Section 5
Antenna Elements Design

from

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

by

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MICROWAVES IS MY RACQUET

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This set of 28 pages is a section focusing on single antenna elements, taken from an extended presentation on microwave design. If you have a question, feel free to write me at R.L.Eisenhart@ieee.org.

Antenna Element Design

Element Design Outline

- Antenna Design Process
- Antennas as Circuit Components
- Waveguide End Slot (linear pol)
- Pyramidal Horn (linear pol)
- Corrugated Horn (circular pol)
- Slot-fed Dipole (linear pol)
- Turnstile (circular pol)
- Cross-Dipole (circular pol)

I'm going to discuss a little philosophy on antennas and then address the aspects of a few designs.

How does the design process go?

Antenna Design Process

1. Antenna Requirements

- Given - Size (3 dimensional constraints, conformal)
  - Weight, Wind resistance, Frequency
- Desired - Pattern (Directivity, Beamwidth, Sidelobe levels)
  - Polarization (Cross-pol isolation)
  - Bandwidth (instantaneous and tunable)
  - Efficiency (Gain/Directivity, losses, matching)
  - Scanning, Scan loss

2. Come up with a Concept (A miracle occurs!)

- Multiple tradeoffs of the requirements played against designers experience. 1st order approximation sufficient to relate various parameters. Gain $\propto f^2 A_{rea}$ Gain $\theta_h \theta_v = K$
- Select element, i.e. Patch, horn, dipole, slot, helix, lens etc.

A typical set of antenna requirements often defies the Laws of Physics

Step 1 - Antenna design is complicated by the fact that it is more like a system design than a component, even for a simple single element.

a) there are usually many performance criteria, and

b) there are so many different ways to do the design, which is the best?

Step 2 - Usually experience gives the best leads.

More education is necessary for people who want antennas than any other type circuit.

For example I had a client who specified the gain, frequency and antenna size!

Look at the equation, you only get to pick two out of the three.

Antenna Design Process (cont'd)

3. **Break down concept into definable problem areas and develop precise characterization for each.**
   - Single element performance (match, bandwidth, etc.)
   - Mutual coupling effects in arrays
   - Feed design
   - Mechanical layout
4. **Finalize Prototype design and Fabricate**
5. **Evaluate Prototype with chamber testing**
6. **Iterate design as needed**

> 1. **Closed form solutions rarely exist for real antennas**
> 2. **Arrays are needed to satisfy most antenna requirements**
> 3. **With radiation, physical influences on performance come from well beyond the model**

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Step 3 – Isolate various parts that can be dealt with independently.

Step 4 – Assemble design and build.

Step 5 - Test and evaluate (note: the "virtual lab" concept doesn't work quite as well with antennas, usually because the models are not as accurate/complete)

Step 6 – Decide when to stop, because

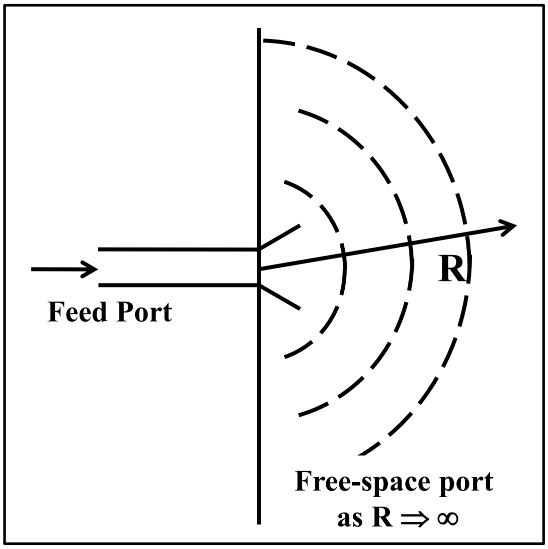
Modeling antennas is tougher than closed circuits

Consider an antenna as a circuit element.

An Antenna as a 2-port Circuit Component

Feed Port

- Connects to a system with single mode transmission line (coax, waveguide etc.)
- Primary issue – impedance match
- S-parameter characterization



Free Space Port

- Deals with Energy distribution
- Radiation environment – terminated in perfect match
- Electric field distribution is determined on outer boundary
- Post processing interprets the boundary field distribution as a new distribution at R = ∞ (far field).
- This $|\text{far field distribution}|^2$ is called the antenna pattern
- Pattern characterized by # and direction of beams, mainbeam gain*, beamwidth, sidelobe levels & polarization.
- Pattern plotted vs. angular position on spherical surface

* Antenna does not amplify: Gain ≡ directive power relative to isotropic power

Really just a two-port circuit, consider then the **Feed Port**

Transmission line choice is determined by impedance level, type of radiator, and mechanical / configurational criteria. A great deal of “antenna” design is in the feed components, particularly for arrays

Free space Port

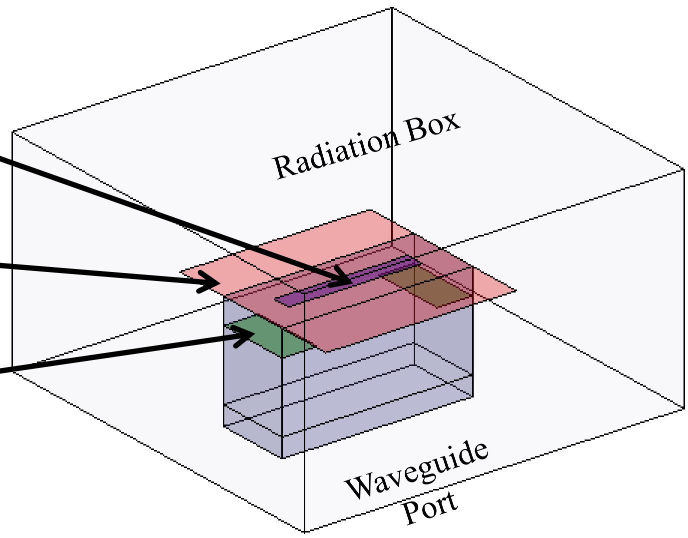
Most of the design of antenna patterns is done mathematically through determination of the excitation (mag & Phase) of multiple elements of an array. These values are then part of the requirements for the Feed Port which sets these excitation values for the elements.

So let’s look at some example designs.

Waveguide End Slot Element

The slot element is a radiation slot (100 x 700 mils) in the end of a waveguide with a 1 in square ground plane

Matching is done with inductive elements inside waveguide



This simple element is easily adapted for use with arrays

Resonant frequency is set by the slot length and the ground size affects the pattern.

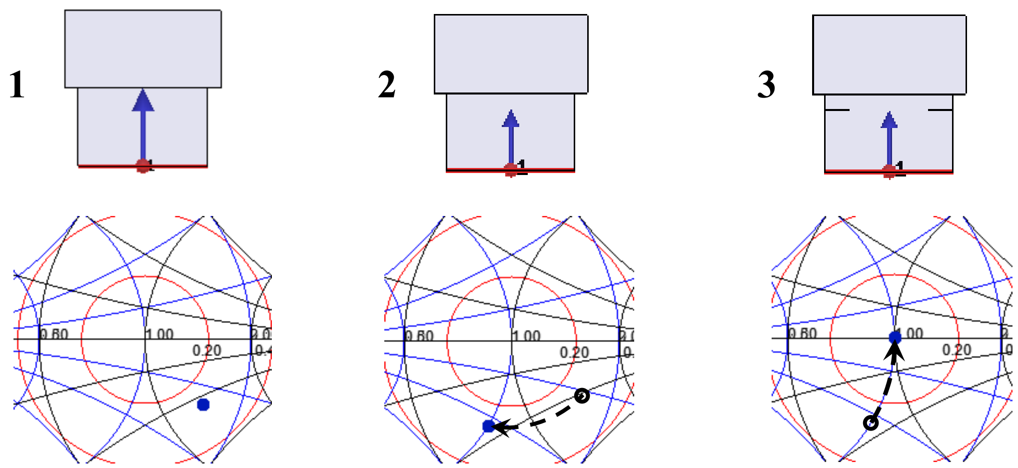
Remember the slot line from the transmission line discussion?

Elements within the feed are used to provide the matching, enabling better radiation efficiency.

Let’s match the element first.

Matching Process at 8.5 GHz

Determine Impedance | Determine Position | Determine Dimensions



ρ = 0.284 ∠-46° | ρ = 0.284 ∠-107° | ρ = 0.002 ∠42°

Add inductive irises to cancel susceptance in radiating slot

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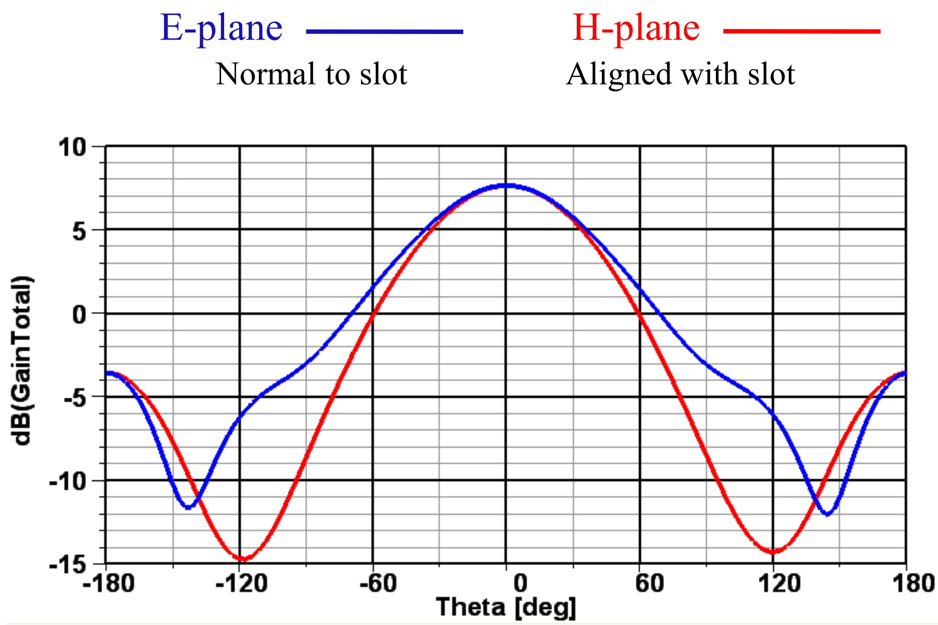
Matching is a simple three step process for this element. First see what it is you have to match on the Smith Chart Grid.

Shift reference plane to G = 1 curve on the Smith Chart.

Add symmetrical inductance elements. Resulting in excellent match

Let’s see the patterns

Single Slot E & H Plane Patterns



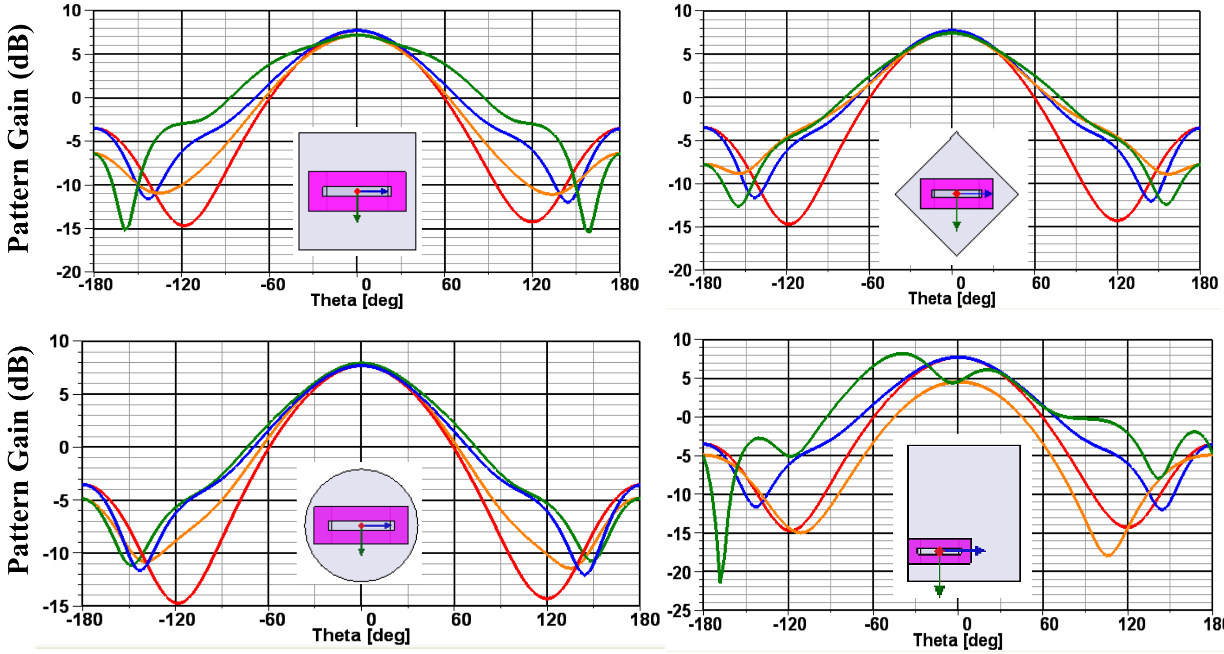
Radiation condition used on Radiation Box

A few comments on these pattern cuts. Pattern goes beyond ± 90 degrees because of the limited size ground plane. E-plane has a broader pattern because the element extent is smaller in that plane. Conversely, the larger the element, the narrower the pattern.

So what if we used a larger or different ground plane?

Ground Plane Size/Shape Effects

Green and Orange lines are for modified ground planes



The ground plane shape and size has a big effect on the patterns

Here we have a series of plots. . . .

The blue and red lines are E & H-plane patterns for the 1” x 1” ground plane from pages 6-8. For comparison the green and orange lines represent the modified ground shapes. First plot has a 1.6” x 1.6” ground plane.
Then rotate the ground by 45 degrees, see the change in patterns.

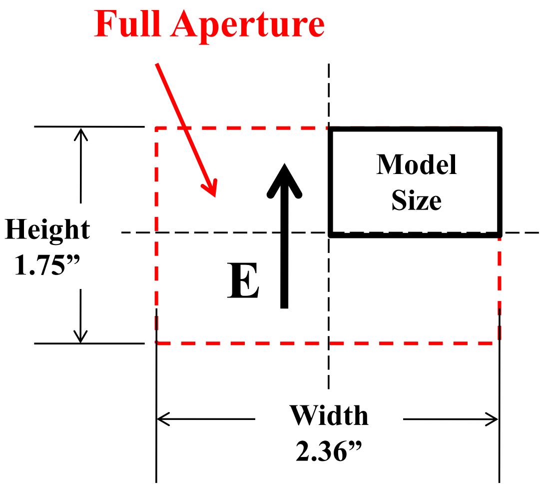
Next is the Circular ground 1.2” diameter

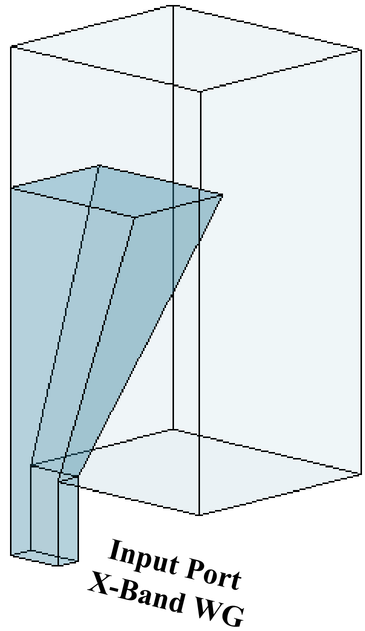
And then the Offset position. 1.4 x 1.6, we lose symmetry

So we see how the ground is very much a part of the antenna element.

How about a pyramidal horn?

Pyramidal Horn Model





- **Enclose horn in a radiation boundary (no ground)**
- **Use symmetry planes (E & H) for faster simulation**

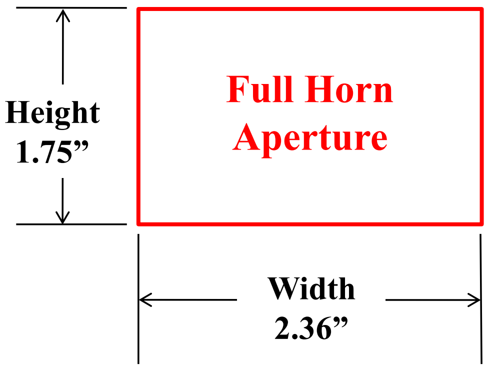
Only one quadrant of the model is needed to simulate the horn

Nothing fancy – typical horn

Let’s make a guess at the gain

What is the Pyramidal Horn Gain?

We have the size:



And at 10 GHz., knowing :

$$Gain = \frac{4\pi A_e}{\lambda^2}$$

Where A_e **= Effective Area**

≈ 0.85 Area,

And $\lambda = 1.18”$

Then Gain = $(4\ \pi\ 0.85)\ (1.75)\ (2.36)\ /\ (1.18)^2 \rightarrow 32$

or Gain = 15 dB

It’s always smart to have a good idea of what to expect as the answer

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Reciprocity is an important characteristic with antennas as well as circuits. This ties back to the earlier page of considering an antenna as a 2-port. The effective S12 or S21 is the same whether receiving or transmitting. So, as a receiving antenna, think in the concept of Effective Area (Ae) of an antenna – the collection ability to an incoming EM plane wave, like a funnel to rain. That is, how big does the antenna look to the incoming wave?

The Gain is directly proportional to the Effective Area normalized to lambda squared and related to the physical area.

So without running the simulation we expect Gain = 15 dB.

The point is . . . called a sanity check. If the simulation resulted in Gain as 10 or 20 dB I would suspect that something is wrong.

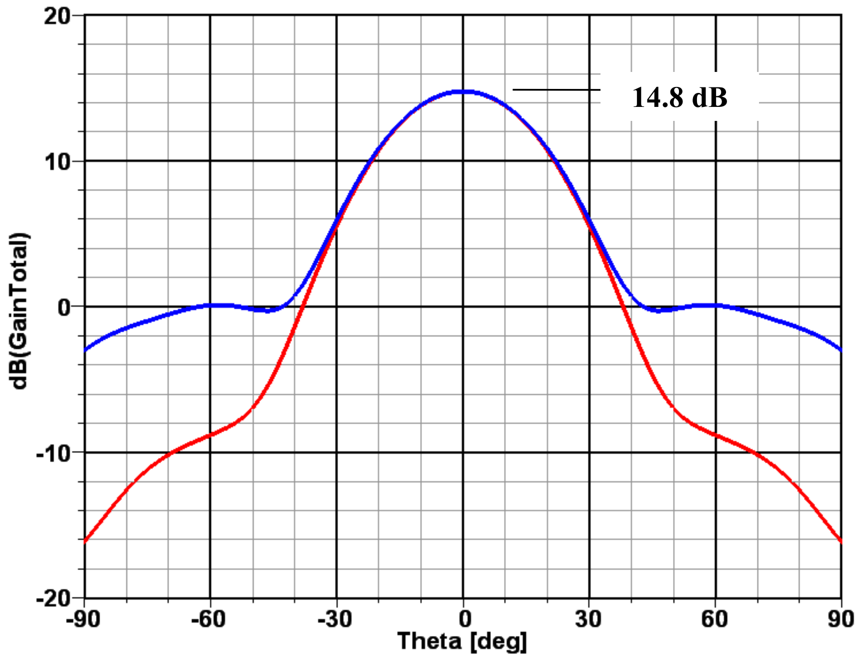
Back to the horn.

Horn E & H Plane Patterns

Patterns
@ 10 GHz

E-plane

H-plane



Equal Beam Widths are generated with width ≈ 1.35 height

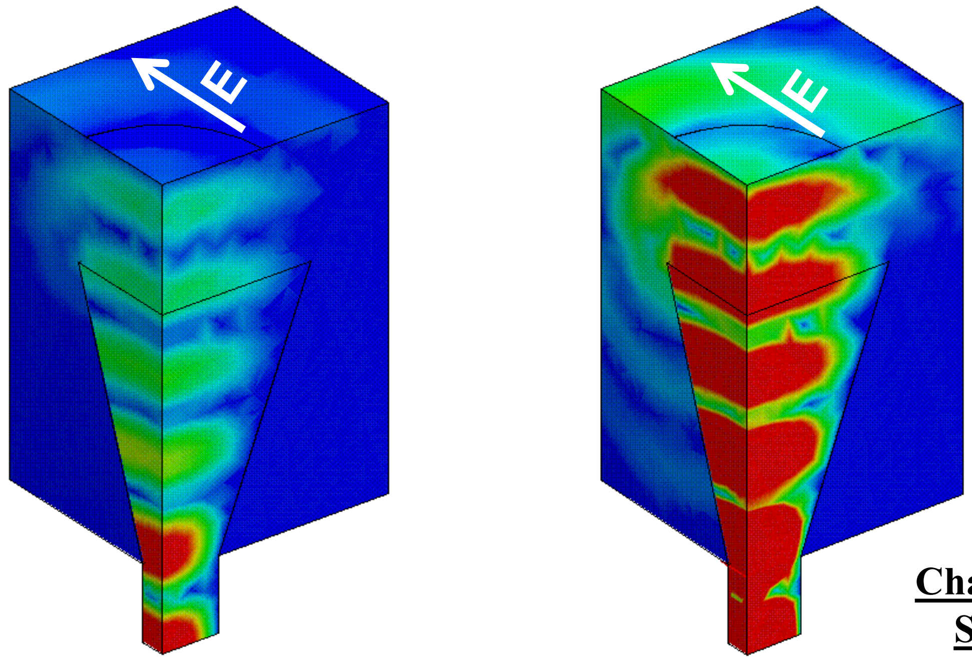
Now we have confidence in the simulation with our estimate for gain. What's unique about these patterns?

The aspect ratio of the horn aperture was adjusted to balance the beam widths. Why was this necessary?

Field magnitude is uniform in the E-plane but is sinusoidal in the H-plane, so we have to widen the width to make it look electrically the same as the E-plane size.

So let's look at these fields.

Horn E & H-Plane Fields



Changing Scale

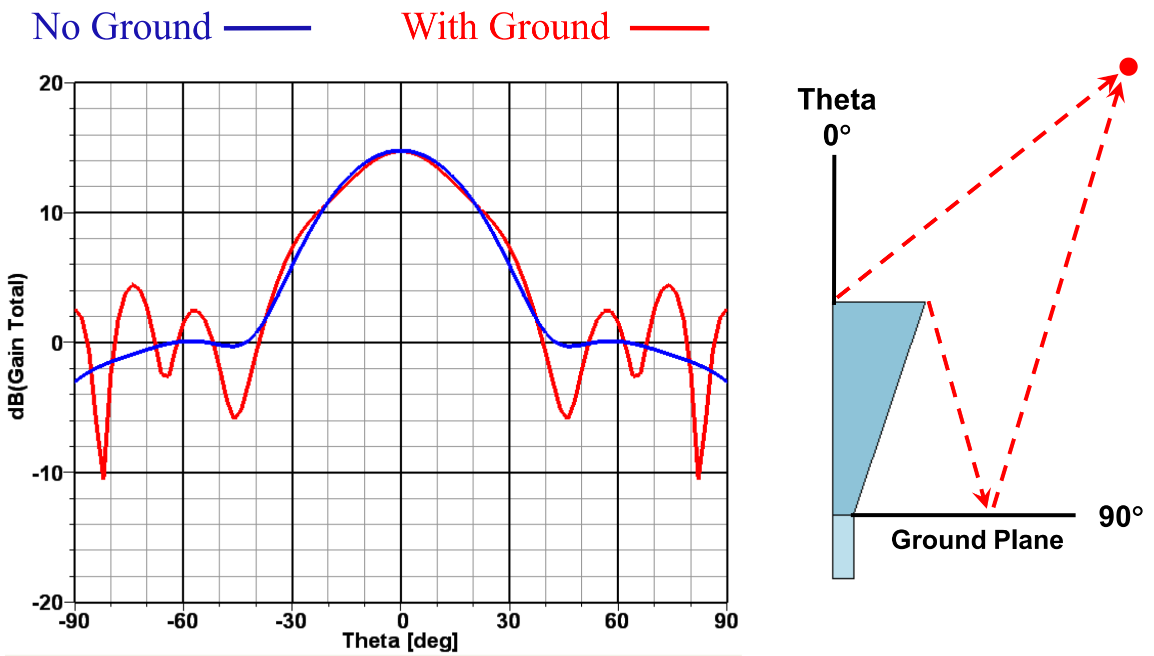
Note the "spillover" in the E-plane

What's going on around the horn?

If we put an array of horn apertures in a ground plane there would be strong coupling along the E-plane axes due to current aligned with the E-fields. This would occur also for an open ended element WG array.

What if we put a ground at the base of the horn?

Horn E-Plane Patterns with Large Ground



A large ground plane creates reflections

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We're seeing that we must always consider the shape, size and position of the ground plane.

Ripples are the interference pattern of two waves. Why should we suspect that this is the E-plane pattern?

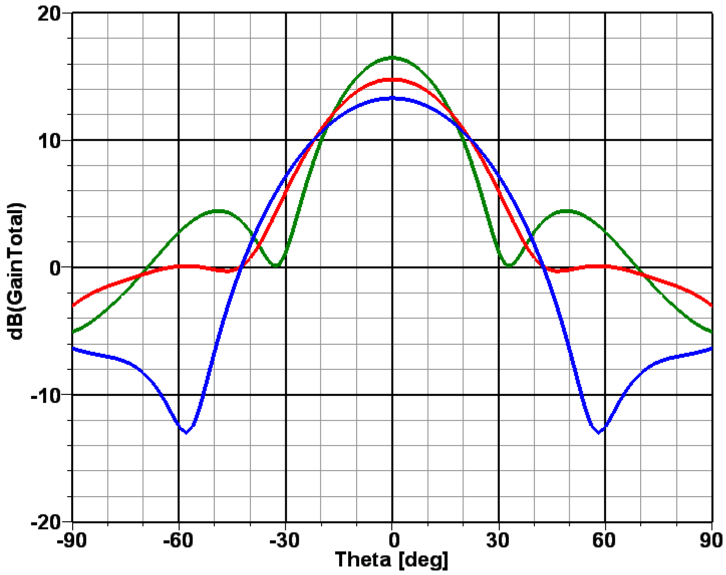
How does this pattern change with ground position?

Lower ground will have faster ripples of diminishing size.

What about changing frequency?

Horn E-Plane Patterns vs. Frequency

Patterns for 8, 10 & 12 GHz



$$Gain \propto f^2$$

$$\theta_E \; \theta_H \cong \frac{3\,x10^4}{Gain}$$

Where $\theta_E \, \theta_H$ are E & H plane beamwidths

Important to understand the relationships

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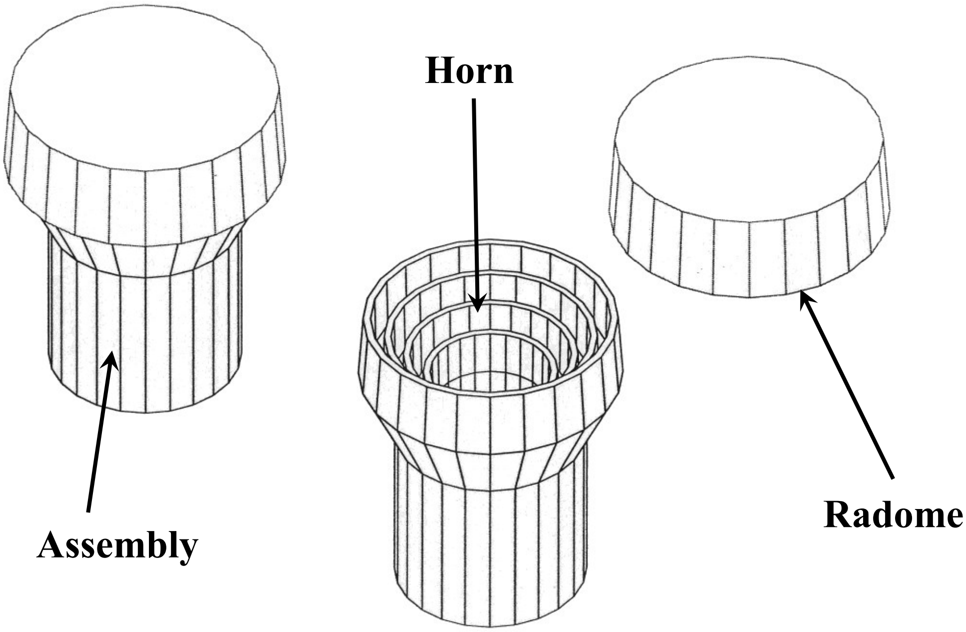
Earlier we saw that gain is inversely proportional to lambda squared, so gain ~ freq^2, so it "looks" bigger as the frequency increases.

Another useful "rule of thumb" is that the product of the two principal plane beamwidths is inversely proportional to gain. i.e. higher gain – narrower beam.

Consider next a circular horn

Corrugated Horn & Radome Assembly



Corrugated horn commonly used with satellite dishes, supports both linear and circular polarization modes

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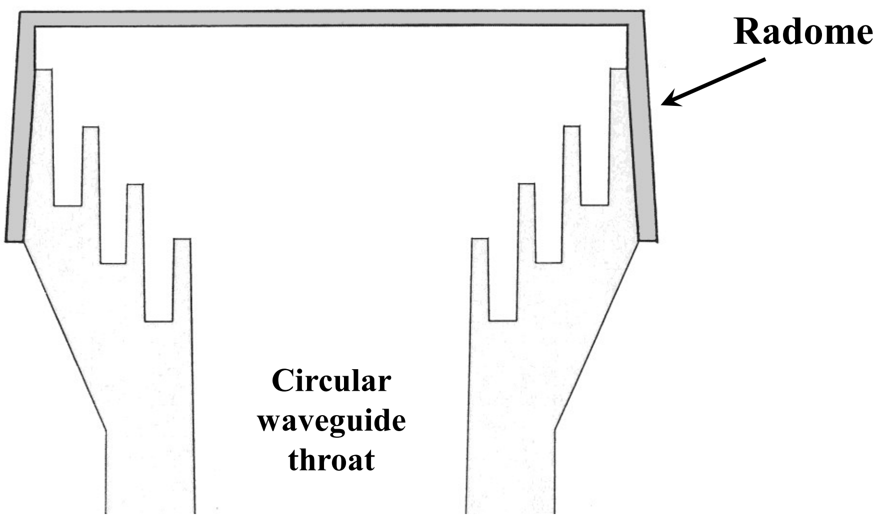
This type horn is usually used with a dish for efficient illumination of the reflecting surface. This horn also uses a different technique to create the same beamwidth for both E & H field patterns, in other words a circular beam shape.

How do the corrugations work?

Corrugated Horn Cross-section

Complex shape required for casting – all axial surfaces are tapered at 1 deg.
Radome position tuned for best match – modeled with quadrant only



Corrugations suppress the E-plane edge currents to balance pattern

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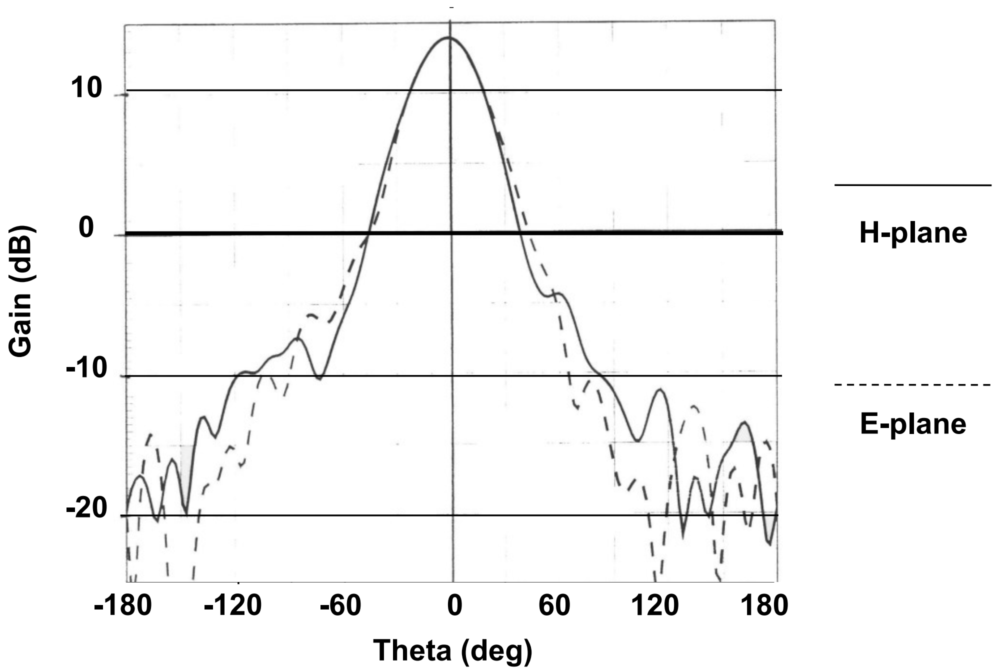
Corrugations are ≈ λ/4 deep to appear as an open circuit at the opening to kill the currents that flow in the E-plane, making the pattern circularly symmetric.
Corrugations have little effect on the H-plane.
This creates a low axial ratio for circularly polarized radiation along with a circular pattern shape.

HFSS is ideal for designing because of the 1 deg taper, particularly in designing the polarizer. This means that the cutoff frequency, lambda guide/gamma and guide impedance are all a function of position along the guide!

A typical pattern set

Measured Corrugated Horn Patterns



Results in a nice circular pattern to fill reflecting dish

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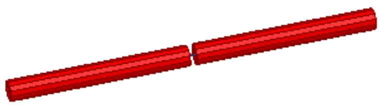
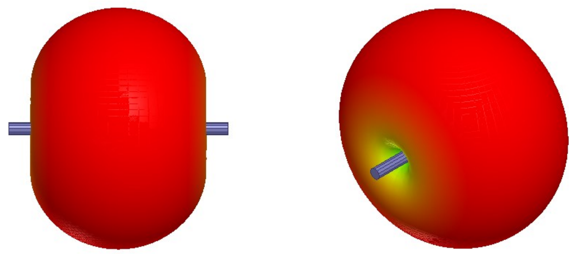
As a TV satellite horn it receives both right and left circular polarizations. A polarizer sits immediately in the throat of the horn separating the two modes into two linear modes oriented orthogonal to one another.

Let’s change direction and look at a simple dipole

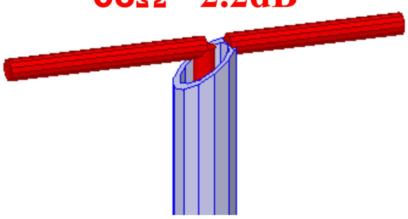
Dipoles-1

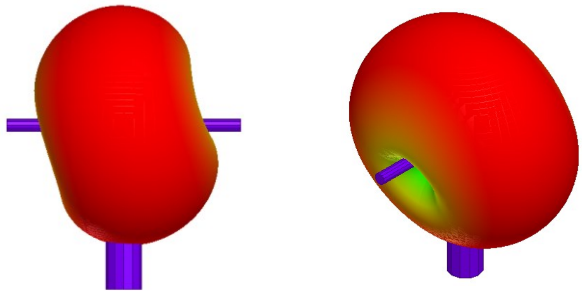
Ideal
74Ω - 2.7dB





Cable Fed
68Ω - 2.2dB





Unbalanced feed distorts the pattern and input impedance and gain

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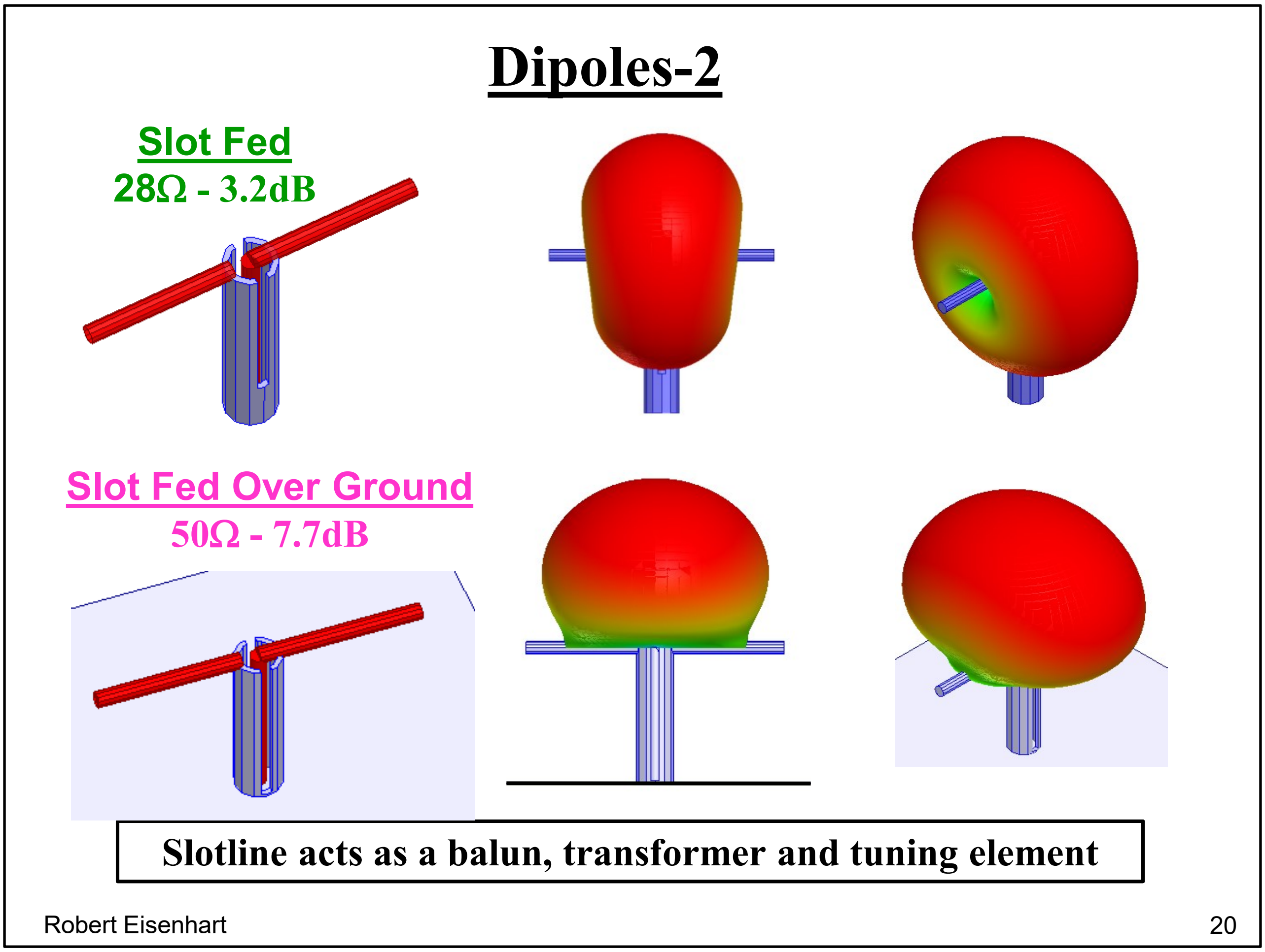
Consider the ideal dipole with a gap source. This is a balanced element which requires a balanced feed, and results in
a symmetrical pattern. The old “rabbit ears” antennas of early TVs were fed by twin lead cable which is a balanced line. However, most feed lines are unbalanced like a cable so the hardest part about a dipole is feeding it.

Next we see a Cable Fed dipole. The unbalanced feed distorts the pattern, the match and lowers the gain. Currents flow down on the outer portion of the cable jacket creating additional radiation.

This can be corrected with a Balun, a circuit configuration that converts an unbalanced line to balanced line. Consider next a Slot Fed dipole.



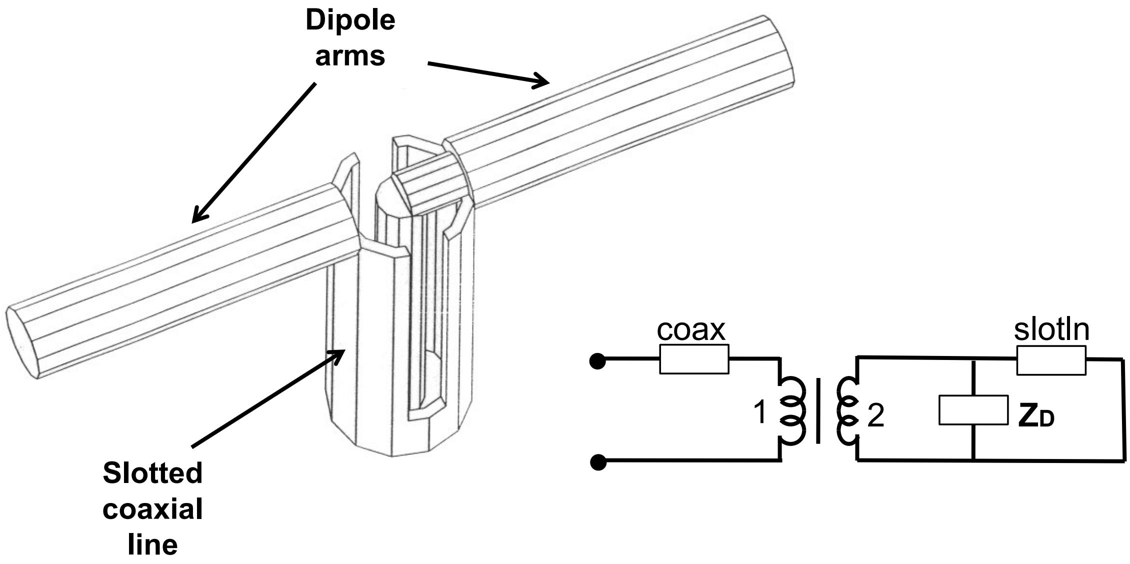
In this Slot Fed dipole the slot along the cable jacket acts as a built in choke to the unbalanced currents that want to flow on the outside of the outer conductor, and it also acts as a transformer reducing the dipole impedance by a factor of 4.

Going one step further by putting the Slot Fed Dipole over a ground plane increases the impedance and the gain.

So that . . .

Looking closer at the slot-fed dipole.

Slot – Fed Dipole



Slotline acts as a balun, transformer and tuning element

First of all it isn’t all that simple. This acts as a Balun, a circuit configuration that converts an unbalanced line to balanced line.

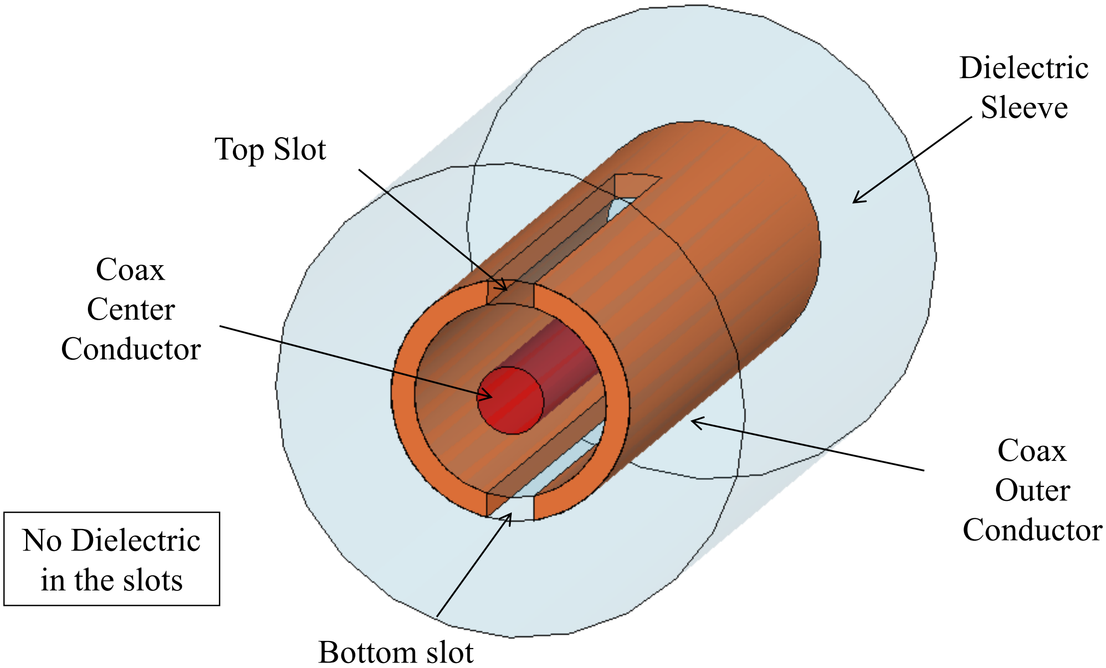
Therefore I use the coax to impedance transform back up to a reasonable value.

When the old “rabbit ears” antennas of TVs were fed by twin lead cable, the balun was inside the TV.

Looking closer at the modes in a slot-fed dipole.

Slotted Coaxial Line

File 5-Dipole

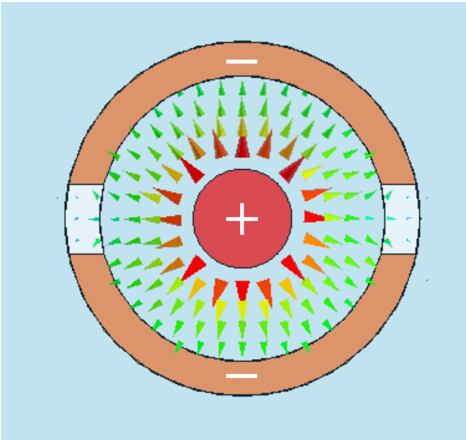
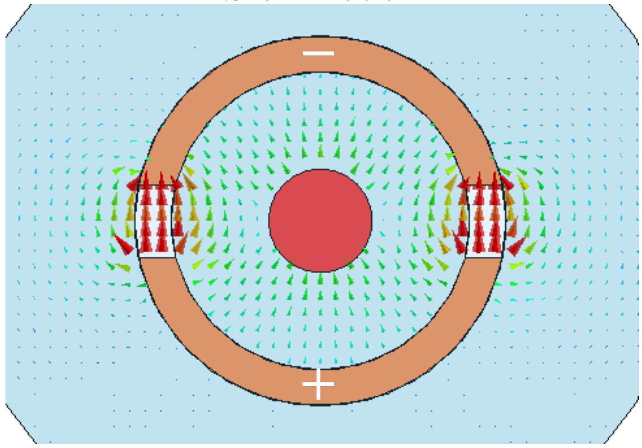


Slotline line has two independent TEM modes

Having three separate conductors will support 2 TEM modes. How do we characterize these modes?

First we have the coax mode -

Slotted Coaxial Line Characterization

Coax Mode	Slot Mode
	
Zc - 36.2 Ω	**Zc - 51.7 Ω**
er - 3.17	**er - 2.72**

No dielectric in the slot results in a lower effective er for that mode

The Coax mode ignores the slots, with the impedance set by the center diameter and the internal dielectric.

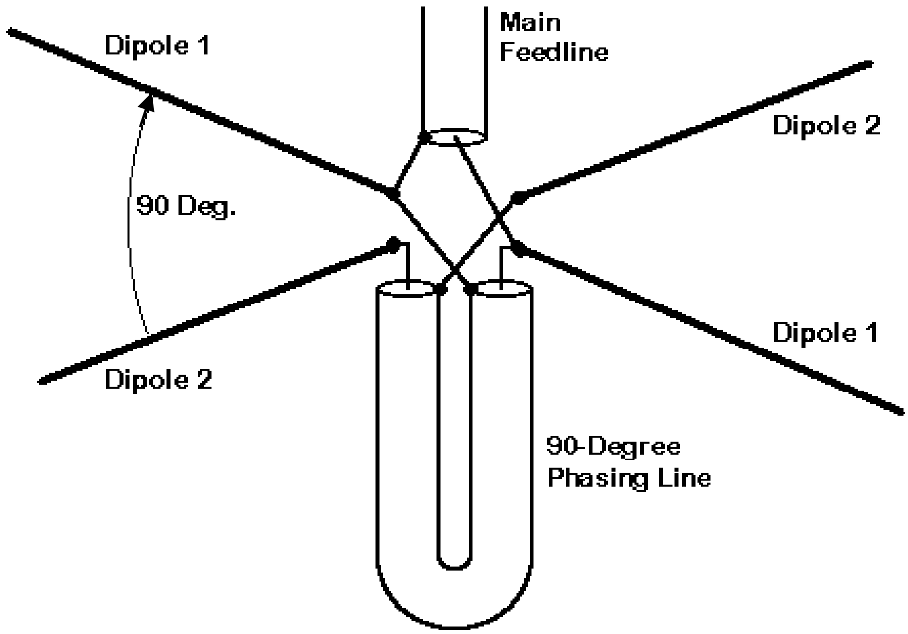
Slot mode has the impedance set by the slot size and an effective dielectric, from both the air in the slot and the dielectric around it.

Consider how you would determine the line characteristics for the Slot mode without HFSS?

The dipole is still just a dipole, the trick here is driving it with unbalanced coax line, often with some antennas, the balun is the hardest part to design.

Another interesting antenna element is the turnstile

Turnstile Schematic



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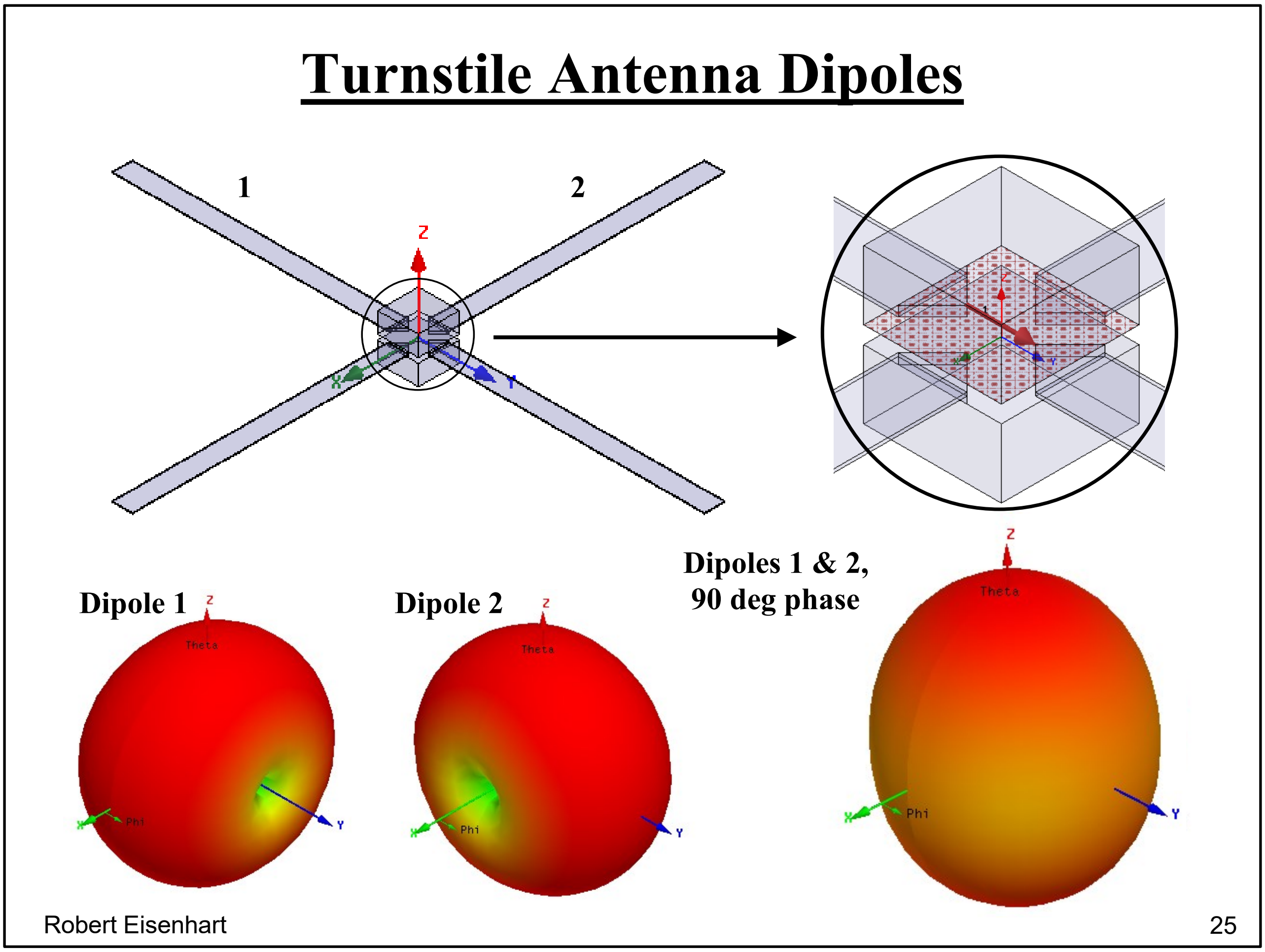
Two orthogonal and otherwise identical dipoles in the same X-Y plane with

90 deg phase difference in excitation

Consider the patterns



This is really an array, but often considered as an antenna element. You can feed the dipoles independently to get various patterns

Dipole one only

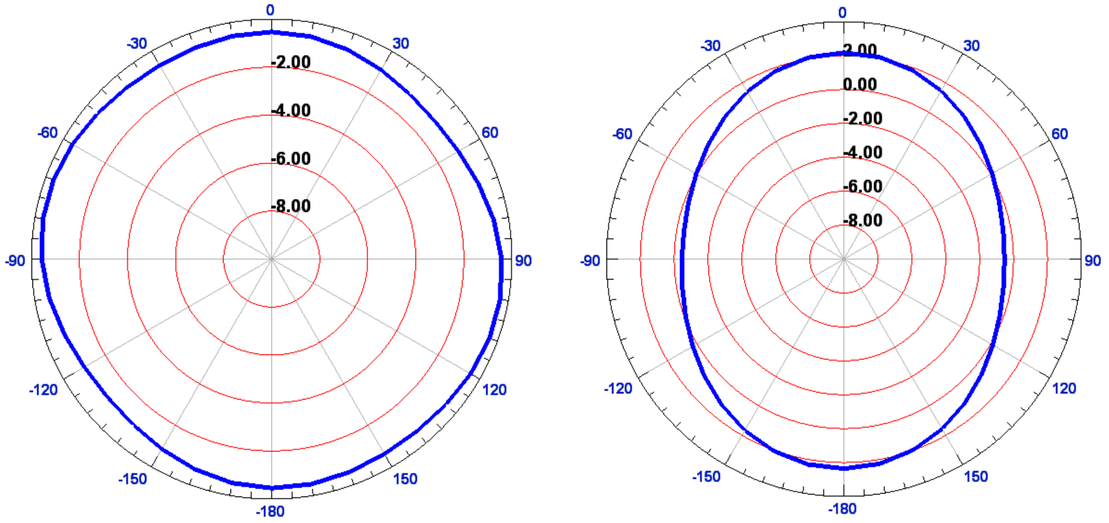
Dipole two only, or

Dipoles together, same phase, and

with the 90 deg difference

Resulting in a very nice circular pattern with horizontal polarization

Turnstile Gain (dB) Patterns



Horizontal **Vertical**

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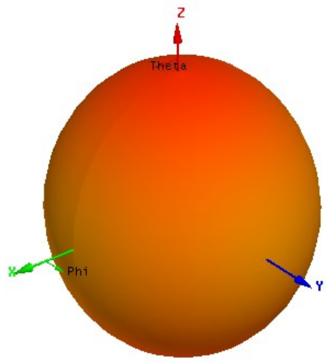
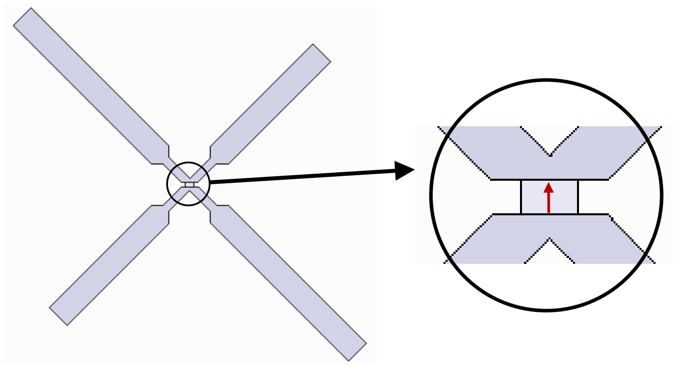
This is about as omni-directional as you're going to get. Why not just use a vertical monopole if you want an omni pattern?

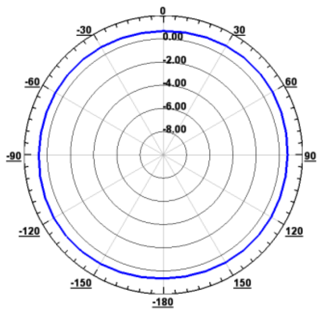
Sometimes horizontal polarization is required, plus this antenna has a good circular polarization along the Z-axis – monopole has a null.

Another similar element is the cross dipole

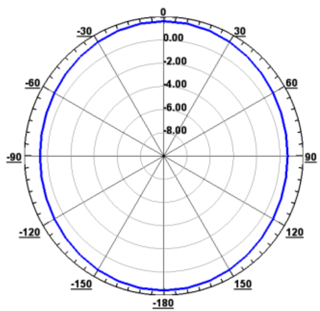
Cross Dipole Antenna



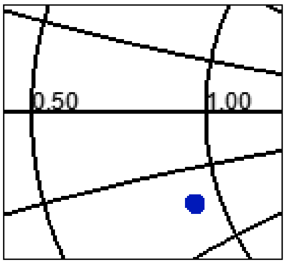




Horizontal



Vertical



Match
.18 / -108 deg

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This only requires one feed, and the 90 deg delta phase shift is created by shortening one dipole to make it capacitive and lengthening the other to be inductive.

Very nice omni pattern,

and can be well matched

You have to have a single element before you can expand to arrays.

Science aims to understand the origins, nature, and behavior of the universe.

Engineering aims to use that knowledge to enhance our quality of life.

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Clarifying the differences in the disciplines.