RF Fundamentals Seminar
Part 2: RF Transmission Characteristics

ROHDE & SCHWARZ

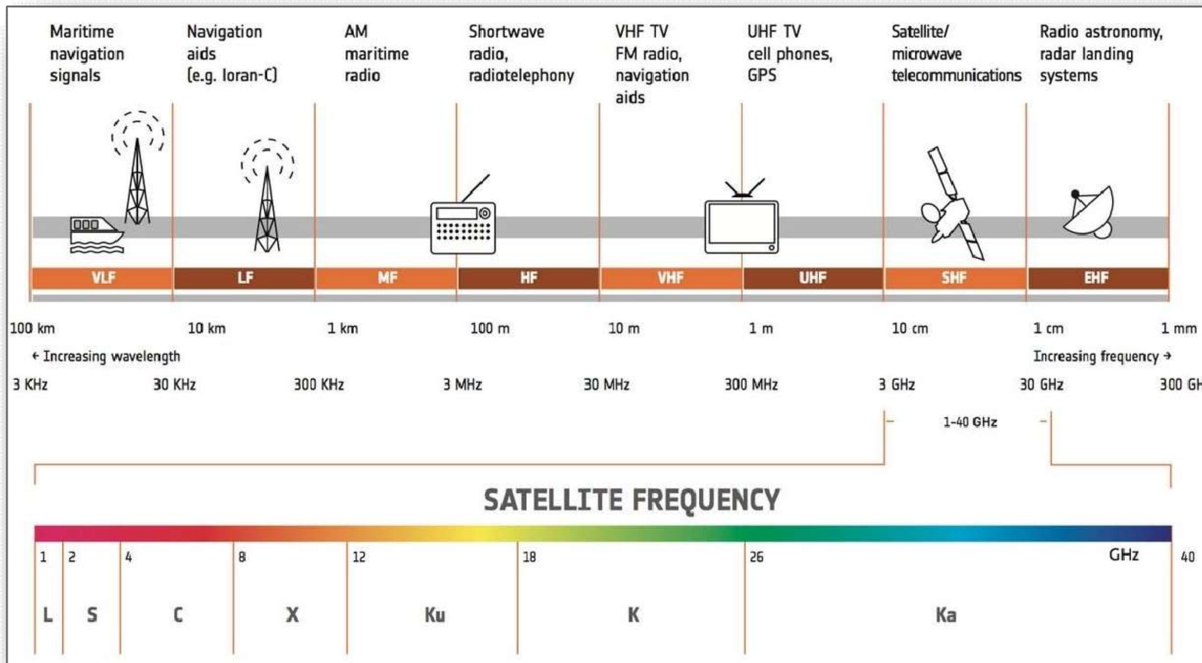
Make ideas real

RF Transmission Characteristics

- ► Topics
  - – Transmission Lines
  - – Wavelength
  - – Impedance

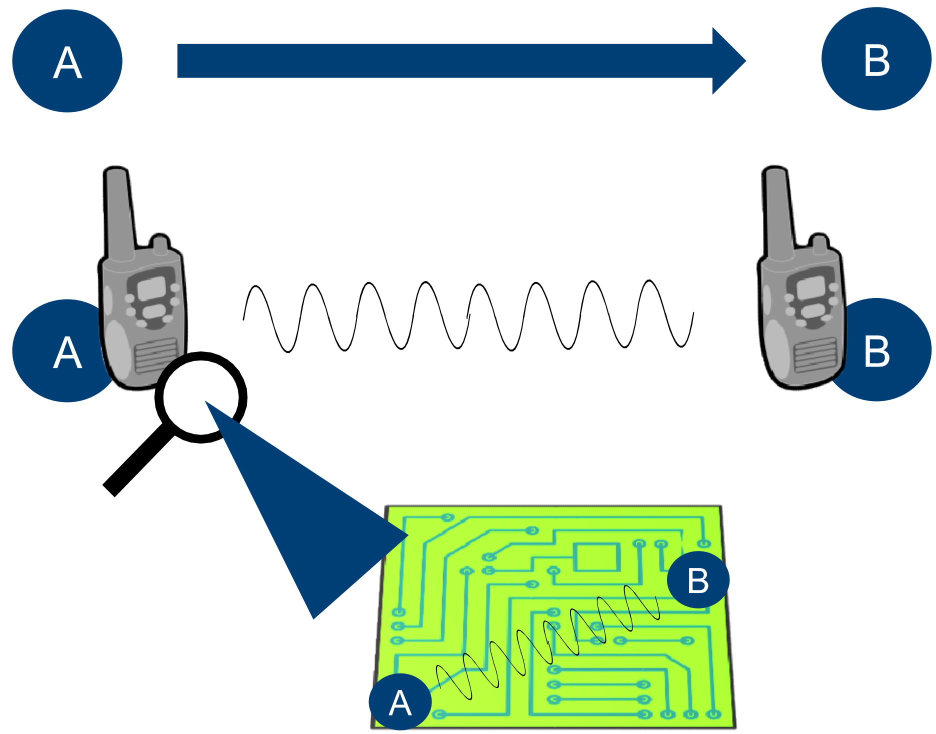
What is RF?

- RF: Radio Frequency
- Frequencies from ~3 kHz to ~300 GHz (according to Wikipedia)
- Some commonly used terms:
  - RF: < 6 GHz
  - Microwave: 6 GHz - 30 GHz
  - mmWave: > 30 GHz



RF Transmission

- Transmission
- RF (Radio Frequency)
- Circuit → Transmission Line



Transmission Lines?

- **Transmission line** is a physical path that is designed to handle RF signals.

- Would a clip lead work for connecting RF signals?
  - Maybe, if the wavelength of RF signal is long in comparison to the length of the wires, then it could work.

    Wavelength > wire length = OK

  - If the wavelength is short in comparison to line length, then we can’t use clip lead but must use a ‘transmission lines.’

    Wavelength < wire length = Transmission Line

Transmission Lines

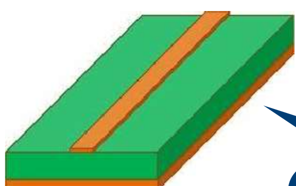
Twisted-pair

- Low Frequency
- Low Cost

Coax

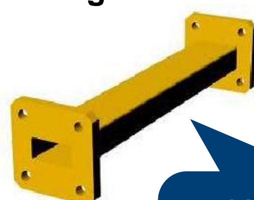
- High Bandwidth
- Easy to use

Microstrip



- High Bandwidth
- Small Size
- Easy to create

Waveguide



- High Frequency
- High Power
- Low Bandwidth

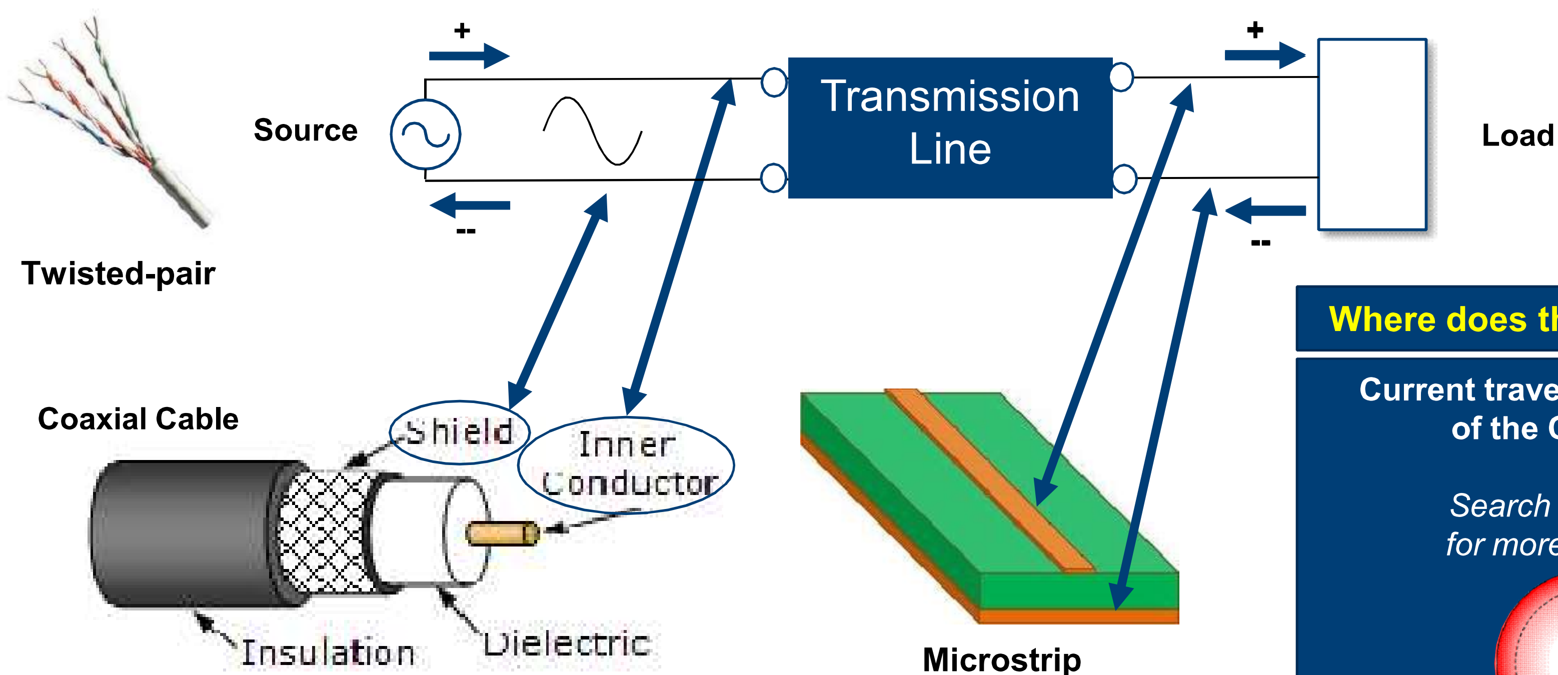
Why Different type?

Cost
-Material
-Construction
-Assembly

Power Handling
-Voltage or Current
-Power Loss

Frequency
-Frequency Range
-Bandwidth
-Isolation

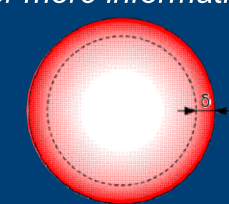
Transmission Line – Basics



Where does the current travel?

Current travels on the Surface of the Conductors

Search 'Skin Depth' for more information



Frequency and Wavelength

Application	Frequency (Hz)	Wavelength (meters)	1/4 Wavelength (meters)
Electrical outlet AC	60	5,000,000 (*3107 miles*)	1,250,000 (*776.75 miles*)
Human Voice	2,000	152,500	38,125
AM Radio	530,000	566	141.5
VHF Television	54,000,000	5	1.25
FM Radio	88,000,000	3	0.75
Cell Phone	824,000,000	0.3 (30 cm)	0.075 (7.5 cm)
Wi-Fi 2.4	2,400,000,000	0.13 (13 cm)	0.0325 (3.25 cm)
Satellite TV	11,750,000,000	0.02 (2 cm)	0.005 (5 mm)

Wi-Fi Router

Car Antenna

Older Cell Phone Antenna

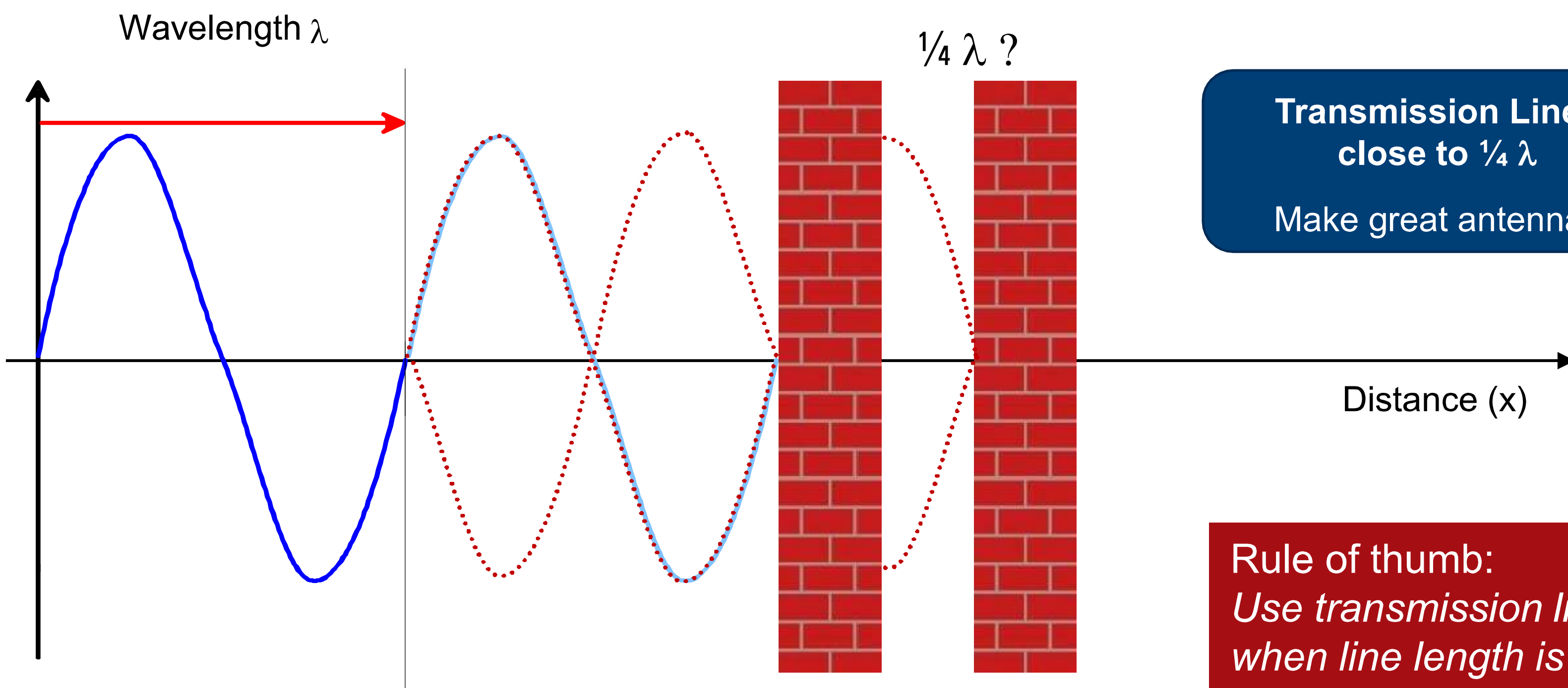
Wi-Fi USB Adapters

$f = c / \lambda \rightarrow \lambda = c / f$

300 kHz	1000 m	250 m
3 MHz	100 m	25 m
30 MHz	**10 m**	2.5 m
300 MHz	1 m	25 cm
1 GHz	30 cm	7.5 cm
3 GHz	10 cm	2.5 cm
30 GHz	1 cm	10 mm

Antenna:
¼ Wavelength

Transmission Line – Wavelength

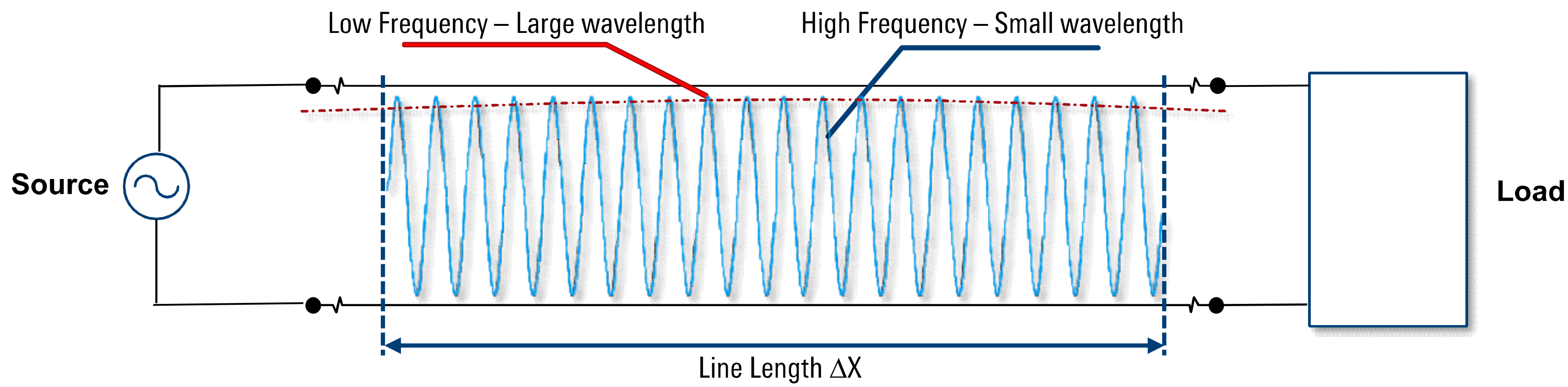


Transmission Lines close to ¼ λ

Make great antennas

Rule of thumb:
Use transmission line theory when line length is more than ~10% of wavelength

Transmission Line – Wavelength vs Line Length



Low Frequency

Wavelength >> wire length

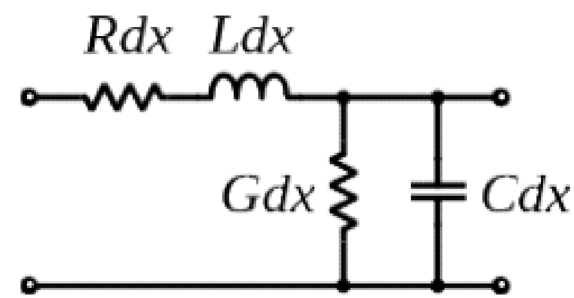
- Measured voltage not dependent on position along the wire.
- Voltage travels down wires easily for efficient power transmission.

High Frequency

Wavelength ≤ length of transmission line

- Measured voltage dependent on position along line
- The Transmission lines Impedance (Zo) is important match to get a low reflection and maximum power transfer.

What Defines Transmission Lines?



- Main feature of a transmission line is *characteristic* impedance, Z_0

$$Z_0 = R + jX$$

- The *characteristic* impedance is that it is uniform along the length of the line.

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

- Capacitance and inductance determine the transmission line's *characteristic* impedance, Z_0

$$Z_0 = \sqrt{\frac{L}{C}}$$

Impedance

$$Z = R + jX$$

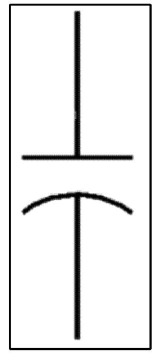
Z = Impedance (ratio of Voltage/Current)

R = Resistance (real)

X = Reactance (imaginary)

Mathemeticians use i for $\sqrt{-1}$

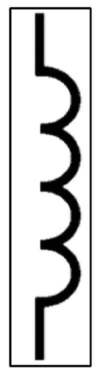
Engineers use j because i is for current!



Capacitor

$$Z = X_c = \frac{1}{j\omega C} = \frac{(-j)}{\omega C}$$

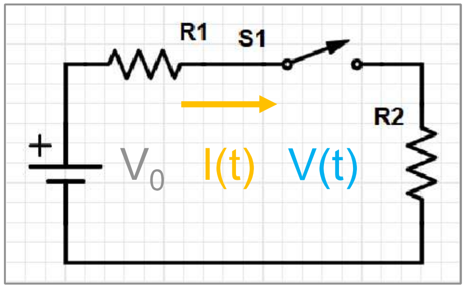
Reminder $\omega = 2\pi f$



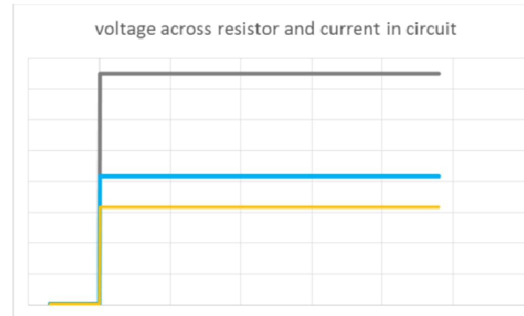
Inductor

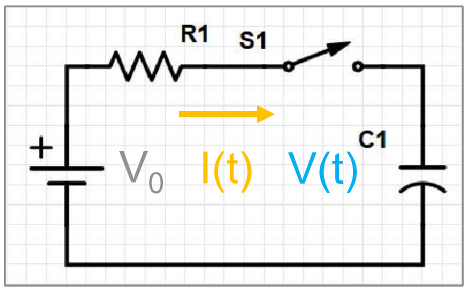
$$Z = X_L = j\omega L$$

Resistance vs Reactance

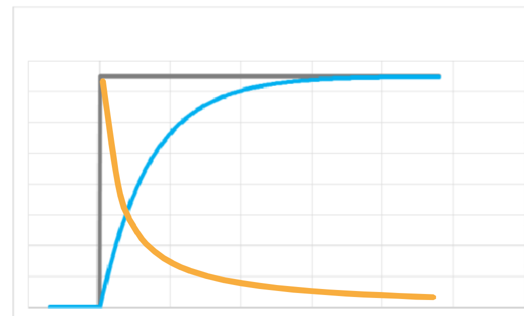


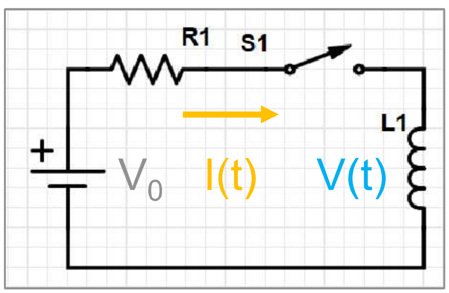
The current through a resistor is proportional to the voltage across it, and the voltage across it is proportional to the current through it



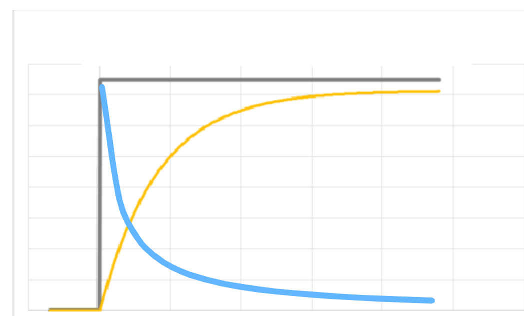


Capacitors resist any instantaneous changes in voltage.

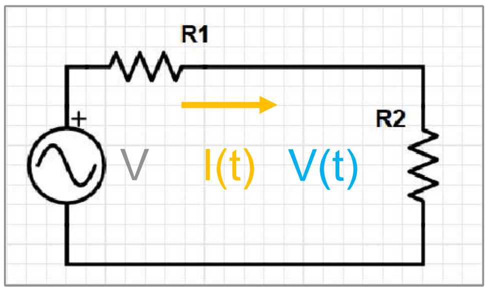


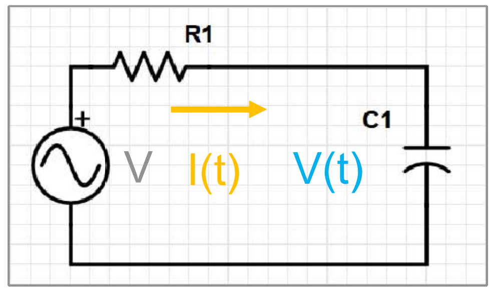


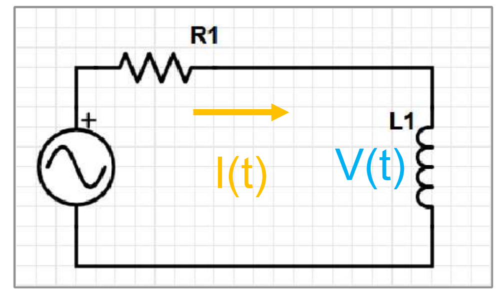
Inductors resist any instantaneous changes in current.



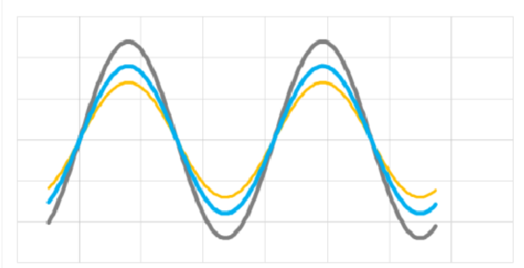
Reactance and Sinusoidal Signals



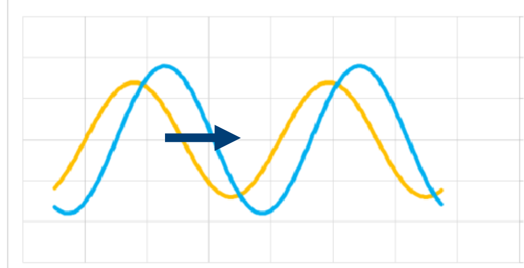




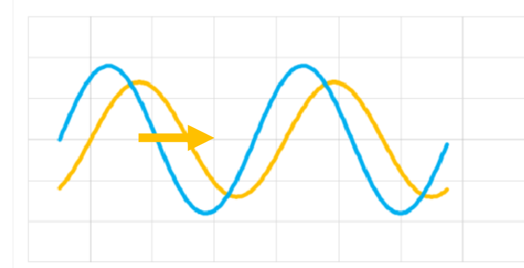
voltage and current are in phase with source



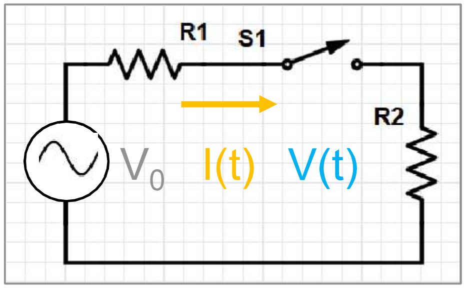
capacitance causes the voltage to lag the current



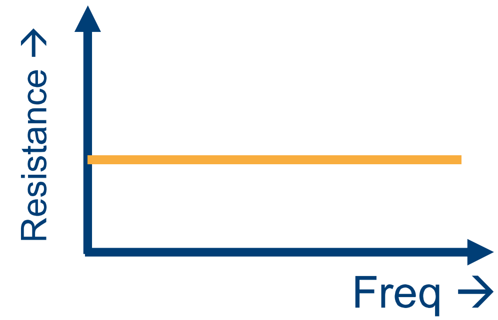
inductance causes current to lag the voltage

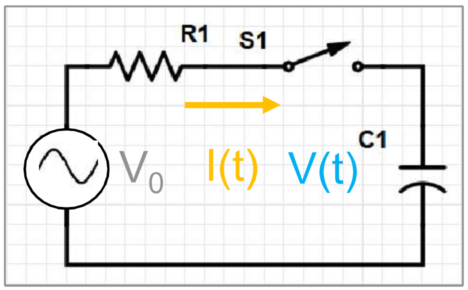


Resistance and Reactance vs Frequency

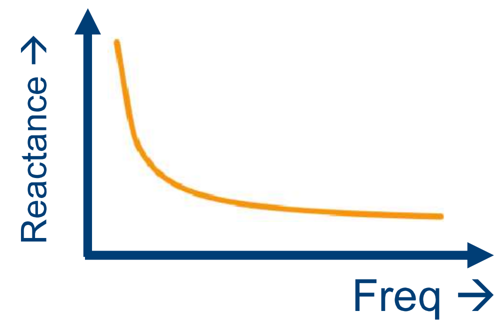


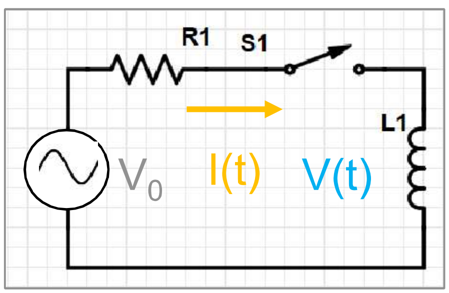
Resistance
The voltage/current ratio is independent of frequency



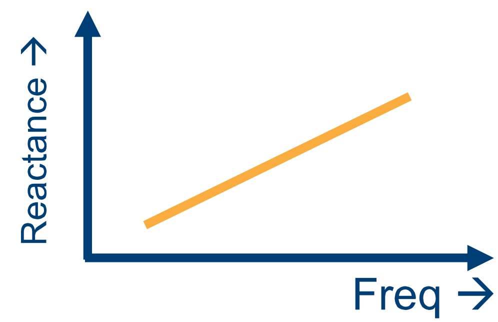


Capacitance
The *higher the frequency*, the lower the voltage, thus higher current. In general this means *lower impedance.*

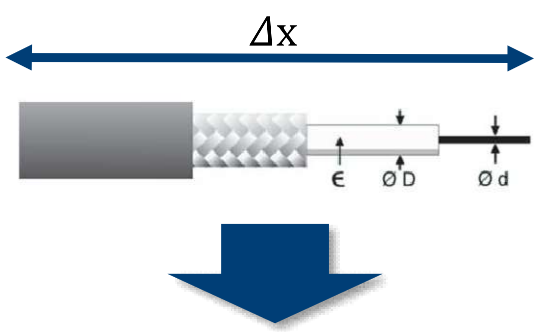




Inductance
The *higher the frequency*, the lower the current. In general this means *higher impedance.*



Transmission line model (telegraph equation)



$$Z_O = \sqrt{\frac{R + j\omega L'}{G + j\omega C'}}$$

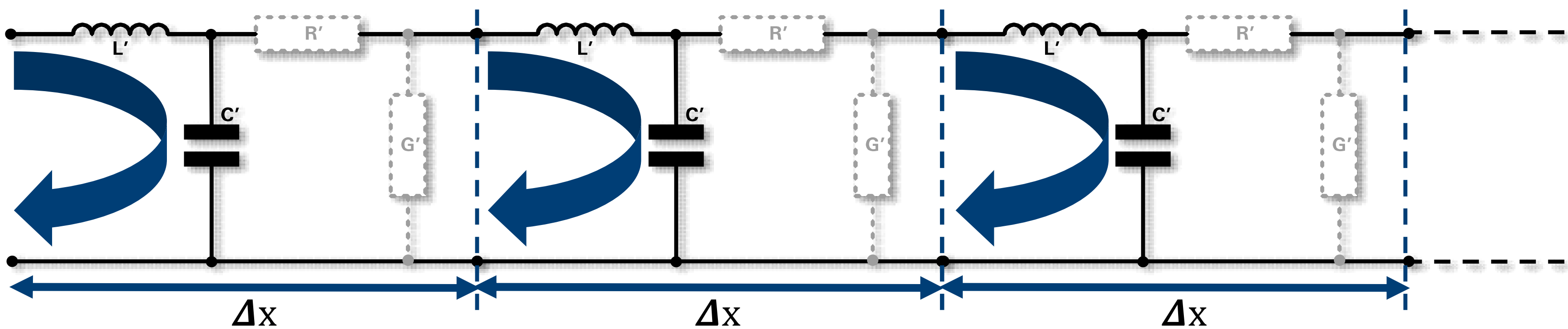
For a low loss transmission line:

$$G' \ll j\omega L'$$
$$R' \ll j\omega C'$$

$$Z_O = \sqrt{\frac{L'}{C'}}$$

Infinitely small length of line

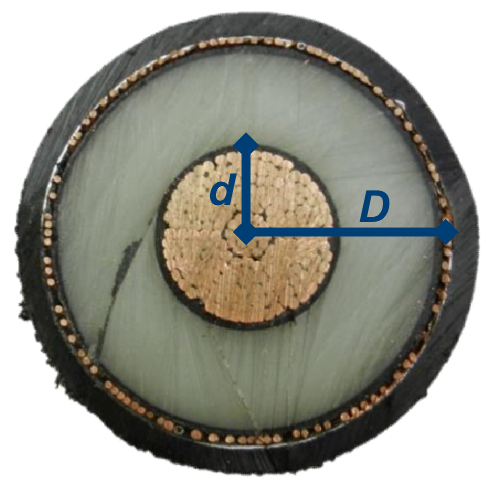
Infinitely long transmission line



Transmission line impedance: Coax Z_0

- Z_0 determines relationship between voltage and current waves
- Z_0 is a function of physical dimensions and dielectric constant, ε_r
- Z_0 is typically 50 ohms (75 ohms in CATV systems)

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\, ln\frac{D}{d}$$



Propagation through coaxial mediums

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\, ln\frac{D}{d} = Z_O = \frac{138.2}{\sqrt{\varepsilon_r}}\log\left(\frac{D}{d}\right)$$

Example 3.5 mm connector

Outer diameter of conductor:

$D = 3.50\ mm$

Inner diameter of conductor:

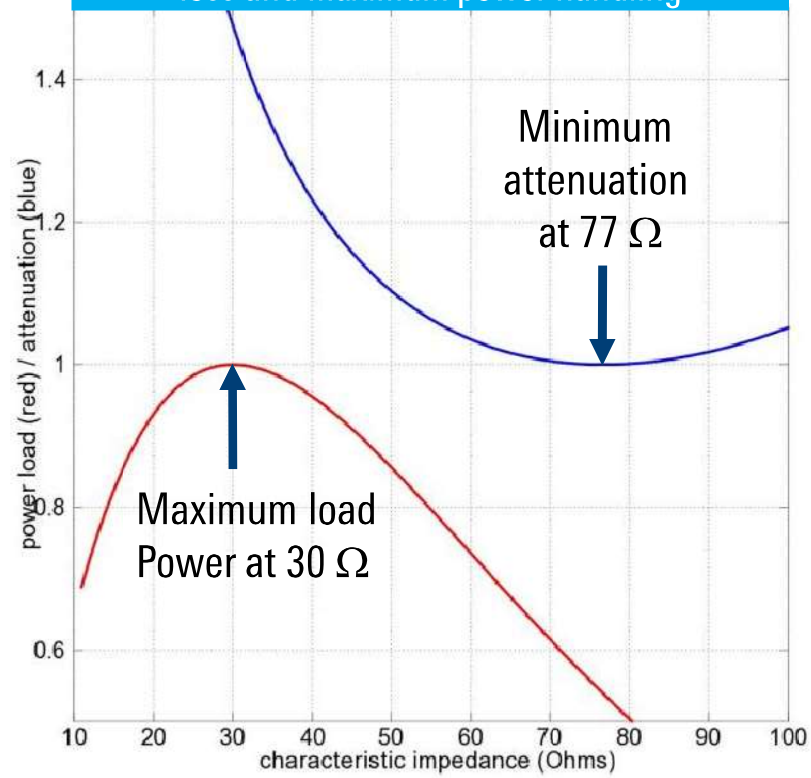
$d = 1.52\ mm$

Dielectric constant of insulator:

$\varepsilon_r = 1$

$$Z_O = \frac{138.2}{\sqrt{1}}\log\left(\frac{3.50}{1.52}\right) = 50\ \Omega$$

50 Ω is the compromise between low insertion loss and maximum power handling



Transmission line characteristic Impedance

Z_L	D/d	Special Characteristics	Application
77 Ω	3.6	min. attenuation	TV-receiving-antenna-line
60 Ω	2.72	max. voltage capability	No special use
30 Ω	1.65	Best power loading capacity	For very high transmitter-power
150 Ω	13	min. capacity per unit length	Low capacity test-lines (sensing head)
50 Ω	2.3	Compromise between α_{min} and P_{max}	Universally normed, RF measurement technique
93 Ω	4.8	Compromise between α_{min} and C_{min}	Lines used in data-communications

Transmission Line - Effect of dielectric material

Speed of Light (in vacuum)

$C_0 = 3 * 10^8$ m/s
(300 000 Km/s)

Example

In a vacuum the wave travels at the speed of light:

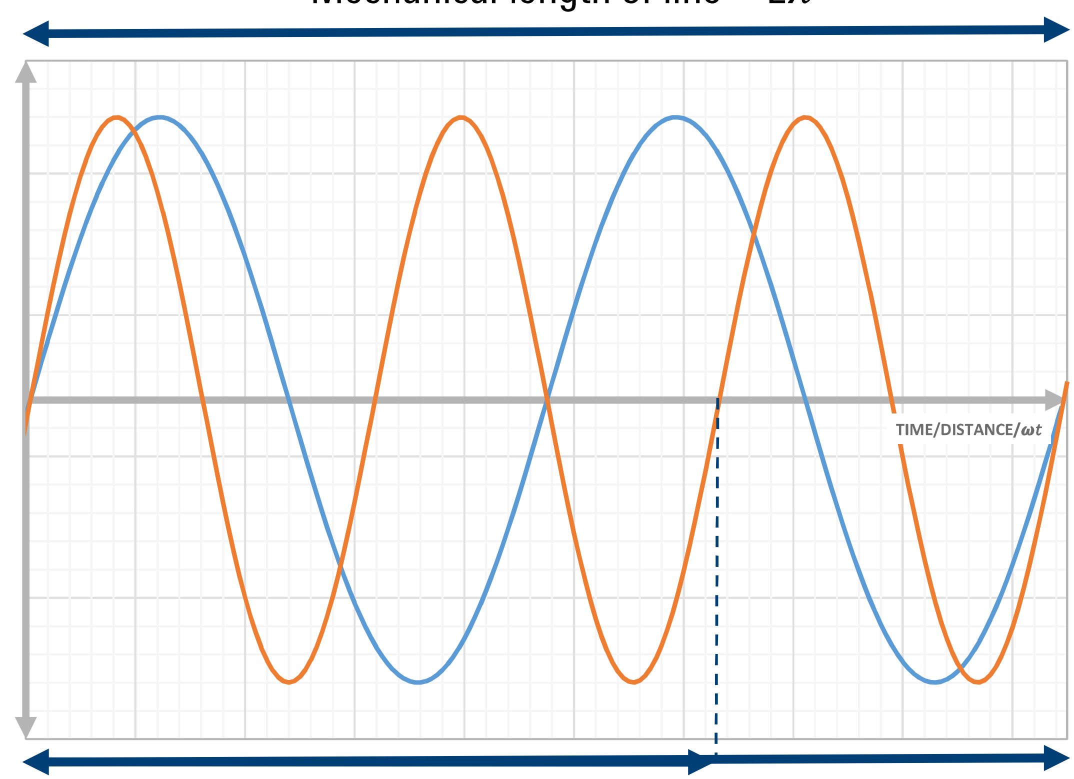
$C = C_0$ mechanical length = electrical length

travelling through a dielectric medium $\varepsilon_r = 2.25$:

$$C = \frac{C_0}{\sqrt{\varepsilon_r}} \qquad \sqrt{2.25} = 1.5 = \frac{2}{3}$$

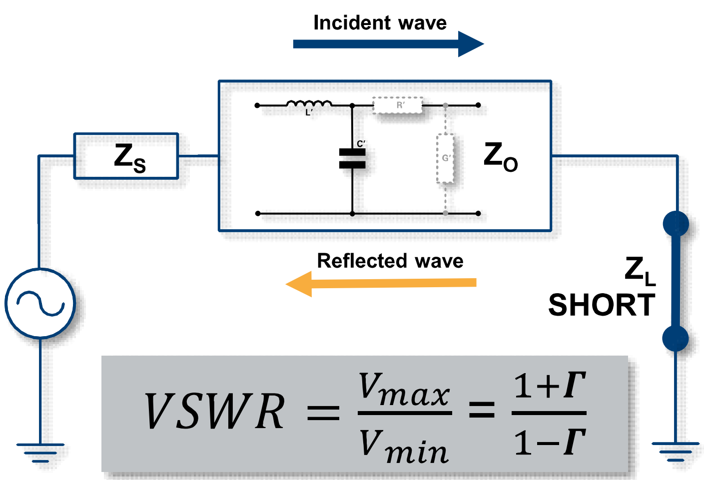
$C = \frac{2}{3} C_0$ mechanical length = $\frac{2}{3}$ electrical length

Mechanical length of line = 2λ



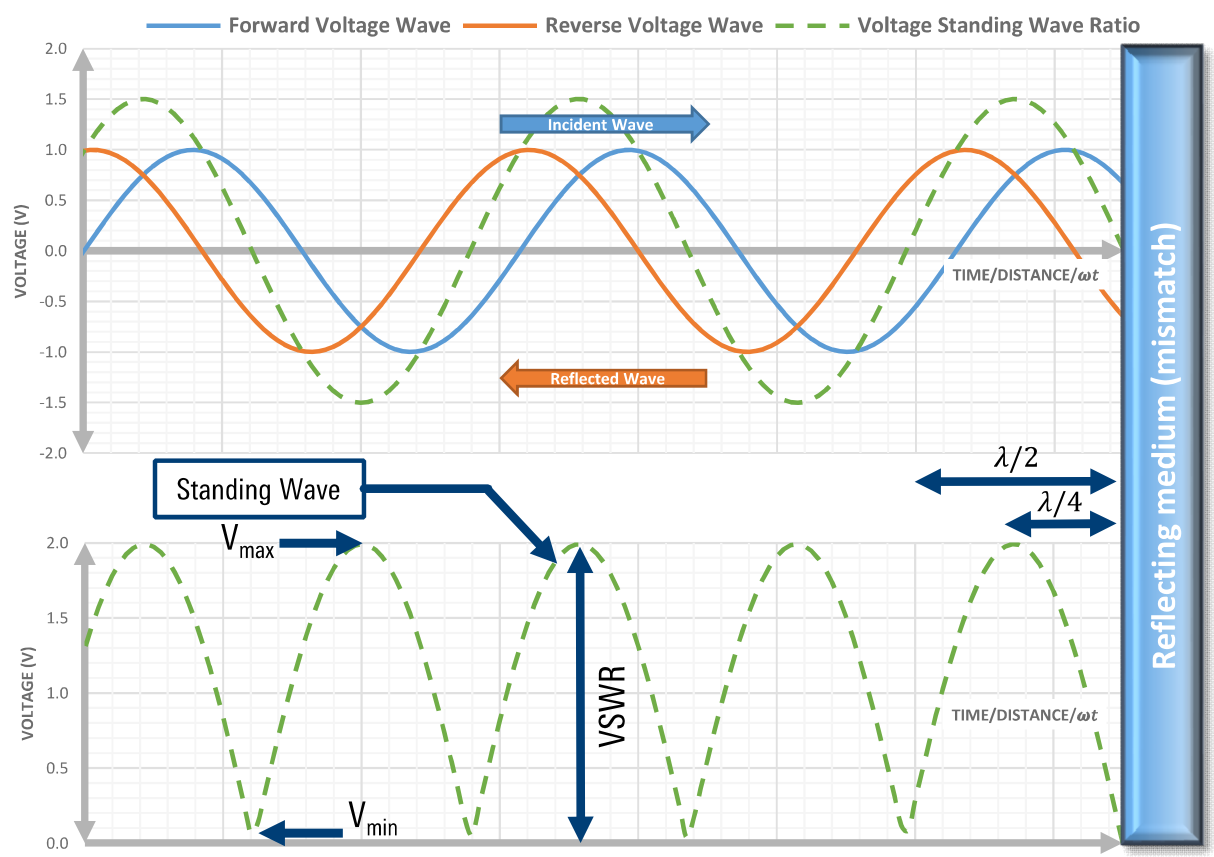
Electrical length of line = 2λ

Voltage Standing Wave Ratio (SWR)

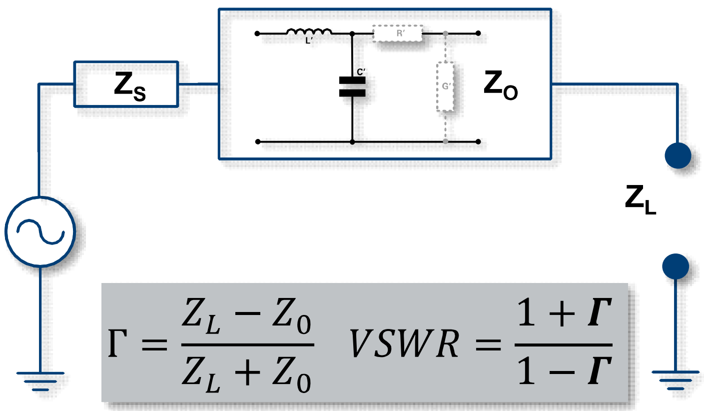


$$VSWR = \frac{V_{max}}{V_{min}} = \frac{1+\Gamma}{1-\Gamma}$$

For any mismatch a standing wave is created by the reflecting wave



Line terminations and the reflection coefficient



$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad VSWR = \frac{1+\Gamma}{1-\Gamma}$$

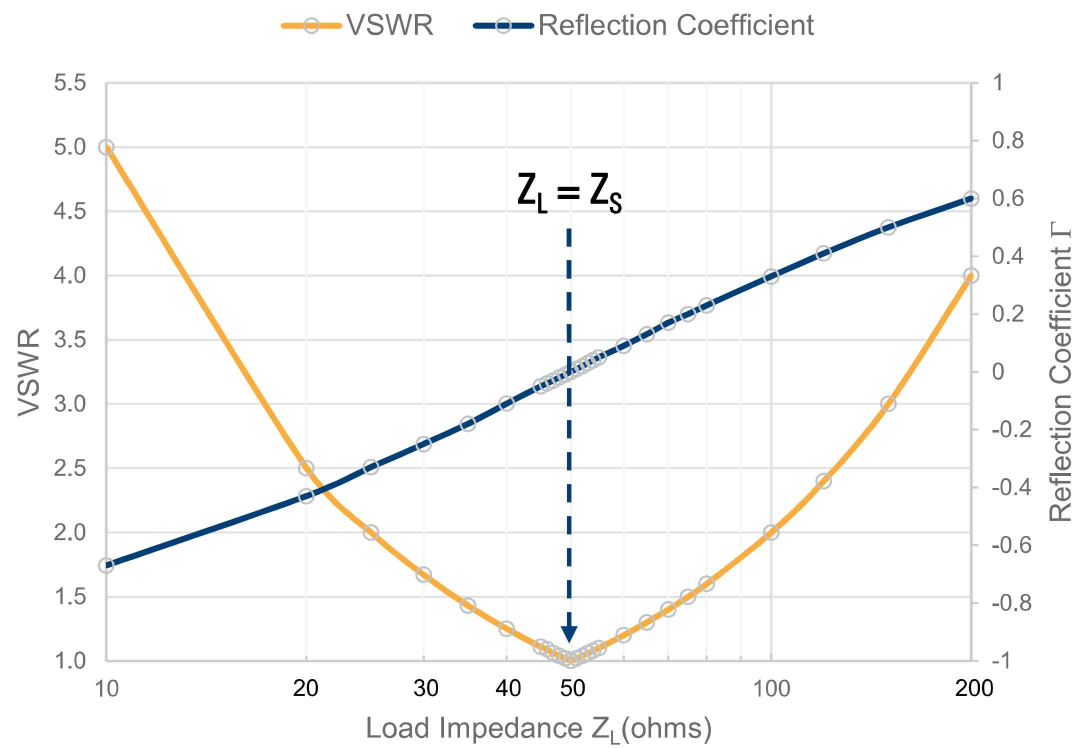
Maximum power is achieved when

$Z_L = Z_S$

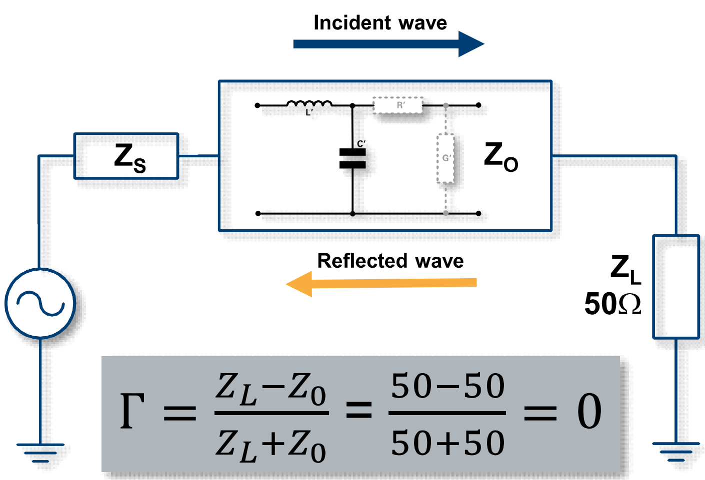
Therefore:

VSWR = 1

$\Gamma = 0$



Reflections and transmissions – MATCH

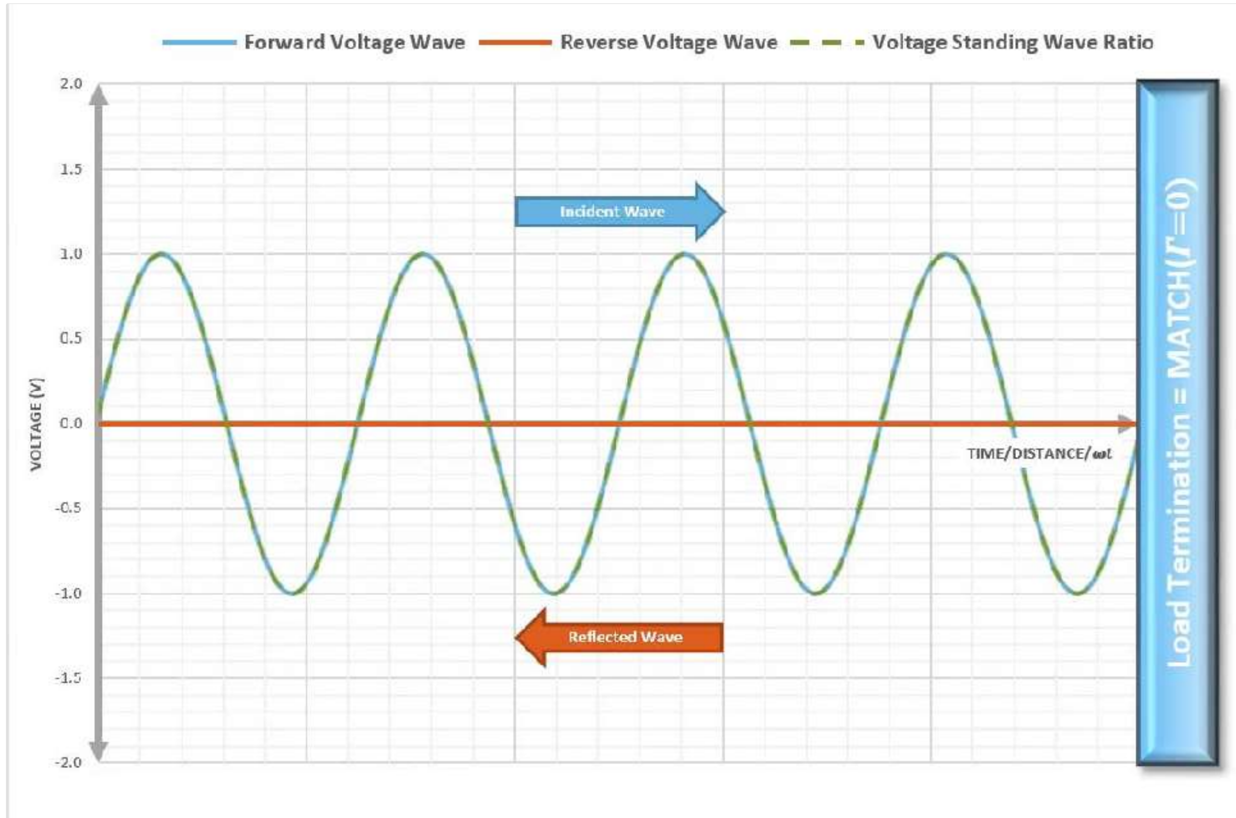


$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{50-50}{50+50} = 0$$

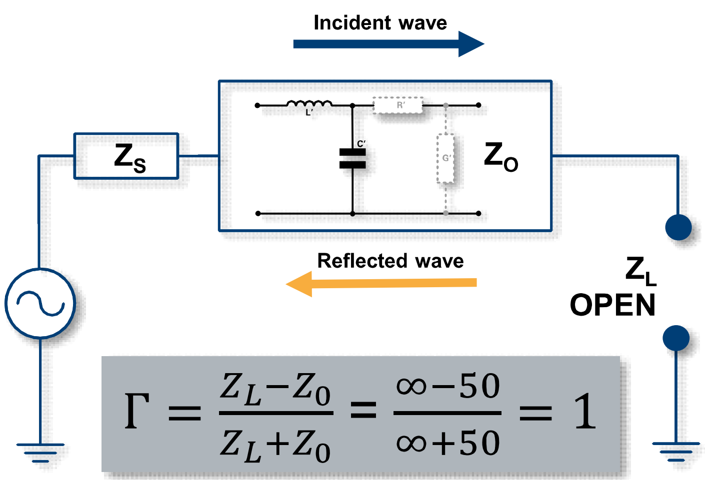
Perfect travelling wave

No space dependence

Perfect power transmission from source to load

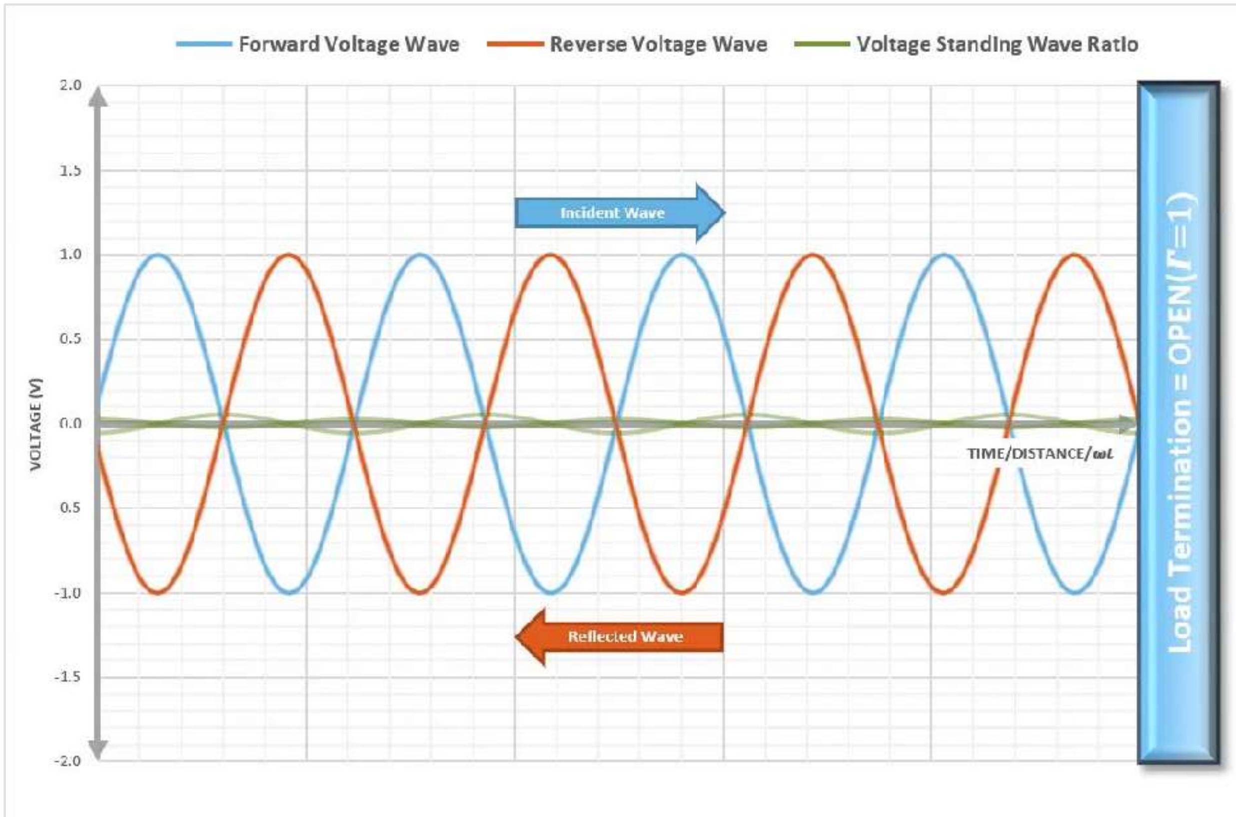


Reflections and transmissions – OPEN

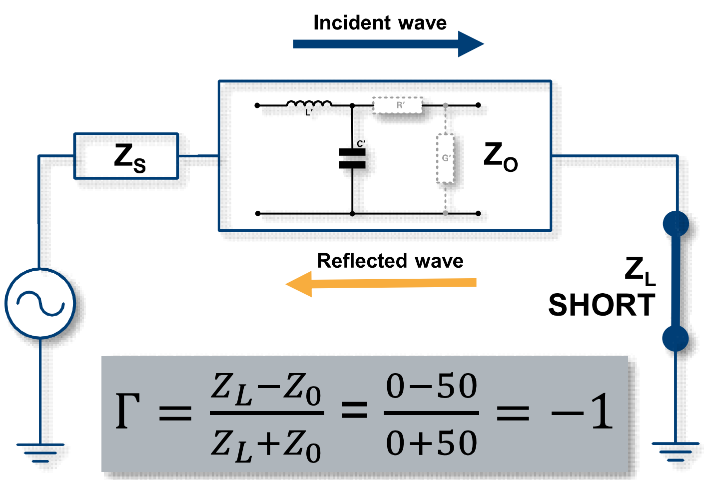


$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{\infty - 50}{\infty + 50} = 1$$

- Reactive behavior (V,I=-90°)
- Standing wave
- Voltage/current is space dependent
- Voltage oscillates along the length of the line



Reflections and transmissions – SHORT



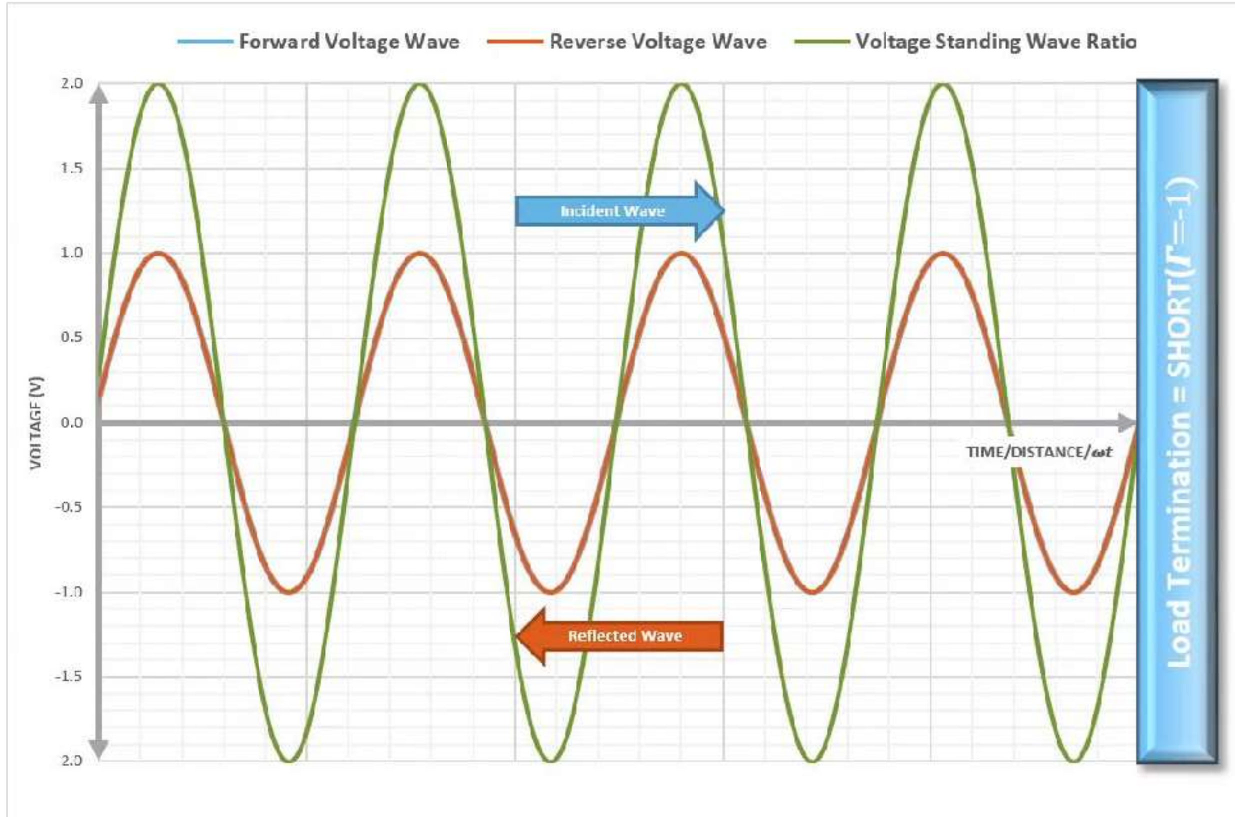
$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{0-50}{0+50} = -1$$

Reactive behavior (V,I=+90°)

Standing wave

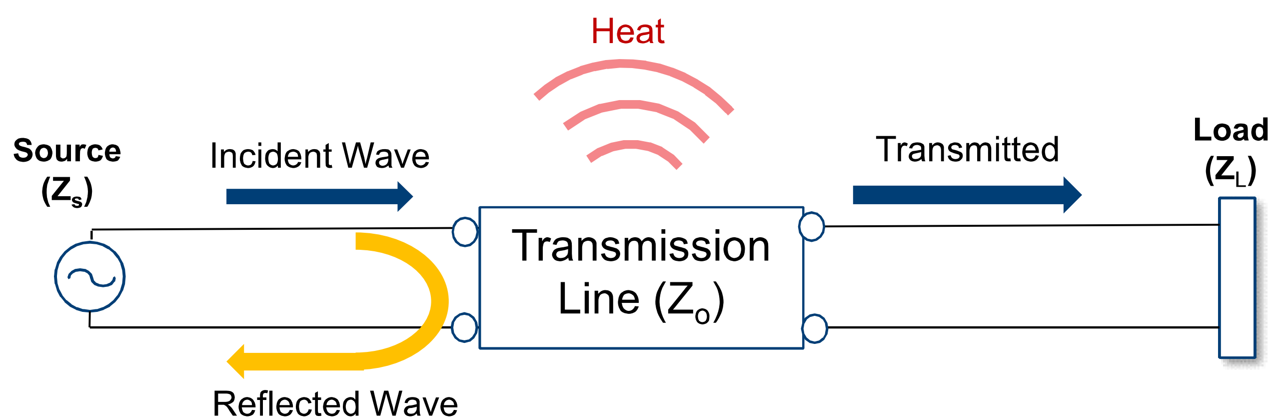
Voltage/current is space dependent

Voltage oscillates along the length of the line



Transmission Line – Loss

All Transmission Lines have some power loss.
**Unless they are super cool* 😎



Delay

Recap – RF Transmission Characteristic

- **Transmission line** is a physical path that is designed to handle RF signals
- Transmission lines are a necessary medium to carry signals efficiently at higher frequencies
- Use transmission line theory when line length is more than ~10% of wavelength
- Transmission lines are defined by **characteristic impedance**
- Transmission lines must be terminated with a matching characteristic impedance at the load for efficiently power transfer.
- **Impedance Mismatch** will create a Standing wave.

Thank you for Attending

RF Fundamentals:

SIX-PART WEBINAR SERIES

Part 2: RF Transmission Characteristics