Radio Design 201 Microwave Circuits and Antennas
Episode 3 - Project-Oriented Learning

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

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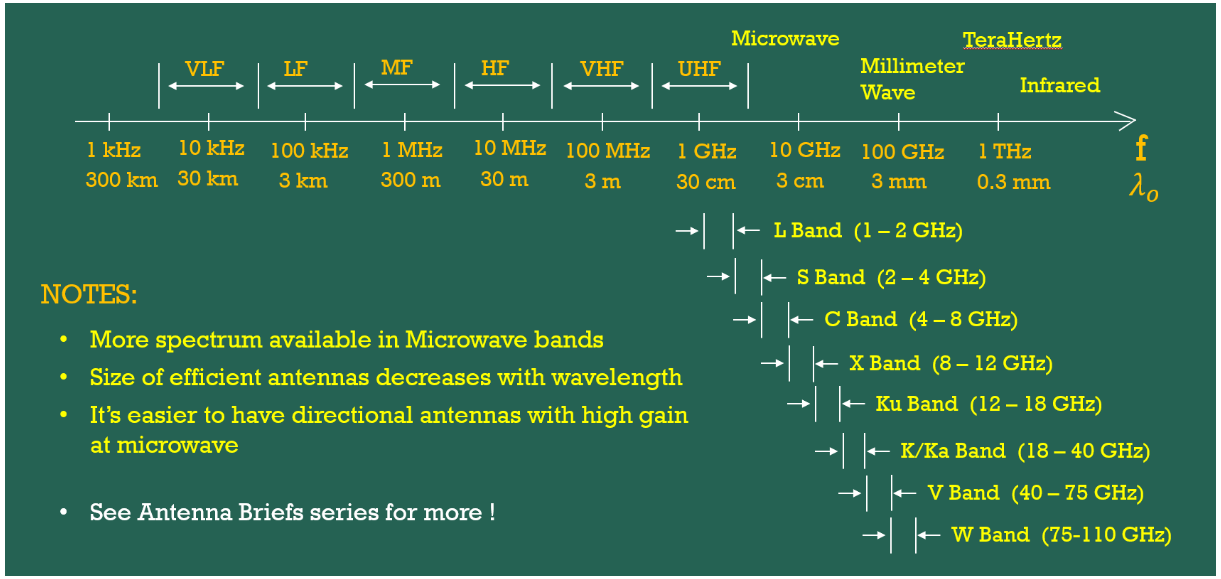
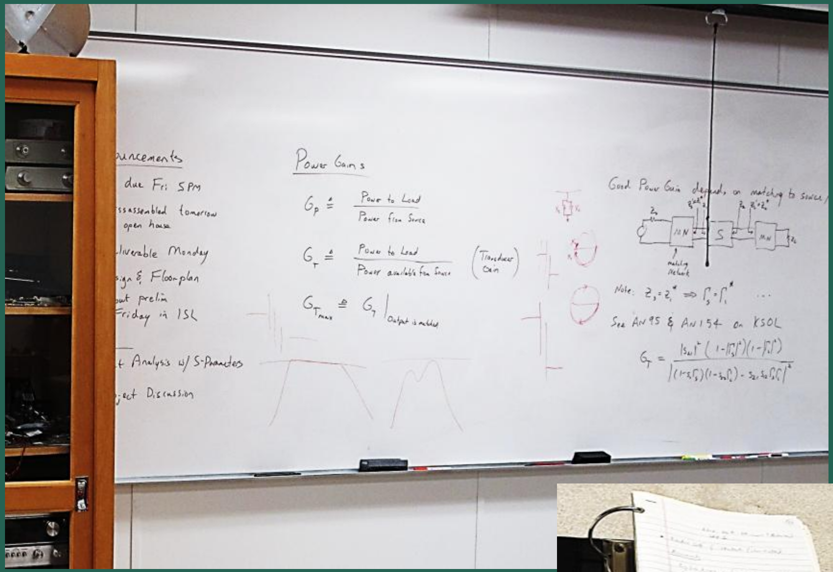
Episode 3 in the introduction to Radio Design 201contains the first-day lecture from the university course that RD201 is abstracted from, as well as a 'syllabus' of what is coming in subsequent episodes. The Day-1 "lecture" covers radio and antenna basics, frequencies and wavelengths, and applications of the microwave spectrum. The syllabus covers recommended books, the project-oriented (a.k.a. project-based) course design, schedule of topics, and examples of electronic parts used in associated labs and projects done in the course.

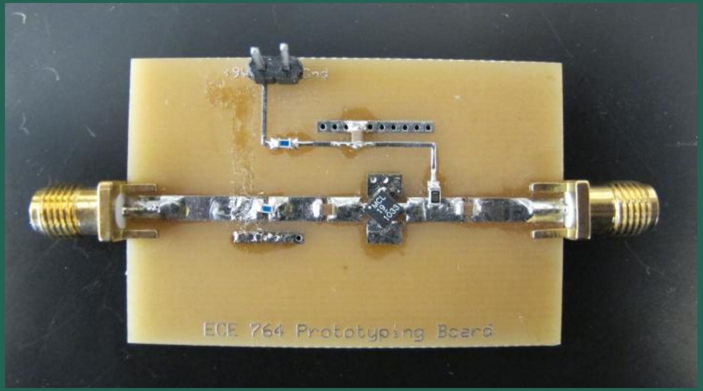


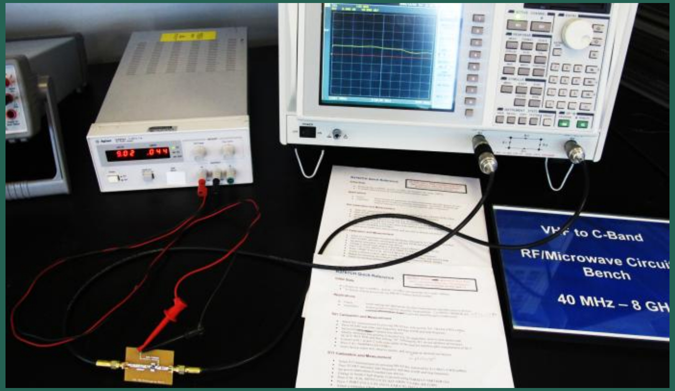
Radio Design 201 #3

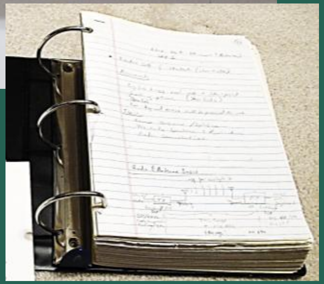
Microwave Circuits and Antennas

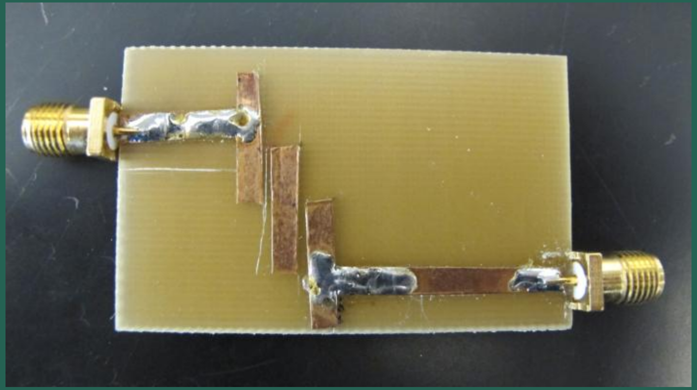
Project-oriented Learning

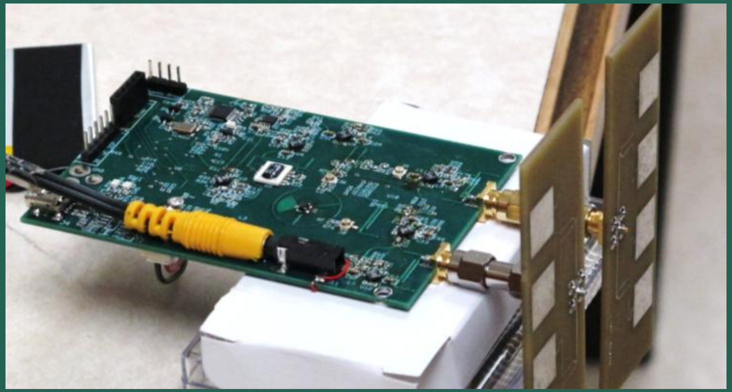












MegawattKS - YouTube

https://ecefiles.org

Radio Design 201
"Day-1 Lecture"

Announcements

Welcome to Episode 3!

See Episodes 1 and 2 for

- *definitions of "microwave", and*
- *example semester projects*

Today's Topics

➡ *Radio and antenna basics*

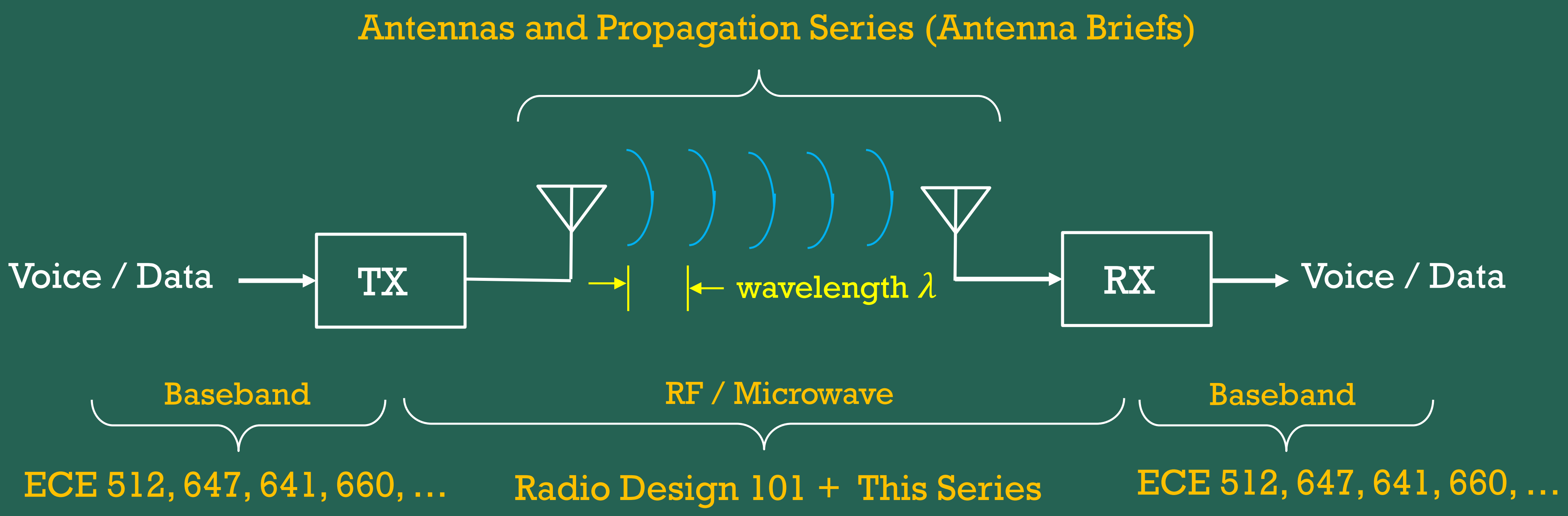
Frequencies and wavelengths

Microwave spectrum and example applications

Course syllabus, schedule, parts list

Demos, lab, and project possibilities for Radio Design 201

Radio and Antenna Basics

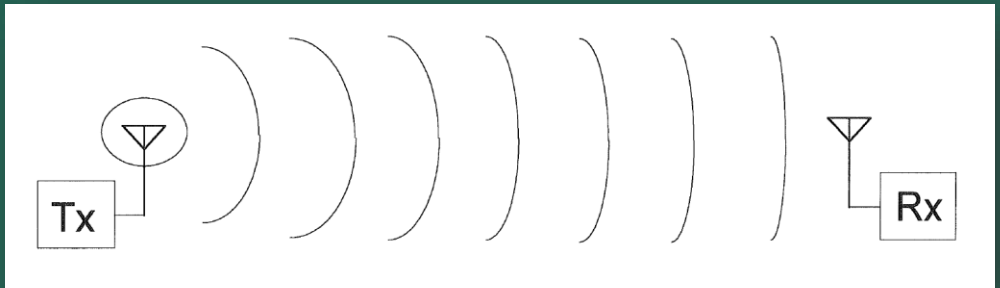


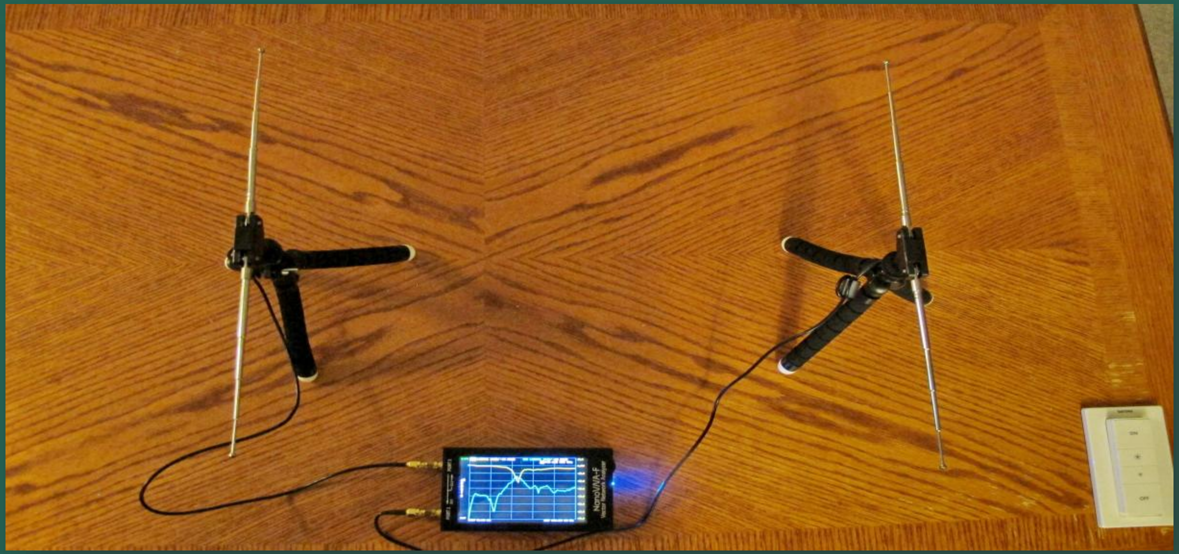
Pre-requisites and Related Material

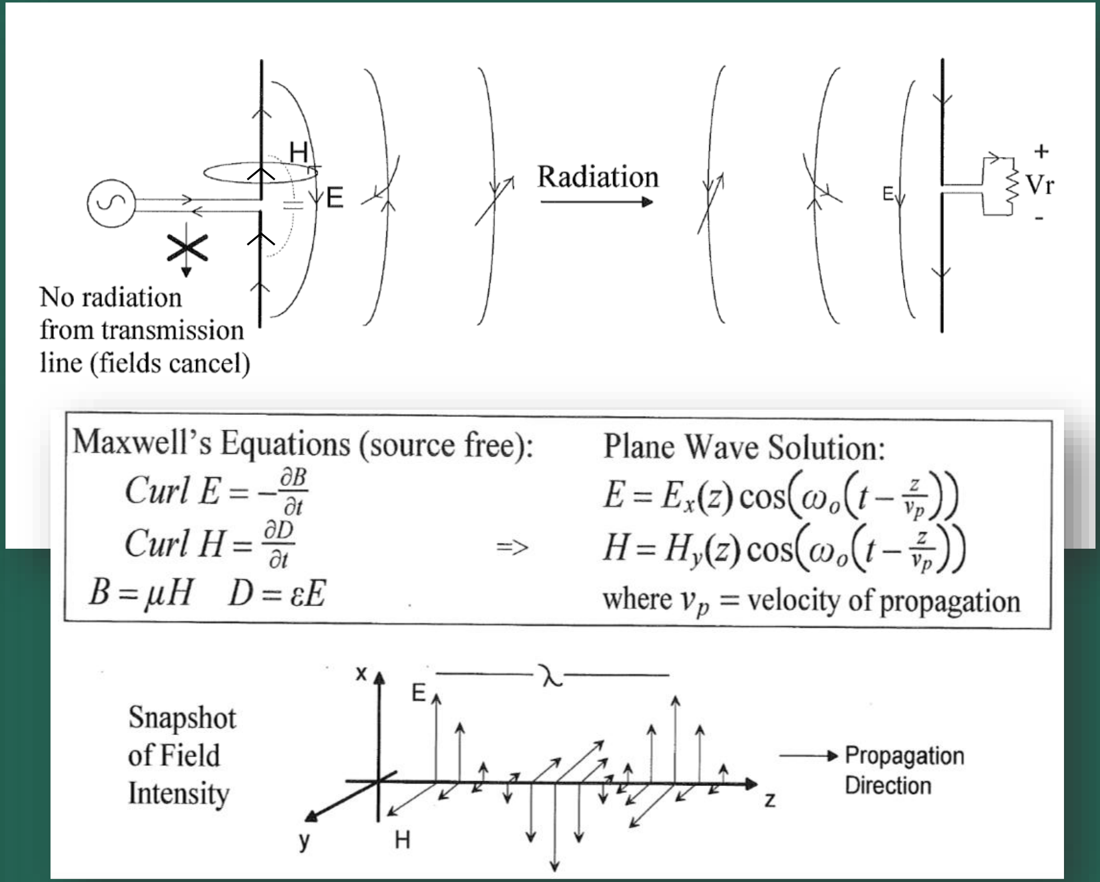
- Physics
- Math (Algebra, Calculus, Probability)
- Circuits and Electronics
- Linear Systems w/ Fourier/Laplace/Z Transforms
- Digital Signal Processing
- Logic Synthesis
- Comm Systems

What's Going On Here ?

(from Antenna Briefs series, Episode 1)







Day-1 Lecture

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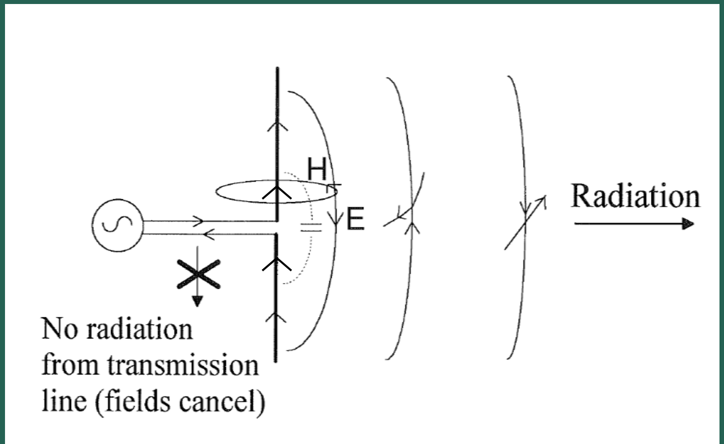
Wavelength vs Frequency (Derivation)



- Wave travels away from antenna with velocity c
- Wavelength λ is distance traveled in one cycle-time or "period" T of sinewave source
- Distance is velocity (m/s) times time (s)
- So… $\lambda = cT = c\frac{1}{f}$

Wavelength in meters (in free space) → $\lambda_o = \frac{c}{f}$ ← Speed of light in meters/sec; Frequency of source in cycles/sec (Hertz)

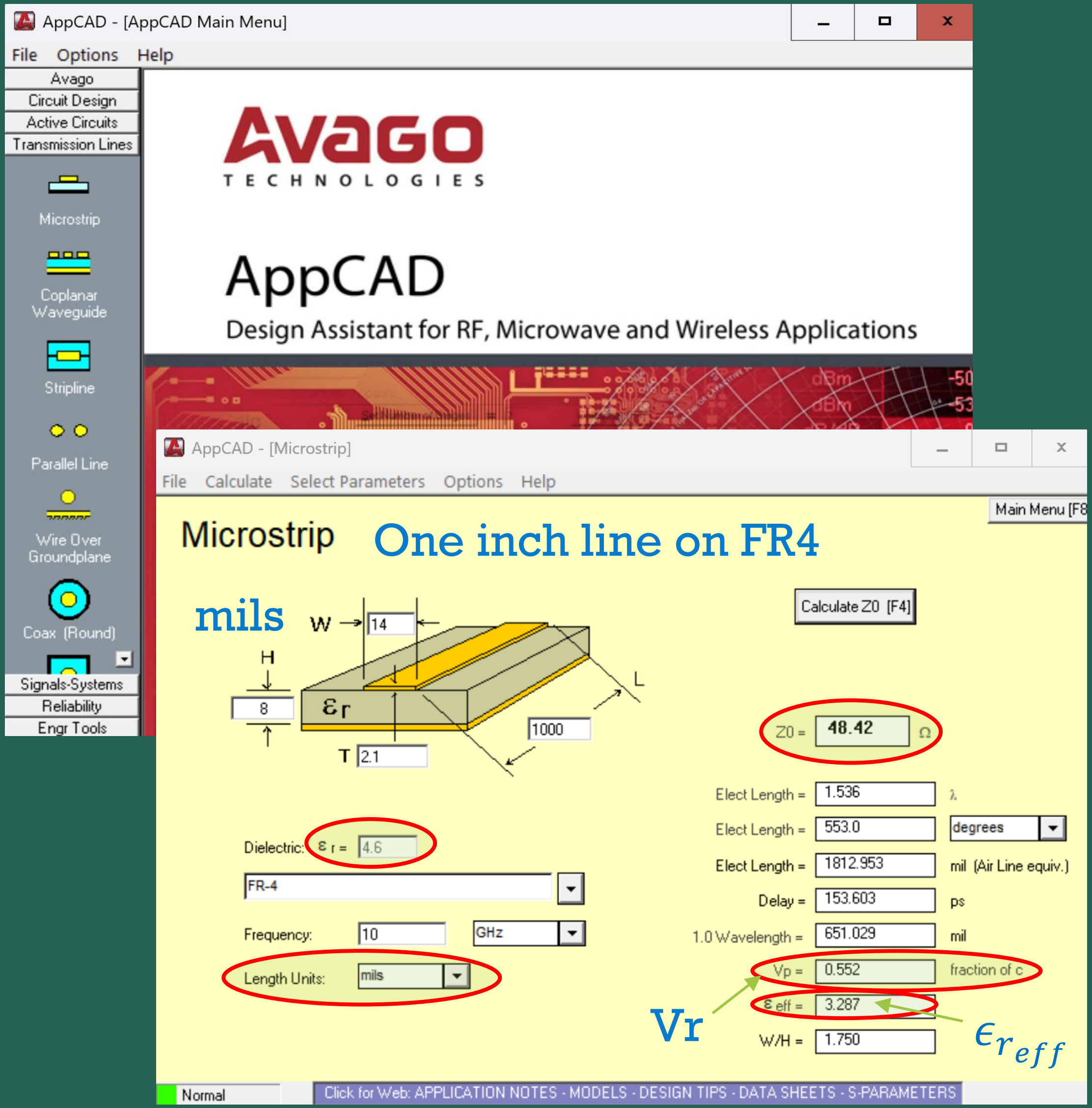
$$c = \frac{1}{\sqrt{\mu_o \epsilon_o}} = 299{,}792{,}458\ m/s \approx 3E8\ m/s$$ (In free-space)

$f = 1\ MHz \qquad \lambda_o = 300m$

$f = 100\ MHz \qquad \lambda_o = 3\ m$

$f = 10\ GHz \qquad \lambda_o = 3\ cm$

Wavelength on PC Boards



- Wave travels along PCB trace with velocity (v_r)c
- v_r is the "relative velocity" of light (or radio waves) in the PC-board. E.g. $v_r = \frac{v}{c} \approx 0.5$
- Actual value of v_r depends on dielectric's relative permittivity ϵ_r , trace type (microstrip, CPW, etc.), width of traces, and distance to ground plane.
- For Microstrip lines, we use $\epsilon_{r_{eff}}$ since some fields are in the board, and some above it in the air…

$$\lambda = v_r c T = \frac{1}{\sqrt{\mu_o \epsilon_o \epsilon_{r_{eff}}}} \frac{1}{f} = \underbrace{\frac{1}{\sqrt{\epsilon_{r_{eff}}}}}_{v_r} \underbrace{\frac{1}{\sqrt{\mu_o \epsilon_o}}}_{c} \frac{1}{f}$$

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

Example (Microstrip on FR4 PCB):

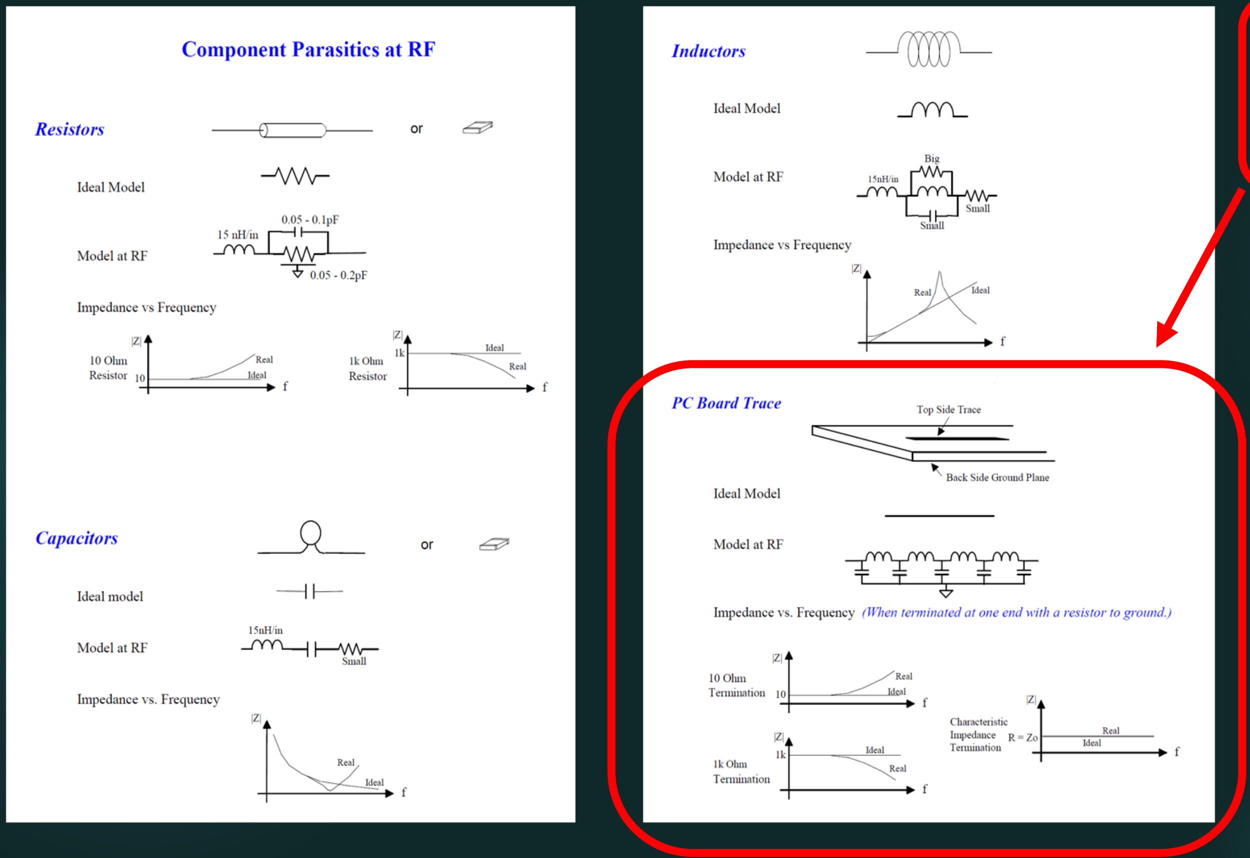
f = 10 GHz

$v_r = 0.552$

$\lambda = (0.552)(3\text{cm})\ or\ 0.652"$

Recall from Episode 2 and Radio Design 101

Kirchoff's Laws don't (easily) apply if $L \geq \lambda/10$!



PCB traces, wires, etc are *transmission lines* at "high frequency".

Important if length is > 1/10 wavelength

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

$$v_r \sim 0.5$$

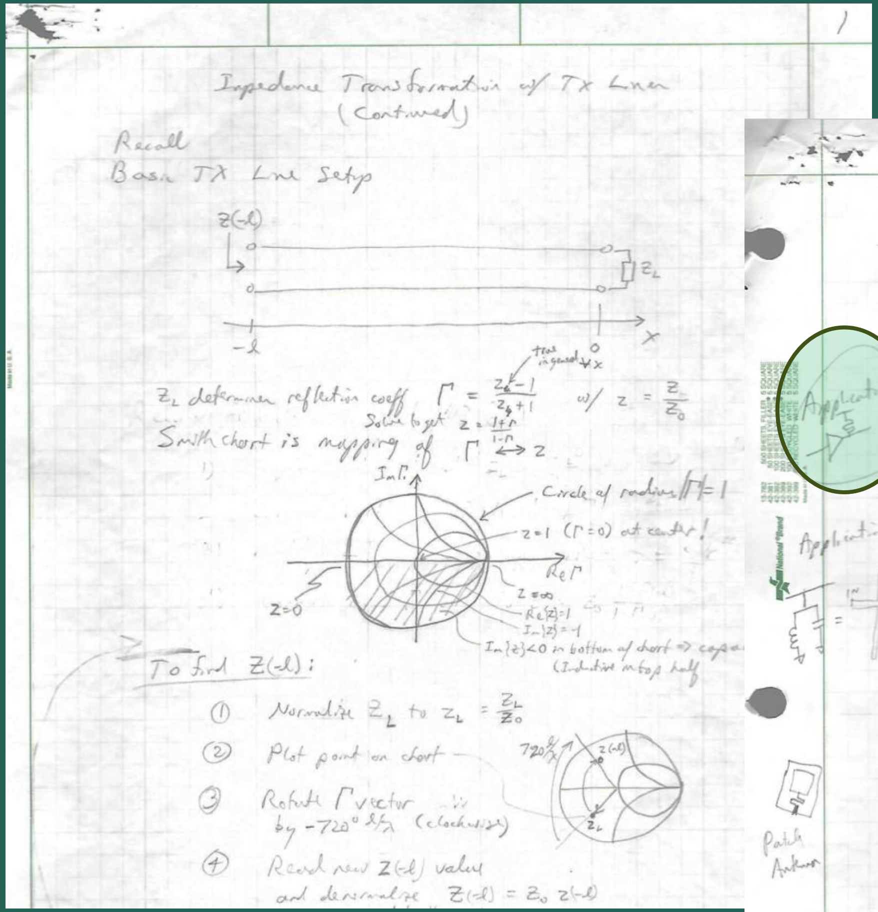
$$\Rightarrow \frac{\lambda}{10} \approx 1.5\ cm\ at\ 1\ GHz$$

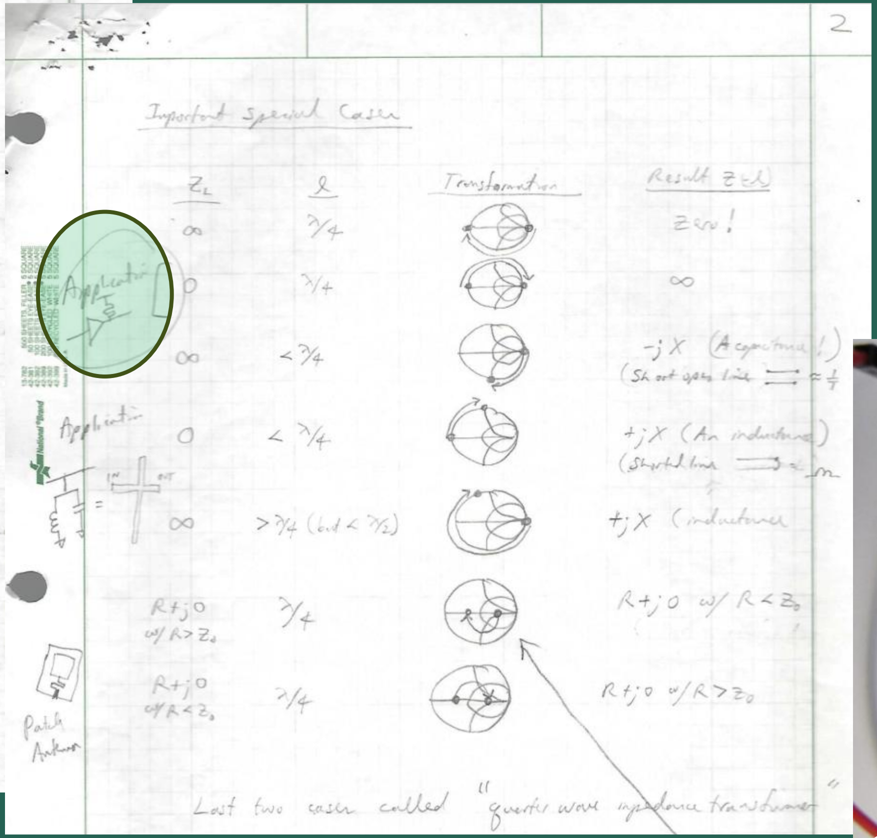
1.5 mm at 10 GHz !

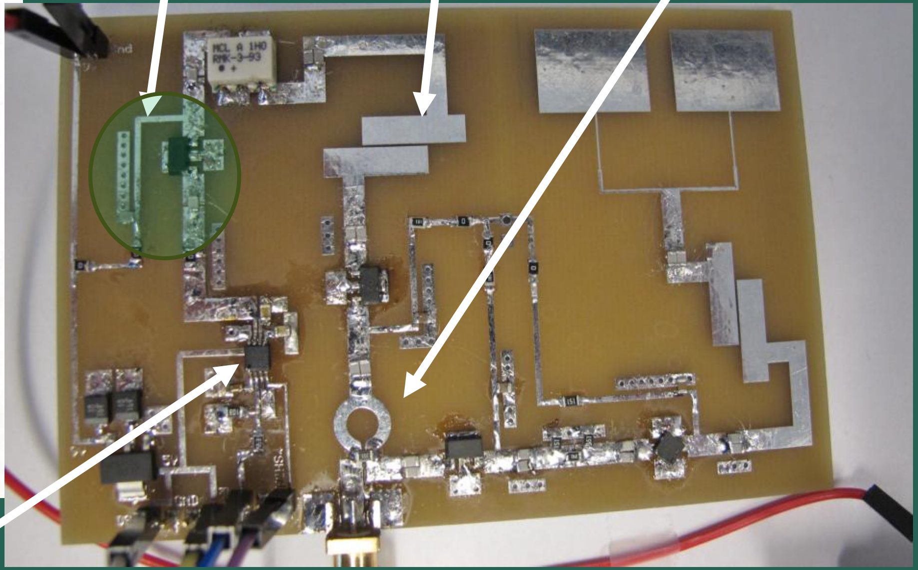
L, C, and characteristic impedance varies with trace width and board interlayer thickness

Microwave Circuits

… Where we're headed …







λ/4
Bias line
at 2.9 GHz

5.8 GHz
Bandpass
Filter

5.8 GHz
Wilkinson
Power
Divider

2.9 GHz
VCO

Credit: KSU ECE Students

Day-1 Lecture

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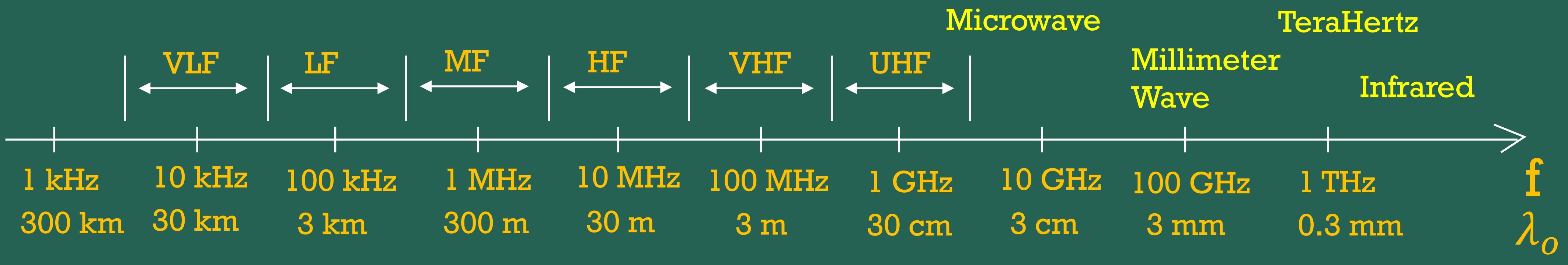
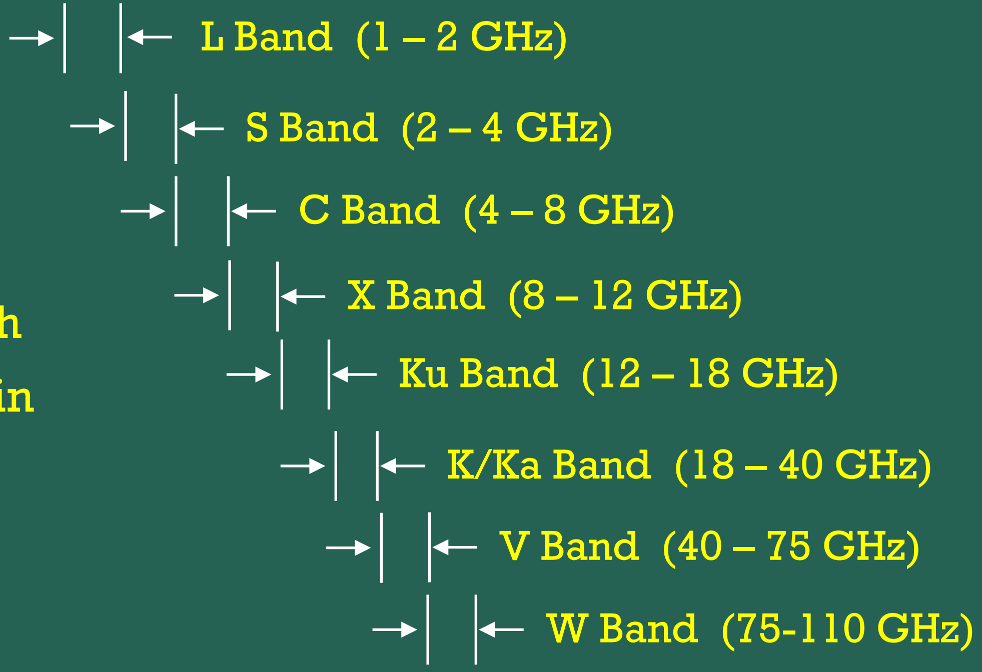
The RF and Microwave Spectrum





NOTES:

- More spectrum available in Microwave bands
- Size of efficient antennas decreases with wavelength
- It’s easier to have directional antennas with high gain at microwave

- See Antenna Briefs series for more !

Example Applications

- VLF - Communication with submarines (due to larger skin-depth)
- LF - Early wireless and classic radio-location systems
- MF - AM broadcast
- HF - International shortwave broadcast, CB, Ham Radio, OTH radar, …
- VHF - FM/TV broadcast, public safety, aircraft, 2-meter ham band, …
- UHF - Arguably, the most valuable spectral region,

  TV, cell-phones, keyless entry, sensors, WiFi, FRS, and lots more !
- Microwave - 5G cellular, WiFi, DVB satellites, radar, …
- Millimeter - Automotive radar, deep-space links, future 6G, medical, …

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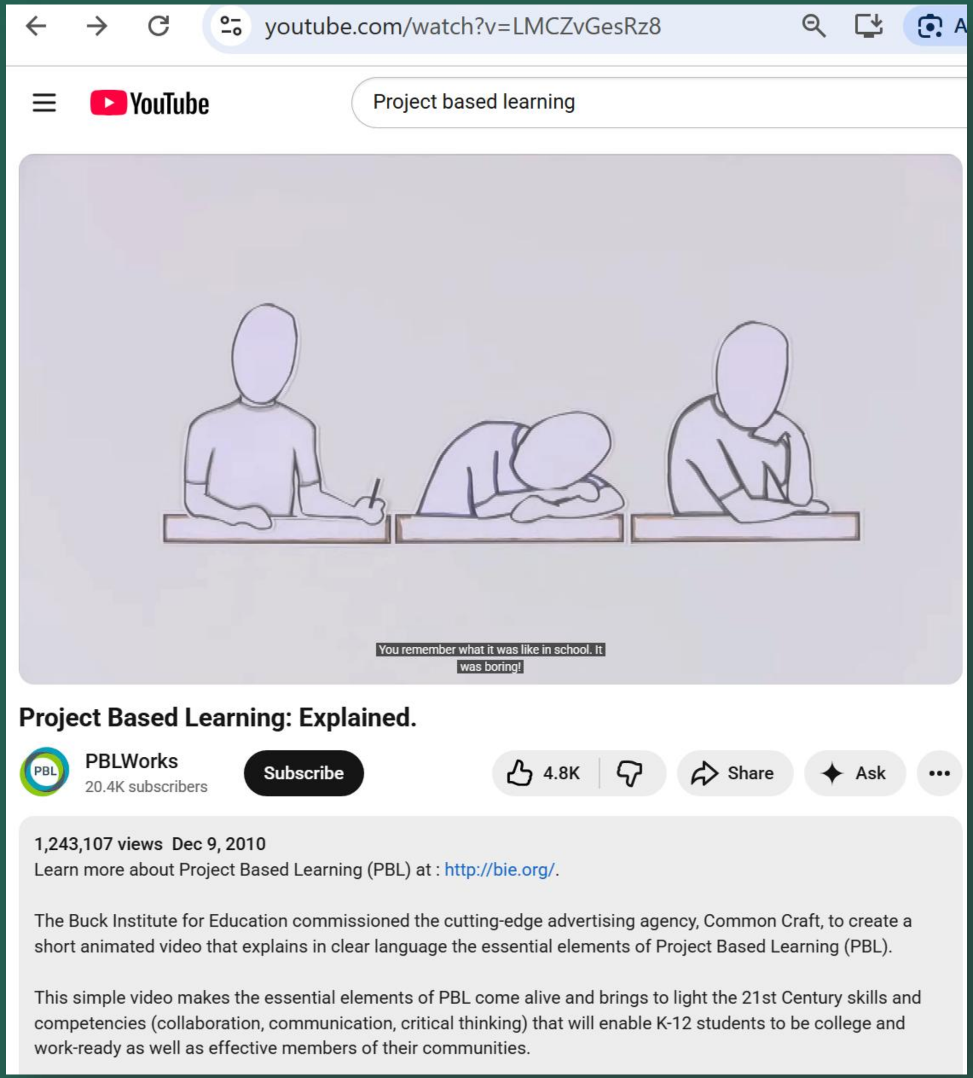
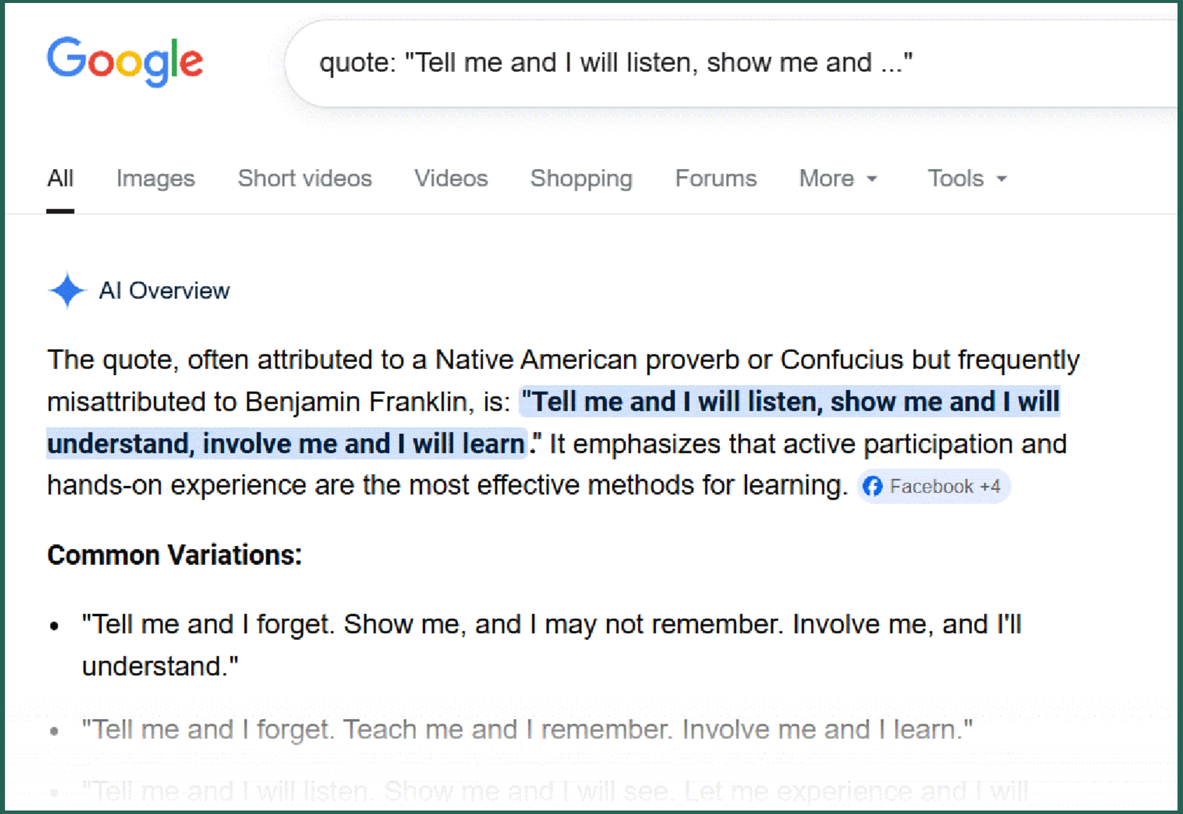
Videos on Project-Based Learning



Project/Lab-*Oriented* Learning

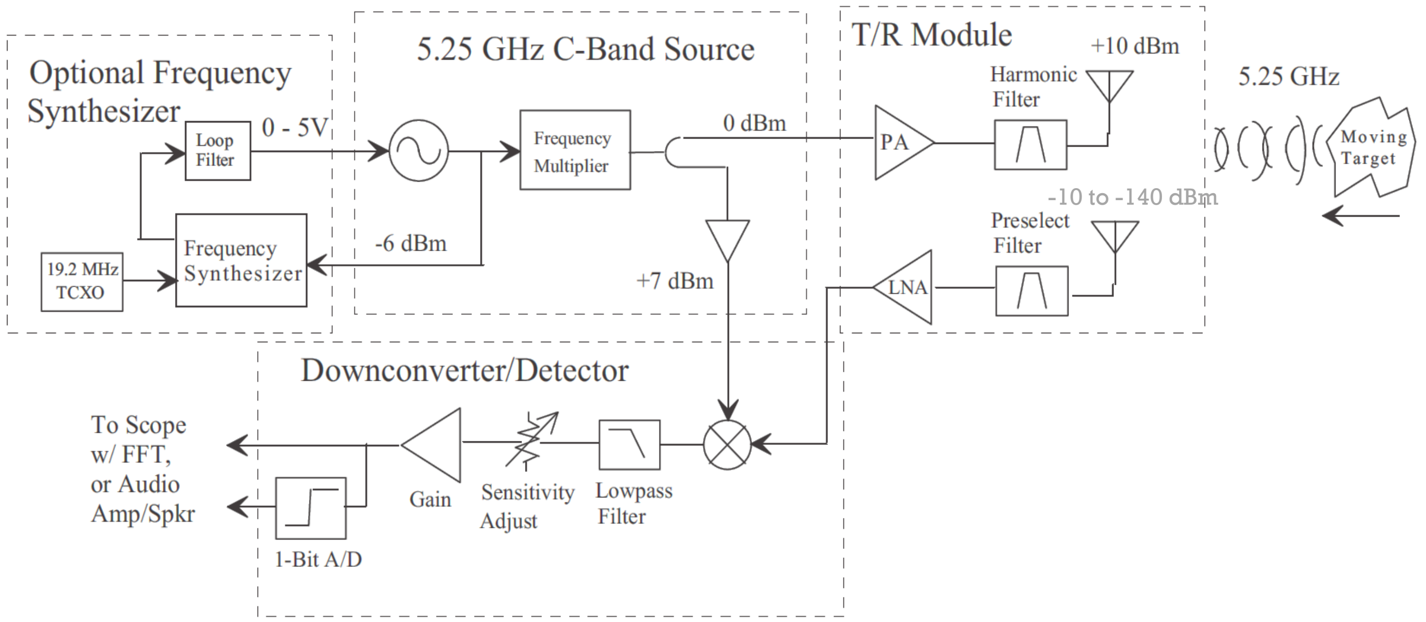
(See episode 2 for project examples)



Doppler Radar Project

(See Episode 2)

A block diagram of the three main subsystems (and optional frequency synthesizer) connected together to form the complete doppler radar is shown below together with interface specifications. Note that circuit details are not shown and detailed design procedures are not given. For example, additional amplifiers, power slitters, and/or pads may be needed in a given component. It is up to you to work out details by carefully studying the device data sheets and radar-system specifications, and thinking carefully about what you are doing!



Example University Course Syllabus

ECE 764
Design of Antennas and Microwave Circuits
Fall 2017

Office Hours: MWF 3:30 to 4:30 (right after our class)
Others by appointment, or when my door is open, or when you can find me in the lab...

Prerequisites: Electronics II, Electronics Lab, Linear Systems, and EM theory

References: (Texts available in our lab)

"Microwave and RF Design of Wireless Systems" by David M. Pozar, Copyright 2001, John Wiley and Sons, Inc.

"Planar Microwave Engineering, A Practical Guide to Theory, Measurements and Circuits," by Thomas H. Lee, Copyright 2004, Cambridge University Press.

Chang, Kai, Ed. "Handbook of Microwave and Optical Components, Volume 1," Wiley Interscience, 1989.

Various class handouts. E.g. HP/Agilent/Keysight "Application Notes" on transmission lines, S-parameters, etc.

Course Description:

This course combines lectures and laboratory work to introduce you to wireless circuits and systems operating at microwave through millimeter wave frequencies (e.g. 1 through 100+ GHz). We will be covering topics including antennas, transmission lines, S-parameters, amplifiers, filters, oscillators, phased-locked loops, mixers, digital signal processing, and microwave measurement techniques and equipment.

The course includes a sequence of labs and project assignments in which you will design, build and test antennas and microwave circuits. The semester project goal is to create a Doppler/FMCW radar operating at 5.8 GHz. Such a device could be used for security, automotive, sports, and many other applications.

A companion course (ECE662) offered in the alternate semesters covers the design of HF through UHF circuits for those interested in a more complete exposure to the wireless hardware field. Other recommended courses include ECE660, ECE647, and ECE696. ECE660 covers the mathematical foundations of digital communications, while 647 covers digital signal processing. ECE696 covers IC design, and when combined with the other courses, a foundation for studying the field of RF integrated circuits (RFICs).

Objectives: The primary learning objectives of ECE 764 are:

- to familiarize you with radio waves, antennas, propagation,
- to familiarize you with circuits used in wireless and remote-sensing equipment at GHz frequencies,
- to introduce you to common performance measures and test equipment used in radio frequency and microwave circuit laboratories, and
- to help you gain a solid foundation for specifying and designing wireless equipment at the system level.

Homework: Work in this course centers around the design, construction, testing, and documention of real-world antennas, circuits, and systems. Therefore, there are no classic homework problems. Rather, "homeworks" consist of lab and project assignments and associated documentation.

Labs/Projects: During the first half of the semester, we will be covering antennas, propagation, and transmission line fundamentals. We will be learning through lectures, lab exercises, and associated writeups. ***The lab exercises will be done in teams of 2 or 3*** and will include:

- Lab 1: Measurement of radio propagation in the field
- Lab 1: Basic antennas and performance measurements.
- Lab 3: Circuit component parasitics, transmission lines, matching networks, and other "microstrip" component design.

During the second half of the semester, we will be designing, building, and testing a microwave system - a Doppler/FMCW radar operating in the 5.8 GHz Industrial, Scientific, and Medical (ISM) frequency band. This will be accomplished in two stages:

- Prototyping of main radar functions (e.g. amplifiers, filters, etc.)
- Full radar product design, construction, and testing.

As with the labs, the radar designs will be done in teams (in this case, of 3 or 4 person "companies"). Each person within your company will be responsible for a separate part of the design, and the whole company must work out interfaces between sections and get the product functional by the end of the semester.

For the final project demos, we will run tests in the lab to prove that you can measure speed and distance. We may also go out to the street and check the speed of some cars driving by if it is not too cold at the end of the semester :-)

Exams: The final-exam will be this demonstration of your project plus a company report with each student writing his/her section.

Project Kit: You will need to purchase a project kit that contains the core components required to complete the labs/project. This kit may be obtained from the ECE shop and is in two parts. ***Each student** needs to purchase **one individual kit** and **one group kit***. Some of the larger parts as well as fabrication of PCBs will be available with proof-of-purchase.

Example Course Syllabus (Pgs 3-4)

Grading: Your grade in this course will be based on your demonstrated understanding of lecture material, lab assignments, the successful operation of your radar, and on timely completion of the required work. *(See weightings and late policy below.)*

Weighting of the individual components of your grade will be computed as follows:

- Labs 1 thru 3 — 15% each
- Project prototyping deliverables — 25%
- Demo and documentation of final radar — 30%

Lab/project writeups will be graded on the basis of **completeness**, **correctness**, and overall **quality** (technical and presentation) with 5 points each. For the project, an additional 5 points will be assigned based on your preliminary design/layout, meeting of fabrication due dates, and general observations of your work in the lab.

Each lab or project score identified above will be individually scaled to a 100 point range and then your final grade is computed using the weights shown.

The overall semester grading curve is subject to the discretion of the instructor but will generally follow the classical assignment pattern: 90 - 100 = A, 80 - 90 = B, etc. so that you can keep track of your progress.

Late Work: To receive full credit, ***you must turn in your work by close-of-business (COB) on the due dates specified***. Assignments turned in late (without documentation of illness, or other significant circumstances outside your control) will be pro-rated as follows:

- 0 - 48 hrs. — 90 % maximum credit
- 48 - 96 hrs. — 70 % maximum credit
- > last week of semester — 0 % credit

The demonstration/documentation of the final radar system operation for the final exam must be done on time, of course...

Lab Hours: The Communications Circuits Laboratory will generally be open during normal business hours (8 a.m. - 5 p.m., Monday - Friday, excluding holidays.) It is also possible to work after hours thanks to key-card access.

Tools: Soldering stations, solder, and drilling equipment is provided in the lab. Be careful and neat as you use these since we are all sharing the same construction benches.

In particular, ***be certain soldering irons are always stowed in their holders and always turned off before you leave the room (regardless of whether you are the one who turned them on or not !)***

Academic Honesty:

This is a challenging course configured as an open laboratory in which collaboration with other students is both desired and inevitable. You are encouraged to seek help from your teammate(s) or fellow classmates to understand the basic theory as you do labs/project assignments. However, in order to provide equitable grading, ***certain activities must be completed on your own***. These include:

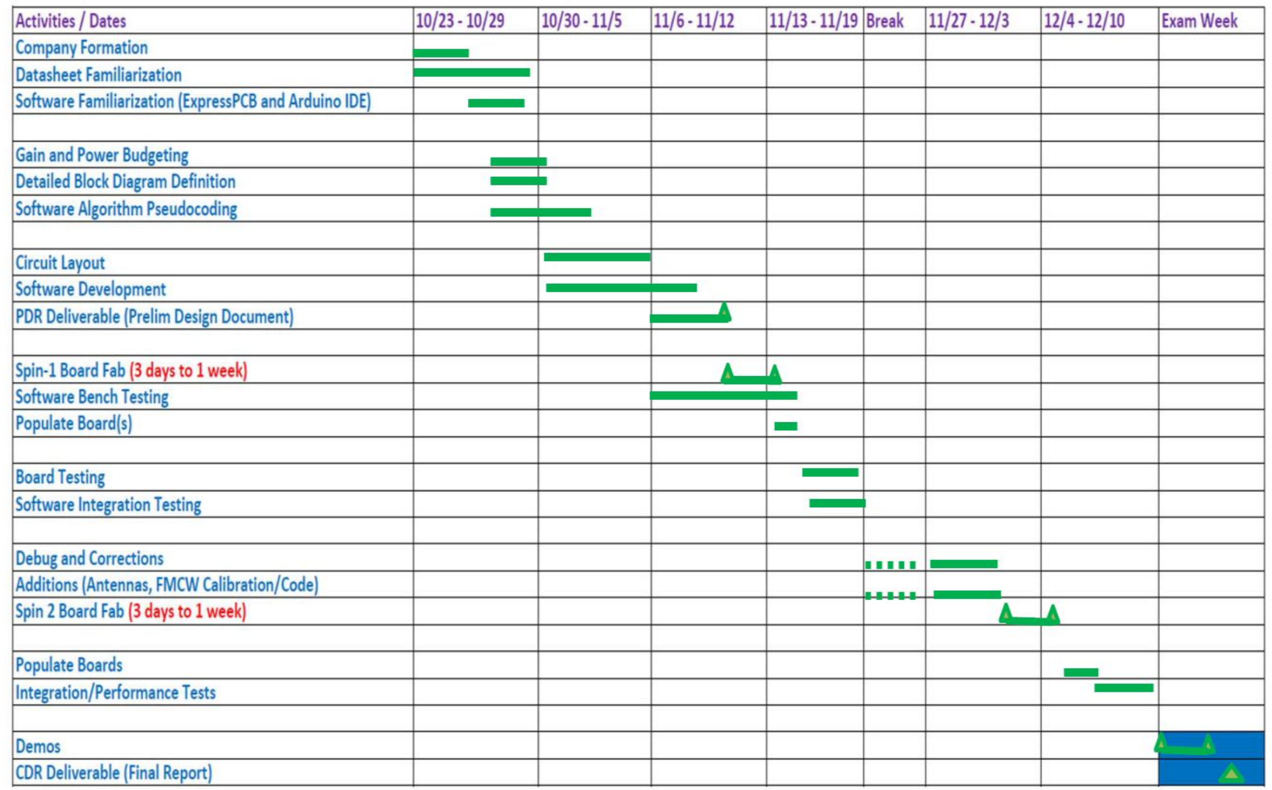
- Your lab/project *designs*.
- The portion of the lab write-ups you are responsible for.
- Your section of the project writeups

While collaborating to perform lab experiments and to understand the fundamental concepts is permitted and even expected in many cases, each student must do their own individual designs, measurements, and writeups.

In particular, copying of any portion of another student's designs/measurements/plots/writeups is strictly forbidden and will be appropriately dealt with.

Lecture, Lab, and Project Schedules

Week	*Material*	*Assignments*
1	Introduction to comm systems, frequencies, and wavelengths Calculating and measuring received signal strengths	Verify you have lab access Lab 1 assigned
2	EM theory review and demos Basic antenna theory	Purchase lab kit
3	Basic antenna types: dipoles, monopoles, loops Antenna characterisitics: 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 transformation with microstrip Microstrip components and coupled-line microwave filters	Lab 2 due
7	PC board design, layout, and parasitics Two-port circuits and 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 (including needed 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 synthsizers 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



Lab and Project Parts List

Fall 2017 Parts List

Qty	Description	Part # and vendor	
	Parts for Labs 1 through 3		
1	M-BNC crimp connector for RG174, Amphenol 31-315-RFX	(Digikey ARFX1049-ND)	2.35
1	Minicircuits LEE-39+ 8 GHz low noise Amplifier	(Minicircuits LEE-39+)	1.35
1	Minicircuits Gali-1 InGaP HBT 8 GHz microwave Amplifier	(Minicircuits Gali-1+)	1.15
4	F-SMA pcb-mount connectors suitable for 62 mil board edge mount	(Digikey CON-SMA-EDGE-S-ND)	8.40
	SUBTOTAL		14.21
	Additional parts for 5.8 Ghz doppler/FMCW radar design *		
2	F-SMA pcb-mount connectors suitable for 62 mil board edge mount	(Reuse above connectors)	0.00
2	Hirose U.FL surface-mount ultra-mini coax connector	(Digikey H9161CT-ND)	2.61
1	Maxim 1.9 - 2.3 GHz VCO	(Digikey MAX2752EUA+)	2.17
1	3X Frequency multiplier (5.4 - 9 GHz out)	(Minicircuits RMK-3-93+)	13.95
1	2.8 - 8.5 GHz mixer, with high LO-RF isolation	(Minicircuits MCA1-85L+)	9.45
2	DC - 8 GHz 10 dB gain InGaP HBT 8 GHz microwave Amplifier	(Minicircuits Gali-1+)	2.30
2	DC - 8 GHz 14 dB gain InGaP HBT 8 GHz microwave Amplifier	(Minicircuits Gali-2+)	2.30
2	DC - 8 GHz 12 dB gain Amplifier	(Minicircuits LEE-19+)	2.70
2	DC - 8 GHz high-gain, low-noise Amplifier	(Minicircuits LEE-39+)	2.70
1	LMV822 low-voltage dual opamp SOIC-8	(Digikey LMV822MXCT-ND)	KSU residual
1	LMV751 low-noise opamp SOT23-5	(Digikey LMV751M5CT-ND)	KSU residual
1	19.2 MHz, 3.3V TCXO (Abricon ASVTX-11-121-19.200MHz-T	(Digikey 535-13278-1-ND)	1.46
1	2.8 Ghz PLL synthesizer, National Semi LMX2326	(Obsolete)	KSU residual
2	3.3V, 150 mA regulator in SOT23-5 package (Microchip TC1185)	(Digikey TC11853.3VCT713CT-ND)	0.76
2	5V, 1A regulator in SOT223 package (Diodes Inc, ZLDO1117)	(Digikey ZLDO1117G50DICT-ND)	1.00
2	10uF tantalum capacitors 16V SMD		KSU residual
1	3.35mm (1/8") stereo headphone jack	(Digikey CP-43516SJGRCT-ND)	1.24
1	Teensy LC (Arduino compatible board with DAC and ADC)	(PJRC Teensy-LC)	11.65
1	10 segment LED light-bar display KWL-R1025VB (red)	(Adafruit 1921)	1.75
1	10 element 330 Ohm resistor array, 11 pin SIP	(Digikey 4611X-101-331LF-ND)	0.72
1	9V battery connector	(Digikey 36-84-4-ND)	0.71
	SUBTOTAL		64.90
	GRAND TOTAL		**79.11**

* Radars will be designed by teams/companies of 3 to 4 students. Quantites listed are per-student, allowing for enough of each part to build at least two radars - one in a prototyping phase, and one in a final phase, as well as for breakage losses. Additional parts may be left over from the team to build copies of the final product design if desired - and/or additional parts may be purchased at that time.

In addition, PC board fabrications will be needed in the project work. These will be done through ExpressPCB at $41 per board (plus any expedited shipping). To help keep the cost per student as low as possible, your instructor will cover this expense in part. A "voucher" worth up to $50 toward fabrication cost is included when you purchase your parts. This can fund up to one board per student of a 2-layer board design which allows for up to 4 boards for a team of 4 students. That should be sufficient for

two revs of a 2-board radar. Alternatively, a confident team may elect to use the vouchers to fund two 4-layer boards (one rev only). Additional board-spins will be at your own expense - although it is doubtful there will be enough time for that, so be careful and double-check your designs and layouts before you submit them ! (Have your team review them in a "Critical design review")

In addition, the following items will be provided free of charge and/or available in the lab (in limited quantity):

1	18" wood rod 3/8" diameter for dipole for antenna build in Lab 2	(Home depot)	
3	Plastic tie wraps for antenna build in Lab 2	(Home depot)	KSU stock
-	Copper solid-core 12 gauge wire for antenna elements in Lab 2	(Home depot)	KSU stock
1	KSU-designed amplifier prototype PCB for Lab 3 (for testing Gali-1 / LEE-39 amps and familiarization with PCBs)		
1	1-sided 62-mil PC board - 4 x 4 or 3 x 5 inches for filters/matching-network design in Lab 3		
-	RG174 coax (Digikey 473-1000-ND) for antenna build in Lab 2	(Home depot)	KSU stock
-	1/4" wide copper tape for filters/matching-network design in Lab 3	(Digikey 3M1181A-ND)	KSU stock
-	3.9 and 18 nH 0603 SMD inductors	(Ebay or Digikey)	KSU stock
-	Ferrite beads 0603	(Ebay or Digikey)	KSU stock
-	Wire (various gauge/colors)	(Digikey)	KSU stock
-	0.1" header pins and jumpers		
-	Solder, etc...		

See the following page for information on available discrete resistor and capacitor components

Available Resistor/Capacitor Values

Surface Mount Components

The Communication Circuits Lab maintains a stock of "0805" and "0603" surface mount resistors and capacitors. These components are 0.08" x 0.05" and 0.06" x 0.03" respectively, so that their parasitics (series inductance and shunt capacitance) are reasonably small at low GHz frequencies. Note that commercial products often use 0402, 0201, or even smaller parts to make the end product compact and to operate up to Ku band and above (> 10 GHz).

Component values available

For resistors, we have values from about 10 Ohms to 1 MOhm (In E12 series increments. 10, 12, 15, 18, 22, etc.)

IMPORTANT: We do NOT stock 1% and other resistors with silly values like 123.4 Ohms. We only have the E12 series noted above. Please don't design for or ask for exact values. ***Think about and use only the precision you need.*** Google for the EIA definition of the E12 series.

For capacitors, the range is about 0.5pF to 0.1uF. Values below 10pF may not follow the standard 10% (E12) value spacing. Instead they are 0.5, 1.0, 1.5, 2, 3, 4, 5, 6, 7, 8, and 9pF.

For those needing higher than 0.1uF, there is also a limited quantity of 1uF value available.

Component tolerances and ratings:

The tolerance on resistors is generally 5%, and their power dissipation is 1/10 watt.

The voltage rating for the surface mount capacitors we stock is generally 50 VDC, and the tolerance is 5% for the NPO types between 10 pF and 1000 pF and 10% for X7R types that span the range from 1200pF to 0.1uF.

Small valued caps in the range of 6 pF to 10 pF have tolerances of +- 0.5pF, while caps below 6pF have tolerance of +-0.25pF.

Day-1 Lecture

Announcements

Welcome to Episode 3!

See Episodes 1 and 2 for
- *definitions of "microwave", and*
- *example semester projects*

Today's Topics

- ✓ *Radio and antenna basics*
- ✓ *Frequencies and wavelengths*
- ✓ *Microwave spectrum and example applications*
- ✓ *Course syllabus, schedule, parts list*
- ⇨ *Demos, lab equipment, software, and project possibilities for Radio Design 201*

In Episode 4 …

Thanks For Watching !

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