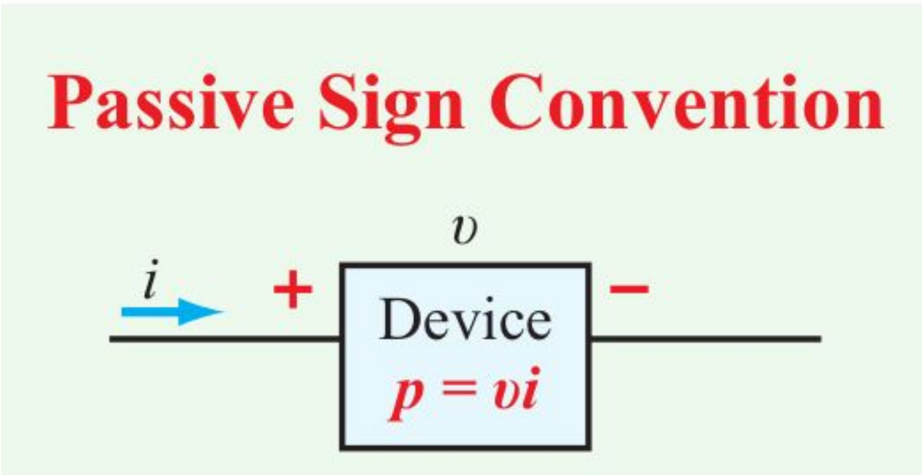
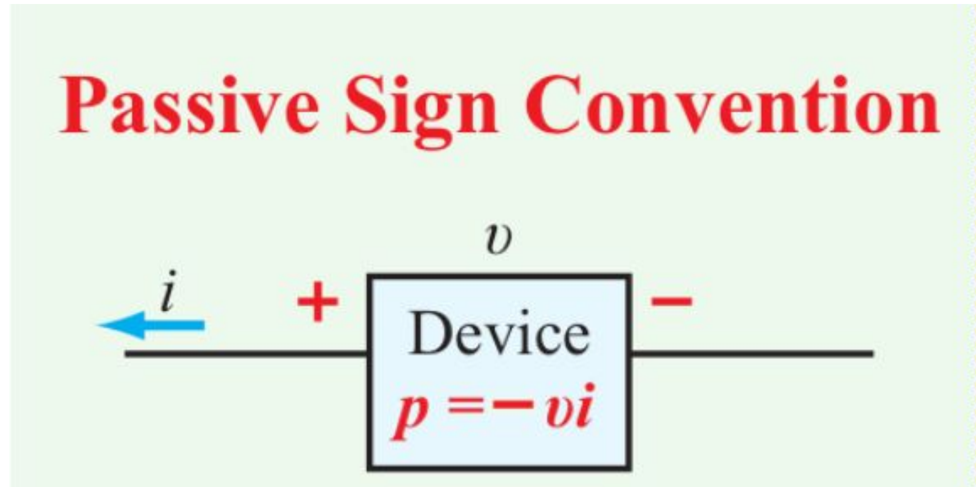
EECS 230
ENGINEERING ELECTROMAGNETICS

Leland Pierce

Transmission Lines 1

Power





$p > 0$	power delivered to device
$p < 0$	power supplied by device

Chapter 2 Overview

What is a transmission line?

Why study transmission lines?

model

diffeq

solve diffeq

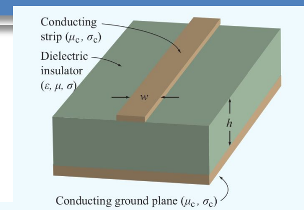
wave propagation

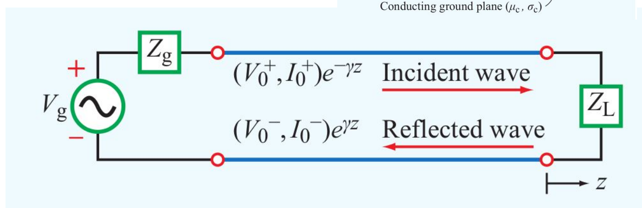
lossless xmission lin

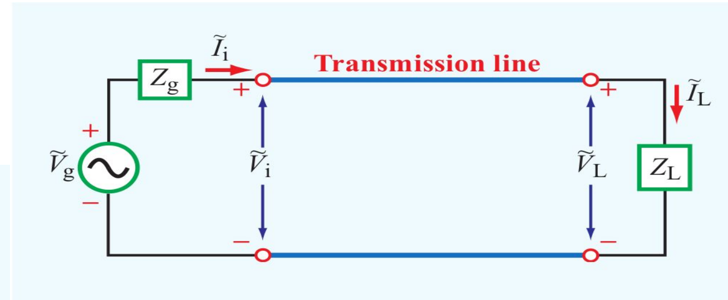
- microstrip lines
- reflections
- standing waves
- impedance
- short, open
- matching
- power flow

smith chart

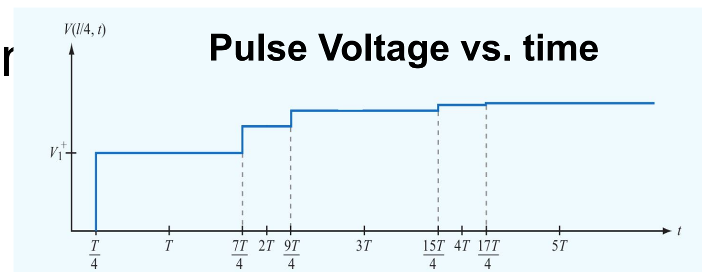
transients

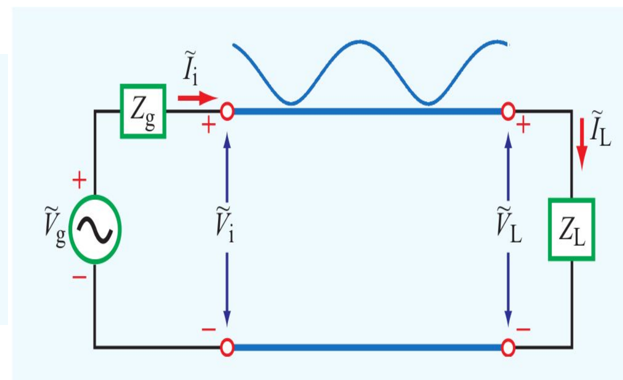




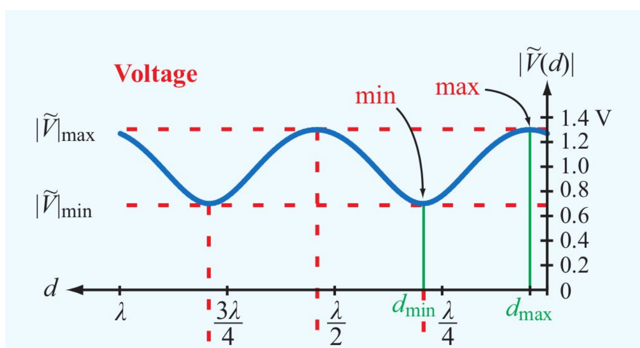


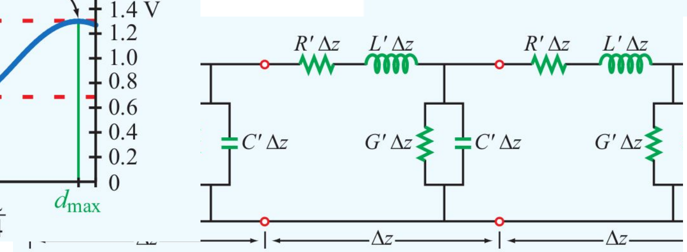
Typical High-Frequency Circuit

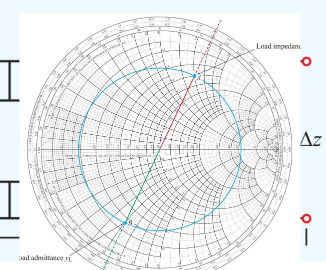




Waves on line: old methods don't work







Chapter 2 Applications

Radios: **cell phones, internet, broadcast radio/tv, GPS**

Radar: **civilian, aeronautical, military, vehicle collision sensors, weather, remote sensing**

Heating: **Microwave Ovens, Cancer Treatment**

Relevant EECS Classes

411/413: RF circuits

330/430/455: Wireless circuits, systems

525: Advanced RF circuits

531: Antenna Design

532/632: Remote Sensing

Today's Lecture Coverage

Sections 1-6, 2-1, 2-2 of the book:

1-6: Review of complex numbers

2-1: What is a transmission line?
Why study transmission lines?

2-2: Lumped-Element Model

1-6 Complex Numbers

Already used complex numbers when discussing phasors last time.

This is a review of properties and best practices.

$$j = \sqrt{-1}$$

to avoid any confusion with current, *i*.

A complex number has a real-part and an imaginary-part:

$$z = x + jy$$

Operators to get these:

$$x = \Re e(z), \qquad y = \Im m(z).$$

1-6 Complex Numbers

Rectangular Form: $z = x + jy$

Polar Form: $z = |z|\, e^{j\phi}$

alternate notation:

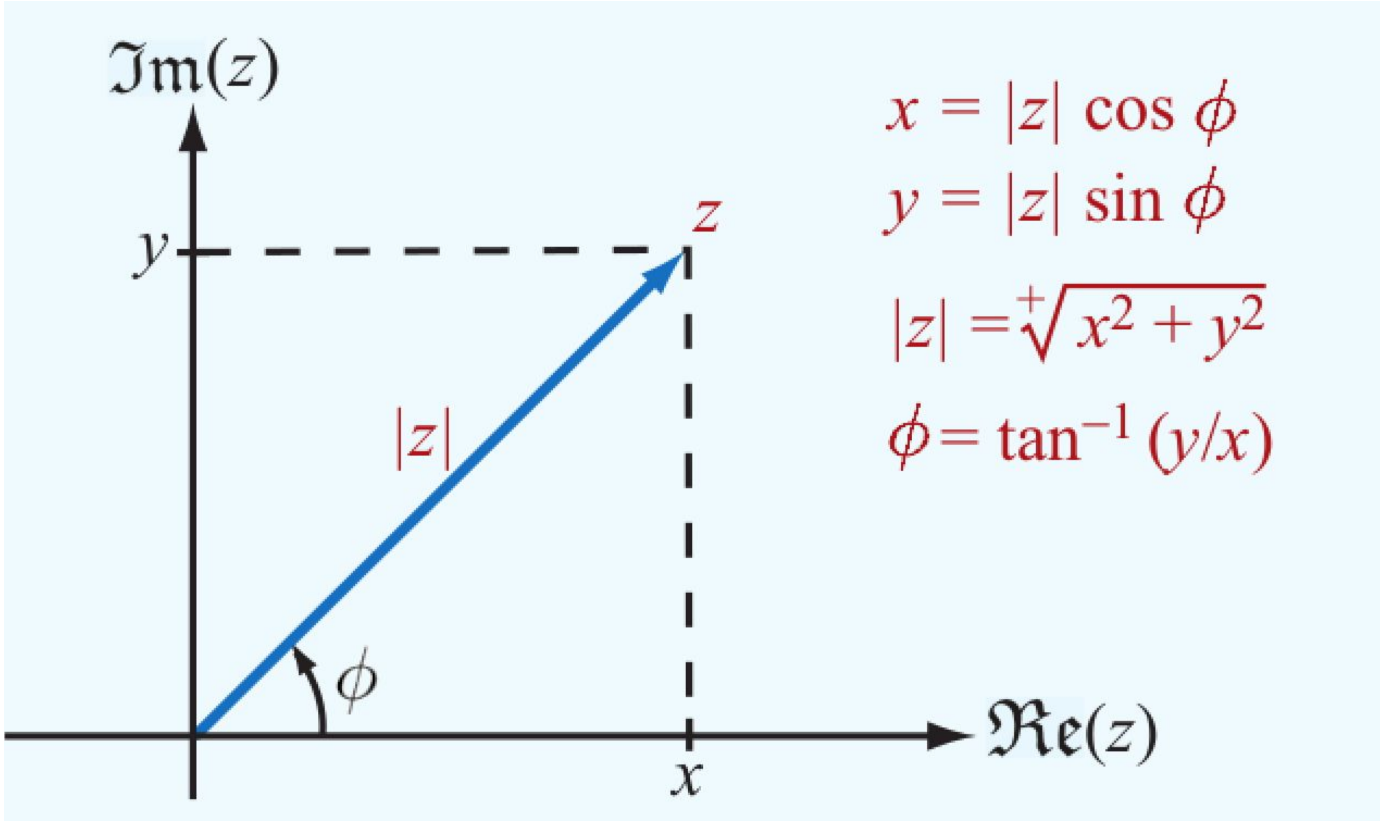
$$z = |z| \angle \phi$$

Euler's identity: $e^{j\phi} = \cos\phi + j\sin\phi$

$$z = |z|e^{j\phi} = |z|\cos\phi + j|z|\sin\phi$$

1-6 Complex Numbers

Complex Plane:



1-6 Complex Numbers

Complex Conjugate: replace *j* with *-j*:

$$z^* = (x + jy)^* = x - jy = |z|e^{-j\theta} = |z|\underline{/-\theta}.$$

so:

$$|z| = \sqrt[+]{zz^*}.$$

1-6 Complex Numbers

Addition/subtraction is easier with the rectangular form:

$$z1 + z2 = (x1+x2) + j\,(y1+y2)$$

Multiplication is easier with the polar form:

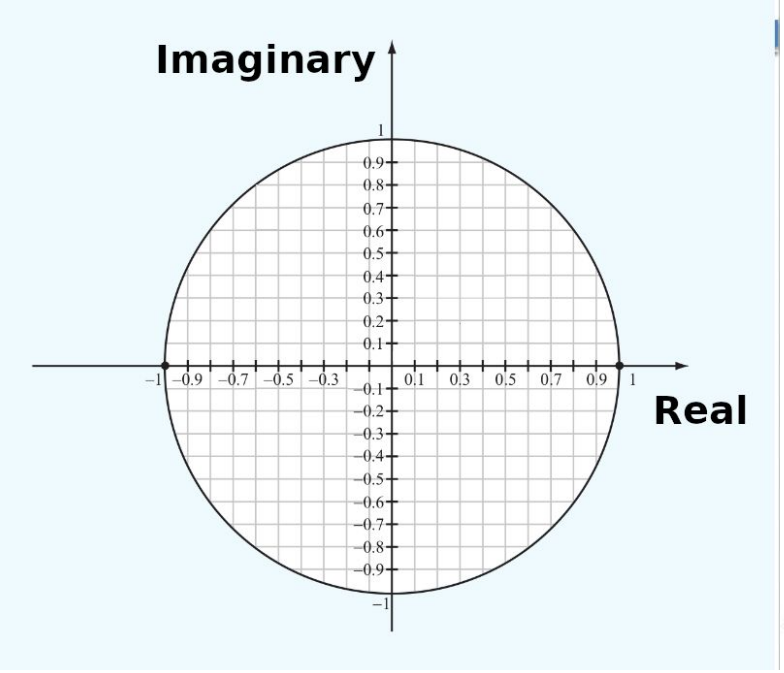
$$z1 \times z2 = |z1||z2|\, e^{j(\phi 1+\phi 2)}$$

Powers are easier with the polar form:

$$\begin{aligned} z^n &= \left(|z|e^{j\theta}\right)^n \\ &= |z|^n e^{jn\theta} \end{aligned}$$

1-6 Complex Numbers

Useful Relations:



$$-1 = e^{j\pi} = e^{-j\pi} = 1\underline{/180^\circ},$$

$$j = e^{j\pi/2} = 1\underline{/90^\circ},$$

$$-j = -e^{j\pi/2} = e^{-j\pi/2} = 1\underline{/-90^\circ},$$

$$\sqrt{j} = (e^{j\pi/2})^{1/2} = \pm e^{j\pi/4} = \frac{\pm(1+j)}{\sqrt{2}},$$

$$\sqrt{-j} = \pm e^{-j\pi/4} = \frac{\pm(1-j)}{\sqrt{2}}.$$

Example 1-3

Given two complex numbers:

$$V = 3 - j4, \qquad I = -(2 + j3),$$

Express each in polar form:

$$\begin{aligned} V &= |V| e^{j\phi_V} \\ |V| &= \sqrt[+]{VV^*} \\ &= \sqrt[+]{(3 - j4)(3 + j4)} \\ &= \sqrt[+]{3^2 + 4^2} \\ &= 5 \\ \phi_V &= \tan^{-1}(-4/3) \\ &= -53.1^\circ \end{aligned}$$

$$\boxed{V = 5e^{-j53.1^\circ} = 5\angle{-53.1^\circ}}$$

Example 1-3

Given two complex numbers:

$$V = 3 - j4, \qquad I = -(2 + j3),$$

Express each in polar form:

$$I = |I|e^{j\phi_I}$$

$$|I| = \sqrt[+]{II^*}$$

$$= \sqrt[+]{(-2 - j3)(-2 + j3)}$$

$$= \sqrt[+]{2^2 + 3^2}$$

$$= \sqrt[+]{13}$$

$$= 3.61$$

$$\phi_I = \tan^{-1}(-3/-2)$$

Example 1-3

Given two complex numbers:

$$V = 3 - j4, \qquad I = -(2 + j3),$$

Express each in polar form:

Calculators only give the correct arctan when in the 1st and 4th quadrants (x>0),

since this is in the 3rd quadrant, use:

$$\phi_I = 180^\circ + \tan^{-1}(3/2)$$

$$\phi_I = 236.3^\circ$$

$$\boxed{I = 3.61 e^{j236.3^\circ} = 3.61\underline{/236.3^\circ}}$$

Example 1-3

Given two complex numbers:

$$V = 3 - j4, \qquad I = -(2 + j3),$$

Multiply:

Use polar forms:

$$VI = 5e^{-j53.1^\circ} \times 3.61e^{j236.3^\circ}$$

$$= 18.03e^{j(236.3^\circ - 53.1^\circ)}$$

$$\boxed{VI = 18.03e^{j183.2^\circ}}$$

Example 1-3

Given two complex numbers:

$$V = 3 - j4, \qquad I = -(2 + j3),$$

Divide:

Use polar forms:

$$\frac{V}{I} = \frac{5e^{-j53.1^\circ}}{3.61e^{j236.3^\circ}}$$

$$= 1.39e^{-j289.4^\circ}$$

$$\boxed{\frac{V}{I} = 1.39e^{j70.6^\circ}}$$

Example 1-3

Given two complex numbers:

$$V = 3 - j4, \qquad I = -(2 + j3),$$

Square-root of I:

Use polar form:

$$\sqrt{I} = \sqrt{3.61 e^{j236.3^\circ}}$$

$$= \pm\sqrt{3.61}\, e^{j236.3^\circ/2}$$

$$\sqrt{I} = \pm 1.90 e^{j118.15^\circ}$$

Note that there are 2 roots, as usual.

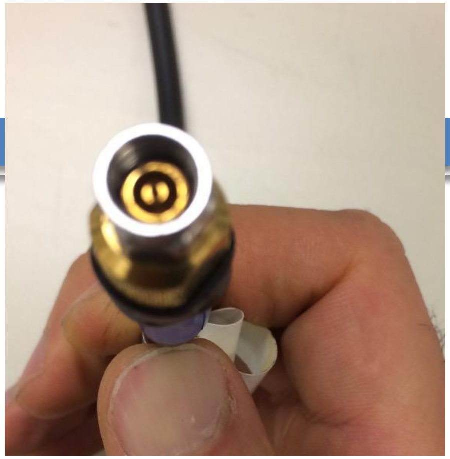
2-1 Transmission Lines

- Transfers energy (or information) between two points in a circuit (sort of conduit of EM signals).

- It can take different shapes and forms.

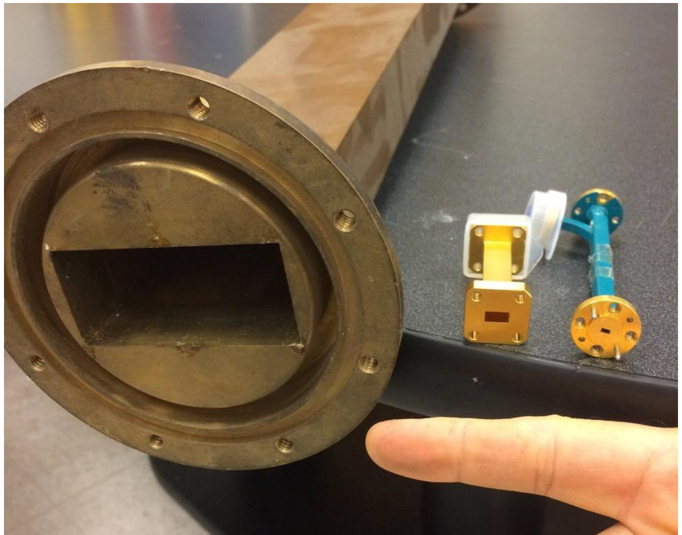
- A transmission line connects a generator to a load.

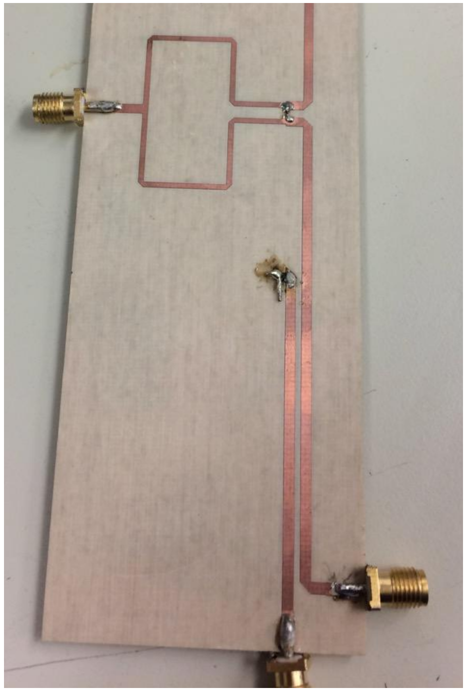
2-1 Transmission Lines



Transmission lines include:

- Two parallel wires
- Coaxial cable
- Microstrip line
- Optical fiber
- Waveguide
- etc.





2-1 Transmission Lines

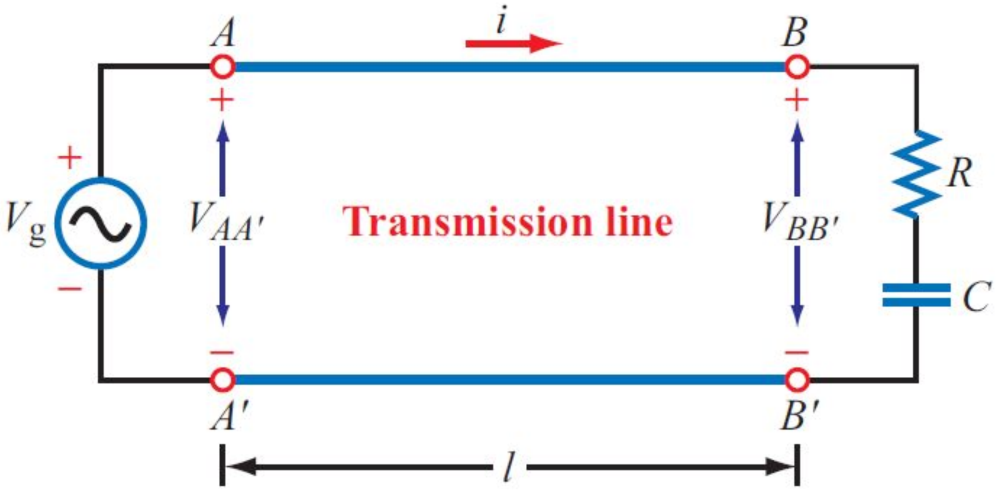
Which transmission line to use?

Selection depends on many factors and priorities:

- Frequency and signal bandwidth
- Transmitted power
- Acceptable signal loss / distortion
- Distance
- Available space (volume)
- Cost
- Convenience
- Standards compliance

2-1 Transmission Line Effects

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



For now, assume u_p=c.

At port B, the voltage is delayed by l/c:

$$V_{BB'}(t) = V_{AA'}(t - l/c)$$
$$= V_0 \cos[\omega(t - l/c)]$$
$$= V_0 \cos(\omega t - \phi_0),$$

$$\phi_0 = \frac{\omega l}{c} = \frac{2\pi f l}{c} = 2\pi \frac{l}{\lambda}$$

Phase delay is one important effect:
when length is a significant fraction of the wavelength.

2-1 Transmission Line Effects

Example 1: Given:

$$t = 0\,\text{sec}$$
$$f = 1\,\text{KHz}$$
$$l = 5\,\text{cm}$$

1

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8\ \text{m/sec}}{1 \times 10^3\ \text{Hz}}$$
$$= \frac{3 \times 10^8\ \text{m/sec}}{1 \times 10^3\ \text{cycles/sec}}$$
$$\lambda = 3 \times 10^5\ \text{m}$$

2

$$\phi_0 = 2\pi \frac{l}{\lambda}$$
$$= 2\pi \frac{0.05\ \text{m}}{3 \times 10^5\ \text{m}}$$
$$= 3.3 \times 10^{-7}\,\pi$$
$$\phi_0 = 1 \times 10^{-6}\ \text{radians}$$

3

$$V_{BB'}(t) = V_0 \cos(\omega t - \phi_0)$$
$$V_{BB'}(t = 0) = V_0 \cos(\phi_0)$$
$$= V_0 \cos(1 \times 10^{-6}\ \text{radians})$$
$$V_{BB'}(t = 0) = 0.999999999\, V_0$$

2-1 Transmission Line Effects

Example 2: Given:

$$t = 0\,\text{sec}$$
$$f = 1\,\text{KHz}$$
$$l = 20\,\text{Km}$$

1

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8\,\text{m/sec}}{1 \times 10^3\,\text{Hz}}$$
$$= \frac{3 \times 10^8\,\text{m/sec}}{1 \times 10^3\,\text{cycles/sec}}$$
$$\lambda = 3 \times 10^5\,\text{m}$$

2

$$\phi_0 = 2\pi\,\frac{l}{\lambda}$$
$$= 2\pi\,\frac{2 \times 10^4\,\text{m}}{3 \times 10^5\,\text{m}}$$
$$\phi_0 = 0.133\,\pi = 0.42\,\text{radians}$$

3

$$V_{BB'}(t) = V_0 \cos(\omega t - \phi_0)$$
$$V_{BB'}(t=0) = V_0 \cos(\phi_0)$$
$$= V_0 \cos(0.42\,\text{radians})$$
$$V_{BB'}(t=0) = 0.91\,V_0$$

2-1 Transmission Line Effects

Example 3: Given:

$$t = 0\,\text{sec}$$
$$f = 1.5\,\text{GHz}$$
$$l = 5\,\text{cm}$$

1

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8\ \text{m/sec}}{1.5 \times 10^9\ \text{Hz}}$$
$$= \frac{3 \times 10^8\ \text{m/sec}}{1.5 \times 10^9\ \text{cycles/sec}}$$
$$\lambda = 0.2\,\text{m}$$

2

$$\phi_0 = 2\pi \frac{l}{\lambda}$$
$$= 2\pi \frac{0.05\,\text{m}}{0.2\,\text{m}}$$
$$\phi_0 = \frac{\pi}{2}$$

3

$$V_{BB'}(t) = V_0 \cos(\omega t - \phi_0)$$
$$V_{BB'}(t=0) = V_0 \cos(\phi_0)$$
$$= V_0 \cos\left(\frac{\pi}{2}\right)$$
$$V_{BB'}(t=0) = 0\ \text{Volts}$$

2-1 Transmission Line Effects

So, line length has an effect on the voltage at the load.

This showed that the phase of the voltage is different.

But we'll see later that the amplitude of the voltage is also affected.

2-1 Transmission Line Effects

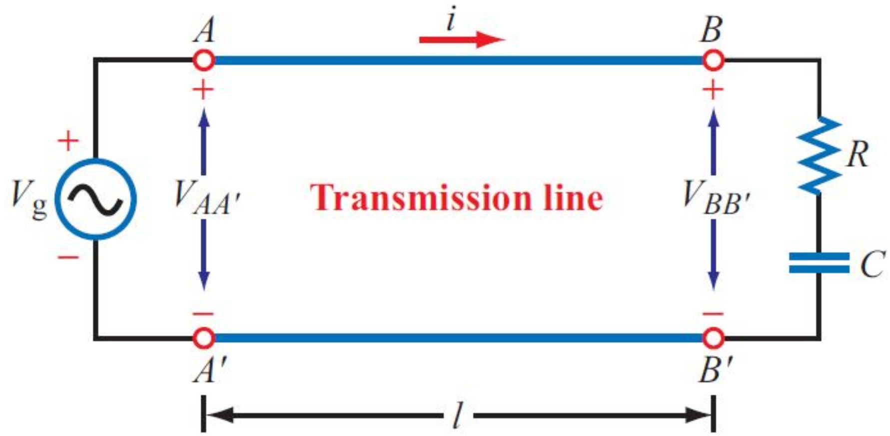
Common mistake:

When using calculator to compute cos():

Entering value in radians, when calculator assumes it's in degrees.

or vice-versa.

2-1 Transmission Line Effects



$$\phi_0 = \frac{\omega l}{c} = \frac{2\pi f l}{c} = 2\pi \frac{l}{\lambda} \quad \text{radians.}$$

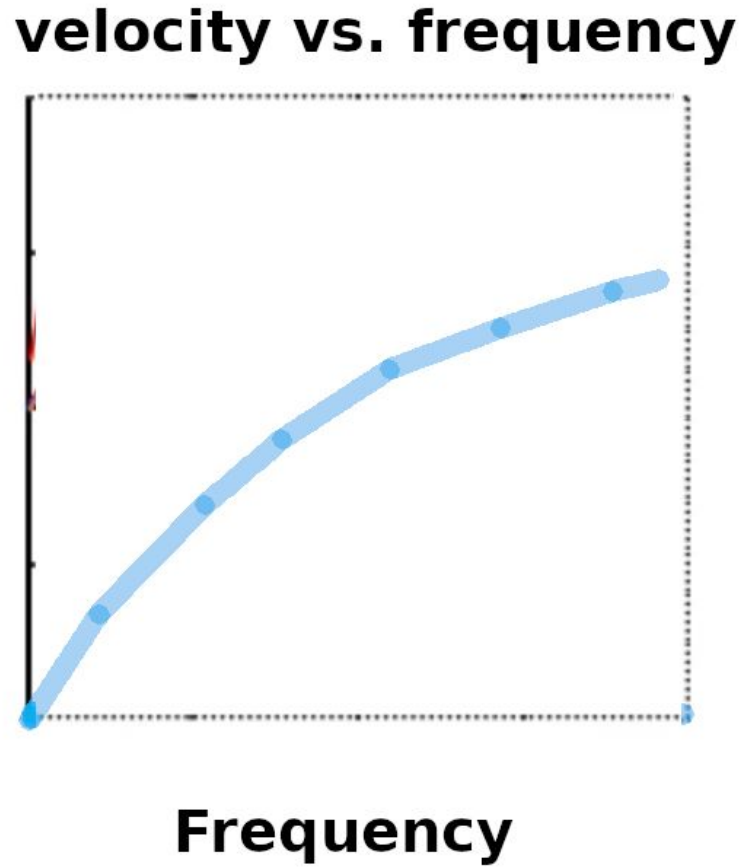
$l/\lambda \lesssim 0.01$: Can ignore transmission-line effects

$l/\lambda \gtrsim 0.01$: Must deal with phase shift,
and other effects...

2-1 Dispersion

Velocity as a function of frequency:

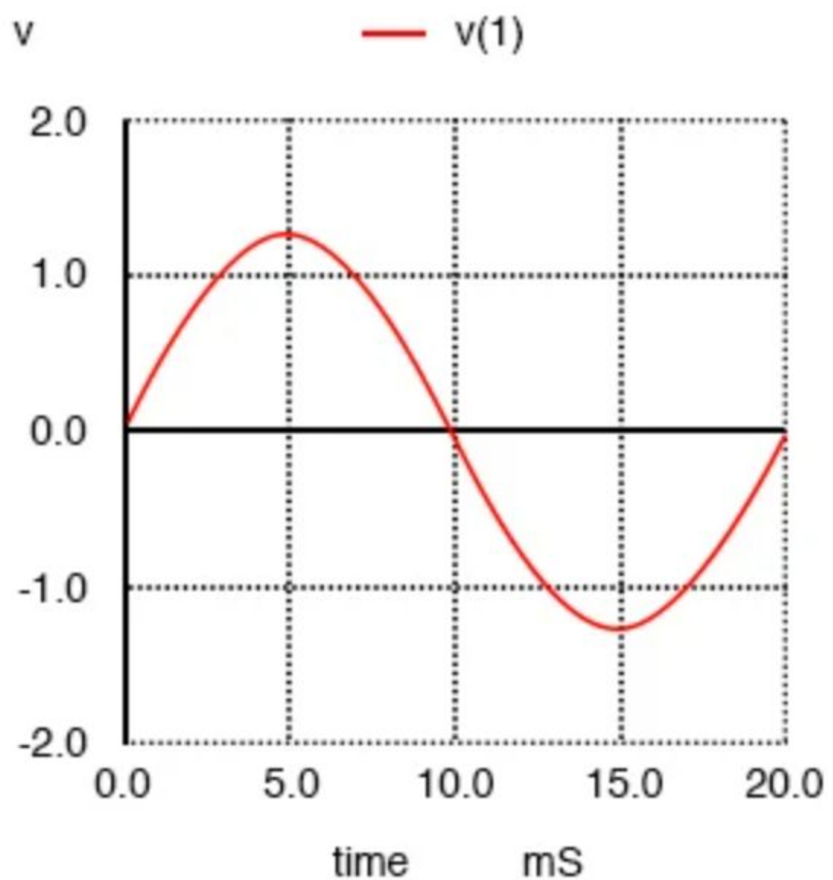
Because the material parameters ε, μ, σ vary with frequency, so does the velocity of the signal in the transmission-line.



2-1 Dispersion

A pulse is composed of a band of frequencies:

Add up several sinusoids with different amplitudes and phases:
can get a rectangular pulse



(allaboutcircuits.com)

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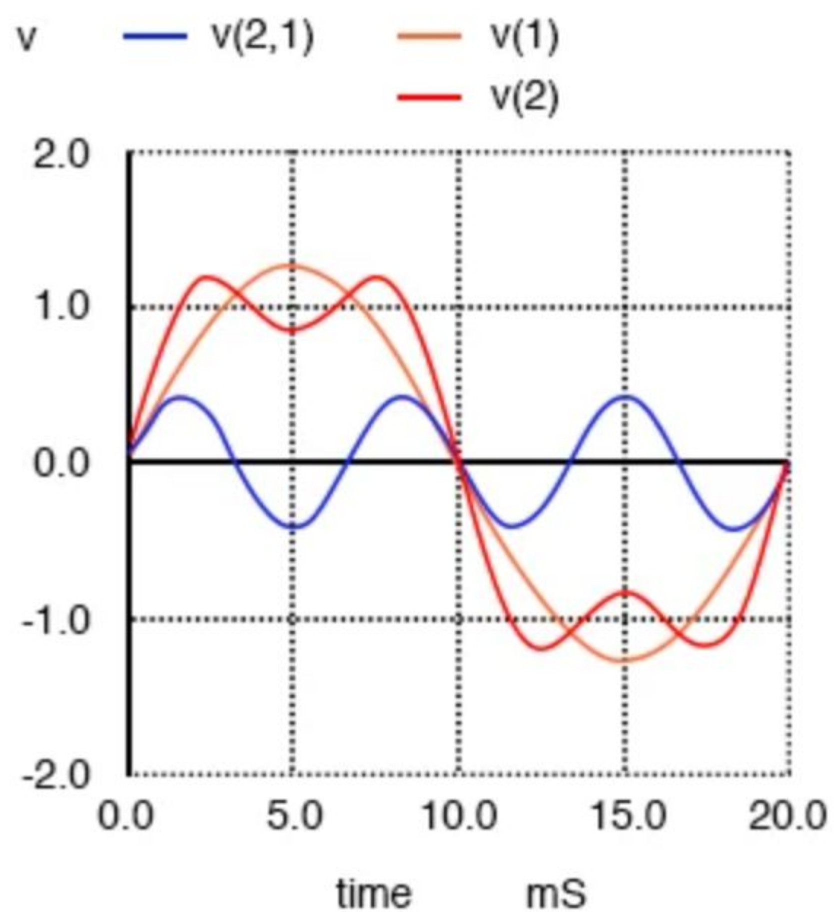

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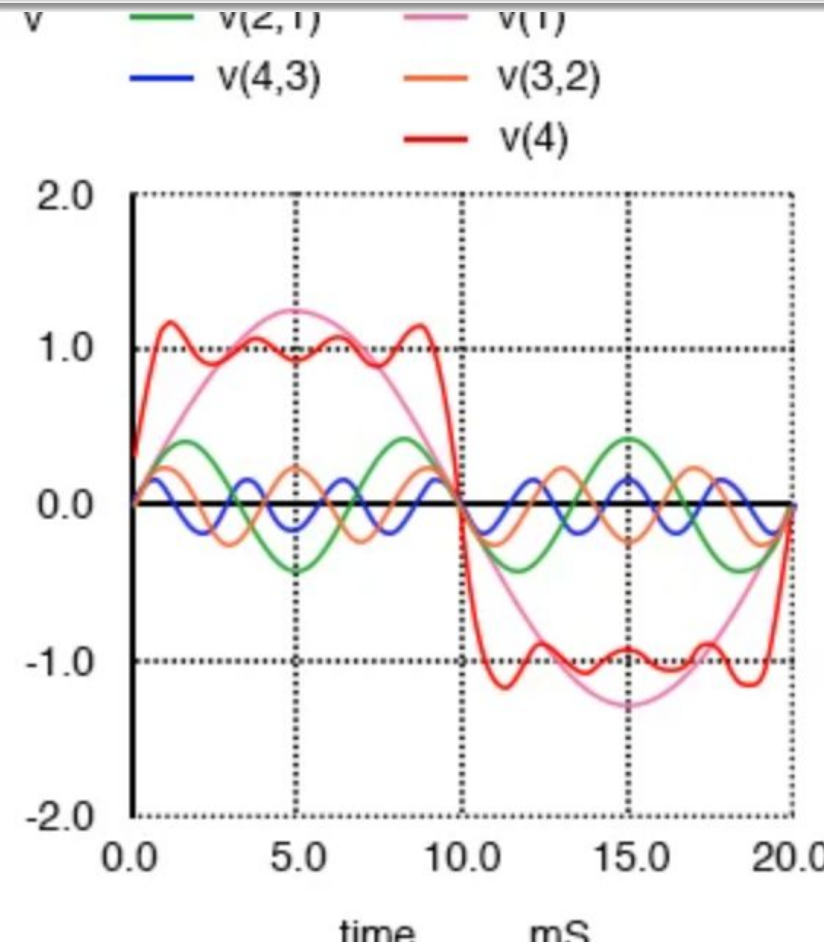

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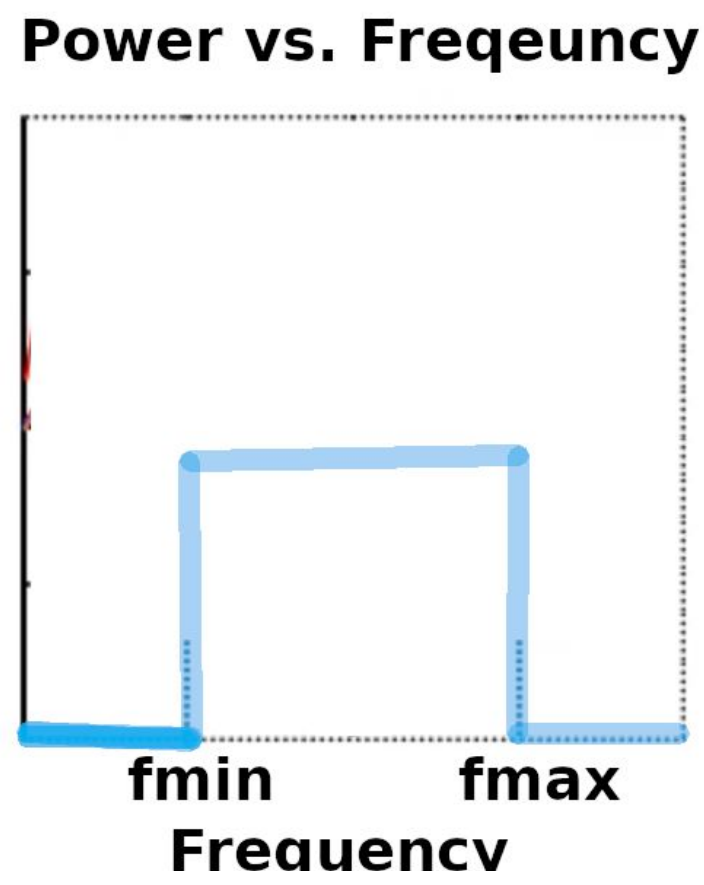
2-1 Dispersion

A pulse is composed of a band of frequencies:

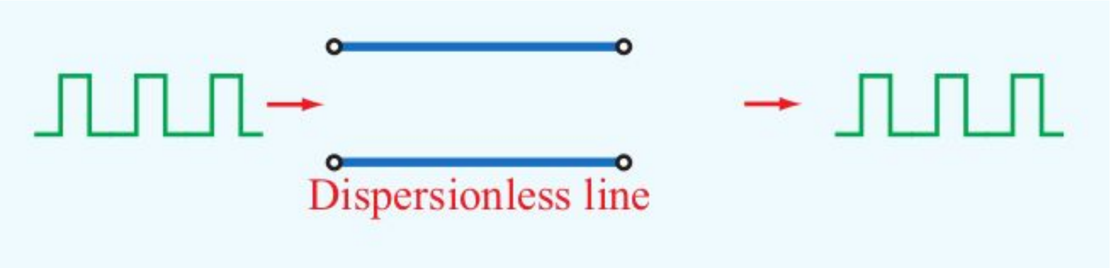
Add up several sinusoids with different amplitudes and phases:
can get a rectangular pulse

So will have all frequencies from some minimum to some maximum propagating in the transmission line.



2-1 Dispersion

Dispersion for digital communications:

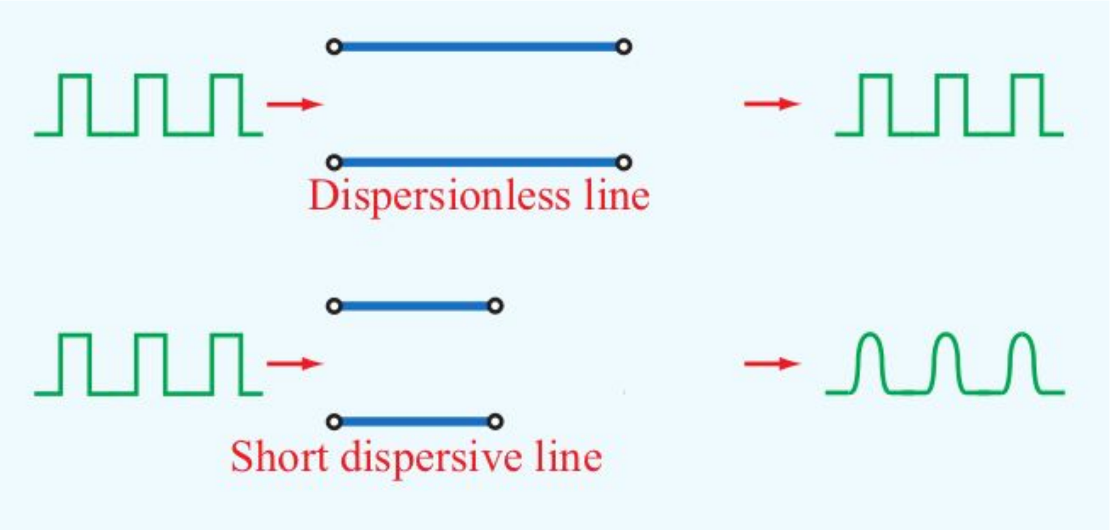


DIspersionless lines preserve the pulse train that was input.

2-1 Dispersion

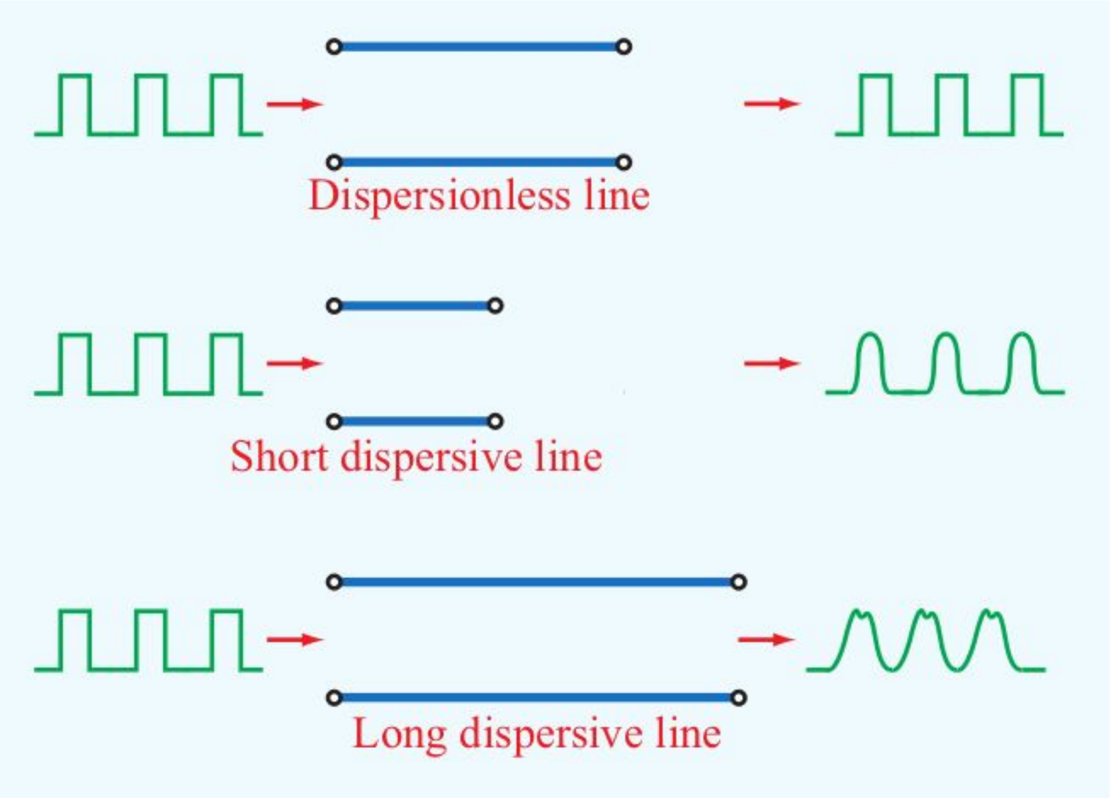
Dispersion for digital communications:

Short dispersive lines blur the pulse shape.



2-1 Dispersion

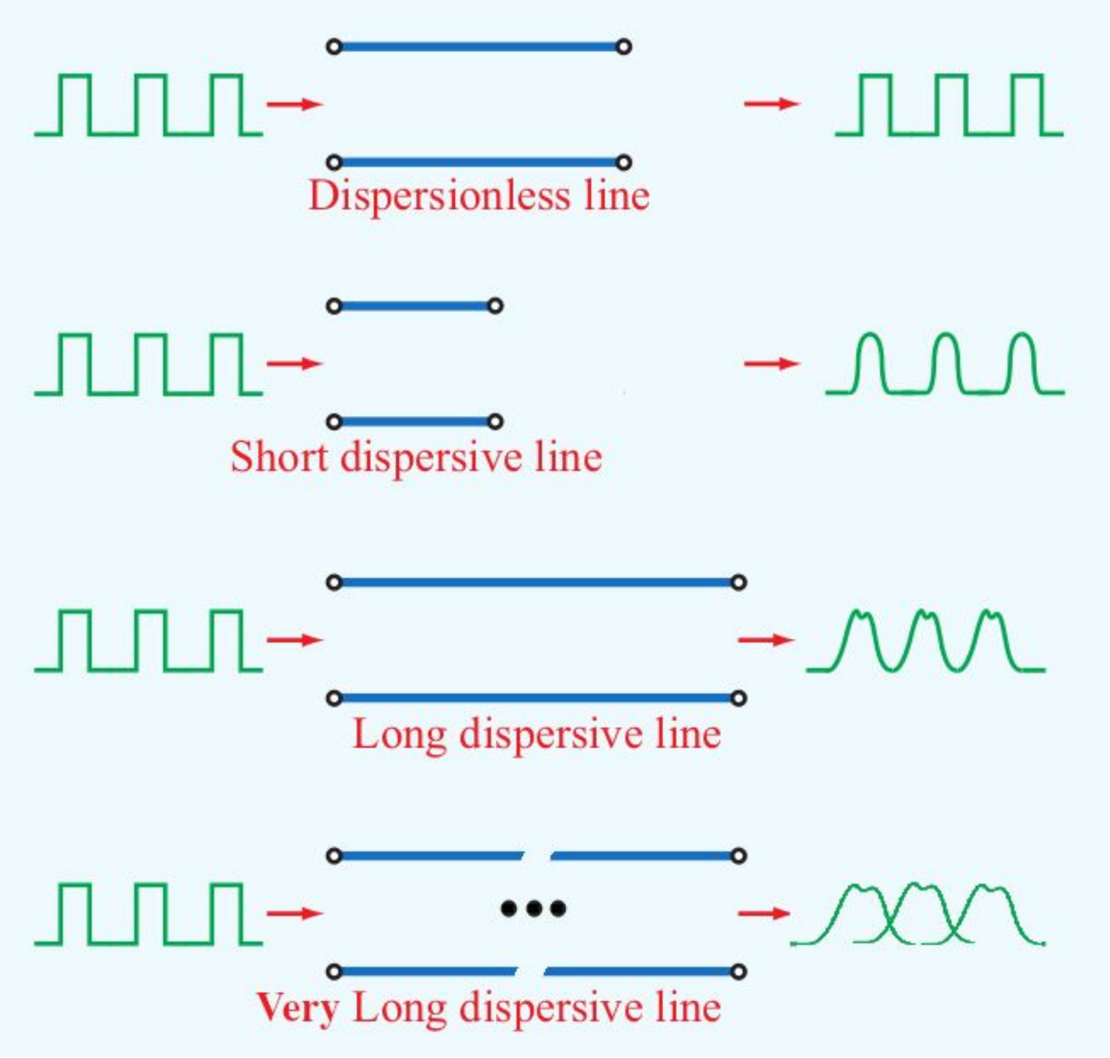
Dispersion for digital communications:



Longer dispersive lines noticeably distort the pulse shape.

2-1 Dispersion

Dispersion for digital communications:



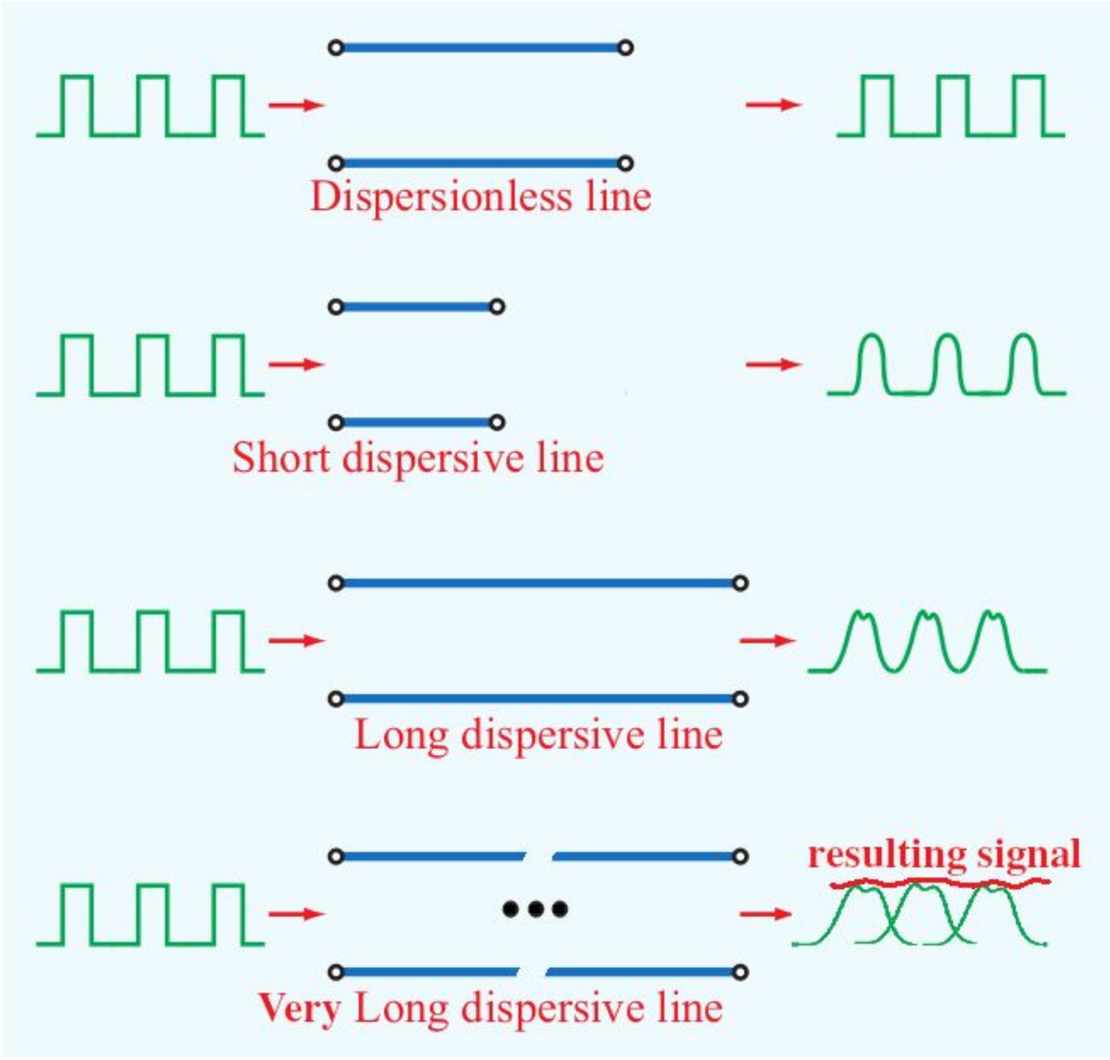
Long dispersive lines blur each pulse so much that they overlap with each other.

2-1 Dispersion

Dispersion for digital communications:

So the pulses are lost, and no information is transmitted.

This happens when the pulses spread by half a pulse-width in each direction.



2-1 Dispersion

Dispersion for digital communications:

The velocity-difference between the lowest-frequency and the upper-frequency causes this pulse spreading.

Assume these frequencies have different velocities:

u_1, u_2

The time it takes for each freq to propagate 1 meter is:

$t_1 = 1m/u_1 \qquad t_2 = 1m/u_2$

The time offset is therefore:

$$\Delta t = t_1 - t_2 = 1m/u_1 - 1m/u_2$$

2-1 Dispersion

Dispersion for digital communications:

Transmission lines are characterized by a parameter called "delay", which is defined as:

$$\text{delay} = 1/u_1 - 1/u_2$$

with units of sec/m

For example: delay = 0.01 nsec/m

This is only relevant when the min and max frequency are also specified.

2-1 Dispersion

Dispersion for digital communications:

The maximum line length, L_{max}, is defined as the length where the pulse spreading is half of the pulse width, *w*, where the spreading causes the pulses to become indistinguishable:

$$L_{max} = 0.5w \, / \, \text{delay}$$

Example: Dispersion

Given: A digital transmission system.

Pulse width: 1 nsec

Line dispersion: delay: 0.003 nsec/m

Find: Maximum length of line

Solution: We know: $L_{max} = 0.5w$ / delay

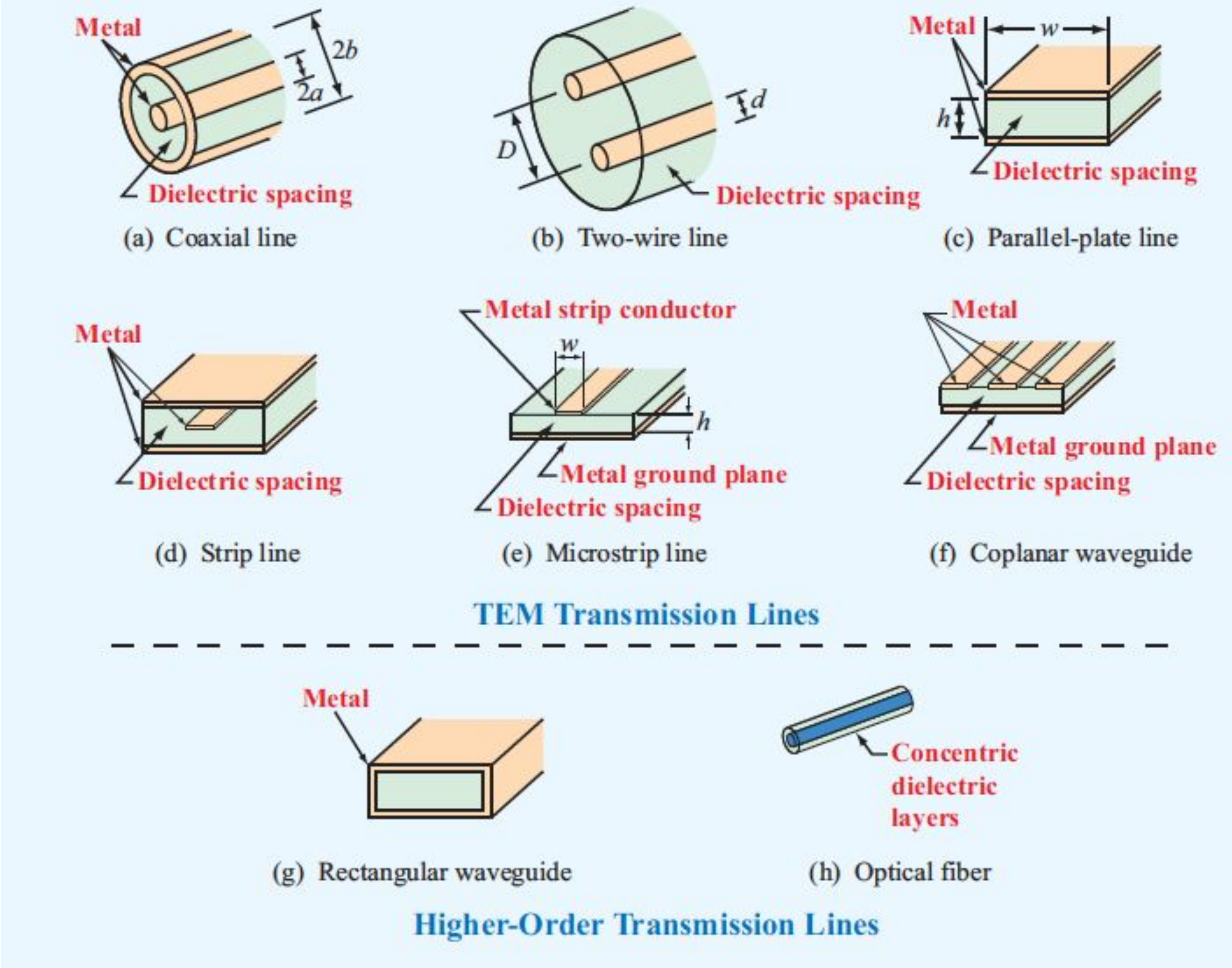
so: L_{max} = 0.5 nsec / 0.003 nsec/m

L_{max} = 167 m

This is why certain interfaces have max cable-lengths

2-1 Types of Transmission Modes

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



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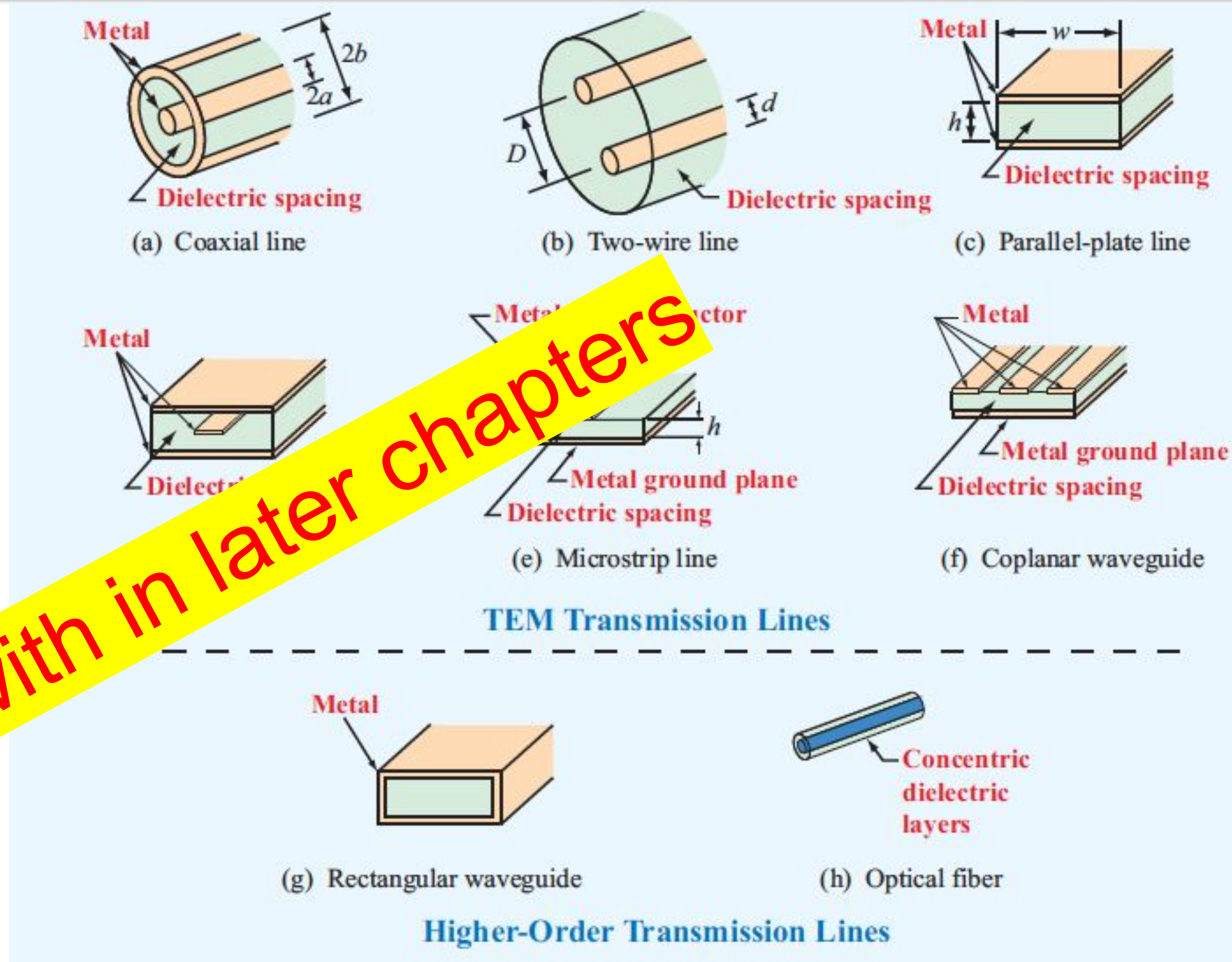
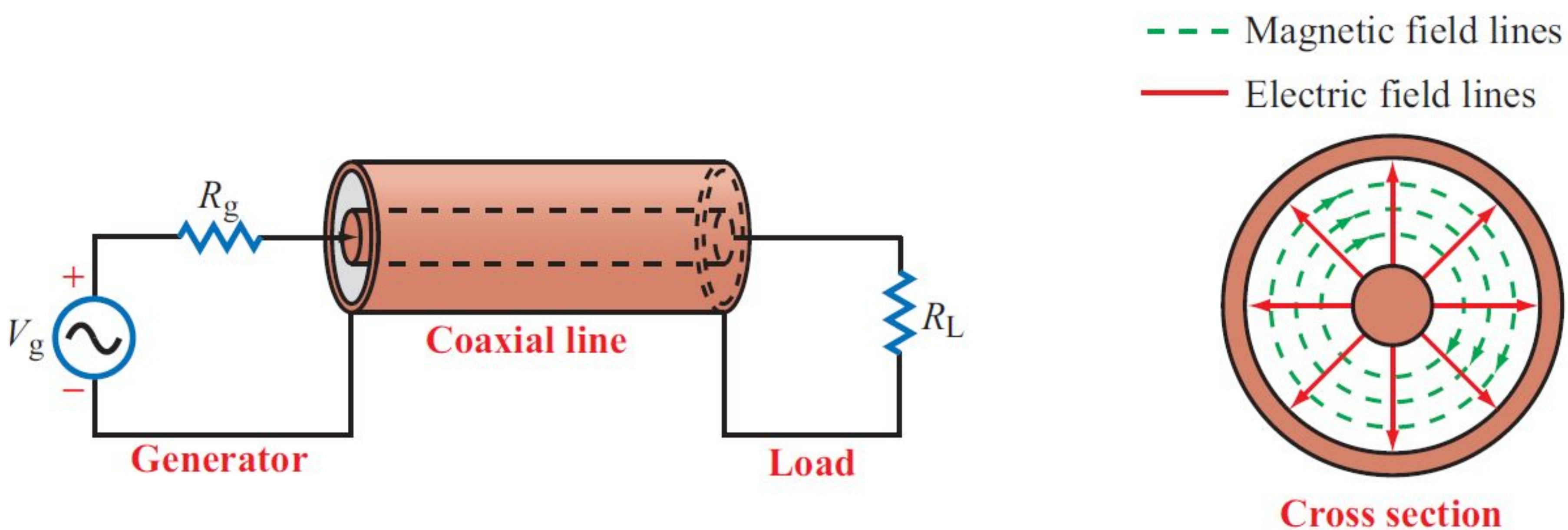


Deal with in later chapters

2-1 Example of TEM Mode



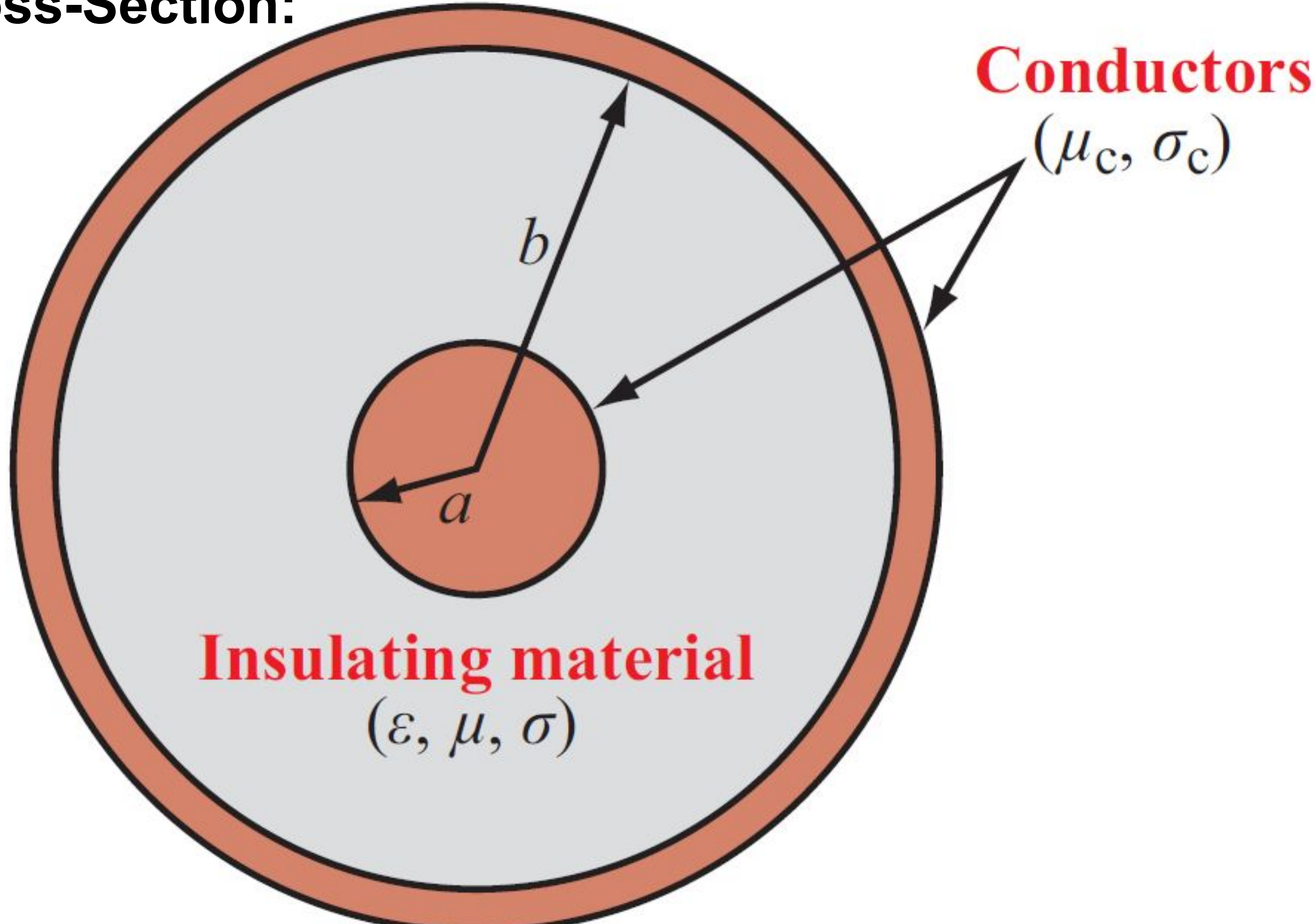
From Physics240:

Current along its length gives rise to magnetic field

Voltage between wire and sheath gives rise to electric field.

2-2 Transmission Line Model

Coax Cross-Section:



2-2 Transmission Line Model

Modeling Expectations:

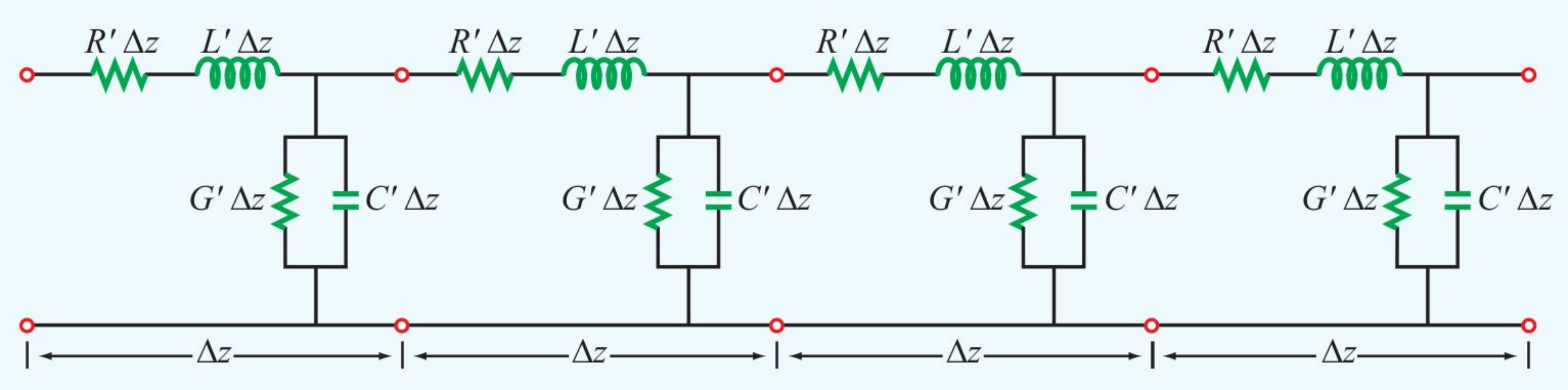
The metal conductors aren't perfect: so resistance

The current in the metal conductors creates a magnetic field, so there must be some inductance.

The insulator is not perfect, so we expect a small amount of leakage current: conductance.

There is some charge separation from one conductor to the other, hence there must be some capacitance.

2-2 Transmission Line Model



All parameters are "per unit length":

R'**: Combined Resistance of BOTH conductors: □/m**

L'**: Combined Inductance of BOTH conductors, H/m**

G'**: Conductance of insulation between inner and outer conductor, S/m**

C'**: Capacitance between inner and outer conductors, F/m**

2-2 Transmission Line Model

These expressions will be derived in later chapters:

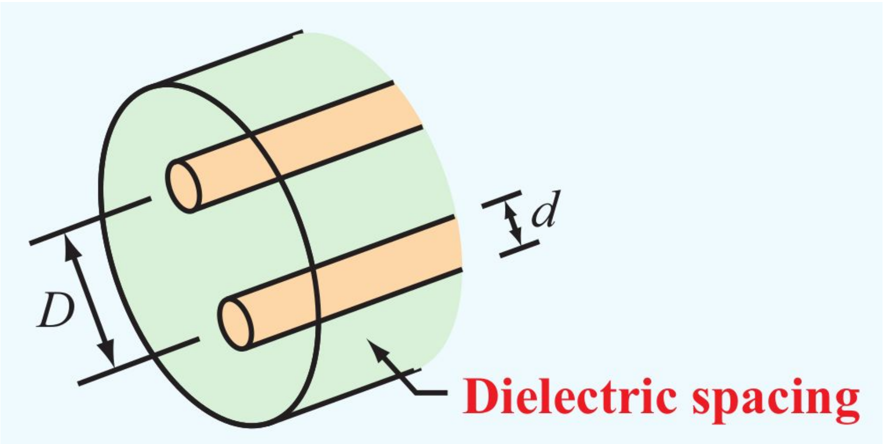
Table 2-1 Transmission-line parameters R', L', G', and C' for three types of lines.

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

$$R_s = \sqrt{\pi f \mu_c / \sigma_c}$$

Exercise 2-1

A two-wire copper transmission line is embedded in a dielectric material with ε_r = 2.6 and σ = 2x10^{-6} S/m. The two wires are separated by 3 cm and their radii are 1 mm each. Calculate the line parameters R′, L′, G′, and C′ at 2 GHz.



$$R_s = \sqrt{\pi f \mu_c / \sigma_c}$$

Check Table B-2 (Appendix B) for copper conductivity

Parameter	Two-Wire
R'	$\dfrac{2R_s}{\pi d}$
L'	$\dfrac{\mu}{\pi} \ln\left[(D/d) + \sqrt{(D/d)^2 - 1}\right]$
G'	$\dfrac{\pi \sigma}{\ln\left[(D/d) + \sqrt{(D/d)^2 - 1}\right]}$
C'	$\dfrac{\pi \varepsilon}{\ln\left[(D/d) + \sqrt{(D/d)^2 - 1}\right]}$

Exercise 2-1

Solution: always do this first, converting as needed:

$$f = 2 \times 10^9 \text{ Hz},$$

$$d = 2 \times 10^{-3} \text{ m},$$

$$D = 3 \times 10^{-2} \text{ m},$$

$$\sigma_c = 5.8 \times 10^7 \text{ S/m (copper)},$$

$$\varepsilon_r = 2.6,$$

$$\sigma = 2 \times 10^{-6} \text{ S/m},$$

$$\mu = \mu_c = \mu_0.$$

Exercise 2-1

Solution:

$$R_s = \sqrt{\pi f \mu_c / \sigma_c}$$

$$= \left[\frac{\pi \times 2 \times 10^9 \text{ Hz} \times 4\pi \times 10^{-7} \text{ H/m}}{5.8 \times 10^7 \text{ S/m}} \right]^{1/2}$$

$$= 1.17 \times 10^{-2} \, \Omega$$

Check the units: H = kg m^2 s^{-2} A^{-2}

Ω = kg m^2 s^{-3} A^{-2}

so: $H\Omega s^{-1} = \Omega^2$ good.

Exercise 2-1

Solution:

$$R' = \frac{2R_s}{\pi d} = \frac{2 \times 1.17 \times 10^{-2}\,\Omega}{\pi \times 2 \times 10^{-3}\,\text{m}}$$

$$= 3.71\,\Omega/\text{m}$$

Exercise 2-1

Solution:

For convenience, define:

$$m := \ln\left[(D/d) + \sqrt{(D/d)^2 - 1}\right]$$

$$= \ln\left[15 + \sqrt{15^2 - 1}\right]$$

$$= \ln\left[15 + 14.97\right]$$

$$= 3.4 \qquad \text{(unitless)}$$

Exercise 2-1

Solution:

$$L' = \frac{\mu}{\pi} m$$

$$= \frac{4\pi \times 10^{-7} \, \mathrm{H/m}}{\pi} 3.4$$

$$L' = 1.36 \times 10^{-6} \, \mathrm{H/m}$$

$$G' = \frac{\pi\sigma}{m}$$

$$= \frac{\pi \times 2 \times 10^{-6} \, \mathrm{S/m}}{3.4}$$

$$G' = 1.85 \times 10^{-6} \, \mathrm{S/m}$$

Exercise 2-1

Solution:

$$C' = \frac{\pi\epsilon}{m} = \frac{\pi\epsilon_r\epsilon_0}{m}$$

$$= \frac{\pi \times 2.6 \times 8.85 \times 10^{-12}\,\mathrm{F/m}}{3.4}$$

$$C' = 21.26 \times 10^{-12}\,\mathrm{F/m}$$

Exercise 2-1

Solution: Summary

$$
\begin{aligned}
R' &= 3.71\,\Omega/\mathrm{m} \\
L' &= 1.36 \times 10^{-6}\,\mathrm{H/m} \\
G' &= 1.85 \times 10^{-6}\,\mathrm{S/m} \\
C' &= 21.26 \times 10^{-12}\,\mathrm{F/m}
\end{aligned}
$$

Exercise 2-1

Solution: Summary (with preferred use of prefixes)

$$R' = 3.71\,\Omega/\mathrm{m}$$

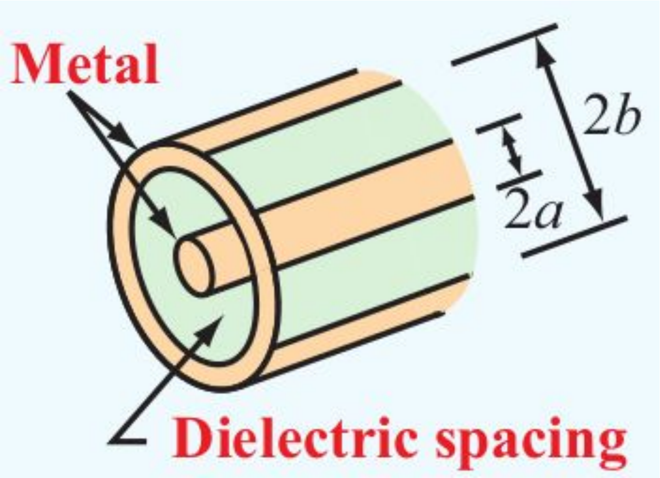
$$L' = 1.36\,\mu\mathrm{H/m}$$

$$G' = 1.85\,\mu\mathrm{S/m}$$

$$C' = 21.26\,\mathrm{pF/m}$$

Exercise 2-2

A coaxial copper transmission line uses air for a dielectric material. The inner conductor diameter is 0.6cm, the outer diameter is 1.2cm. Calculate the line parameters R′, L′, G′, and C′ at 1 MHz.



$$R_s = \sqrt{\pi f \mu_c / \sigma_c}$$

Check Table B-2 (Appendix B) for copper conductivity

Parameter	Coaxial
R'	$\frac{R_s}{2\pi}\left(\frac{1}{a}+\frac{1}{b}\right)$
L'	$\frac{\mu}{2\pi}\ln(b/a)$
G'	$\frac{2\pi\sigma}{\ln(b/a)}$
C'	$\frac{2\pi\varepsilon}{\ln(b/a)}$

Exercise 2-2

Solution:

$$f = 1 \times 10^6\,\mathrm{Hz}$$

$$a = 0.3\,\mathrm{cm} = 0.003\,\mathrm{m}$$

$$b = 0.6\,\mathrm{cm} = 0.006\,\mathrm{m}$$

$$\varepsilon = \varepsilon_0$$

$$\mu = \mu_0$$

$$\sigma = 0$$

$$\mu_c = \mu_0$$

$$\sigma_c = 5.8 \times 10^7\,\mathrm{S/m}$$

Exercise 2-2

Solution:

$$R_s = \sqrt{\pi f \mu_c / \sigma_c}$$

$$R_s = \left[\frac{\pi \times 1 \times 10^6 \,\text{Hz} \times 4\pi \times 10^{-7} \,\text{H/m}}{5.8 \times 10^7 \,\text{S/m}} \right]^{1/2}$$

$$R_s = 2.6 \times 10^{-4} \,\Omega$$

Exercise 2-2

Solution:

$$R' = \frac{R_s}{2\pi}\left(\frac{1}{a} + \frac{1}{b}\right)$$

$$R' = \frac{2.6 \times 10^{-4}\,\Omega}{2\pi}\left(\frac{1}{0.003\,\text{m}} + \frac{1}{0.006\,\text{m}}\right)$$

$$R' = 2.07 \times 10^{-2}\,\Omega/\text{m}$$

Exercise 2-2

Solution:

$$L' = \frac{\mu}{2\pi}\ln(b/a)$$

$$L' = \frac{4\pi \times 10^{-7}\,\mathrm{H/m}}{2\pi}\ln(0.006\,\mathrm{m}/0.003\,\mathrm{m})$$

$$L' = 0.14\,\mu\mathrm{H/m}$$

Exercise 2-2

Solution:

$$G' = \frac{2\pi\sigma}{\ln(b/a)}$$

$$G' = 0$$

because σ =0

Exercise 2-2

Solution:

$$C' = \frac{2\pi\varepsilon}{\ln(b/a)}$$

$$C' = \frac{(2\pi)(8.85 \times 10^{-12}\,\mathrm{F/m})}{\ln 2}$$

$$C' = 80.3\,\mathrm{pF/m}$$

Exercise 2-2

Solution:

$$R' = 20.7\ \mathrm{m\Omega/m}$$

$$L' = 0.14\ \mu\mathrm{H/m}$$

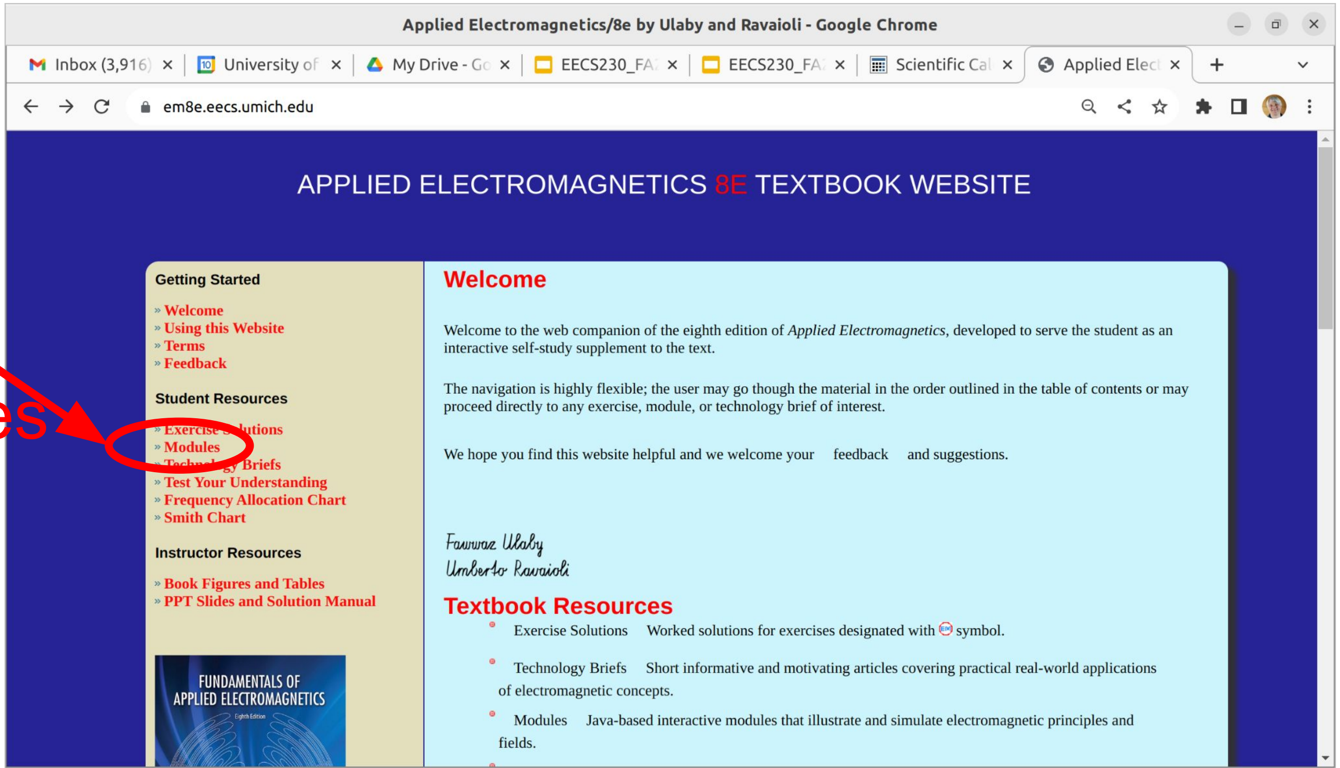
$$G' = 0$$

$$C' = 80.3\ \mathrm{pF/m}$$

2-2 Transmission-Line Parameters

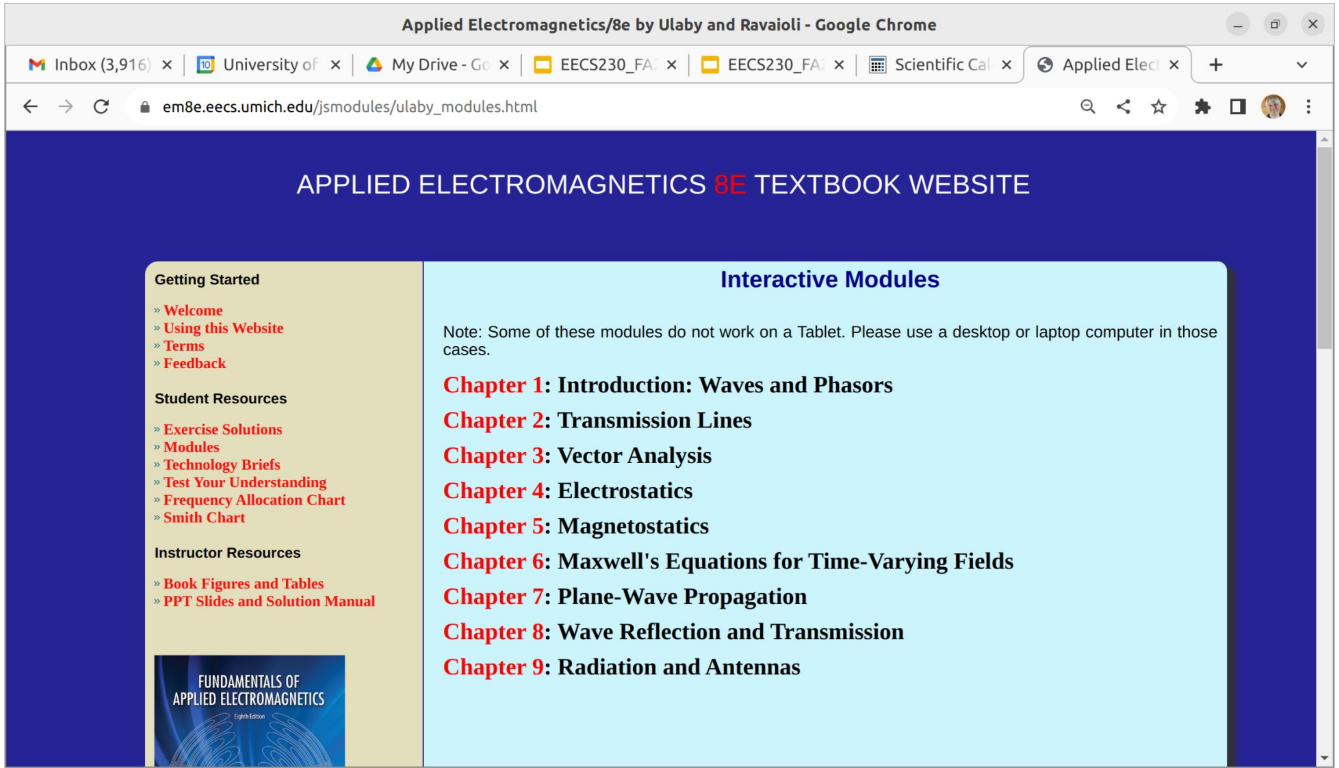
On-Line Educational materials:
https://em8e.eecs.umich.edu/

CLICK on Modules



2-2 Transmission-Line Parameters

On-Line Educational materials:
https://em8e.eecs.umich.edu/



2-2 Transmission-Line Parameters

On-Line Educational materials:
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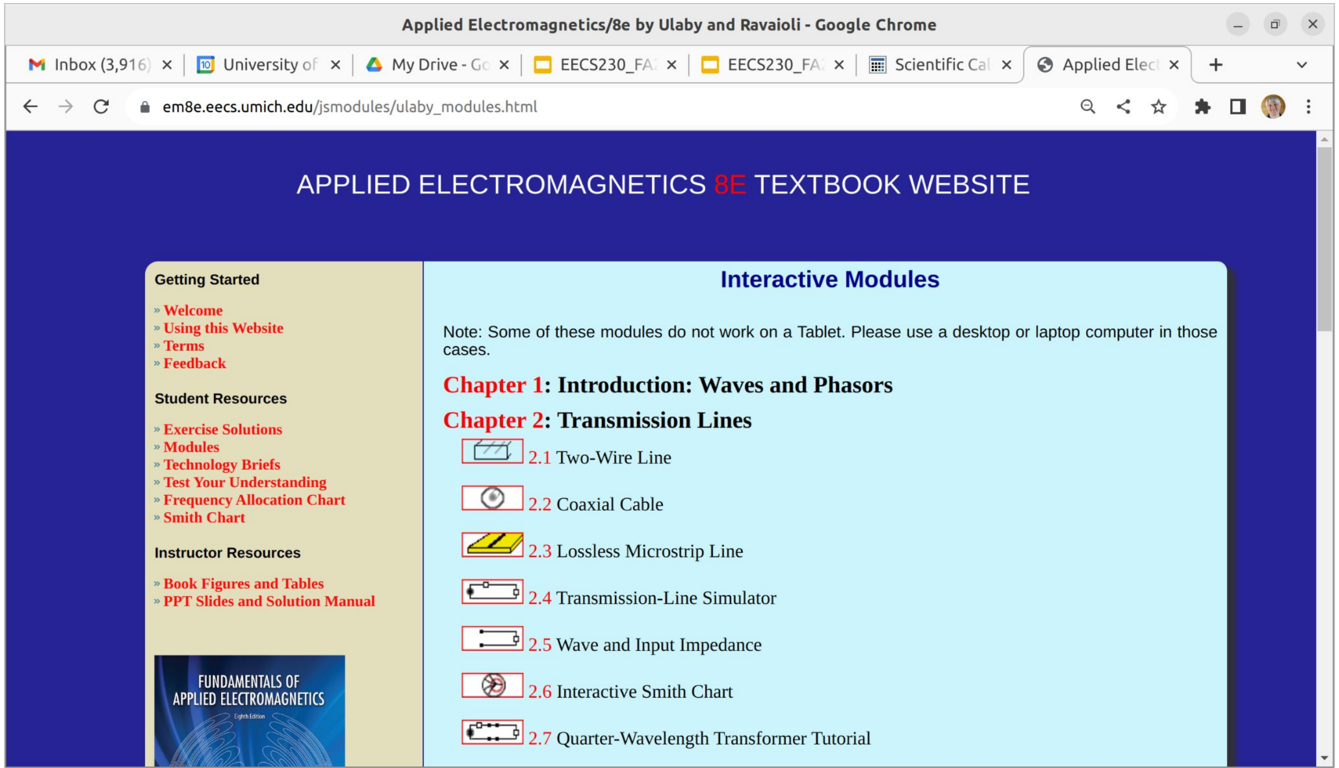
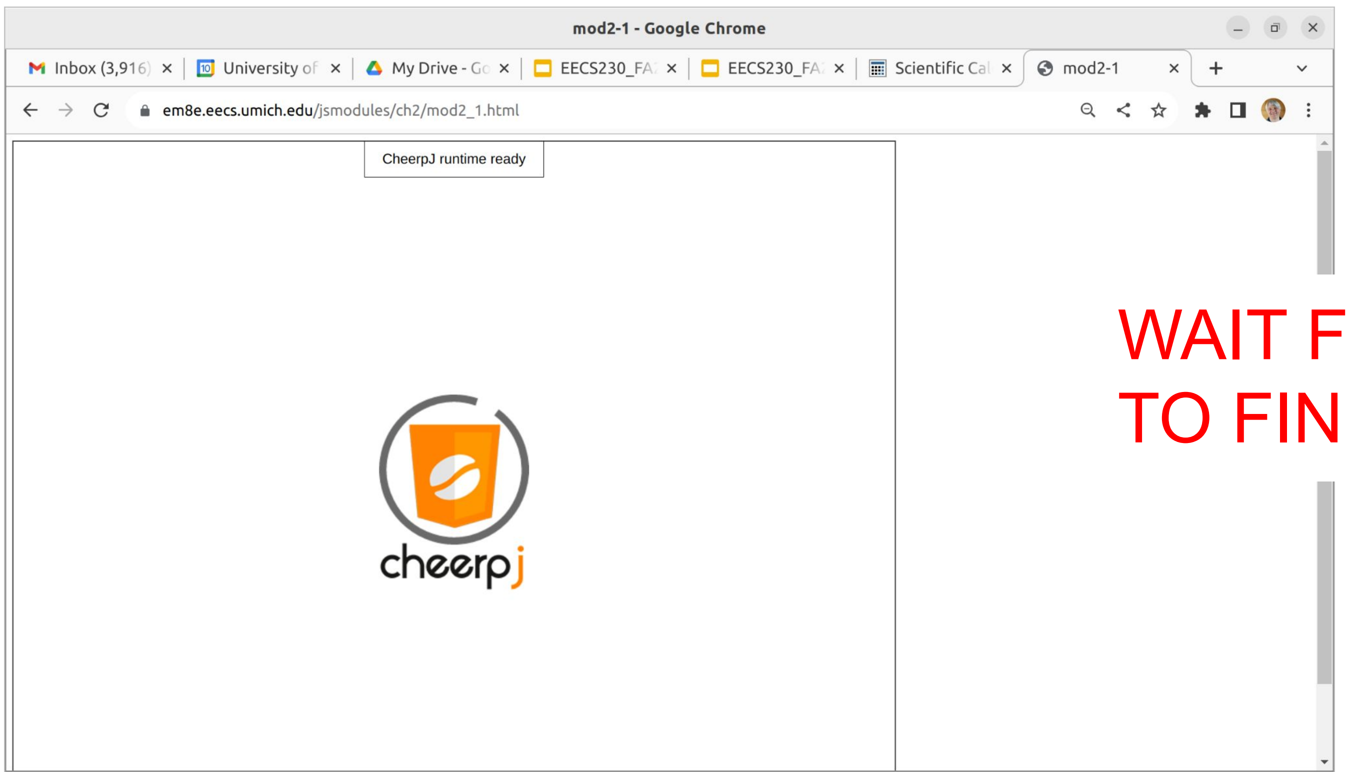


2-2 Transmission-Line Parameters

On-Line Educational materials:
https://em8e.eecs.umich.edu/



WAIT FOR THIS
TO FINISH

2-2 Transmission-Line Parameters

On-Line Educational materials:
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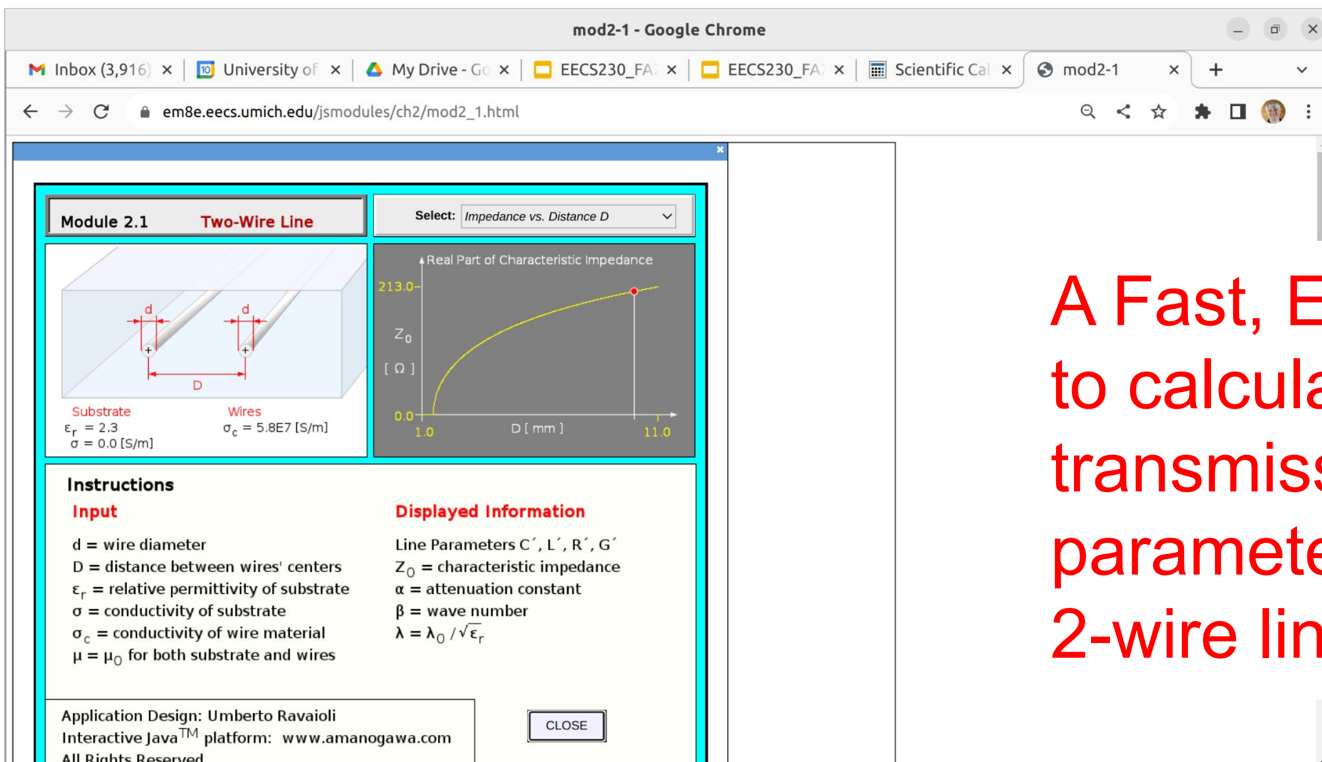
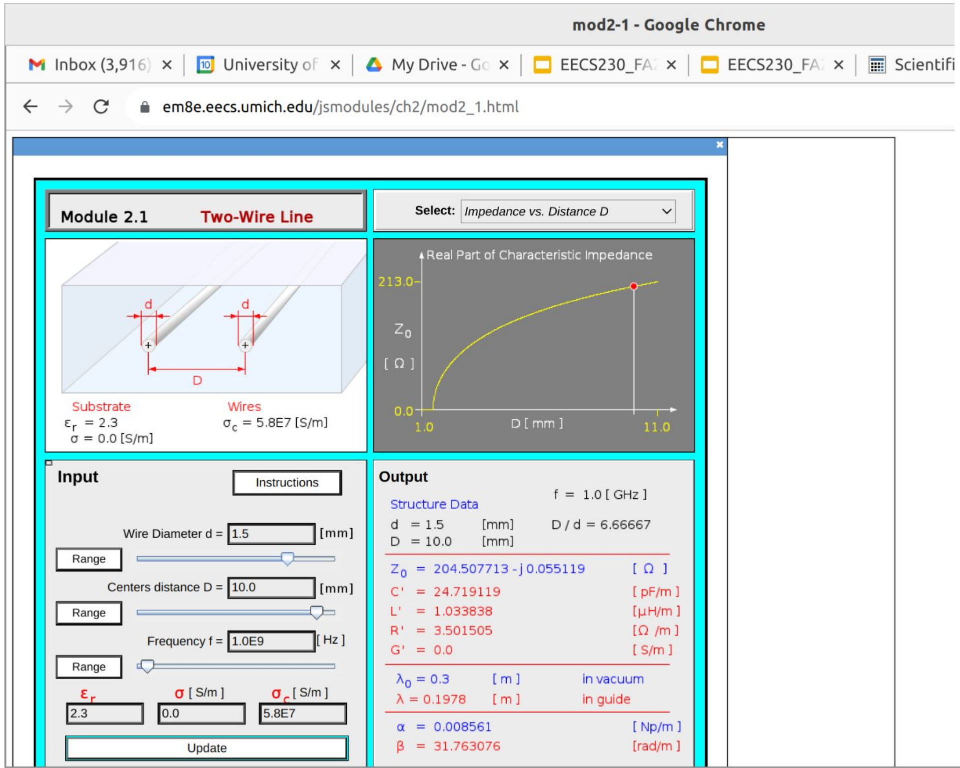


A Fast, Easy way to calculate the transmission-line parameters for a 2-wire line

Transmission-Line Parameters

On-Line Educational materials:
https://em8e.eecs.umich.edu/

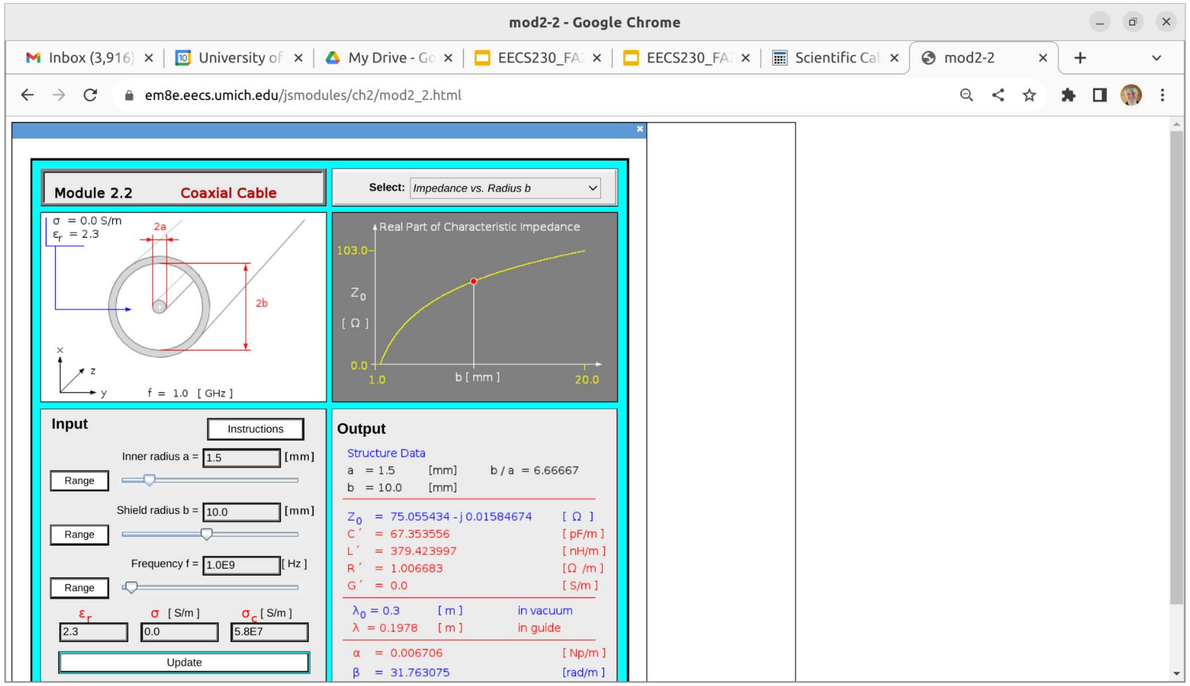


Vary the geometry and material properties with sliders: Immediately see the R, L, G, C params of the resulting line.

Transmission-Line Parameters

On-Line Educational materials:
https://em8e.eecs.umich.edu/

For a coax too.



Homework

Homework 3 is due tomorrow at midnight.

submit to gradescope via the canvas site.

Next Time

Sections 2-3, 2-4, and 2-5:

Form the governing differential equation

Get the form of the solution as traveling waves.

Specify source and load and solve for the 2 unknowns, giving us a complete solution.