

Radio Design 201 Microwave Circuits and Antennas

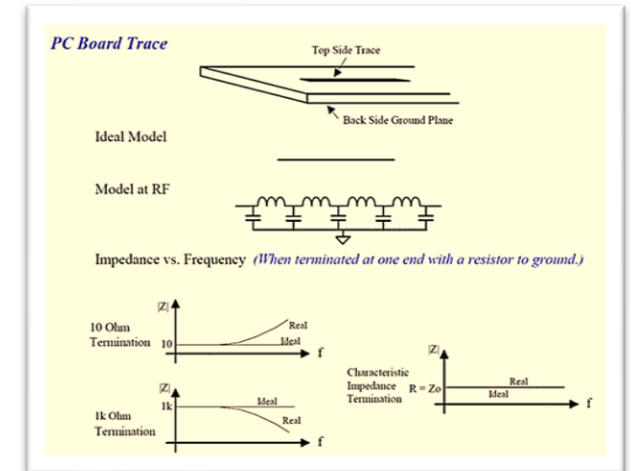
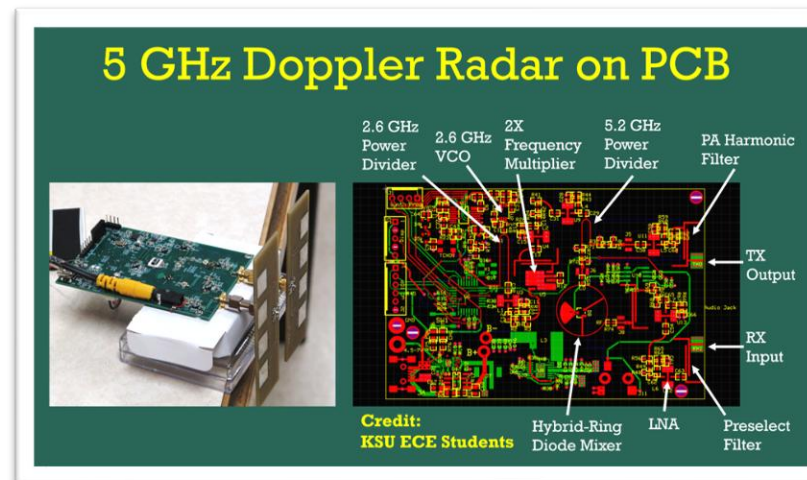
Episode 9 RF Parasitics and Transmission Lines

Slides downloaded from: <https://ecefiles.org/>

Companion videos at: <https://www.youtube.com/playlist?list=PL9Ox3wpnB0kpOb7NdpHAK-jDpsZm3Xedx>

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Designing radio frequency (RF) and microwave circuits requires an understanding of component and printed circuit board parasitics, and how PCB traces become transmission lines when their length exceeds about 1/10 of a wavelength. Episode 9 dives into these issues and illustrates them with circuits made in associated university courses. The second half of the episode elaborates the mathematics, operation, and practical applications of transmission lines, including characteristic impedance, velocity of propagation, and signal reflections.

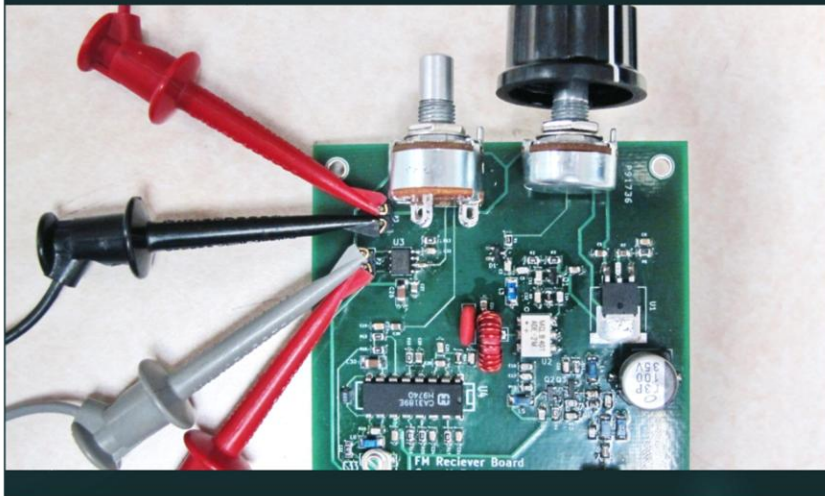


Microwave Circuits and Antennas

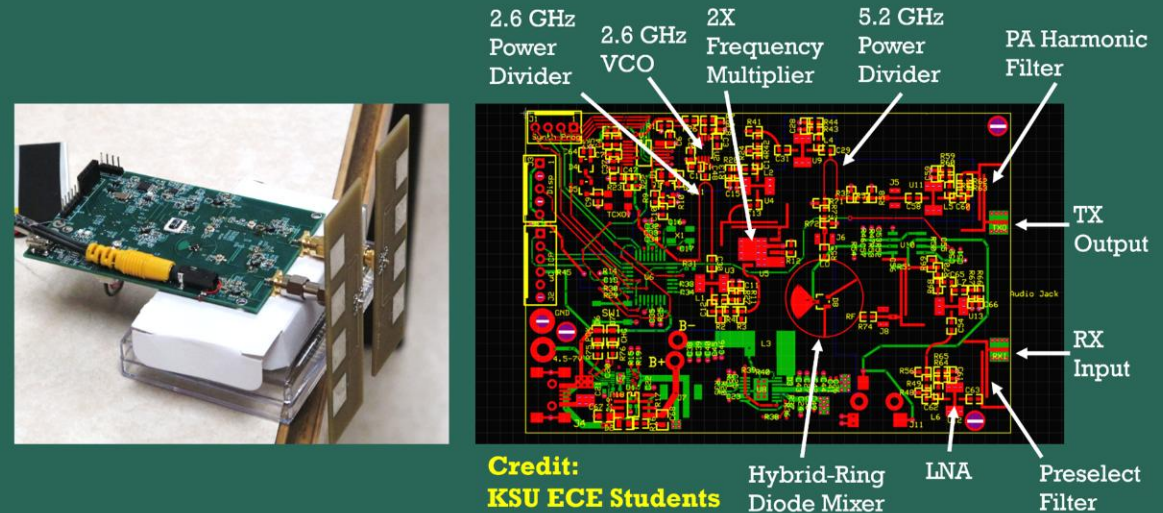
Radio Design 201 #9

RF Parasitics and Transmission Lines

VHF Receiver on PCB



5 GHz Doppler Radar on PCB

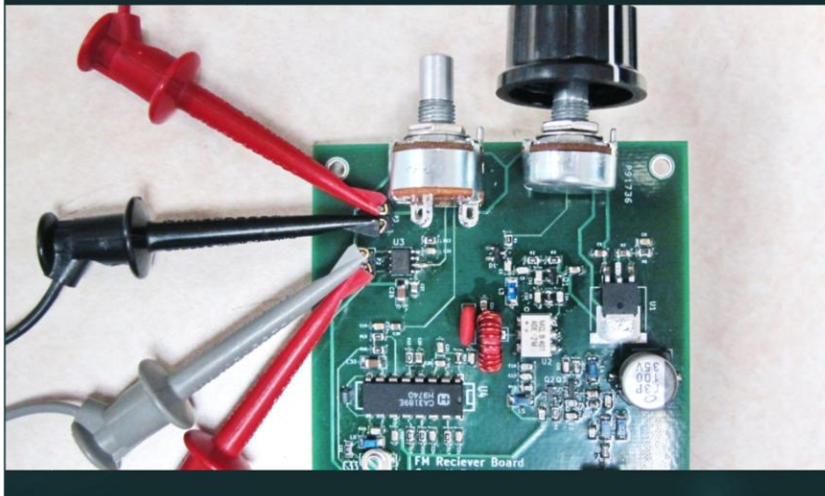


Microwave Circuits and Antennas

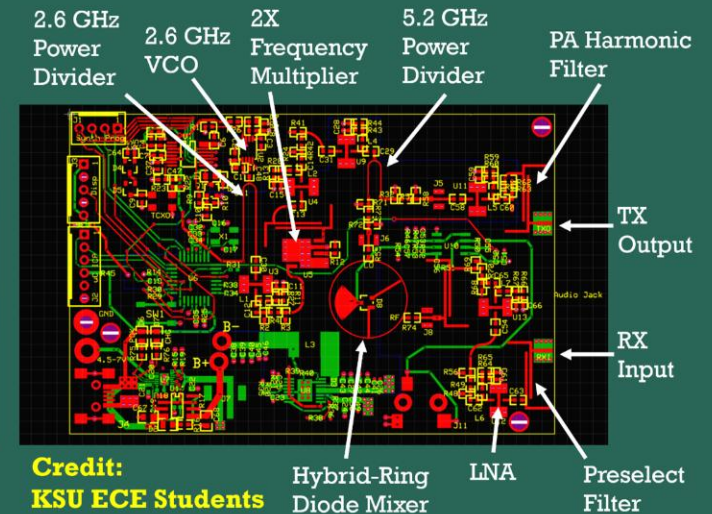
Radio Design 201 #9 (Part 1 of 2)

PC Board and Component Parasitics

VHF Receiver on PCB



5 GHz Doppler Radar on PCB



Related Course Syllabi

ECE 662 (Radio Design 101)

ECE 764 (Radio Design 201)

Week	Material	Assignments
1	Course Introduction, radio transmission, wireless link budgets, and received signal powers in dBm Signal generator, oscilloscope, and spectrum analyzer demos	
2	Soldering and connector assembly demos Electronics review: DC bias and AC circuits, transistor large/small signal models	Project 0 out
3	CE/CC/CB amplifier configurations, I/O impedances, coupling/bypass cap review Transistors at RF, resonance, and tuned RF amplifier design Resonant circuits, Q and bandwidth	Project 0 build due
4	Miller effects, stability, common-base and cascode circuits. Voltage vs. power gain Series/parallel equivalent circuits, impedance matching with L networks	Project 0 due Project 1 out
	Component and board parasitics at RF. Introduction to transmission-lines Transmission lines and Smith Charts. Impedance measurements at RF	Pjt 1 design due
6	Return loss, SWR, and introduction to S-parameters Network analyzers, calibrations, and demonstrations	Pjt 1 design back
7	Large signal response of amplifiers - compression and intermodulation Oscillator design, common base and common collector Colpitts configuration	Pjt 1 due, Pjt 2 out
8	Frequency stability and phase noise, buffering, PLLs and VCOs, Analog and digital modulations (FM and FSK) and Bluetooth standards overview	Pjt 2 design due
9	Transmitter designs, power amplifiers, FCC rules and regulations Antenna types and operational principles	Pjt 2 design back
10	Receiver design (tuned-RF, superhet, and direct-conversion architectures) Mixer design	Pjt 2 due, Midterm out
11	IC mixer circuit descriptions RF and IF Bandpass filters, filter technologies	Midterm due Pjt 3 out
12	IF amplifiers, IF limiting amps, and automatic gain control techniques FM Demodulator circuits	
13	FM IF subsystem integrated circuit descriptions Audio amplifiers	Pjt 3 due Pjt 4 out
14	Additional topics - Troubleshooting techniques	
15	Assemble receiver and test/debug. Bit slicing, bit/frame sync, bit-error-rate testing, and other digital comm topics	Pjt 4 due
16	Final Exam Demonstrate receiver and take oral quiz on its operation on or before Friday	

Week	Material	Assignments
1	Introduction to comm systems, frequencies, and wavelengths Calculating and measuring received signal strengths with spectrum analyzer	Verify you have lab access Lab 1 assigned
2	EM theory review Antenna theory	Purchase lab kit (before lab 2)
3	Basic antenna types: dipoles, monopoles, patches, arrays Antenna characteristics: polarization, patterns, and impedance	Lab 1 due
4	Measurement of antenna patterns and signal reflection/transmission Transmission lines and reflection coefficient	Lab 2 assigned
5	Introduction to Smith Charts, plotting of impedance/admittance Simulation with Agilent ADS	
6	Lambda/4 lines and impedance transformations with microstrip Microstrip components and coupled-line microwave filters	Lab 2 due
7	PC board design, layout, and parasitics Two-port circuit theory review and introduction to S-parameters	Lab 3 assigned
8	Circuit analysis and simulation with S-parameters Amplifier insertion gain, matching, stability, noise figure, and compression specs	Lab 3 due
9	Project discussion (microwave plus baseband, ADC and DSP functions) Basic mixer concepts and hybrid-ring microstrip implementations	Project assigned
10	Voltage controlled oscillators Frequency multipliers	Prototype design/layouts due
11	Project discussions (pads, RF connector test points, test planning)	Probotype boards back
12	Frequency synthesizers and phase-locked loops	
13	Project testing/debugging discussions	Test, debug, respin boards Submit final board layouts
14	Analysis and design of directional antennas: Array theory Dish antennas and antenna feeds: e.g. helix, horn, and patch antennas Antenna simulations with ADS, EZNEC and other tools	
15	Additional radar and wireless performance issues	
16	Final Exam:	Radar demos and writeups

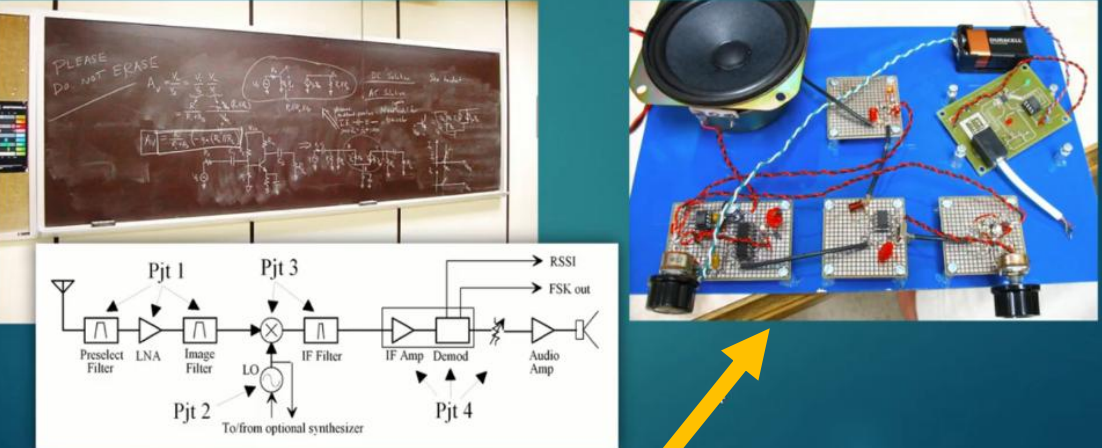
Radio Design 101 - Overview

YouTube

Search

New Radio Design 101 series

Abstracted from a senior-design University class



Block Diagram

Antenna

Pjt 1

Preselct Filter

LNA

Image Filter

Pjt 2

LO

To/from optional synthesizer

Pjt 3

IF Filter

IF Amp

Demod

Pjt 4

RSSI

FSK out

Audio Amp

Radio Design 101 - Episode 1 - Transceivers and Filters - Part 1

MegawattKS

14.5K subscribers

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68K views 5y ago Radio Design 101

This video overviews radio / wireless transmitters and receivers, circuit component impedances, voltage divider circuits, and simple one-pole lowpass / bandpass filters. The material is based on a University senior-design course, but is intended for anyone interested in the nuts and bolts of electronics and radio circuits. This is part 1 of a two part episode focused on bandpass filters - including their application, design, and measurement. Part 2 will go into filter design in depth, including an overview of impedance matching networks. Future episodes will center around and support the more

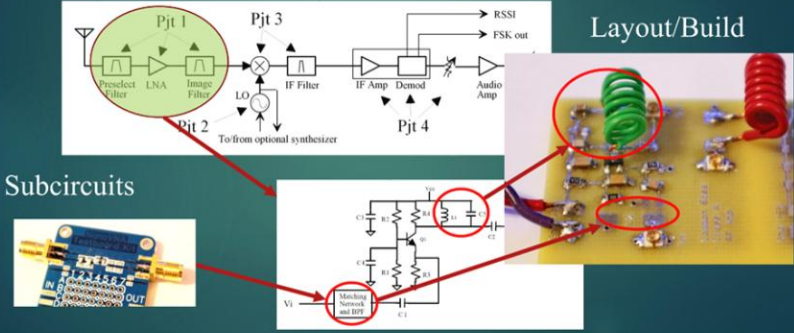
Student-designed FM Receiver !

Receiver and Filter Design

Block Diagram

Layout/Build

Subcircuits



Capacitor Parasitics

• Why does response go back up at high frequencies ?



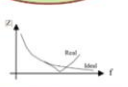
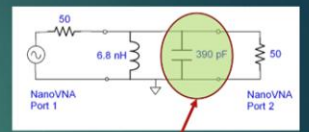
50 kHz to 500 MHz

Capacitors

Ideal model

Model at RF

Impedance vs. Frequency



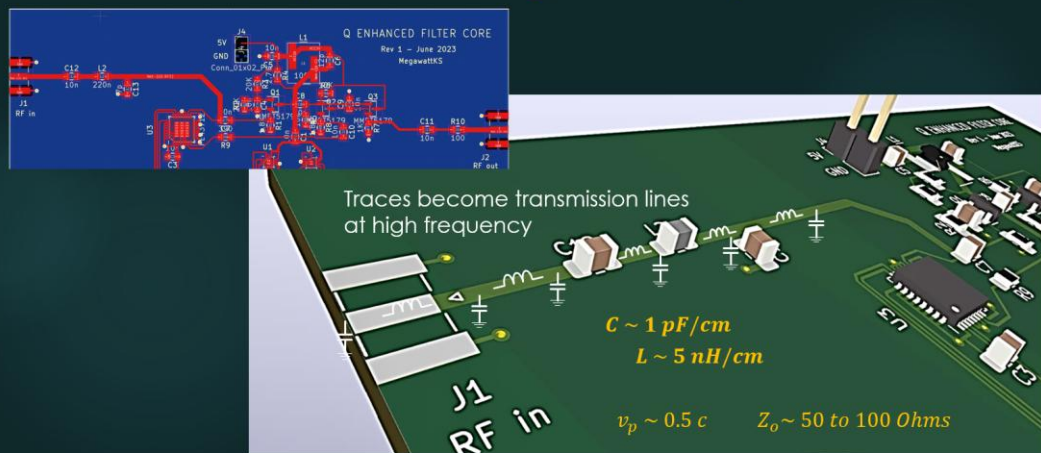
Component and PCB Parasitics

From Radio Design 101 Appendix C

PCB Traces above Ground Plane (“Microstrip” Traces)

7

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Class Handout on Parasitics

8

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Component Parasitics at RF

Resistors

Ideal Model

Model at RF

Impedance vs Frequency

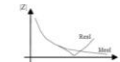


Capacitors

Ideal Model

Model at RF

Impedance vs Frequency

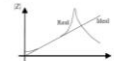


Inductors

Ideal Model

Model at RF

Impedance vs Frequency

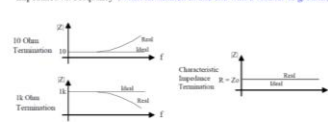


PC Board Trace

Ideal Model

Model at RF

Impedance vs. Frequency (When terminated at one end with a resistor to ground.)



PCB traces, wires, etc are transmission lines at “high frequency”.

Important if length is $> 1/10$ wavelength

$$\lambda = \frac{c}{f} v_r$$

$$v_r \sim 0.5$$

$$\Rightarrow \frac{\lambda}{10} \approx 1.5 \text{ cm at } 1 \text{ GHz}$$

L, C, and characteristic impedance varies with trace width and board interlayer thickness

Parasitics Demos

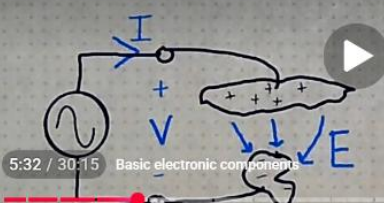
NanoVNA - Measuring RLC Components

YouTube · MegawattKS · Jan 8, 2021

NanoVNA - Measuring RLC Components

MegawattKS

Capacitance



$$V = I Z_c$$
$$C = \epsilon \frac{\text{Area}}{\text{Distance}}$$

5:32 / 30:15 Basic electronic components

More videos

YouTube

In this video

11:44 Surface-Mounted Resistor Example

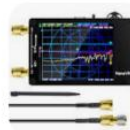
15:10 Summary

18:17 Measurement setup

22:21 Parallel Resonance

25:12 What happens at 1GHz

Related products



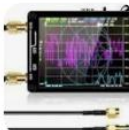
Aursinc
Nanovna
Vector Netwo...
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NanoVNA-F V2
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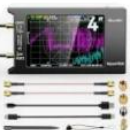
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6.3GHz...
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\$44+



NanoVNA
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5.0 ★ (3)
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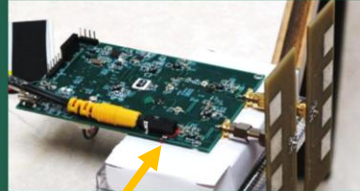
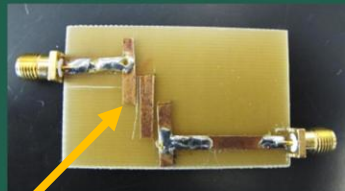
SeeSii
Upgraded
NanoVNA-H4...
4.8 ★ (59)
\$81+



NanoVNA-i
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Radio Design 201 – Review

Radio Design 201 #3 *Microwave Circuits and Antennas* *Project-oriented Learning*



[MegawattKS - YouTube](#)

<https://ecefiles.org>

Microwave
Bandpass Filter

Student-team designed
5 GHz Radar !

A Definition of “Microwaves”

- Radio frequencies where the size of the electronic components and /or interconnects used is larger than about 1/10th to 1/20th of a wavelength

Speed of Light
$$\lambda = \frac{c}{f}$$

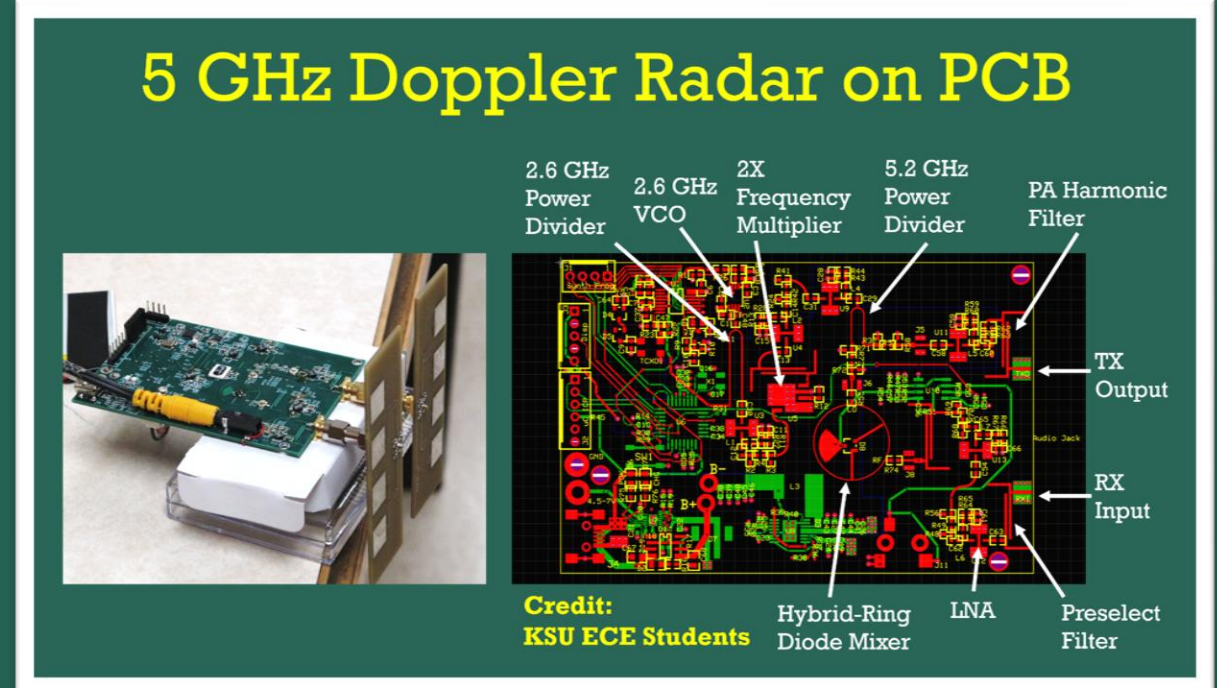
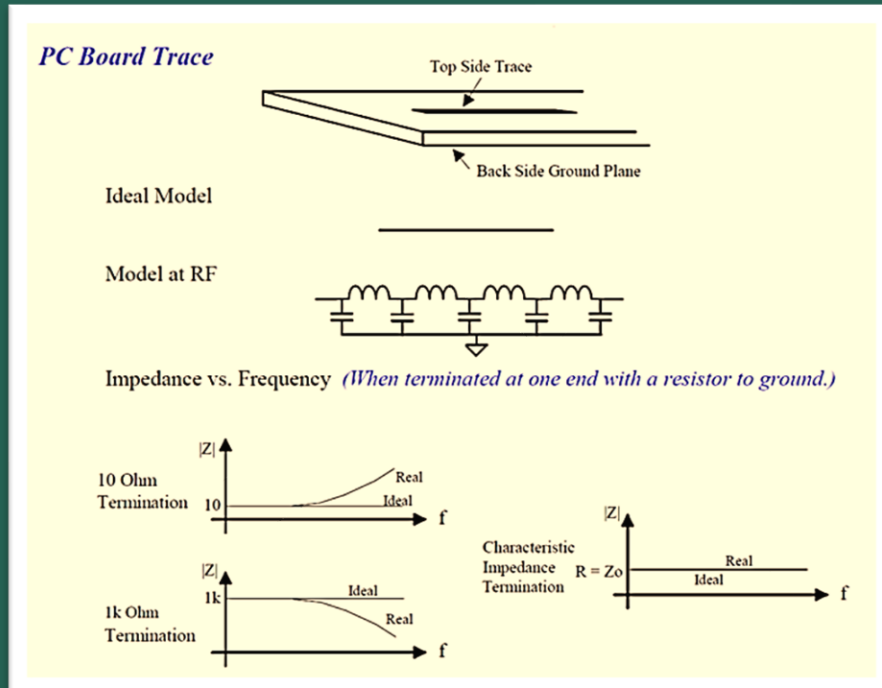
Wavelength
Frequency

Frequency (f)	Wavelength(λ)	λ/20	Microwave ?
100 MHz	3 meters	15 cm (6 inches)	Nope. Just RF
2.4 GHz	12.5 cm	6 mm (240 mils)	Yes? Depends ...
24 GHz	1.25 cm	600 um (24 mils)	Yes, for PCB design. Maybe for IC design. Yes, for (most) packaging.

Microwave Circuits and Antennas

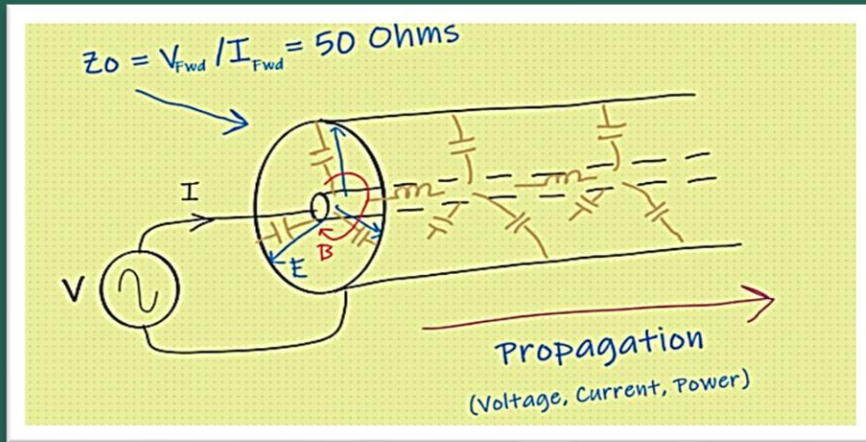
Radio Design 201 #9 (Part 2 of 2)

Transmission Lines – Theory and Practice

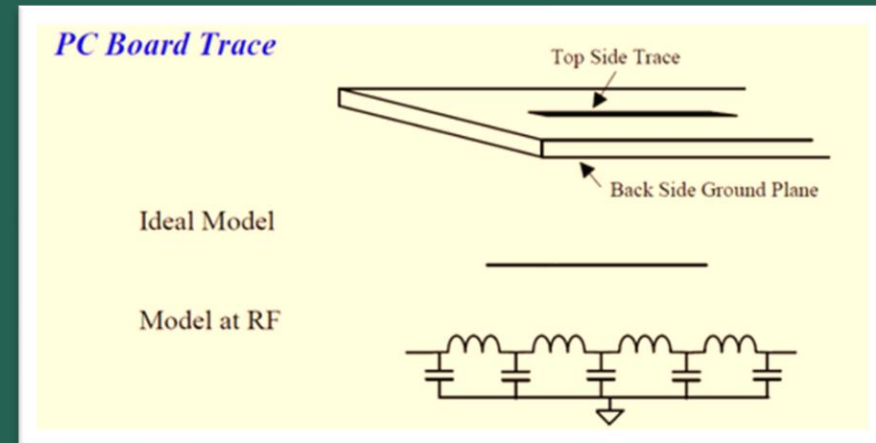


Transmission Lines at Microwave

Any connection with distributed
Series L and Shunt C



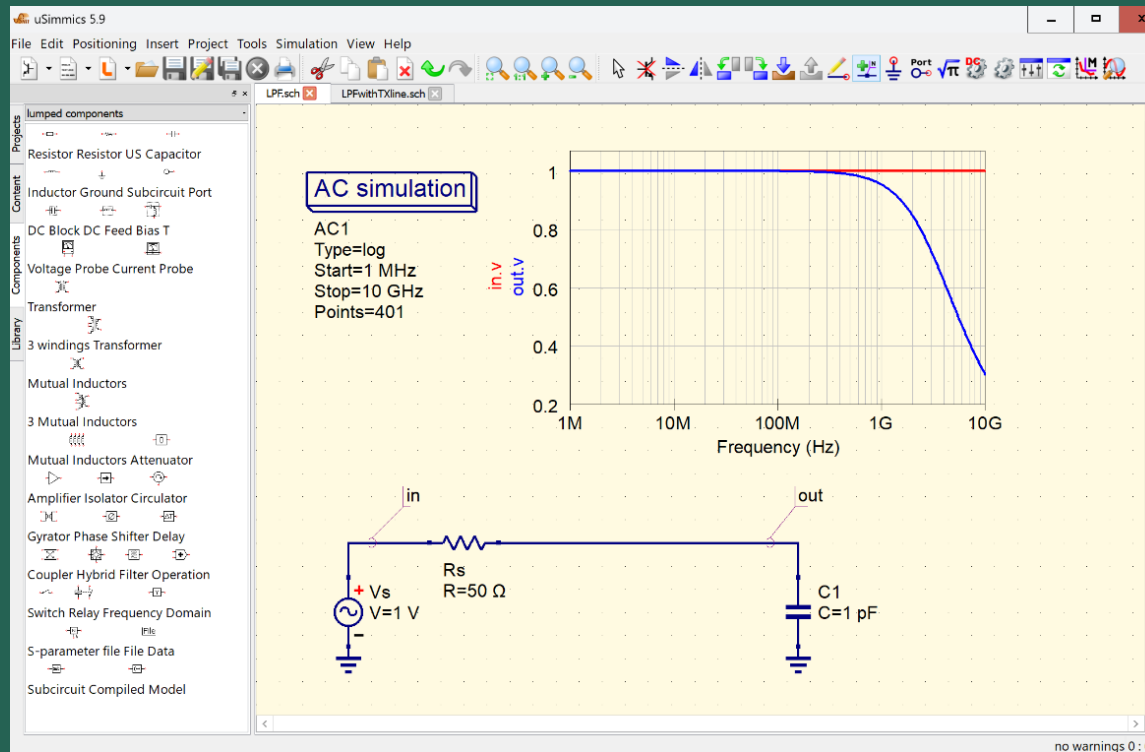
- Coax,
- Twisted-pairs (USB, Ethernet),
- Ribbon-cable with grounds,
- Connectors,



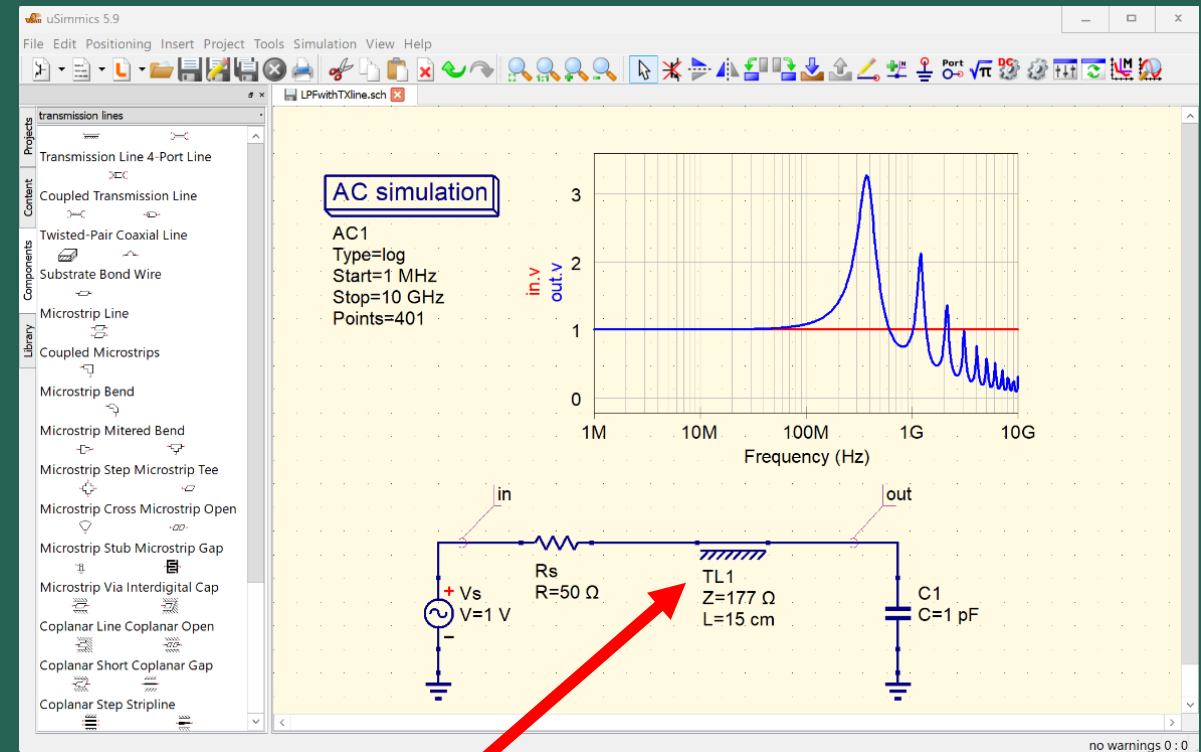
- PCB traces (with ground plane),
- Variants: (Microstrip, CPW, stripline ...)
- ...

A “simple” 3 GHz Lowpass Filter

Simulations using “uSimmics” (see also: “QucsStudio”)

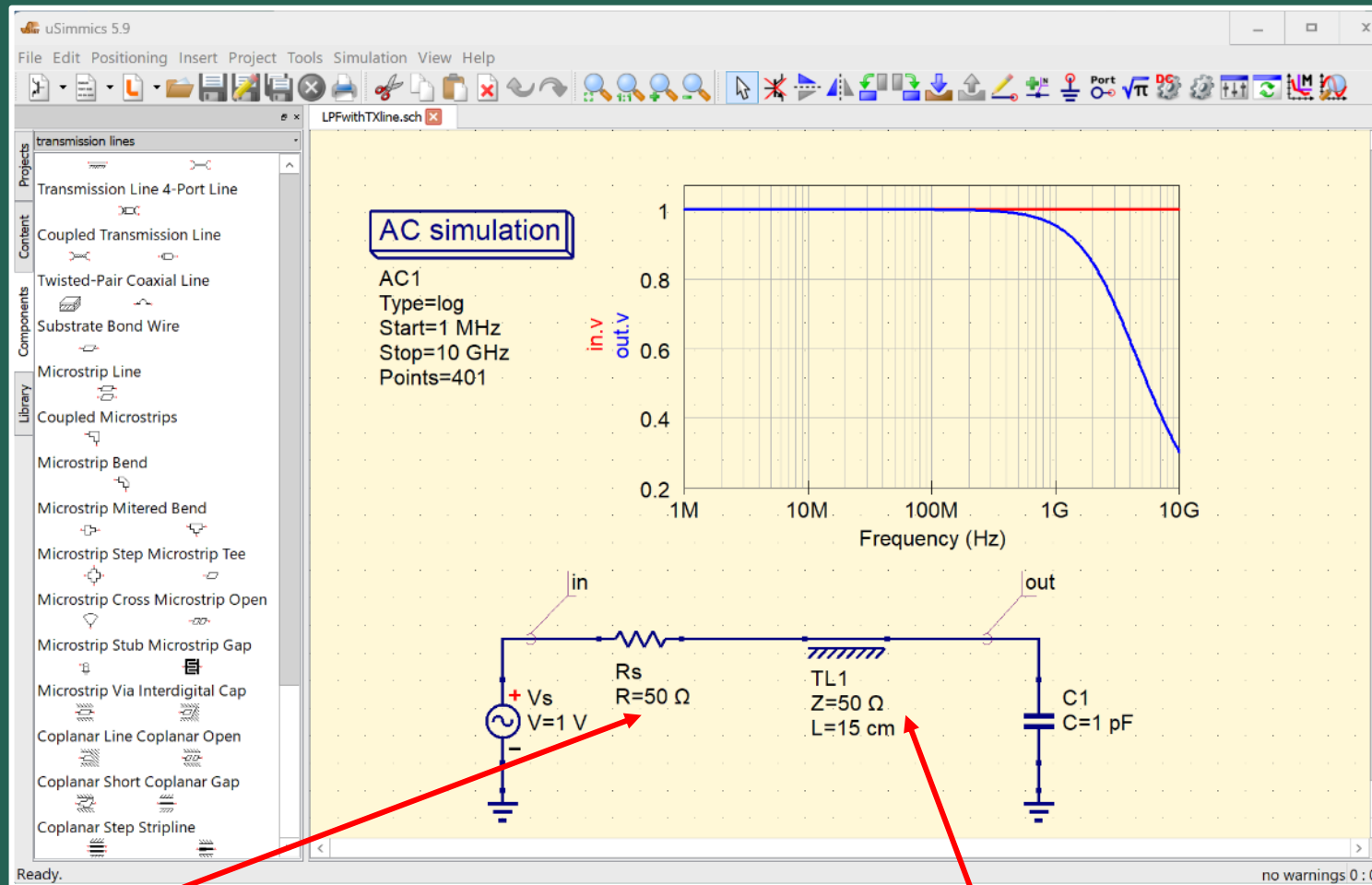


Simple Textbook View



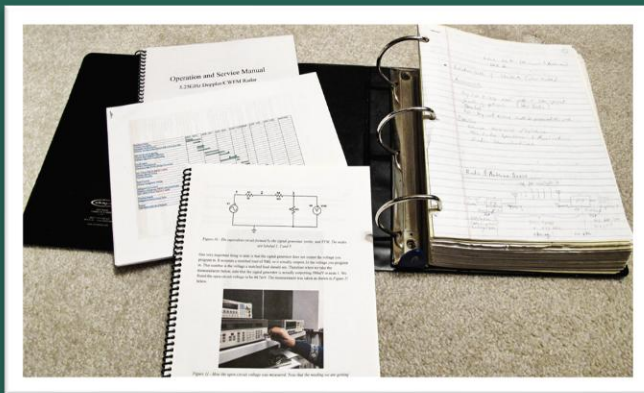
Narrow PCB Trace Model

Fixing the Problem



Match R_s and Characteristic Impedance (Z_o) of transmission line

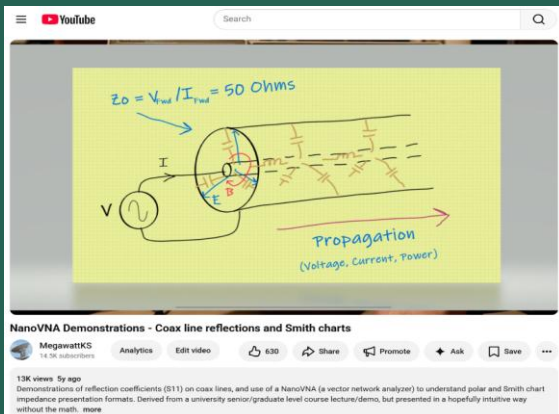
Today's "Course Lecture"



Play

<https://www.youtube.com/watch?v=jo6H5ZeBuYM>

from 2:12 to 2:36



Result TX Systems

(AKA "feeding")

Transmission Line Characterization

- "No" reflection (if $Z_L = Z_0$) if length $\ll \lambda/4$
- Single connection ($Z_{in} = Z_{out}$) if length $\ll \lambda/4$
- Discrete LC circuit if length $\geq 0.1\lambda$ ($\approx 0.1 \times 106\text{cm}$)
 $\Rightarrow Z_{ANT} \neq Z_{ANT}$ (except in special case of $Z_{ANT} = Z_0$ of line) Length of pin on mic

TX Line modeling

$\Delta I = \frac{V}{Z_0} = \frac{V}{\sqrt{L/C}}$ where $\Delta C = C(\Delta x)$ (Typically 1 to 3 pF/inch)

$\Delta V = j\omega L I$ with $\Delta L = L(\Delta x)$ (Typically 5-20 nH/inch)

OR "TWS-WIRE" OR PCB "microstrip" trace

Current I draws thru ΔC , Voltage drop across ΔL (but no power loss if L or C are "lossless" (V, I 90° apart))

$\Rightarrow V, I$ change phase along link

$\Rightarrow$ "Guided wave" propagates away from source toward load

IMPORTANT

At RF & microwave, any "nodes" $Z \approx 0.05\lambda$ is NOT a node - it's a complicated LC network!

At 2.6GHz / 0.115m
 $\lambda = \frac{300}{2.6} \approx 115\text{mm}$
 $\Rightarrow \lambda/20 = 5.75\text{mm}$

Characteristic Impedance of Line:

Consider case of lossless line: (So no reflection)

What is Z seen by source? At source end:
 $I = \frac{V}{Z_0}$ "Line looks like an impedance Z "

To find Z_0

$$Z = sAL + \frac{1}{sC} \parallel Z$$

$$= sAL + \frac{Z_0 sC}{Z_0 + sC}$$

$$= \frac{s^2 AL C Z_0 + sAL + Z_0}{sC Z_0 + 1}$$

NOTE:
 $Z \equiv Z_0$
 in this derivation

Let $\Delta x \rightarrow 0$, so that $sC, sAL \rightarrow 0$

Then $Z_0 = \frac{sAL + Z_0}{sC Z_0 + 1}$ Since at Δx variation goes to zero, Z_0 is constant

$\Rightarrow Z_0 = Z \frac{1 + sAL/Z_0}{1 + sC Z_0}$

Hence, $\frac{AL}{Z_0} = \Delta C Z_0$

$\Rightarrow Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{\Delta L / \Delta x}{\Delta C / \Delta x}} = \sqrt{\frac{L}{C}}$ (L per length, C per length)

Called "Characteristic Impedance of Line" Z_0

Typical value $\sim \sqrt{\frac{5\text{ nH/in}}{2.5\text{ pF/in}}} \approx 50\Omega$ Res. stove !!

Analogous to $Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$ free space!

Today's Course "Lecture"

Infinite Line draws some I on resistor of value Z_0 (e.g. 50 Ω resistor)

$$V \text{ @ } \frac{I}{Z_0} = \frac{V}{Z_0} = 50$$

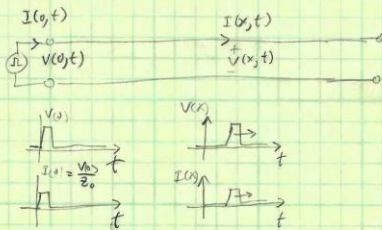
V, I propagate away from source w/ velocity $v_p = 0.5c$ to $0.8c$

can be shown $v_p = \frac{1}{\sqrt{LC}}$

use L, C parameter!

Analogous to $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$ But slower

Now consider finite length line w/ open circuit end



At open End, I must be zero

$\Rightarrow$ I Pulse is reflected back toward source at open end of line

$$I_{inc} + I_{refl} = I_{total} = 0 \Rightarrow I_{refl} = -I_{inc}$$

Inc pulse has accompanying $V_{refl} = I_{refl} Z_0$!
(Same as incident pulse $\Rightarrow$ Full reflection)

$$\Rightarrow V_{tot} = V_{inc} + V_{refl} = 2V_{inc} \text{ @ end!}$$

Define Reflection coefficient $\Gamma = \frac{V_{refl}}{V_{inc}}$

SKIP!

Γ for arbitrary Z_L

$$\text{Note: } V_{tot} = V_{inc} + V_{refl} = V_{inc}(1 + \Gamma)$$

$$I_{tot} = I_{inc} - I_{refl} = I_{inc}(1 - \Gamma) \text{ at end}$$

$$\text{Boundary condition } Z_L = \frac{V_{tot}}{I_{tot}} \Rightarrow Z_L = \frac{V_{inc}(1 + \Gamma)}{I_{inc}(1 - \Gamma)} = Z_0 \frac{1 + \Gamma}{1 - \Gamma}$$

Other Terminations

Shorted End

$$I_{inc} = I_{refl} \quad V_{tot} = 0 \quad R_L = 0$$

New Boundary Condition

$$V_{tot} = 0 \Rightarrow V_{refl} = -V_{inc}$$

$$\Gamma = -1 \text{ for short ckt}$$

$$R_{Load} = Z_0$$

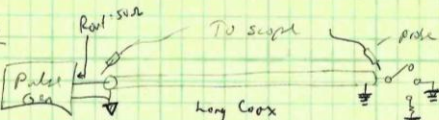
$$I_{inc} = I_{refl} \quad V_{tot} = 2V_{inc} \quad R_L = Z_0$$

Boundary condition

$$\frac{V_{tot}}{I_{tot}} = R_L = Z_0 \equiv \frac{V_{inc}}{I_{inc}} \Rightarrow V_{refl} = I_{refl} = 0!$$

$\Rightarrow$ No reflection (equivalent to connecting infinite length line)
 $\Gamma = 0!$ for $R_L = Z_0$

★ Demos



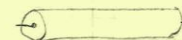
Line ≈ 20 ft ≈ 35 ns delay
Pulse Gen 5ns Pw, 150ns period (1ns/div in air)

Scope = 20ns/div, Trigger on Pulse Gen (look for 1st edge)

- Probe at source end to show emitted pulse
- Attach 50 Ω termination $\Rightarrow$ half pulse height
- Attach cable. Note - 1/2 amplitude due to 50 Ω char $\&$ second pulse due to reflection!
- Extend cable $\&$ see minimum in delay
- Probe at end of cable (2x amplitude, 1/2 delay of step pulse)
- Discuss shorted case $\Rightarrow \Gamma = -1$ $\&$ demo
- Discuss Z_0 term $\in$ whole cable! $\&$ case of 150 Ω @ end?

TX Line technologies

Coax Line



$Z_0 = f$ of OD of inner cond
ID of outer cond
 ϵ_r of insulator

Typical types (see handbook)

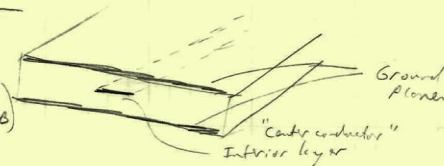
50 Ω	RG174, RG58, RG142, RG214
75 Ω	RG59, RG6, RG11, CATV
93 Ω	RG62

High Performance
50 Ω Semi-rigid RG 402

Printed Circuit Line

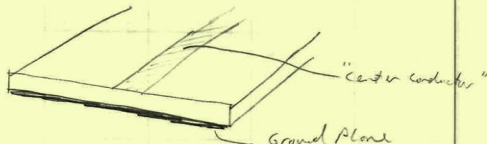
Strip line

(Needs multi-layer PCB)

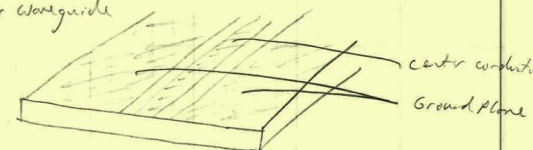


Microstrip

(cheap!)



Coplanar Waveguide



(No via interference problem)

PCB Materials

FR4, Alumina, Rogers, PTFE

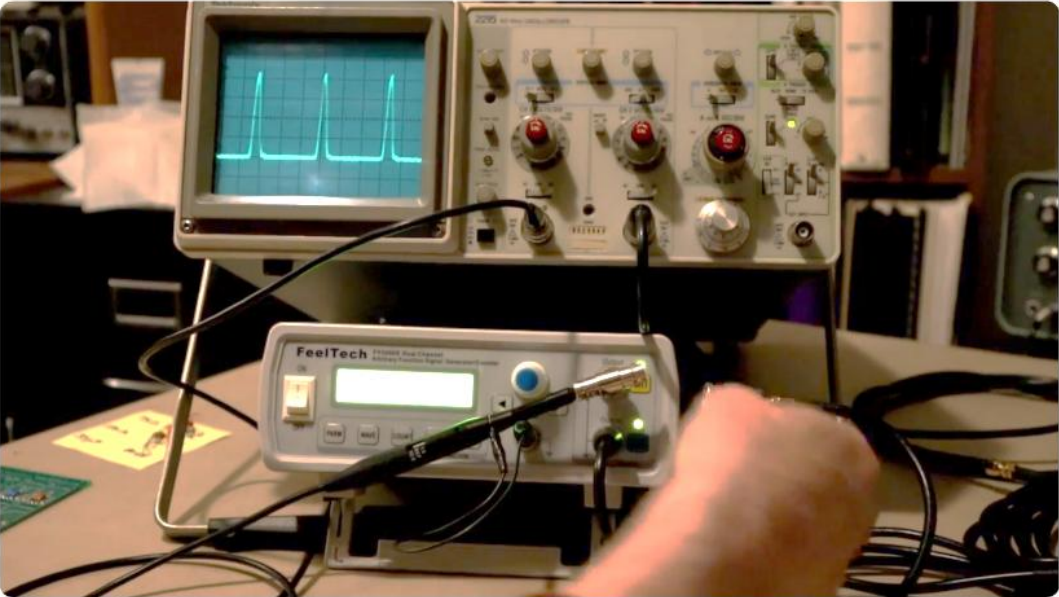
$$Z_0 = f(\text{thickness, trace width, etc})$$

Show charts of Z_0 vs thickness

TX-line Reflections Demo

← → ↺ 📄 youtube.com/watch?v=jo6H5ZeBuYM

☰ YouTube Search 🔍



NanoVNA Demonstrations - Coax line reflections and Smith charts

 **MegawattKS**
14.5K subscribers

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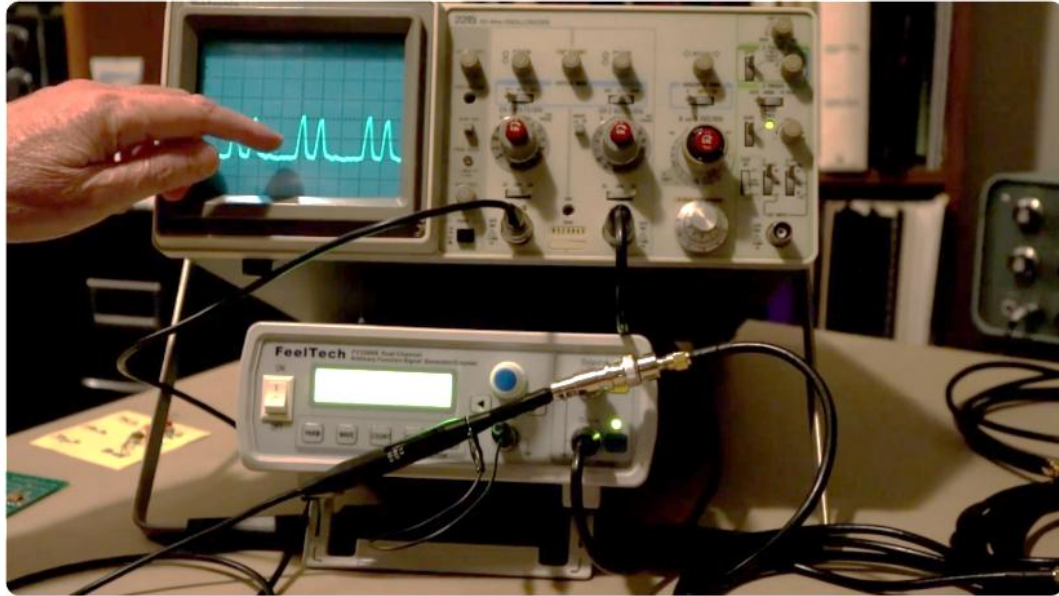
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Demonstrations of reflection coefficients (S_{11}) on coax lines, and use of a NanoVNA (a vector network analyzer) to understand polar and Smith chart impedance presentation formats. Derived from a university senior/graduate level course lecture/demo, but presented in a hopefully intuitive way without the math. [more](#)

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NanoVNA Demonstrations - Coax line reflections and Smith charts

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Demonstrations of reflection coefficients (S_{11}) on coax lines, and use of a NanoVNA (a vector network analyzer) to understand polar and Smith chart impedance presentation formats. Derived from a university senior/graduate level course lecture/demo, but presented in a hopefully intuitive way without the math. [more](#)

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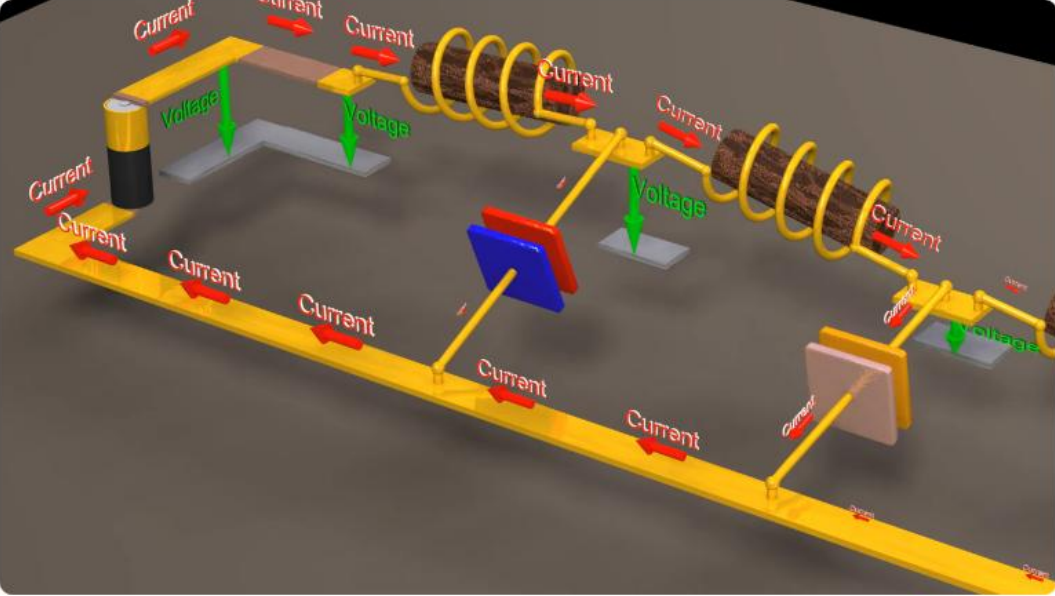
Summary / Take-homes

- At RF, consider/model RLC parasitics when designing / simulating circuits
- At Microwave, we treat interconnects as “controlled impedance” transmission lines
- “RF vs Microwave” depends on the length of the tx-lines (and size of components) relative to wavelength
- Tx-lines are characterized by their “Characteristic Impedance” Z_o
- Z_o is determined by series-L and shunt-C per unit length (and hence, by size and separation of conductors) $Z_o = \sqrt{dL/dx / dC/dx}$ (recall in free-space, $Z_o = \sqrt{\mu_o / \epsilon_o}$)
- Z_o for TX-lines is usually 50 Ohms, but Z_o can range from about 5 to 500 Ohms
- Tx-line initially draws current and power from source like a resistor of value Z_o (because propagation velocity is < speed-of-light, which itself is finite)
- When signal reaches end of tx-line, it may be (partially) reflected ...

An Interesting Animation Video showing TX-line Reflections

YouTube

Transmission Lines - Signal Transmission and Reflection



Transmission Lines - Signal Transmission and Reflection

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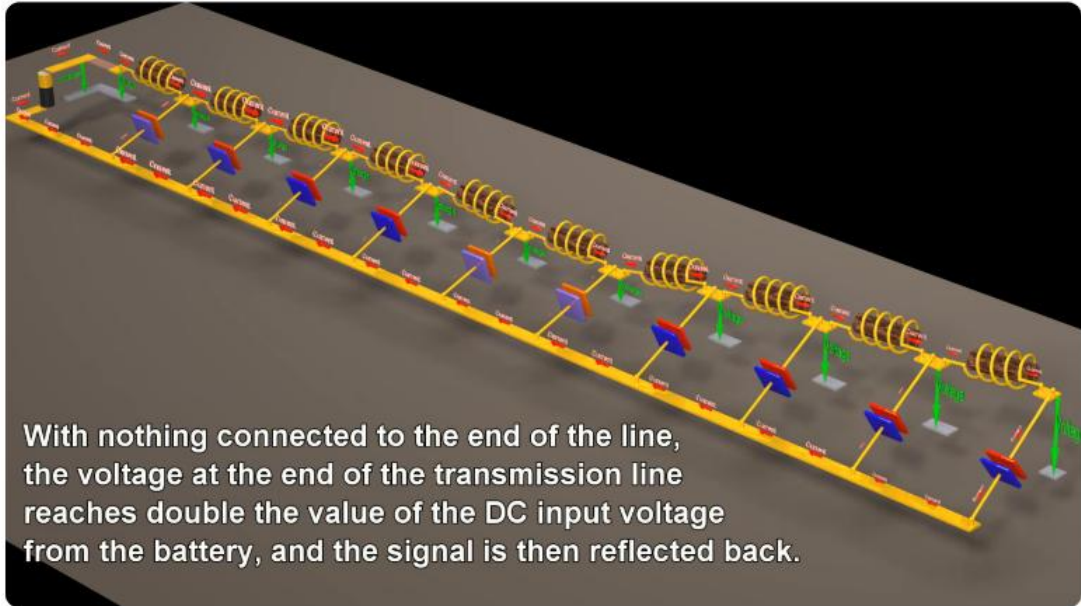
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913K views 10y ago

Visualization of the voltages and currents for electrical signals along a transmission line. My Patreon page is at [eugenek](#) more

YouTube

Transmission Lines - Signal Transmission and Reflection



With nothing connected to the end of the line, the voltage at the end of the transmission line reaches double the value of the DC input voltage from the battery, and the signal is then reflected back.

Transmission Lines - Signal Transmission and Reflection

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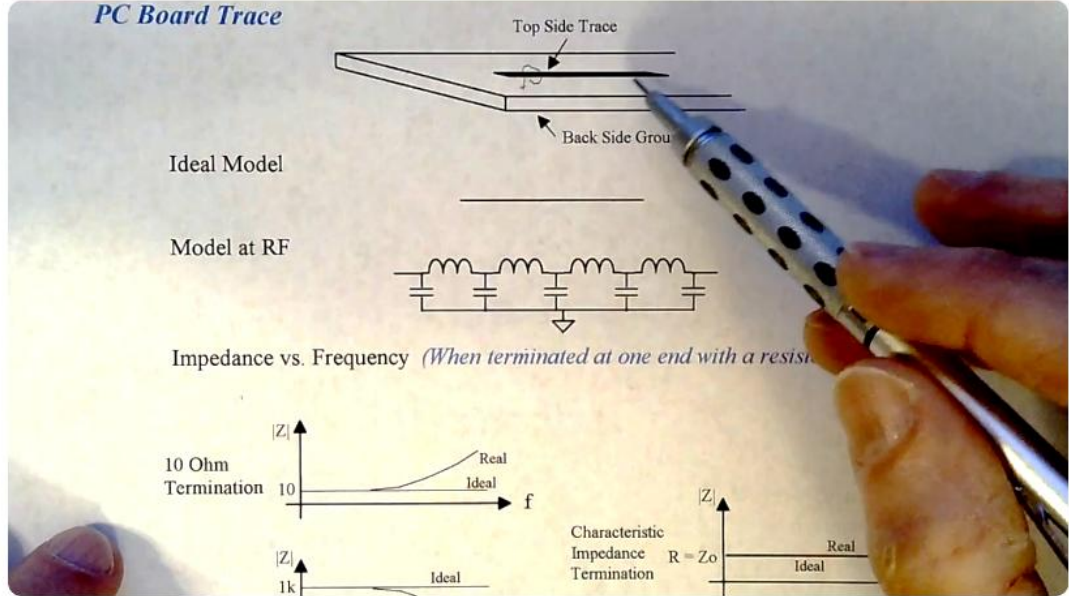
913,430 views Aug 3, 2016

Visualization of the voltages and currents for electrical signals along a transmission line. My Patreon page is at [eugenek](#)

Homework 😊

- Watch this video →
- Possibly get a NanoVNA and try some measurements
- See full “Test Equipment” video series at <https://ecefiles.org/rf-circuits-course-section-9/>

Play Video Trailer here 😊



PC Board Trace

Top Side Trace
Back Side Grou

Ideal Model

Model at RF

Impedance vs. Frequency (When terminated at one end with a resistor)

10 Ohm Termination

Real
Ideal

Characteristic Impedance Termination $R = Z_0$

Real
Ideal

NanoVNA - Measuring RLC Components

MegawattKS
14.5K subscribers

Analytics Edit video

1.7K Share Promote Ask

75,637 views Jan 8, 2021

Using a Vector Network Analyzer (VNA) to measure and understand RLC parasitics in radio / wireless design and construction. Looks at resistors, capacitors, and inductors and their non-ideal behaviors at radio and microwave frequencies. Also includes brief discussions of EM fields, both in free space and around circuit components.

AI-generated video summary · AI can make mistakes, so double-check it.

MegawattKS explores the impact of parasitic capacitance and inductance on standard resistors, capacitors, and inductors at high frequencies. By utilizing a NanoVNA to test various components and board traces, this demonstration clarifies why physical design limitations and circuit layout choices are critical when moving from theoretical models to practical radio frequency electronics.

*Thanks For
Watching !*