TriEmbed
RF Aspects of Circuit Design

Hi, I'm Kevin
-- Kevin McClaning

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Who Am I?

- Kevin McClaning
- Electrical engineer, MSEE
- 34 years experience in technical design at DoD
- Ten years teaching at JHU
- Three years at various contractors
- All RF/DSP related work
- Co-author (with Tom Vito) of a textbook, **Radio Receiver Design**, published in 2000 (ISBN 1-884932-07-X).
- Author of **Wireless Receiver Design for Digital Communications**, published in 2012 (ISBN 978-1-891121-80-7).

RF Design

- It's informal
  - Ask questions
  - Bring up things you've wanted to know
  - Microwave ovens, TV, Wireless LAN
- Trying the online teaching for the first time
  - Like flying a plane

RF Design is Understandable and Predictable

- Not "magic"
- Mostly analog circuit design
  - Small things matter
  - Non-obvious things often matter
- It's often the background assumptions of the designer that are the issue
- Let's examine some of these assumptions
  - Stray components
  - Transmission lines
  - Radiating structures

Stray Components – Small Inductors

- An inch of wire is an inductor whose value is about 20nH
- The impedance of an inductor is given by:

$$X_L = 2\pi fL$$

- At 1 MHz, this inductor has an impedance of

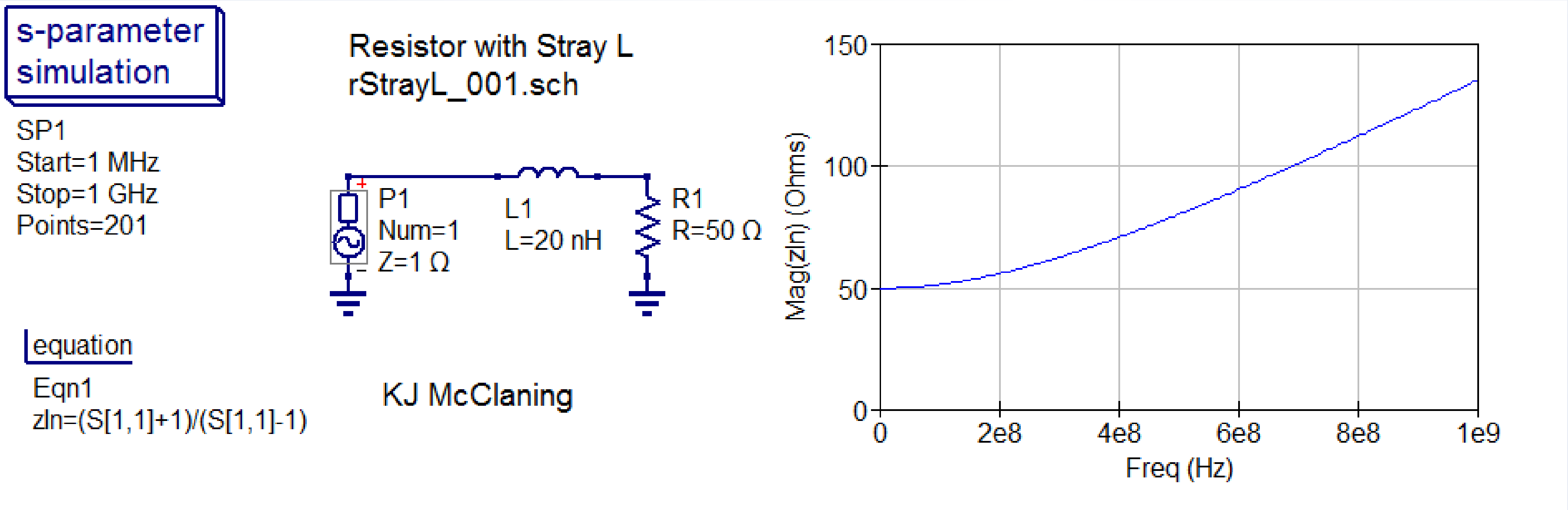
$$\begin{aligned} X_L &= 2\pi fL \\ &= 2\pi(1e6)(20e-9) \\ &= 0.1256\Omega \end{aligned}$$

- At 1 GHz, the inductor's impedance is:

$$\begin{aligned} X_L &= 2\pi fL \\ &= 2\pi(1e9)(20e-9) \\ &= 125.6\Omega \end{aligned}$$

Stray Components – Small Inductors

- A circuit model of a 50 Ohm resistor with a half-inch of wire on each end looks like:



- The resistor's performance deviates from ideal as the frequency increases.

Stray Components – Small Capacitors

- An 0805 chip resistor may have PCB solder pads of 1mmx1mm. Let's place this resistor on 0.24mm thick FR4 (ε_R = 4.4) with a ground plane on the opposite side of the board
- The capacitance of each pad to ground is given by

$$C = \varepsilon_R \varepsilon_0 \frac{A}{d} = (4.4)(8.854e-12)\frac{(0.001)(0.001)}{(0.00024)}$$

$$= 0.16\text{pF}$$

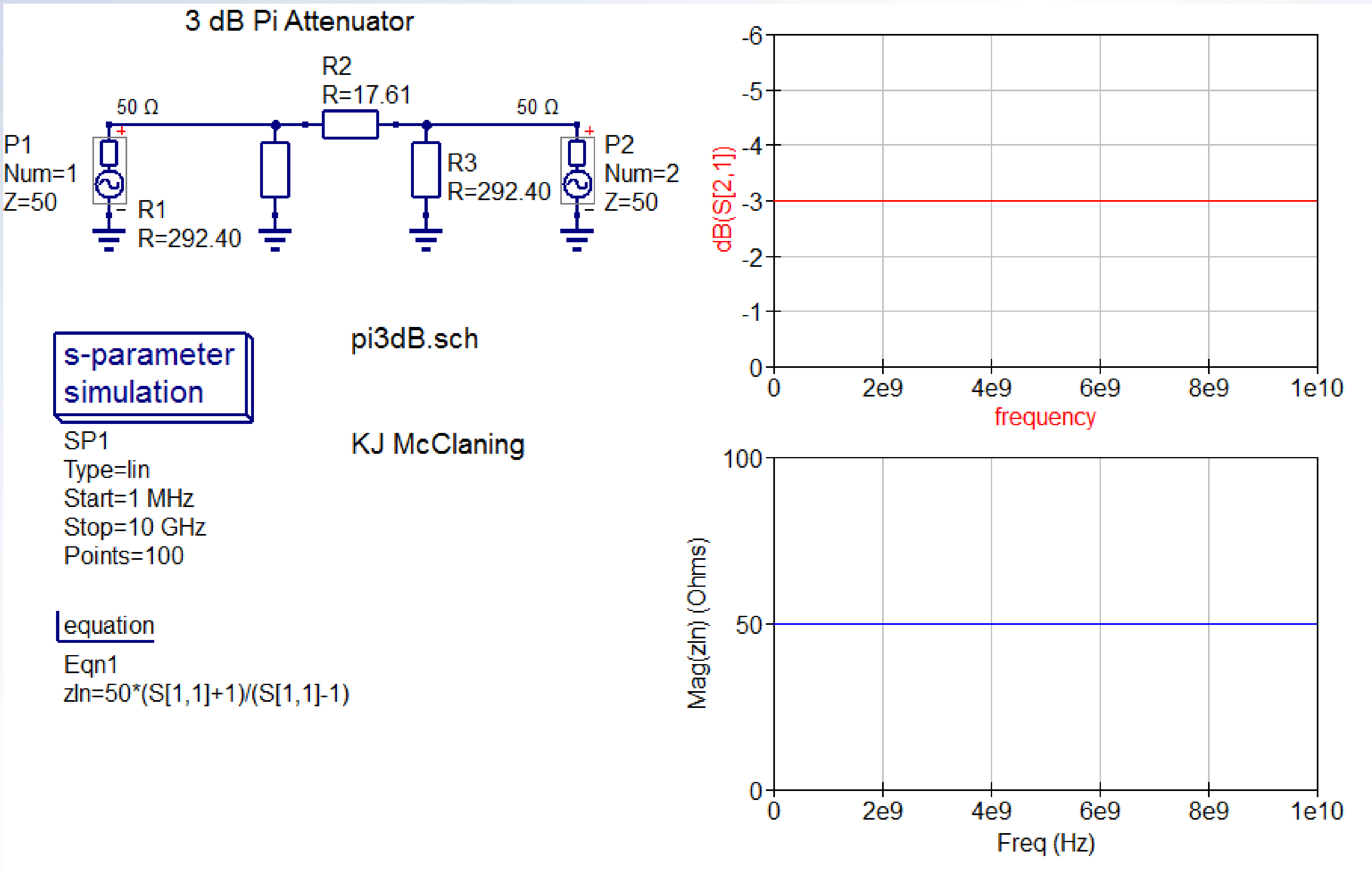
(the capacitance is actually a little higher because of effects this equation doesn't model)

- The impedance of each capacitor to ground at 1 GHz is:

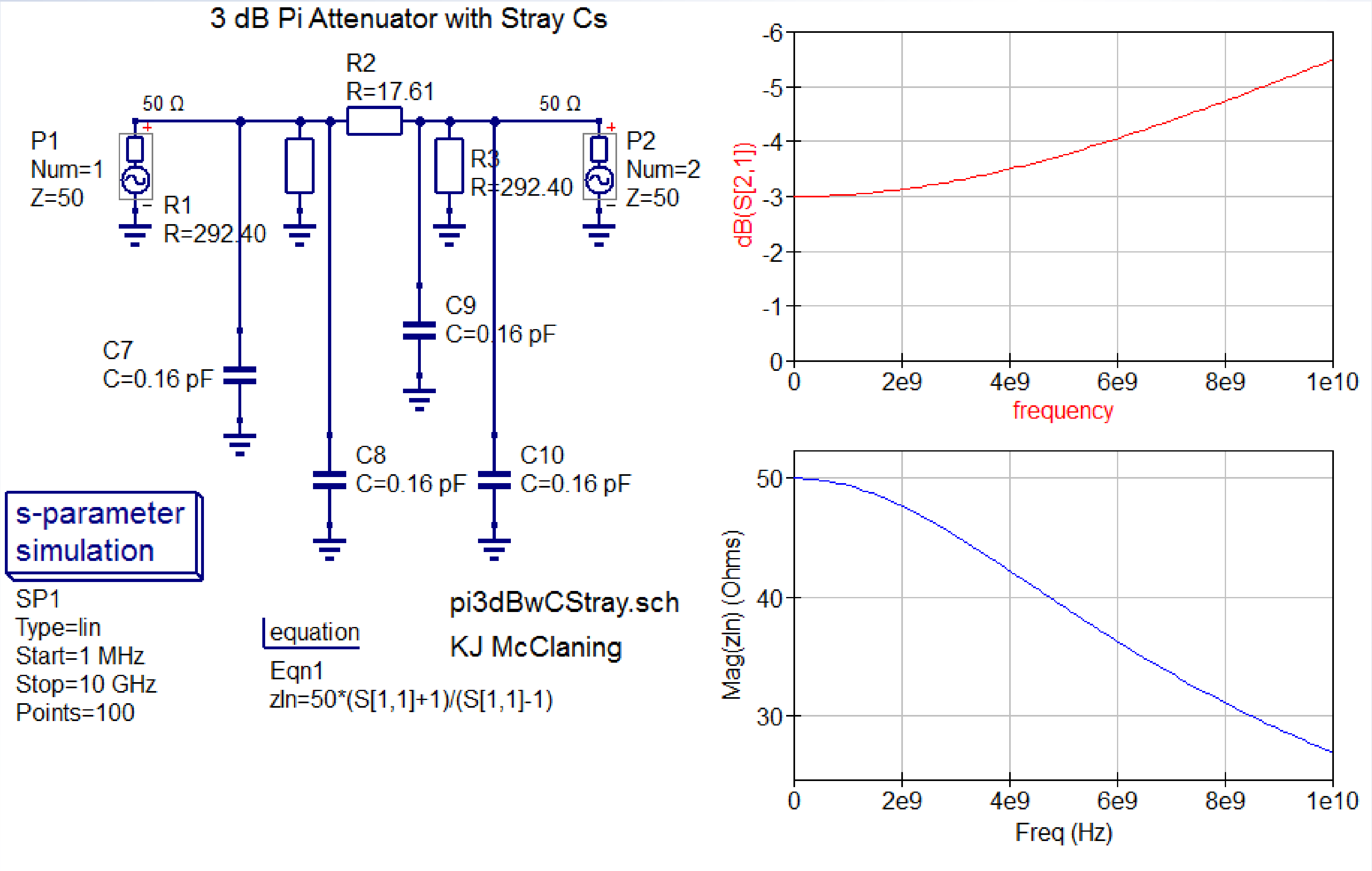
$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi(1e9)(0.16e-12)}$$

$$= 995\Omega$$

Stray Components – 3 dB Resistive Attenuator

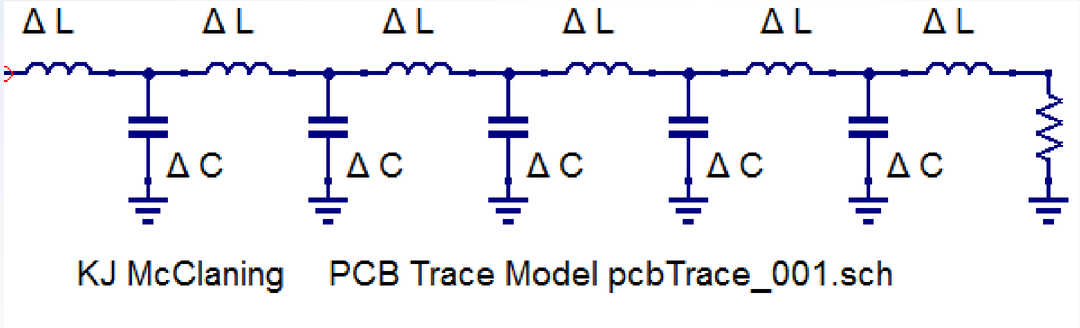


Stray Components – 3 dB Resistive Attenuator with Stray Capacitance



Transmission Lines from Stray Components

- Transmission lines are everywhere!
- We can model a trace on a Printed Circuit Board (PCB) as "a little bit" of series inductance followed by "a little bit" of shunt capacitance.

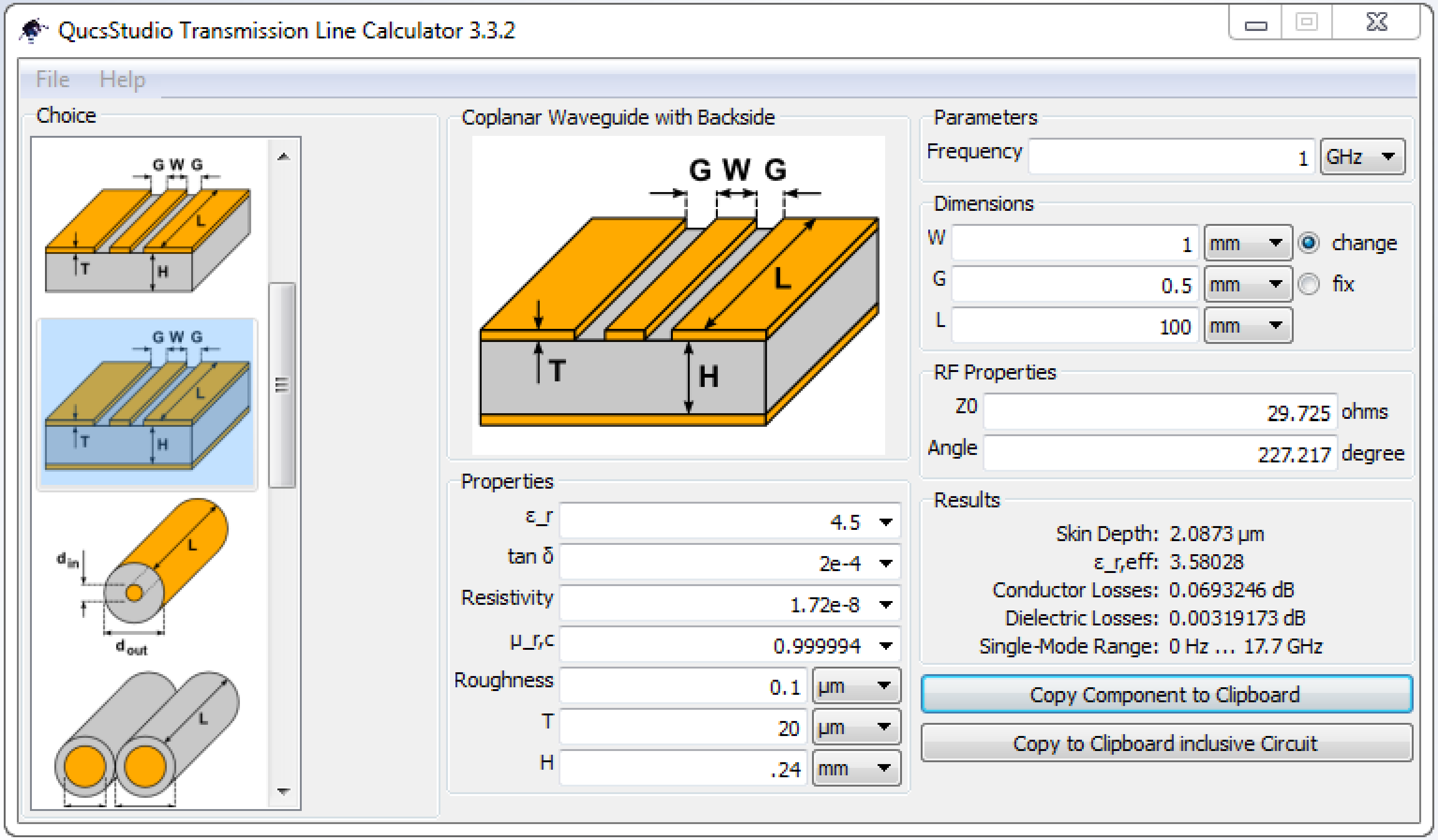


- Mathematical analysis reveals this structure to be a "transmission line" whose characteristic impedance is

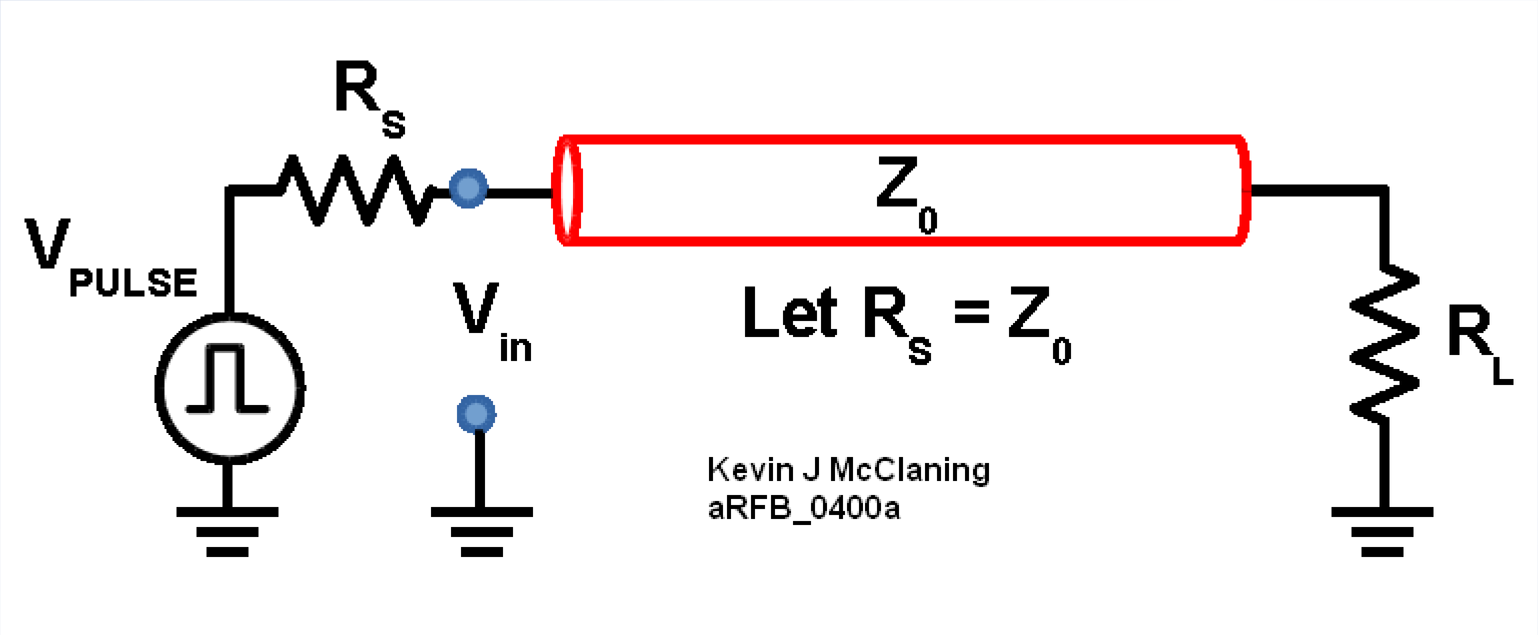
$$Z_0 = \sqrt{\frac{\Delta L}{\Delta C}} \text{ (Ohms)}$$

PCB Transmission Lines

- A PCB trace modeled as a transmission line



Digital Signals and Transmission Lines

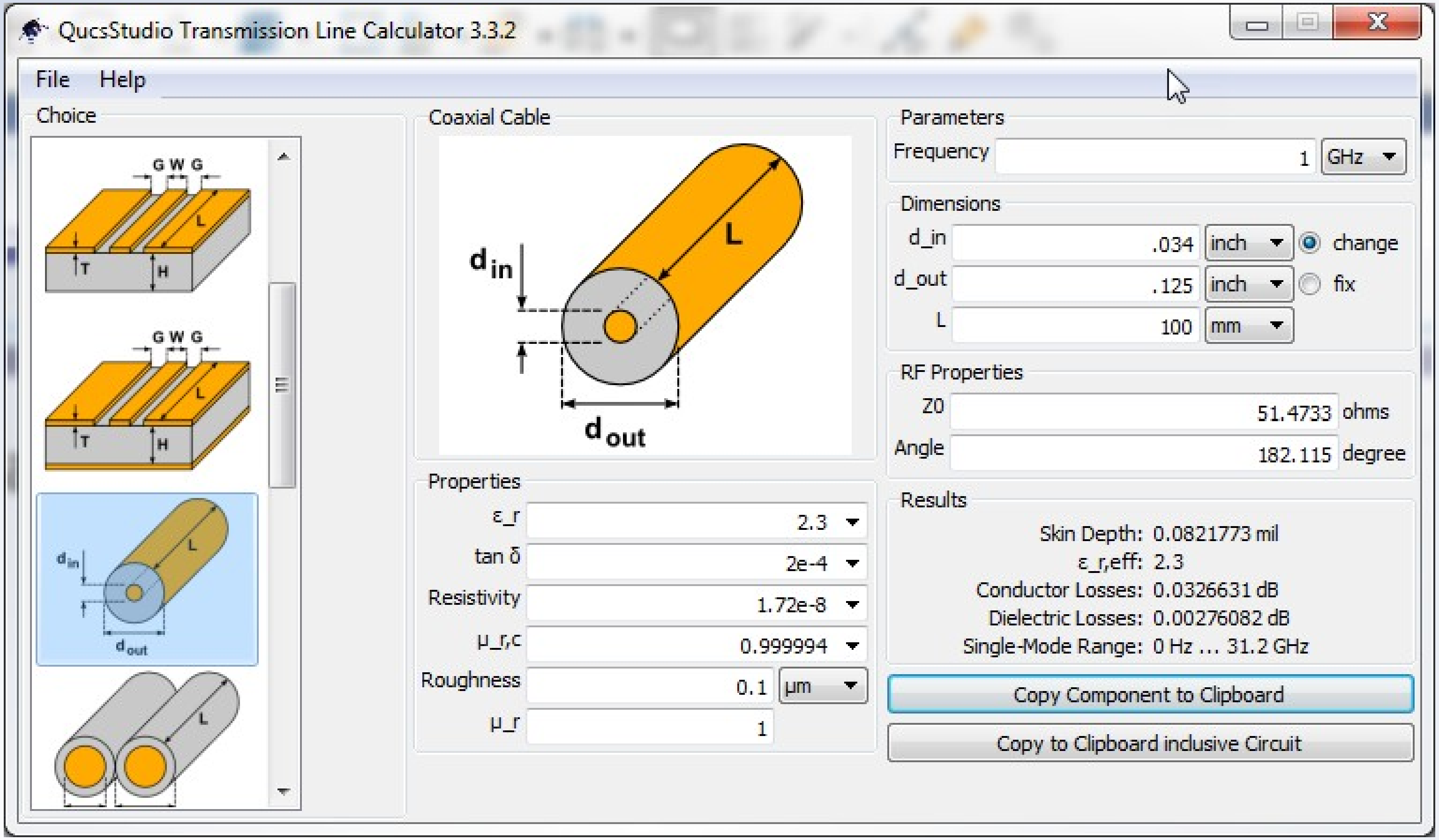


- Connect a pulse generator to a terminated transmission line.
- Send pulses down the line.
- Monitor the Voltage V_{IN} at the input to the T-Line as we vary the load resistor R_L

Digital Signals and Transmission Lines

- Tline_004.gif
- Tline_003.gif

Physical Transmission Lines – Coaxial Lines



- Crude relationship

$$Z_0 = \frac{138}{\sqrt{k}} \log\left(\frac{d_{OUT}}{d_{IN}}\right) \text{ (Ohms)}$$

Physical Transmission Lines – Coaxial Lines

$$Z_0 = \frac{138}{\sqrt{k}} \log\left(\frac{d_{OUT}}{d_{IN}}\right) \text{ (Ohms)}$$

- Z_0 changes with a change in the ratio of d_{OUT}/d_{IN}
  - Stepping on a cable
  - Any change in the physical arrangement of the conductors
- Tline_002.gif
  - Stepping on a cable
  - Oscilloscope probe
- Tline_001.gif
  - Connectors

Transmission Lines – Sinusoidal Drive

- This discussion also applies to sinusoidal drive, although it's less intuitive
    - Standing_Wave_2.gif
- VSWR – Voltage Standing Wave Ratio
    - Easy to measure but not very useful
    - Converts easily to reflection coefficient

$$\rho = \frac{VSWR - 1}{VSWR + 1}$$

- VSWR often gives wavelength in the transmission line

Frequency, Wavelength and Propagation Velocity

- Frequency, wavelength and propagation velocity are related by

$$\lambda f = \upsilon \ \text{(General Case)}$$

$$\lambda_0 f = c \ \text{(Free Space)}$$

where λ = the wavelength of the signal in any medium

λ_0 = the wavelength of the signal in free space

ν = the velocity of propagation

f = the frequency of the signal

c = the speed of light

The Speed of Light

- c = 2.998E8 m/sec ≈ 3E8 m/sec
- Light travels about 1 ft/ns (< 2% error)

Example: Satellite Time Delay

- A geostationary satellite is 35.863E6 meters (= 22,284 miles or 117.66E6 feet) above the Earth. How long does it take a signal to travel from the Earth to the satellite and back to the Earth again?

$$t_{RT} = \frac{(2)\left(35.863 \bullet 10^6\right)\text{ meters}}{2.9979 \bullet 10^8 \text{ meters/second}} = 0.239 \text{ seconds}$$

$$\approx (2)\left(117.66 \bullet 10^6 \text{ feet}\right)\left(\frac{1 \text{ nsec}}{\text{foot}}\right) = 0.235 \text{ sec}$$

Frequency and Wavelength in Free Space

Frequency (MHz)	Wavelength			
	Meters	Yards	feet	inches
1	300.0	328.0	984.0	11,800.0
20	15.0	16.4	49.2	591.0
100	3.0	3.28	9.84	118.0
150	2.0	2.19	6.56	78.7
300	1.0	1.10	3.28	39.4
600	0.50	0.547	1.64	19.7
1,000	0.30	0.328	0.948	11.8
3,000	0.10	0.109	0.328	3.94
10,000	0.03	0.0328	0.0948	1.18
30,000	0.01	0.0109	0.0328	0.394
100,000	0.003	0.00328	0.00948	0.118

- Memory aid: 300 MHz is 1 m, then work out the wavelength using the frequency ratio

Physical Size Measured in Wavelengths

F	λ	λ/2π	λ/20
10 Hz	30,000 km	4,800 km	1,500 km
60 Hz	5,000 km	800 km	250 km
100 Hz	3,000 km	480 km	150 km
400 Hz	750 km	120 km	38 km
1 kHz	300 km	48 km	15 km
10 kHz	30 km	4.8 km	1.5 km
100 kHz	3 km	480 m	150 m
1 MHz	300 m	48 m	15 m
10 MHz	30 m	4.8 m	1.5 m
100 MHz	3.0 m	48 cm	15 cm
1 GHz	30 cm	4.8 cm	1.5 cm
10 GHz	3.0 cm	4.8 mm	1.5 mm

λ/20 = antenna effects begin to occur in wires and slots

λ/2π = wave number (relates wavelength to radians)

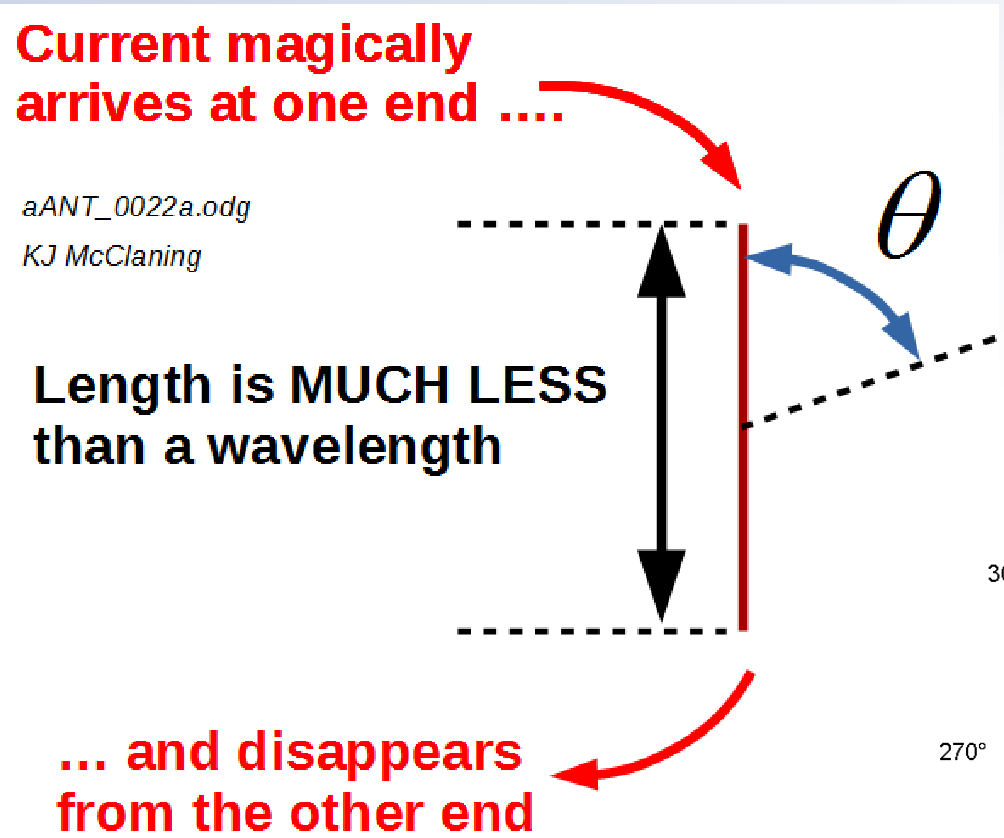
Frequency, Wavelength and Propagation Velocity

- Signals move slower in a transmission line
- Rough rule:
    - Propagation velocity in a t-line is about 50% of the speed of light
    - Wavelengths in cables are halved
    - 300 MHz is 0.5m

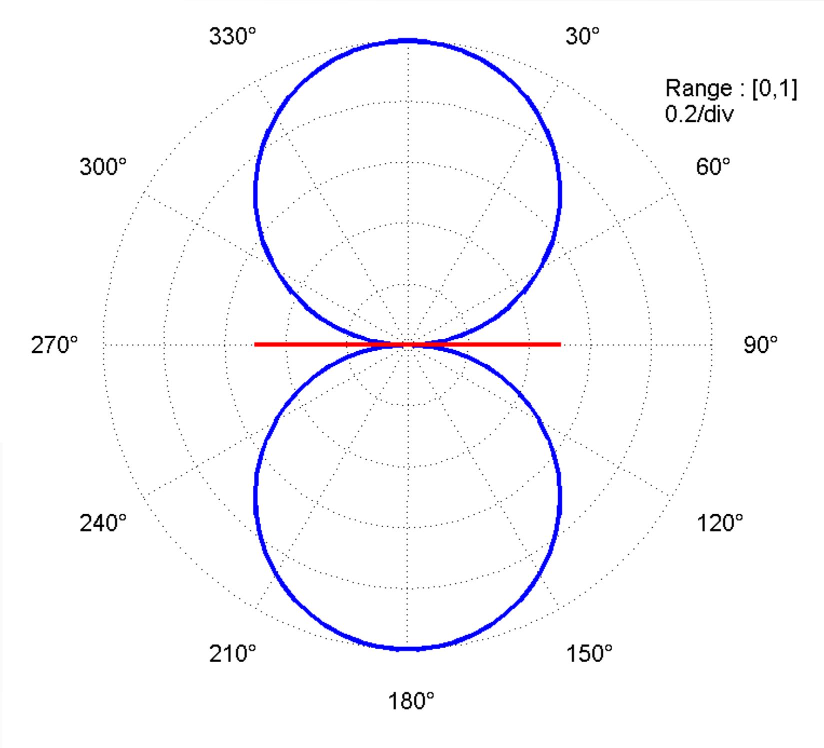
Frequency and Wavelength Effects

- Propagation time: The time a signal takes to travel from one part of a circuit to another becomes interesting
  - Clock skew
  - Circuit components connected by a "wire" are no longer at the same potential.
- Slots and structures whose physical size greater than $\lambda/20$ begin to radiate or allow energy to propagate.
  - Microwave oven windows and doors

Antennas - The Short Dipole

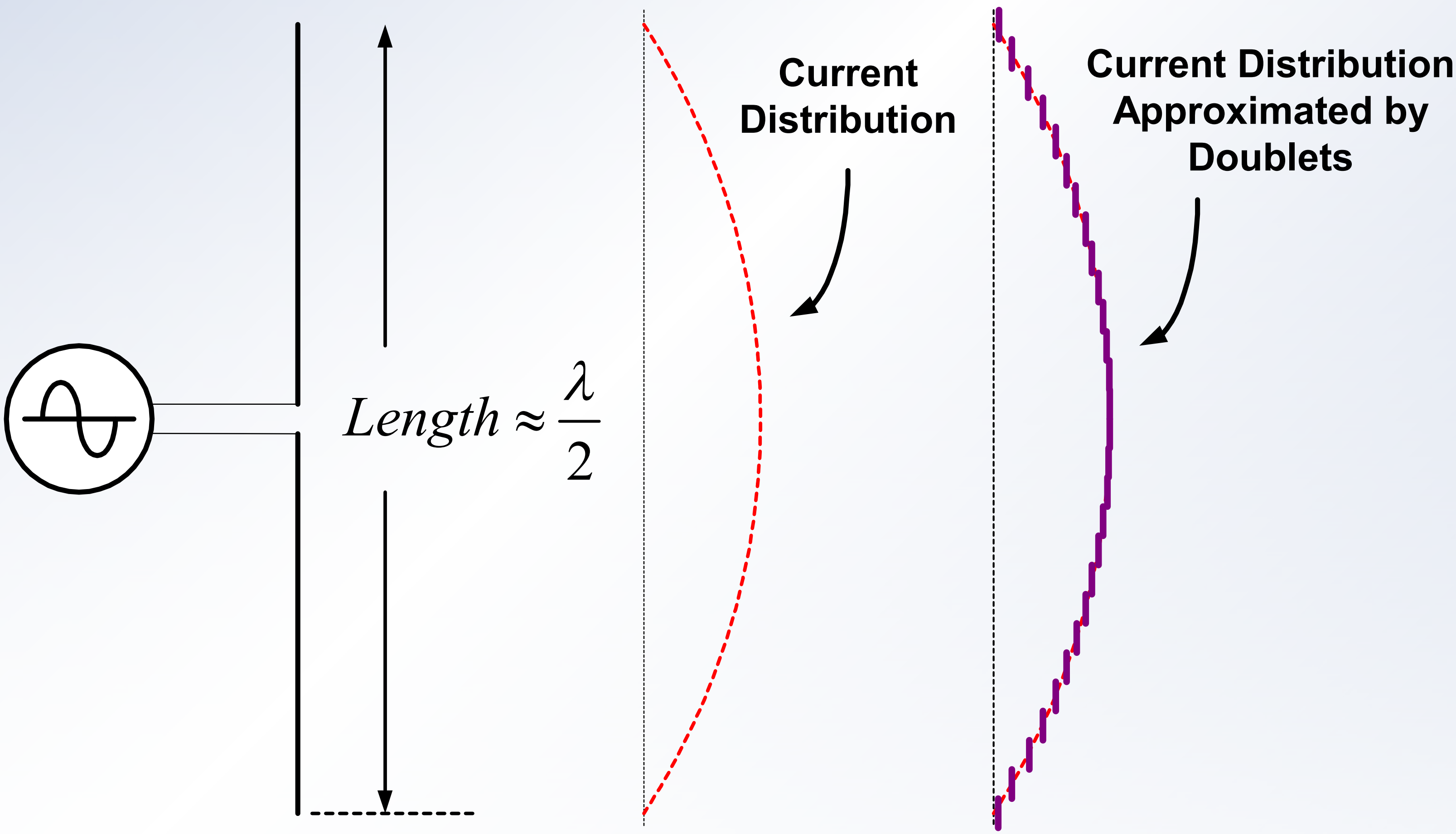


Oops! Accidentally rotated the graph by 90 degrees!



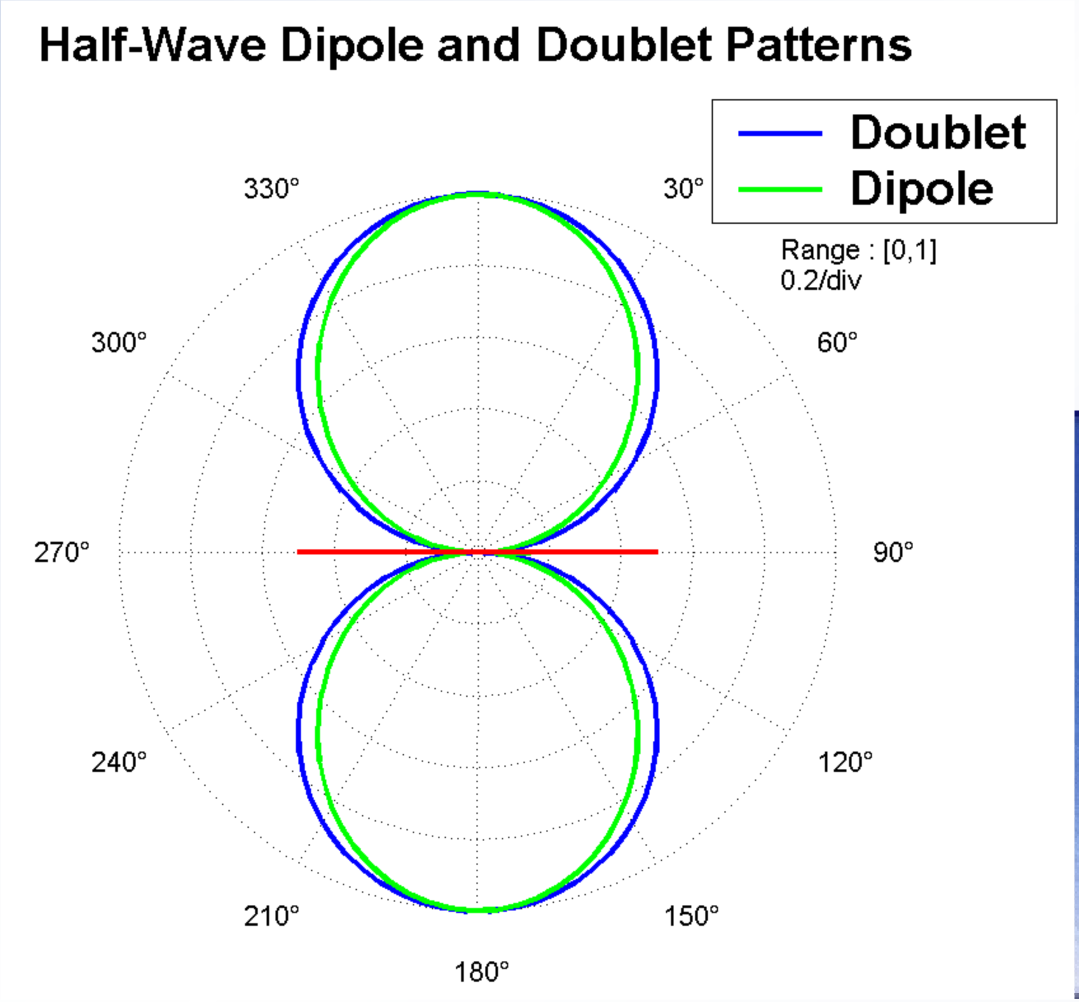
Half-Wave Dipole

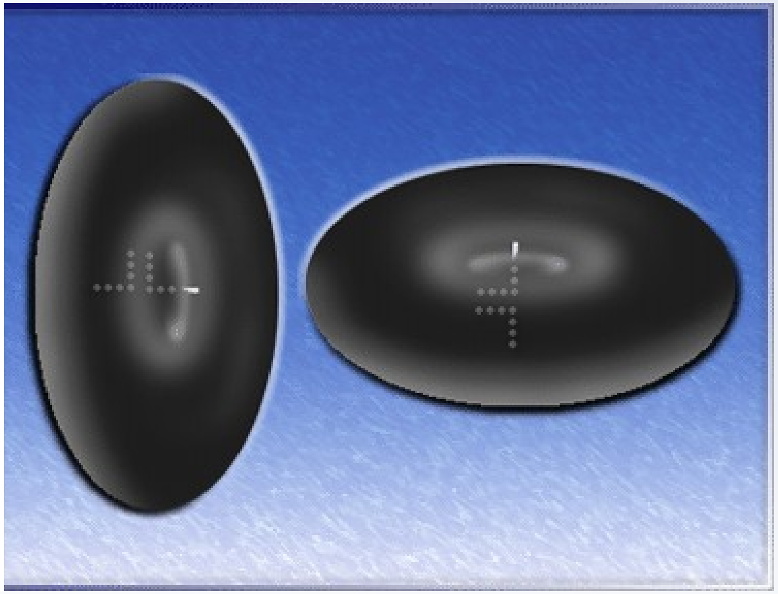
- Most antennas are variations on a dipole or made from arrays of dipoles



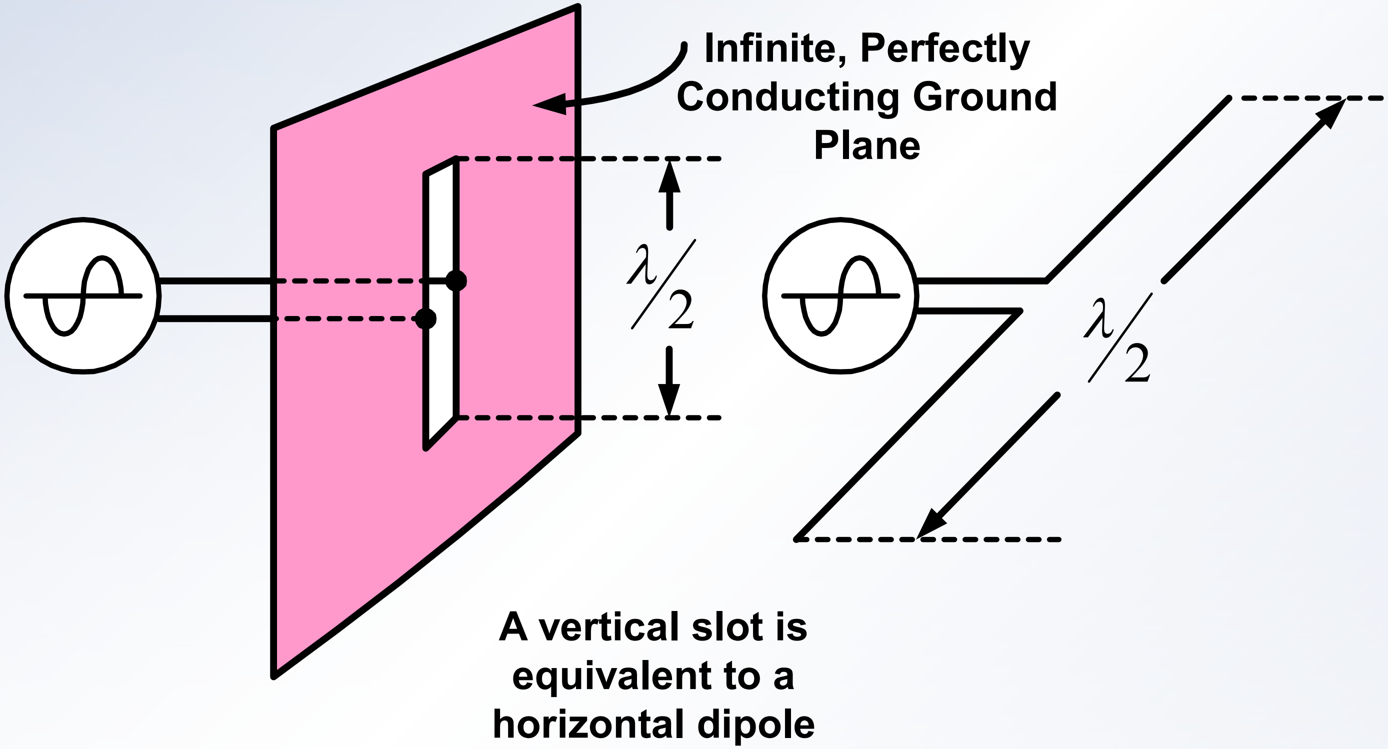
Half-Wave Dipole - Pattern

- The familiar doughnut pattern





Slot Antennas



Bibliography

- Circuit diagram and simulations - QucsStudio
  - http://dd6um.darc.de/QucsStudio/qucsstudio.html
  - Windows only
  - Not open source
- QUCS – Quite Universal Circuit Simulator
  - http://qucs.sourceforge.net/
  - Open source
  - Multiple platforms
  - Not active
- Coplanar Waveguide Circuits Components & Systems by Rainee N. Simons
- McClaning, Kevin J., Wireless Receiver Design for Digital Communications, 2nd Edition; SciTech Publishing; ISBN-10: 1891121804, ISBN-13: 978-1891121807.

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