

Section 8

Dual Band Common Aperture Array Design

from

**A Collection of Thoughts, Tips and
Techniques for Microwave Circuit Design**

by

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This set of 41 pages is a section focusing on the design of a complex antenna system, taken from an extended presentation on microwave design.

If you have a question, feel free to write me at R.L.Eisenhart@ieee.org.

Dual Band Common Aperture **Array Design**

Presentation Outline

- Approach
- Design Requirements
- Design Issues
- Corporate Feed
- Radiating Elements
- Simulation Program Features
- Summary

For this section we'll consider a design from start to finish using many of the techniques covered in earlier sections.

Review subjects as a normal design flow.

So where do we start? . . . Approach

Presentation Approach

Go through the design of one of two frequency bands of a large, complicated, Dual-Band common aperture antenna array and show how these bands are integrated. Also, point out how various features of HFSS and Designer are used.

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This design has enough complexity to demonstrate many different areas of circuit design.

The two bands use two similar but separate circuits so we will just focus on one of the bands. We will address the receive band because it is the more difficult in being the lower frequency, to fit in the same size as the upper (transmit).

The common aspect is the integrated antenna plane having alternating rows of antennas for the two bands.

We need a set of requirements or design specifications.

Array Design Requirements

Situation -

- * • Design an antenna array with both Transmit and Receive bands within the same 10.5" x 42" aperture.
- Low side-lobes in the narrow beam (< 4 deg) plane
- Receive Left Hand Cir. Pol. @ 7.25-7.75 GHz.
- Transmit Right Hand Cir. Pol. @ 7.9-8.4 GHz.
- * • Simple radiator assembly (plug in)
- Input match $\leq 2:1$ VSWR (≈ -10 dB Return Loss)
- * • Printed radiating element preferred
- * • Total insertion loss below 2.0 dB
- 1.0 Kw CW power level on Transmit

* Items Focused on in presentation

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Here's what we need to do. So what areas will be the tough parts?

Integrated elements often means dimensional constraints.

Simple radiator designed for easy (cheap) assembly.

Printed element?

Requires paying a lot of attention to match through 8 levels of corporate feed.

How do these relate to design issues?

Array Design Issues

Things to deal with -

- To avoid grating lobes, keep array spacing ≤ 1.3 inch.
- * • Narrow spacing requires use of ridge waveguide (RWG)
- * • Ridge WG characteristics – Z_0 , β (wavelength) and cutoff frequency are a function of ridge gap size.
- Low side-lobes requires use of tapered aperture.
- 256 elements/band with tapered excitation requires 19 independent splitter designs for each freq. band.
- * • All splitters must be well matched, no isolation; keep each splitter return loss less than -40 dB
- Element design must be done in array environment
- Are there any possible field breakdown regions?

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These issues put different constraints on the design.

The creative part will be in using Ridge WG in the corporate feed.

Ridge WG parameters are configuration dependent.

No room for isolation design – requires excellent match.

On to the design

Outline Continued

- Approach
- Design Requirements
- Design Issues
- Corporate Feed
- Radiating Elements
- Simulation Program Features
- Summary

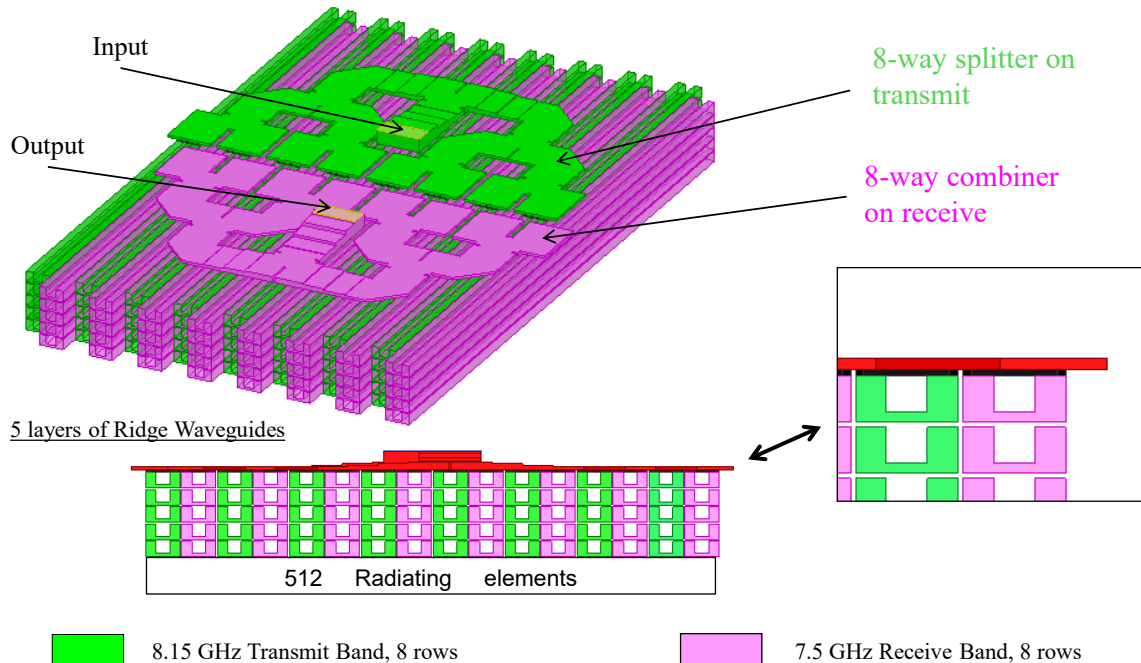
When you have a system design, it is often worth your while to work through a “rough-out” design to highlight where the difficult design points will be.

In this antenna, the key component is the rectangular to ridge waveguide transition, going from a Rec WG 1120 mils wide to a RWG only 620 mils wide. And in second place the unbalanced power splitters in the ridge waveguide.

These parts are in the corporate feed, transforming through a total impedance ratio of ≈ 1440 to 1 while splitting up the signal 256 ways.

To establish the design we must consider the overall configuration of the feed circuits.

Overall Perspective of Feed Circuit



Two independent antennas are integrated into a common aperture.
The radiating elements are fed by the bottom layer.

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This page shows the configuration with the horizontal Rectangular WG (RecWG) splitting the signal 8 ways.

The 8 ports couple into the top of a stack of ridge WGs for each of the 8 ports, where the signals are then split through the other 4 levels to connect to the radiating elements (not shown here) below the bottom layer.

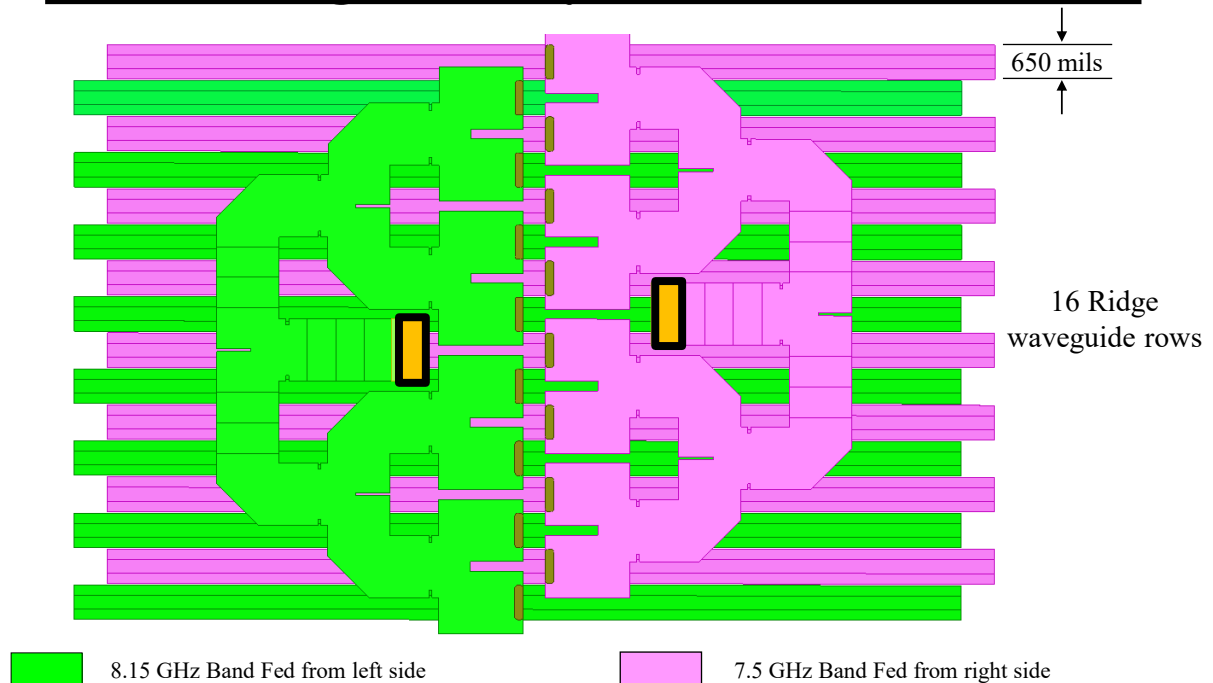
The receive circuit is interlaced with the transmit side, back through a combiner to the output. The transmit splitter and receive combiner are essentially the same with minor tuning changes for the two different frequency bands.

The ridge waveguide doesn't run through the whole length of the sections shown, just where needed (more on that later).

So we have our common aperture.

Consider a top-down view of the structure.

Interleaving of Array Rows for both Bands



Each band uses 8 rows. The rows are interleaved forming the total dual aperture of 16 x 32 elements for a 10.5 x 42inch array.

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This page gives a little better idea of how the rows of ridge WGs are positioned.

Only 650 mils is available for the low X-band feed lines for the radiating elements to fit within the total area allowed.

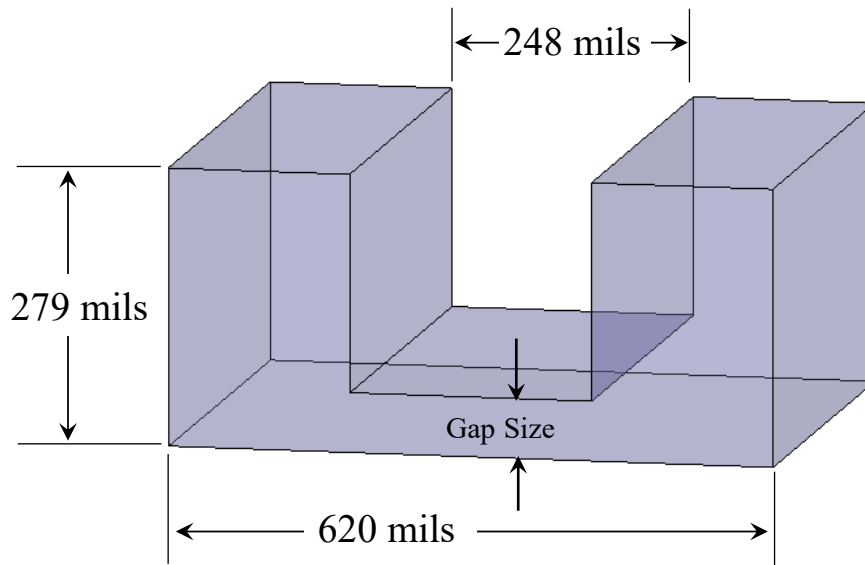
The input for the transmit band is shown here on the left, feeding 8 rows, and note the coupling slots.

And the receive output is on the right side.

The total array size was determined by the pattern required, gain and beam-widths.

Consider first the custom ridge WG.

Custom Ridge Waveguide Design



Gap size varied from 20 to 100 mils to create the impedances required by the splitter designs. The nominal gap used was 60 mils.

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Dimensions must be established. WG width is fixed at 650 mils center to center with 30 mil thick walls between waveguides.

This sets internal WG width at 620 mils.

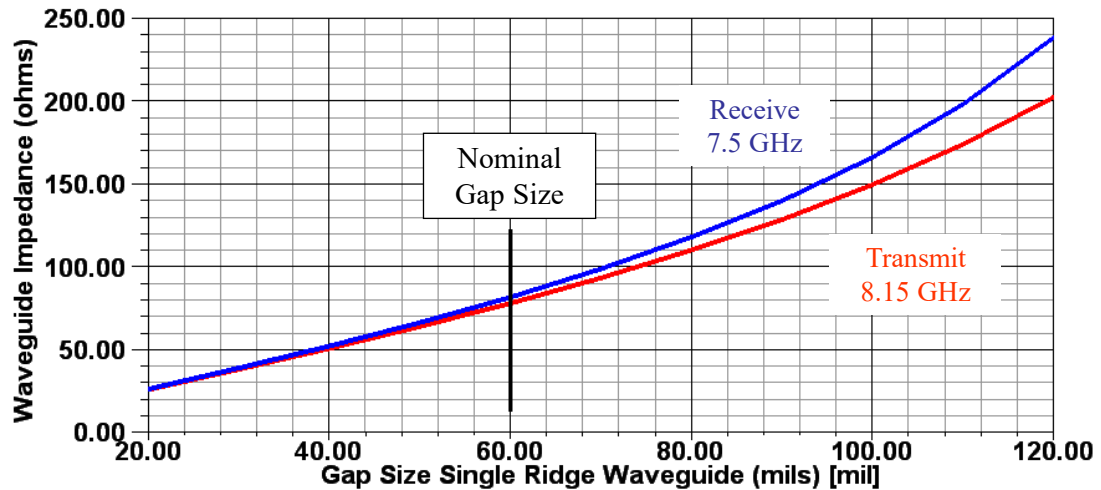
Best bandwidth ridge width = $0.4 \times \text{guide width} = 248 \text{ mils}$.

Height, used max allowed to reduce cutoff frequency $\Rightarrow 279 \text{ mils}$. This height also gives more line space between layers to do the matching.

Then the gap size was used to control the guide impedance for the range of values needed.

Let's look at the impedance issue.

Gap Size Influence on Ridge WG Characteristic Impedance (Z_{pv})



Impedances from 26.5 ohms to 142.5 ohms allowed the design of splitters up to 84/16 power split. The nominal value of 82.5 ohms was used when possible.

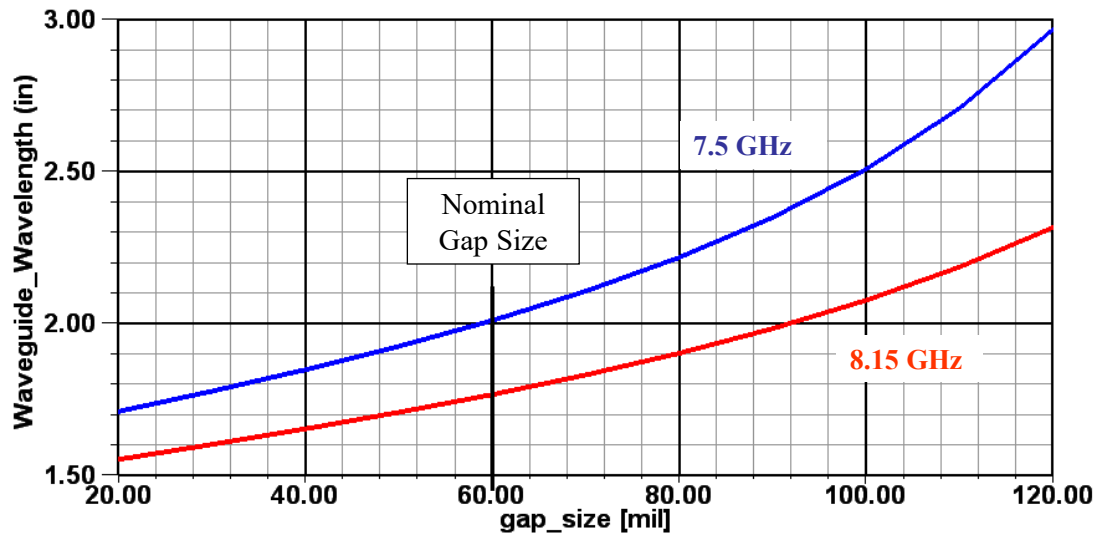
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Use the parametric sweep to generate design curves like impedance vs. gap size for each band. The nominal gap size of 60 mils was selected as a good mid-range.

Consider then how the gap size also affects lambda guide.

Gap Size Influence on Ridge WG Guide Wavelength (λ_g)



More design curves, important to
know your limitations

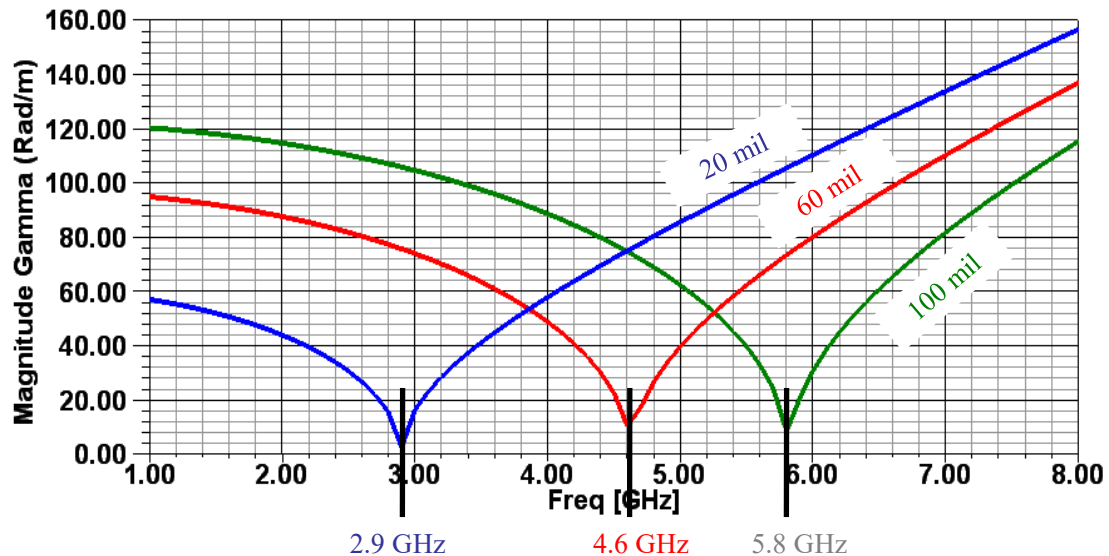
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With lambda varying so much it turns into an iterative process of designing impedance transformers and unequal power tees.

Also cutoff frequencies.

Gap Size Influence on Ridge WG Guide Cutoff Frequency (f_{co})



Need to keep the cutoff frequency low enough for the low band, large gap case. Ridge guide height affects the cutoff.

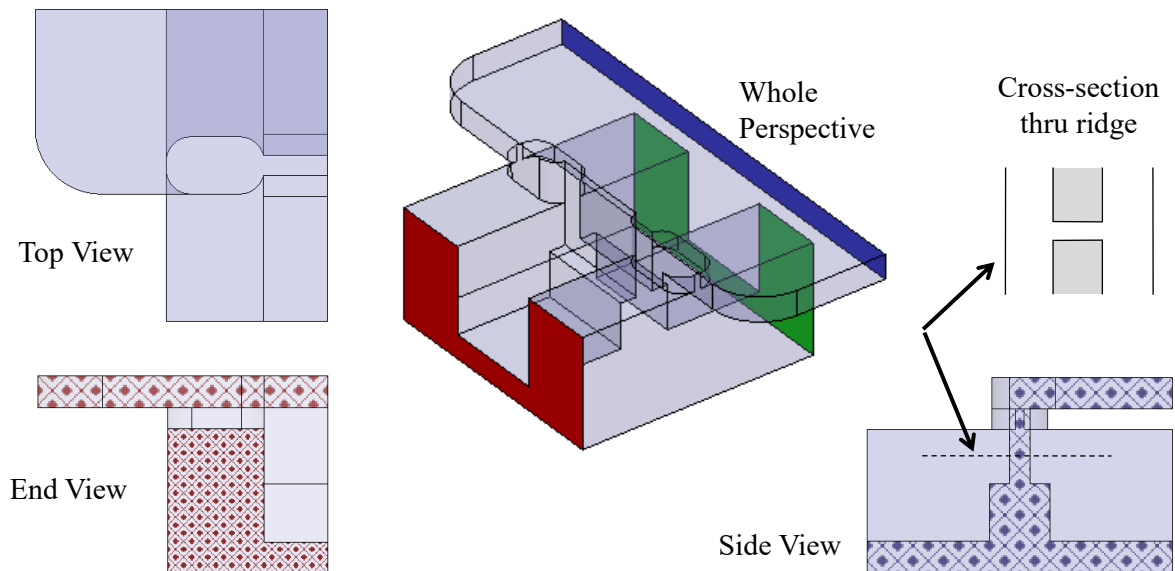
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Keeping the worst-case cutoff frequency to be below 6 GHz. to insure good performance.

Now consider the ridge WG transition to rectangular WG.

Rectangular WG to Ridge WG Transition/Splitter



Reduced height WR112 input through a dumbbell slot with
a 50-50 power split into a custom ridge waveguide.

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This is the key element in the whole design.

It sets the impedance levels of both the rectangular and ridge WGs. It also provides an E-plane bend which splits into two ridge WGs. The path is vertically down through the ridge to the gap at the bottom of the Ridge WG. This break in the ridge region is like a double ridge WG section. (note cross-section) Four different dimensions setting impedances are variables in matching this transition.

From the top view (half model) note the dumb-bell aperture coupling the upper wider rectangular WG to the narrow ridge WG.

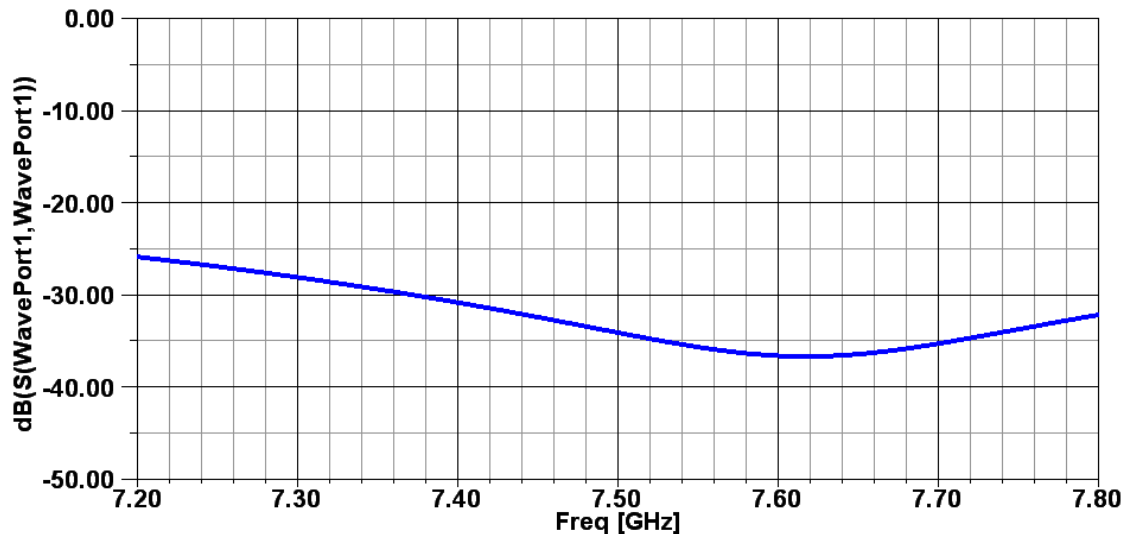
Complete the picture with an end view showing half-WG sections.

Resulting in a transition from the dark blue port to the red port.

How's the performance

Rectangular WG to Ridge WG Splitter

Performance



Reasonable performance given the dimensional constraints

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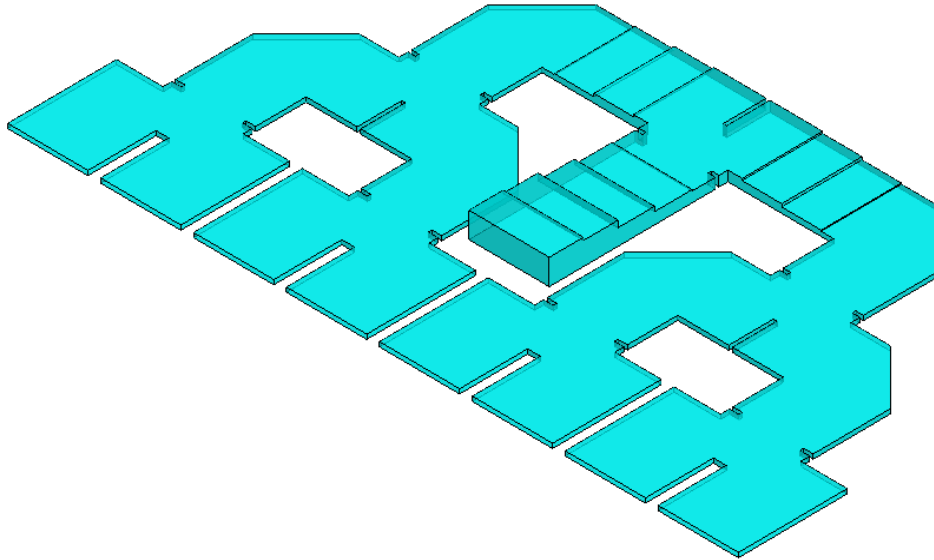
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Acceptable performance.

The impedance needed for the upper rectangular WG sets the height at 62 mils.

Now we can complete the 8-way input splitter design.

8-Way Top Layer Splitter



Most of this layer design was pretty straight forward

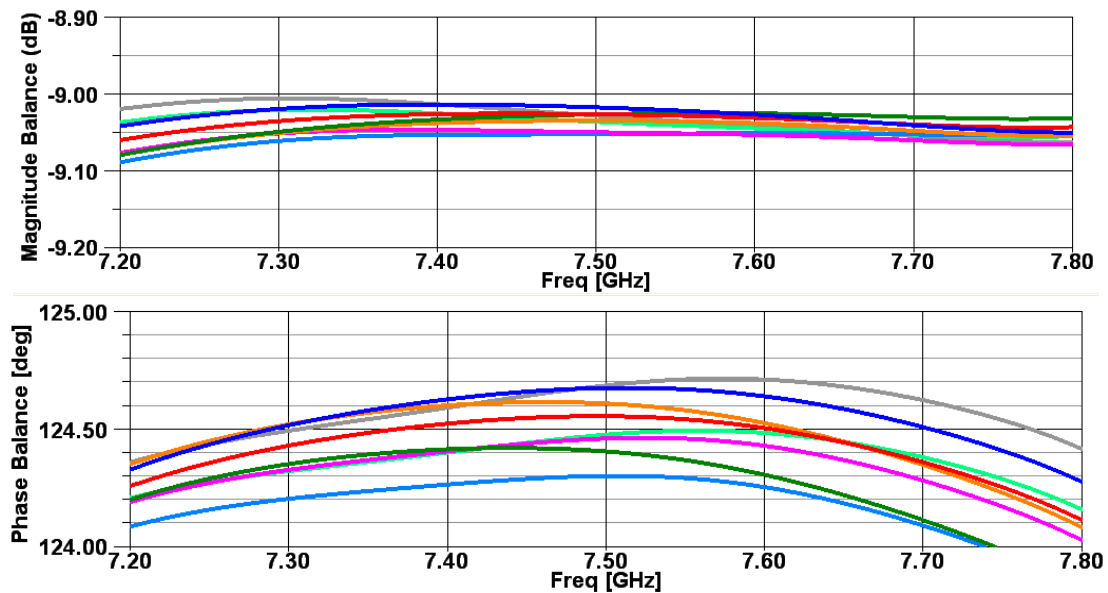
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This cross-row portion of the feed transforms from 350 mil to 62 mil while splitting the signal 8 ways. Notice the triple section impedance transformer before the first tee, and then another set of two sections after it.

How about this splitter performance?

Output Balance in 8-Way Top Layer Splitter



8-way split is 9.03 dB. Mag spread is less than 0.05 dB across the band with less than 0.05 dB insertion loss. Phase spread is less than 0.5 degree.

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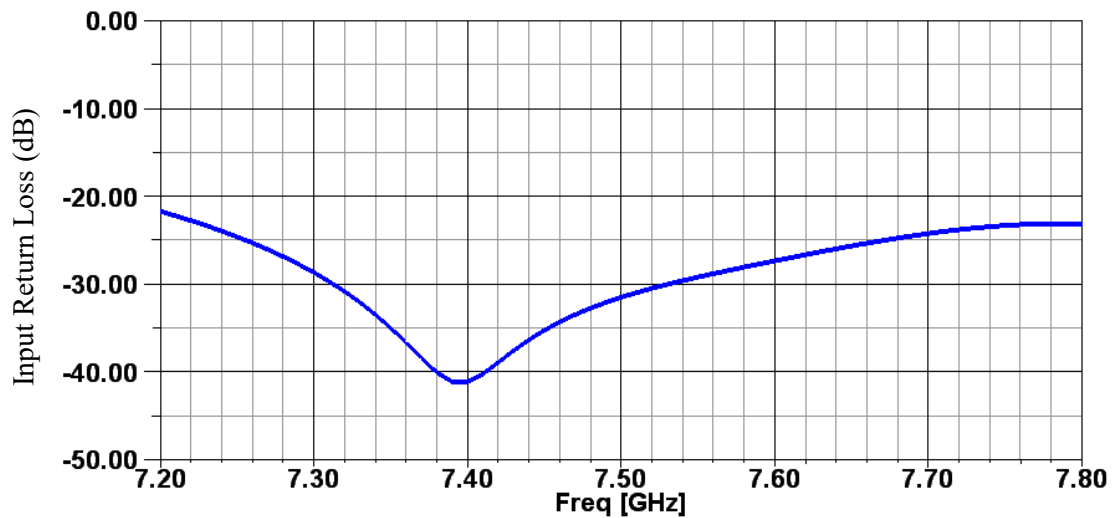
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Mag plot

Phase plot

And the input match?

8-Way Top Layer Receive Band Match

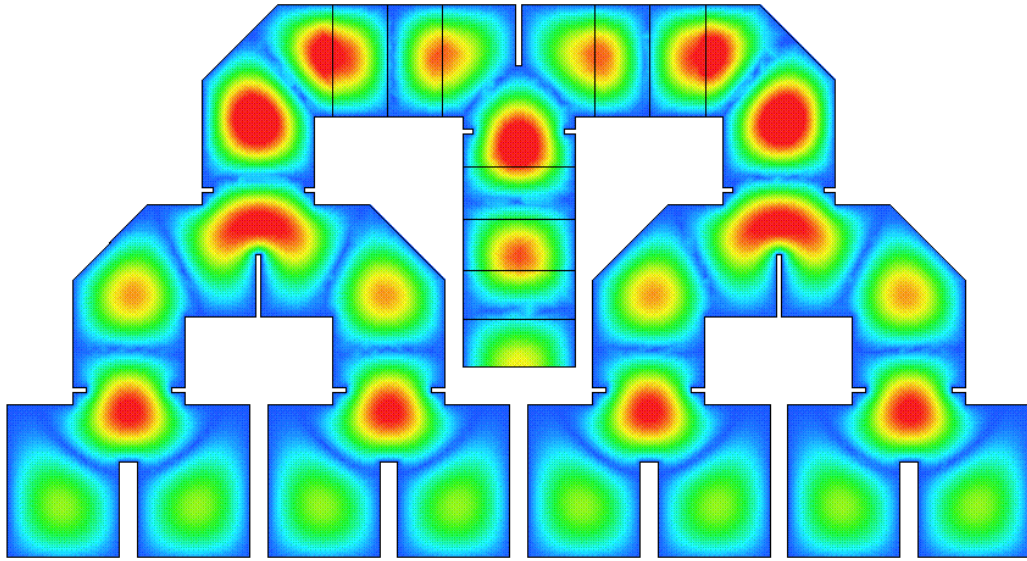


Return Loss is better than 20 dB across the band. Complete design match goal is better than 10 dB.

This does not include the transition to the ridge WG.

A look at the field flow.

8-Way Fields Flow



The 8-way splitter is the integration of 6 corner miters, 2 transformers and 3 tees with routine designs.

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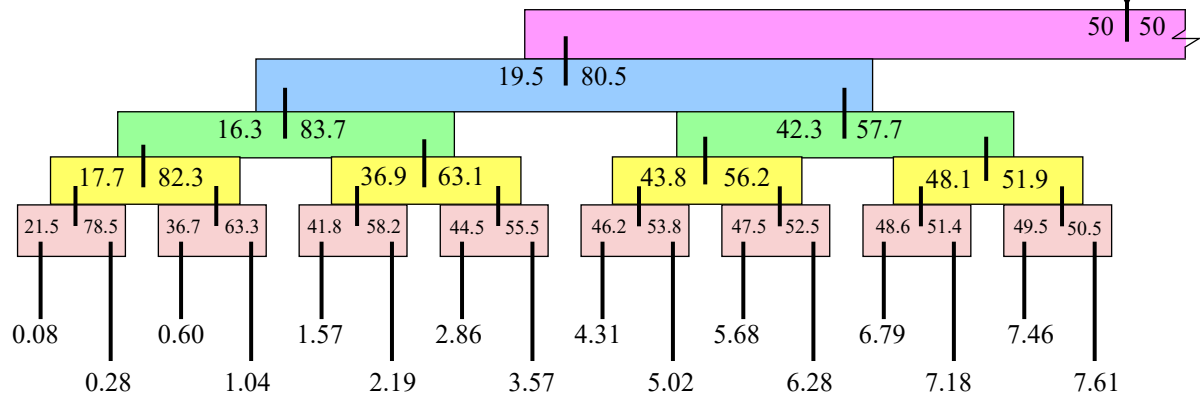
This is the way to look for the E-field breakdown hot spots. The first 2-way splitter height is set to 140 mils to avoid high fields. The 2nd and 3rd layer splitters are at the output height of 62 mils. When concerned with breakdown it is better to use inductive tuning elements rather than capacitive.

Now address the ridge WG 16-way non-uniform corporate feed.

5 Layers of Ridge WG Corporate Feed

Power Splits for one side (16 elements) of a “stick”

Feed input from
top layer



Power Distribution (Watts) in Transmit mode ($\Sigma = 62.5$ watts)

Cosine on a -20 dB pedestal aperture distribution requires 16 unique splitter designs for each band in ridge WG.

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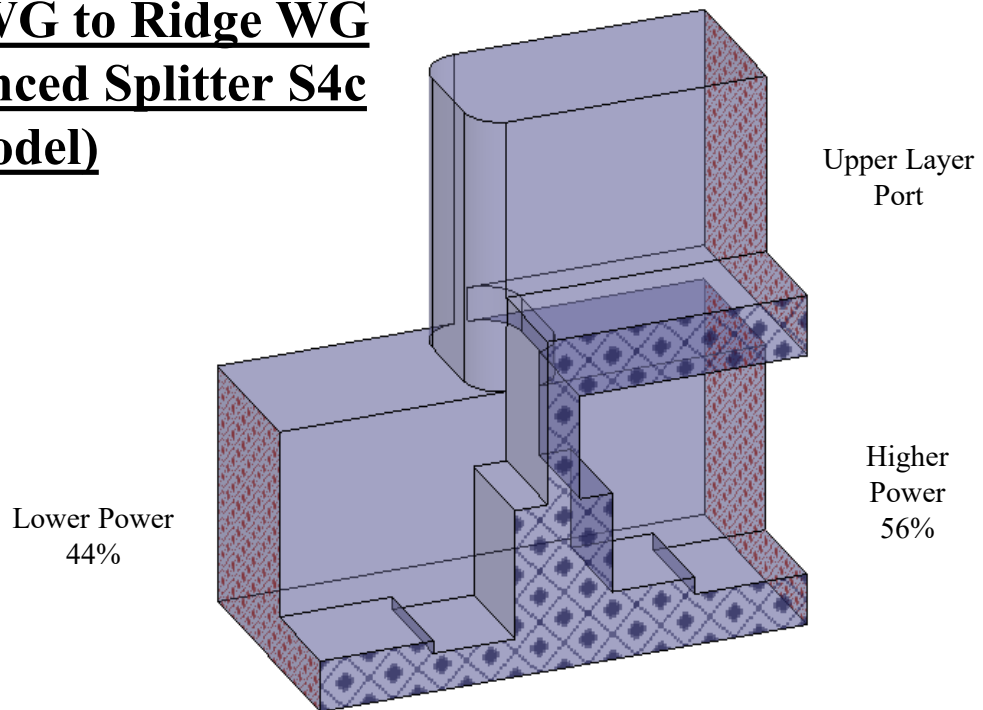
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This distribution design was done for both frequency bands. Remember, this mates up with the other side with 16 more radiators for an antenna stick length of 32 elements.

The aperture distribution was established by a side-lobe requirement on the single broadside beam.

Looking at an individual splitter circuit

Ridge WG to Ridge WG **Unbalanced Splitter S4c** **(half-model)**



The gap and junction dimensions were altered to achieve the power ratios. Phase unbalance was adjusted by splitter positioning.

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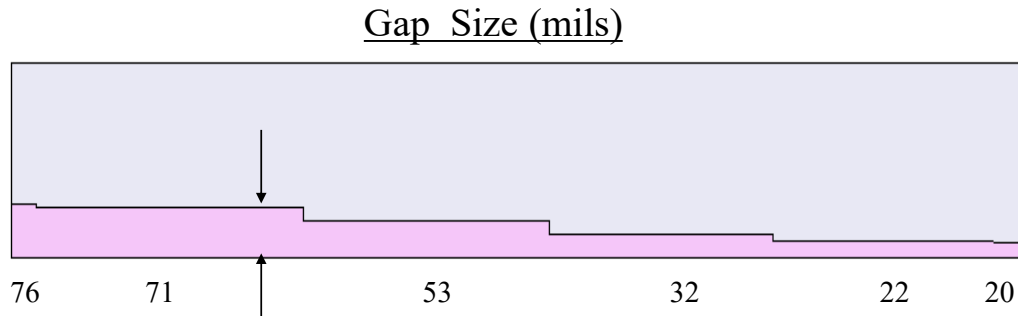
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Still using the dumb-bell aperture to couple through the Ridge WG floor.

Now look at the transformers.

Ridge WG Transformer Designs

Many sections were used to maximize bandwidth since the space was available.



Eleven different impedance transformer designs were necessary to connect up the various splitters. Straight forward but tedious because λ_g varied with gap size in each section.

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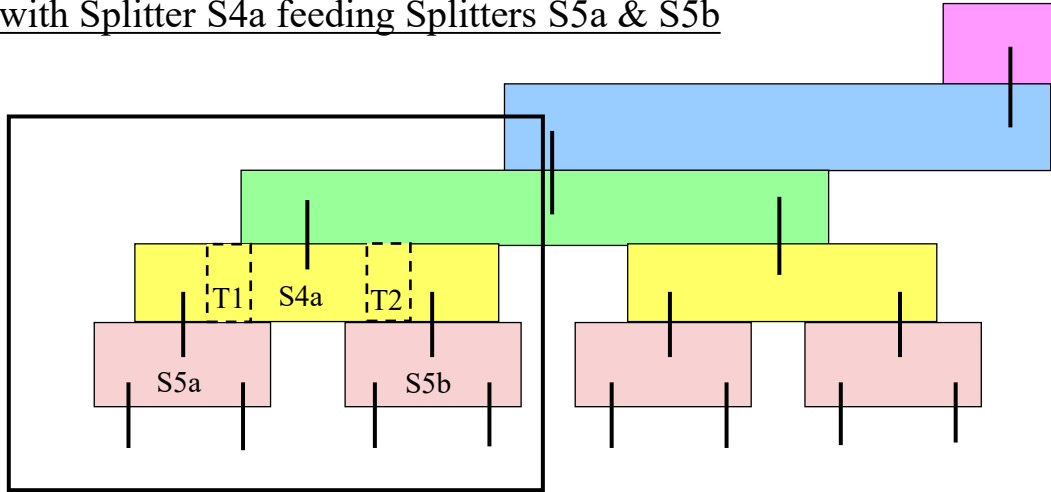
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These are matched between two splitters which have different gap sizes.

Now let's put some of these circuits together

Designer Analysis of Assembled Portion of 3rd to 5th Layers

Start with Splitter S4a feeding Splitters S5a & S5b

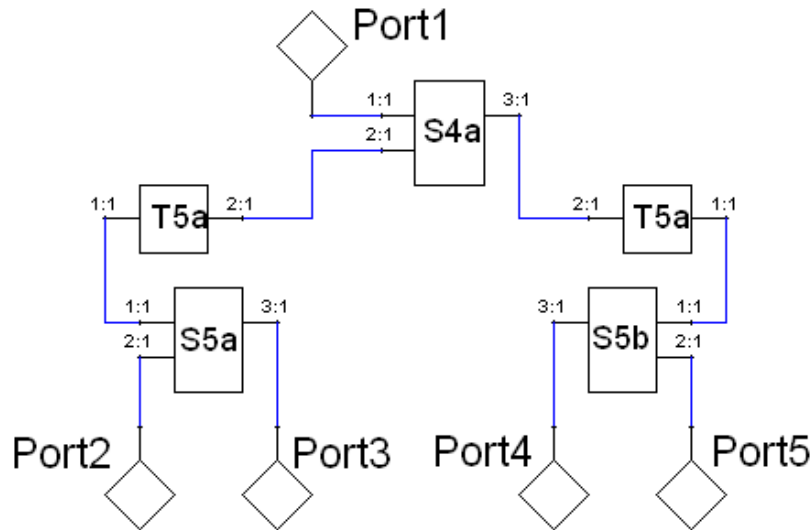


Transformers (T1 & T2) are inserted to connect the splitters.
Splitter and transformer positions are adjusted to match phase.

Three splitters plus two transformers.

How is this seen in Designer?

Circuit Connections for a 4-way section, with 3 splitters and 2 transformers



Line lengths are adjusted by shifting the reference planes within the various components, eliminating more parts

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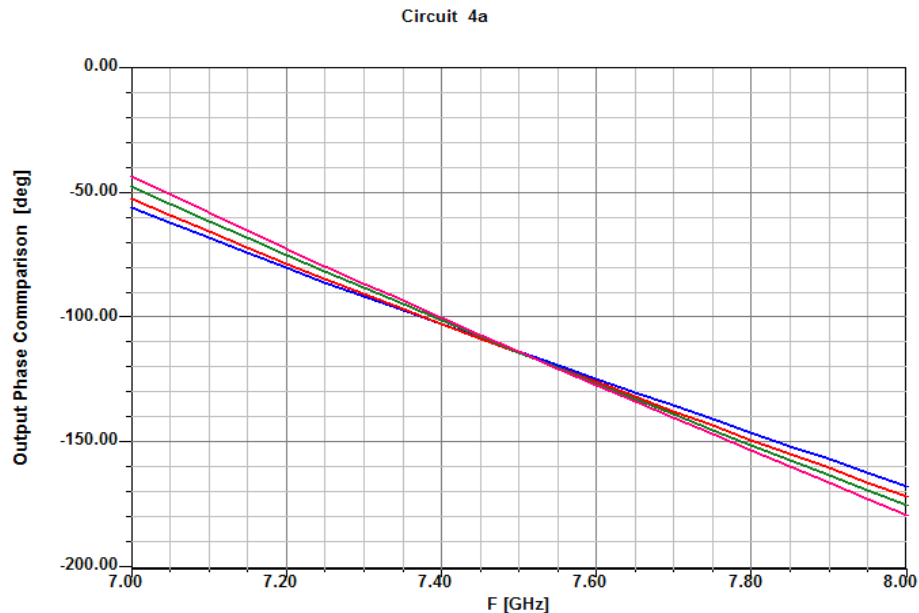
Simulations of each component are first done in HFSS, and then the S-matrix is imported into Designer along with the port data which allows connection as a larger circuit. This is an example of co-simulation where two different programs are used in concert to determine a solution. Discussion in Section 7, pages 11-13.

Simply the use of multiple simulation programs to address a design problem, avoiding the limitations of one program and taking advantage of features of another.

The common language between programs is the use of S-parameters, defining circuits blocks with properly defined Port characteristics.

Performance?

Output Phase for one 4-way section, with 3 splitters and 2 transformers



Phases match well at the design frequency of 7.5 GHz., verifying the circuit layout.

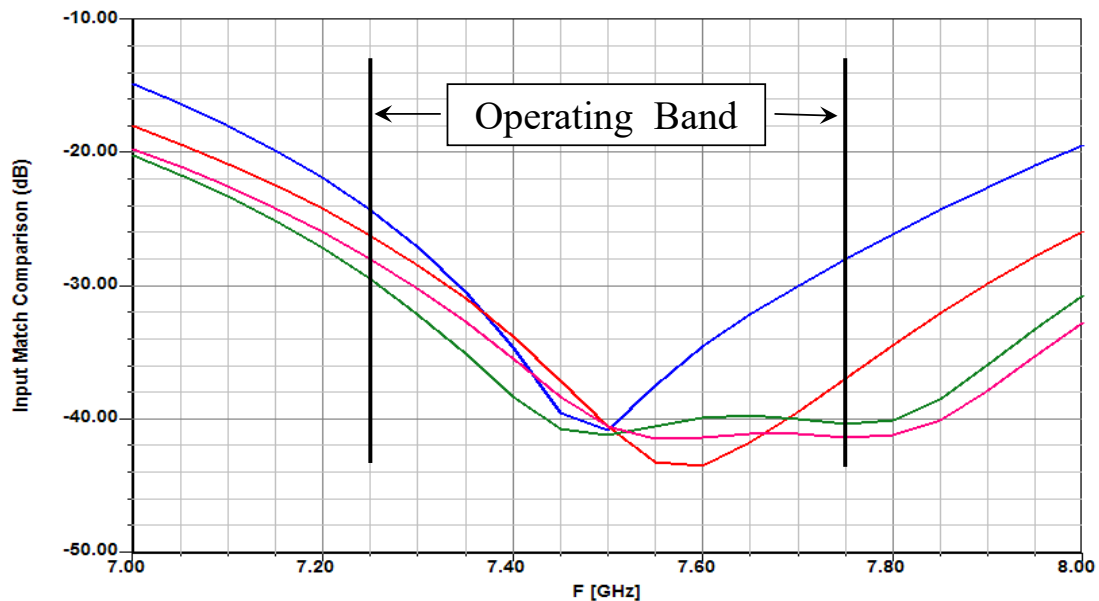
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Good phase performance

and Match?

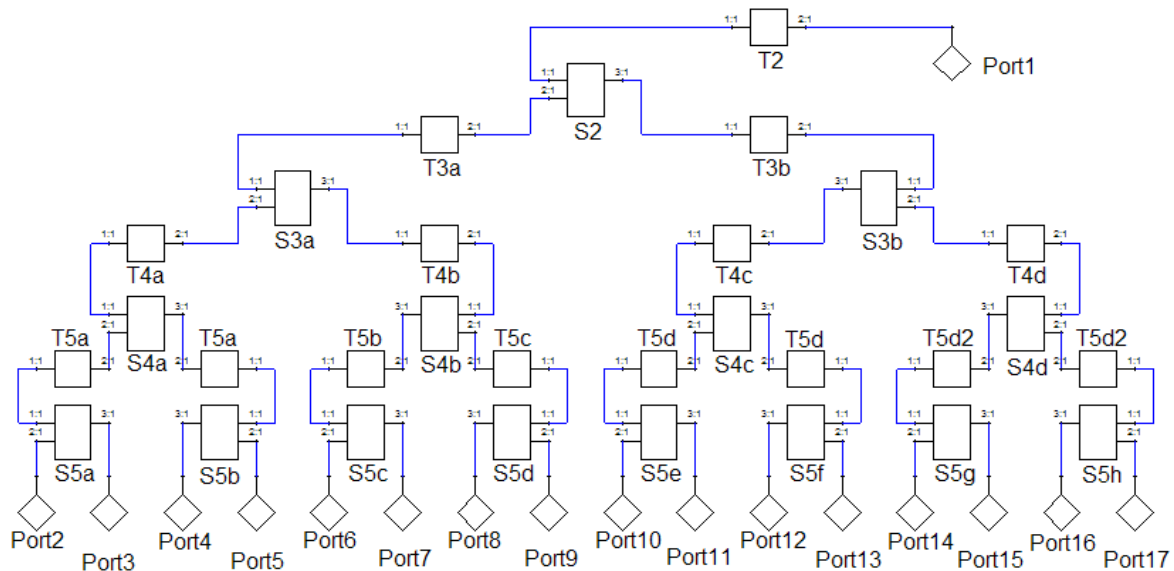
Input Matches at Layer 3 for the four individual sets of 4-way sections



The four sets are better than -20 dB return loss in band. The greatest power ratio split is the narrowest curve.

Putting the complete ridge WG part of the feed together

Circuit Connections for a one-half line array (sixteen port elements, 30 components)



17 ports, 15 unequal splitters and 15 transformers (connected by 11 different transmission lines) are accurately modeled in Designer

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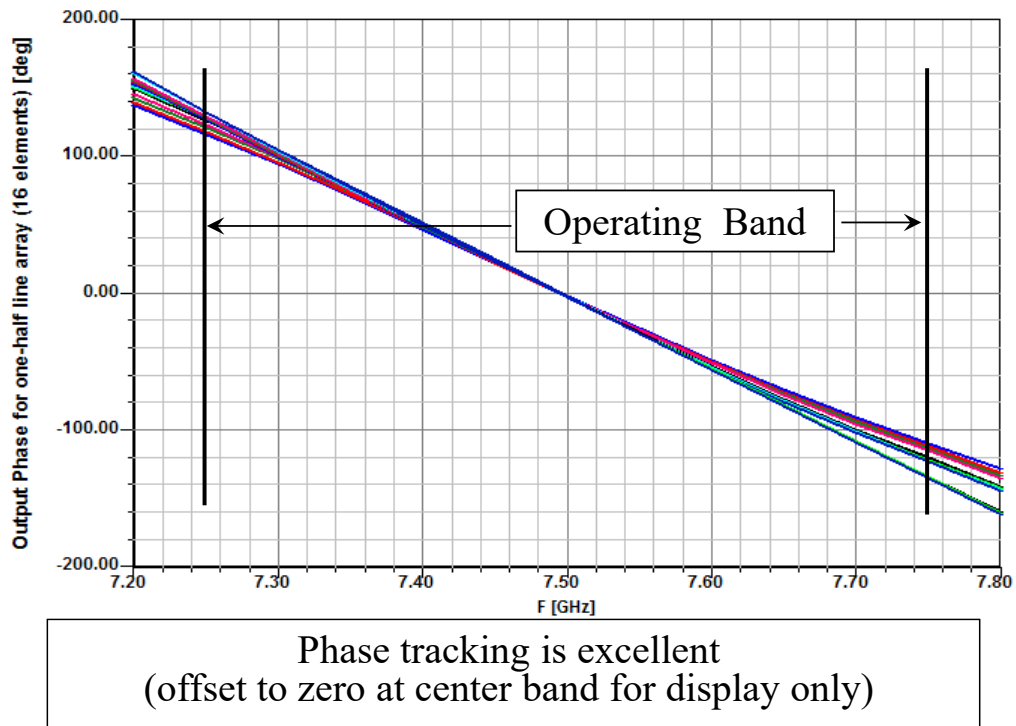
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This example shows how we can build a large circuit by consolidating the many parts which have all been accurately characterized in the 3-D simulator, where this total circuit size is much too large for the 3-D simulator to handle as a single model.

This circuit distributes power from Port 1 to 16 ports (2 thru 17) in a prescribed non-uniform excitation with over 20 dB variation across the 16 output ports.

So that we can now show the overall performance. First look and the output phases.

Output Phase for a one-half line array (sixteen elements)



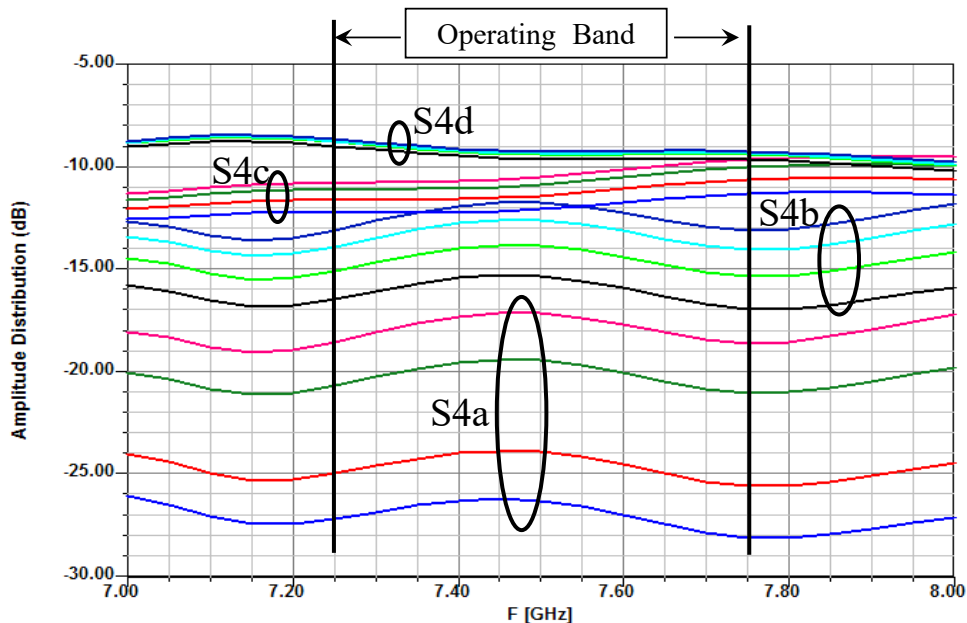
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Good verification of design

And transmission values?

Output Excitation for a one-half line array (16 elements) from the input port



The individual characteristics are very dependent on the transmission path, i.e. which splitters and transformers are involved.

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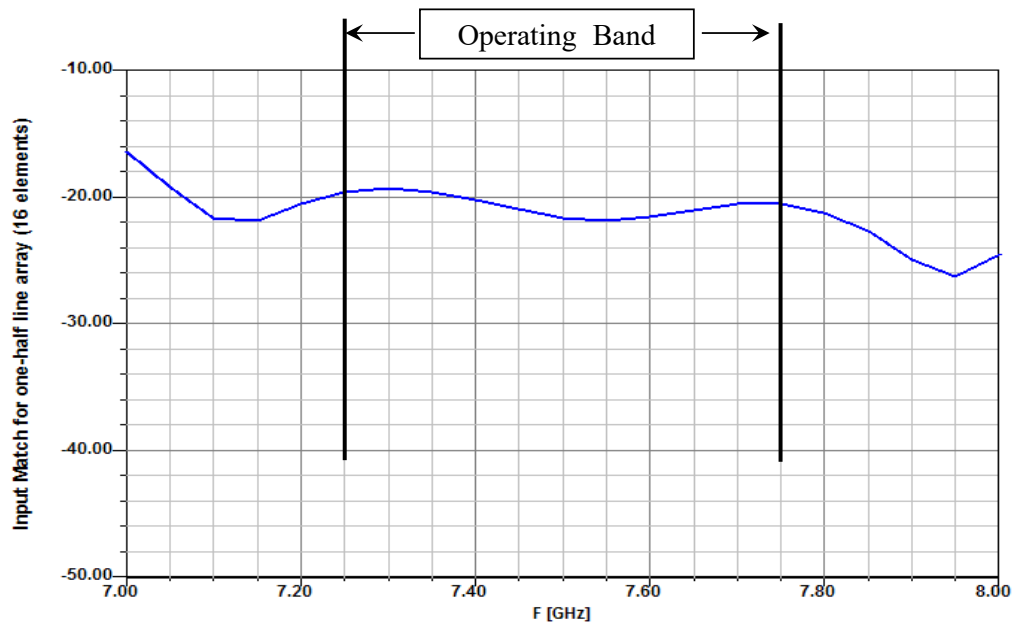
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The 15 splitters and 15 transformers are connected as S-parameter defined blocks to simulate the array feed with 17 ports.

We're looking for a -20 dB variation from top to bottom, the result averages about -18 dB.

Overall match?

Input Match for a one-half line array (feeding sixteen elements)



Ripple comes from the different path lengths between the layer splitters.

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Acceptable match into the ridge WG feed.

How are we going to radiate this energy?

Continuing On

- Approach
- Design Requirements
- Design Issues
- Corporate Feed
- Radiating Elements
- Simulation Program Features
- Summary

We finally get to the radiation part now that we've got the energy properly spread out.

What kind of element is best?

Radiating Elements Considered

Linear polarization elements:

- Transverse slots
- Longitudinal slots
- Printed dipoles*
- Folded dipole

Required an additional
polarizer layer in front
of the array

Circular polarization elements:

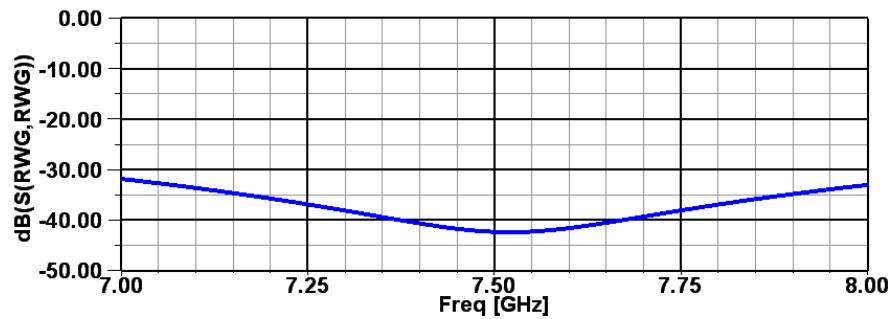
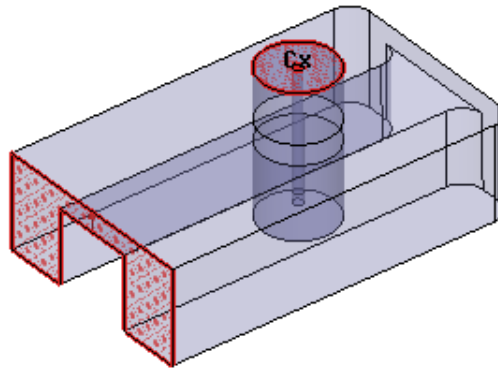
- Crossed dipoles
- Helices

*Selected element

The printed dipoles were the least expensive and provided the most flexibility in the design.

First task is to convert from the ridge WG to a coax to feed the dipole.

Ridge Waveguide to Coax Transition



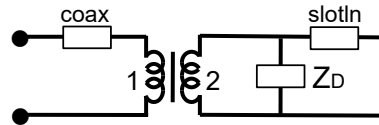
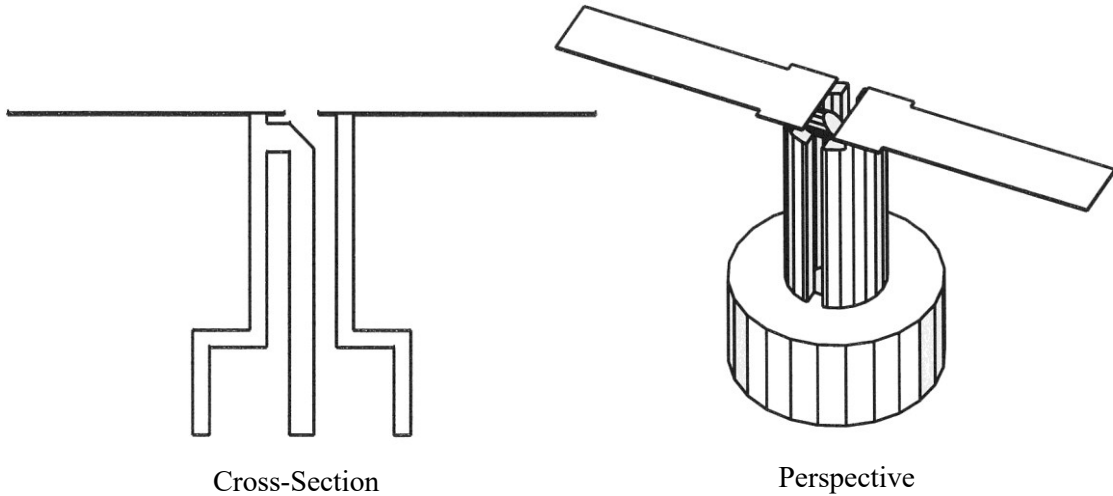
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This design was covered in the section on interconnects, Section 4, pages 16-18.

Go on to the dipole design.

Flat Printed Dipole



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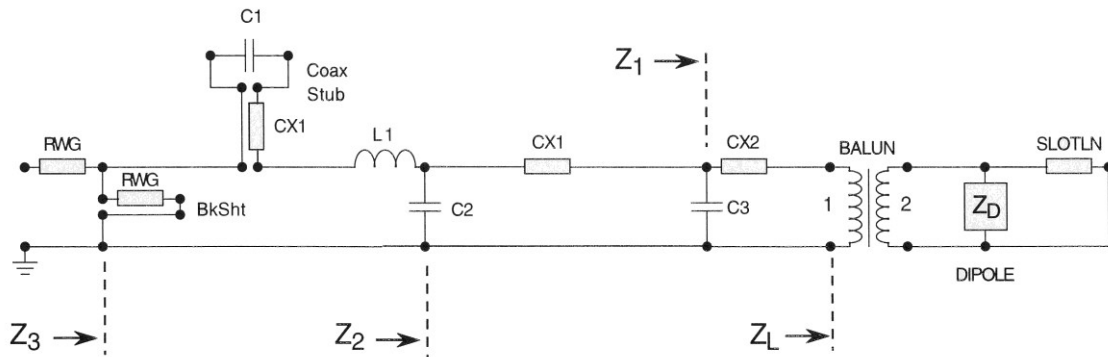
This design was discussed in the section on antennas. (Section 5, pages 21-23)

The only change is from round to flat dipole arms. The balun circuit is the same.

The flat dipole arms allow a printed layout on a substrate to be aligned with the tops of the slot section and flow soldered for all 512 elements of both bands at once over the whole array face.

Integrating the ridge WG and the dipole.

Overall Equivalent Circuit Model



$Z_D \approx 72 \Omega$	$Z_L \approx 18 \Omega$
$Z_{SLT} \approx 48 \Omega$	$Z_1 \approx 69 \Omega$
$Z_{CX2} \approx 36.5 \Omega$	$Z_2 \approx 69 \Omega$
$Z_{CX1} \approx 69 \Omega$	$Z_3 \approx 82 \Omega$
$Z_{RWG} \approx 82 \Omega$	

Most line lengths
are $\lambda/4$

An accurate equivalent circuit is handy to have before a good understanding of the circuit operation is possible.

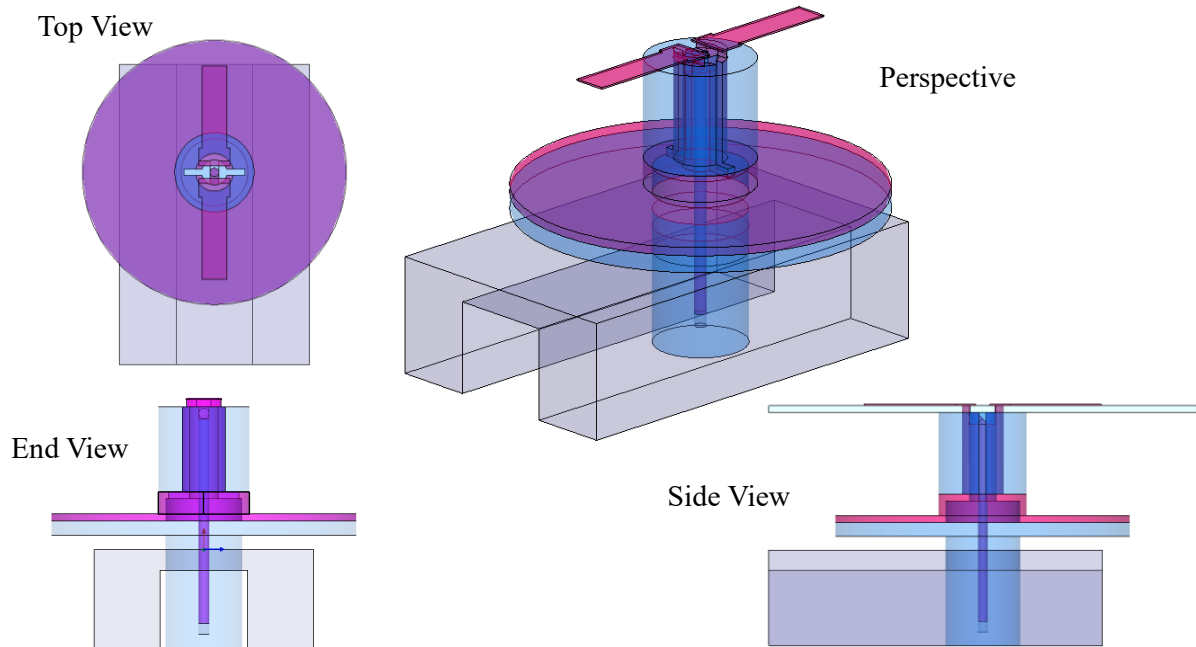
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This circuit takes you all the way back to the ridge WG input to the antenna element.

And the hardware looks like

Slot Fed Printed Dipole with Radial Choke



The element uses probe coupling to the Ridge WG and a radial line DC block to the ground plane to eliminate soldering between the dipole and the feed structure.

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We see an added disk to the element. This is a radial line DC block for the ground return.

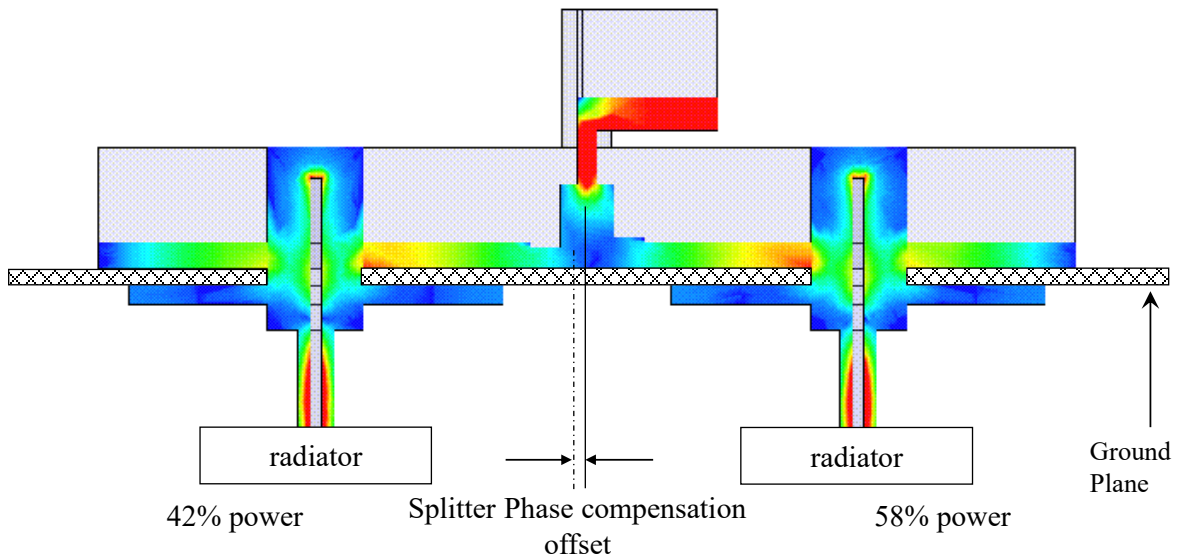
The side view shows the DC block.

complete the picture

The substrate is attached holding all the elements in place.

See how it works

Ridge WG to Coax line feeding Radiating Elements



Feed energy is actually 180 degrees out of phase at the 2 radiators so that one of the elements must be rotated to compensate.

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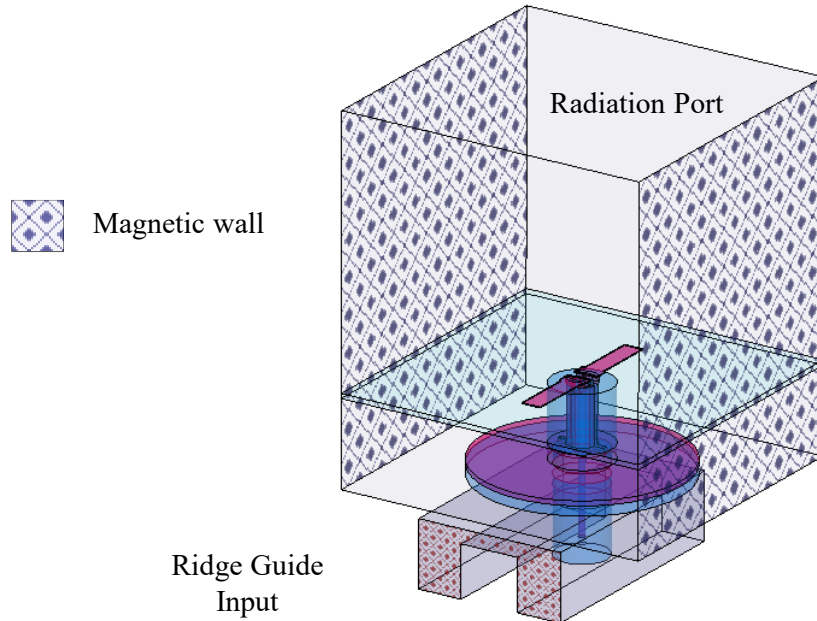
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You can barely see there is a little more power on the right side element due to the unequal split.

Have to be careful of the radiating phase.

And just the radiation cell.

Array Cell w/ Dipole Element



Circular Polarization elements could not be simulated in the array environment with HFSS at the time of the design

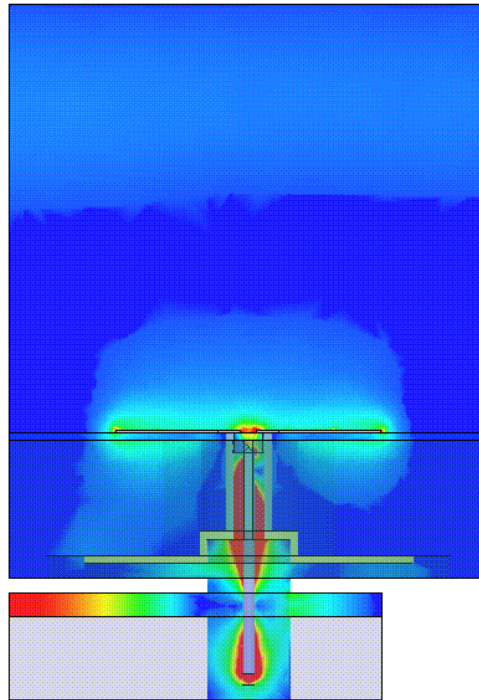
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The cell covers two ridge WGs because this element is cross-polarized to the elements in the adjacent rows.

So let's see this work.

Radiation Port



Ridge Guide
Input

Broadside
Operation
from
Ridge WG
thru to
Free Space

Four types of transmission line and two baluns are involved in this “plug-in” design

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Ridge WG – Coax – Radial line – Coax - Slotline

So how was HFSS used in this antenna array design?

HFSS Feature Review

Design process dependent upon HFSS - ?

- | | |
|--|-----|
| • Ridge waveguide characteristics | Yes |
| • Ridge WG to coax transition (plug-in) | Yes |
| • Unbalanced splitter design | Yes |
| • Impedance matching implementation | Yes |
| • Slot-Fed Dipole (w/balun) impedance | Yes |
| • Array environment effects | Yes |
| • Loss determination | Yes |
| • Potential electric field breakdown regions | Yes |

HFSS was used in every aspect of the design. Schedule and cost could not have been met using cut-and-try hardware methods.

Summary

Dual Band Design

Summary

A variety of component examples have been reviewed in the design of a complex antenna array where Electromagnetic Simulation tools were used for design. In many cases unique program features facilitated the design process, resulting in a timely and cost effective antenna.

Six units were fabricated, four presently in operation and two as spares for a military Air-to-Satellite Communication System.

**When asked if he had stood on
the shoulders of Issac Newton,
Einstein said that is not quite
right, “I stood on Maxwell’s
shoulders”.**

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And so have all of us!

Thank You