RF Transmission Lines

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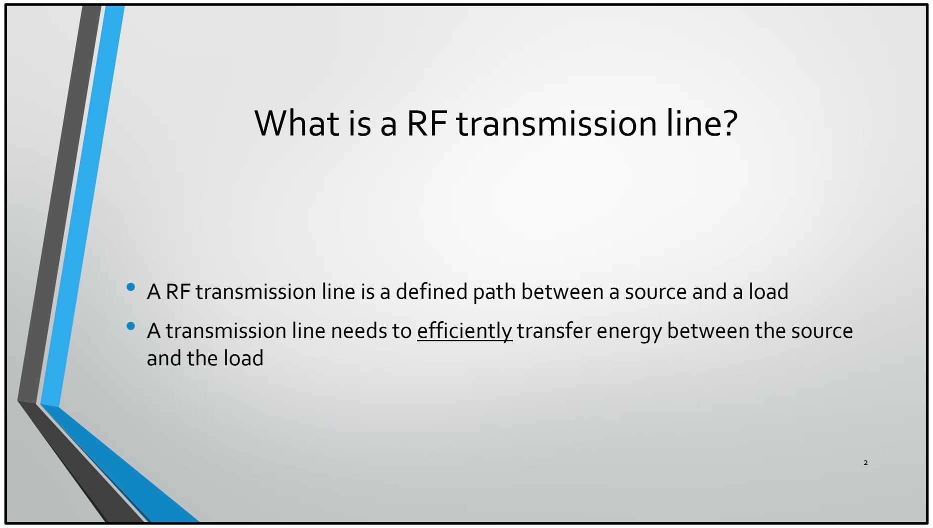

Transmission lines efficiently transfer energy by CONTAINING the energy INSIDE the line. Transmission lines PREVENT energy from being radiated or lost as heat.

Even this is a transmission line…

- A type of transmission line called a cage line, used for high power, low frequency applications. It functions similarly to a large coaxial cable.
- This example is the antenna feed line for a longwave radio transmitter in Poland, which operates at a frequency of 225 kHz and a power of 1200 kW.

https://en.wikipedia.org/wiki/Transmission_line#/media/File:Solec_Kujawski_longwave_antenna_feeder.jpg

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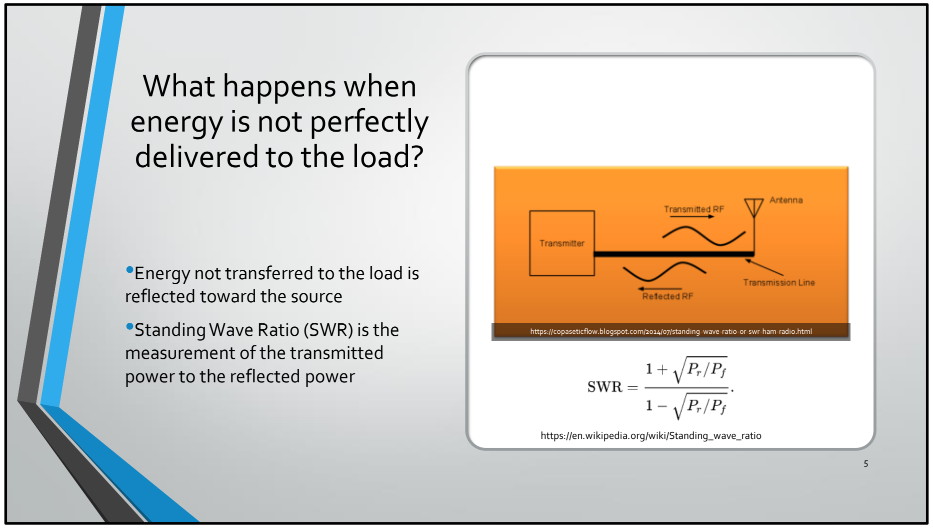
This is a coaxial transmission line. The central “bundle” of wires forms the center conductor. The outer wires form the outer conductor.

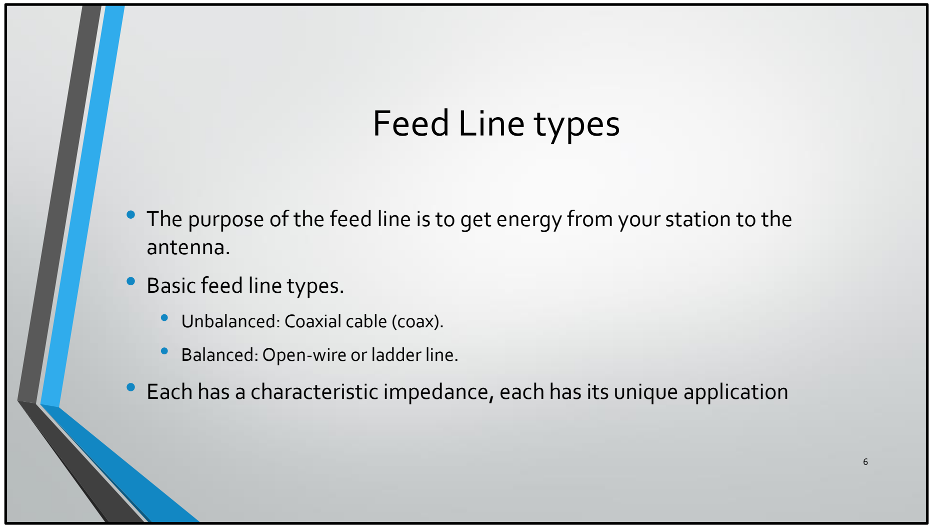
Antenna, Transmission Line and Feed Line

- Feed line is just another name for a transmission line
- For efficient transfer of energy from the transmitter to the feed line and from the feed line to the antenna, the various impedances need to match.
- When there is mismatch of impedances, things may still work, but not as effectively as they could.

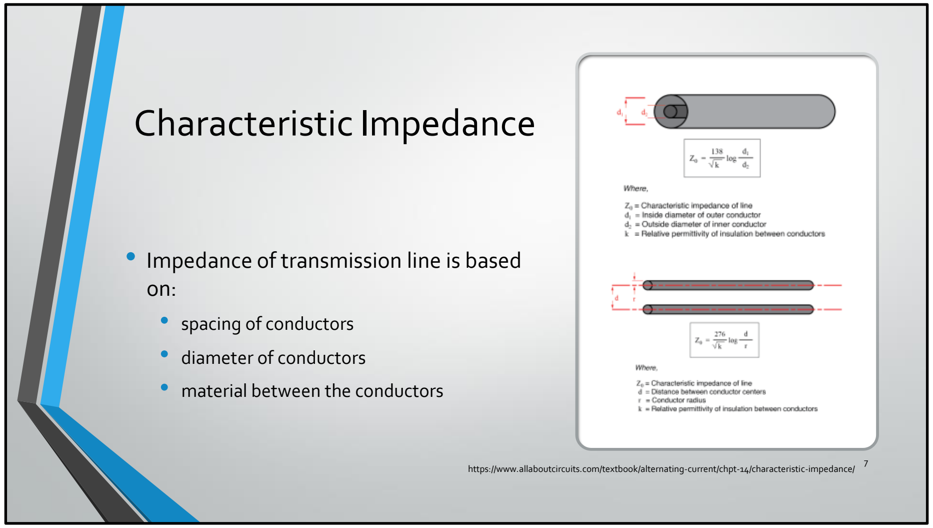
The key to efficient power transfer requires that the source, the load and the transmission line all have the same impedance. Impedance mismatches cause power to be reflected from the load back to the source.



An impedance mismatch occurs when the antenna impedance is different than the transmission line impedance. The power that is not absorbed by the antenna (either radiated as electromagnetic waves or dissipated as heat) is reflected along the transmission line toward the source. At certain distances along the transmission line (at half-wavelength increments) “hotspots” form where the peak of the transmitted power “lines up” with the peak of the reflected power. You can think of this as ripples in a pond hitting a barrier, causing ripples to propagate back toward the source. At certain locations, these two waves cross, causing peaks in the ripple heights. In a transmission line, these hotspots cause heating at that location which can lead to cable breakdown. As the standing wave ratio (SWR) formula shows, this behavior is related to the reflected power and the forward (transmitted) power.

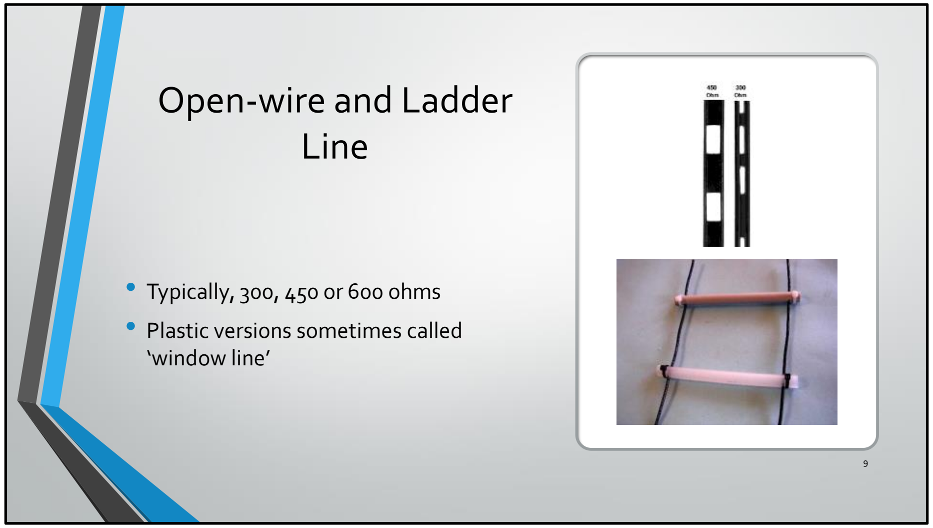


Characteristic impedance of a transmission line is based on the physical construction parameters such as conductor diameter, conductor spacing, and the dielectric material between the conductors. A coaxial cable is considered an ‘unbalanced’ line because the two conductors are not identical in size and thickness. A balanced transmission line has identical conductors.



In the above formulas, the variable k is the dielectric constant of the insulating material. Many textbooks will use the variable epsilon (ε_r) instead of k, but the meaning is the same. The value for ε_r is 1.0 for air. For polyethylene (used in coaxial cable like RG-8X), the value is 2.25.

The dielectric material is an insulator (typically a plastic) that controls the separation between the inner and outer conductors. The outer braid is woven over the dielectric. A cable jacket protects the entire cable assembly.



Open wire line uses air as the dielectric material between the conductors. The spacers have minimal impact on the impedance of the transmission line.

Feed Line Losses

- Feed line losses dissipate energy as heat
  - Losses in the cable's conductors
  - Losses in the cable's dielectric material
- Loss is also called attenuation
  - Expressed in dB per unit length
  - Losses increase with frequency
- Air dielectric cables have the lowest loss

Feed Line Losses

- In general, larger diameter cables have less loss than smaller diameter cables
  - Larger conductors have lower resistance since they have more surface area
- Cables with solid shields or multiple braids have less loss than poorly constructed single-braid cables
  - Commonly referred to as braid density

https://nassaunationalcable.com/products/belden-single-conductor-rg-59-u-pe-insulation-double-braided-analog-video-coax-cable

https://www.alldataresource.com/Commscope-HJ11-50-HJ11-50-HELIAX-Standard-Air-Dielectric-Coaxial-Cable-corrugated-copper-4-in-black-PE-jacket_p_376114.html

Care and Feeding of Feed Lines…

- Keep the lines dry
  - Seal connector/cable joints to keep out moisture
  - Moisture ingress for coaxial cable causes cable deterioration
- UV-rated cable jackets are designed for long-term outdoor exposure
- Do not exceed cable bend radius recommendations
- Do not exceed maximum power rating of feed line

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Transmission Lines…under the hood

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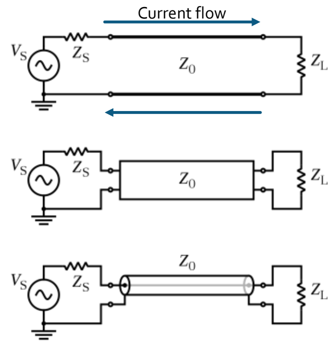
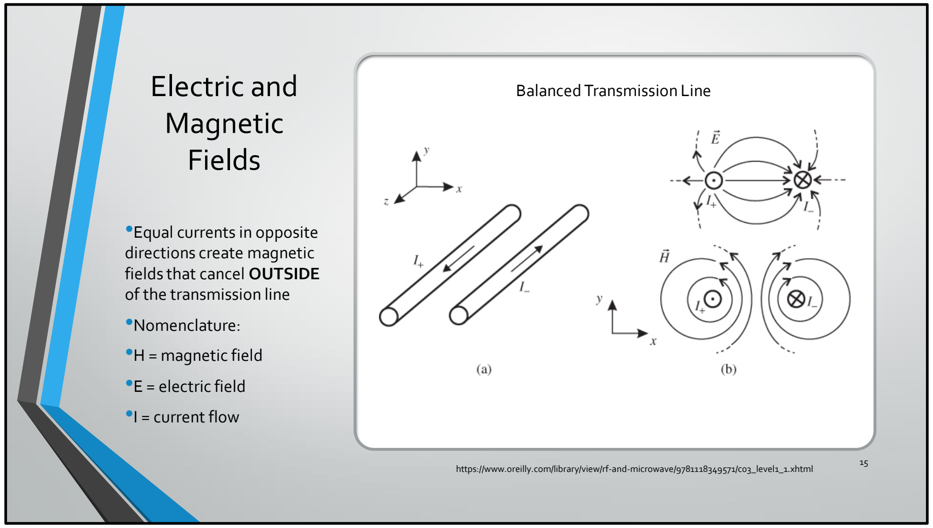
Transmission Line Nomenclature

- V_S: source voltage
- Z_S: source output impedance
- Z_O: characteristic impedance of the transmission line
- Z_L: load impedance



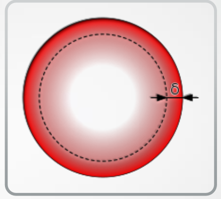
https://en.wikipedia.org/wiki/Transmission_line#/media/File:Transmission_line_symbols.svg



The magnetic and electric fields are confined between the conductors. Because the conductors are in proximity, the magnetic fields generated by each conductor cancel at distances far from the transmission line.

Skin Effect

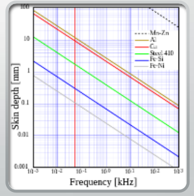
- AC currents flow on the **outer part** of the conductor
- The higher the frequency, the more the currents are confined to the surface
- Separate currents can flow on the **inside and the outside** of a hollow tube (like a coax cable shield) or the surfaces of a flat conductor (like a circuit board layer)
- Copper foil thickness on a PCB is about 1.4mils (35.5μm)
- Diameter of a human hair: 17-181μm



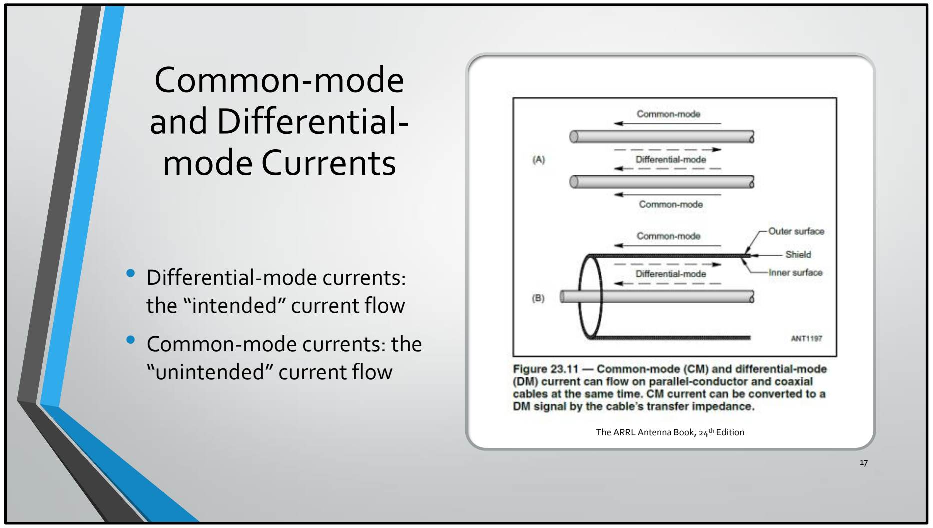
The skin depth, δ, is defined as the depth where the current density is just 1/e (about 37%) of the value at the surface

Skin depth in copper

Frequency	Skin depth (μm)
50 Hz	9220
60 Hz	8420
10 kHz	652
100 kHz	206
1 MHz	65.2
10 MHz	20.6
100 MHz	6.52
1 GHz	2.06



https://en.wikipedia.org/wiki/Skin_effect

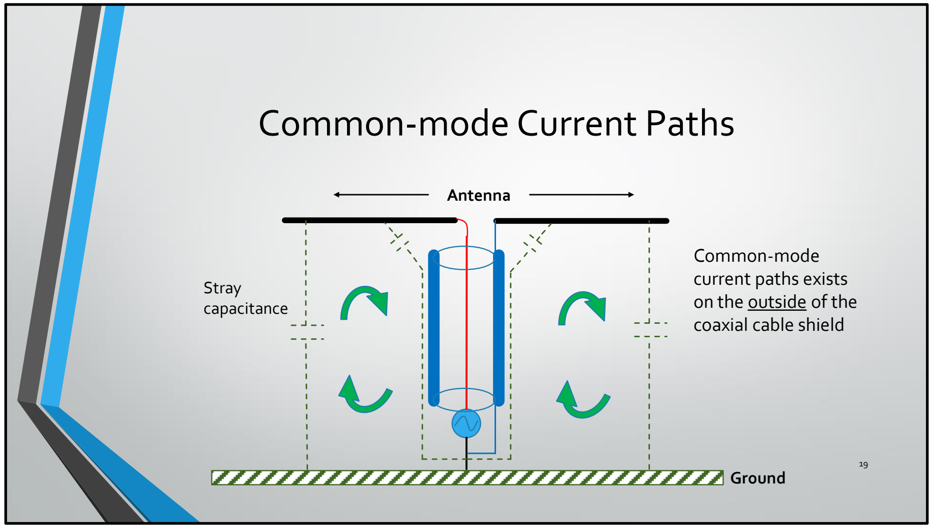


The cable's characteristic impedance is related to the differential currents that flow on the conductors. Cable transfer impedance a measure of how much interaction occurs between currents flowing on the outside of a cable shield vs. inside a cable. It is a measure of the cable's shielding effectiveness.

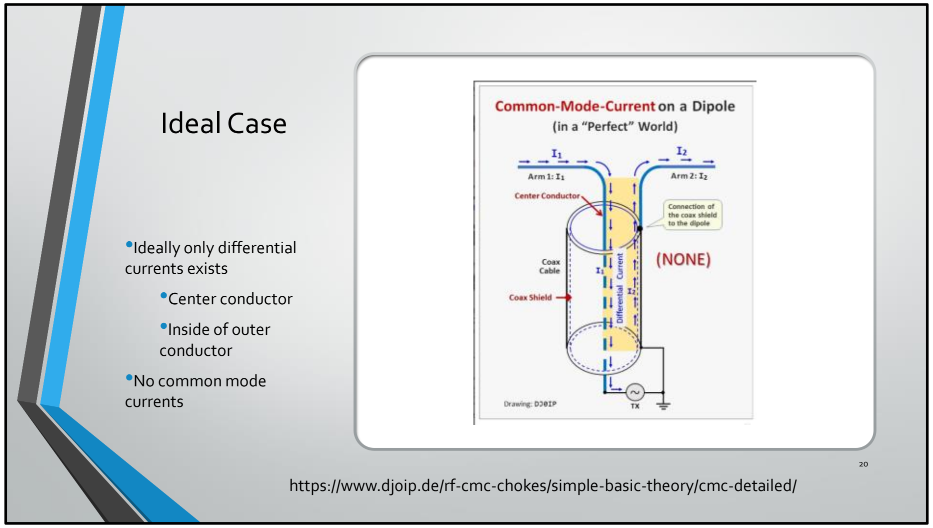
A description of cable transfer impedance measurements (refer to Figure 2): https://global-sei.com/technology/tr/bn79/pdf/79-05.pdf

Everything's fine…until it isn't…

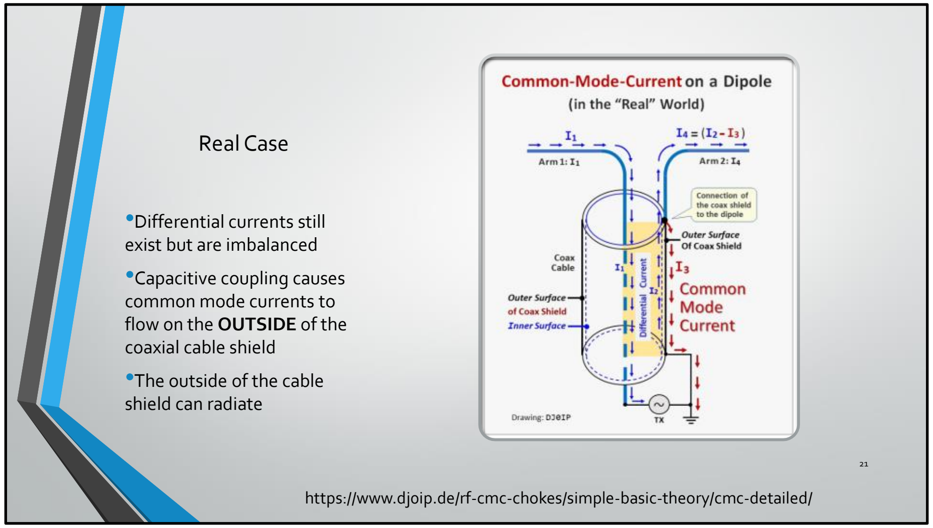
- If conductors are away from "external" paths the fields remain "contained" inside the transmission line
- What's an "external" path?
  - Other nearby conductors
  - Ground
- Common-mode currents flow on the "external" path



Due to skin effect, currents can flow on the OUTSIDE of the shield. The antenna radiates, creating currents that flow to ground through capacitive coupling (the stray capacitance shown). Since the outside of the coaxial cable has currents flowing through it, the outer portion of the shield can radiate, just like the antenna.

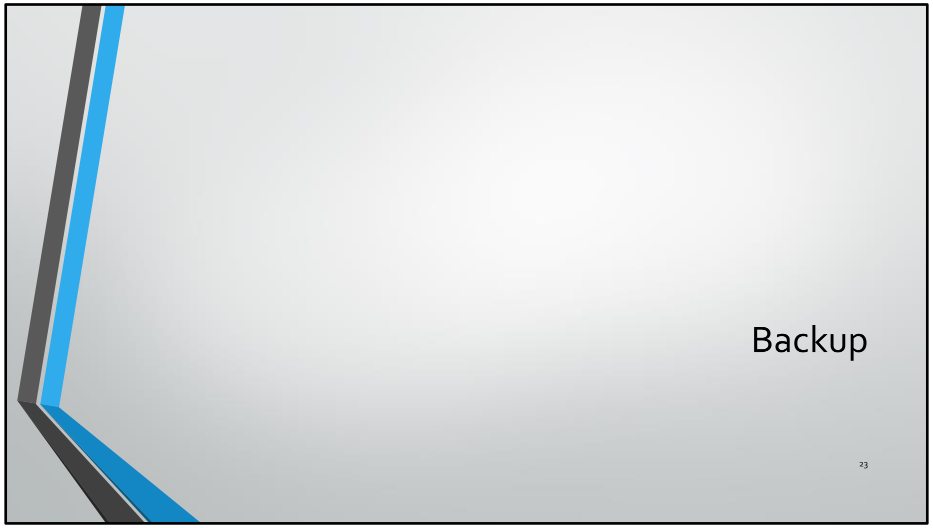


Ideally, only differential mode currents would flow from the source to the load (i.e., the antenna). There would be no common mode currents flowing on the outside of the shield.



The outside of the coaxial cable can support common mode current flow. Note that the direction of the common mode current is opposite of the internal current flow (i.e., the inside surface of the shield) in this example because the outside of the shield is connected to the reference point (i.e.,, the ground connection). The common mode current is generally much weaker than the differential mode current. Regardless of current mode direction, the common mode current causes the current flow in one 'arm' of the antenna to be different than the other arm. This causes the antenna radiation pattern to become asymmetrical.

Regardless of the construction method, a balun provides a transition from a balanced connection (i.e., the antenna) to an unbalanced connection (i.e., the coaxial cable). By winding the coaxial cable into a loop, the OUTSIDE of the shield (i.e., where the common mode currents flow) forms an inductor. This inductance greatly reduces the flow of current along the outside of the shield. This inductance can also be substantially increased by using magnetic materials such as ferrite.


Backup
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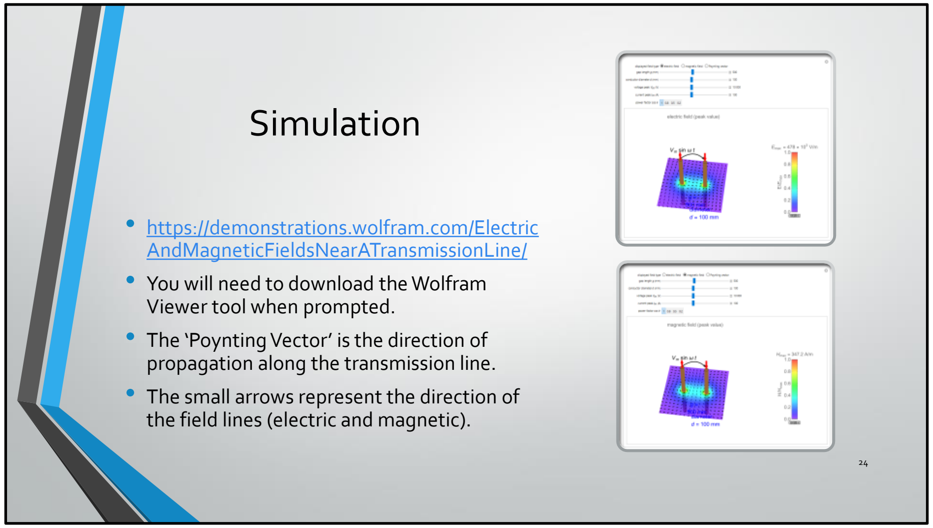
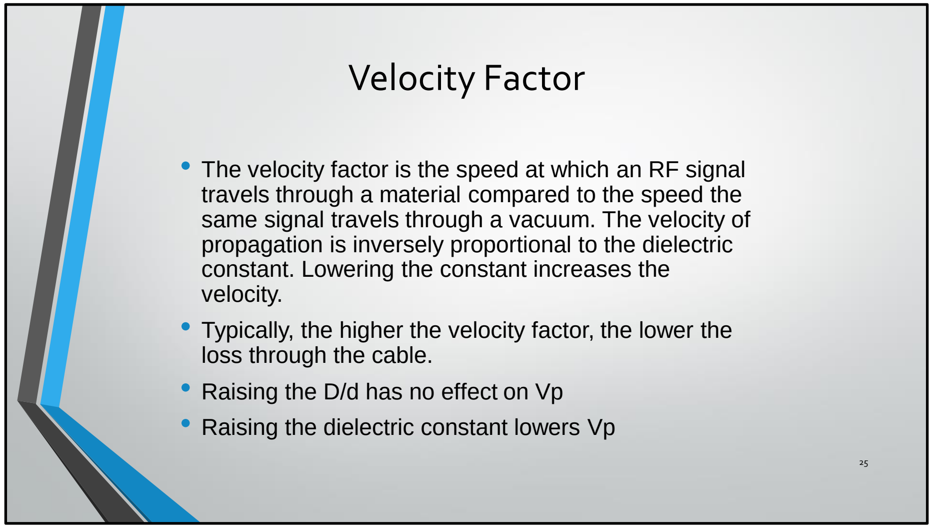


It's difficult to see the simulation results in this slide; running the simulation directly makes the results more visible. The small arrows show the direction of the electric and magnetic field lines. For the magnetic lines, the arrows point in opposite directions far from the transmission line. This behavior is what causes the magnetic fields to 'cancel' far away from the transmission line. The electric fields are 'tightly' confined between the two conductors.



Velocity factor is important when using specific lengths of transmission lines for impedance matching, resonant stubs, etc. A wavelength in the cable is ‘shortened’ or ‘compressed’ based on the velocity factor. For example, if the wavelength in free-space is 10 meters, the same ‘wavelength’ in a cable with a velocity factor of 66% is only 6.6 meters long. Compared to air (or a vacuum), a dielectric has higher ‘inherent’ loss due to dissipation in the material itself. For a dielectric material this is referred to as the loss tangent.

Velocity Factor

Typical velocity factors of common transmission lines

VF%	Transmission line type
95	ladder line
82	twin-lead
79	coaxial cable / foam dielectric
75	RG-6 and RG-8 coax (thick)
66	RG-58 and RG-59 coax (thin)

$$VF = \frac{1}{\sqrt{(\epsilon_r)}}$$

Note: multiply VF by 100% to express velocity factor as a percentage