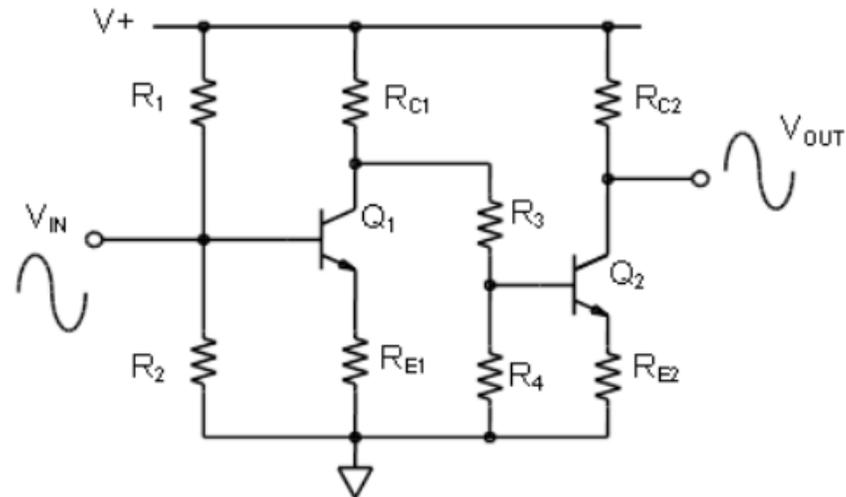
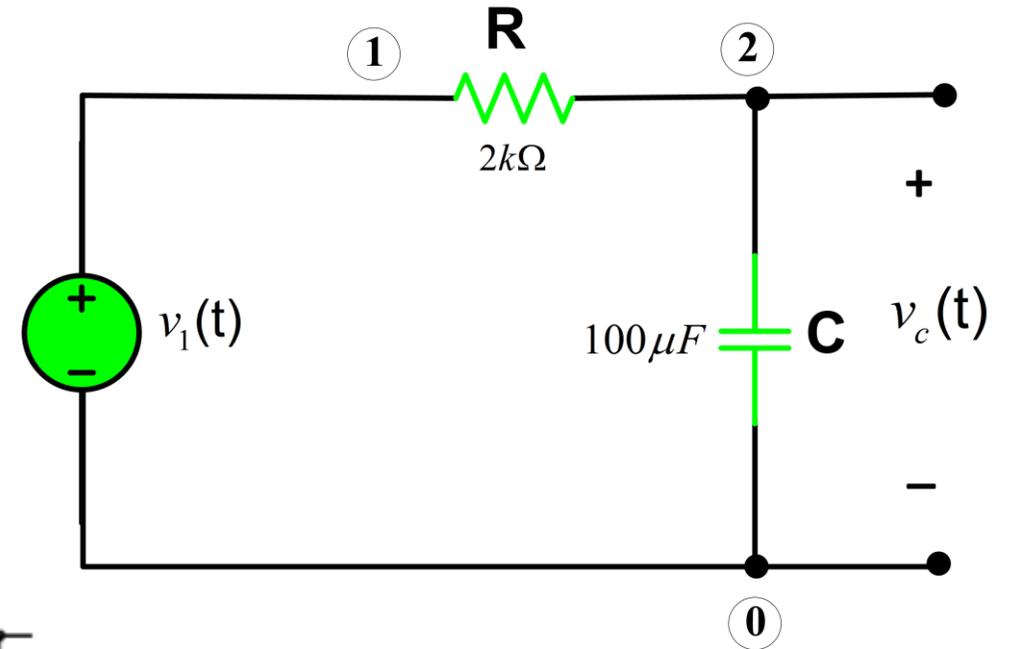
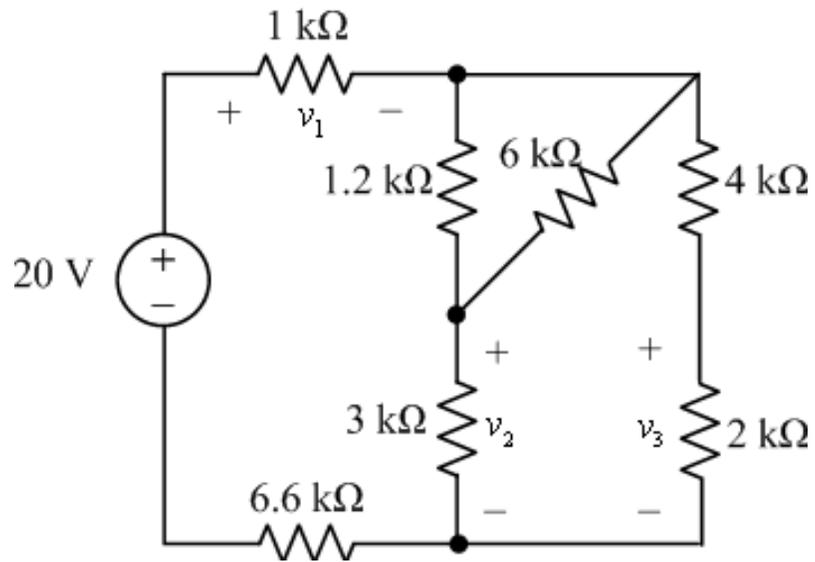




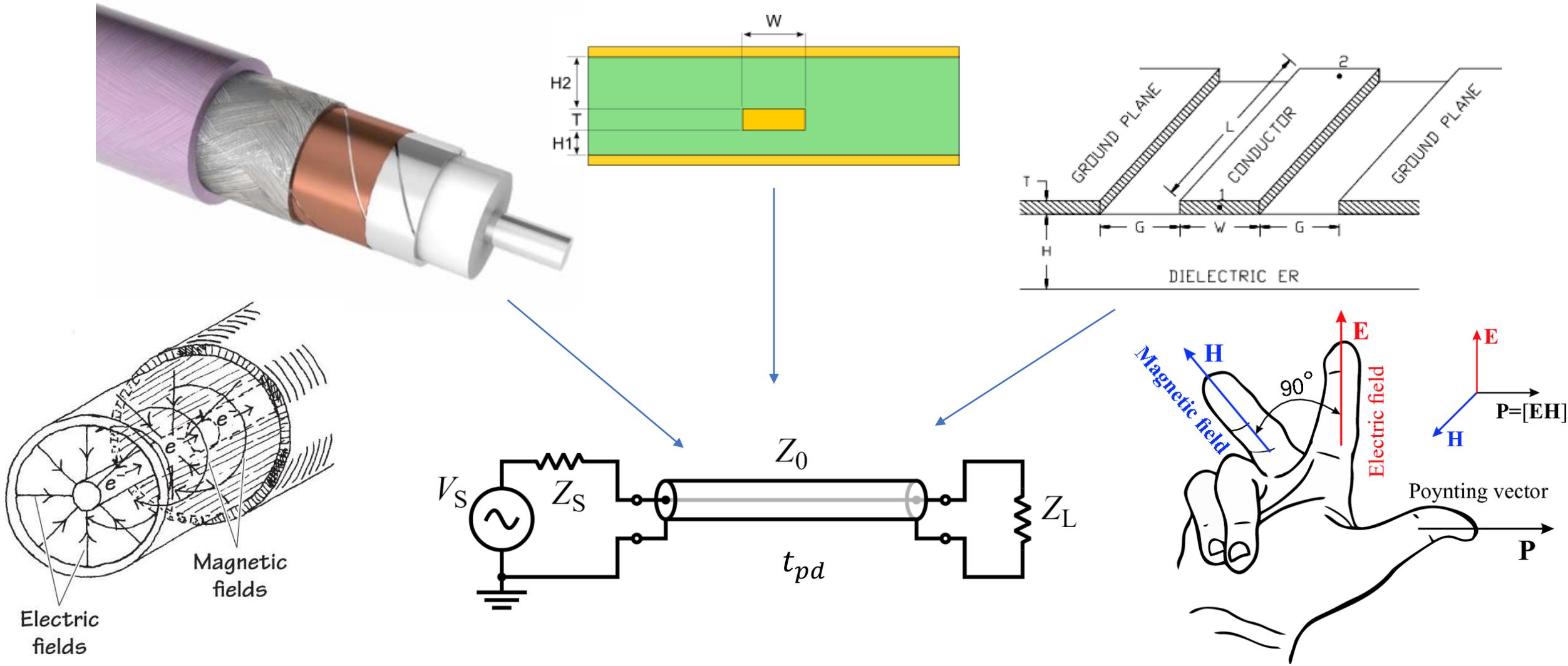
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Waveguides, Modes, and Cutoff Frequencies | Presenter: Kelly Garrison

Electrostatics in the time domain



The Exclusivity of TEM



Transmission Lines without Signal Conductors



Introduction

- Waveguide Basics
- Waveguides where you don't want them (we're mostly Signal Integrity Engineers here)
- Waveguides where you **do** want them

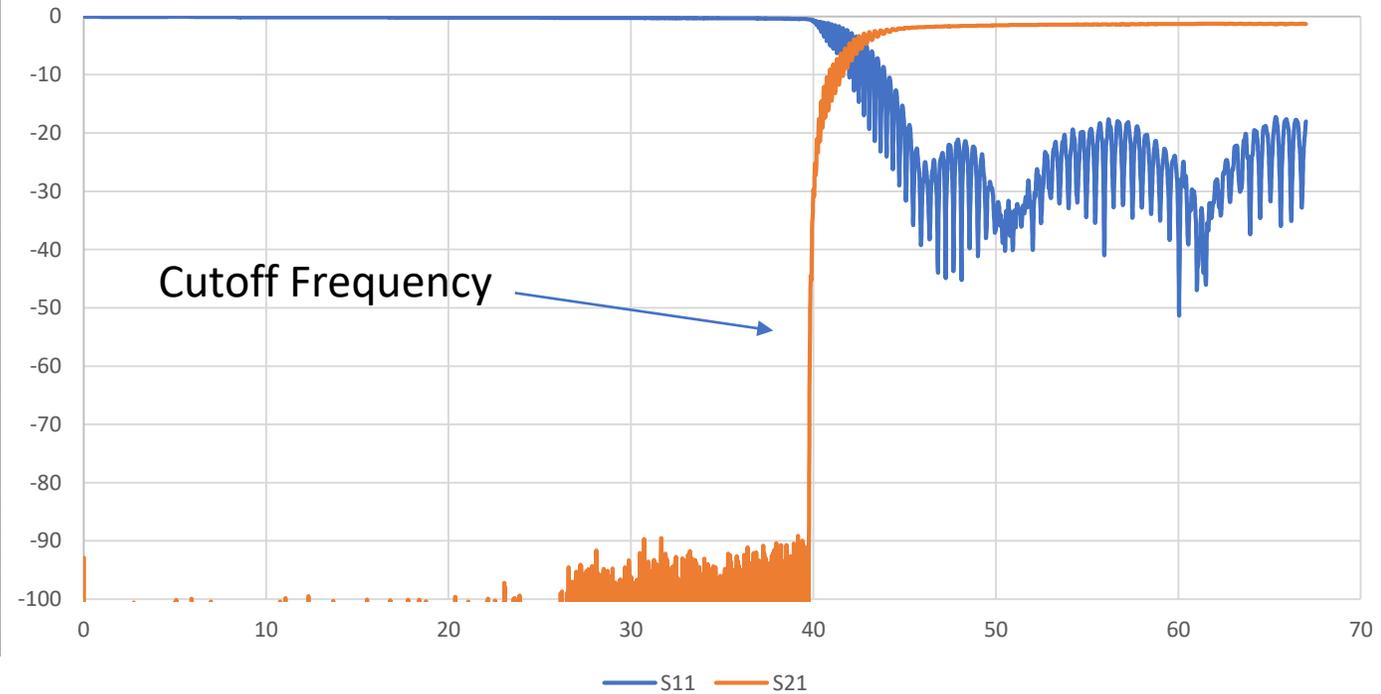
samtec

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The Concept of Cutoff Frequency

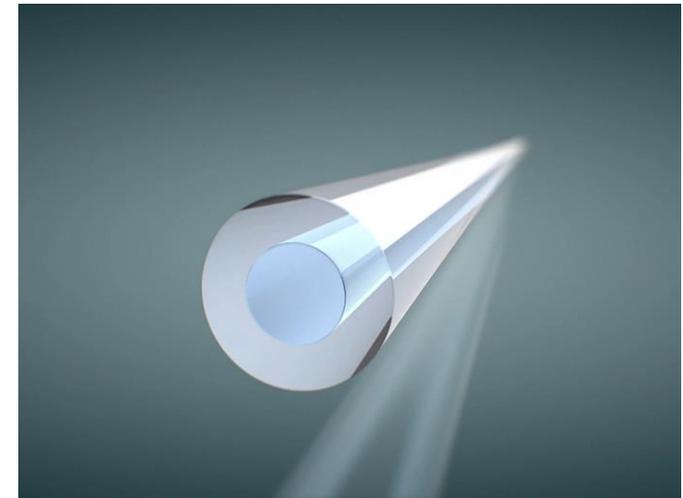


WR15 Cutoff Frequency Example

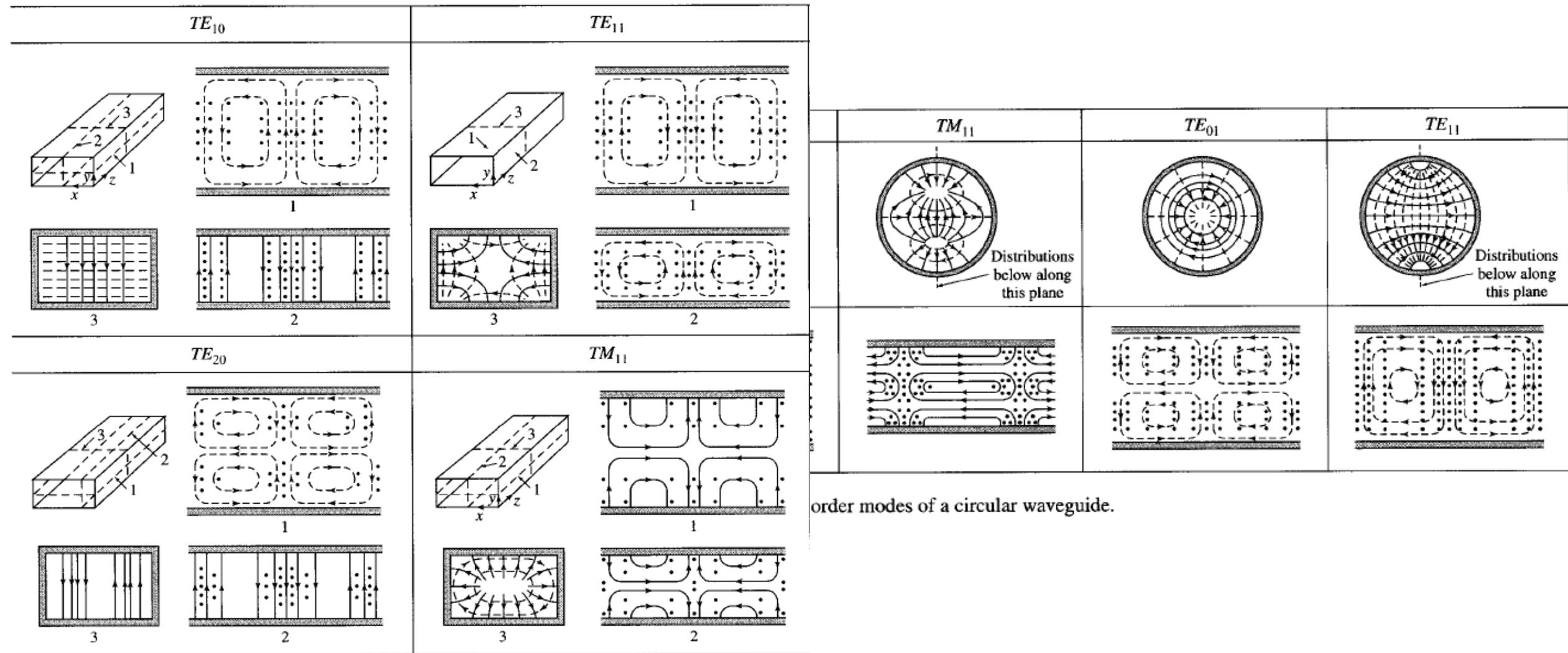


Tubes, Structures, Boxes

- Any structure will support SOME KIND of waveguide propagation or resonance at SOME frequency



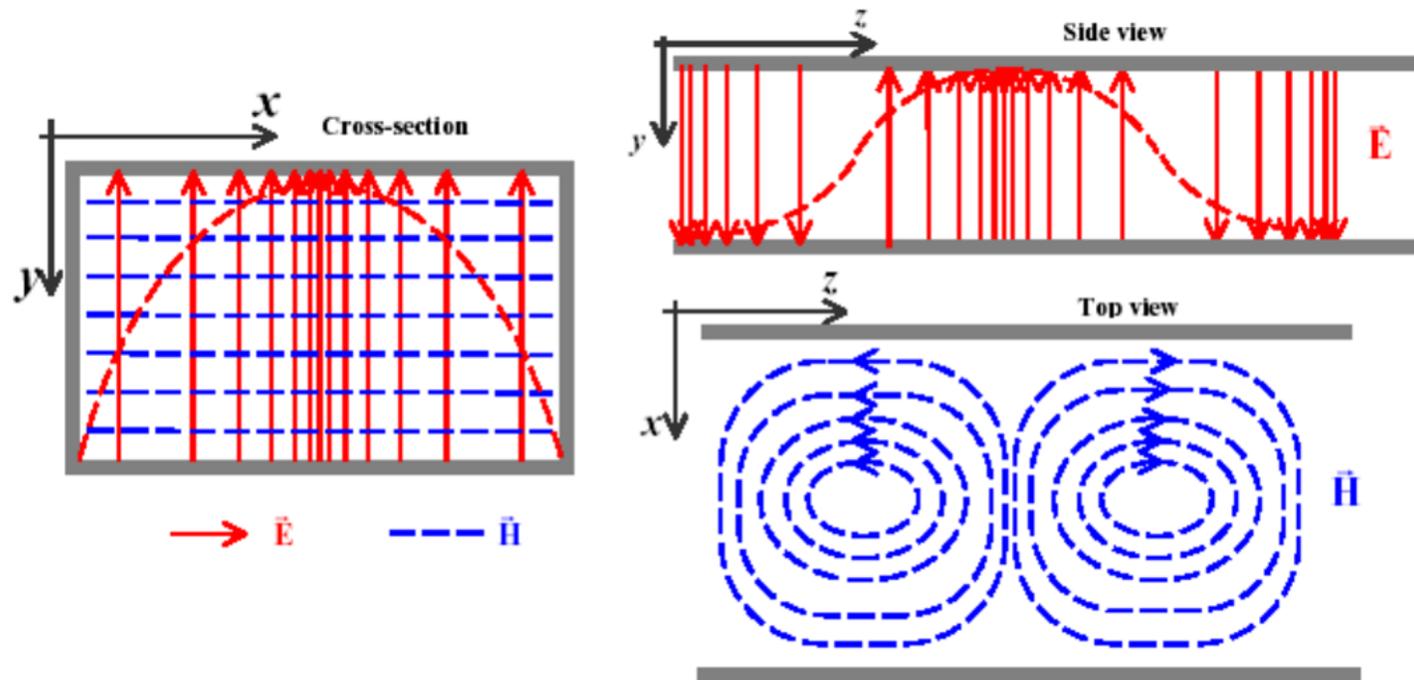
Modes



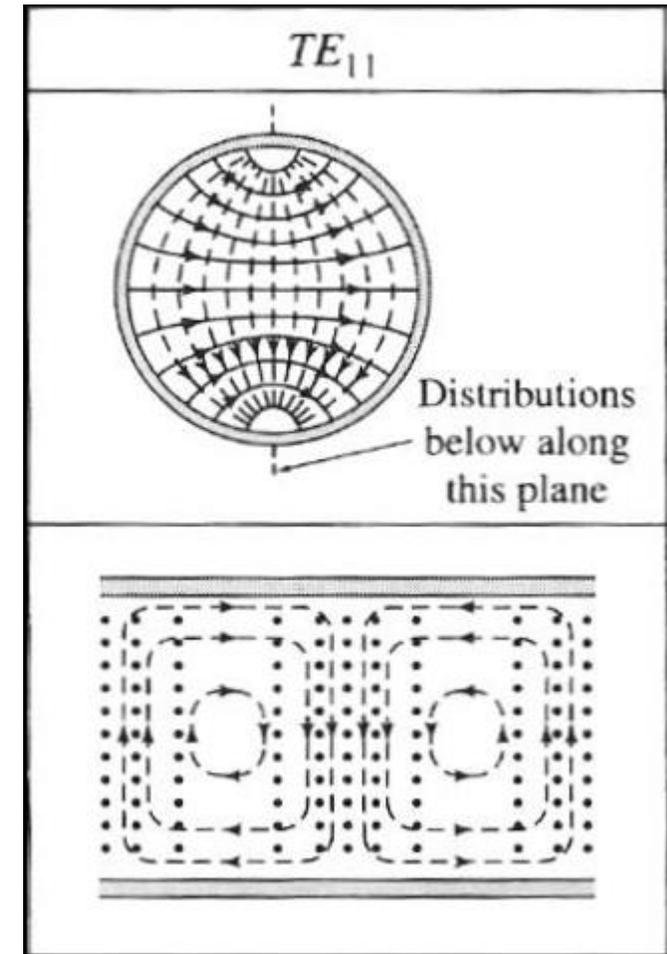
order modes of a circular waveguide.

FIGURE 3.9 Field lines for some of the lower order modes of a rectangular waveguide.

Modes - Continued

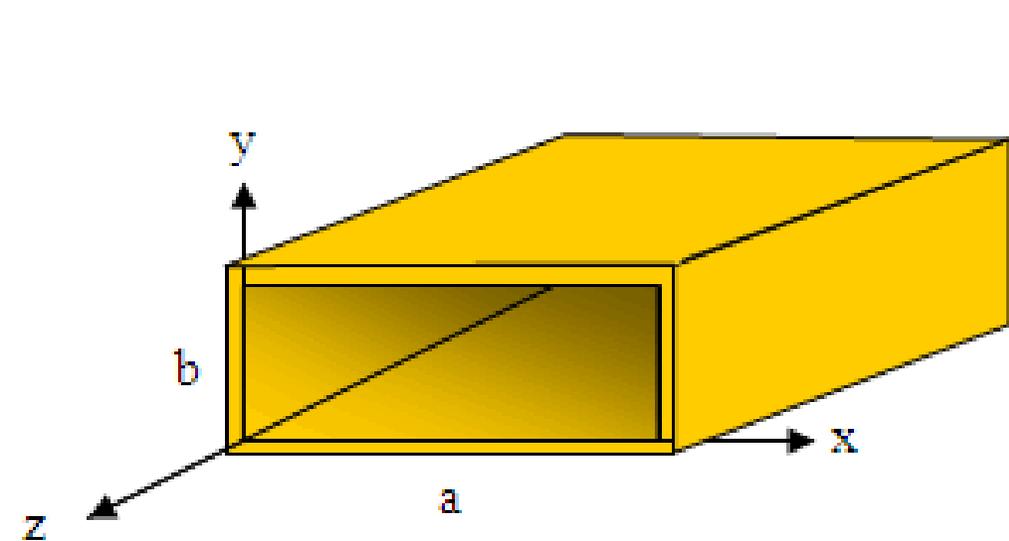


TE₁₀ mode in rectangular waveguide cross-section



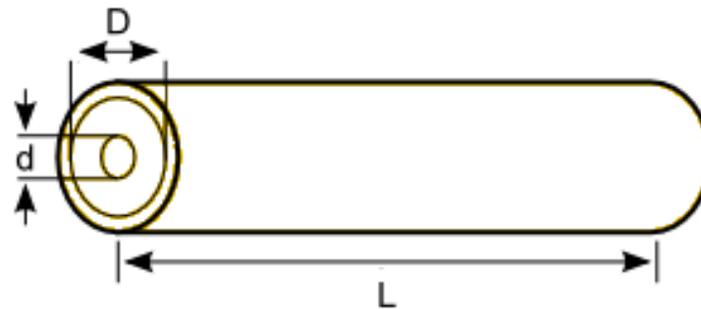
TE₁₁ in circular waveguide cross-section

Modes – Continued

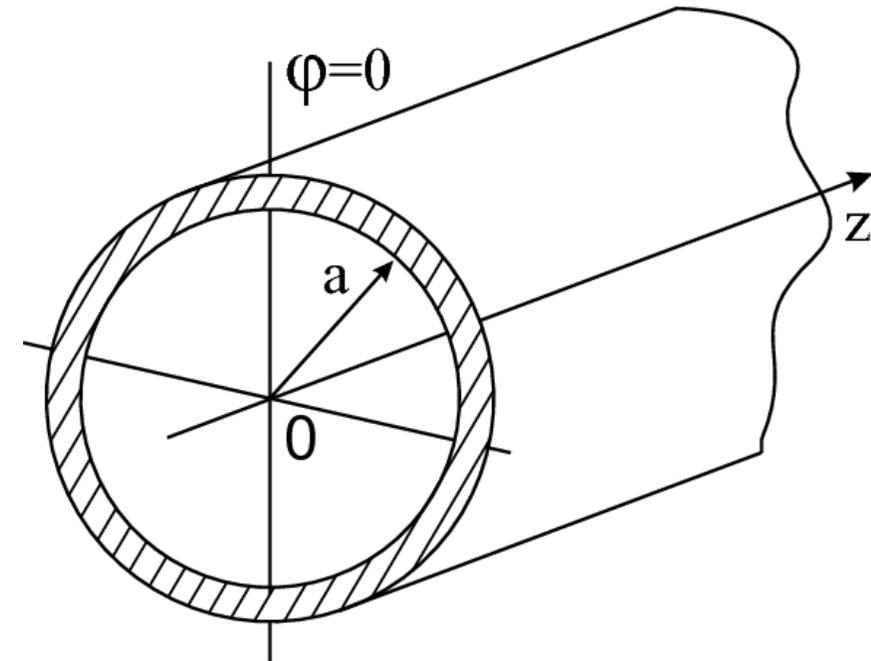


$$a = \frac{\lambda_{cutoff}}{2} = \frac{c}{2f_{cutoff}\sqrt{\epsilon_r}}$$

$$f_{cutoff} = \frac{c}{2a\sqrt{\epsilon_r}}$$



$$f_{cutoff} = \frac{c}{\pi \left(\frac{D+d}{2} \right) \sqrt{\epsilon_r}}$$

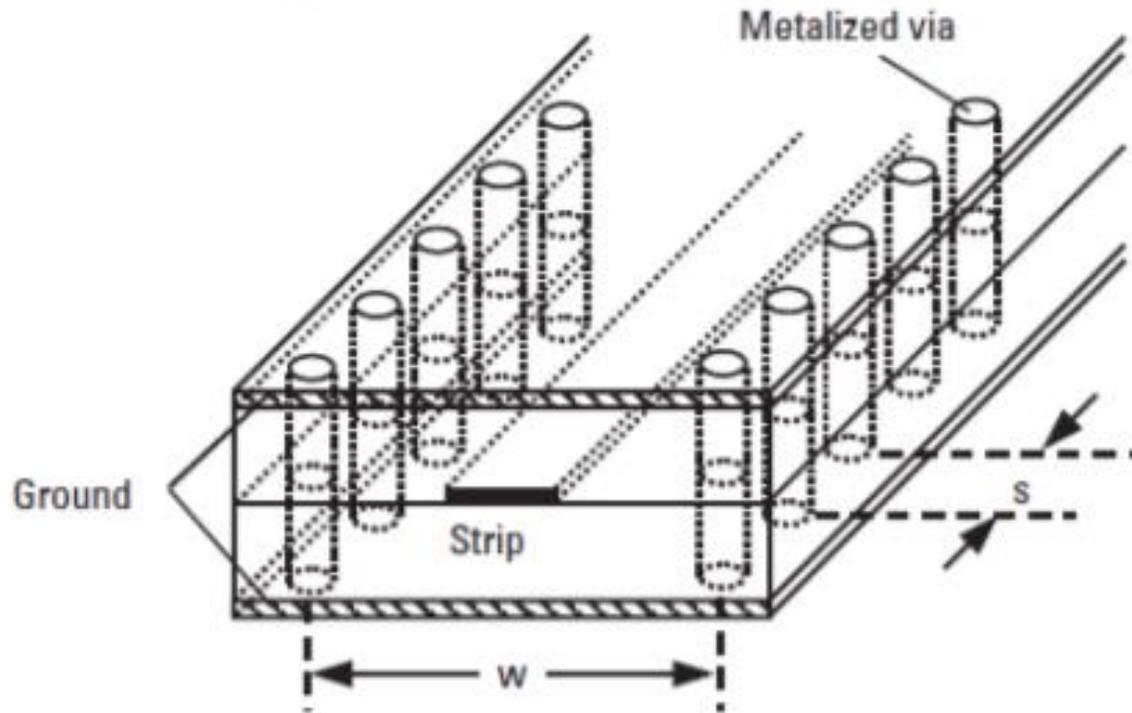


$$f_{cutoff} = \frac{1.841c}{2\pi a\sqrt{\epsilon_r}}$$

As modes in an otherwise TEM Board Design

- **So what does it mean when something is “moding”?**
 - An unwanted waveguide (non-TEM) mode has appeared because you’ve gone past F_{cutoff}
- **How does it show up?**
 - If the waveguide is a cavity or otherwise reflective, the reflected signals will return from whence they came and interfere as they convert back to TEM mode from waveguide
 - If it’s not reflected, the parasitic waveguide will cause either additional loss (as signal radiates away) or it could rejoin the main signal path at some later point and interfere with the desired signal
- **How do we avoid it?**
 - Watch your ground vias!

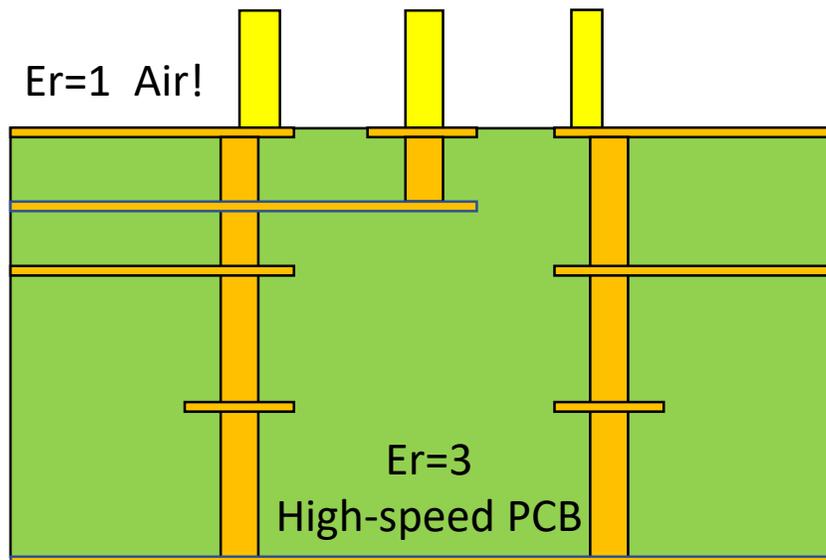
In Stripline with Stitching Vias



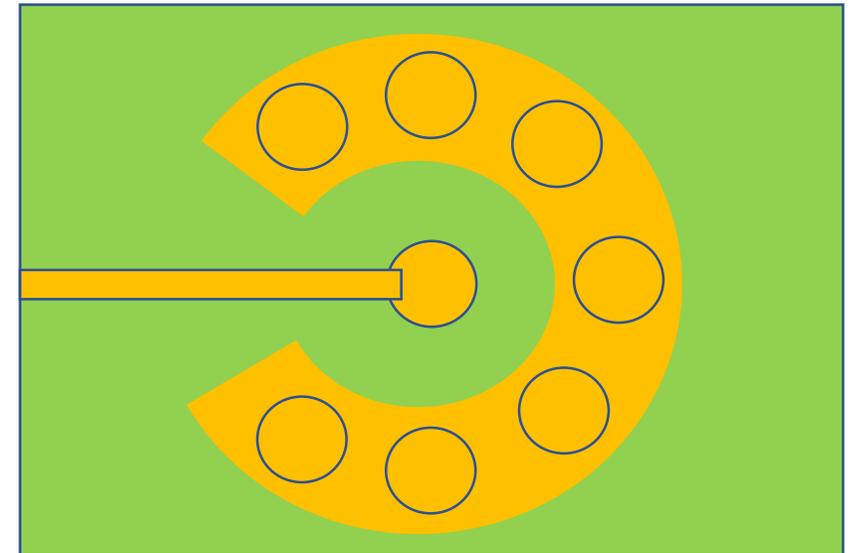
- Stripline presents a similar case to circular waveguide with a center conductor (ie, coax above cutoff)
- 2 weeks ago, Gus Blando showed that the distance “s” needed to be smaller than $\frac{1}{2}$ of a wavelength to avoid resonances
- For complex launches and transitions, you may need to tighten your stitching vias “w” dimension to less than $\frac{1}{2}$ of a wavelength to avoid potential parasitic waveguide modes
- In other cases, they can be pulled away from your trace without consequence

Vertical Launches

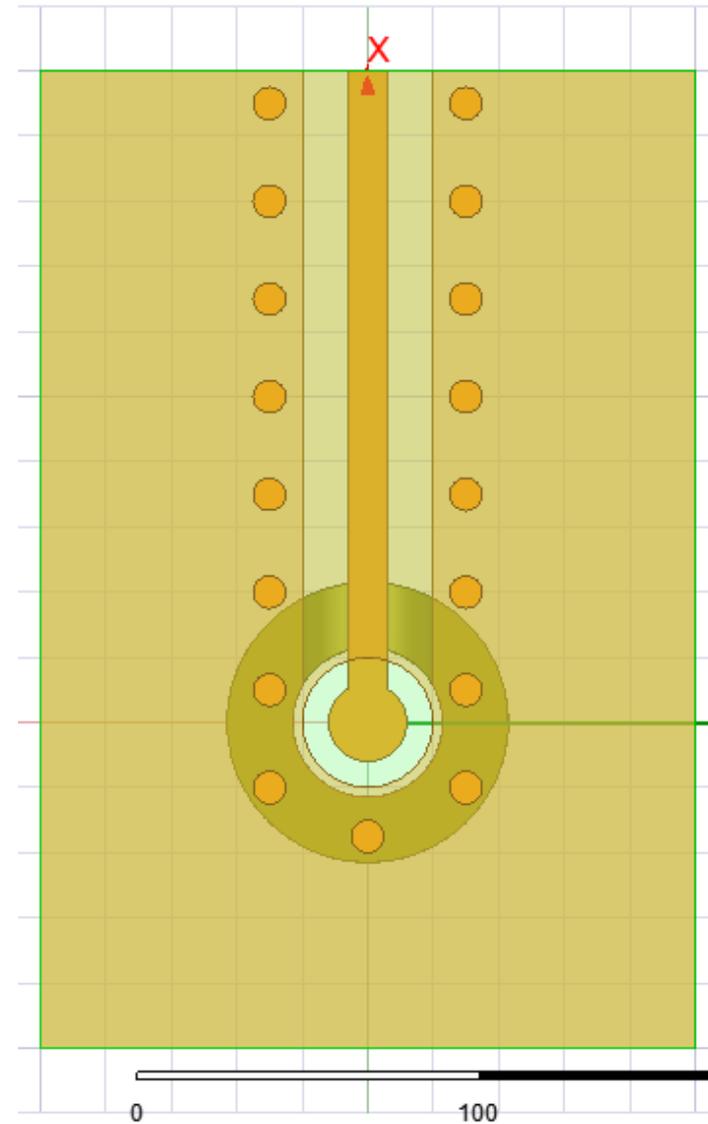
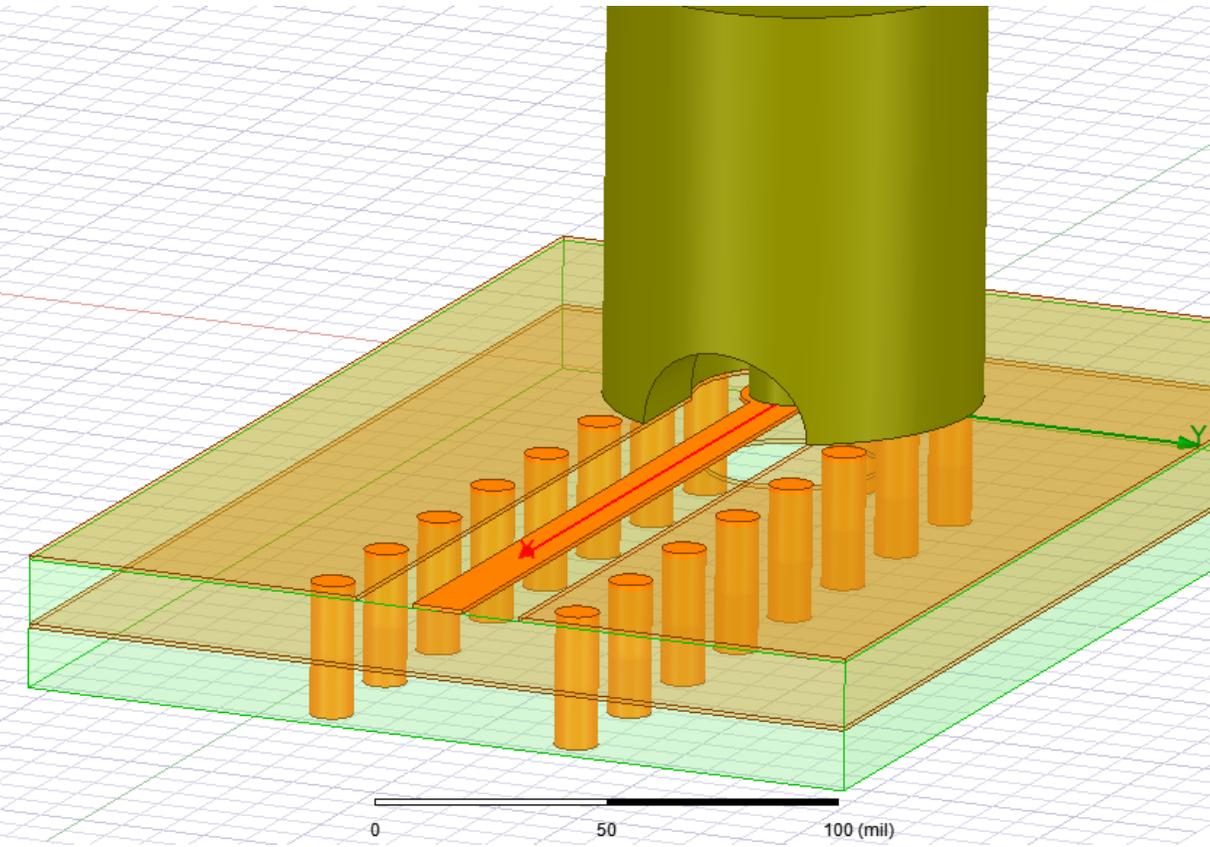
- This could be the cross-section of any kind of vertical launch
 - Coax
 - GSG pins
- Often it's desirable to manage the step transition by keeping the ground continuous
 - "D" on coax, pitch on GSG
- The connector designer has an interest in making "D" large, to maximize "d" and reduce loss, make it easier to build, etc
- However, for a coax design, if you're near cutoff in air, the frequency will drop by 1/sqrt(3) (42%!) once the signal hits the board dielectric



$$f_c \propto \frac{1}{\sqrt{\epsilon_r}}$$

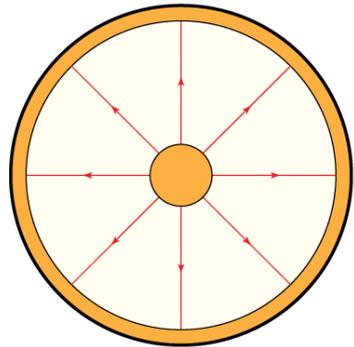


Under Microstrip/CPW



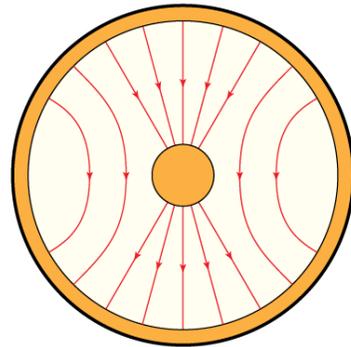
In coax cables and connectors above cutoff frequency

**SPEED
LIMIT
40
GHz**



(a)

Desired mode



(b)

Undesired mode

Connector	"D"	"d"	Fcutoff (GHz)
2.92mm	0.00292	0.0012	46.17
2.4mm	0.0024	0.001	56.17
1.85mm	0.00185	0.00077	72.87
1mm	0.001	0.00042	134.81

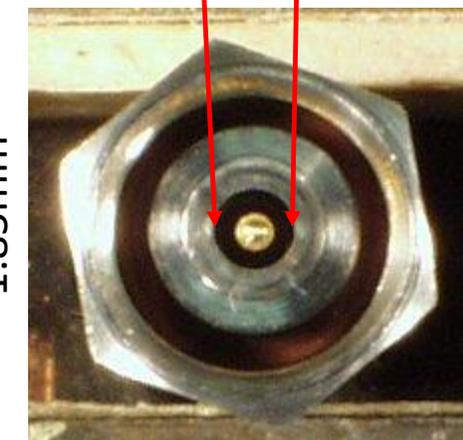
2.92mm



2.4mm



1.85mm

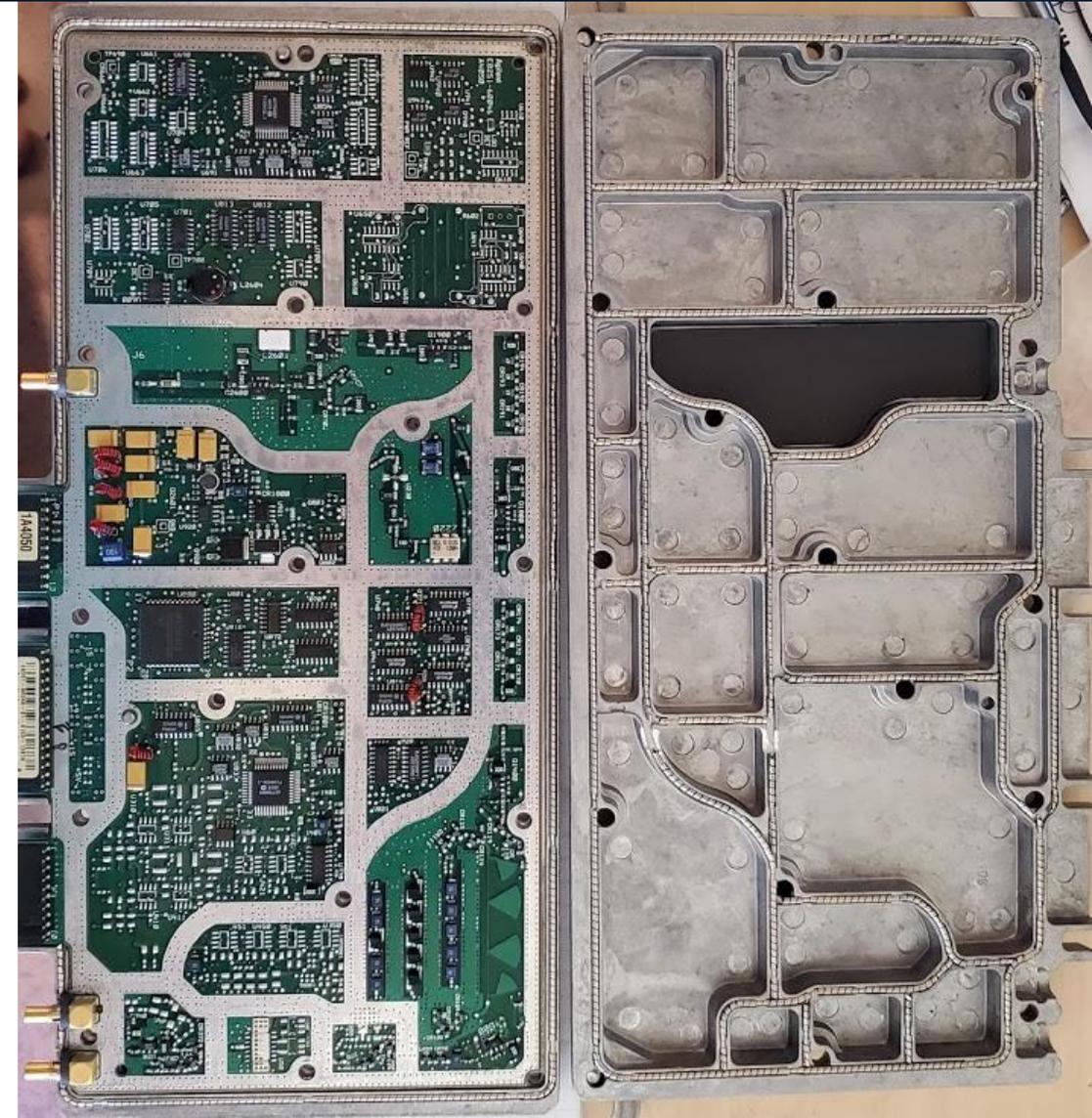
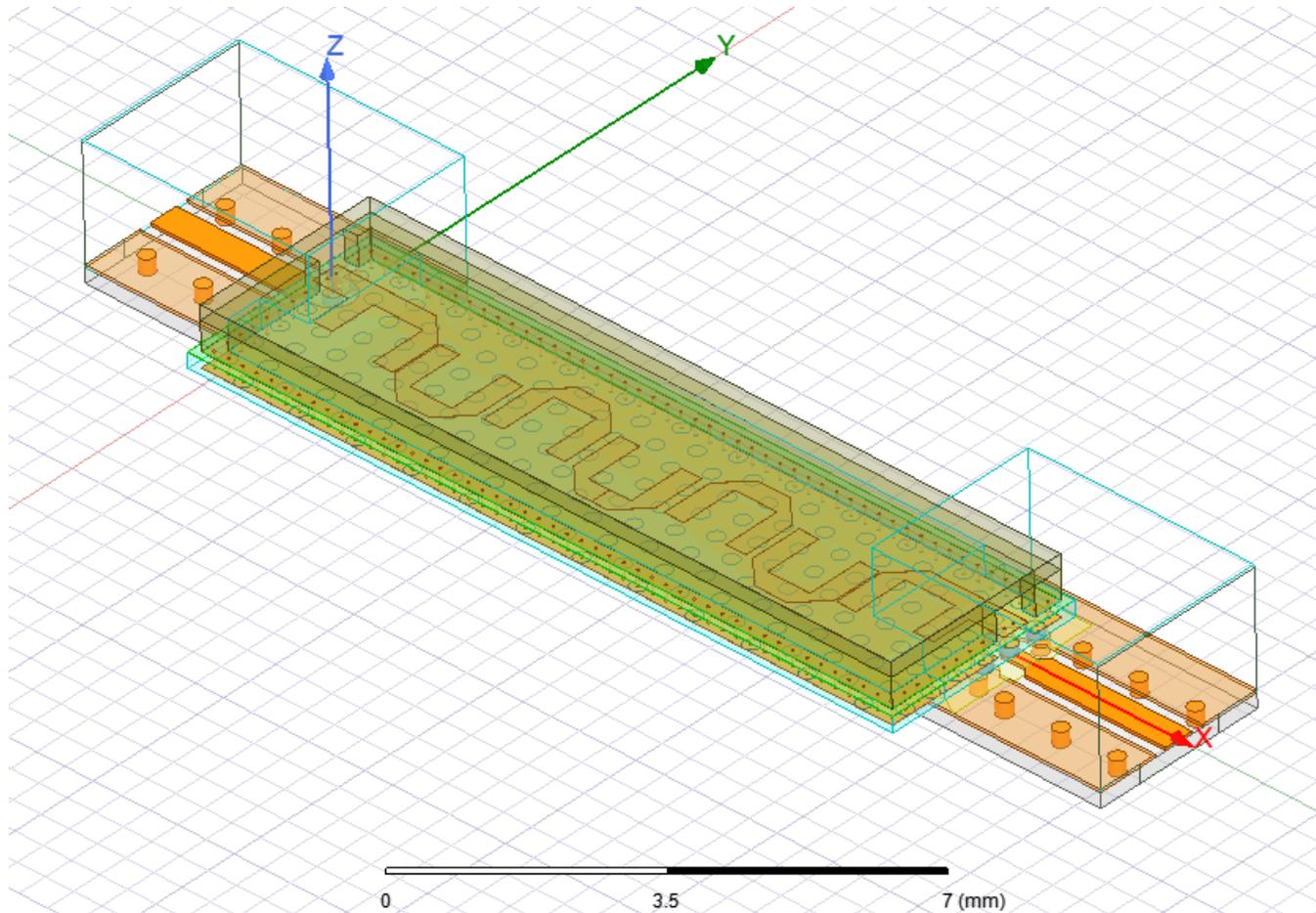


**SPEED
LIMIT
67
GHz**

“Moding” is the reason why 2.92mm RF connectors are good to 40GHz, 2.4mm connectors to 50GHz, and 1.85mm connectors to 67GHz.

Moding sets physical size limitation on coax cable. The dominant loss mechanism on coax cable is the diameter of the center conductor. But if you make it larger, the outer diameter grows too, and cutoff frequency drops. This is a reason why cable Manufacturers are producing foamed dielectrics: it reduces “D” for a given larger “d”.

In packages and under shields



- By default, HFSS models the universe as an infinite block of PEC metal, into which you add your model and ports that insert and extract energy
- As long as you're aware that the walls are solid metal, you can avoid the common sort of waveguide problems by keeping your airbox small
- Radiation and absorbing boundaries should always be used at some point to make sure you don't have a radiation problem in your circuit
 - You will have to grow the airbox to do this properly, since the absorbing boundary is only perfectly matched to fields that are normal to the boundary.
 - Tangential fields are not as well matched and can scatter
- Remember that your ports are openings in the PEC metal, so therefore the walls of your port are PEC and need to be sized appropriately to the transmission line you're launching onto
 - Too big and you'll get moding
 - Too small and you'll couple your transmission line to ground
- Also, remember that when you draw a model, it's "perfect". Lines are centered, vias are in the right place, etc. Perfection suppresses TEM to waveguide conversion. Waveguide modes feed on asymmetries, so think about adding a couple of dozen microns of offset where you can and resimulating

The rule of resonators in waveguide

- There's an equation that describes the frequency of what we call a "cavity resonator"
- This is a waveguide "box" that is excited by some means, by some coupling of power into the box
- And if you know the dimensions and material properties of the box, you can find the lowest frequency resonance, which is often the most troublesome for the kind of work that we do
- So to cut to the chase, I'm just going to insert a paragraph from "Microwave Engineering" by Pozar and try to give it a different spin

Resonators in Waveguide - Continued

which implies that the cavity must be an integer multiple of a half-guide wavelength long at the resonant frequency. No nontrivial solutions are possible for other lengths, or for frequencies other than the resonant frequencies. The rectangular cavity is thus a waveguide version of the short-circuited $\lambda/2$ transmission line resonator.

A resonant wavenumber for the rectangular cavity can be defined as

$$k_{mnl} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{\ell\pi}{d}\right)^2}. \quad (6.39)$$

Then we can refer to the TE_{mnl} or TM_{mnl} resonant mode of the cavity, where the indices m, n, ℓ refer to the number of variations in the standing wave pattern in the x, y, z directions, respectively. The resonant frequency of the TE_{mnl} or TM_{mnl} mode is then given by

$$f_{mnl} = \frac{ck_{mnl}}{2\pi\sqrt{\mu_r\epsilon_r}} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{\ell\pi}{d}\right)^2}. \quad (6.40)$$

If $b < a < d$, the dominant resonant mode (lowest resonant frequency) will be the TE_{101} mode, corresponding to the TE_{10} dominant waveguide mode in a shorted guide of length $\lambda_g/2$. The dominant TM mode is the TM_{110} mode.

Resonators in Waveguide - Continued

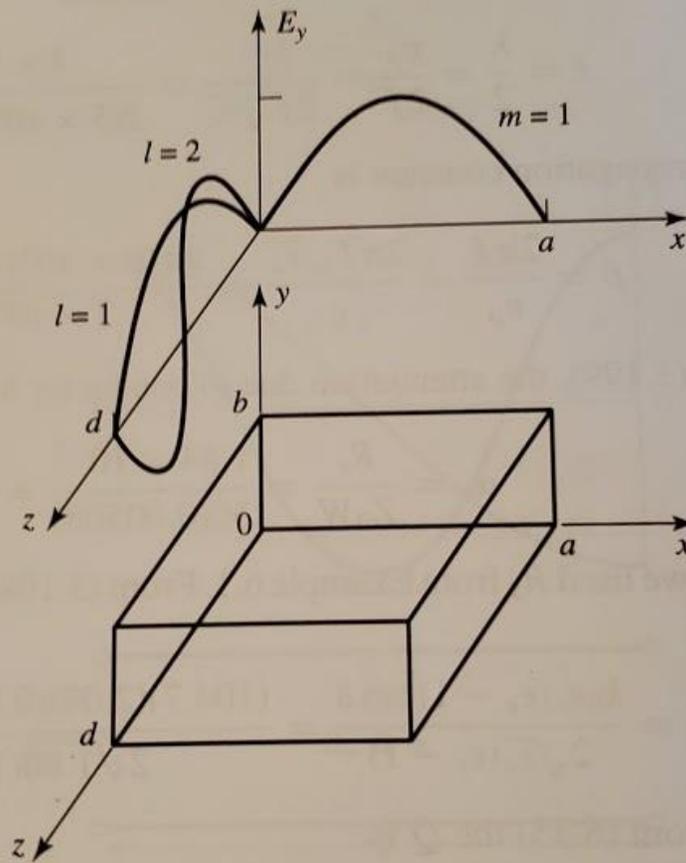
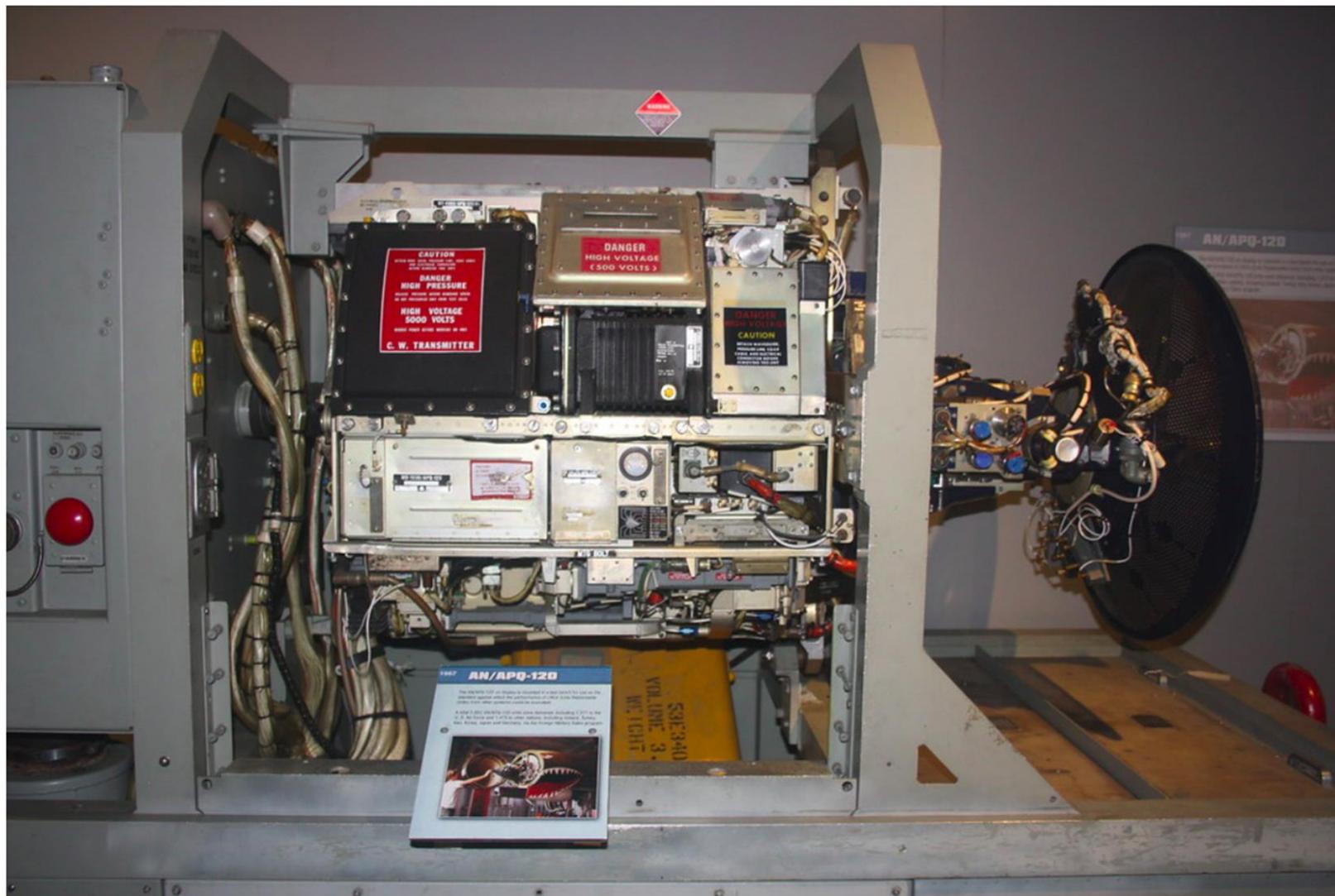


FIGURE 6.6 A rectangular resonant cavity, and the electric field distributions for the TE_{101} and TE_{102} resonant modes.

Why does anyone use waveguide?

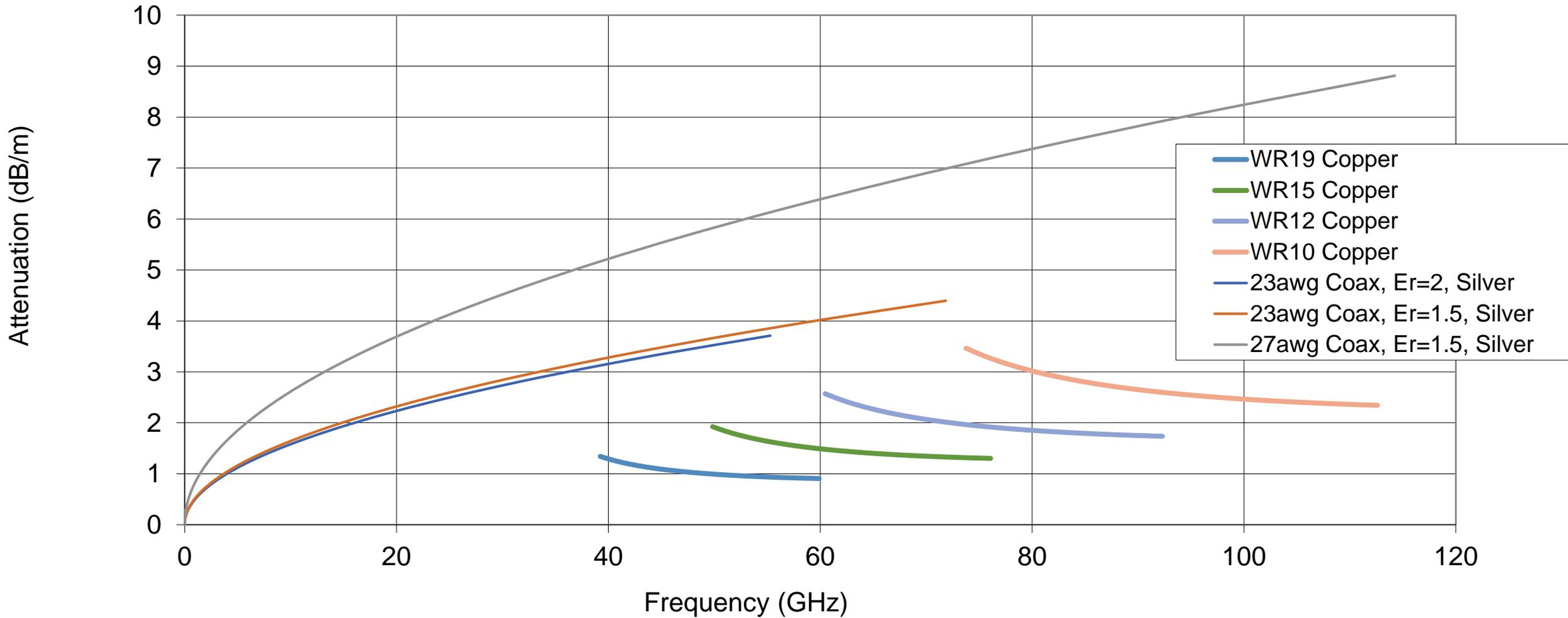
- It's narrow-band, less than an octave
- It's fiddly, especially for small, high frequency waveguide, and the tiny screws will drive you mad
- It's relatively hard to launch into. PCB to waveguide launches are not trivial.
- Waveguide is very dispersive, especially near cutoff
- It's not flexible. There's a reason that the hose in your backyard is not just 50ft of copper pipe like in your walls
- It's expensive. This is all gold plated precision machined hardware.

High Power



Low Loss

Standard Air-Filled Rectangular Waveguide losses vs Ideal Coax



Antennas



Is this the future for waveguide?



- This phased array radar might have 1000 10W transceivers with a built-in antenna rather than a single large power amplifier requiring waveguide
- Or are 5G and automotive radar going to require waveguide infrastructure?

Summary

- **So we covered**
 - Awareness of potential waveguide issues in PCBs
 - Some explanation about “moding” and what it means for coaxial cables and connectors
 - Having to add potential waveguides to prevent radiation in the form of shields and lids and how to think about designing them so that they won’t resonate
- **What I hope you take away from this:**
 - Your designs may have waveguide structures in them. Identify them and mitigate!
 - Could there be an opportunity for you to use waveguide in a positive way in a future design?



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