Transmission Lines

ABCs of Feedlines

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Transmission Lines

- The transmission line (feeder or feed line) connects the radio to the antenna
- The job of the transmission line is to transfer power from the transmitter to the antenna
  - You can compensate for transmission line loss by increasing transmitter power output
- The transmission line also transfers power from the antenna to the receiver
  - Once signal is lost in the transmission line receive path, it is gone.
  - Preamps will boost the signal AND the noise—exception is mast-mounted preamps.

Three Basic Classifications

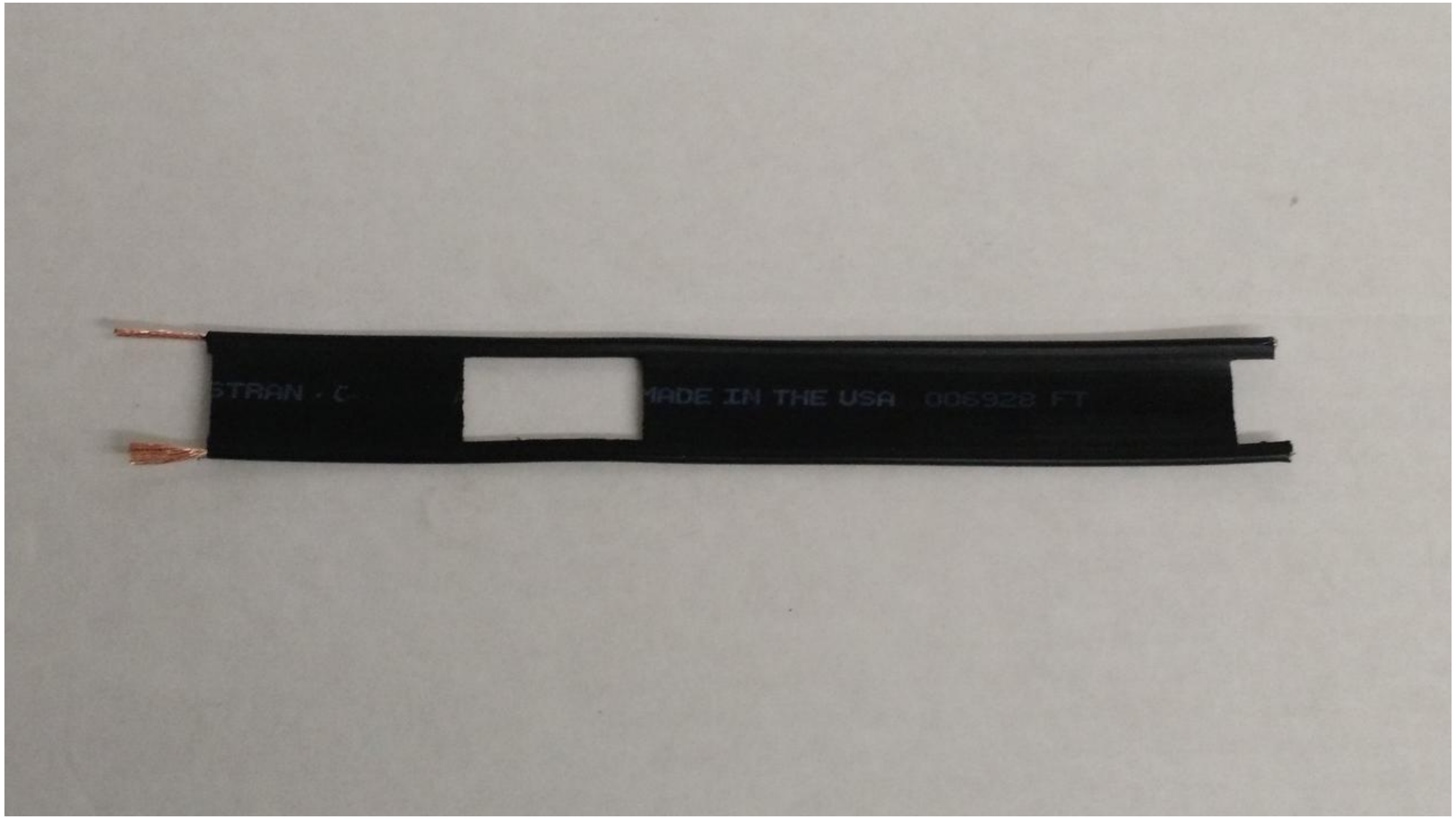
- Balanced transmission lines look the same from one conductor to the other, i.e. the conductors are a mirror image.
  - Ladder line and twin-lead are examples of balanced transmission line construction.
- Unbalanced transmission lines are not a mirror image.
  - One conductor is inside the other and they are typically centered on the same axis, hence they are coaxial.
- Waveguides
  - Waveguides act as a conduit for electromagnetic waves and would be prohibitively large at frequencies below the microwave region.

Balanced Lines

- The original, and some would say best, line is the balanced line.
- A balanced feed line is simply two conductors held at a fixed distance with some sort of spacers.
- If you are old enough to remember “twin lead” on television antennas, this is an example of a balanced feedline.
- Balanced lines should be installed away from metallic structures and periodically transposed to minimize interaction with ground.

Open Wire (trueladderline.com)

Window Line (thewireman.com)



A little theory

- Balanced line is the easiest to visualize, so that is what we will use to start talking about the theory and characteristics of transmission line.
- Basic characteristics of all transmission lines include:
  - Propagation delay or velocity factor (VF) commonly designated as v_0
  - Losses typically specified in dB/length at a certain frequency
  - Characteristic impedance commonly designated Z_0

Balanced Line Current Flow

- If a pulse of voltage is applied to the transmission line, a corresponding current will result.
- Current flow in one wire of the line is matched by the return current in the other wire. The current flow in each wire is in opposite directions.
- The current in each wire results in opposing magnetic fields.
- If the distance (spacing) between the conductors is <u>electrically</u> small, the resulting magnetic field around the transmission line will be nearly zero, minimizing radio frequency (RF) radiation and loss.

Propagation Delay

- The current does not “appear” in all segments of the wire simultaneously. It takes a finite amount of time for the current to propagate along the line.
- In a vacuum the speed of the pulse propagation is approximately 300,000,000 meters per second. It is about the same in open air.

Velocity Factor

- The ratio between the speed of propagation in an insulating media and a vacuum is the velocity factor (VF), sometimes designated v_0.
- VF = $1/\sqrt{\varepsilon}$, where ε (Greek letter epsilon) is the dielectric constant.
- According to ARRL Antenna Book data, VF for open wire = 0.95-0.99 depending on the insulator material.
- More about VF and when it is important to us later.

Line Loss

- Main sources of line loss are:
  - The effect of current on the resistance in the conductor (i^2R).
  - Insulation or dielectric loss
  - Radiation loss
- Loss is dependent on frequency.
  - As frequency goes up, losses also increase.
  - It is important to look at the frequency the loss is specified at.
  - Impedance mismatch also increases loss, so loss is specified as “matched loss.”
- In the case of open-wire line, the ARRL Antenna Book tells us that loss is about 0.02 dB at 1 MHz and 0.2 dB at 100 MHz per 100 feet.

Characteristic Impedance

- All conductors have inductance.
  - Inductance is the characteristic that opposes change in current flow, this is called inductive reactance designated X_L.
  - While inductance increases when you form a coil, even straight conductors exhibit inductive reactance.
- All conductors have capacitance.
  - Capacitance is the characteristic that opposes change in voltage, this is called capacitive reactance and is designated X_C.
- Conductors also have resistance, but that does not affect the characteristic impedance much.

Characteristic Impedance (continued)

- If we apply a voltage to the line, the capacitance will draw current to oppose the change in voltage, i.e. charge the capacitance.
- As the capacitance charges, the inductance generates a voltage to oppose the capacitive charging current.
- If the line is very long (infinitely long), the applied voltage and flowing current will have a relationship that results in the Z_0 of the line.
- Z_0 will appear to be resistive in nature.
- $Z_0 = (L/C)^{1/2}$
  - Narrow-spaced large conductors ➔ Low Z
  - Wide-spaced small conductors ➔ High Z

Characteristic Impedance and SWR

- If we replace the section of this theoretical infinitely long line that trails off into infinity with a resistive load equal to Z_0 of the line, we will have a perfect match.
- Two ways of expressing a perfect match are: SWR = 1.0 or return loss = ∞. Both mean the same thing—no power is reflected.
- As long as Z_0 = antenna radiation resistance, there is no "magic" line length.
  - Transmission lines do have some interesting characteristics based on length when the match is not perfect, more on that later.
  - Even if the magnitude of antenna impedance $|Z|$ is equal to Z_0 of the line it will not represent a perfect match unless it is purely resistive.

Example - homebrew ladder line

- As long as spacing (S) is much larger than conductor diameter (d), we can approximate Z_0 with the equation $Z_0 = 276 \log (2S/d)$
- What would Z_0 be for No. 14 AWG spaced at 6"? Diameter of 14 AWG solid wire is 64 mils or 0.064".
- $276 \log (12/.064) = 627\ \Omega$
- Charts are available showing conductor size, spacing, and characteristic impedance so you do not have to work the math. See ARRL Antenna Book for an example.

Unbalanced Lines (Coaxial)

- Coaxial lines, or coax, consist of two (or more) conductors that share a common axis.
- The inner conductor may be solid, stranded, or tubular.
- The outer conductor may be braided, foil, tube, or some combination of those.
- The conductors are separated by a dielectric medium.
- Coax cables come in many different types.

RG213/u Coax (RFParts.com)

LMR400 Coax (RFParts.com)

Notice the braid and foil outer conductor.

AVA5P-50-C HELIAX® (RFParts.com)

Triaxial Cable (nassaunationalcable.com)

Current Flow in Coaxial Lines

- Current through the inner conductor is balanced by current in the opposite direction on the inside surface of the outer conductor.
  - Skin effect causes high-frequency current to flow on the surface of a conductor.
  - RF current does not penetrate the outer conductor because of skin effect, consequently the RF energy is effectively contained within the coax.
- Unlike balanced line, the conductors do not need to be electrically close together to prevent radiation.
- Proximity to ground does not affect them because the RF is effectively contained within the shield.

Characteristic Impedance

- Z_0 is dependent on the dielectric characteristics and the geometry of the cable.
  - As long as the load is matched to the cable Z_0, there will be no power reflected (SWR = 1).
  - Reflected power will increase cable loss.
- Coaxial cables will typically have lower Z_0 than balanced lines.
  - Lower impedance means the conductors will carry more current for a given power level.
  - This contributes to increased conductor (i^2R) loss.

Hi Z vs. Low Z Example

- Comparison between 100 watts on a 50Ω feed line and a 600Ω line:
- $P = i^2R$ or $i = (P/R)^{1/2}$
  - At 50Ω: $(100/50)^{1/2} = 1.4$ amps
  - At 600Ω: $(100/600)^{1/2} = 0.4$ amps
- Since conductor loss is proportional to the square of current, this represents loss reduction by more than 10 times for a similar current-carrying cross sectional area. Skin effect can not be disregarded when talking about RF.

Line Loss in Coax

- The two main sources of line loss are:
  - The effect of current on the resistance in the conductor (i^2R).
  - Insulation loss—the insulating media in coax is lossier than in balanced lines, which largely depend on air for insulation.
- Loss is dependent on frequency.
  - As frequency goes up, losses also increase.
  - It is important to look at the frequency the loss is specified at.
- In the case of open-wire line, the ARRL Antenna Book tells us that loss is about 0.02 dB at 1 MHz and 0.2 dB at 100 MHz per 100 feet.

Coax Loss vs. Open Wire

Comparing loss in dB/100’ for some commonly used cable types to open wire at 1 MHZ and 100 MHz:

Frequency	1 MHz	100 MHz	1000 MHz
Open wire	0.02 dB	0.2 dB	n/a
RG-8X(7808A)	0.20 dB	2.3 dB	7.4 dB
RG-8X(9258)	0.30 dB	3.2 dB	11.2 dB
RG-213	0.20 dB	2.1 dB	8.0 dB
LMR-600	0.10 dB	0.8 dB	2.7 dB
7/8 Heliax	0.03 dB	0.4 dB	1.3 dB

Velocity Factor

- VF = $1/\sqrt{\varepsilon}$, where ε (Greek letter epsilon) is the dielectric constant.
- Coax will typically use either a solid dielectric or a foam dielectric.
  - Looking up the value of ε for polyethylene (clippercontrols.com) shows a range of 2.2-2.4. If we plug the value of 2.3 into the above formula, we get 0.66. This corresponds to the data in the ARRL Antenna book for RG-213 cable.
  - Cables using foam dielectric will have a higher velocity factor, on the order of 0.8.
  - You can estimate (guess) VF from the dielectric type, but it is better to consult the manufacturer’s data and even better to measure it.

Waveguides

- Waveguides resemble a tube.
  - Waveguides do not conduct RF current in the conventional sense of a feedline.
  - The wavelength that a waveguide can effectively carry is dependent on its dimensions.
- Various geometries may be used, but the most common are circular and rectangular.
  - A circular waveguide for use on the 70 cm band would need to be approximately 16 inches in diameter.
  - Waveguides are not very practical at frequencies much below 2 GHz (15 cm).

Elliptical Waveguide (Andrew.com)

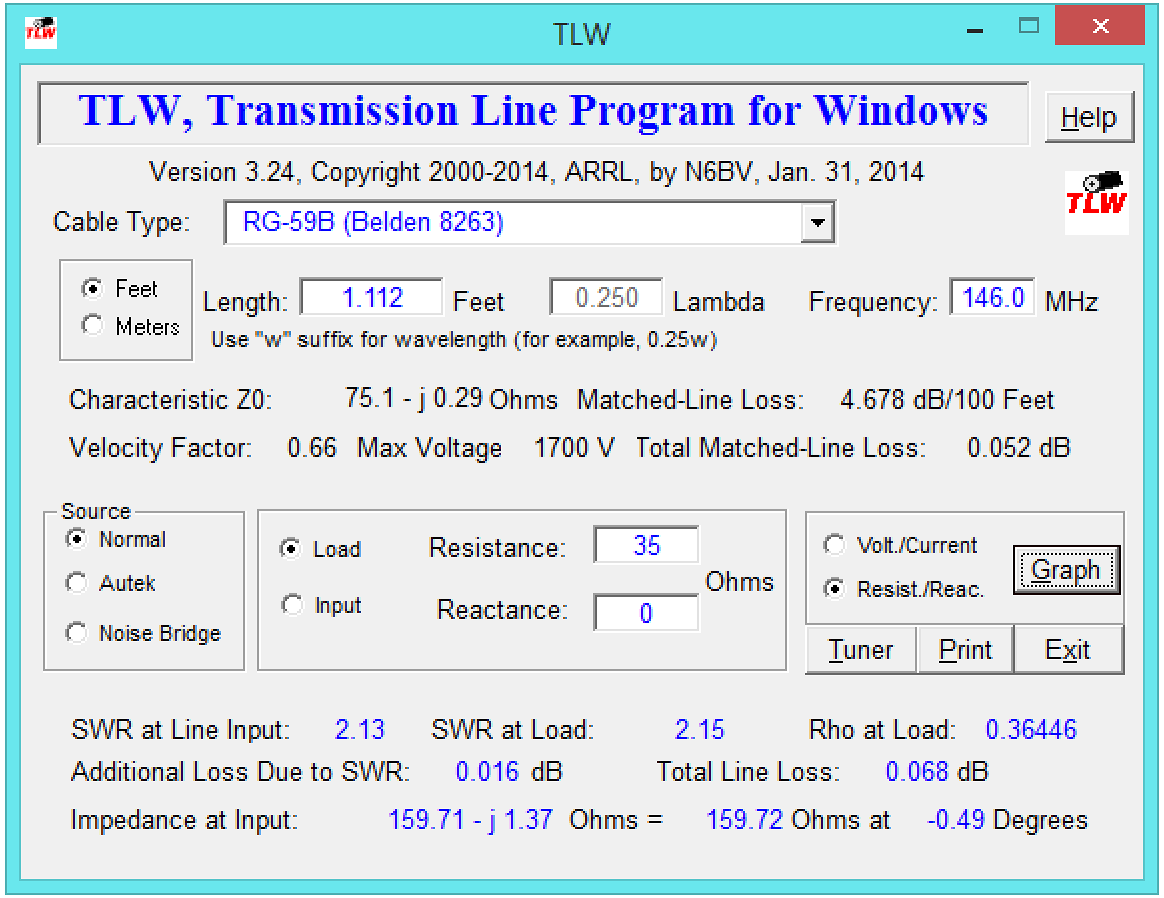
Other Tricks

- Feedlines can perform other functions.
  - Impedance matching
  - Phase delay
  - Filtering

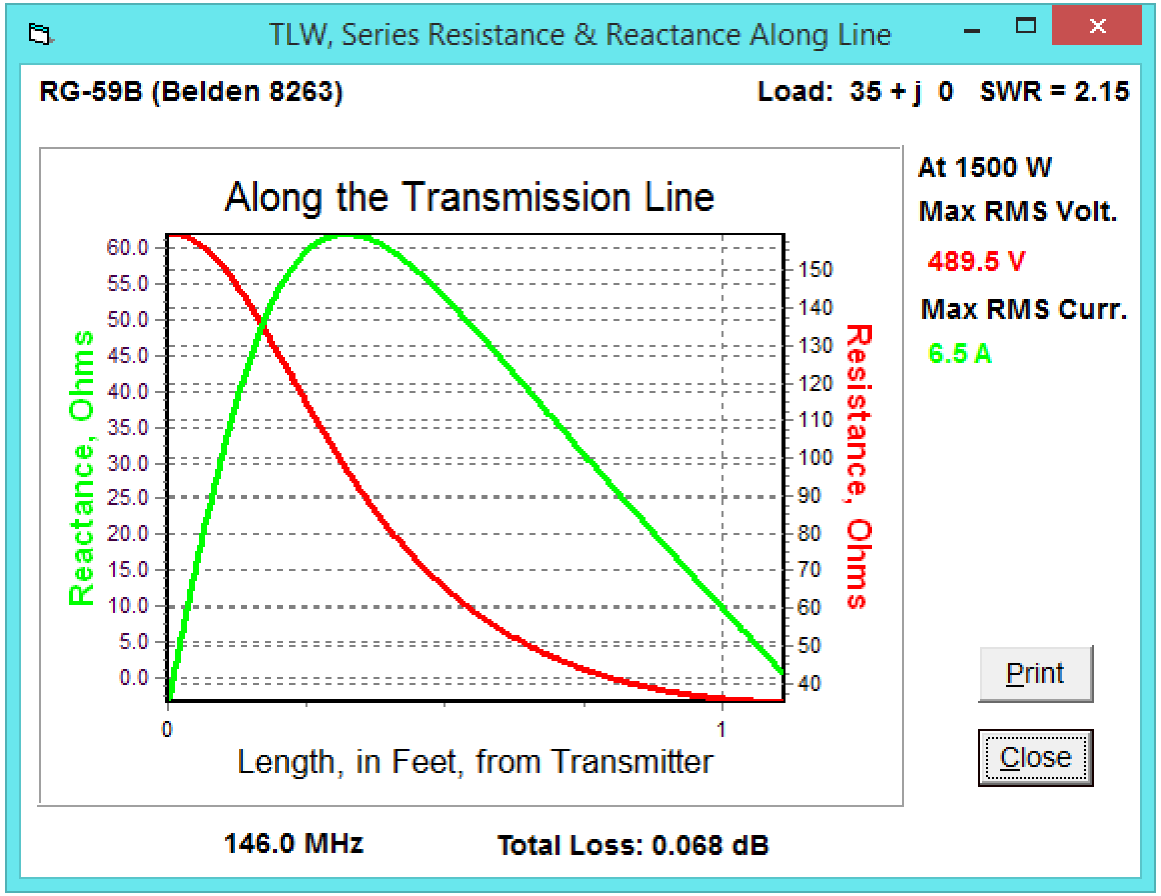
Impedance matching

- A common impedance matching device is the ¼-wave transformer.
  - A section of line ¼-wavelength (electrical length) is inserted between the load and the transmission line.
  - This only works for a certain frequency and is sometimes called a synchronous transformer.
- The required Z of the matching section is determined from the formula $Z = (Z_L Z_0)^{1/2}$, where Z_L is the load impedance and Z_0 is the transmission line impedance.
- This is a specialized case and you can use Transmission Lines for Windows to solve more general cases. The program comes with the ARRL Antenna Book.

Transmission Lines for Windows (TLW)



TLW (cont.)



TLW, Series Resistance & Reactance Along Line
RG-59B (Belden 8263)
Load: 35 + j 0 SWR = 2.15
Along the Transmission Line
Reactance, Ohms
Resistance, Ohms
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
150
140
130
120
110
100
90
80
70
60
50
40
0
1
Length, in Feet, from Transmitter
At 1500 W
Max RMS Volt.
489.5 V
Max RMS Curr.
6.5 A
Print
Close
146.0 MHz
Total Loss: 0.068 dB

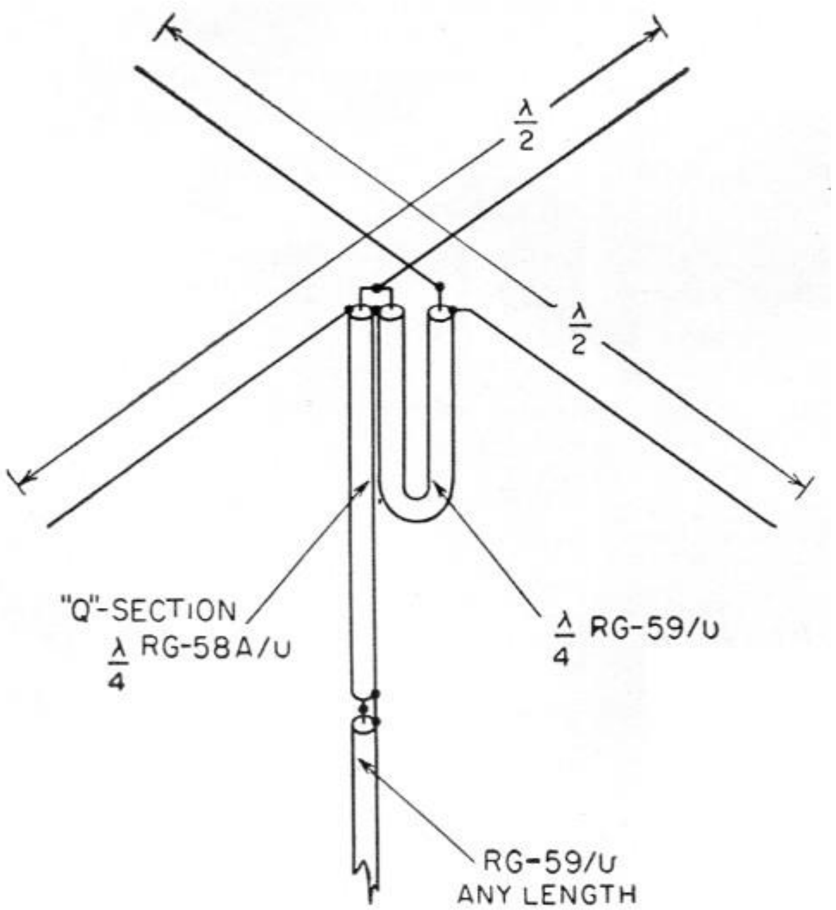
Impedance Matching Example

- Quad antennas typically have a characteristic impedance of around 100 Ω at resonance.
- If fed directly from a 50 Ω line, the mismatch will result in SWR = 2.
- Solution: 100 Ω antenna fed with 50 Ω coax: $[(100)(50)]^{1/2} = 71$.
  - A section of 75 Ω coax, ¼ wavelength long, inserted between the 50 Ω feedline and the 100 Ω antenna will make a nice match.
  - Of course, you will need to consider VF when determining the physical length of the matching section.

Phase Delay

- The relationship between current and voltage repeats along the transmission line at distances of one electrical wavelength.
  - This can be used to our advantage in phased arrays and other multi-element antenna types.
  - The transmission line is cut to a specific electrical length to ensure that the phasing of each antenna is as desired.
- In a turnstile antenna (crossed dipole), it is desirable to feed the antennas with a 90° phase shift. This is accomplished with a ¼ wave phasing line.

Turnstile Antenna (ARRL Radio Amateur's VHF Manual)



- The λ/4 RG-59 ($Z_0 = 75\Omega$) section acts as a phase delay.
- The two dipoles are in parallel $72\Omega/2 = 36\Omega$.
- The λ/4 RG-58 ($Z_0 = 50\Omega$) Q-Section acts as an impedance matching transformer to get the impedance back to ≈ 70Ω.

Filters

- Electrical filters are comprised of inductive and capacitive elements.
  - I am differentiating between “electrical” filters and “cavity” filters.
  - A cavity filter can be thought of as a section of waveguide constructed to specific electrical dimensions.
  - Examples of tunable cavity filters can be found in the duplexer of a typical VHF or UHF repeater installation.
- Transmission lines have distributed inductance and capacitance.
- We can make filters from transmission lines by trimming them to certain electrical lengths.

Transmission Line as Circuit Element (shorted stub)

- Shorted stub characteristics for electrical length:
  - Length = λ/8 ➔ Inductive
  - Length = λ/4 ➔ Parallel LC (band block)
  - Length = 3λ/8 ➔ Capacitive
  - Length = λ/2 ➔ Series LC (band pass)
  - Length = 5λ/8 ➔ Inductive
  - Length = 3λ/4 ➔ Parallel LC (band block)
  - Length = 7λ/8 ➔ Capacitive
  - Length = λ ➔ Series LC (band pass)
- Notice that the characteristic repeats every ½ wavelength.

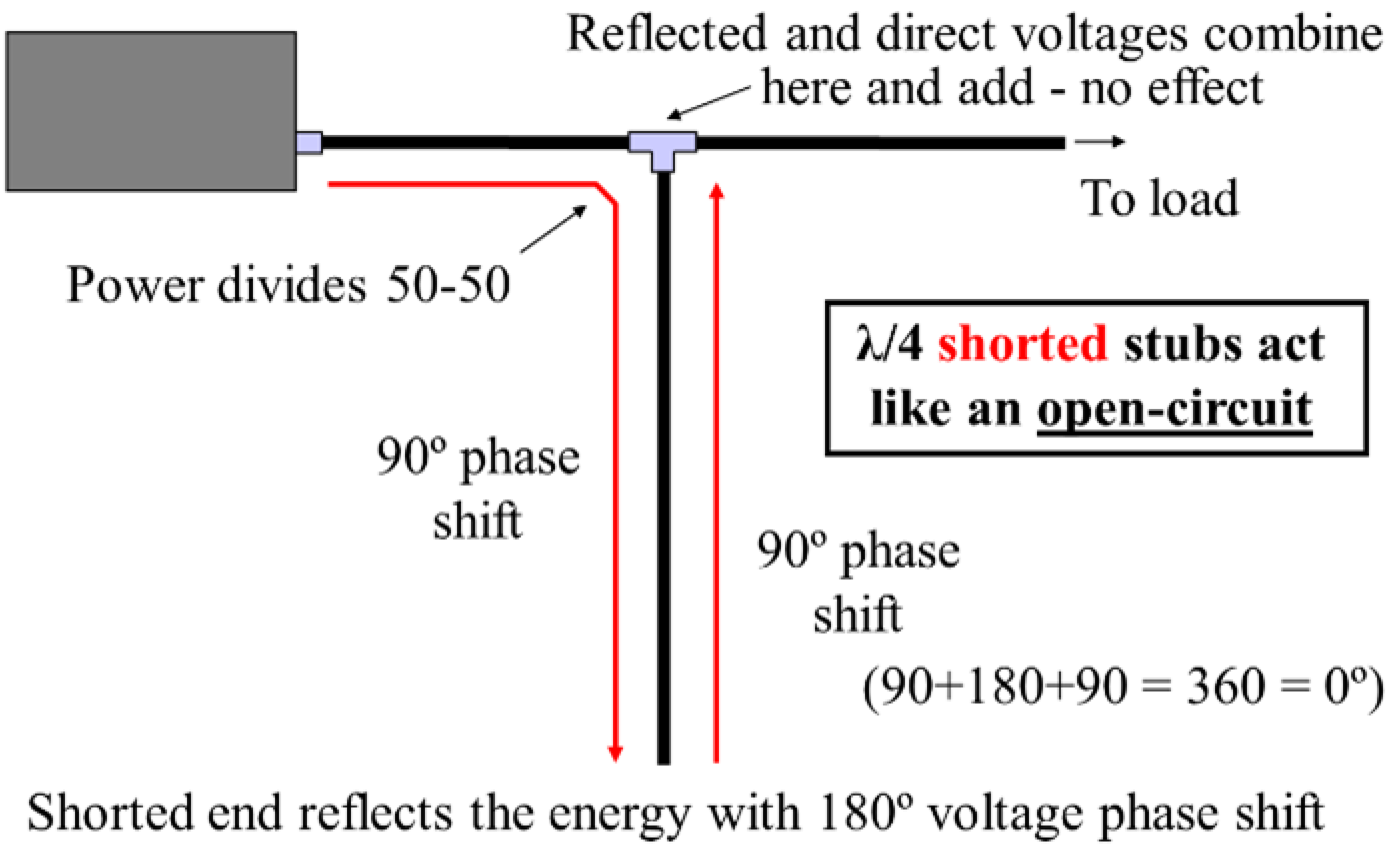
Transmission Line as Circuit Element (open stub)

- Open stub characteristics for electrical length:
  - Length = λ/8 ➔ Capacitive
  - Length = λ/4 ➔ Series LC (band pass)
  - Length = 3λ/8 ➔ Inductive
  - Length = λ/2 ➔ Parallel LC (band block)
  - Length = 5λ/8 ➔ Capacitive
  - Length = 3λ/4 ➔ Series LC (band pass)
  - Length = 7λ/8 ➔ Inductive
  - Length = λ ➔ Parallel LC (band block)
- Notice that the characteristic repeats every ½ wavelength.

Example

- To construct a harmonic blocking filter for a transmitter on 80 meters, you would attach a ¼-wave (at 80 meters) shorted stub to a “T” connector in the transmission line.
  - The ¼-wave stub acts as a band blocking at 80 meters, so the fundamental frequency proceeds down the transmission line ignoring high-impedance of the stub.
  - At the second harmonic, the stub is now ½ wavelength long and acts as a band pass circuit diverting the harmonics from the transmission line.

Stub Diagram (onallbands.com DXEngineering)



Summary

- Open wire has the lowest loss and is best suited for HF applications where proper installation is possible.
  - Open wire is especially useful in applications where SWR is high, e.g. multi-band wire antennas.
  - The electrical distance between open wire conductors becomes significant at VHF and UHF, limiting its use.
- Coax is much easier to install.
  - Coax can be installed next to ground since the outer conductor acts as a shield.
  - Not all "RG-8" is equal. Even though the "RG" number may be the same, the cable performance may differ significantly.
  - Good coax is sufficient for most applications.
  - Some (not all) coax is useful well into the upper UHF range.
  - Since loss increases with frequency, use low-loss cable for VHF and UHF applications.