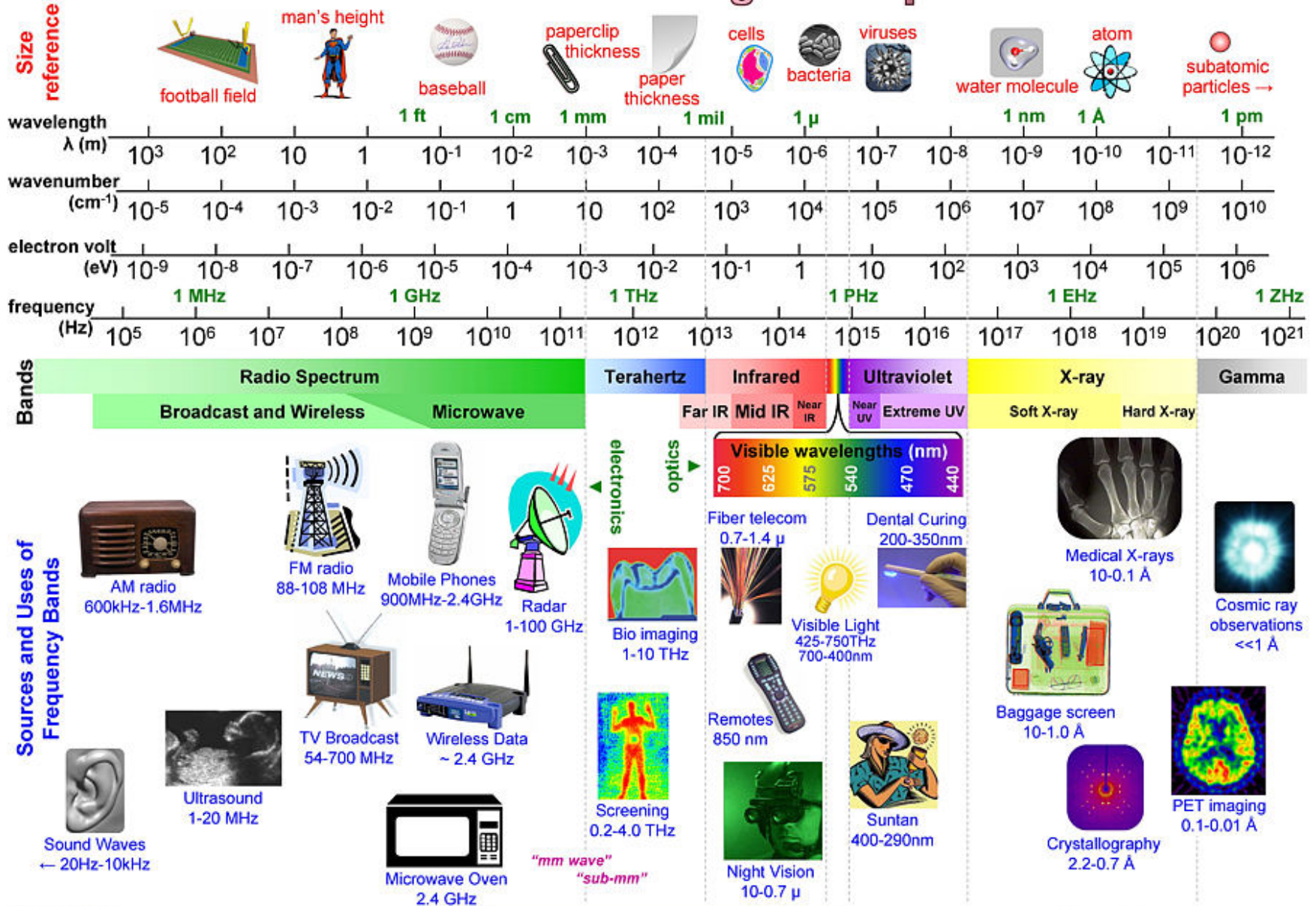


# INTRODUCTION TO TRANSMISSION LINES

DR. FARID FARAHMAND  
FALL 2012

# Chart of the Electromagnetic Spectrum



$$\lambda = 3 \times 10^8 / \text{freq} = 1 / (\text{wn} * 100) = 1.24 \times 10^{-6} / \text{eV}$$

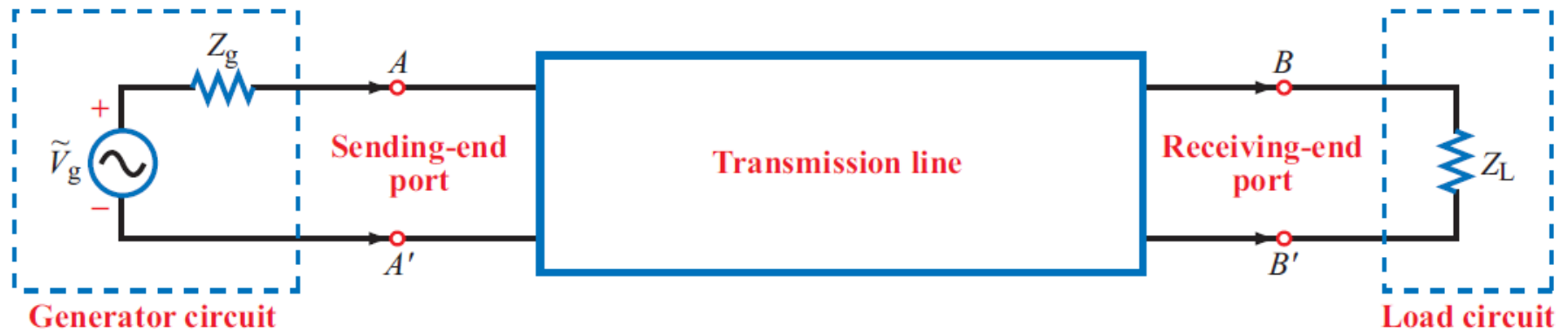
# RF Design

- In RF circuits RF energy has to be transported
  - ▣ Transmission lines
  - ▣ Connectors
- As we transport energy energy gets lost
  - ▣ Resistance of the wire → lossy cable
  - ▣ Radiation (the energy radiates out of the wire → the wire is acting as an antenna)

We look at transmission lines and their characteristics

# Transmission Lines

A transmission line connects a generator to a load – a two port network

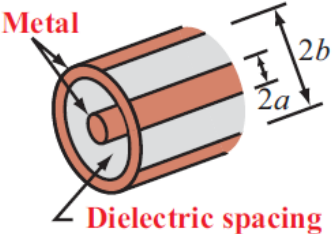


**Transmission lines include (physical construction):**

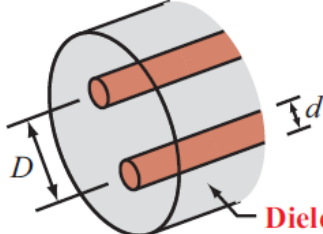
- Two parallel wires
- Coaxial cable
- Microstrip line
- Optical fiber
- Waveguide (very high frequencies, very low loss, expensive)
- etc.

# Types of Transmission Modes

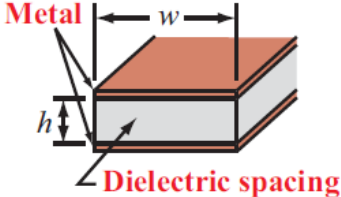
**TEM (Transverse Electromagnetic):** Electric and magnetic fields are orthogonal to one another, and both are orthogonal to direction of propagation



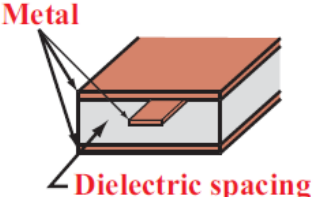
(a) Coaxial line



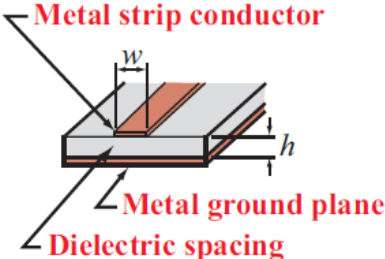
(b) Two-wire line



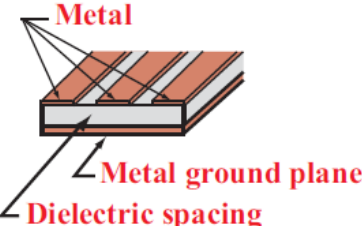
(c) Parallel-plate line



(d) Strip line

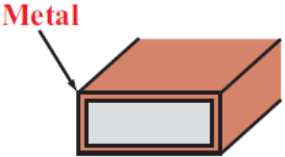


(e) Microstrip line

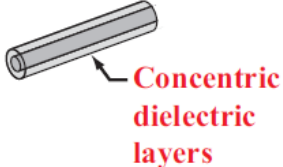


(f) Coplanar waveguide

**TEM Transmission Lines**



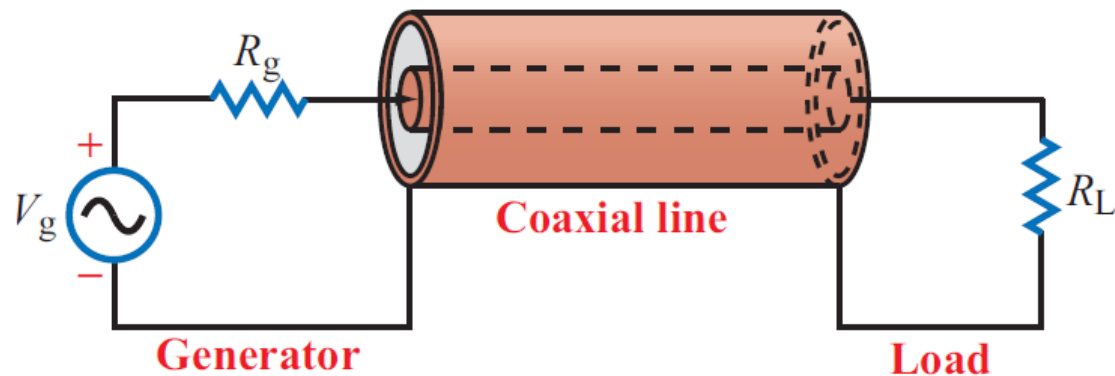
(g) Rectangular waveguide



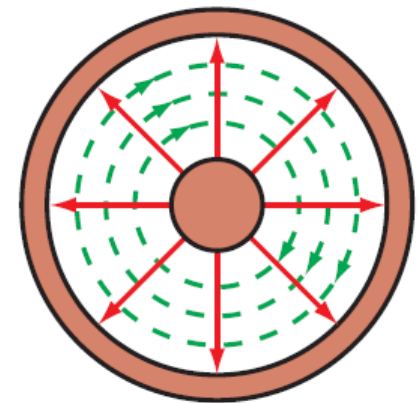
(h) Optical fiber

**Higher-Order Transmission Lines**

# Example of TEM Mode



--- Magnetic field lines  
— Electric field lines



Cross section

**Electric Field  $E$**  is radial  
**Magnetic Field  $H$**  is azimuthal  
Propagation is into the page

# Examples of Connectors



Connectors include  
(physical construction):

BNC  
UHF  
Type N  
Etc.

Connectors and TLs must match!

# Transmission Line Effects

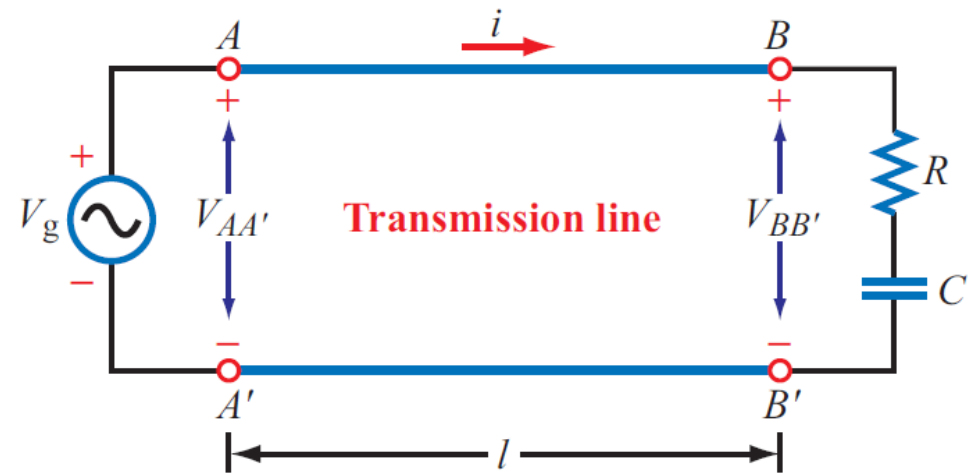
$$V_{AA'} = V_g(t) = V_0 \cos \omega t \quad (\text{V})$$

$$\begin{aligned} V_{BB'}(t) &= V_{AA'}(t - l/c) \quad \text{Delayed by } l/c \\ &= V_0 \cos [\omega(t - l/c)] \\ &= V_0 \cos(\omega t - \phi_0), \end{aligned}$$

At  $t = 0$ , and for  $f = 1 \text{ kHz}$ , if:

(1)  $l = 5 \text{ cm}$ :

$$V_{BB'} = V_0 \cos(2\pi f l/c) = 0.9999999999998 V_0$$



(2) But if  $l = 20 \text{ km}$ :

$$V_{BB'} = 0.91 V_0$$



# Properties of Materials (constructive parameters)

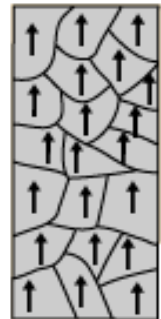
Remember: **Homogenous** medium is medium with constant properties

- Electric Permittivity  $\epsilon$  (F/m)
  - ▣ The higher it is, less E is induced, lower polarization
  - ▣ For air:  $8.85 \times 10^{-12}$  F/m;  $\epsilon = \epsilon_0 * \epsilon_r$
- Magnetic Permeability  $\mu$  (H/m)
  - ▣ For air:  $4\pi \times 10^{-7}$  H/m
  - ▣ Higher value  $\rightarrow$  **more** retention of magnetic property can be experienced in the material after removing B field
    - For ferromagnetic materials (Nickel, Cobalt)
  - ▣ If diamagnetic (gold) and paramagnetic (air)  $\mu \sim 1$
- Conductivity (S/m = Siemens/meter)
  - ▣  $\sigma = \infty \rightarrow$  perfect conductor
  - ▣  $\sigma = 0 \rightarrow$  perfect dielectric

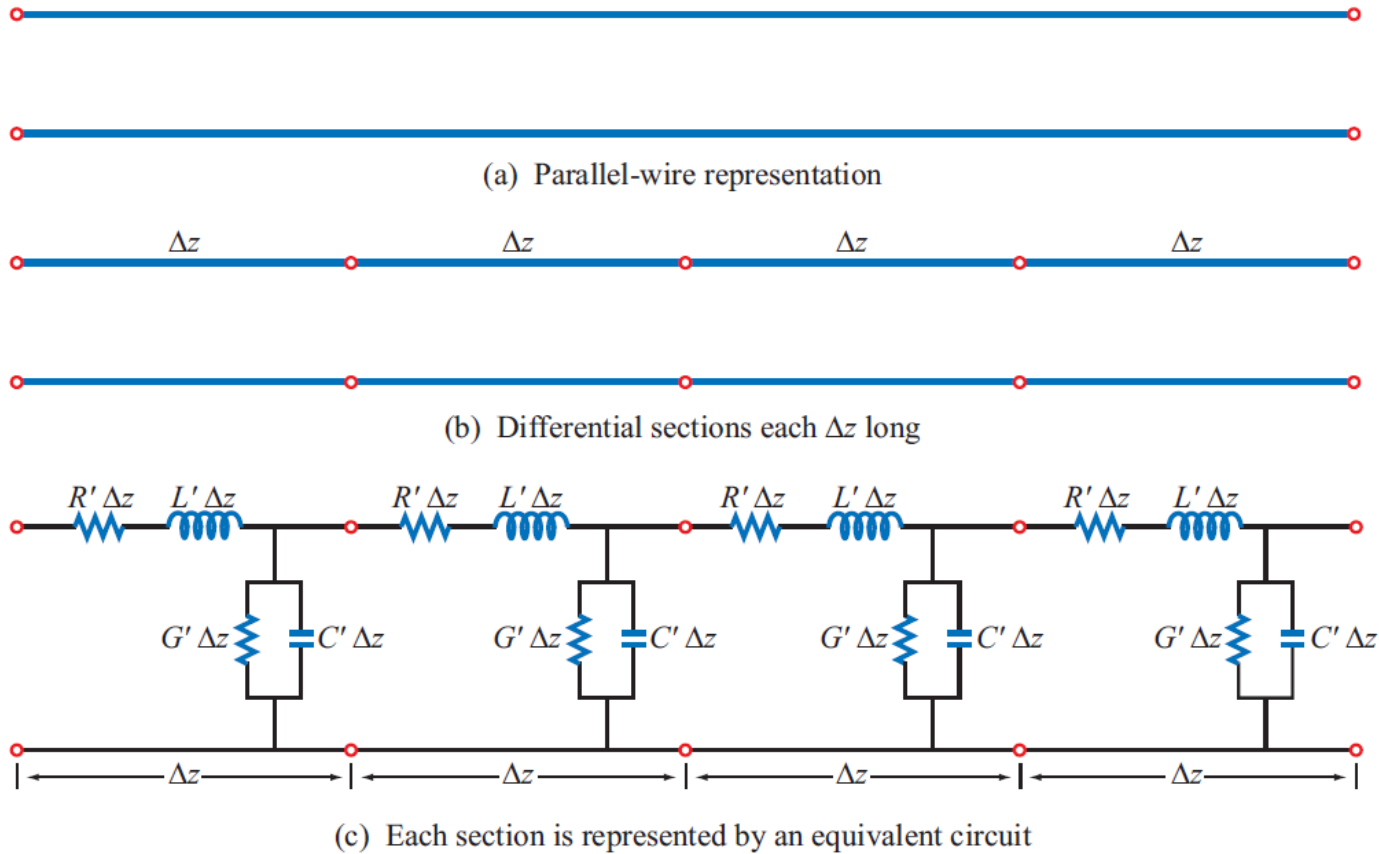
Relative permittivity and permeability (for air they are 1)

# Properties of Materials

- ❑ Ferromagnetic materials (Nickel, Cobalt, pure Iron) – magnetic material
  - Retain magnetic property
  - Higher  $\mu_r \rightarrow$  more retention
  - **Electrons are unpaired** orbiting around
- ❑ Diamagnetic materials (Gold, Copper) – non-magnetic material
  - Composed of atoms which have no net magnetic moments (i.e., all the orbital shells are filled and there are **no unpaired electrons**)  
- no net magnetic moment
  - When exposed to a field, a negative magnetization is produced
  - $\mu_r = 1$  (slightly less than 1)
- ❑ Paramagnetic materials (Air, Aluminum) – non-magnetic material
  - some of the atoms or ions in the material have a net magnetic moment due to **unpaired electrons** in partially filled orbitals
  - Magnetization is zero when the B field is removed
  - In the presence of a B field, there is a partial alignment of the atomic magnetic moments in the direction of the field, resulting in a net positive magnetization
  - $\mu_r = 1$  (slightly more than 1)



# Transmission Line Model



- $R'$ : The combined *resistance* of both conductors per unit length, in  $\Omega/\text{m}$ ,
- $L'$ : The combined *inductance* of both conductors per unit length, in  $\text{H}/\text{m}$ ,
- $G'$ : The *conductance* of the insulation medium between the two conductors per unit length, in  $\text{S}/\text{m}$ , and
- $C'$ : The *capacitance* of the two conductors per unit length, in  $\text{F}/\text{m}$ .

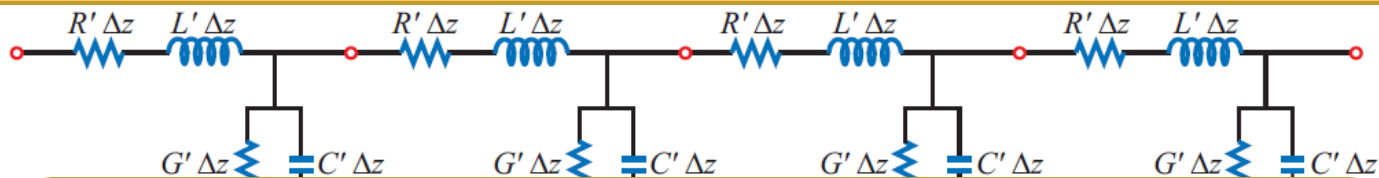
# Transmission Line Model

## Three Basic Properties:

**Resistance:** impacts the flow of current; controlled by the cross section area

**Inductance:** due to magnetic field; thus impacted by magnetic object

**Capacitance:** generally impacted by the grounding



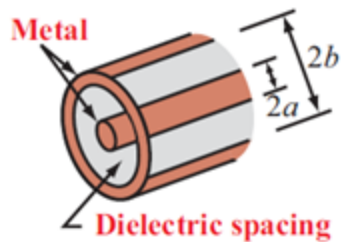
**Note that these parameters are very low when the input voltage is DC or operating at low frequency, thus they can be ignored!**

- $R'$ : The combined resistance of the two conductors per unit length, in  $\Omega/\text{m}$ .
- $L'$ : The combined inductance of the two conductors per unit length, in  $\text{H}/\text{m}$ .
- $G'$ : The conductance between the two conductors per unit length, in  $\text{S}/\text{m}$ .
- $C'$ : The capacitance of the two conductors per unit length, in  $\text{F}/\text{m}$ .

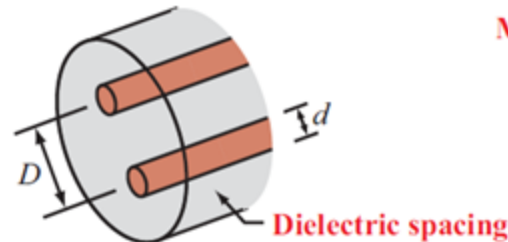
Transmission-line parameters  $R'$ ,  $L'$ ,  $G'$ , and  $C'$  for three types of lines.

Parameter	Coaxial	Two-Wire	Parallel-Plate	Unit
$R'$	$\frac{R_s}{2\pi} \left( \frac{1}{a} + \frac{1}{b} \right)$	$\frac{2R_s}{\pi d}$	$\frac{2R_s}{w}$	$\Omega/\text{m}$
$L'$	$\frac{\mu}{2\pi} \ln(b/a)$	$\frac{\mu}{\pi} \ln \left[ (D/d) + \sqrt{(D/d)^2 - 1} \right]$	$\frac{\mu h}{w}$	$\text{H}/\text{m}$
$G'$	$\frac{2\pi\sigma}{\ln(b/a)}$	$\frac{\pi\sigma}{\ln \left[ (D/d) + \sqrt{(D/d)^2 - 1} \right]}$	$\frac{\sigma w}{h}$	$\text{S}/\text{m}$
$C'$	$\frac{2\pi\epsilon}{\ln(b/a)}$	$\frac{\pi\epsilon}{\ln \left[ (D/d) + \sqrt{(D/d)^2 - 1} \right]}$	$\frac{\epsilon w}{h}$	$\text{F}/\text{m}$

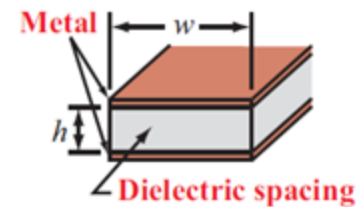
Notes: (1)  $R_s$  is the surface resistance of the conductors. (2)  $\mu$ ,  $\epsilon$ , and  $\sigma$  pertain to the insulating material between the conductors. (3)  $R_s = \sqrt{\pi f \mu_c / \sigma_c}$ . (4)  $\mu_c$  and  $\sigma_c$  pertain to the conductors. (5) If  $(D/d)^2 \gg 1$ , then  $\ln \left[ (D/d) + \sqrt{(D/d)^2 - 1} \right] \simeq \ln(2D/d)$ .



(a) Coaxial line



(b) Two-wire line



(c) Parallel-plate line

# TEM Transmission Line

- For all TEMs:

$$L' C' = \epsilon \mu$$

*Perfect Conductor* :  $\sigma = \infty; R_s \approx 0$      $G' / C' = \sigma / \epsilon$

*Perfect Dielectric* :  $\sigma = 0; G' \approx 0$

- If the TL is lossless:

$$Z_o = \sqrt{L' / C'}$$

$$c = 1 / \sqrt{\epsilon_o \mu_o}$$

$$v_p = \lambda \cdot f = 1 / \sqrt{L' C'} = c / \sqrt{\epsilon_r \mu_r} = \omega / \beta$$

$$V(t, x) = A \cos(\omega t - \beta x + \varphi_o)$$

Lossless medium

$$V(t, x) = A e^{-\alpha x} \cos(\omega t - \beta x + \varphi_o)$$

Lossy medium;  
a is the attenuation constant (Neper/m)

Sinusoidal traveling wave representation

# Wave Propagations

- Propagation Velocity

- Assuming lossless line

$$v_p = \lambda \cdot f = 1 / \sqrt{LC'}$$

- Velocity Factor VF =  $v_p / C$  (less than one)

- Where  $C = 3 \times 10^8$  m/s

- Dispersion effect is due to  $V_p$  variations due to frequency differences

- Remember any composite signal is made up of many difference frequency components (cf., Fourier Analysis)
- The result is a narrowed pulse!

Example 1  
See Notes

The speed of light = 299 792 458 m / s

# Energy Loss

- As the wave propagates it may lose energy
  - ▣ Ohmic Loss: Due to resistance of the wire; at high frequency current flows outside the surface of the conductor → **Skin Effect** (thus circumference is critical)
  - ▣ Dielectric Loss: Energy is lost in dielectric → converted to heat! The best dielectric is air!
- How much energy is lost
  - ▣ Measured in dB/unit\_of\_length

$$dB_{gain} = 10 \log(P_{out} / P_{in})$$

Example 2  
See Notes

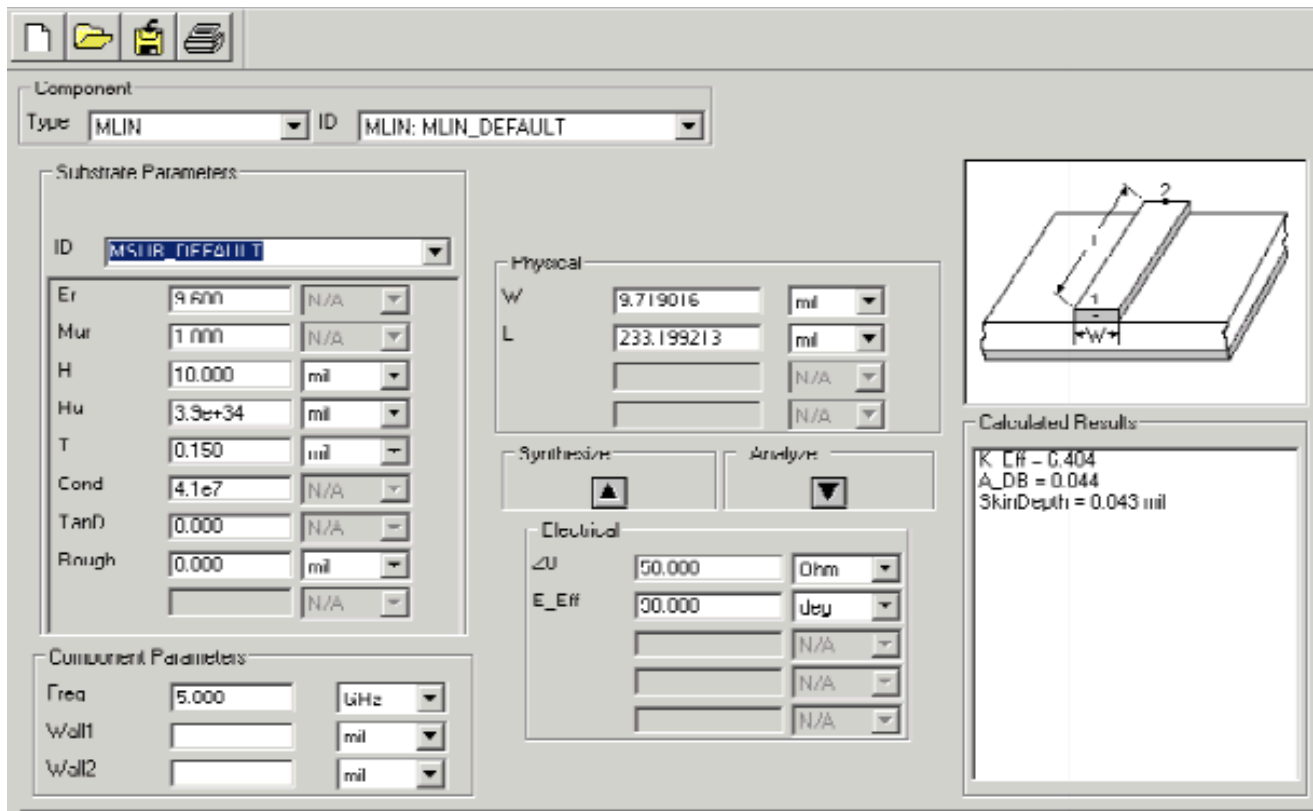


# ADS LineCalc Tutorial – (1)

Tutorial Available at:

[http://newport.eecs.uci.edu/eceware/ads\\_docs/pdf/linecalc.pdf](http://newport.eecs.uci.edu/eceware/ads_docs/pdf/linecalc.pdf)

- ADS has many other tools built into it. A popular one is LineCalc. This tool calculates impedances and dimensions for the much different geometry of wave-guides and microstrip lines. To start the tool, there must already be a schematic open. Use the quarter-wave circuit just built. From the schematic at the top choose Tools → LineCalc → Start LineCalc. A window such as that below will appear.

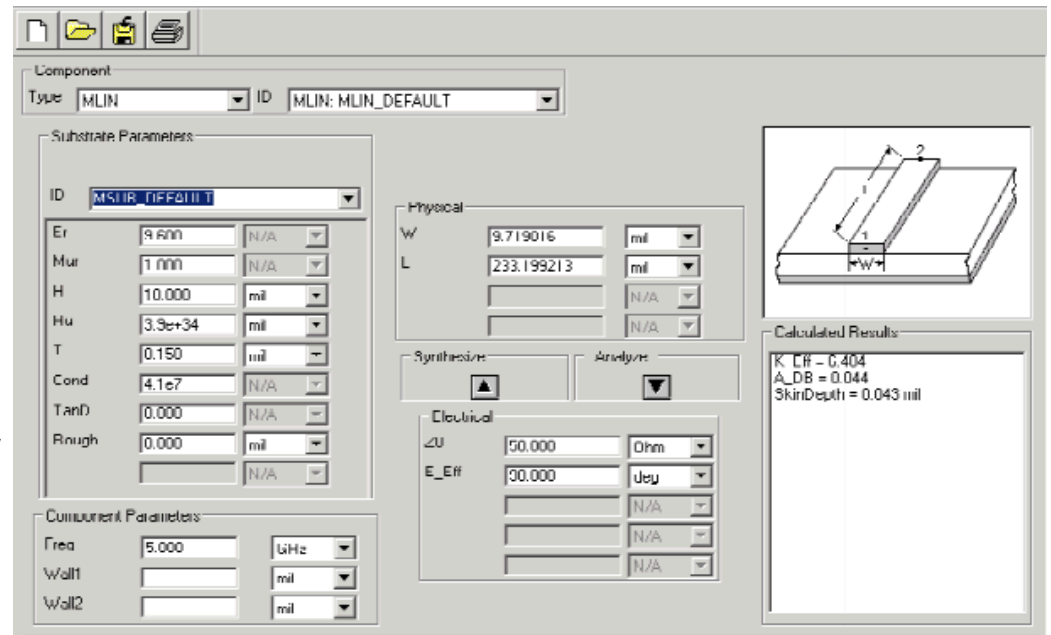


# ADS LineCalc Tutorial – (2)

- At the top is the Type of structure to be analyzed. The program defaults to microstrip. Take a look at some of the other available such as COAX and CPW. The ID is the name of the defaults being viewed. This has initial parameter values and an initial Type. You can make your own ID if you wish. For the microstrip the parameters stand for:
- Er – relative permittivity
- Mur – relative permeability
- H – height of the substrate
- Hu – if the design was covered by a metal box, this would be its height
- T – conductor thickness
- Cond – conductivity of the conductor
- TanD – dielectric loss tangent
- Rough – RMS surface roughness of the dielectric
- W – width of conductor
- L – length of line
- Z0 – characteristic impedance of line
- E\_Eff – effective electrical length
- K\_Eff – effective dielectric permittivity of the system
- A\_DB – total attenuation of the system

# ADS LineCalc Tutorial – (3)

Let's go through an example. Set all but the Physical parameters (W and L) to those as in the Fig. Notice there are two arrows. Clicking the arrow pointing up will calculate W and L of the microstrip while clicking the down arrow will calculate Z0 and E\_Eff. Push the up arrow. The simulator will run and the W and L will be calculated as in the Fig. Let's go the other way. Set W = 50 mil and click the down arrow. Now Z0 = 17.806900 and E\_Eff = 98.733400. A wider conductor gives lower impedance as would be expected.

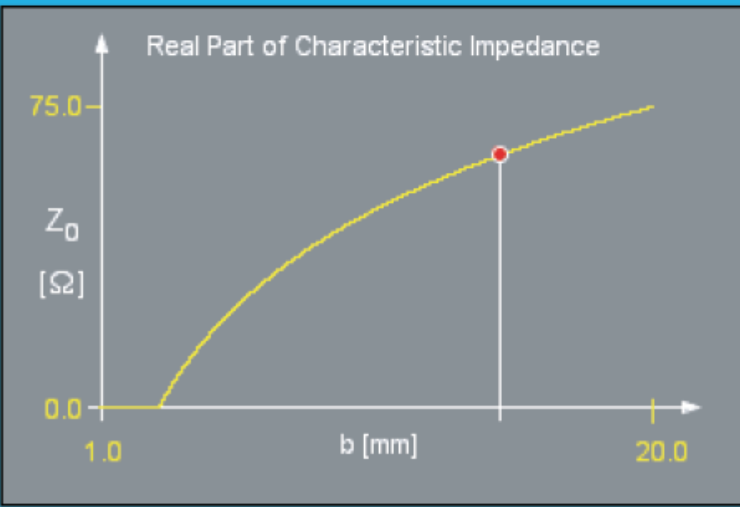
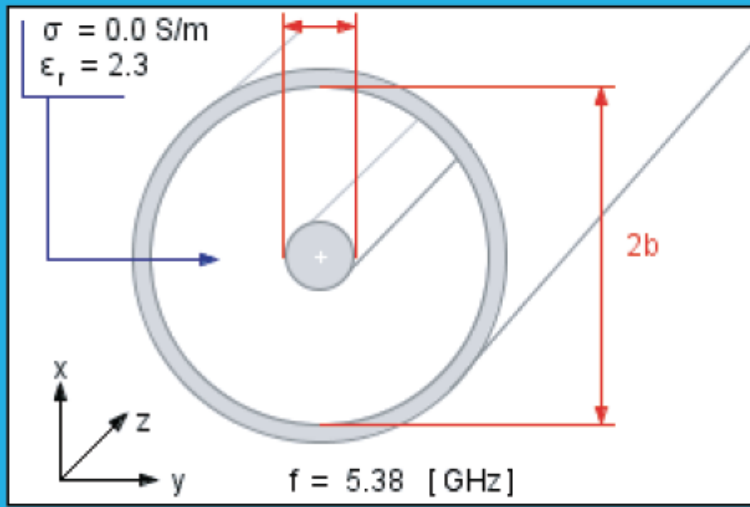


For more information use the online help command!

LineCalc  
Example

**Module 2.2 Coaxial Cable**

Select: Impedance vs. Radius b



**Input**

Inner radius a =  [mm]  
 Range

Shield radius b =  [mm]  
 Range

Frequency f =  [Hz]  
 Range

$\epsilon_r$        $\sigma$  [S/m]       $\sigma_c$  [S/m]  
           

**Output**

Structure Data

a = 3.034 [mm]      b / a = 4.86417  
 b = 14.7579 [mm]

---

$Z_0 = 62.584306 - j 0.0035419$  [Ω]  
 $C' = 80.775048$  [pF/m]  
 $L' = 316.37933$  [nH/m]  
 $R' = 1.210519$  [Ω/m]  
 $G' = 0.0$  [S/m]

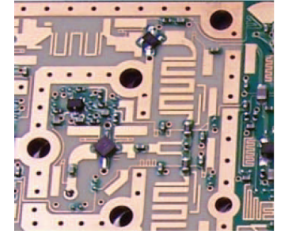
---

$\lambda_0 = 5.5762$  [cm]      in vacuum  
 $\lambda = 3.6768$  [cm]      in guide

---

$\alpha = 0.009671$  [Np/m]  
 $\beta = 170.88534$  [rad/m]

# Practice:



- Estimate the impedance of a coaxial cable assuming the relative permeability of the conductor is 1; this is actually the simplified form for calculating the lossless coaxial TL. You must simplify the expression as much as possible. The expression must be a function of dimensions and relative permittivity of the line.
- Assuming  $E(x,t) = 2\cos(3 \times 10^{15}t - 10^7x)$  V/m, calculate the wave velocity.
- Assume we have a transmission line in which air separates the two perfect conductors. Assume the impedance of the line is 50 ohm, phase constant is 20 (rad/m) and the operating frequency is 700 MHz. Calculate the line inductance/meter and capacitance/meter.
- Refer to the Microstrip Transmission Line Applet and design a 33 ohm microstrip. Assume  $h=0.635$  mm;  $t=0.005$  mm;  $f=1.794$  GHz; relative permittivity of the substrate is 9.8 with perfect conductor. What happens to the impedance if the width of the trace changes by 10 percent? Show a snapshot of your results.
- Learn about EEsof LineCalc. Repeat the LineCalc Example in the previous slides. Show what happens if the conductor's width is increased by 10 percent. Show a snapshot of your results.