S11 increases, more and more power is being coupled back toward the transmitter in adjacent elements and not radiated
 - ◆ Therefore a plot of *Active S11* with respect to excitation vector sets representing increasing beam scan angles will display
- ◆ *Scan Blindness* is defined as the angles over which an array is ‘blind’ because mutual coupling effects prevent scanning of a usable pattern in that direction
 - ◆ If you can’t transmit in that direction, neither can you receive due to reciprocity

Antenna Arrays: Definition of Active Element Pattern

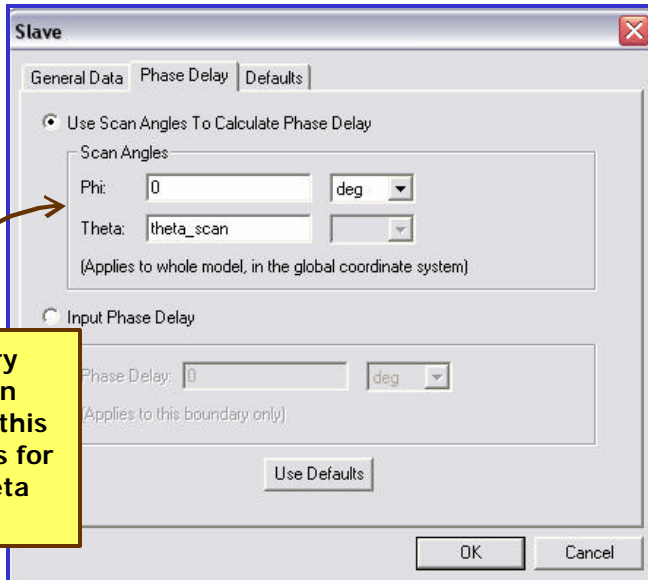


- Another antenna array characteristic often referred to is the antenna pattern of *one* sample element in the condition with *all other elements match loaded and quiescent*
 - Relatively easy to measure in real life (single setup)
 - Generally performed for ‘middle’ elements of large arrays
 - Mutual coupling of that element to neighbors fairly generically-relatable to most other elements
 - Results in a pattern which can be multiplied by an array factor including magnitude weighting to produce a reasonable result for the complete array
- This is referred to as the **Active Element Pattern**
- In Simulation, this is harder to obtain
 - Most lattice-friendly analysis methods discussed earlier assume some sort of periodicity where the adjacent elements are excited with *equal* weighting and a phase delay, not left quiescent

Antenna Arrays: Unit Cell Analysis with LBCs

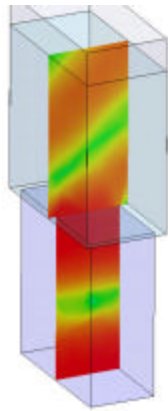


- Produces *Active S11* results
 - Linked boundary periodicity provides effect as if all surrounding elements excited with equal magnitude weighting, known phase weighting
 - Result of single solution is Active S11 for that condition
- Swept vs. scan angle generates *Scan Blindness* results
 - Set up as parametric sweep and solve sequentially to plot Active S11 vs. scan
- Computed pattern at any given scan angle includes element pattern and mutual coupling
 - Coupling specific to scan angle
 - Specific to equal magnitude weights
 - **This is NOT the same as the Active Element Pattern**
 - Multiply by appropriate array factor to produce array pattern neglecting only 'edge effects'



Slave boundary setup with scan angle settings – this example provides for scanning in theta only.

Antenna Arrays: Example Array Results



WR90 WG in 0.5 x 1 inch lattice. Scanned in E-plane from 0 – 90 degrees. Animation at left shows 40 degree scan angle

- ◆ Example JRM Array [4]
 - ◆ WR-90 endfire in rectangular array
 - ◆ 0.5 x 1.0 inch lattice
 - ◆ Scannable in E or H plane. Example is E-plane scanning.

- ◆ Results demonstrate Active S11 vs. E-plane Scanning

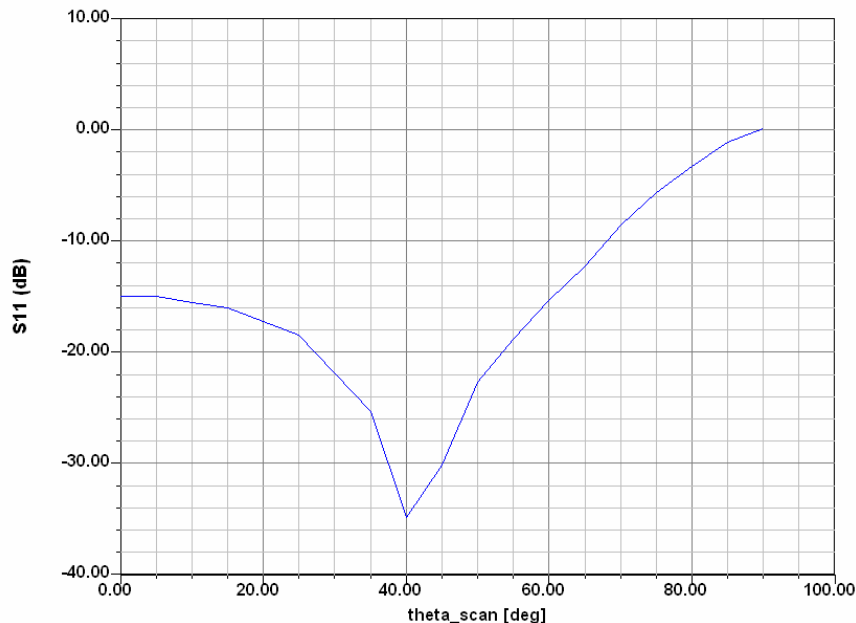
- ◆ Reasonable match at boresight (endfire WGs do couple) improves with some scanning
- ◆ 40 degrees is 'optimum' scan angle.
- ◆ Return Loss breaks -10 dB at about 67 degrees scan angle, indicating effective *Scan Blindness* beginning about here.
- ◆ Similar scans of both phi and theta simultaneously can demonstrate loss of scanning earlier at the 'corners' (e.g. can scan further in phi or theta when other angle is non-scanned)

05 Apr 2005

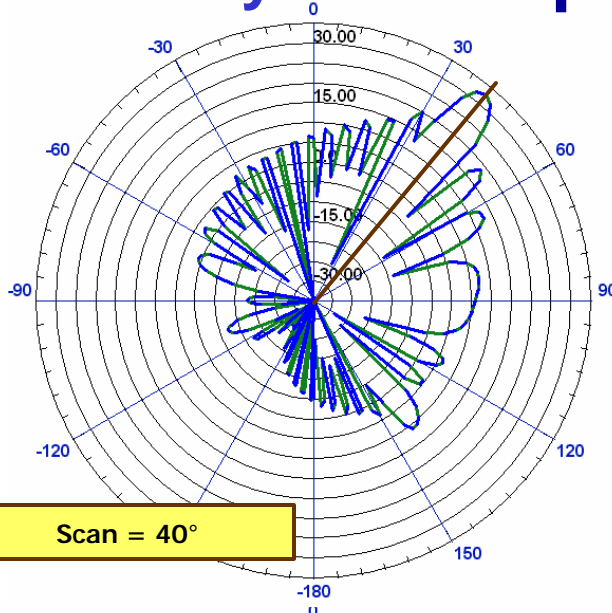
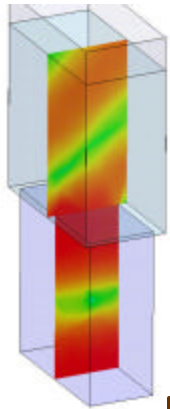
S11 vs. Array Scan Angle in Theta

10:59:38

HFSSModel1

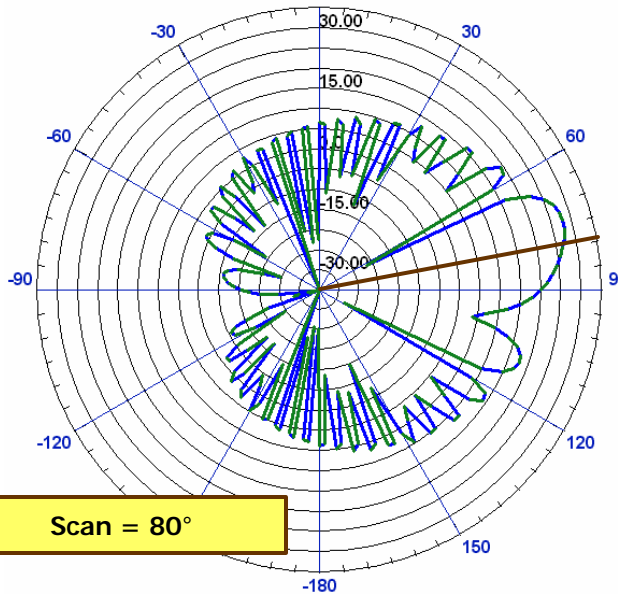
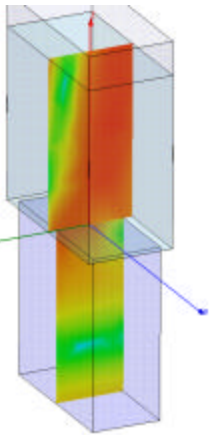


Antenna Arrays: Example Array Results, cont.



Scan = 40°

- 25 x 25 element array, 40 degree scan
 - Beam Peak 33.6 dBi (Realized Gain)
 - Beam Peak on 40 degrees exactly
 - Field animation shows good field propagation
- (Pattern shows behavior below azimuth as this is simply an analytical array factor applied to the single contribution surface data present, thus knows nothing about ground plane location).



Scan = 80°

- 25 x 25 element array, 80 degree scan
 - Beam Peak degraded over 6 dB to 26.8dBi (Realized Gain)
 - Beam Peak actually at 76 degrees, not 80 degrees
 - Field animation shows visible standing wave component in waveguide, resulting from coupling to adjacent elements permitting energy back into the WG.

Antenna Arrays: Active Element Pattern – Method 1

- The Active Element Pattern is related to the Active S11
 - As scan angle increases and mutual coupling pushes energy ‘back’ into an array element, the element pattern will suffer since that power is not radiated
- Therefore a semi-analytical Active Element Pattern can be computed simply using Active S11 scaling
 - Define a nominal element pattern as some standard ‘blob’ shape such as $\cos(\theta)/\theta$
 - Or for planar array, compute from analytical aperture assumptions, as:

$$G^E(\mathbf{f}, \mathbf{q}) = \frac{4pD_x D_y}{l^2} \cos(\mathbf{q})$$

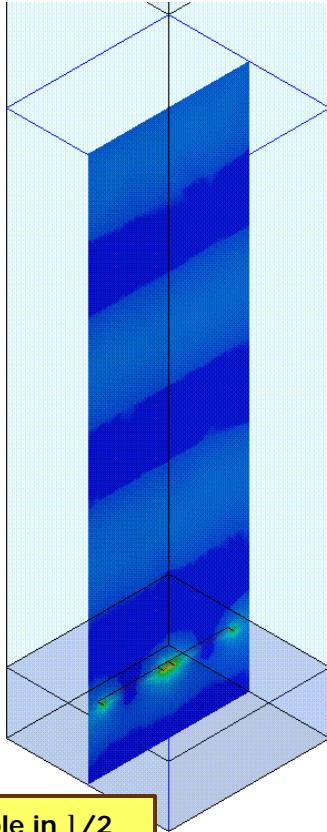
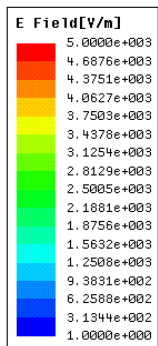
- Multiply by the Active S11 output from a parametric sweep analysis of scan angle

$$G^{Active\ E}(\mathbf{f}, \mathbf{q}) = \frac{4pD_x D_y}{l^2} \cos(\mathbf{q}) [1 - |\Gamma(\mathbf{f}, \mathbf{q})|^2] \quad [11]$$

- Post-processing can be performed within HFSS™ as an Output Variable operation upon the S11 results

Antenna Arrays: Active Element Pattern – Method 2

- Consider unit cell as power contribution of one element with others also powered.
 - Near-field sampling is on evaluation surface above only one cell of array
 - Infinite array assumption must compute far fields from only a planar near-field distribution above the array
- At the intended scan angle for any iteration, all elements add coherently, yet power contribution of only one is present.
- Therefore this single point corresponds to the equivalent point of the *Active Element Pattern*
- This suggests a technique for computing Active Element Pattern from field results directly:
 - Compute parameterized sweep, and compute the antenna pattern for **Realized Gain** from each scan angle
 - “Realized” Gain includes mismatch loss, thus is S11-scaled.
 - Assemble diagonal components ($\theta = \theta_{\text{scan}}$) to get *active element pattern*
- Use this technique rather than semi-analytical one for passive element patterns not easily approximated by size
 - Directive elements like Quasi-Yagi, Powder Horns, Y-U, etc.
 - Fan patterns like sectoral elements
 - Wideband antennas with frequency dependence to pattern shape



1/2.5 dipole in 1/2 array spacing.
Animation shows MagE as scan angle sweeps 0 - 80°

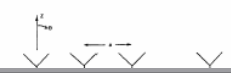
Antenna Arrays: Active Element Example

1178

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 42, NO. 8, AUGUST 1994

Communication

The Active Element Pattern
D. M. Pozar

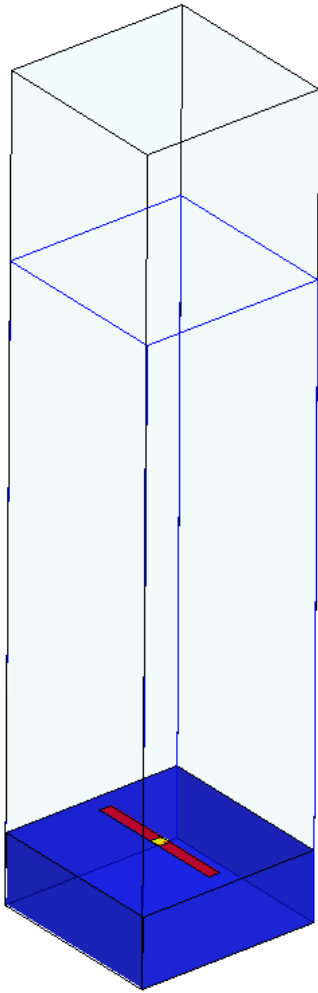


Abstract—This review article will discuss the use of the active element pattern in generalizing the concept of the active element pattern to an arbitrary planar array of elements. First, element patterns are defined and the active element pattern is defined. Next, at a distance r from the center of the array, the active element pattern is shown to be the same as the element pattern of a single element in a plane parallel to the plane of the array. The element pattern of a single element is then characterized by an $N \times N$ scattering matrix whose elements are given by (1). where V_{in}^+ and V_{in}^- are the incident and reflected voltage wave amplitudes at the n th element. The incident and reflected voltages are related as (2). and the total voltage and current at the n th element are (3) and (4). For a normalized feed line characteristic impedance Z_0 , the active element pattern is (5). which models the practical case of constant incident power to each element, as in a corporate-fed array. The active reflection coefficient at the n th element is, from (3) and (5), (6). Note that Γ_{in} depends on the scan angle θ , unless $S_{nn} = 0$ for $n \neq n$ (no mutual coupling). The fields radiated by the fully excited array, phased according to (5), are (7). Evaluating these at the main beam angle $\theta = \theta_0$ gives (8). The gain of the fully excited array for $\theta = \theta_0$ is then, (9). The gain definition includes the effect of reflected power, and is usually called the total gain. If the array is large enough so that virtually all of the Γ_{in} 's are identical, then $\Gamma_{in} = \Gamma$, and (8) reduces to (10). where G_0 is the gain of a single isolated element: (11). Now consider the active element pattern, where the n th element is driven with voltage V_n , and all others are terminated. The radiated fields are (12). where we have used the fact that $S_{nn} = S_{nn}$, which is true for an array of reciprocal elements. The gain of the active element pattern is (13). This is an interesting result, showing that the active element pattern is simply related to the active reflection coefficient magnitude of the fully excited phased array. Furthermore, comparison with (9) shows that (14). This result shows that the gain $G^*(\theta_0)$ of the fully excited array at the scan angle θ_0 is directly proportional to the active element pattern at that same angle. Therefore, if the measured active element pattern has dips or nulls at particular angles, it can be concluded that the fully excited phased array will have comparable dips in gain when scanned to those same angles. The extension to the more general planar array case is obtained from the above results by replacing $G_0(\theta)$ with $4\pi \cos^2 \theta / \lambda^2$, which

- Classic Pozar paper [11] derives relationships for Active Element Pattern from base principles
- Uses dipole antenna as example
 - Shown prior page
- Construct unit-cell pattern in HFSS and compare to supplied plot of linear gain vs. scan angle in E-plane
 - Paper references all dimensions with respect to wavelength
 - Select one such configuration and simulate

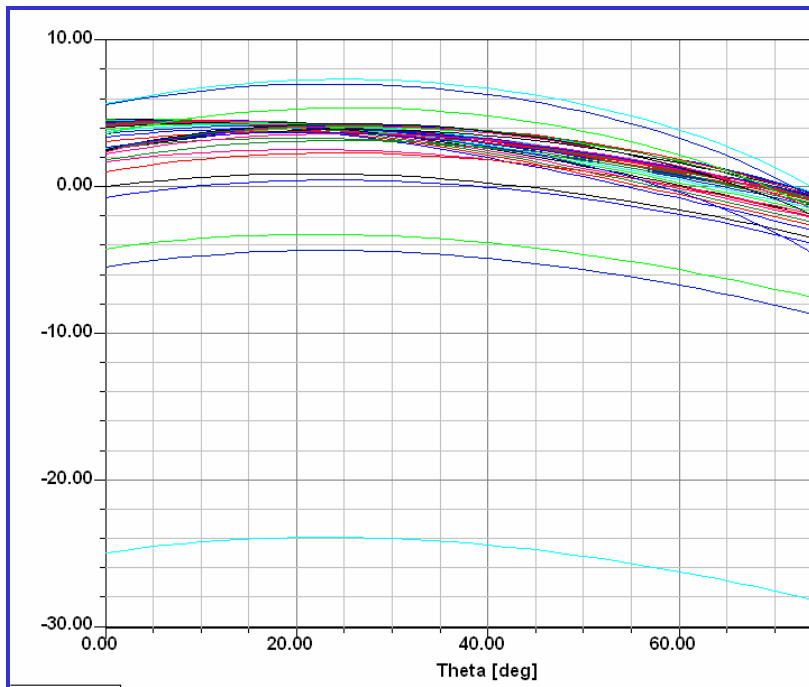


Antenna Arrays: HFSS Project



- ◆ HFSS Project constructed to match that in the paper as best as possible
 - ◆ Arbitrarily picked 3 GHz solution for easy wavelength (100 mm)
 - ◆ $\lambda/30$ used as dipole 'width'.
 - ◆ No dipole length given, arbitrary length of $\lambda/2.5$ selected to fit inside $\lambda/2.5$ unit cell
 - ◆ Linked Boundary Conditions applied on sides
 - ◆ Lumped port placed in center, 50 Ω normalized
 - ◆ Substrate constructed to appropriate thickness and $\epsilon_r = 2.55$ per reference
 - ◆ Air height left at 150mm, 50mm thick PML constructed on top
 - ◆ Dipole aligned parallel to Y axis, so "E-plane" is $\phi=90$, θ varying.
 - ◆ Parametric sweep requested for scan angle of every 2° from $\theta = 0$ to 80°

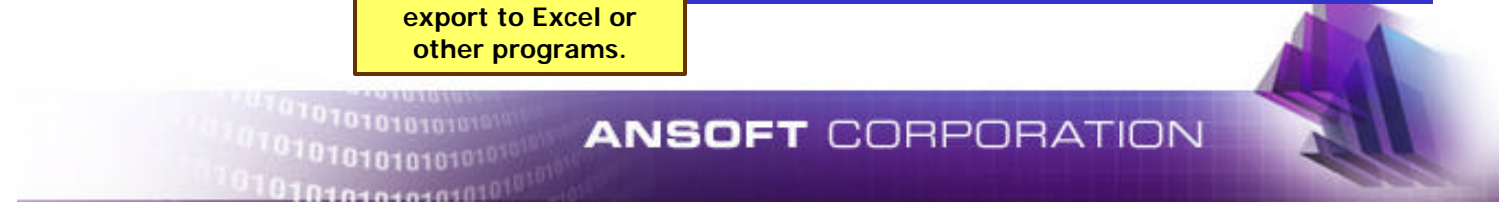
Antenna Arrays: HFSS Raw Results



Realized Gain vs. Theta for each Scan angle (dB). One point of each curve contributes to Active Element Pattern.

Theta [deg]	RealizedGainTotal scantheta=0deg, Fr... Setup2 : LastAdapti...	RealizedGainTotal scantheta=2deg, Fr... Setup2 : LastAdaptive	RealizedGainTotal scantheta=4deg, Freq... Setup2 : LastAdaptive	RealizedGainTotal scantheta=6deg, Fr... Setup2 : LastAdapti...	RealizedGainTotal scantheta=8deg, Freq... Setup2 : LastAdaptive
0.000000	2.886275	2.883754	2.876357	2.864113	2.847063
2.000000	2.881698	2.884921	2.883255	2.876698	2.865263
4.000000	2.867862	2.876789	2.880843	2.879993	2.874220
6.000000	2.844929	2.859467	2.869174	2.873993	2.873870
8.000000	2.813165	2.833165	2.848407	2.858804	2.864283
10.000000	2.772934	2.798199	2.818805	2.834638	2.845594
12.000000	2.724692	2.754977	2.780728	2.801804	2.818074
14.000000	2.668973	2.703994	2.734627	2.760708	2.782080
16.000000	2.606387	2.645819	2.681033	2.711840	2.738057
18.000000	2.537596	2.581087	2.620547	2.655763	2.686533
20.000000	2.463313	2.510483	2.553824	2.593104	2.628098
22.000000	2.384277	2.434728	2.481566	2.524539	2.563404
24.000000	2.301250	2.354572	2.404505	2.450782	2.493144
26.000000	2.214998	2.270772	2.323389	2.372569	2.418033
28.000000	2.126279	2.184087	2.238974	2.290648	2.338810
30.000000	2.035833	2.095262	2.152007	2.205765	2.256233
32.000000	1.944372	2.005017	2.063215	2.118654	2.171027
34.000000	1.852569	1.914041	1.973299	2.030023	2.083895
36.000000	1.761052	1.822981	1.882921	1.940550	1.995543
38.000000	1.670399	1.732434	1.792700	1.850871	1.906610
40.000000	1.581130	1.642947	1.703204	1.761575	1.817728
42.000000	1.493707	1.555008	1.614947	1.673199	1.729433
44.000000	1.408533	1.469047	1.528385	1.586225	1.642234

Same data, tabular format, linear (not dB). Can right-click data table for easy export to Excel or other programs.



Antenna Arrays: Selected Results

Theta [deg]	RealizedGainTotal scantheta=0deg, Freq., Setup2 : LastAdapti...	RealizedGainTotal scantheta=2deg, Freq., Setup2 : LastAdaptive	RealizedGainTotal scantheta=4deg, Freq., Setup2 : LastAdaptive	RealizedGainTotal scantheta=6deg, Freq., Setup2 : LastAdapti...	RealizedGainTotal scantheta=8deg, Freq., Setup2 : LastAdaptive
0.00000	2.886275	2.883754	2.876357	2.864113	2.84706
2.00000	2.881698	2.884921	2.883255	2.876698	2.86526
4.00000	2.867862	2.876789	2.880843	2.879993	2.87422
6.00000	2.844929	2.859467	2.869174	2.873993	2.87387
8.00000	2.813165	2.833165	2.848407	2.858804	2.86428
10.00000	2.772934	2.798199	2.818805	2.834638	2.84559
12.00000	2.724692	2.754977	2.780728	2.801804	2.81807
14.00000	2.668973	2.703994	2.734627	2.760708	2.78208
16.00000	2.606387	2.645819	2.681033	2.711840	2.73805
18.00000	2.537596	2.581087	2.620547	2.655763	2.68653
20.00000	2.463313	2.510483	2.553824	2.593104	2.62809
22.00000	2.384277	2.434728	2.481566	2.524539	2.56340
24.00000	2.301250	2.354572	2.404505	2.450782	2.49314
26.00000	2.214998	2.270772	2.323389	2.372569	2.41803
28.00000	2.126279	2.184087	2.238974	2.290648	2.33881
30.00000	2.035833	2.095262	2.152007	2.205765	2.25623
32.00000	1.944372	2.005017	2.063215	2.118654	2.17102
34.00000	1.852569	1.914041	1.973299	2.030023	2.08389

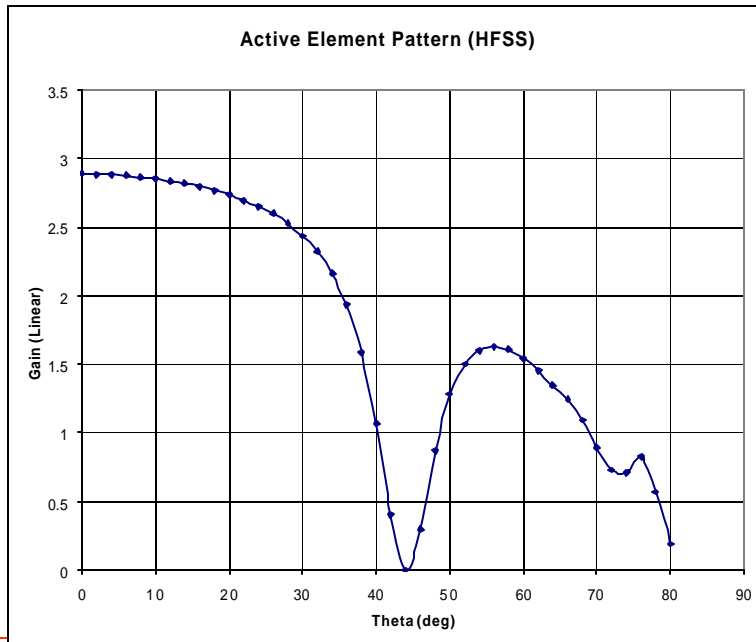
Diagonal points selected for transfer to additional page of Excel Worksheet for plotting.

pozar_comparison.xls

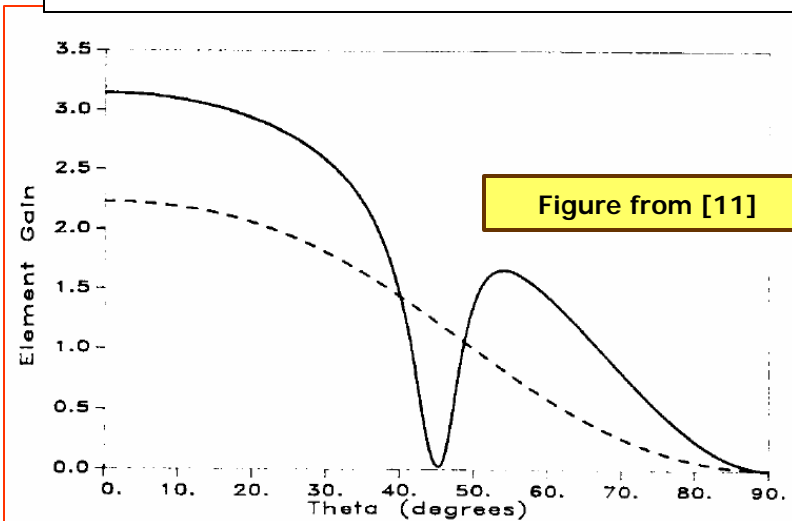
	A	B	C	D	E	F	G	H	I	J	K
1	Theta [deg]	RealizedG	RealizedG	RealizedG	RealizedG	RealizedG	RealizedG	RealizedG	RealizedG	RealizedG	Realizer
2	0	2.886275	2.883754	2.876357	2.864113	2.847063	2.825252	2.798723	2.767494	2.731532	2.69071
3	2	2.881698	2.884921	2.883255	2.876698	2.865263	2.848967	2.827824	2.801823	2.7709	2.7348
4	4	2.867862	2.876789	2.880843	2.879993	2.87422	2.863515	2.847863	2.827222	2.801499	2.7705
5	6	2.844929	2.859467	2.869174	2.873993	2.873876	2.868785	2.858674	2.843472	2.823058	2.7972
6	8	2.813165	2.833165	2.848407	2.858804	2.864282	2.854771	2.860198	2.850462	2.835411	2.8147
7	10	2.772934	2.798199	2.818805	2.834638	2.845594	2.851578	2.852486	2.848188	2.838502	2.8231
8	12	2.724692	2.754977	2.780728	2.801804	2.818074	2.829415	2.835695	2.836756	2.832385	2.8222
9	14	2.668973	2.703994	2.734627	2.760708	2.78208	2.798592	2.810085	2.816374	2.817217	2.8122
10	16	2.606387	2.645819	2.681033	2.71184	2.738057	2.759509	2.776011	2.787351	2.793258	2.793
11	18	2.537596	2.581087	2.620547	2.655763	2.686532	2.712654	2.733918	2.750086	2.760865	2.7658
12	20	2.463313	2.510483	2.553824	2.593104	2.628098	2.658583	2.684325	2.705062	2.720476	2.7301
13	22	2.384277	2.434728	2.481566	2.524539	2.563404	2.597915	2.627819	2.652832	2.672611	2.6867
14	24	2.30125	2.354572	2.404505	2.450782	2.493141	2.53132	2.565044	2.594008	2.61785	2.6361
15	26	2.214998	2.270772	2.323389	2.372569	2.418032	2.459501	2.496681	2.52925	2.556829	2.578
16	28	2.126279	2.184087	2.238974	2.290648	2.338816	2.383183	2.423442	2.459254	2.490221	2.5158
17	30	2.035833	2.095262	2.152007	2.205765	2.256233	2.303104	2.346055	2.384734	2.418729	2.4475
18	32	1.944372	2.005017	2.063215	2.118654	2.171021	2.219998	2.265252	2.306416	2.343069	2.3746
19	34	1.852569	1.914041	1.973299	2.030023	2.083895	2.134586	2.181754	2.225022	2.26396	2.2980



Antenna Arrays: Final Excel Plot



- ◆ Final Active Element Pattern from Excel is shown at right with Pozar plot below [11]
- ◆ Agreement is good considering known limits of comparison example
 - ◆ Element at $\lambda/30$ width is not 'purely linear' analytical dipole, therefore slightly lower peak gain than theoretical
 - ◆ Element length not provided in reference, assumed uncoupled by analysis while simulated model may have displayed end-to-end coupling
 - ◆ Array-factor resultant scan blindness at approximately 45 degrees well matched
- ◆ Simulation was not independently converged for each scan angle and stopped at $\theta_{\text{scan}} = 80^\circ$
 - ◆ Faster simulation
 - ◆ Option to solve adaptively at each scan angle is available for additional accuracy.



Closing Remarks

- ♦ Frequency Selective Surfaces (FSS), Electromagnetic Bandgaps (EBGs), and Antenna Arrays all represent a periodic or latticed type radiation or scattering structure
- ♦ The same type of simulation techniques therefore apply to all such applications
- ♦ Today's Wireless products are demanding more of their designs, such that lattice techniques for improving antenna performance may be of interest to both client-side and host/infrastructure level designers.
 - ♦ This morning's Antenna Session, RB, contained three papers involving Antenna Array applications and one involving EBGs. That's **four out of five** in the session.
- ♦ Knowledge of modern simulation techniques for these applications is but an additional weapon in the designer's arsenal
- ♦ We hope that this information may prove useful to you in the future, and thank you for your attention.

Acknowledgements

- The authors would also like to formally acknowledge the assistance of James Irion of Raytheon Corporation (McKinney, TX) for his suggestions regarding the extraction of the Active Element Pattern from HFSS™.

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