HyperLynx® 3D EM

Applications for Designing Planar and 3D Antennas

Software Version 15.2

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Applications of IE3D™ in Designing Planar and 3D Antennas

Release 15.0

Introduction to IE3D

- **IE3D is an integral equation and method of moment based EM simulator.**
- **IE3D mainly focuses on general planar and 3D metallic structures in layered dielectric environments. It is very efficient, accurate and flexible for such structures.**
- **IE3D can also model 3D dielectric structures such as patch antennas with finite substrates and dielectric resonator antennas.**

Applications of IE3D

- **Microwave circuits and MMICs.**
- **RF circuits, LTCC circuits and RF ICs.**
- **Microwave, RF and wireless antennas.**
- **RFID tag antennas.**
- **HTS filters.**
- **Electronic packaging and signal integrity.**
- **EMC and EMI**
- **Many other low to high frequency structures.**

Applications in Antennas

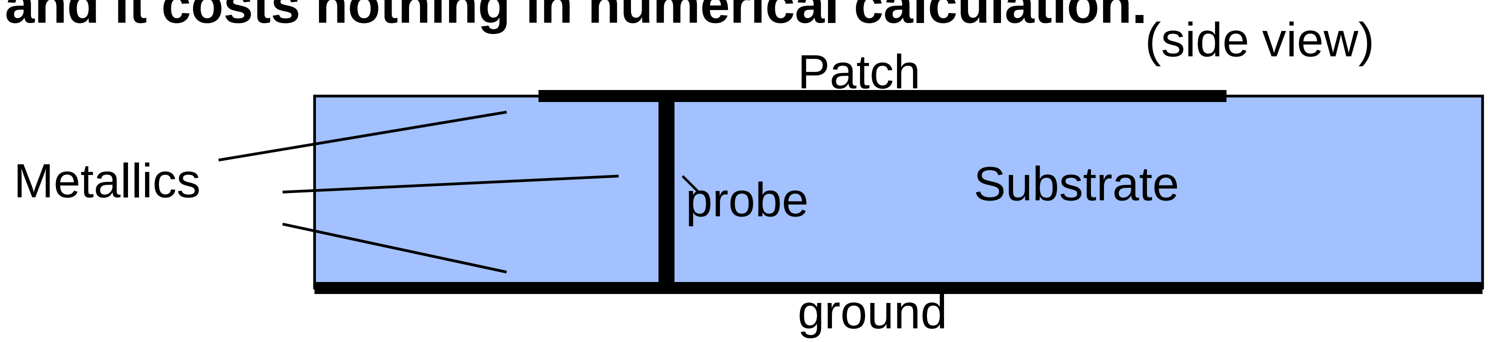
- Planar antennas such as microstrip antennas and slot antennas.
- Wire antennas such as various types of dipole, monopole, helix and quadrifilar antennas.
- Small antennas such as inverted-F antennas and its derivations.
- Dielectric resonator antennas.
- RFID antennas.
- Optical frequency antennas.
- Many other types of antennas

Contents

- Basic concepts in building models.
- Layout editor and editing modes.
- Basic techniques in geometry modeling.
- S-parameter (impedance) display and post processing.
- Pattern handling and post processing.
- Electromagnetic optimization and tuning.
- Advanced techniques in geometry modeling, simulation and optimization.
- Accuracy and efficiency improvements.

Basic Concepts in Building Models (1)

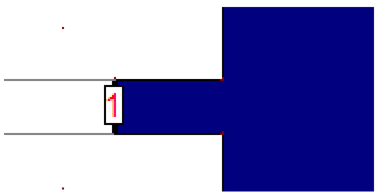
- **For structures in layered environments, the boundary conditions on substrate surfaces are guaranteed by the Green's functions. Normally, we do not need to define substrates as objects.**
- **The boundary conditions on the surfaces of the metallic structure are enforced numerically. We need to build the metallic surfaces as objects. In our cases, the objects are polygons. We need to describe the shape of a metallic body as a set of polygons in certain ways so that the structure can be simulated correctly.**
- **Infinite ground plane can be modeled as a substrate layer and it costs nothing in numerical calculation.**



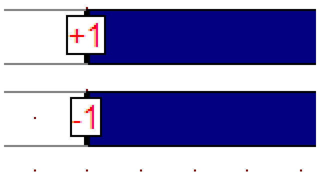
Basic Concepts in Building Models (2)

- Infinite ground planes are considered as the reference terminal for extension ports automatically.
- A finite ground plane needs to be modeled as a group of polygons.
- When there is no infinite ground plane, we need to use differential ports.
- A differential port is a port with a reference (or -) terminal.
- Extension ports need to come as pair (+, -) as a differential port.
- A horizontal or vertical localized port is a differential port by itself because it does have + and – terminals.

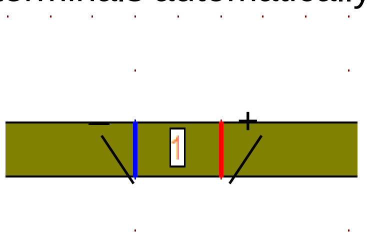
Single-Ended Port for structure with an infinite ground



Differential extension port with + and – terminals for structure without infinite ground



Horizontal Localized Port With + and – terminals automatically



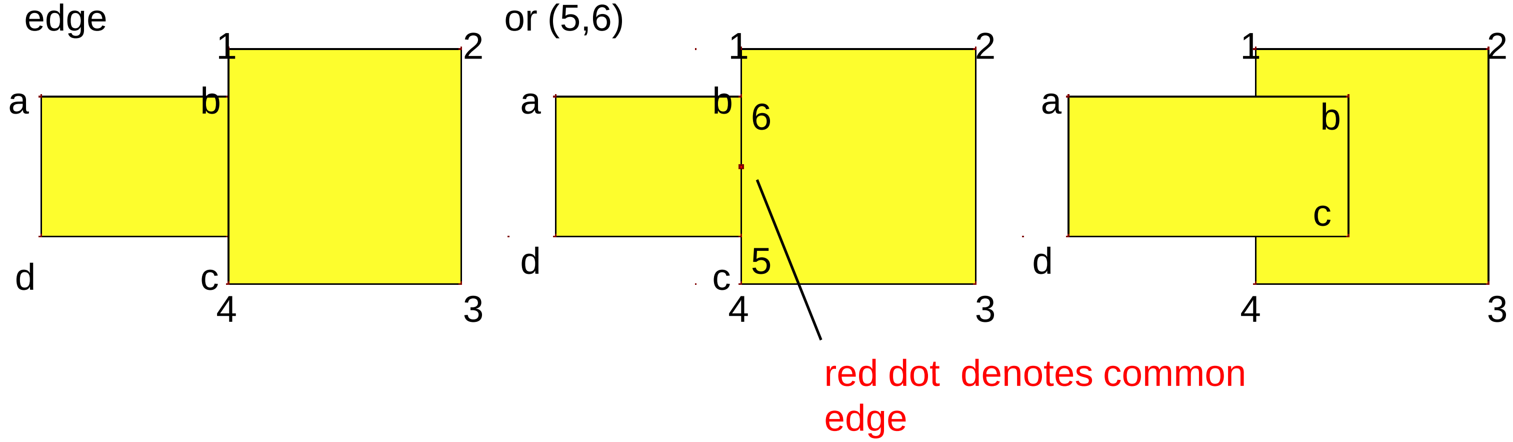
Basic Concepts in Building Models (3)

- A polygon no matter whether it is for a patch, a trace or a finite ground will contribute to the number of unknowns in the solution.
- Polygon vertices are double precision floating point numbers on IE3D. We can model arbitrarily shaped structures.
- Two polygons are considered to be electrically connected only when they have one or more common edges.
- Overlapped polygons are not considered connected and they may not be accepted in current simulator. Future edition will automatically merge overlapped polygons.

Polygons (a,b,c,d) and (1,2,3,4) are not connected because of no common edge

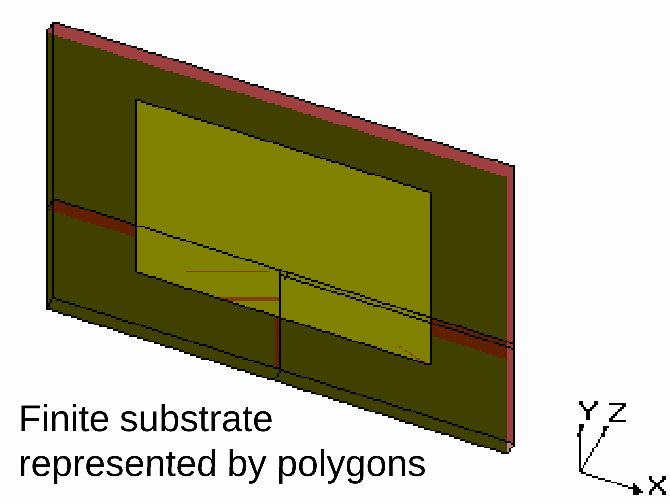
Polygons (a,b,c,d) and (1,2,3,4,5,6) are connected because of common edge (b,c) or (5,6)

Polygons (a,b,c,d) and (1,2,3,4) are not connected even they are overlapped

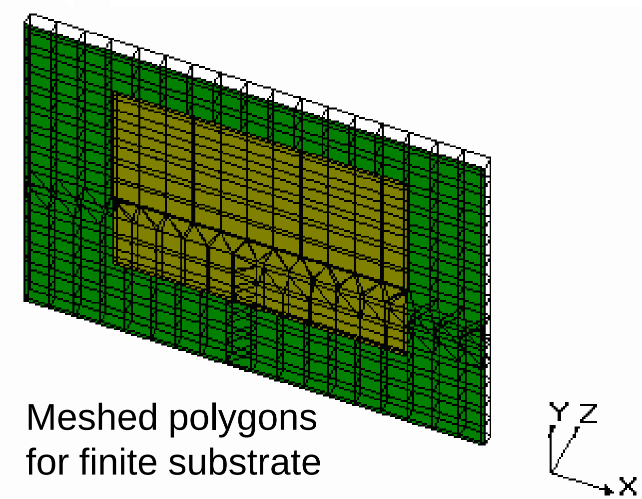


Basic Concepts in Building Models (4)

- When finite substrate is modeled, we need to define the finite substrate using polygons.
- The finite substrate represented as polygons will be meshed and they will contribute to the increase in number of unknowns.
- Meshing alignment between metallic polygons and finite substrate polygons are extremely critical for high accuracy results in modeling finite substrates. Automatic meshing alignment will be available before the end of 2004.
- 3D dielectric modeling includes the finite substrate effects. However, it needs to enforce the boundary conditions on substrate interfaces. It may cause less accuracy in some other parameters due to the extra enforcement.



Finite substrate represented by polygons

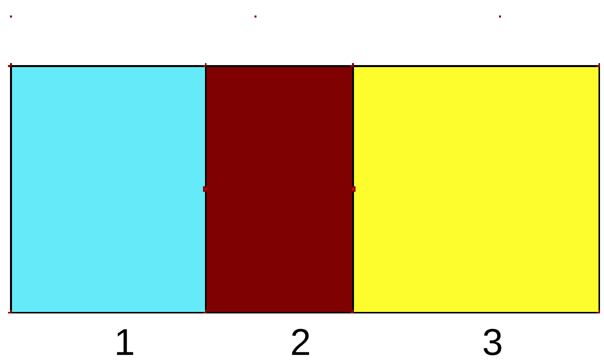


Meshed polygons for finite substrate

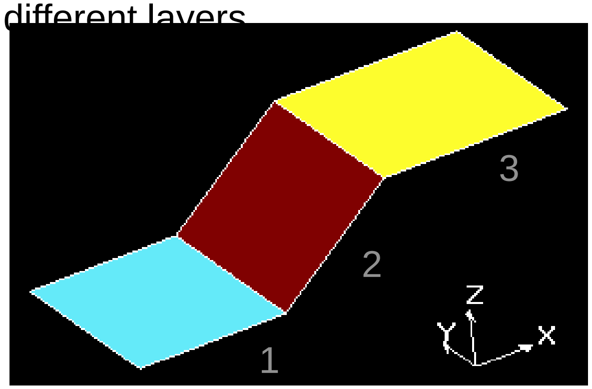
Basic Concepts in Building Models (5)

- **Major editing window is the top view and drawing is on layers.**
- **A 3D polygon can be entered with some vertices on one layer and some vertices on other layers.**
- **Many advanced editing commands allowing users to create and edit complicated planar and 3D geometry shapes.**

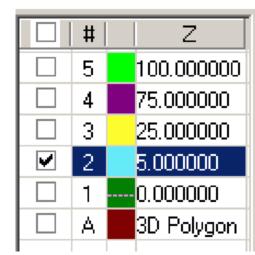
Mouse driven editing on top view



3D View for display and 3D polygons entered as vertices on different layers



Layer window indicates colors and z-coordinates of layers

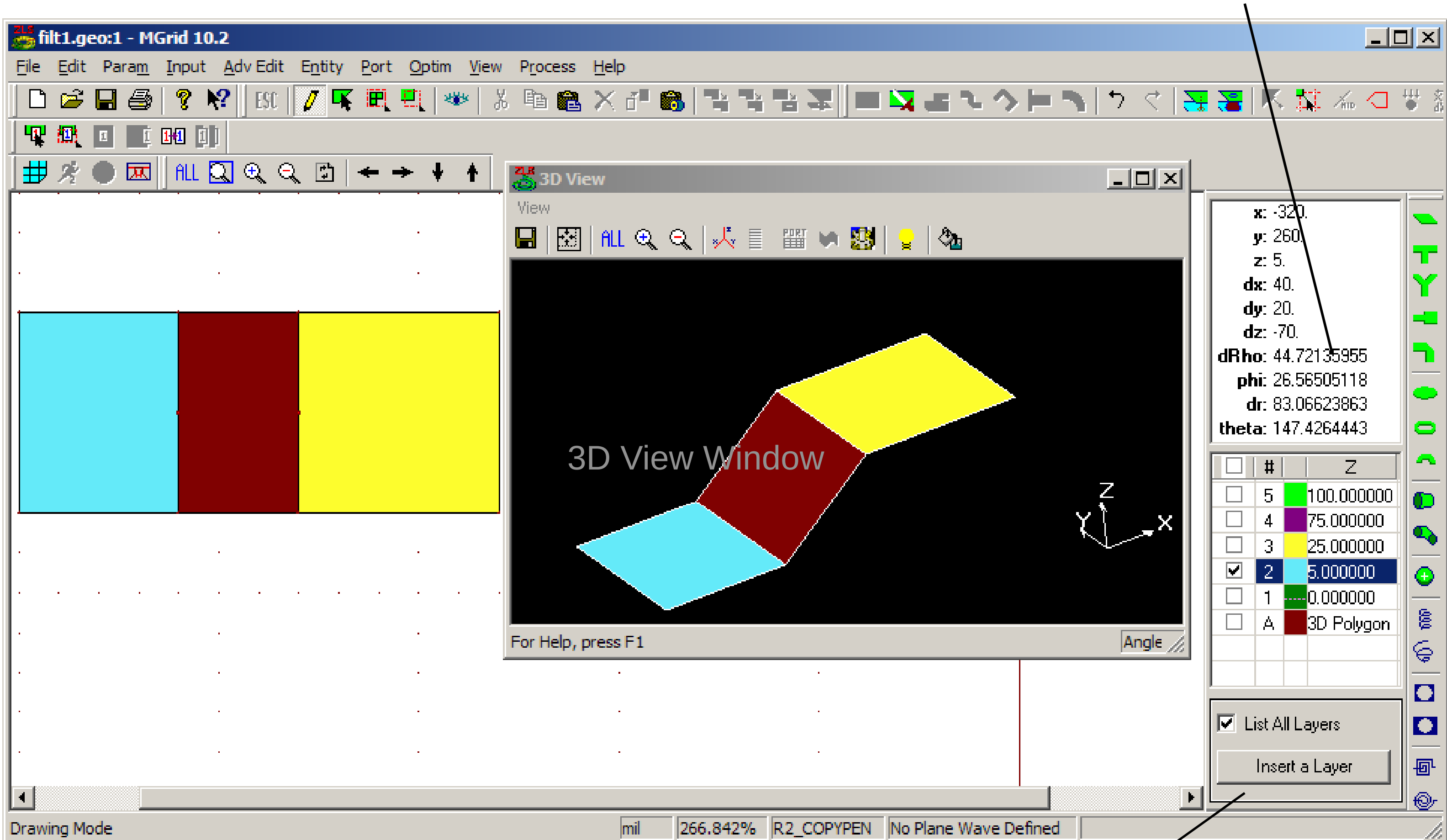


Major Application Programs

Application	Function
MGRID	Layout editor, current distribution and near field post processor. It is the major GUI program of the package.
IE3D	EM simulation and optimization engine.
MODUA	Pre-processor for mixed EM and circuit simulation and optimization; Post processor for s-parameters display and handling, circuit simulation and optimization
PATTERNVVIEW	Display, comparison and handling of radiation patterns.
ZdibAnimator	Current and near field animation program.
IE3Dlibrary	The 2nd layout editor with parameterized library objects for easy construction, simulation & optimization.
MDSPICE	An optional S-parameter based time-transient SPICE simulator for waveform analysis; Wide band RLC extractor from s-parameters.
FilterSyn for IE3Dlibrary	An optional filter synthesis module for IE3Dlibrary. Synthesize a pre-defined filter based upon specs using analytical formula. The result is geometry ready for IE3D.
SpiralSyn for IE3Dlibrary	An optional spiral inductor and transformer synthesis module for IE3Dlibrary. Synthesize a pre-defined spiral based upon specs using the IE3D engine.
ADIX	Optional IE3D⇔GDSII⇔DXF⇔ACIS⇔GERBER converter. Integrated into MGRID 10.2
LineGauge	An optional simple transmission line calculator (Basic edition free)
ZDS/ZDM	Network based distributed IE3D simulation and optimization service allowing multi-frequency simulation or optimization to be distributed into the whole network.

Layout Editor Configuration

Status window for the current editing mode



Top View Window for Editing

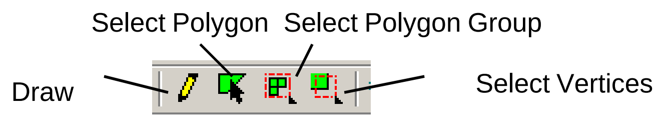
Layer window for the polygon layers

Layout Editor Menu System

Menu	Function
Edit	Editing of the polygons and vertices.
Adv Edit	Advanced editing features for polygons and vertices.
Param	Change and setup of basic parameters and optional parameters. Basic parameters including substrates (top and bottom grounds), metallic types, enclosures, geometry entry grid sizes, finite dielectrics properties. Optional parameters control the default setups for geometry editing, simulation accuracy and efficiency.
Input	Handling vertex entry and manipulation.
Port	Define and edit ports.
Optim	Define and edit optimization variables for EM optimization and tuning.
Entity	Creation of pre-defined objects as polygons in one shot.
View	Setup the 2D and 3D views.
Process	Meshing, simulation setup, optimization setup, invoking other applications for displaying s-parameters, current distribution and patterns.

Major Editing Modes (1)

♦ Polygon Handling:



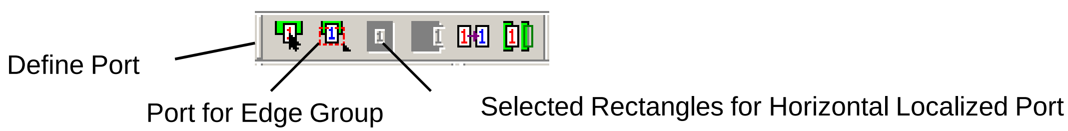
Mode	Command	Function
Draw	Edit->Draw	Allow drawing vertices and polygons using mouse and keyboard
Select Polygon	Edit->Select Polygon	Allow selecting a polygon by clicking at it.
Select Polygon Group	Edit->Select Polygon Group	Allow selecting a group of polygons by windowing them.
Select Vertices	Edit->Select Vertices	Allow selecting a group of vertices by windowing them.
No Entry	When above commands unchecked	Allow no mouse entry

The 3 selection modes are interchangeable. When it is changed from Select Polygon mode or Select Polygon Group mode to Select Vertices mode, all the vertices of the selected polygons are selected. When it is changed from Select Vertices mode to Select Polygon mode or Select Polygon Group mode, those polygons with ALL vertices selected are selected after mode change. If a polygon (or vertex) is selected twice, it becomes de-selected.

Major Editing Modes (2)

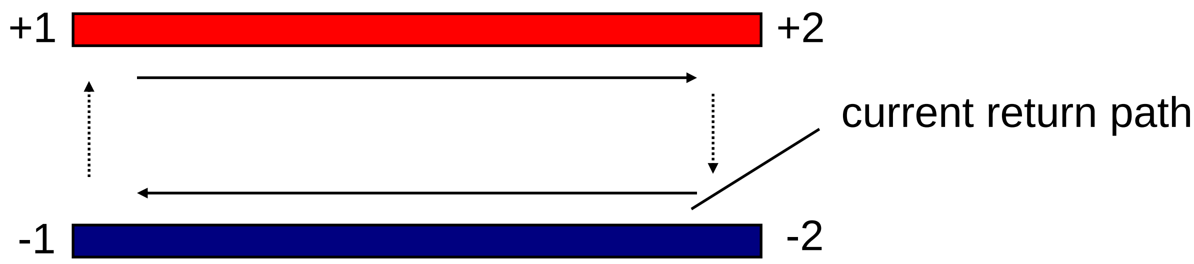
♦ Define Port and Port for Edge Groups:

Mode	Command	Function
Define Port	Port->Define Port	Allow defining a port by clicking at an edge on a layer.
Port for Edge Group	Port->Port for Edge Groups	Allow defining a port by windowing a group of linked edges on different layers.
Define a Horizontal Localized Port in Select Polygon (Group) mode	Port->Selected Rectangles for Horizontal Localized Port	Allow defining a group of connected horizontally placed rectangles (not necessary to be completely horizontal with constant Z) as a horizontal localized port
Define a Vertical Localized Port) in Select Polygon (Group) mode	Port->Selected Rectangles for Vertical Localized Ports	Allow defining a group of connected vertical rectangles as a vertical localized port.
Define an Extension Port in Select Vertices mode	Port->Selected Edges for Extension Port	Allow defining a group of linked edges on different layers as an extension port

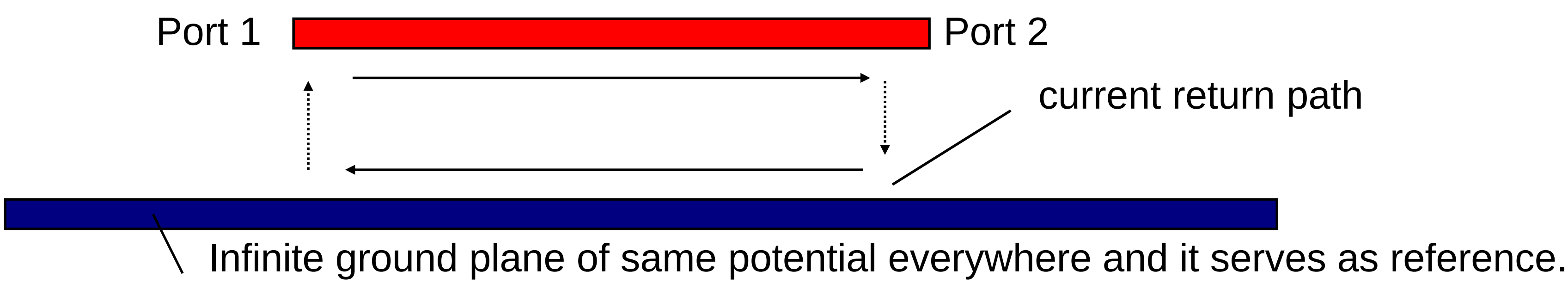


Requirement for Ports

- **Closed Loop for Current:**



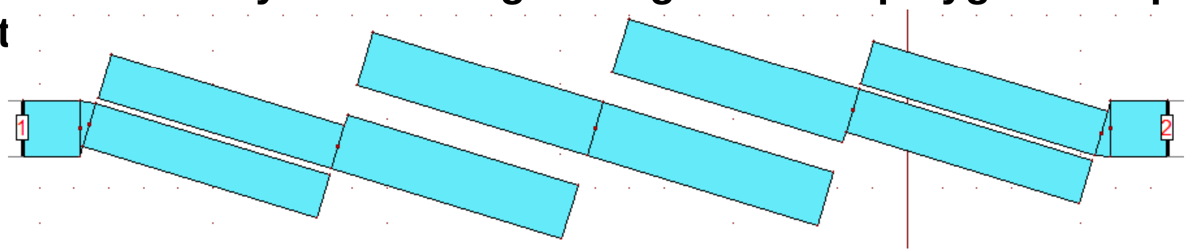
- **Infinite ground plane serves as the return path and reference terminal automatically:**



- **Finite ground is not of same potential everywhere and we need + and – ports or terminals.**

Defining Ports (1)

- **Define Port Mode: Easy for defining an edge on a 2D polygon as a port by clicking at**

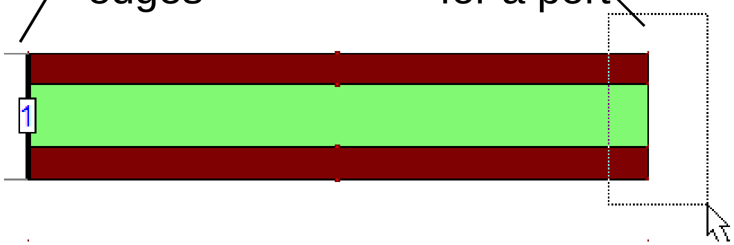


- **Port for Edge Group: Easy for defining a group of edges (on 2D or 3D polygons) as a port. If it is for 3D polygons, at least one edge needs to be from a 2D polygon (for detection purpose):**

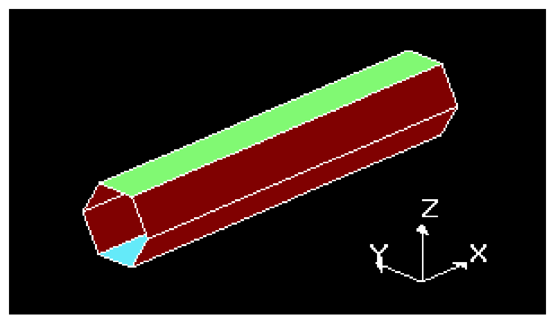
Defined port with multi-edges

Windowing edge groups for a port

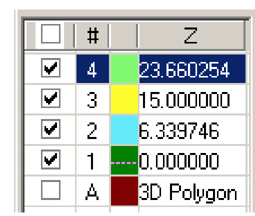
Make sure layers checked where edge vertices are on



Tube like structure on 2D view



Tube like structure in 3D view



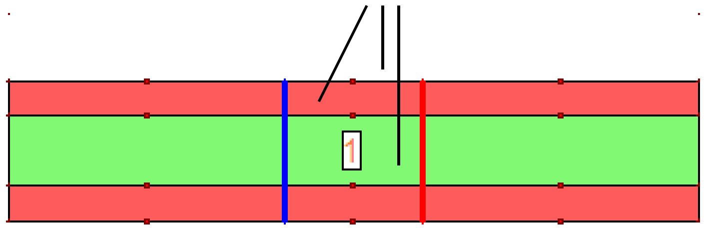
Layer window

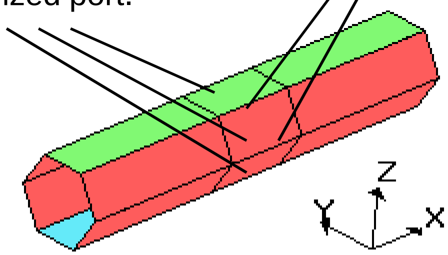
Defining Ports (2)

- **Selected Polygons for Horizontal Localized Port:**

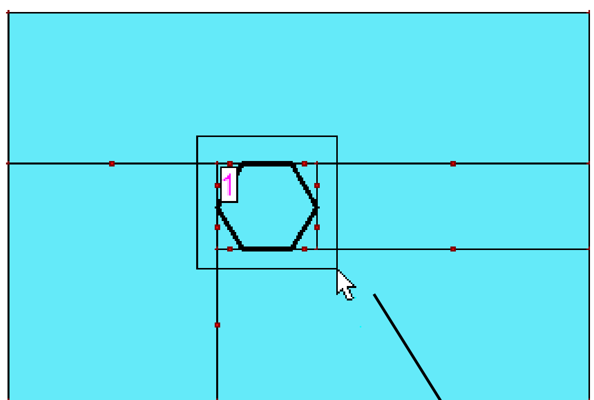
A group of connected rectangles selected and define as a H-localized port.

Common edges for connections

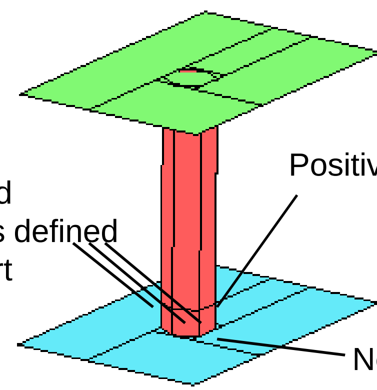




- **Selected Polygons for Vertical Localized Port:**



Connected rectangles defined for the port



Positive Level

Negative Level

Windowing the vertical rectangles on the top view

Major Editing Modes (3)

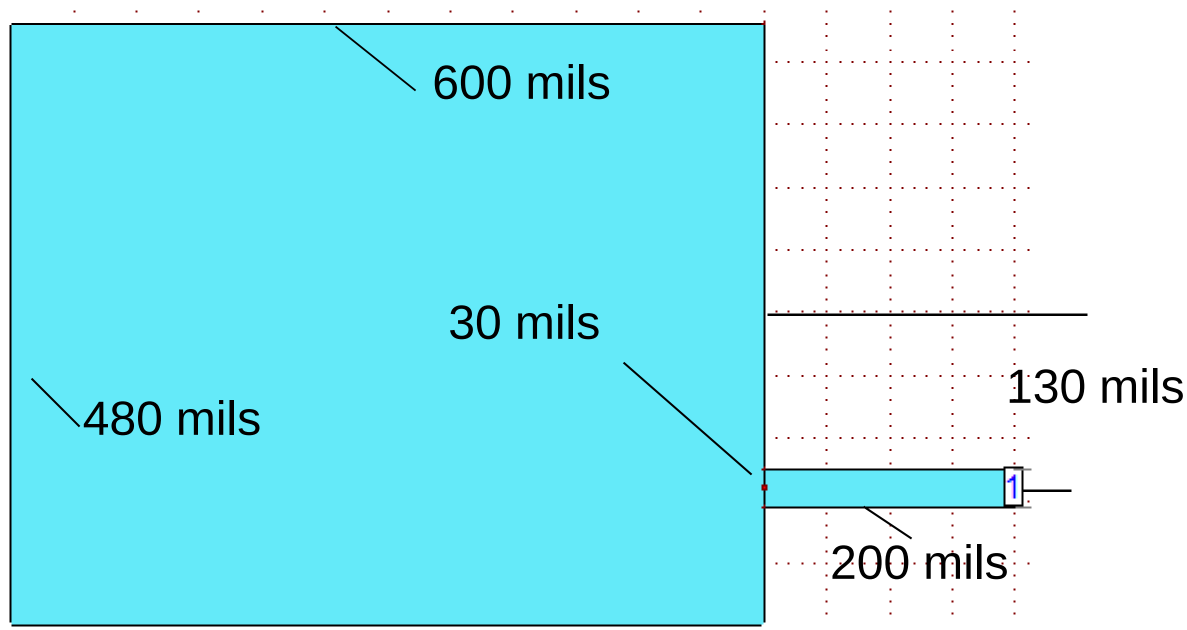
- **Defining Optimization Variable:**

Command	Function
Variable for Selected Objects	Define the location of the selected vertices or the vertices of the selected polygons as an optimization variable. The user will be prompted to define the Tuning Direction, Low Bound and High Bound of the variable. The Tuning Direction defines in which direction the vertices are changing.
Add Selected Objects to Variable	Associate the change of location of the selected vertices (or vertices of the selected polygons) to a defined optimization variable. The user will be prompted to define the Tuning Direction and the Tuning Rate. The Tuning Direction defines in which direction the vertices will change with the variable. The Tuning Rate defines how fast the vertices are changing with the variable

The combination of the two commands provides much flexibility in defining optimization variables. For example, we can define variables to optimize symmetrical structures or circular structures.

Basic Techniques in Geometry Modeling

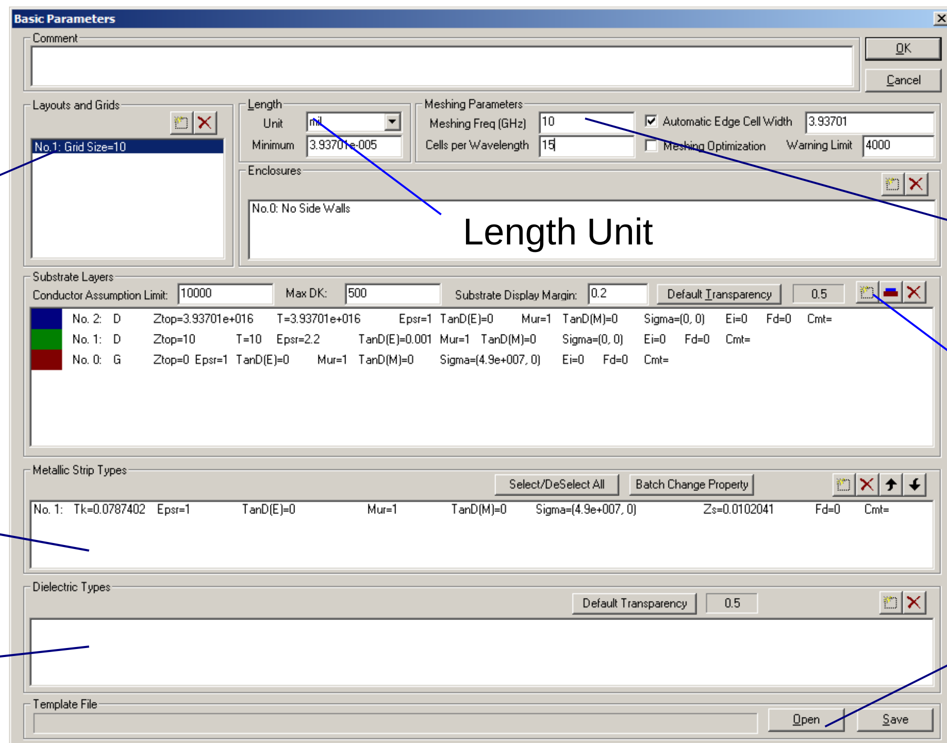
- An edge fed rectangular patch antenna with dimensions of 600×480 mils, substrate thickness T = 10 mils, εr = 2.2, tanδ = 0.001



Top View

An Edge Fed Rectangular Patch Antenna (1)

- **File->New to bring out the Basic Parameters dialog.**
- **Change Length Unit to “mil”, Layout Grid Size to “10”, Meshing Freq to “10” GHz, Cells per Wavelength = “15”.**
- **Select Insert button in Substrates list box to define a substrate with Ztop = “10” mils, εr = “2.2”, tan δ = “0.001”. Select OK after you finish.**



Layout and Grid

Length Unit

Meshing Freq

Insert button for substrates

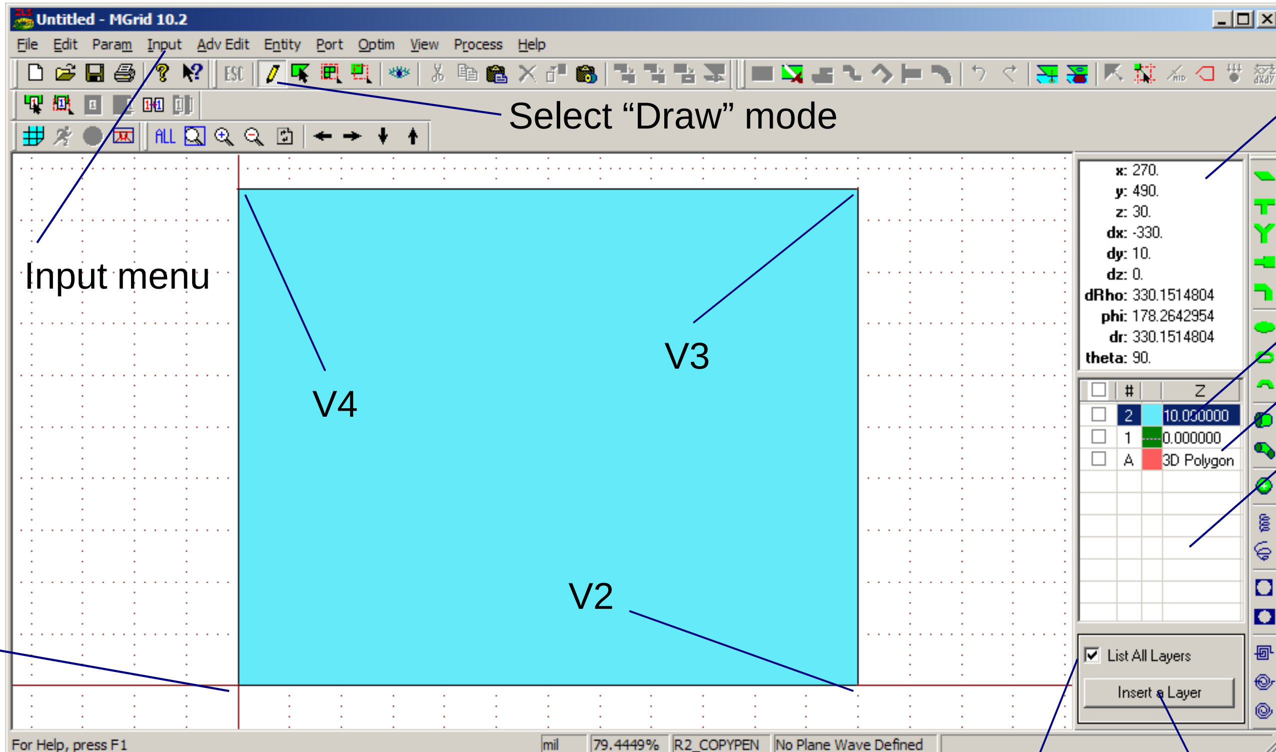
Define metallic strip types (not layers) here

Define finite dielectric types here if any

You can open a template file for the parameters.

An Edge Fed Rectangular Patch Antenna (2)

- **Build the rectangular patch:**
  - **Make sure it is in "Draw" mode. Make sure it is focused at Z = 10 or the No.2 layer.**
  - **Click at (or Input->Key In Absolute Location) X = 0 and Y = 0 for V1. Type Shift+R and enter dX = 600 and dY = 0 for V2. Type Shift+R and enter dX = 0 and dY = 480 for V3. Type Shift+F to form the rectangle. All the commands used here are in Input menu.**



V1

Status window showing the status of the editor. Please pay attention to it.

Input focused on Z = 10 layer

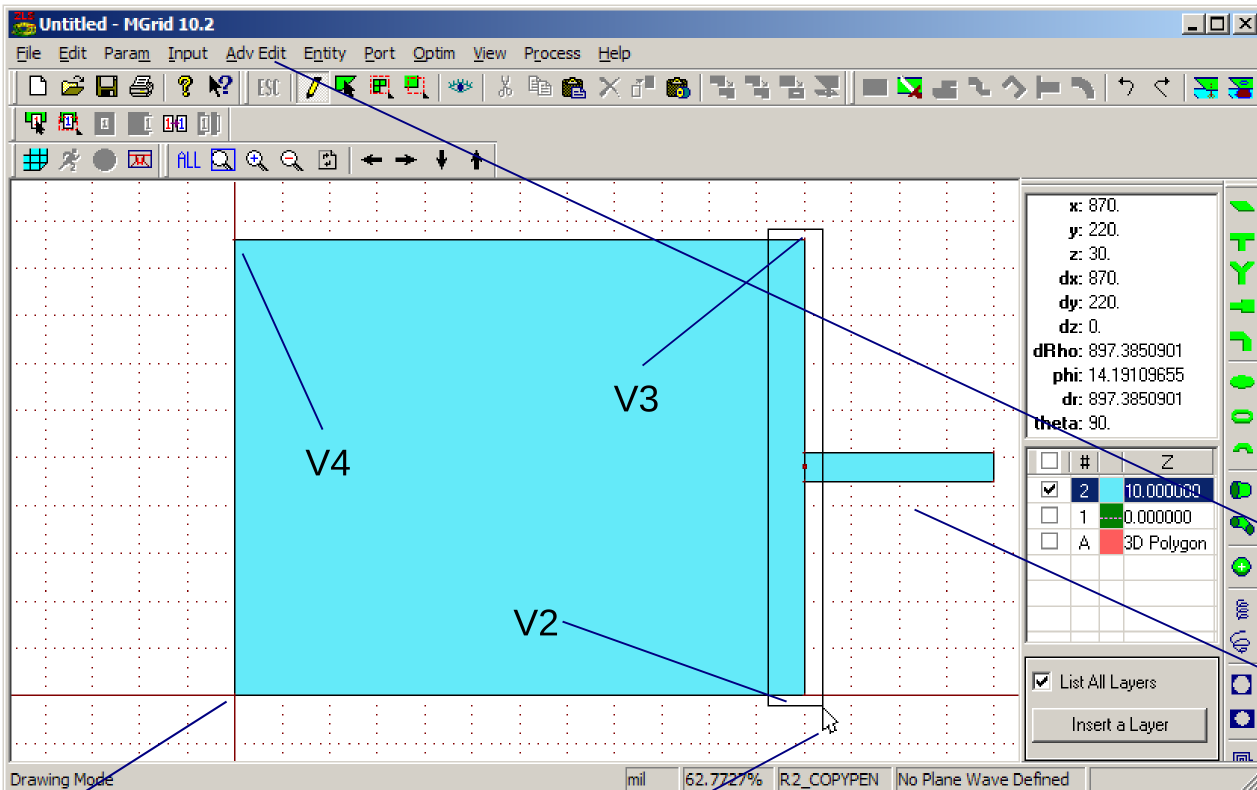
This is the polygon layer window. Polygon layers are different from the substrate layers. You can have polygon layers embedded into substrate layers.

Toggle between listing all polygon layers and listing those layers with polygons on them. You may have polygon layers with vertices on them only

Insert a new polygon layer here

An Edge Fed Rectangular Patch Antenna (3)

- **Build the feed line. There are many ways. The simplest one is demonstrated here:**
  - **Edit->Select Vertices. Window V2 and V3 (as shown).**
  - **Adv Edit->Continue Straight Path and enter Length = 200 and Width = 30 for the feed line.**



Step 2: Select Adv Edit->Continue Straight Path for the 200 mils long, 30 mils wide feed line.

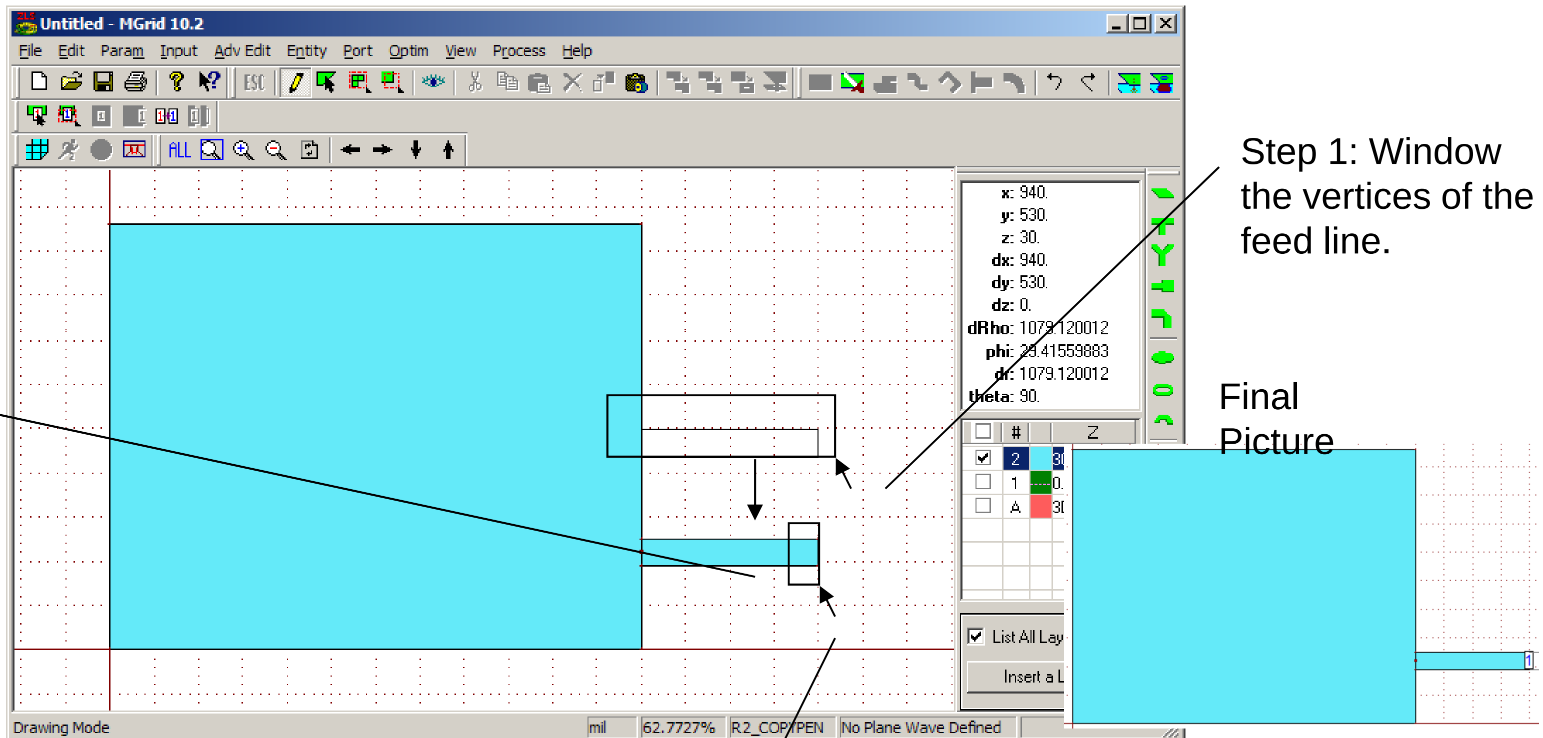
V1

Step 1: Window V2 and V3 in Select Vertices mode

An Edge Fed Rectangular Patch Antenna (4)

- **Modify the feed line with offset and define the port on the feed line:**
  - **Edit->Select Vertices and window the vertices for the feed line.**
  - **Edit->Move Objects, click at some where and enter dY = -130 mils for the offset.**
  - **Port->Port for Edge Group. Choose the Advanced Extension port. Window the end of the feed line for the port 1. Select Port->Exit Port for the final picture of the antenna.**
  - **Save the file as: edge_fed_rpatch1.geo file. It should be ready for simulation.**

Step 2: Move vertices with dY = -130 mils for the offset.



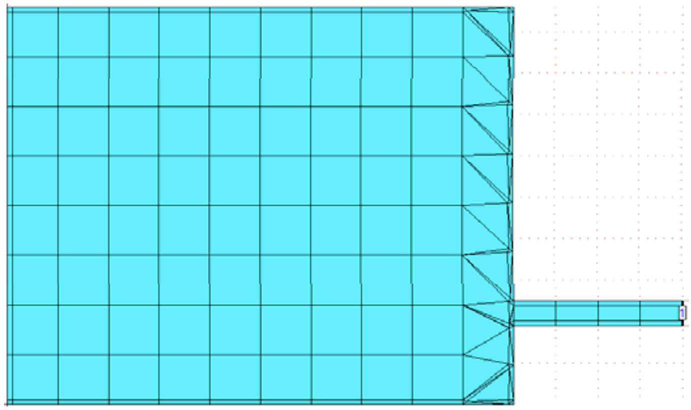
Step 1: Window the vertices of the feed line.

Final Picture

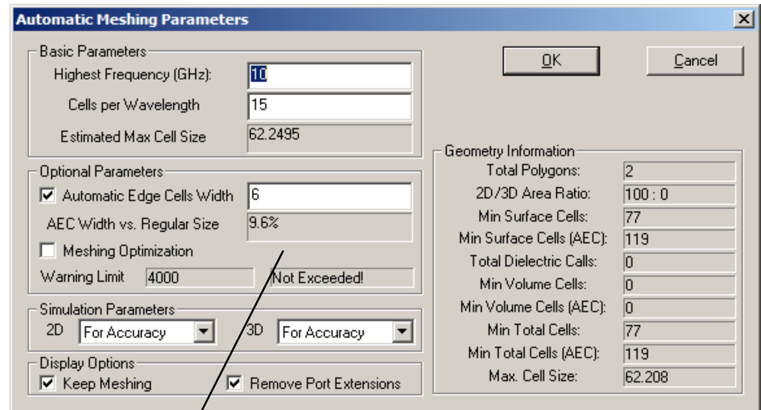
Step 3: In Port for Edge Group mode, window the end of the feed line for the port.

An Edge Fed Rectangular Patch Antenna (5)

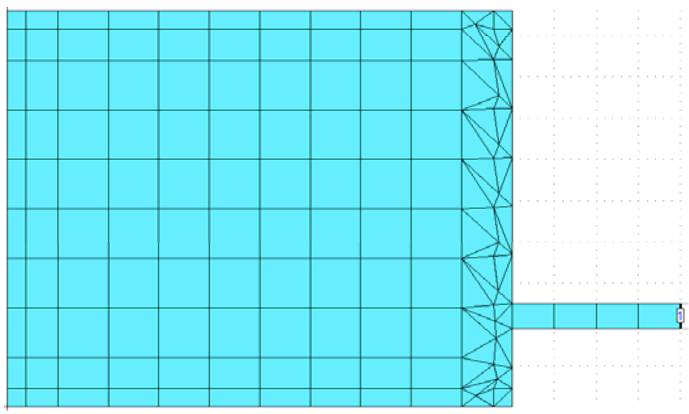
- **Preview Meshing and Automatic Edge Cells:**
  - **Select Process->Display Meshing. Make sure Fmax = 10 GHz, Ncells = 15 cells/λ, Automatic Edge Cell (AEC) enabled and Edge Cell Width = 6 mils. MGRID will show the AEC Width vs. Regular Size = 9.6%. After OK, MGRID will display the meshing.**



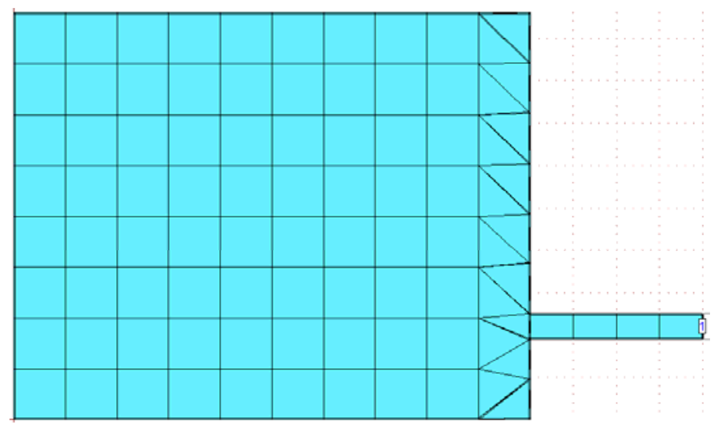
Good meshing with AEC = 6 mils (9.6%)



Good from 5% to 20%



AEC = 22 mils (35.3%) and it is slightly big.

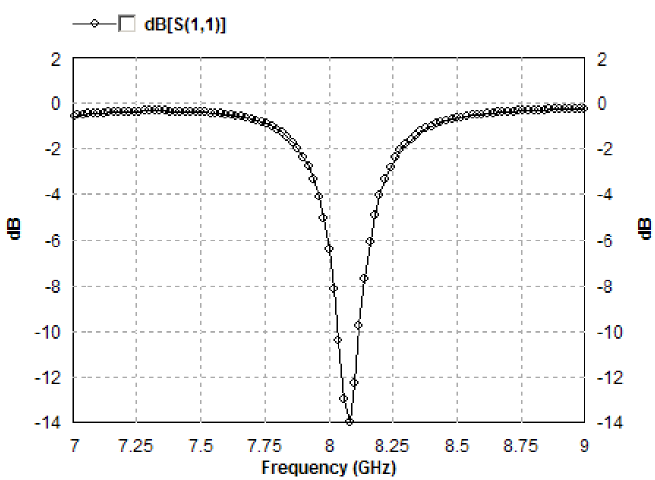


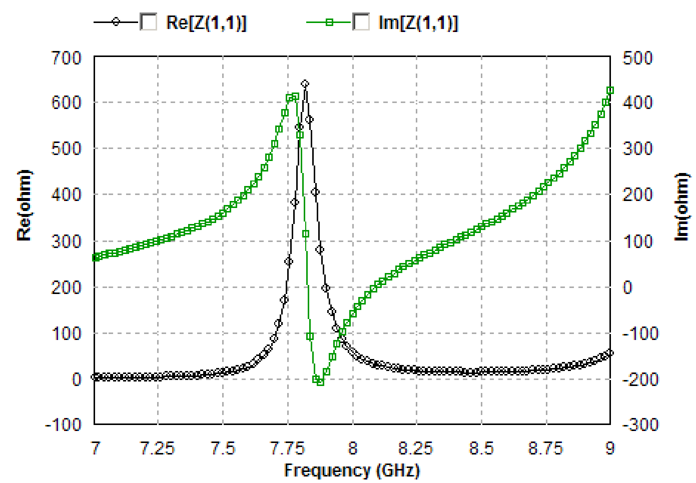
AEC = 2 mils (3.2%) and it is slightly small.

Note: AEC size is not very critical as long as it is not at extreme value.

An Edge Fed Rectangular Patch Antenna (6)

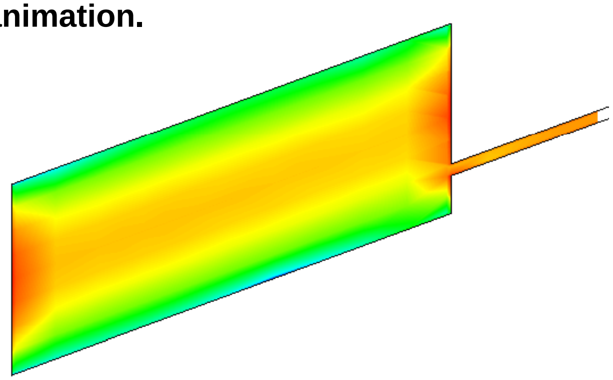
- **EM Simulation:**
  - **Select Process->Simulate. Enter Start Freq = 7, End Freq = 9 and Number of Freq = 101. Select Enter button (or hit Enter) to put the 101 frequency points into the list.**
  - **Enable Adaptive Intelli-Fit (AIF). Please enable it always for the cases with multi-frequency points and without saving the current distribution and pattern calculation.**
  - **Select OK and the IE3D engine is invoked to simulate the structure. After simulation, the s-parameters are saved in: edge_fed_rpatch1.sp. The bundled circuit simulator MODUA is invoked to display the s-parameters.**
  - **To change to other display, please select the Define Display Data, Define Display Graph, Define Display Smith Chart in the Control menu of MODUA for it.**
  - **The simulated s-parameters are always normalized to 50-ohms. To change the normalization impedance, please display the s-parameters first. Then, select Control->Terminating Impedance to change it.**
  - **The s-parameters can be displayed any time later as long as the edge_fed_rpatch1.sp is not deleted. You can select File->Display Parameter Module on MODUA for it.**



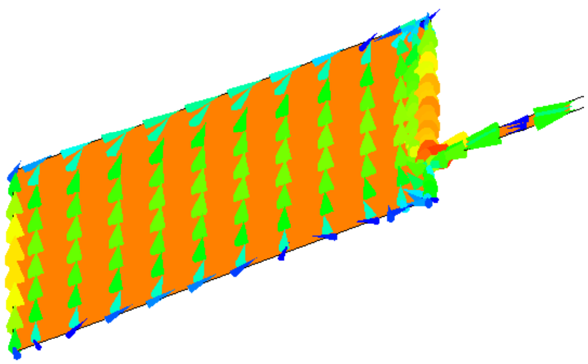


An Edge Fed Rectangular Patch Antenna (7)

- **EM Simulation with Current Distribution Data and Pattern Calculation:**
  - **Save the geometry as: edge_fed_rpatch2.geo. Select Process->Simulate. Select Delete All to delete the frequency points. Enter Start Freq = 7.8, End Freq = 8.3 and Number of Freq = 6. Select Enter button (or hit Enter) to put the 6 frequency points into the list.**
  - **Disable Adaptive Intelli-Fit (AIF). Check Current Distribution File to enable saving the current distribution data. You can check Radiation Pattern File to enable automatic pattern calculation. However, we can always perform the pattern calculation later after we are displaying current distribution.**
  - **Select OK and IE3D engine is invoked to perform the simulation. After simulation, the current data is saved in: edge_fed_rpatch2.cur file. Another MGRID is invoked to display the meshed structure in the .cur file. If you check Radiation Pattern File in the Simulation Setup dialog, the pattern will also be calculated and saved in: edge_fed_rpatch2.pat file. PATTERNVIEW will be invoked for displaying the pattern.**
  - **While MGRID is displaying the meshed structure from edge_fed_rpatch2.cur file, you can select Process->Display Current Distribution command with proper settings to display average current and vector current and animation.**



Average current distribution with color for the average strength of the current

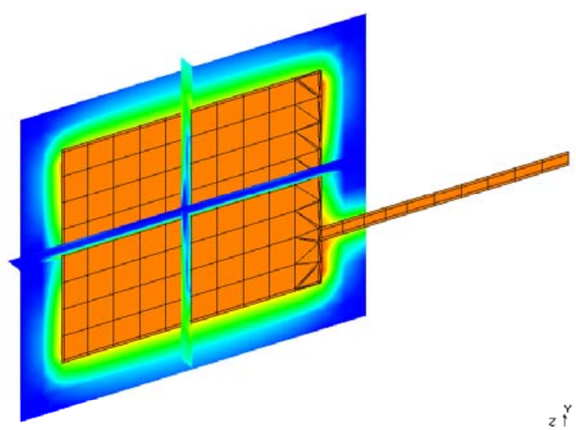


Vector current distribution with properly adjusted Vector Size (=80) and Vector Half Size (=40) in View->Set Graph Parameters of the 3D View window.

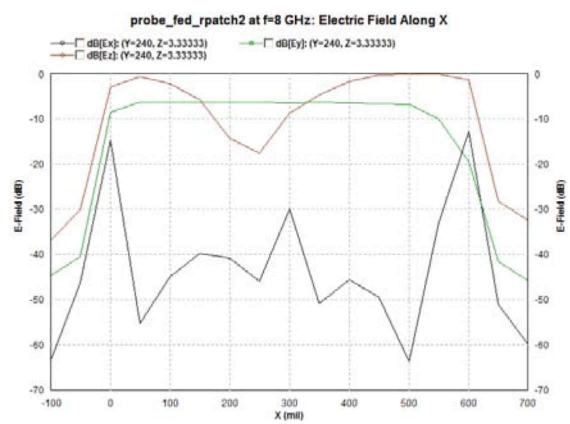
Notes: Vector Half Size = 40 means that doubling the vector size means 40 dB increase in the magnitude in the strength. It is introduced for easy scaling of the vectors.

An Edge Fed Rectangular Patch Antenna (8)

- **Pattern Calculation and Near Field Calculation in Current Display Mode:**
  - **While the current is displayed, you can select Process->Pattern Calculation for pattern calculation. MGRID will prompt you the Pattern Calculation Information dialog to define the Elevation Angles and the Azimuth Angles. It is not time for you to define the excitation yet. After you select OK, it will perform a general pattern calculation. After it finishes, you can select Save General Pattern file (*.mpa) with the excitation undefined and to be defined at the display time.**
  - **You can select Define Excitation button and the Pattern Calculation Information dialog comes up again for you to define the excitation. After you define the excitation and select OK, MGRID will save the pattern data into the specified file (edge_fed_rpatch2.pat) and invoke PATTERNVIEW to display the pattern.**
  - **While the current is displayed, you can also Process->Near Field Calculation for near field calculation. Near field calculation can be time consuming. Please try to limit the number of divisions in the X, Y and Z direction so that it will not take too much time. You should only check those frequency points of interests for it. Calculated near field can be visualized as colorful pictures in Process->Display 3D Near Field Distribution, or as Cartesian graphs in Process->Display 2D Near Field Distribution.**



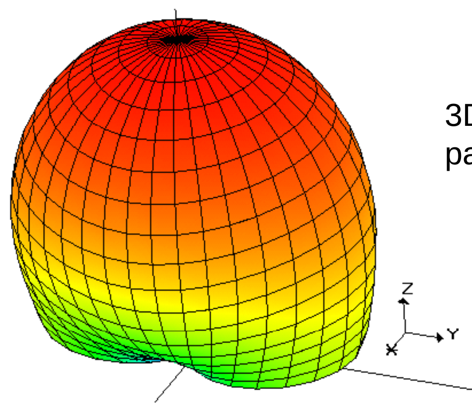
3D Near Field Display



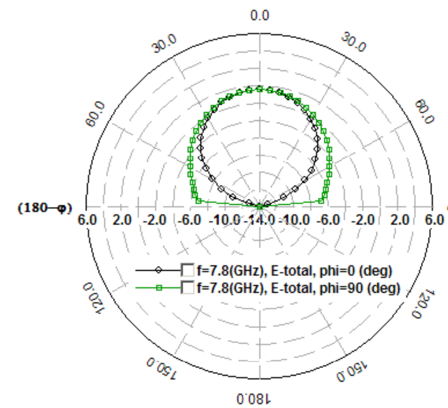
2D Near Field Display

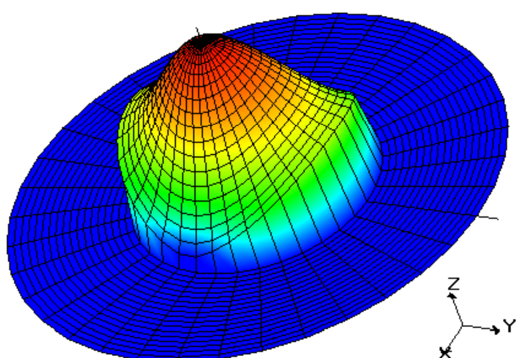
An Edge Fed Rectangular Patch Antenna (9)

- **Pattern Visualization, Processing and Comparison on PATTERNVIEW**
  - **Calculated pattern files (*.pat) can be added into the pattern list for display and comparison (Edit->Add Pattern command). The files added into the list can be compared.**
  - **Calculated general pattern can be processed to get the pattern file (*.pat) with specified excitation (Edit->Process General Pattern). General patterns allow users to define the excitation at the display time without repeated pattern calculations which take much time.**

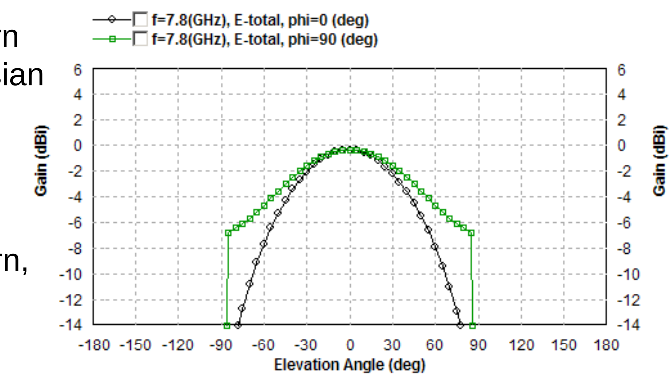


3D pattern cut into 2D polar pattern





3D mapped pattern cut into 2D Cartesian pattern



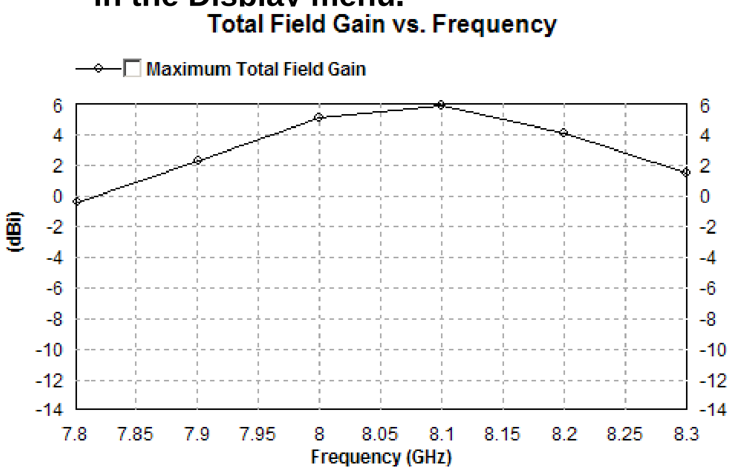
(In 3D mapped pattern, ρ in the picture represents φ angle in the reality)

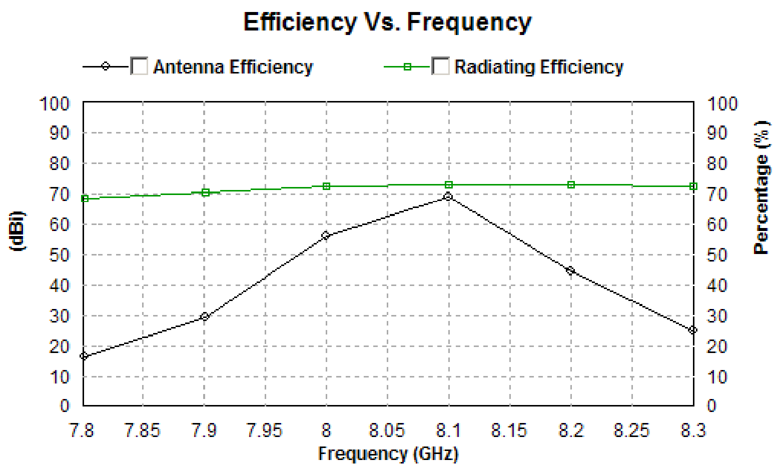
3D Pattern Display

2D Pattern Display

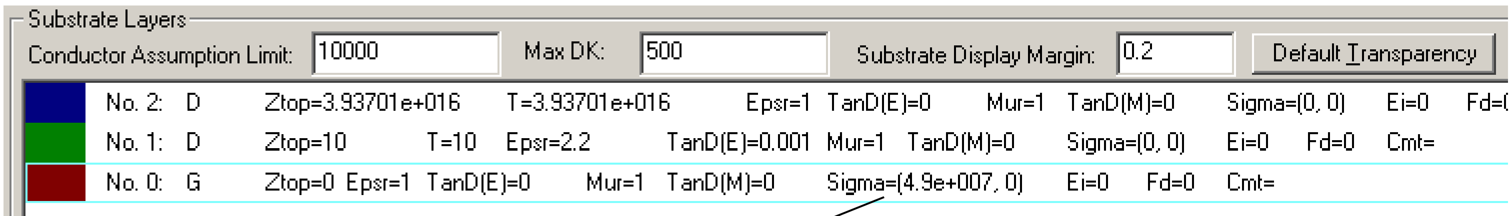
An Edge Fed Rectangular Patch Antenna (10)

- **Pattern Visualization, Processing and Comparison on PATTERNVIEW**
  - **Pattern data in ASCII format can be saved in: File->Save Data File.**
  - **List the major pattern properties: Edit->Pattern Properties.**
  - **Patterns from different geometry files can be merged in: Edit->Merge Patterns.**
  - **Calculating patterns from near field: Edit->Near Field to Far Field Transformation.**
  - **Find TxRx Transfer function from the patterns of Tx antenna and Rx antenna (with plane wave excitation): Edit->Find TxRx Transfer Function. The transfer function as 2-port s-parameters can be used to perform time transient analysis using MDSPICE.**
  - **Find the field distribution in far-field zone based upon the radiation pattern: Edit->Pattern Manipulation and Wave Propagation.**
  - **Find the radiation pattern of an array from the patterns of the elements: Edit->Array Pattern Calculation.**
  - **Display antenna properties (gain, directivity, efficiency vs. frequency) using the different items in the Display menu.**

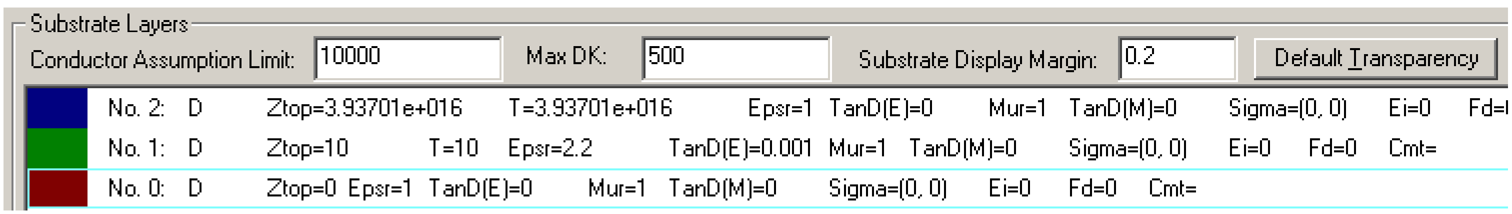




Infinite Ground and Finite Ground

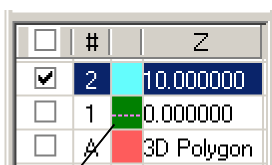


Infinite ground at z = 0 because of the high conductivity



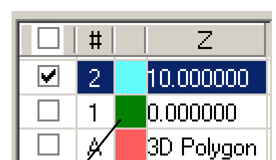
No infinite ground at z = 0 because it is air from $-\infty$ to 0.

Layer window indicating Z = 0 with infinite ground. Any polygons on Z = 0 become slots on the ground.



Horizontal dash line means infinite ground on layer

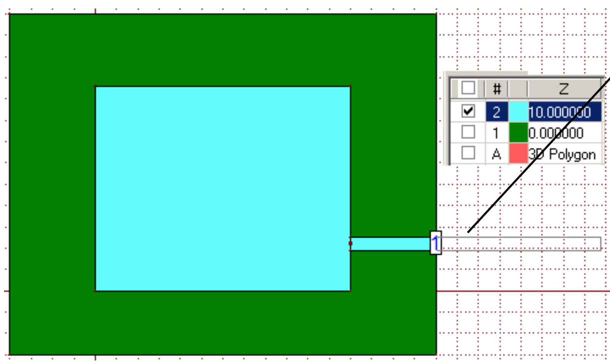
Layer window indicating Z = 0 without infinite ground.



No dash line because Z = 0 is not an infinite ground

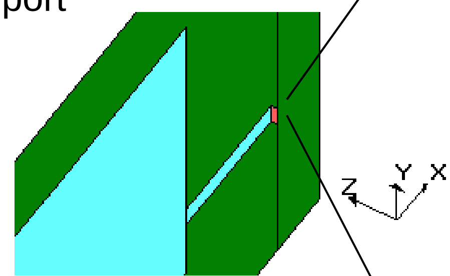
Patch Antenna with Finite Ground

- **Incorrect Finite Ground Model without Differential Port:**

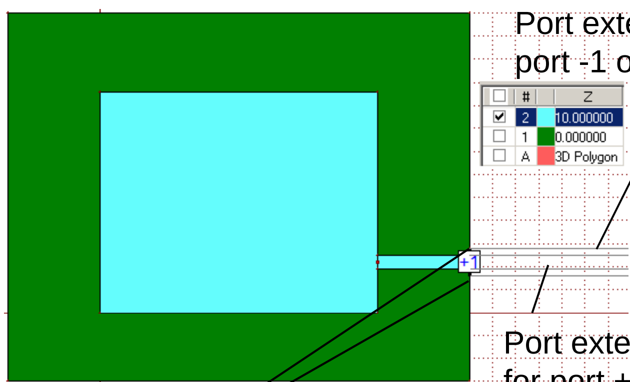


Only port 1 and no port -1

Rectangle connected to feed line and the finite ground defined as v-localized port



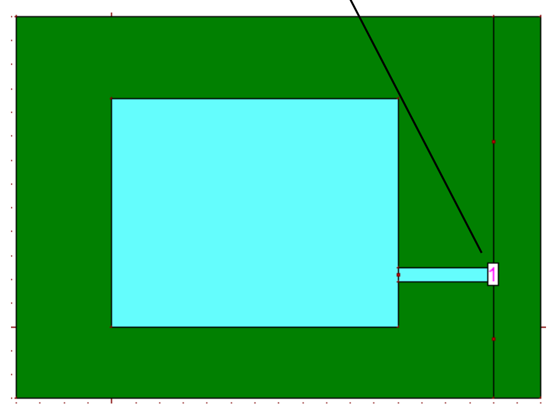
- Correct Finite Ground Model with Differential Port:



Port extension for port -1 on Z = 0

Port extension for port +1 on Z = 10

Inserted vertices on z = 0 for port -1



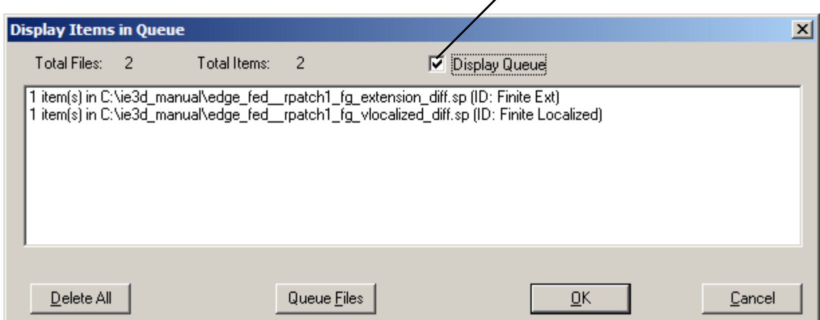
Differential extension port structure (edge_fed_rpatch1_fg_extension_diff.geo)

Vertical localized port structure (edge_fed_rpatch1_fg_vlocalized_diff.geo)

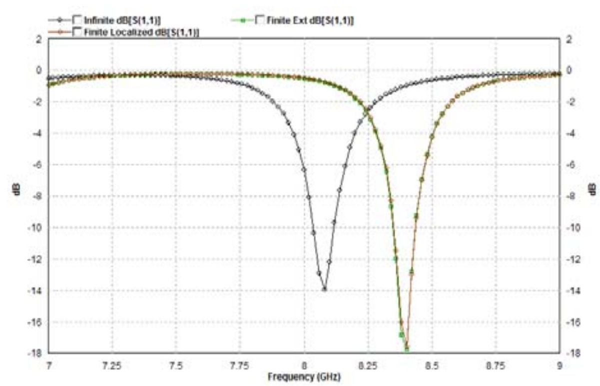
Comparison of Simulation Results

- **We want to compare the s-parameters of the 3 antennas: (1) Infinite ground: edge_fed_rpatch1.sp; (2) Finite ground using extension port: edge_fed_rpatch1_fg_extension_diff.sp; (3) Finite ground using vertical localized port: edge_fed_rpatch1_fg_vlocalized_diff.sp:**
  - **Select File->Display Parameter Module on MODUA. Select edge_fed_rpatch1.sp to display it.**
  - **Select View->Design Identification and enter "Infinite" to identify the curves.**
  - **Select File->Parameter File Queue. Select Add. Select edge_fed_rpatch1_fg_extension_diff.sp. Enter "Finite Ext" to identify it. Select OK and it is added into the queue. Select Add again. Select edge_fed_rpatch1_fg_vlocalized_diff.sp. Enter "Finite Localized" to identify it. Select OK to add it into the queue.**
  - **Select the Display button in the Display Queue Files dialog. MODUA to go directly into the View->Display Queue Items dialog. Select each file in the list and check the items you want to display. Remember to check the Display Queue check box to enable the display of the queue items. The check box is a fast way to toggle between display and no display. Select OK and you will see the display of the s-parameters.**

The Display Queue check box



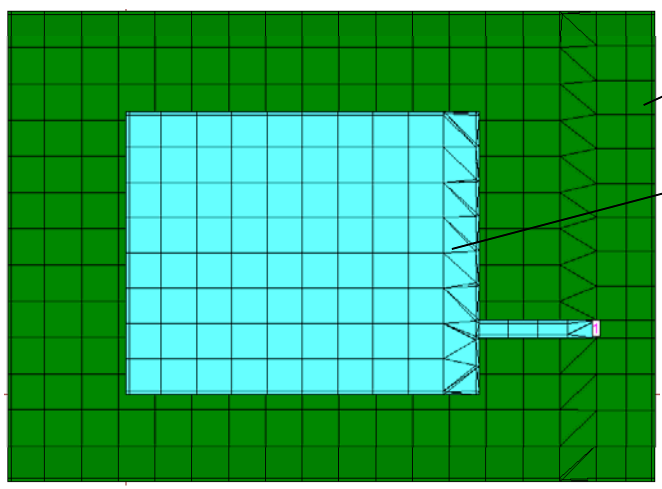
The View->Display Queue Items dialog



The compared s-parameters

Division and Meshing Alignment for High Accuracy (1)

- Normally, division and meshing alignment is not necessary. As long as AEC is used, we should get good results.
- When two layers are too close, division and meshing alignment will improve the accuracy. Meshing alignment is certainly necessary for MIM capacitors.
- For our particular finite ground plane example, due to the fact the patch is quite close to the finite ground, meshing alignment will improve the simulation accuracy.



Meshing on the finite ground

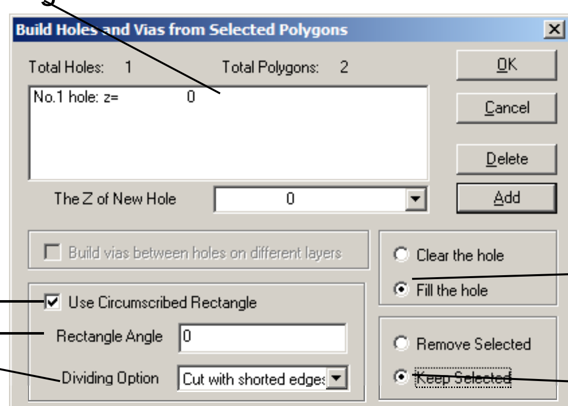
Meshing on the patch

Note: The meshing does not match between the two closely coupled layers. Aligned meshing may improve accuracy.

Division and Meshing Alignment for High Accuracy (2)

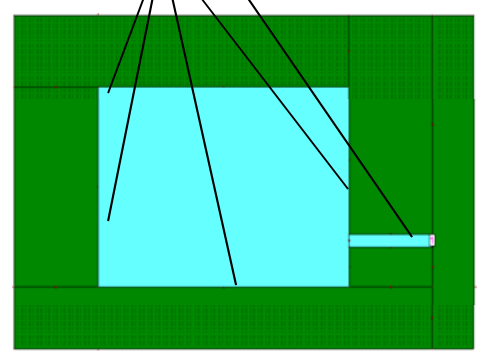
- **Open edge_fed_rpatch1_fg_vlocalized_diff.geo.**
- **Select Edit->Select Polygon Group. Focus the selection to Z = 10. Window the polygons for the patch and feed line to select them.**
- **Select Adv Edit->Build Holes and Vias from Selected Polygons. Enter the parameters as shown. Select OK and MGRID will create matched division lines between the polygons on the two layers. Matched division lines normally can yield matched meshing.**

We want to match the shape of the patch and the feed line on the finite ground



The options will affect the dividing lines for the holes.

Matched division lines

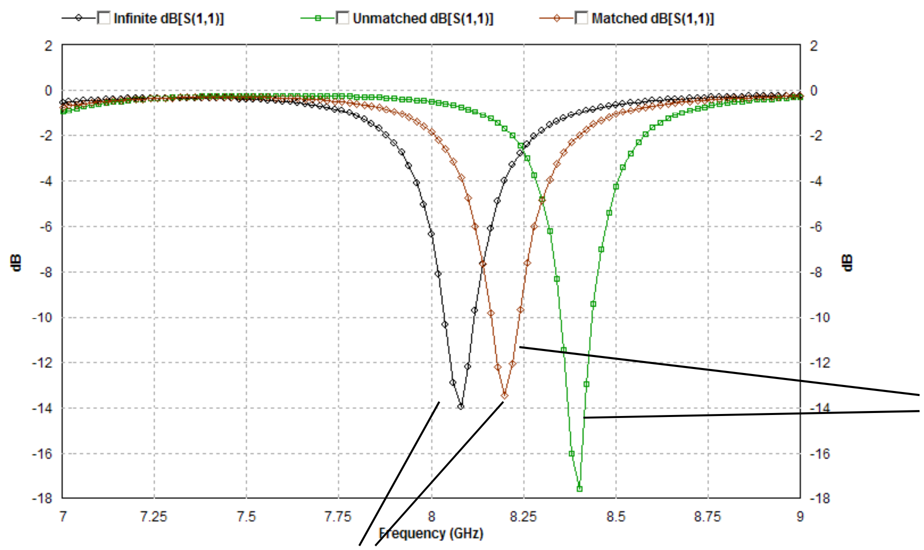


We just want to match the division lines and we do not want a hole on it.

We still want to keep the polygons for the patch and the feed line after the process.

Division and Meshing Alignment for High Accuracy (3)

- Save the geometry as: **edge_fed_rpatch1_fg_vlocalized_diff_aligned.geo.**
- **Simulate it and compare the results:**
  - **Infinite: Infinite ground case in edge_fed_rpatch1.geo**
  - **Unmatched: Finite ground with unmatched meshing in edge_fed_rpatch1_fg_vlocalized_diff.geo.**
  - **Matched: Finite ground with matched meshing in edge_fed_rpatch1_fg_vlocalized_diff_aligned.geo**
- **Meshing alignment between close layers is critical for high accuracy results. Manual alignment is needed for current version. Automatic meshing alignment will be available on the next IE3D to be released before the end of 2004.**



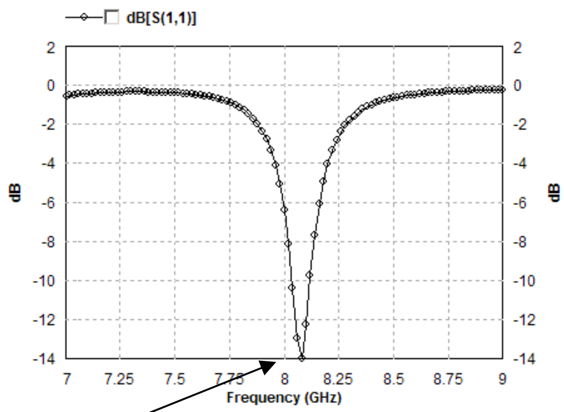
Note: This is a narrow band antenna. Meshing mis-alignment yield some slight shift in the resonant frequency. However, the slight shift in resonant frequency may be quite critical.

Frequency shift due to meshing mis-alignment for the two close layers.

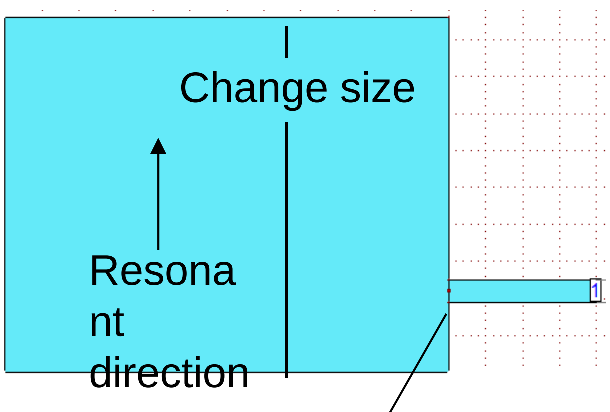
Frequency shift due to difference in finite and infinite ground

Electromagnetic Optimization and Tuning (1)

- **Identify what we want to do (the goals):**
  - **We want the resonant frequency to be at 8 GHz.**
  - **We want the antenna to be perfectly matched at resonance.**
- **Identify how we can do it (what can be changed):**
  - **Change the resonant length to shift the resonant frequency.**
  - **Change the feed point to achieve perfect match.**



Want perfect match at 8 GHz



Change feed location

Electromagnetic Optimization and Tuning (2)

- For the 1st IE3D layout editor MGRID, the basic objects for geometry editing are the vertices (polygons). We can control the locations of the vertices (polygons) for tuning of a structure's shape. We need to define vertices (or polygons) as optimization variables. MGRID has much flexibility in geometry modeling while defining optimization variables is less straight-forward than IE3DLibrary.
- For the 2nd IE3D layout editor IE3DLibrary, the basic objects are the parameterized elements. We can map the dimensions of the elements to a set of variables. IE3DLibrary allows users to create a parameterized structure easily while it is less flexible in changing the shapes of a geometry. IE3DLibrary has a user-programmable object allowing users to program their own parameterized objects for sophisticated EM optimization.
- Both IE3D layout editors are complementary. We will focus on MGRID in this presentation.

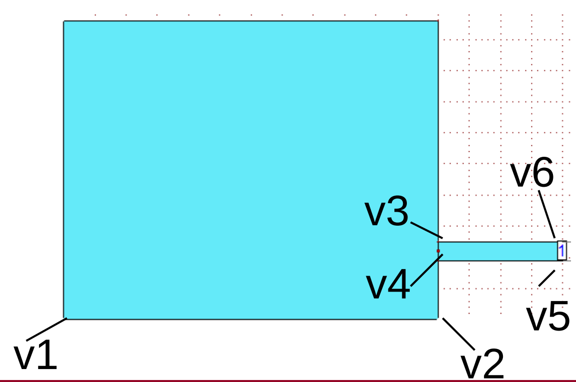
Electromagnetic Optimization and Tuning (3)

- **Identify how we can control the vertices for changing the patch size and feed location while still keeping it a valid geometry within the low bound and high bound.**

Scheme 1:
Variable 1: v1 and v2 change in direction at φ = 90° to control the patch size; Variable 2: v3-v6 change in direction at φ = 90° to control the feed location. Such a scheme is straight-forward but may easily create invalid geometry when the y-coordinate of v2 is larger than that of v4.

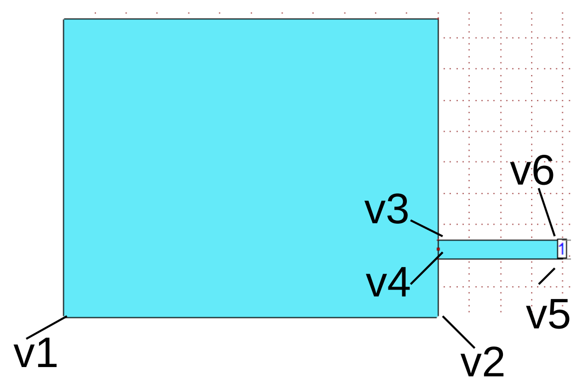
Scheme 2:

Variable 1: v1 and v2 change in direction at φ = 90° to control the patch size; Variable 2: v1-v6 change in direction at φ = 90° to control both the feed location and patch size simultaneously. We can easily define the bounds to guarantee that the y of v2 will not be larger than that of v4. This is a better scheme.



Electromagnetic Optimization and Tuning (4)

- **Defining v1 and v2 as variable 1:**
  - **Open edge_fed_rpatch1.geo. Select Edit->Select Vertices. Window v1 and v2.**
  - **Select Optim->Variable for Selected Objects. Enter Tuning Angle = 90. Select OK. MGRID will be waiting for you to define the Low Bound and High Bound.**
  - **Move the mouse downward and click. Enter the Low Bound as -40.**
  - **Move the mouse upward and click. Enter the High Bound as 70. Be very careful not to let the Y of v2 to be above that of v4 when you define the High Bound. Select OK to finish the definition. MGRID will warn you not to change the geometry anymore.**
- Defining v1- v6 as variable 2:
  - Select Edit->Select Vertices. Window v1 to v6. Select Optim->Variable for Selected Objects. Enter Tuning Angle = 90. Select OK.
  - Move the mouse downward and click. Enter the Low Bound as -30. Move the mouse upward and click. Enter the High Bound as 30. As you can see, no matter what Low Bound we define, it will not cause the Y of v2 to be larger than the Y of v4.



- Save as: edge_fed_rpatch1_optim.geo.

Note: Try to define smaller range between Low Bound and High Bound for faster optimization.

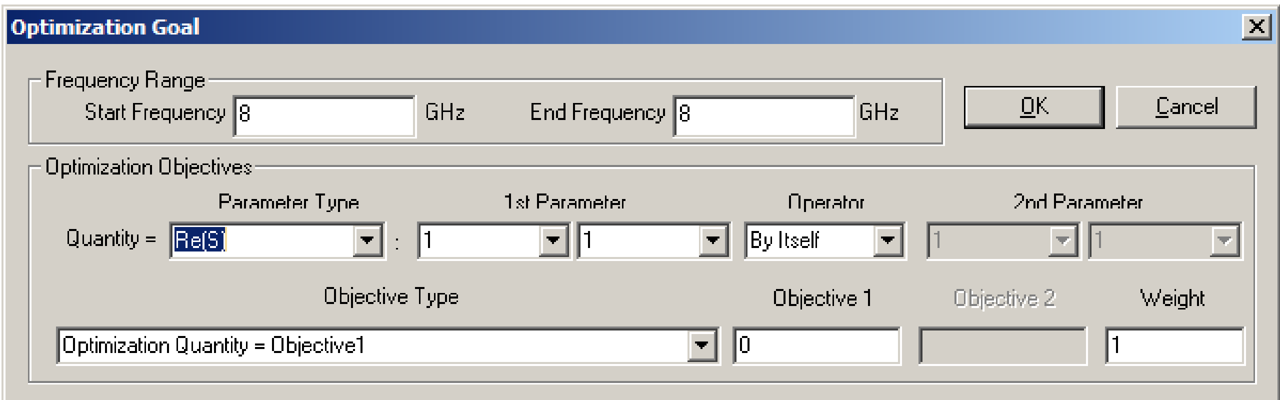
Electromagnetic Optimization and Tuning (5)

- **Electromagnetic Tuning:**
  - **Select Process->Simulate for simulation with sweeping of dimensions.**
  - **Enter the frequency points.**
  - **Select Define or Define All in the Tuning Setting of the Simulation Setup dialog to define a simulation sweeping. The feature allows you to simulate the structure with different combinations of values for the optimization (or tuning) variables. You can choose the s-parameter file name to include the indices of the tuning or the values of the tuning variables.**

- Electromagnetic Optimization:
  - What can you optimize? S-parameters (50-ohms or non-50 ohm normalized), Y and Z-parameters, Maximum Gain or Gain at Specific Angles, Maximum Directivity or Directivity at Specific Angles, Axial Ratio, RCS, Efficiency etc.
  - You can enter simple formula such as Objective1 < S(2,1)/S(3,1) < Objective2.
  - For optimization of pattern parameters, you need to enable Radiation Pattern Calculation first. When you check it, it will prompt you for the pattern calculation angles, excitations and terminations of the ports.

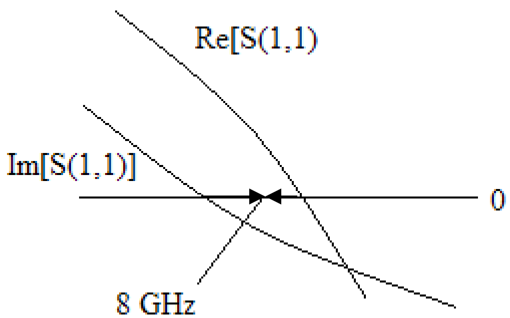
Electromagnetic Optimization and Tuning (6)

- **Electromagnetic Optimizations:**
  - **Select Process->Optimize.**
  - **Enter one frequency point at 8 GHz because we want to optimize it at 8 GHz only. Disable Adaptive Intelli-Fit (no enough frequency points).**
  - **Select Add button in Optimization Definition. Define the Optimization Goal as shown: Re[S(1,1)] = 0 at 8 GHz. Select Add button again. Define the Optimization Goal as: Im[S(1,1)] = 0 at 8 GHz. Basically, we want S(1,1) = 0 (perfect match) at 8 GHz. Other options can be:**
    - **Re[Z(1,1)] = 50 and Im[Z(1,1)] = 0 at 8 GHz (good)**
    - **dB[S(1,1)] < -40 dB at GHz (less good).**

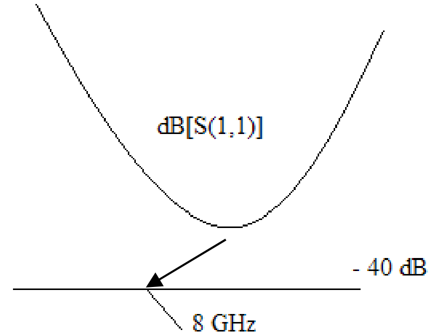


Electromagnetic Optimization and Tuning (7)

- **Strategy in Defining the Optimization Goals:**
  - **Try to avoid invalid goals: MAG[S(1,1)] = 0 and ANG[S(1,1)] = 90° are invalid goals because ANG[S(1,1)] does not have any meaning when MAG[S(1,1)] = 0.**
  - **Try to avoid multiple local minimums (discussed later).**
  - **Try to use monotonic error functions. Error functions are generated automatically internally. However, you ... error**



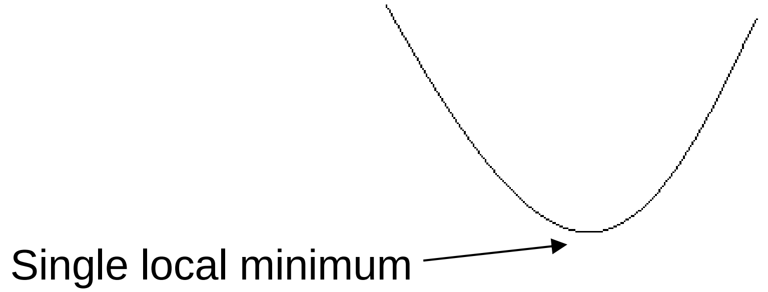
The changes of the error functions are monotonic and it is very good.

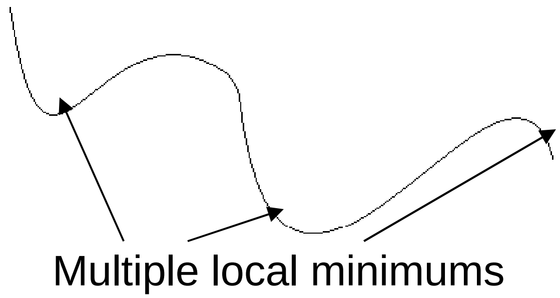


The changes of the error functions are not monotonic and it is less good.

Electromagnetic Optimization and Tuning (8)

- **Optimization Schemes:**
  - **Powell Optimizer is very efficient for local optimization with single local minimum. It may be locked to one local minimum (not the best) when multiple local minimums happen.**
  - **Genetic Optimizer is very robust for global optimization with multiple local minimums. However, it may converge slow when it is getting close to the goal.**
  - **Adaptive Optimizer is even more efficient than Powell Optimizer for local optimization and much more efficient than Genetic Optimizer for global optimization and it is also very robust.**
  - **Typical single local minimum examples: (1) An antenna perfect match at a specific frequency. (2) A coupler with specified coupling at a single frequency.**
  - **Typical multiple local minimum examples: (1) A filter with specified pass-band and stop-band performance (in a frequency range). (2) A wide band antenna with specified return loss(in a frequency range).**



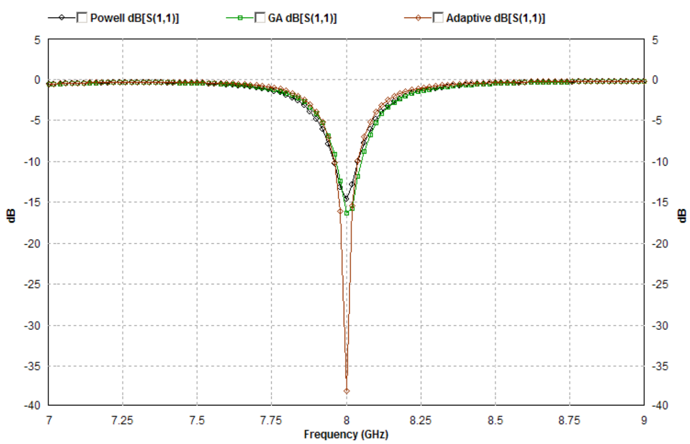


Electromagnetic Optimization and Tuning (9)

- Using the Ultra-Fast Adaptive Optimizer:
  - Adaptive Optimizer combines the multiple technologies to achieve the goal using the fewest EM simulations. It is very robust and efficient.
- Comparison between different schemes for the particular structure:
  - Although it is a problem for perfect match at a single frequency of 8 GHz, this particular example may have multiple local minimums due to the fact there are 2 close resonant frequencies around 8 GHz.
  - The default convergence residual is 0.01 and it is an arbitrarily chosen value. Powell Optimizer indicates convergence at No.46 simulation with residual 0.184374. Genetic Optimizer does not converge at the last call (No.565). Adaptive Optimizer indicates convergence at No.50 simulation with residual = 0.0125524.
  - Adaptive Optimizer is clearly the best scheme.

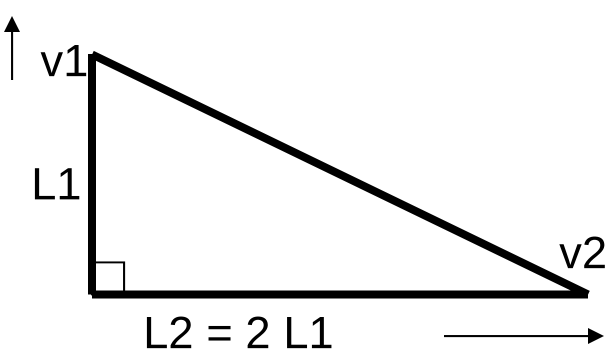
Scheme	Calls	Simulations	Residual
Powell	57	46	0.184374
Genetic	565	187	0.153546
Adaptive	50	50	0.0125524

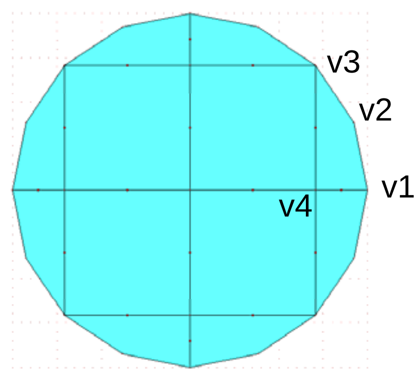
Note: Some calls may have the same variable values. They will not be simulated again when a call is detected to be the same as a previous one.



Electromagnetic Optimization and Tuning (10)

- **Mapping Multiple Vertices to the Same Variable with Different Tuning Rate:**
  - **Assume we want to optimize the dimensions of a right-angle rectangle with its shape unchanged.**
  - **Select Edit->Select Vertices. Window v1 to select it. Select Optim->Variable for Selected Objects. Define the Tuning Angle = 90°. Define the appropriate Low Bound and High Bound.**
  - **Select Edit->Select Vertices. Window v2 to select it. Select Optim->Add Selected Vertices to Variable. Make sure the "Vertices Mapped to" the right variable for "v1". Define the Tuning Angle = 0° and the Tuning Rate = 2. Select OK. The reason we choose the Tuning Rate = 2 is that we want the v2 changing in the 0° direction twice as fast as the v1 changing in the 90° direction.**
  - **The above scheme is very flexible and it allows us to define variables to control very complicated structures (see the circle radius example).**





Define circle radius as optimization variable:
1. Define v1 at 0° as variable.
2. Add v2 at 22.5° & rate = 1.
3. Add v3 at 45° & rate = 1.
4. Add v4 at 0° & rate=0.707…

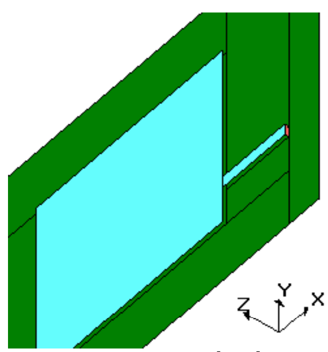
…

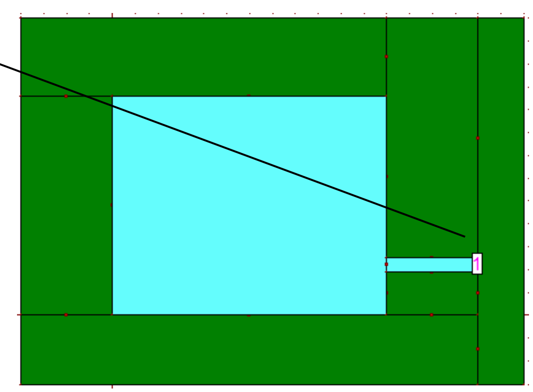
Go through all vertices and we will have the radius as a variable.

Modeling of Antennas with Finite Substrates (1)

- **A rectangular patch antenna with finite substrate and finite ground plane:**
  - **Take the edge_fed_rpatch1_fg_vlocalized_diff_aligned.geo as an example. Assume the substrate size is the same as the ground size.**
  - **The basic procedures:**
    - **Define dielectric type in the Basic Parameters dialog.**
    - **Define some horizontal polygons as a call for dielectrics with span in z-direction.**
  - **The key to high accuracy modeling: Align the division lines or even the meshing between the polygons and the finite substrates. We have demonstrated the importance of meshing alignment in edge_fed_rpatch1_fg_vlocalized_diff_aligned.geo. We will use it as the starting point for our finite ground modeling.**

Rectangle connected to feed line and the finite ground defined a v-localized port



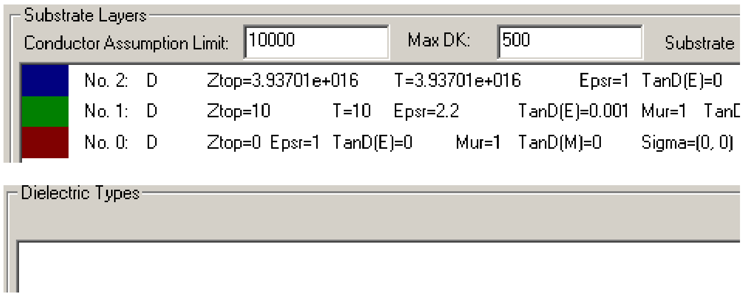


Vertical localized port structure (edge_fed_rpatch1_fg_vlocalized_diff_aligned.geo)

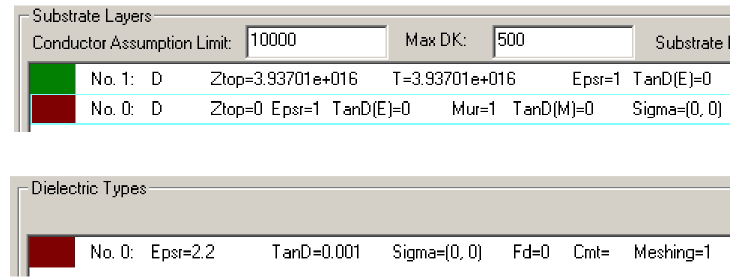
Modeling of Antennas with Finite Substrates (2)

- **Modify the substrates and add finite dielectric types in Basic Parameters:**

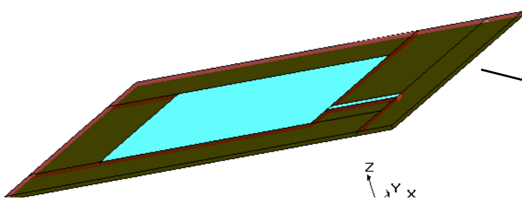
Before Modification



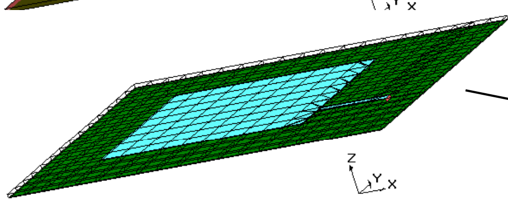
After Modification



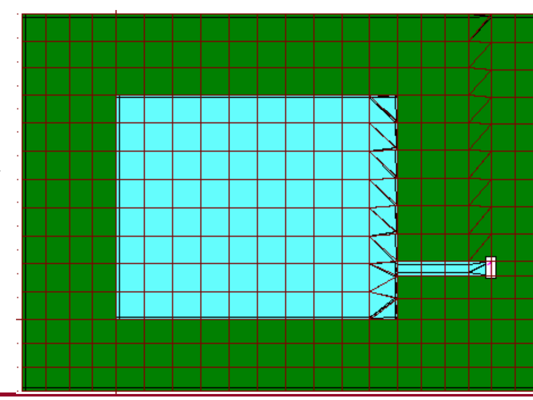
- **Define the shape of the finite ground as the finite substrate:**
  - **Select Edit->Select Polygon Group. Focus selection to Z = 0 layer. Select the polygons for the finite ground.**
  - **Select Adv Edit->Define Dielectrics Call. Enter Z1 = 0 and Z2 = 10 for the finite substrate spanning from 0 to 10 mils. Select the only dielectrics type in the list. Check “Keep original polygons after defining dielectrics” because we want to keep the selected polygons for the finite ground. Select OK and the finite substrate is defined. Save the file as: edge_fed_rpatch1_fg_vlocalized_fd.geo.**



3D View of the finite substrate structure



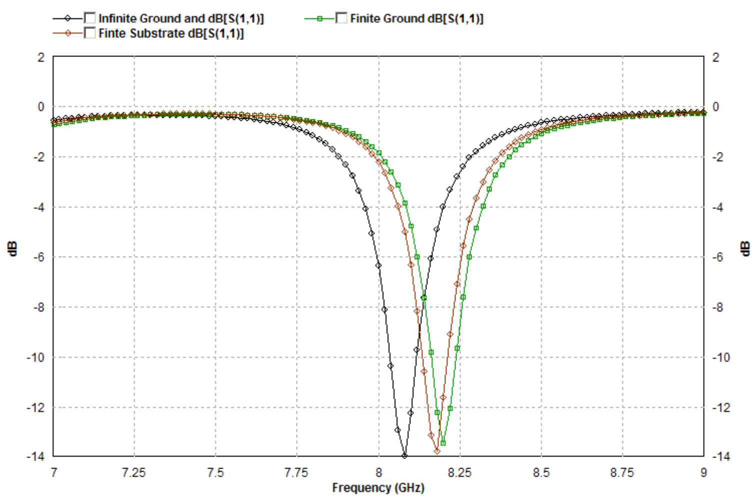
3D view of the meshed structure

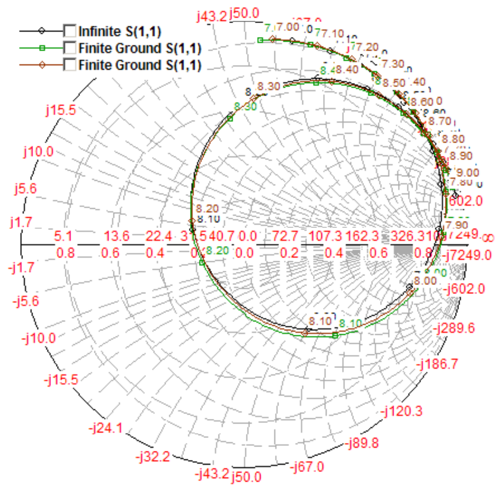


Top view of the meshed structure

Modeling of Antennas with Finite Substrates (3)

- Simulate the finite substrate structure and compare the result with infinite ground and substrate case and the finite ground and infinite substrate case:
  - The input impedance is almost the same for the 3 cases. Finite substrate does not have very serious impact to the input impedance. The Smith Chart locus is almost identical for the 3 cases. It only shifts the resonant frequency slightly.
  - Finite ground changes the radiation pattern much. Normally, finite ground does not have serious impact to the radiation pattern for bore side antennas. It only changes the pattern at $\theta = 90°$ only. For end-fired antenna, it may change the pattern shape significantly.
  - Finite ground creates much less surface wave than infinite ground. The infinite ground effectively double the substrate thickness, and causes much more surface wave.
  - Finite substrate will convert the surface wave back to the radiation wave. It normally yields higher efficiency.

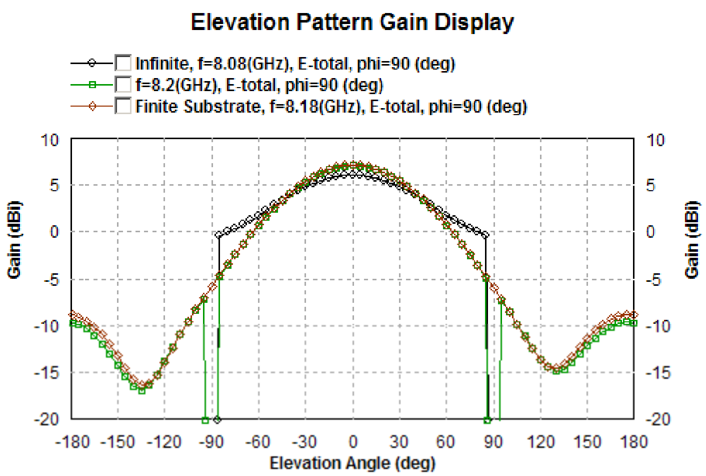


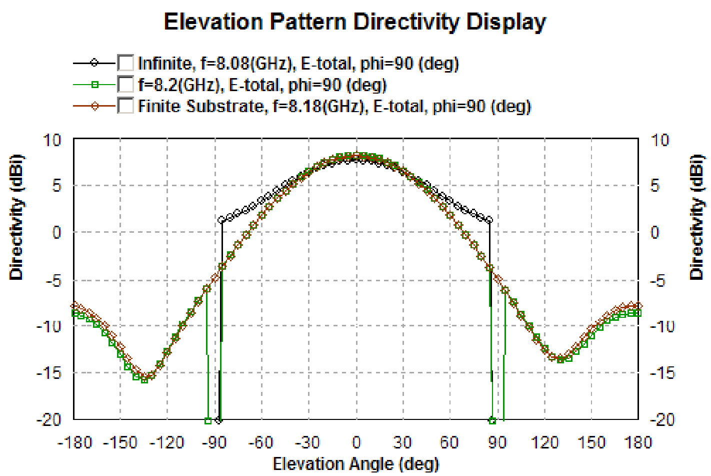


Modeling of Antennas with Finite Substrates (4)

- **Comparison between infinite ground & substrate, finite ground, and finite substrate cases:**

Case	Unknowns	Simulation Time (s)	Resonant Freq (GHz)	Gain (dBi)	Directivity (dBi)	Efficiency
Infinite Ground	327	2	8.08	6.06	7.61	69.9%
Finite Ground	999	17	8.20	7.03	8.17	76.8%
Finite Substrate	2232	173	8.18	7.07	8.08	79.3%

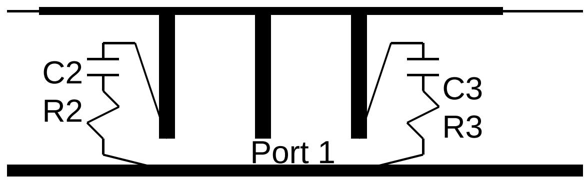


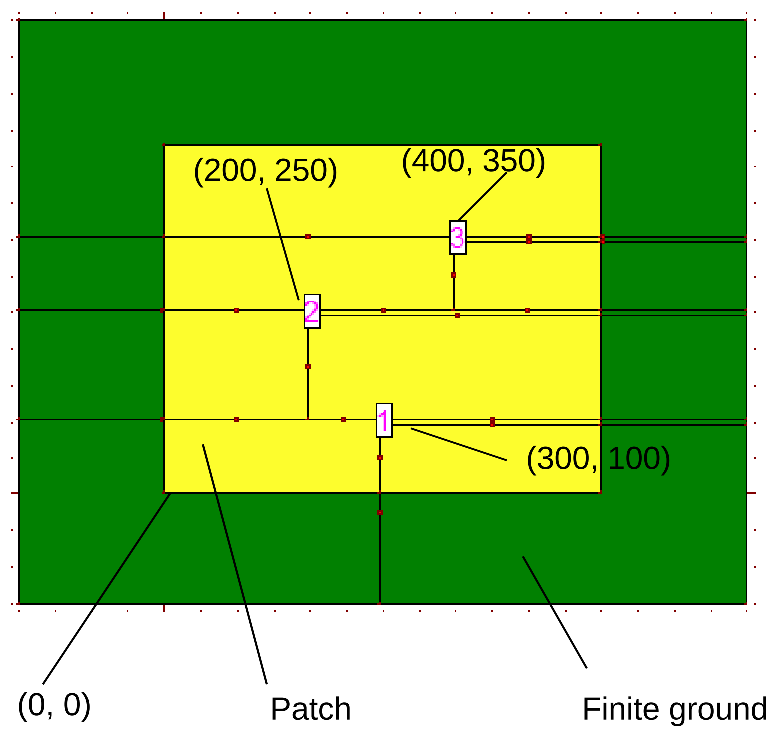


Note: Again, division and meshing alignment is needed for high accuracy results in modeling finite dielectrics. Division and meshing alignment must be done manually on the IE3D 10.2. Automatic meshing alignment will be available before the end of 2004.

Modeling of Antennas with Lumped Elements (1)

- Lumped elements are used to excite or tune an antenna. Assume we want to build a probe-fed antenna with 2 turning elements based upon edge_fed_rpatch1_extension_diff.geo. It is a finite ground plane structure:
  - Each turning element can be a number of circuit elements.
  - In the layout editor, we should use ports to replace them first.

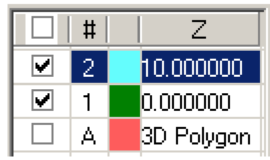


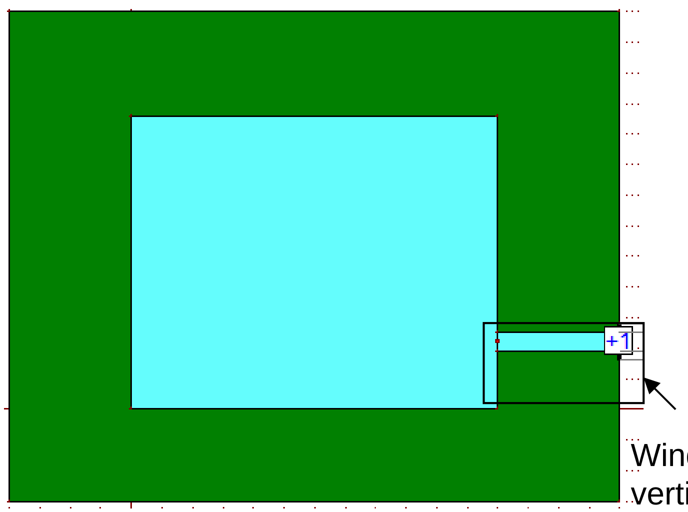


Modeling of Antennas with Lumped Elements (2)

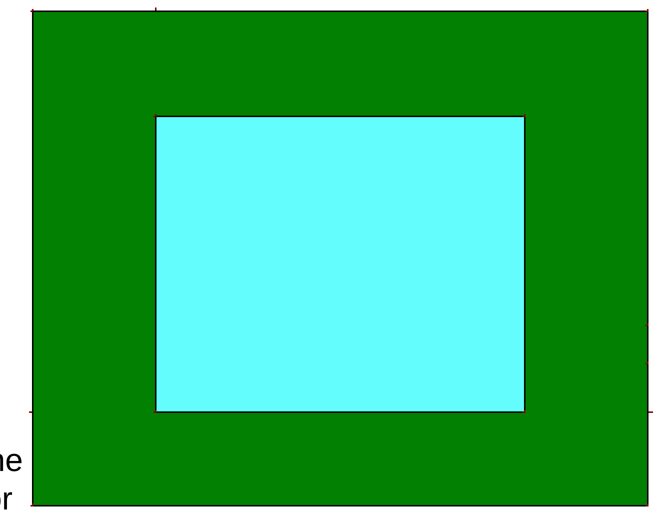
- **Create the 3-port model:**
  - **Open file: edge_fed_rpatch1_fg_extension_diff.geo.**
  - **Select Edit->Select Vertices. Make sure selection focus on both layers (Z = 0 and Z = 10).**
  - **Window the vertices for the feed line and the ports.**
  - **Select Edit->Delete to delete the vertices. The ports are also deleted.**

Layer window with 2 layer checked





Window the vertices for the feed line and the ports

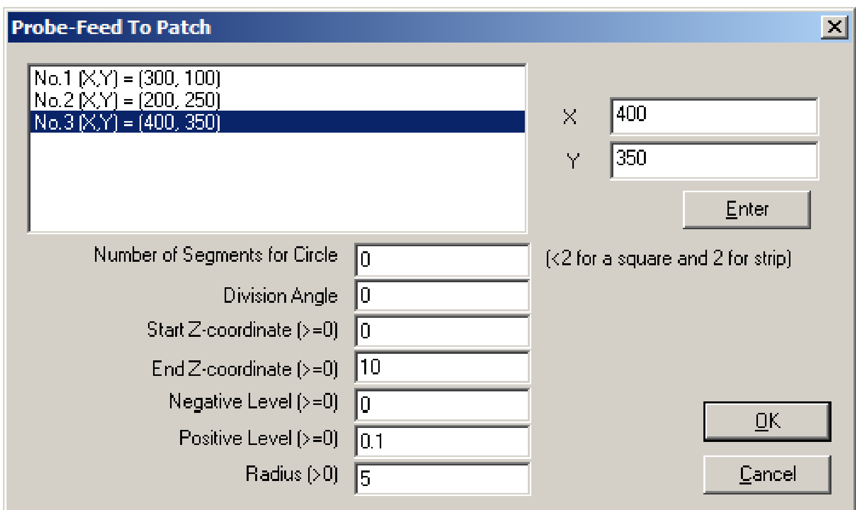


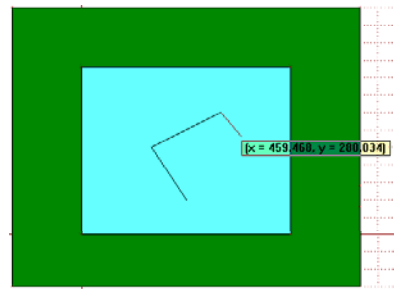
Before deleting the vertices

Feed line and ports removed after vertices deleted

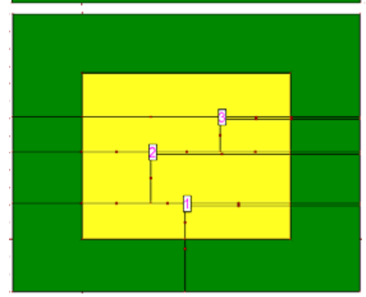
Modeling of Antennas with Lumped Elements (3)

- **Create the 3-port model:**
  - **Click at the No.2 layer (Z = 10) on the layer window to focus the input on the layer.**
  - **Type Shift+A (Input->Key In Absolute Location) and enter (X, Y) = (300, 100) for the location of port 1. Type Shift+A and enter (X, Y) = (200, 250) for the location of port 2. Type Shift+A and enter (X, Y) = (400, 350) for the location of port 3. It is as if you are entering the vertices of a polygon.**
  - **Select Entity->Probe Feed to Patch. Enter the parameters as shown. Select OK to create the ports. Save the file as: probe_fed_patch3.geo.**





Geometry with 3 vertices entered.



Final geometry with 3 ports built.

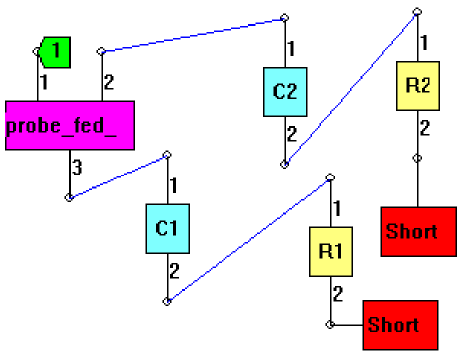
Note: Number of Segments for Circle = 0 means a square probe and it is accurate enough. Normally, a coaxial probe is modeled precisely when we choose distance from Negative Level to Positive Level about 1% of the distance from Start Z-Coordinate to End Z-Coordinate with Negative Level the same as Start Z-Coordinate.

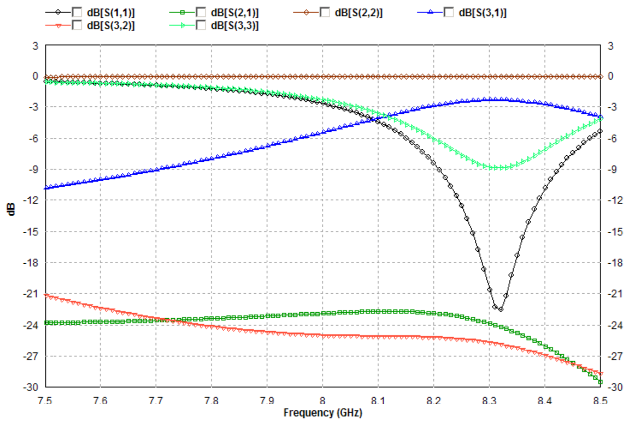
Modeling of Antennas with Lumped Elements (4)

- **Two Ways to Simulate the Antenna with Lumped Elements:**
  - **Simulate the geometry first and connect the lumped elements on MODUA for the final results:**
    - **Pros: This way make the most flexibility because you can change the lumped elements' values or even the configuration anytime later without re-simulating the geometry.**
    - **Cons: You can not do mixed EM and circuit optimization. When pattern calculation is involved, all the 3 ports are considered as the input. You can not consider port 1 as the final input.**
  - **Connect the geometry and the lumped elements on MODUA and perform mixed EM and circuit simulation and optimization simultaneously.**
    - **Pros: You can do mixed EM and circuit optimization. The Gain and efficiency are calculated based upon port 1 as the only input.**
    - **Cons: You need to perform the EM simulation again when you change the values of the lumped elements.**
  - **Both ways yield the same results (except the Gain and Efficiency due to difference in definition). Both ways have their own advantage and they should be used together to achieve the best results with the most flexibility.**

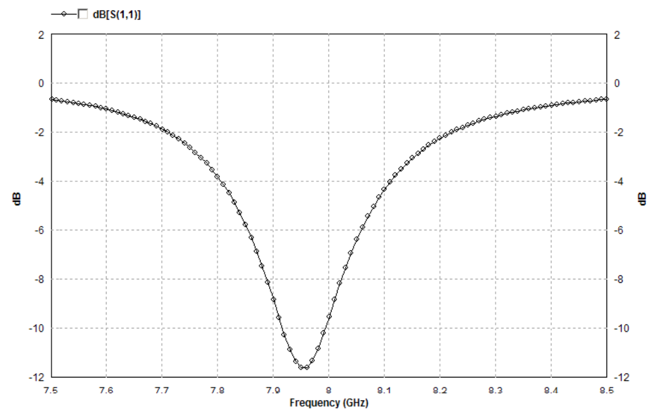
Modeling of Antennas with Lumped Elements (5)

- **Simulate the geometry:**
  - **Simulate the geometry from 7.5 to 8.5 GHz for 101 frequency points. Select Control->Define Display Graph on MODUA and display the S11, S21, S31, S22, S32 and S33.**
- **Simulate the antenna with lumped elements:**
  - **Select Control->Display Toggle to get to the schematic view.**
  - **Select P2 and P3 and delete them.**
  - **Select Element->Capacitor to create the 2 capacitors (C=1p).**
  - **Select Element->Resistor to create the 2 resistor (R=1).**
  - **Select Element->Connection to wire them up (as shown).**
  - **Select Element->Short to connect the Local Ground.**
  - **Select Process->Simulate on MODUA to get the final s-parameters.**
  - **Select File->Save S-Parameters to save the final 1-port results.**





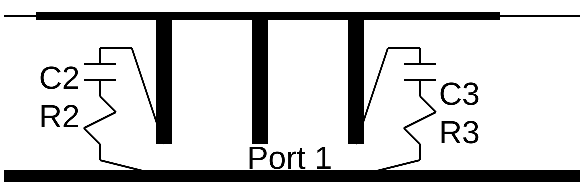
3 port intermediate results



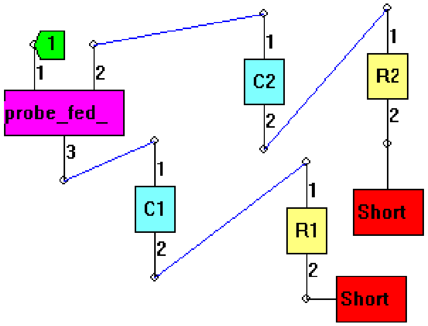
1 port final results

Modeling of Antennas with Lumped Elements (6)

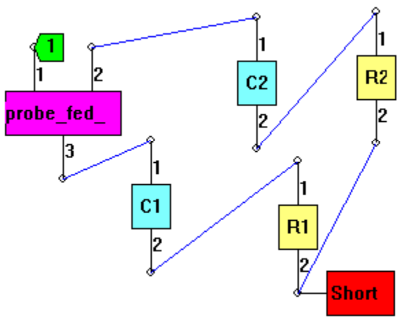
- **Discussion on Lumped Element Connections:**
  - **On the geometry, a port has 2 terminal. On MODUA, a port is represented as 1-terminal. How can be connect a lumped element with 2 terminal on MODUA?**
  - **Basically, we need to connect one terminal of the lumped element to the terminal for the port. The 2nd terminal of the lumped element is connected to an INDIVIDUAL SHORT. The INDIVIDUAL SHORT represents the RETURN PATH for the port.**
  - **Can we share the SHORT between 2 different lumped elements? We may be able to do it if the 2 ports' return paths have the same potential. If our antenna has an infinite ground plane, the 2 ports' return paths have the same potential and we can let them share the same SHORT. For finite ground plane structures, the return paths of the 2 ports do not have the same potential. We can not let them to share the same SHORT.**



Geometry



Correct connections on MODUA



Probably incorrect connections

Modeling of Antennas with Lumped Elements (7)

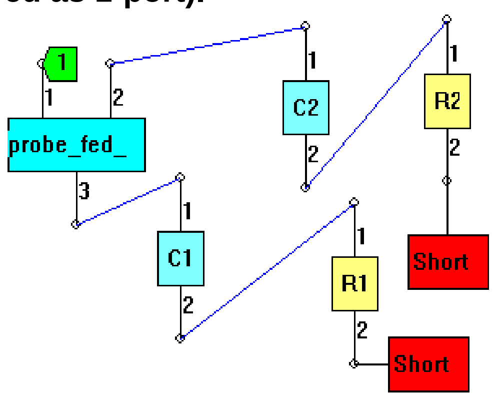
- **Current Distribution and Radiation Pattern with Lumped Elements:**
  - **Simulate the geometry from 7.5 to 8.5 GHz for 5 frequency points with Current Distribution Data saved (Geometry file: probe_fed_rpatch3a.geo). MODUA will be invoked to display the s-parameters and another MGRID will be invoked to display the meshed geometry (and current distribution).**
  - **Select Control->Display Toggle on MODUA and connect the lumped elements again. Save the design as: probe_fed_rpatch3_for_1a.dsg.**
  - **Select Process->Simulate and Find Excitation on MODUA. MODUA will perform a circuit simulation on it. Then, MODUA will prompt you for the excitations and terminations on the final ports (only port 1).**
  - **Select OK to accept the default wave source setting (Inc= 1 V and Ri = 50 ohms). MODUA will list all the excitation and termination information on the final port and all the terminals of the elements (s-parameters, C's and R's). Basically, we need to define the excitations on the geometry in order to visualize the current distribution and calculate radiation pattern with the lumped elements connected.**
  - **Select File->Save Excitation to save the data into: probe_fed_rpatch3_for_1a.ect file. The file will be used to define the excitation on MGRID for the current distribution and radiation pattern.**

Modeling of Antennas with Lumped Elements (8)

- **Current Distribution and Radiation Pattern with Lumped Elements:**
  - **On the MGRID displaying the meshed structure, select Process->Display Current Distribution. Select Freq = 8 GHz. Select the Feed Network button and select the ECT file: probe_fed_rpatch3_for_1a.ect. Select OK. MGRID will be displaying the current distribution on the antenna with the lumped elements connected.**
  - **Select Process->Pattern Calculation. Select OK to start the pattern calculation. After the calculation, you can save the General Pattern. You can also select Define Excitation for the pattern with specified excitations, MGRID will prompt you for the excitation. Please make sure file: probe_fed_rpatch3_for_1a.ect file is attached as the Feed Network. Select OK. The radiation pattern for the patch antenna with lumped elements connected is calculated and PATTERNVIEW is invoked to display the pattern.**
- **Perform Mixed EM Simulation and Circuit Simulation Directly:**

On the MODUA with the connections, select the s-parameter module. Go to Module Properties and replace it with a geometry module: probe_fed_rpatch3a.geo. Save the design as file: probe_fed_rpatch3_for_1b.geo. Select Process->Simulate. Remember to check Radiation Pattern File. Select OK and IE3D engine is invoked to perform co-simulation. PATTERNVIW is invoked to display the pattern. You will see some pattern parameters are the same while same others are different. Basically, the two ways yield identical pattern. Some parameters are different just because the definitions are different for the two cases (One case is considered as 3-port and the other is considered as 1-port).

Geometry module replacing the s-parameter module.

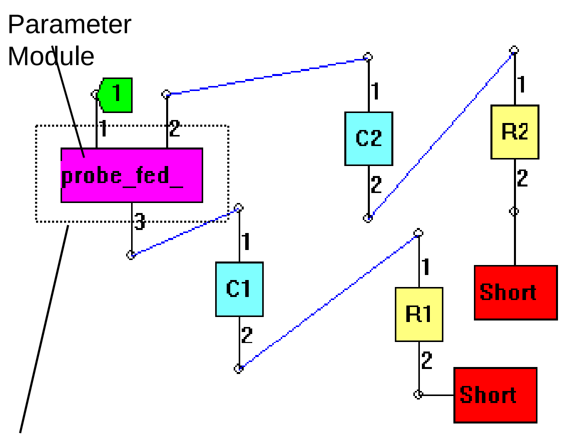


f = 8- GHz	Using ECT File	Co-Simulation
Incident Power	0.0485137 W	0.01 W
Input Power	0.00613088 W	0.008885 W
Radiated Power	0.00484491 W	0.00484491 W
Rad. Efficiency	79.0247%	54.529%
Ant. Efficiency	9.98668%	48.4491%
Gain	-2.16777 dBi	4.69088 dBi
Directivity	7.83802 dBi	7.83802 dBi

Modeling of Antennas with Lumped Elements (9)

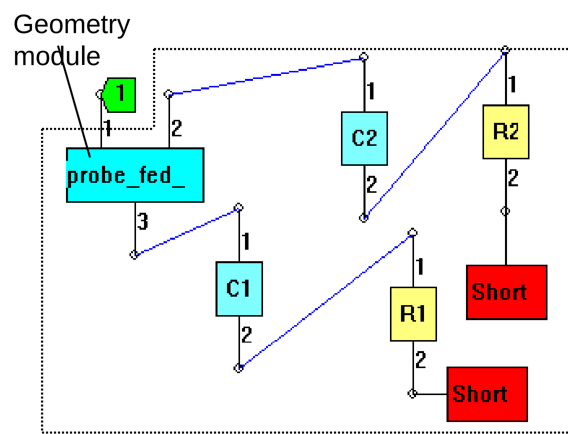
- **Differences in Pattern Calculation Between the Way Using .ECT File and Mixed EM and Circuit Simulation on MODUA:**

MODUA setup for “Simulate and Find Excitation” for the .ECT file for the feed network for pattern calculation on MGRID.



The calculated pattern is for the 3-port antenna (in the box of dashed lines) instead of the 1-port final circuit. Incident power, input power, mis-match and efficiency are calculated based upon the 3-ports of the parameter module instead of the 1-port of the final circuit. Using the .ECT file, we allow the users to find the pattern of the antenna with all the lumped elements connected. It only allows the users to find the pattern of one parameter (or geometry) module once at a time if the circuit consists of multiple parameter (or geometry modules).

MODUA setup for “Simulate” with pattern calculation enabled



The calculated pattern is for the final 1-port circuit (in the box of dashed lines) instead of the 3-port geometry module. Using the geometry module, we allow the users to find the pattern of the whole system including the geometry module and other lumped elements. We even allow the users to find the pattern of the whole circuit consisting of multiple geometry modules.

Summary

- IE3D is a very capable EM simulation and Optimization package for both 2.5D and 3D antenna modeling.
- Its accuracy and efficiency are proven by wide range industrial verifications.
- The geometry modeling is extremely capable and we can not demonstrate all of them in this course note. Interested users should try to explore it from the user’s manual and using the software.

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4.1. Portions or all of certain Software may contain code for experimental testing and evaluation ("Beta Code"), which may not be used without Mentor Graphics' explicit authorization. Upon Mentor Graphics' authorization, Mentor Graphics grants to Customer a temporary, nontransferable, nonexclusive license for experimental use to test and evaluate the Beta Code without charge for a limited period of time specified by Mentor Graphics. This grant and Customer's use of the Beta Code shall not be construed as marketing or offering to sell a license to the Beta Code, which Mentor Graphics may choose not to release commercially in any form.

4.2. If Mentor Graphics authorizes Customer to use the Beta Code, Customer agrees to evaluate and test the Beta Code under normal conditions as directed by Mentor Graphics. Customer will contact Mentor Graphics periodically during Customer's use of the Beta Code to discuss any malfunctions or suggested improvements. Upon completion of Customer's evaluation and testing, Customer will send to Mentor Graphics a written evaluation of the Beta Code, including its strengths, weaknesses and recommended improvements.

4.3. Customer agrees to maintain Beta Code in confidence and shall restrict access to the Beta Code, including the methods and concepts utilized therein, solely to those employees and Customer location(s) authorized by Mentor Graphics to perform beta testing. Customer agrees that any written evaluations and all inventions, product improvements, modifications or developments that Mentor Graphics conceived or made during or subsequent to this Agreement, including those based partly or wholly on Customer's feedback, will be the exclusive property of Mentor Graphics. Mentor Graphics will have exclusive rights, title and interest in all such property. The provisions of this Subsection 4.3 shall survive termination of this Agreement.

5. **RESTRICTIONS ON USE.**

5.1. Customer may copy Software only as reasonably necessary to support the authorized use. Each copy must include all notices and legends embedded in Software and affixed to its medium and container as received from Mentor Graphics. All copies shall remain the property of Mentor Graphics or its licensors. Customer shall maintain a record of the number and primary location of all copies of Software, including copies merged with other software, and shall make those records available to Mentor Graphics upon request. Customer shall not make Products available in any form to any person other than Customer's employees and on-site contractors, excluding Mentor Graphics competitors, whose job performance requires access and who are under obligations of confidentiality. Customer shall take appropriate action to protect the confidentiality of Products and ensure that any person permitted access does not disclose or use it except as permitted by this Agreement. Customer shall give Mentor Graphics written notice of any unauthorized disclosure or use of the Products as soon as Customer learns or becomes aware of such unauthorized disclosure or use. Except as otherwise permitted for purposes of interoperability as specified by applicable and mandatory local law, Customer shall not reverse-assemble, reverse-compile, reverse-engineer or in any way derive any source code from Software. Log files, data files, rule files and script files generated by or for the Software (collectively "Files"), including without limitation files containing Standard Verification Rule Format ("SVRF") and Tcl Verification Format ("TVF") which are Mentor Graphics' proprietary syntaxes for expressing process rules, constitute or include confidential information of Mentor Graphics. Customer may share Files with third parties, excluding Mentor Graphics competitors, provided that the confidentiality of such Files is protected by written agreement at least as well as Customer protects other information of a similar nature or importance, but in any case with at least reasonable care. Customer may use Files containing SVRF or TVF only with Mentor Graphics products. Under no circumstances shall Customer use Software or Files or allow their use for the purpose of developing, enhancing or marketing any product that is in any way competitive with Software, or disclose to any third party the results of, or information pertaining to, any benchmark.

5.2. If any Software or portions thereof are provided in source code form, Customer will use the source code only to correct software errors and enhance or modify the Software for the authorized use. Customer shall not disclose or permit disclosure of source code, in whole or in part, including any of its methods or concepts, to anyone except Customer's employees or contractors, excluding Mentor Graphics competitors, with a need to know. Customer shall not copy or compile source code in any manner except to support this authorized use.

5.3. Customer may not assign this Agreement or the rights and duties under it, or relocate, sublicense or otherwise transfer the Products, whether by operation of law or otherwise ("Attempted Transfer"), without Mentor Graphics' prior written consent and payment of Mentor Graphics' then-current applicable relocation and/or transfer fees. Any Attempted Transfer without Mentor Graphics' prior written consent shall be a material breach of this Agreement and may, at Mentor Graphics' option, result in the immediate termination of the Agreement and/or the licenses granted under this Agreement. The terms of this Agreement, including without limitation the licensing and assignment provisions, shall be binding upon Customer's permitted successors in interest and assigns.

5.4. The provisions of this Section 5 shall survive the termination of this Agreement.

6. **SUPPORT SERVICES.** To the extent Customer purchases support services, Mentor Graphics will provide Customer updates and technical support for the Products, at the Customer site(s) for which support is purchased, in accordance with Mentor Graphics' then current End-User Support Terms located at http://supportnet.mentor.com/about/legal/.

7. **AUTOMATIC CHECK FOR UPDATES; PRIVACY.** Technological measures in Software may communicate with servers of Mentor Graphics or its contractors for the purpose of checking for and notifying the user of updates and to ensure that the Software in use is licensed in compliance with this Agreement. Mentor Graphics will not collect any personally identifiable data in this process and will not disclose any data collected to any third party without the prior written consent of Customer, except to Mentor Graphics' outside attorneys or as may be required by a court of competent jurisdiction.

8. **LIMITED WARRANTY.**

8.1. Mentor Graphics warrants that during the warranty period its standard, generally supported Products, when properly installed, will substantially conform to the functional specifications set forth in the applicable user manual. Mentor Graphics does not warrant that Products will meet Customer's requirements or that operation of Products will be uninterrupted or error free. The warranty period is 90 days starting on the 15th day after delivery or upon installation, whichever first occurs. Customer must notify Mentor Graphics in writing of any nonconformity within the warranty period. For the avoidance of doubt, this warranty applies only to the initial shipment of Software under an Order and does not renew or reset, for example, with the delivery of (a) Software updates or (b) authorization codes or alternate Software under a transaction involving Software re-mix. This warranty shall not be valid if Products have been subject to misuse, unauthorized modification or improper installation. MENTOR GRAPHICS' ENTIRE LIABILITY AND CUSTOMER'S EXCLUSIVE REMEDY SHALL BE, AT MENTOR GRAPHICS' OPTION, EITHER (A) REFUND OF THE PRICE PAID UPON RETURN OF THE PRODUCTS TO MENTOR GRAPHICS OR (B) MODIFICATION OR REPLACEMENT OF THE PRODUCTS THAT DO NOT MEET THIS LIMITED WARRANTY, PROVIDED CUSTOMER HAS OTHERWISE COMPLIED WITH THIS AGREEMENT. MENTOR GRAPHICS MAKES NO WARRANTIES WITH RESPECT TO: (A) SERVICES; (B) PRODUCTS PROVIDED AT NO CHARGE; OR (C) BETA CODE; ALL OF WHICH ARE PROVIDED "AS IS."

8.2. THE WARRANTIES SET FORTH IN THIS SECTION 8 ARE EXCLUSIVE. NEITHER MENTOR GRAPHICS NOR ITS LICENSORS MAKE ANY OTHER WARRANTIES EXPRESS, IMPLIED OR STATUTORY, WITH RESPECT TO PRODUCTS PROVIDED UNDER THIS AGREEMENT. MENTOR GRAPHICS AND ITS LICENSORS SPECIFICALLY DISCLAIM ALL IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NON-INFRINGEMENT OF INTELLECTUAL PROPERTY.

9. **LIMITATION OF LIABILITY.** EXCEPT WHERE THIS EXCLUSION OR RESTRICTION OF LIABILITY WOULD BE VOID OR INEFFECTIVE UNDER APPLICABLE LAW, IN NO EVENT SHALL MENTOR GRAPHICS OR ITS LICENSORS BE LIABLE FOR INDIRECT, SPECIAL, INCIDENTAL, OR CONSEQUENTIAL DAMAGES (INCLUDING LOST PROFITS OR SAVINGS) WHETHER BASED ON CONTRACT, TORT OR ANY OTHER LEGAL THEORY, EVEN IF MENTOR GRAPHICS OR ITS LICENSORS HAVE BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES. IN NO EVENT SHALL MENTOR GRAPHICS' OR ITS LICENSORS' LIABILITY UNDER THIS AGREEMENT EXCEED THE AMOUNT RECEIVED FROM CUSTOMER FOR THE HARDWARE, SOFTWARE LICENSE OR SERVICE GIVING RISE TO THE CLAIM. IN THE CASE WHERE NO AMOUNT WAS PAID, MENTOR GRAPHICS AND ITS LICENSORS SHALL HAVE NO LIABILITY FOR ANY DAMAGES WHATSOEVER. THE PROVISIONS OF THIS SECTION 9 SHALL SURVIVE THE TERMINATION OF THIS AGREEMENT.

10. **HAZARDOUS APPLICATIONS.** CUSTOMER ACKNOWLEDGES IT IS SOLELY RESPONSIBLE FOR TESTING ITS PRODUCTS USED IN APPLICATIONS WHERE THE FAILURE OR INACCURACY OF ITS PRODUCTS MIGHT RESULT IN DEATH OR PERSONAL INJURY ("HAZARDOUS APPLICATIONS"). NEITHER MENTOR GRAPHICS NOR ITS LICENSORS SHALL BE LIABLE FOR ANY DAMAGES RESULTING FROM OR IN CONNECTION WITH THE USE OF MENTOR GRAPHICS PRODUCTS IN OR FOR HAZARDOUS APPLICATIONS. THE PROVISIONS OF THIS SECTION 10 SHALL SURVIVE THE TERMINATION OF THIS AGREEMENT.

11. **INDEMNIFICATION.** CUSTOMER AGREES TO INDEMNIFY AND HOLD HARMLESS MENTOR GRAPHICS AND ITS LICENSORS FROM ANY CLAIMS, LOSS, COST, DAMAGE, EXPENSE OR LIABILITY, INCLUDING ATTORNEYS' FEES, ARISING OUT OF OR IN CONNECTION WITH THE USE OF PRODUCTS AS DESCRIBED IN SECTION 10. THE PROVISIONS OF THIS SECTION 11 SHALL SURVIVE THE TERMINATION OF THIS AGREEMENT.

12. **INFRINGEMENT.**

12.1. Mentor Graphics will defend or settle, at its option and expense, any action brought against Customer in the United States, Canada, Japan, or member state of the European Union which alleges that any standard, generally supported Product acquired by Customer hereunder infringes a patent or copyright or misappropriates a trade secret in such jurisdiction. Mentor Graphics will pay costs and damages finally awarded against Customer that are attributable to the action. Customer understands and agrees that as conditions to Mentor Graphics' obligations under this section Customer must: (a) notify Mentor Graphics promptly in writing of the action; (b) provide Mentor Graphics all reasonable information and assistance to settle or defend the action; and (c) grant Mentor Graphics sole authority and control of the defense or settlement of the action.

12.2. If a claim is made under Subsection 12.1 Mentor Graphics may, at its option and expense, (a) replace or modify the Product so that it becomes noninfringing; (b) procure for Customer the right to continue using the Product; or (c) require the return of the Product and refund to Customer any purchase price or license fee paid, less a reasonable allowance for use.

12.3. Mentor Graphics has no liability to Customer if the action is based upon: (a) the combination of Software or hardware with any product not furnished by Mentor Graphics; (b) the modification of the Product other than by Mentor Graphics; (c) the use of other than a current unaltered release of Software; (d) the use of the Product as part of an infringing process; (e) a product that Customer makes, uses, or sells; (f) any Beta Code or Product provided at no charge; (g) any software provided by Mentor Graphics' licensors who do not provide such indemnification to Mentor Graphics' customers; or (h) infringement by Customer that is deemed willful. In the case of (h), Customer shall reimburse Mentor Graphics for its reasonable attorney fees and other costs related to the action.

12.4. THIS SECTION 12 IS SUBJECT TO SECTION 9 ABOVE AND STATES THE ENTIRE LIABILITY OF MENTOR GRAPHICS AND ITS LICENSORS FOR DEFENSE, SETTLEMENT AND DAMAGES, AND CUSTOMER'S SOLE AND EXCLUSIVE REMEDY, WITH RESPECT TO ANY ALLEGED PATENT OR COPYRIGHT INFRINGEMENT OR TRADE SECRET MISAPPROPRIATION BY ANY PRODUCT PROVIDED UNDER THIS AGREEMENT.

13. **TERMINATION AND EFFECT OF TERMINATION.** If a Software license was provided for limited term use, such license will automatically terminate at the end of the authorized term.

13.1. Mentor Graphics may terminate this Agreement and/or any license granted under this Agreement immediately upon written notice if Customer: (a) exceeds the scope of the license or otherwise fails to comply with the licensing or confidentiality provisions of this Agreement, or (b) becomes insolvent, files a bankruptcy petition, institutes proceedings for liquidation or winding up or enters into an agreement to assign its assets for the benefit of creditors. For any other material breach of any provision of this Agreement, Mentor Graphics may terminate this Agreement and/or any license granted under this Agreement upon 30 days written notice if Customer fails to cure the breach within the 30 day notice period. Termination of this Agreement or any license granted hereunder will not affect Customer's obligation to pay for Products shipped or licenses granted prior to the termination, which amounts shall be payable immediately upon the date of termination.

13.2. Upon termination of this Agreement, the rights and obligations of the parties shall cease except as expressly set forth in this Agreement. Upon termination, Customer shall ensure that all use of the affected Products ceases, and shall return hardware and either return to Mentor Graphics or destroy Software in Customer's possession, including all copies and documentation, and certify in writing to Mentor Graphics within ten business days of the termination date that Customer no longer possesses any of the affected Products or copies of Software in any form.

14. **EXPORT.** The Products provided hereunder are subject to regulation by local laws and United States government agencies, which prohibit export or diversion of certain products and information about the products to certain countries and certain persons. Customer agrees that it will not export Products in any manner without first obtaining all necessary approval from appropriate local and United States government agencies.

15. **U.S. GOVERNMENT LICENSE RIGHTS.** Software was developed entirely at private expense. All Software is commercial computer software within the meaning of the applicable acquisition regulations. Accordingly, pursuant to US FAR 48 CFR 12.212 and DFAR 48 CFR 227.7202, use, duplication and disclosure of the Software by or for the U.S. Government or a U.S. Government subcontractor is subject solely to the terms and conditions set forth in this Agreement, except for provisions which are contrary to applicable mandatory federal laws.

16. **THIRD PARTY BENEFICIARY.** Mentor Graphics Corporation, Mentor Graphics (Ireland) Limited, Microsoft Corporation and other licensors may be third party beneficiaries of this Agreement with the right to enforce the obligations set forth herein.

17. **REVIEW OF LICENSE USAGE.** Customer will monitor the access to and use of Software. With prior written notice and during Customer's normal business hours, Mentor Graphics may engage an internationally recognized accounting firm to review Customer's software monitoring system and records deemed relevant by the internationally recognized accounting firm to confirm Customer's compliance with the terms of this Agreement or U.S. or other local export laws. Such review may include FLEXlm or FLEXnet (or successor product) report log files that Customer shall capture and provide at Mentor Graphics' request. Customer shall make records available in electronic format and shall fully cooperate with data gathering to support the license review. Mentor Graphics shall bear the expense of any such review unless a material non-compliance is revealed. Mentor Graphics shall treat as confidential information all information gained as a result of any request or review and shall only use or disclose such information as required by law or to enforce its rights under this Agreement. The provisions of this Section 17 shall survive the termination of this Agreement.

18. **CONTROLLING LAW, JURISDICTION AND DISPUTE RESOLUTION.** The owners of certain Mentor Graphics intellectual property licensed under this Agreement are located in Ireland and the United States. To promote consistency around the world, disputes shall be resolved as follows: excluding conflict of laws rules, this Agreement shall be governed by and construed under the laws of the State of Oregon, USA, if Customer is located in North or South America, and the laws of Ireland if Customer is located outside of North or South America. All disputes arising out of or in relation to this Agreement shall be submitted to the exclusive jurisdiction of the courts of Portland, Oregon when the laws of Oregon apply, or Dublin, Ireland when the laws of Ireland apply. Notwithstanding the foregoing, all disputes in Asia arising out of or in relation to this Agreement shall be resolved by arbitration in Singapore before a single arbitrator to be appointed by the chairman of the Singapore International

Arbitration Centre ("SIAC") to be conducted in the English language, in accordance with the Arbitration Rules of the SIAC in effect at the time of the dispute, which rules are deemed to be incorporated by reference in this section. This section shall not restrict Mentor Graphics' right to bring an action against Customer in the jurisdiction where Customer's place of business is located. The United Nations Convention on Contracts for the International Sale of Goods does not apply to this Agreement.

19. **SEVERABILITY.** If any provision of this Agreement is held by a court of competent jurisdiction to be void, invalid, unenforceable or illegal, such provision shall be severed from this Agreement and the remaining provisions will remain in full force and effect.

20. **MISCELLANEOUS.** This Agreement contains the parties' entire understanding relating to its subject matter and supersedes all prior or contemporaneous agreements, including but not limited to any purchase order terms and conditions. Some Software may contain code distributed under a third party license agreement that may provide additional rights to Customer. Please see the applicable Software documentation for details. This Agreement may only be modified in writing by authorized representatives of the parties. Waiver of terms or excuse of breach must be in writing and shall not constitute subsequent consent, waiver or excuse.

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