

Welcome to 6.101

- Introductions, course mechanics
- Course overview
- Practical issues
- Oscilloscope
- Circuit review

Handouts
- Lecture notes
- Lab kit signout
- Lab 1
- Reading assignment course outline

6.101 Analog Electronics Lab

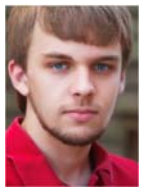
- An introductory electronics laboratory covering basic principles of analog circuit design in a practical, real-world laboratory setting.
- Satisfies AUS2, CIM2, DLAB, EECS

	6.101 S2019	6.111 F2019
Course Rating	6.6	6.2
Hours in classroom	8.8	6.6
Hours outside classroom	9.1	9.3

6.101 Staff


Gim Hom
Lecturer


Negar Reiskarimian
Lecturer


Mark Vrablic
TA




Yukimi Murimoto
LA


Aaron Yeiser
LA

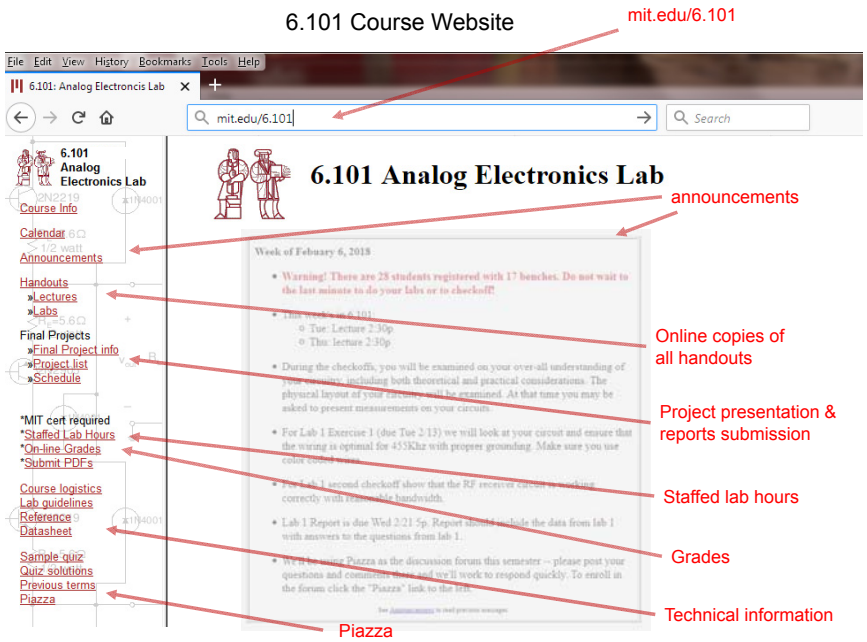

Dave Custer
CIM


Laura McKee
CIM

Communications in 6.101

Dave Custer, Laura McKee
Writing, Rhetoric, and Professional Communications

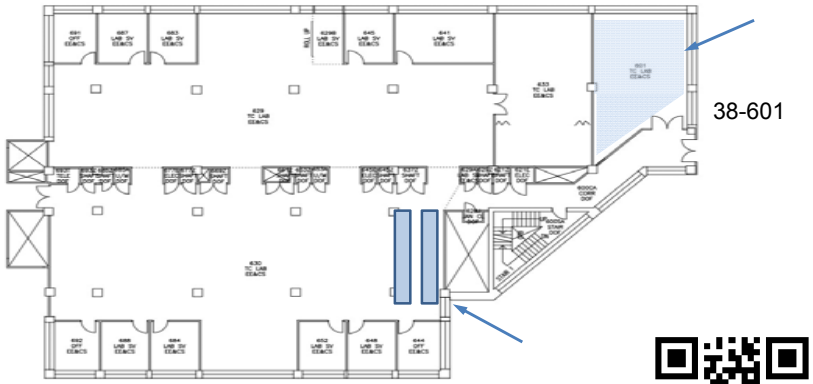
6.101 Course Website



Course Info - Objectives

- Augment theory with hands on experience
- Understand practical limitations of devices
- Breadth vs depth
- Build interesting circuits including surface mounts.
- Work with real parts, part numbers
- Lab intensive! 2-9-1 work load
- Teamwork
- Layout PCB with DIP or surface mount components
- Opportunity to use laser cutter and other tools in the EDS area (38-500).

6.101 Lab

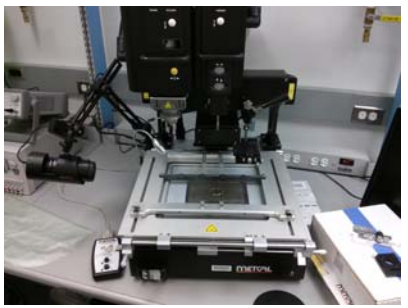


M-R 9a-11:45p, F 9a-5p, Sun 1-11:45p
Lab hours: http://eds.mit.edu/labs

Electronic Design Studio (EDS)



Surface mount solder stations (4)



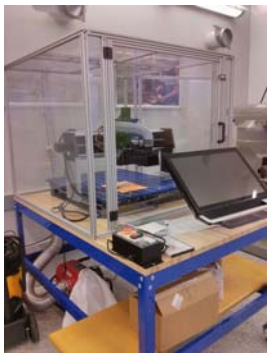
Surface mount placement

Electronic Design Studio (EDS)





Laser cuter – PSL6.75 with 75W laser
Part size: 32" x 18" x 9"
Cut by "printing"



NC Router

Notes

- The textbook is Electronic Circuit Analysis and Design by Donald Neamen - third edition ISBN 007328596X or ISBN 13: 9780073285962.
- Download for reference Operation Amplifier - Theory and Practice, Prof. James K Roberge
  http://web.mit.edu/6.101/www/reference/Op_Amps_J_Roberge.pdf

Labs: learning the ropes

- Lab 1
  RF Transmission and Reception [Note: Experiment 1 of this lab requires a checkoff in lab while in progress]
- Lab 2
  Log Amplifier; Diodes and characteristics using the Tektronix Curve Tracer; photodiodes
- Lab 3
  BJT circuits; 3 stage four transistor amplifier; "Wind Your Own Inductor"; RF energy harvester
- Lab 4
  Op-amp circuits and characteristics.
- Lab 5
  Push-pull amplifer, current sources; 555 IC; ECG – theory and circuit [Note: This lab requires a checkoff in lab while in progress]
- Lab 6
  Pulse ox – design project; H bridge; [Note: this lab requires a checkoff in lab while in progress]

Lab Check-off Policies

- Lab check-offs – done during staff hours
- Please don't assume that you can wait until the last minute!
  - No check-offs on Saturday
- Lab grade = checkoff + lab report; grades on course website
  - Lab report grade = data, neatness, quality, working circuit
  - On-time check-off grade: up to 5 points
    - 1 point /day late penalty after slack days
    - Very late check-off: 1 point (minimum)
  - Students may use up to 5 slack days (penalty free) for late checkoffs.
- All labs must be checked off before you can start your final project.
  The labs provide the necessary background for the final project.

Final Project

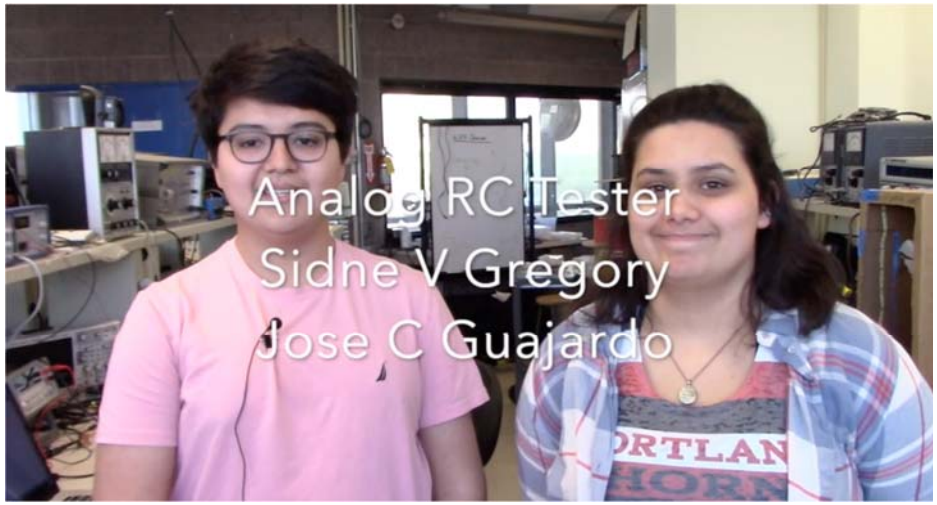
- Done in groups of two or three; one person project by exception
- Open-ended
- You and the staff negotiate a project proposal
  - Must emphasize analog concepts, but can include interfaces to data converters, sensors or motors and in some cases Ardunios
  - No highly integrated chip solutions
  - Proposal Conference, several Design Reviews
  - Safety major consideration
- Staff will provide help with project definition and scope, design, debugging, and testing
- Design presentation to class and staff
- It is extremely difficult for a student to receive an A without completing the final project. Sorry, but we don't give incompletes.
- Final project (proposal, presentation, report, video) will be posted on course website

6.101 Final Projects Spring 2019

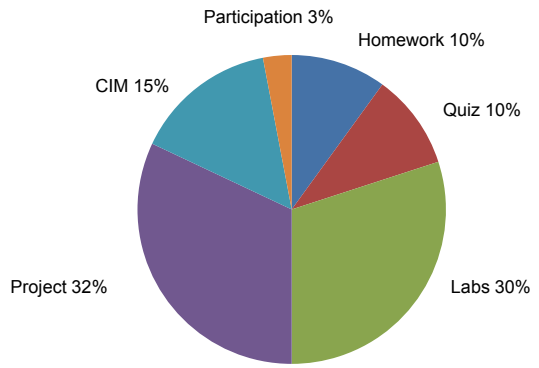
No.	Team members	Project	Staff
1	Rhian A Chavez Jacob E Swiezy	Variable Baud Rate AM/FM Wireless Digital Communication Abstract Proposal Presentation Checklist Report Video	Henry
2	Alan E Casallas Benjamin D Gutierrez	Electric Bike Motor Controller with Regenerative Braking Abstract Proposal Presentation Checklist Report Video	Jimmy
3	Emmanuel Havugimana Wings Yeung	Audio pitch shifting and transmission through optical fiber Abstract Proposal Presentation Checklist Report Video	Jimmy
4	Sidne V Gregory Jose C Guajardo	Analog RC Tester Abstract Proposal Presentation Checklist Report Video	Gim
5	Benjamin G Rowley Luis E Torres	TIMEFRAME Abstract Proposal Presentation Checklist Report Video	Gim
6	Adam B Estes Yukimi Morimoto	Electric Piano Abstract Proposal Presentation Checklist Report Video	Henry
7	Ignacio Estay Forno	Σ Δ ADC Using Discrete Components Abstract Proposal Presentation Checklist Report Video	Henry
8	Aaron Yeiser	Fully Analog Mini Segway Abstract Proposal Presentation Checklist Report Video	Gim
9	Milo Hooper	Ocular Electromyographic Control of Servos Abstract Proposal Presentation Checklist Report	Gim

Sample Project: Automated RC Testor

- Integrated analog/digital system
- Determine component type
  - resistor or capactor
  - display value on TFT display
- Operate over 5 decade range for resistors and capacitors



Grading



A large number of students do "A" level work and are, indeed, rewarded with a grade of "A". The corollary to this is that, since average performance levels are so high, punting any part of the subject can lead to a disappointing grade.

Electrical Units

- Voltage: volts (μv → kv)
- Current: amperes (amps), milliampere (ma 10^{-3}), microampere (μa 10^{-6})
- Resistance: ohms Ω, k-ohms (k 10^{3}), meg ohms (m 10^{6})
- Capacitance: farad, microfarad (μf 10^{-6}), nanofarad (nf 10^{-9}), picofarad (pf 10^{-12})
- Inductance: henry, millihenry, microhenry
- Frequency: mhz, ghz 10^{9}

Fingertip Facts

volts ⇔ kohms ⇔ milliamperes

khz 10^{3} ⇔ 10^{-3} = milliseconds

mhz 10^{6} ⇔ 10^{-6} = microsecond

ghz 10^{9} ⇔ 10^{-9} = nanosecond

60hz ⇔ 16.3 millisecond period

capacitance ⇔ μf 10^{-6}, nf 10^{-9}, pf 10^{-12} (pico), 10^{-15} (femtofarad)

seconds = mohm (resistance) x μf (capacitance)

2^{10} ⇔ 1023

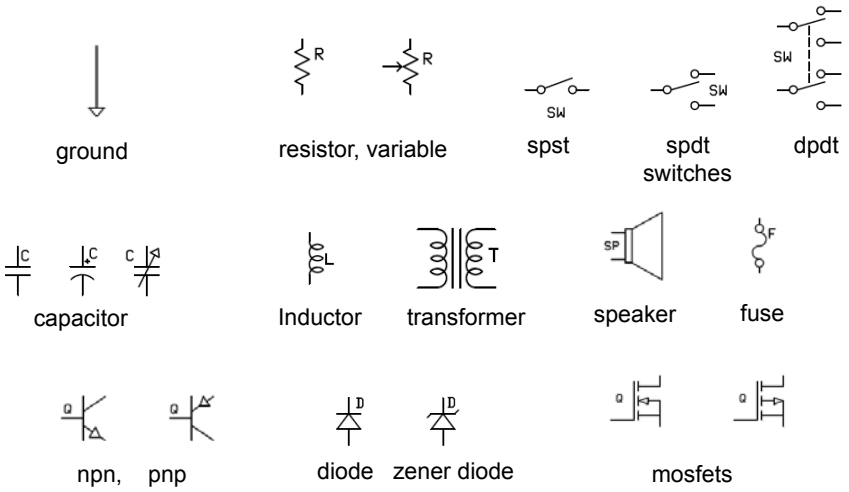
$\omega = 2\pi f$

3dB ⇔ half power point

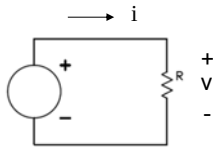
Common Acronyms

- BJT – Bipolar Junction Transistor
- MOSFET – Metal Oxide Field Effect Transistor
- PCB – Printed Circuit Board
- DIP – dual inline package
- SMD, SMT Surface mount device/technology
- cap – capacitor
- pot – potentiometer
- AM – amplitude modulation
- FM – frequency modulation
- RF – radio frequency
- IF – intermediate frequency
- SMA – SubMinature version A
- BNC – Bayonet – Neill – Conelman
- 1Nxxx diodes
- 2Nxxxx transistors

EE Symbols

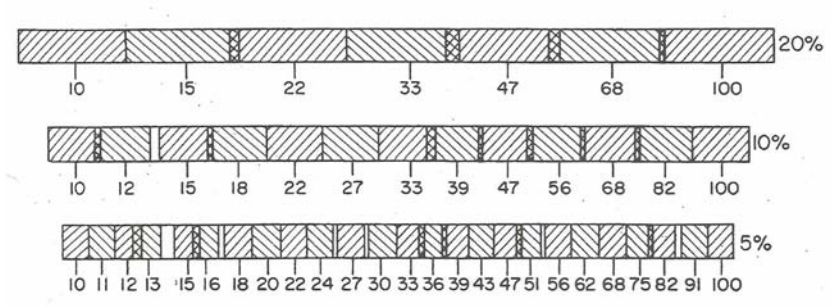


Resistors

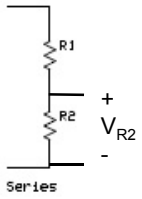


- V = IR
- Resistor parameters: resistance, tolerance and power rating.
- Variable resistors: pots
- Resistors are color coded
- **Standard Values (10%)**
  10 12 15 18 22 27 33 39 47 56 68 82
- Common tolerance: ±5%, ±2%, ±1%
- Series/parallel combination
- Why is high voltage used in power lines?

Nominal Values – Tolerance Ranges

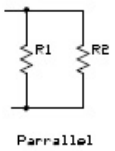


Series Parallel Combination



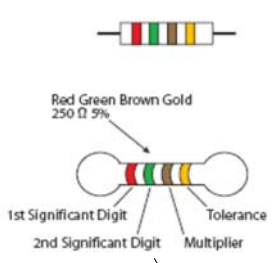
$$R_{eq-series} = R1 + R2 + \ldots$$

$$V_{R2} = \left(\frac{R2}{R1+R2}\right)V$$



$$R_{eq-parallel} = \frac{1}{\left(\frac{1}{R1}+\frac{1}{R2}+\ldots\right)}$$

Resistor Color Code



Color	1st-band Digit	2nd-band Digit	3rd-band Digit	4th-band Digit
Black	0	0	10^0 - 1	
Brown	1	1	10^1 - 10	1%
Red	2	2	10^2 - 100	2%
Orange	3	3	10^3 - 1000	3%
Yellow	4	4	10^4 - 10000	4%
Green	5	5	10^5 - 100000	
Blue	6	6	10^6 - 1000000	
Violet	7	7	10^7 - 10000000	
Gray	0	0	10^8 - 100000000	
White	9	9	10^9 - 1000000000	
Gold				5%
Silver				10%
None				20%

Figure by MIT OpenCourseWare.

red green brown gold
2 5 0 Ω 5%

2%, 1% Resistor Codes

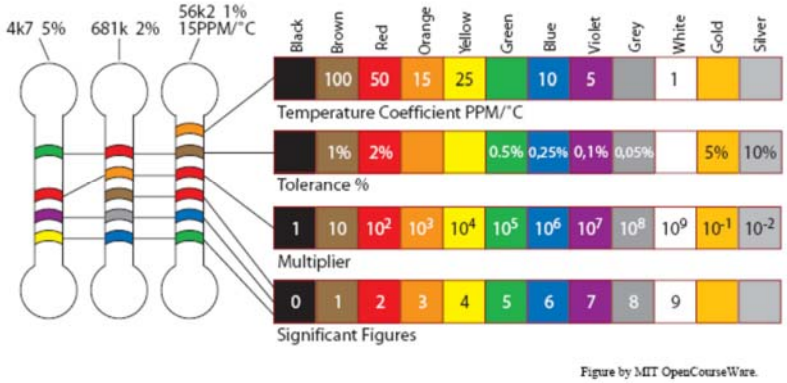
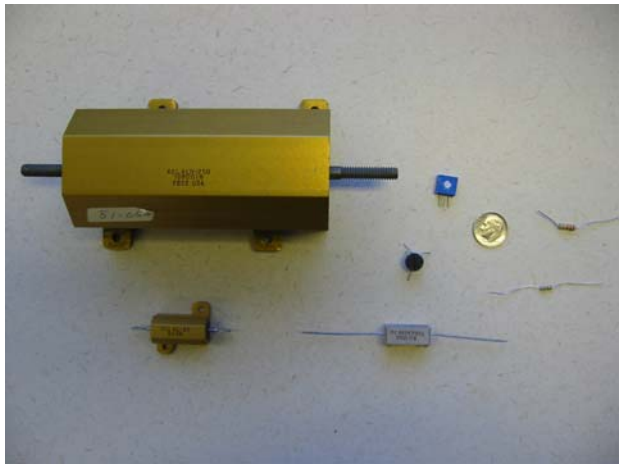
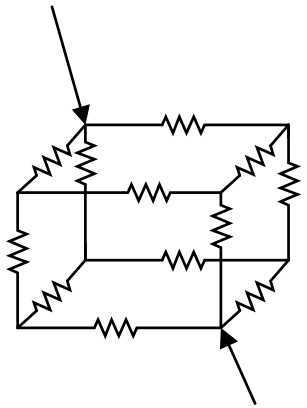


Figure by MIT OpenCourseWare.

Resistors



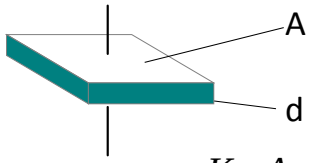
Brain Teaser – Job Interview Question



A resistor cube with (12) 1k resistors.

What is the resistance between the two points?

Capacitance



A = surface area of plates

d = distance between plates.

$$c = \frac{K\varepsilon_0 A}{d} \qquad Z = \frac{1}{sC} \qquad i = C\frac{dv}{dt}$$



Standard Capacitance Values: 10 12 15 18 22 27 33 39 47 56 68 82

Examples: 100pf, 180pf, 270pf,… 1µf , 2.2µf , 4.7µf ,…

Capacitor marking: 104 = 10x10^4 pf = 10^5 x 10^{-12} f = 10^{-7}f = 0.1 µf

Capacitors



- Parallel / Series combination Think!
- Capacitors range for 1 pf (10^{-12}) to 100,000 µf (10^{-1})
- Typically capacitors larger than 1µf are polarized. Non polarized units are marked NP (non-polar) or BP (bipolar).
- All capacitors have maximum voltage ratings.

Capacitors

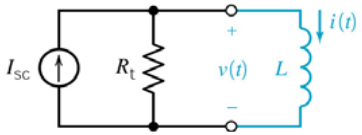


Variable Capacitor – Lab 1



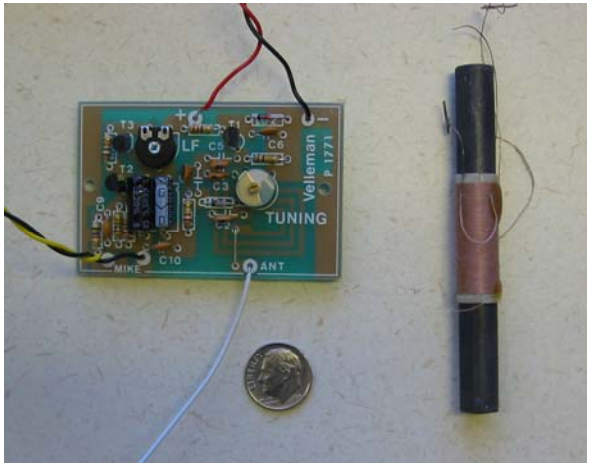
Inductors

$$v(t) = L\frac{d}{dt}i(t) \qquad Z = sL$$

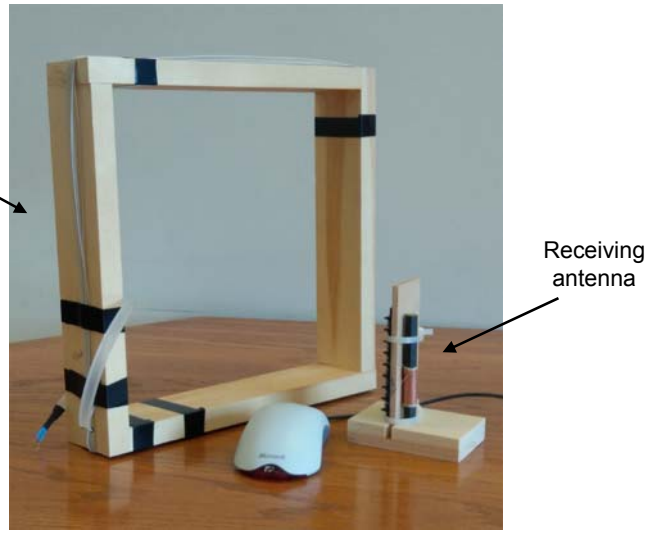


- Inductors are used in tuned circuits, switching power supplies, voltage converters, light dimmers, GFI.
- Inductors vary from a few µh (etched on a pcb) to henries.

Inductors

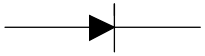


Inductors/Antenna – Lab 1

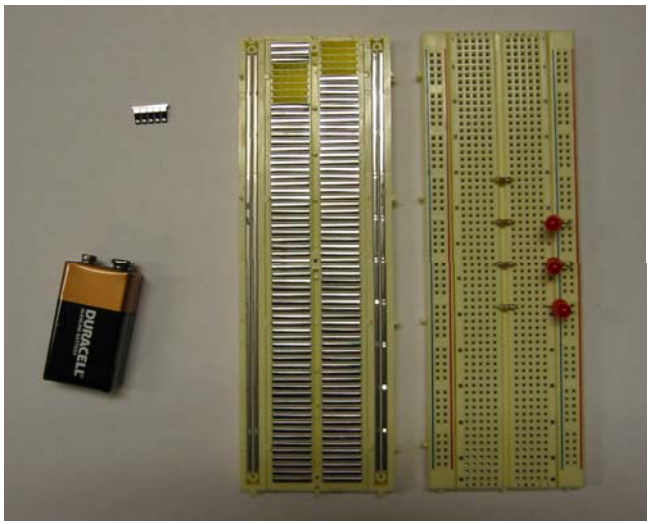


Diodes

- Diodes allow current to flow in the direction of the arrow.
- Can be modeled as an open circuit in one direction and a short circuit in the other (with a 0.6 volt drop)
- Diode parameters: max current, reverse breakdown voltage, reverse recovery time.
- Orientation always indicated.

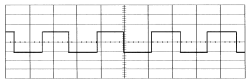


Protoboard

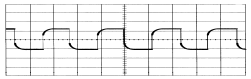


Scope Probe Compensation

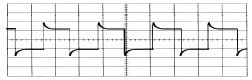
CORRECTLY COMPENSATED



PROBE UNDERCOMPENSATED

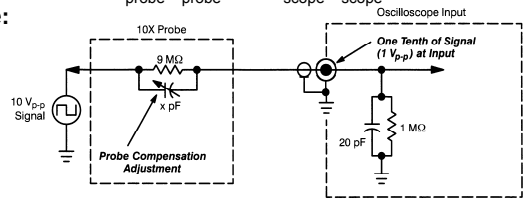


PROBE OVERCOMPENSATED

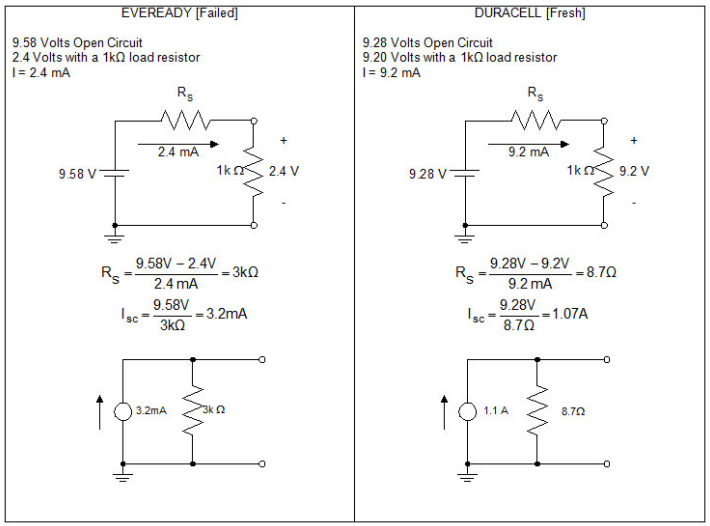


Probes are switchable:
10X or 1X

$R_{probe}C_{probe} = R_{scope}C_{scope}$

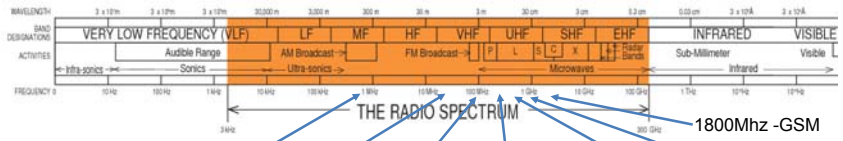


Battery Source Resistance



Frequency Spectrum*

Not complete listing



1800Mhz -GSM

535 kHz - 1.6 MHz: AM Radio stations.
54 MHz - 88 MHz: Television
88 MHz - 108 MHz: FM radio

174 MHz - 216 MHz: Television
470 MHz - 806 MHz: Television
824 Mhz - 849 Mhz: Cell phones

VHF 30-300Mhz
UHF 300-3Ghz

RFID
125 - 134 kHz [MIT ID]*
13.56 MHz [US Passports]*
400 – 960 MHz UHF
[EZPASS 915mhz ~ 1 mw]**
2.45 GHz
5.8 GHz

* Excitation powered

*http://www.ntia.doc.gov/osmhome/allochrt.pdf

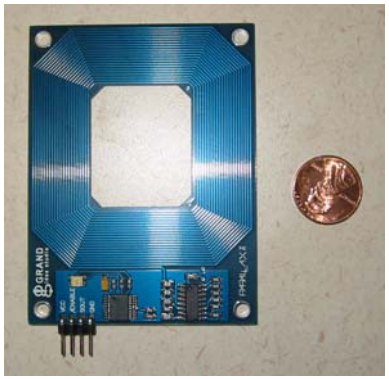
RFID- Radio Frequency Identification

- Used to provide remote interrogation/identification.
- Frequency bands:
  - 125 - 134 kHz [MIT ID]*
  - 13.56 MHz [US Passports]*
  - 400 – 960 MHz UHF
    [EZPASS 915mhz ~ 1 mw]**
  - 2.45 GHz
  - 5.8 GHz

* excitation/broadcast powered

** battery powered

125khz RFID



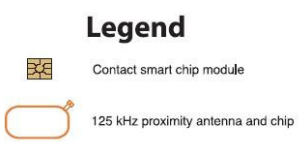


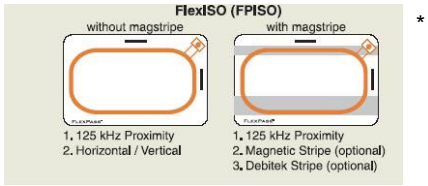
125khz transmitter

Receiver

Powered by 125khz broadcast signal

RFID Internals

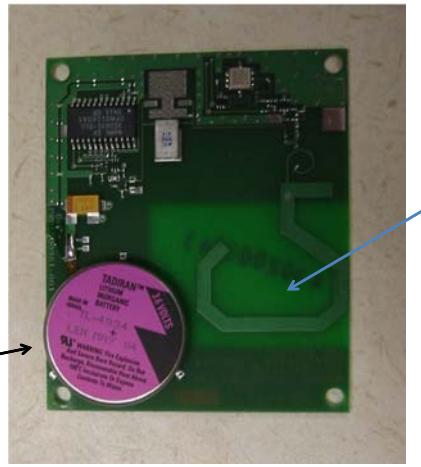




*

*http://groups.csail.mit.edu/mac/classes/6.805/student-papers/fall04-papers/mit_id/#specs

EZ-pass Internals



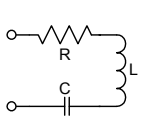
Transmitting antenna

Battery

Resonance: RLC Circuits

- Consider passive circuit
- Required to tune any RF circuits
- Driving point impedance is real if $X_C = X_L$
- Both series and parallel configuration

Impedance Admittance* Notation

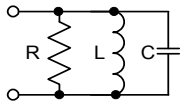


$$X_L = j\,\omega L = sL$$
$$X_C = \frac{1}{j\,\omega C} = \frac{1}{sC}$$
$$Z = R + j\,\omega L + \frac{1}{j\,\omega C}$$
$$Z = R + j\left[\omega L - \frac{1}{\omega C}\right]$$
$$Z = R + j\left[X_L - X_C\right]$$

Ohm's Law

$$V = I\,R; \quad V = I\,Z;$$
$$V = I\left[\frac{1}{Y}\right]; \quad V\,Y = I$$

*Impedance = resistance + reactance
Admittance = conductance + susceptance.



$$Z = \frac{1}{\frac{1}{R} + \frac{1}{j\,\omega L} + j\,\omega C}$$
$$Y = \frac{1}{Z}; \quad B_L = \frac{1}{X_L}; \quad B_C = \frac{1}{X_C}; \quad G = \frac{1}{R}$$
$$Y = G + \frac{1}{j\,\omega L} + j\,\omega C = G + j\left[\omega C - \frac{1}{\omega L}\right]$$
$$Y = G + j\left[B_C - B_L\right]$$

As conductance is the complement of resistance, a complementary expression of reactance, called susceptance.

Decibel (dB) – 3dB point

$$dB = 20\log\left(\frac{V_o}{V_i}\right) \qquad dB = 10\log\left(\frac{P_o}{P_i}\right)$$

$\log_{10}(2)=.301$

3 dB point = ?

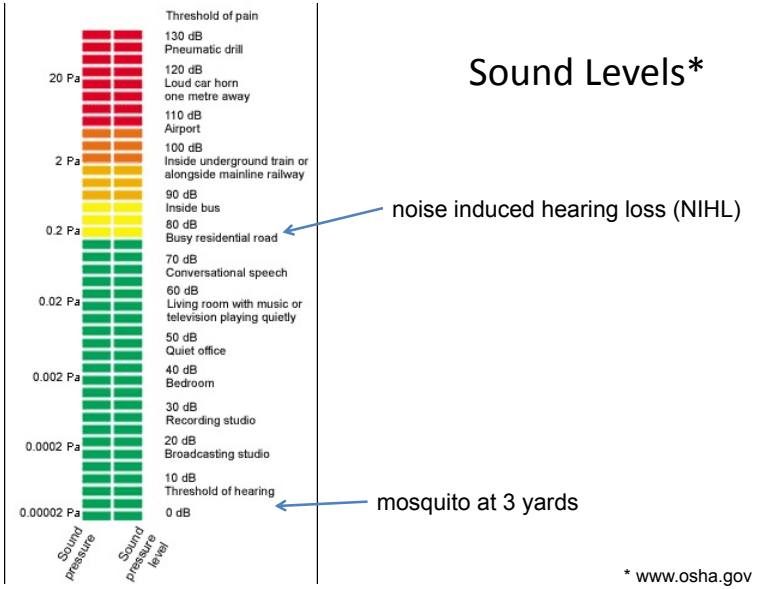
half power point

100 dB = 100,000 = 10^5
80 dB = 10,000 = 10^4
60 dB = 1,000 = 10^3
40 dB = 100 = 10^2

Common Decibel Units

dB UNIT	reference	application
dbV	1 Volt rms	routine voltage measurements [comparisons!]
dBm	1 mW into 50Ω [0.224V] or 600Ω [0.775V]	radio-frequency [50Ω] or audio [600Ω] power measurements [in England, the dBu is used to mean 0.775V reference without regard to impedance or power]
dB mV	1 millivolt rms	signal levels in cable systems
dbW	1 Watt	audio power amplifier output [usually into 8, 4, or 2Ω impedances]
dBf	1 femtowatt [10^{-15} watt]	communications and stereo receiver sensitivity [usually 50Ω, 75Ω unbalanced, or 300Ω balanced antenna input impedances]
dB (SPL)	0.0002μbar, = 20μPa [=Pascals] [1 bar = 10^6 dynes/cm^2 ~1AT]	Sound Pressure Level measurements: the reference is the "threshold of hearing".

Sound Levels*



* www.osha.gov

Bode Plot - Review

- A Bode plot is a graph of the magnitude (in dB) or phase of the transfer function versus frequency.
- Magnitude plot on log-log scale
  - Slope: 20dB/decade, same as 6dB/octave
- Bode plot provides insight into impact of RLC in frequency response.
- Stable networks must always have poles and zeroes in the left-half plane.

Magnitude & Phase

$$H(s) = \frac{1}{s+a} = \frac{1}{j\omega + a} \quad s = j\omega$$

$$|H(j\omega)| = \frac{1}{\sqrt{\omega^2 + a^2}}$$

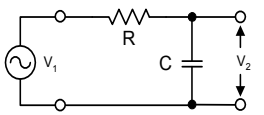
$$\angle H(j\omega) = -\tan^{-1}\left(\frac{\omega}{a}\right)$$

$$recall \quad z = |z|e^{j\angle z}$$

$$H(s) = \frac{N(j\omega)}{D(j\omega)} = \frac{(j\omega + b)^m}{(j\omega + a)^n}$$

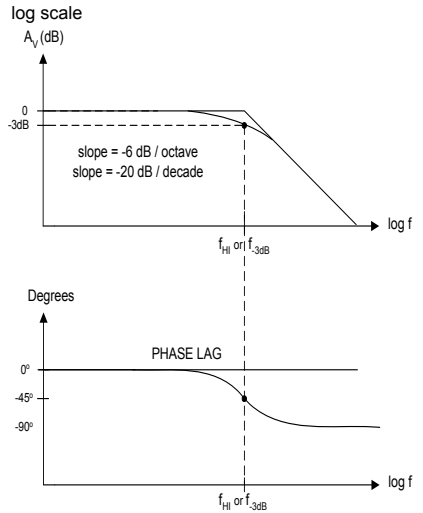
$$\angle H(j\omega) = m\tan^{-1}\left(\frac{\omega}{b}\right) - n\tan^{-1}\left(\frac{\omega}{a}\right)$$

Low Pass Filter LPF

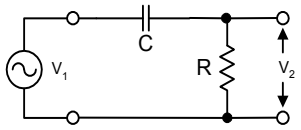


$$A_v = \frac{V_2}{V_1} = \frac{X_C}{R + X_C} = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = \frac{1}{j\omega RC + 1}$$

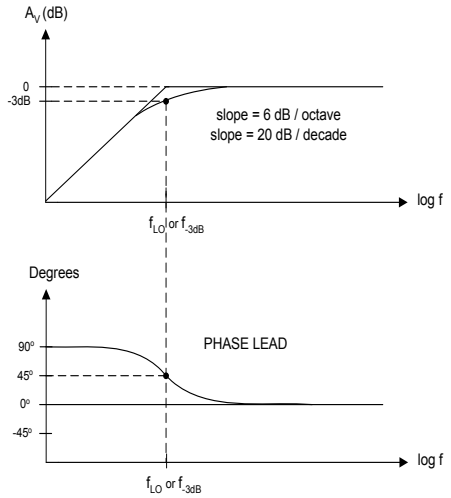
$$A_v = \frac{1}{sRC + 1}$$



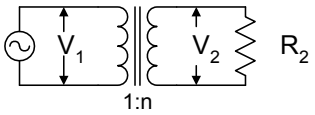
High Pass Filter HPF



$$A_v = \frac{V_2}{V_1} = \frac{R}{R + \frac{1}{j\omega C}} = \frac{j\omega CR}{j\omega CR + 1} = \frac{s\,CR}{s\,CR + 1}$$



Transformer – Step Up



$$V_1 I_1 = V_2 I_2$$

R_1 is equivalent resistance of R_2 reflected back to primary.

$$V_1 \frac{V_1}{R_1} = V_2 \frac{V_2}{R_2}$$

$$\frac{V_1^2}{R_1} = \frac{V_2^2}{R_2}$$

$$R_1 = \frac{V_1^2 R_2}{V_2^2}$$

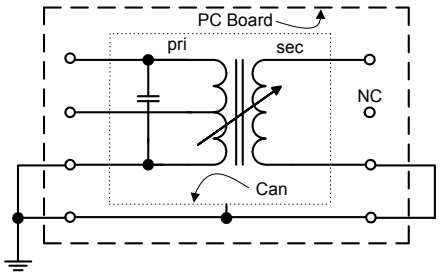
but $V_2 = nV_1$

$$R_1 = \frac{V_1^2 R_2}{(nV_1)^2} = \frac{V_1^2 R_2}{n^2 V_1^2}$$

so

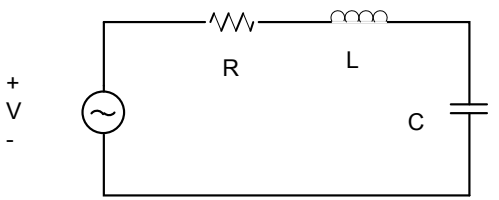
$$R_1 = \frac{R_2}{n^2}$$

Proper External Grounding for Lab 1 IF Transformer





Series Resonance



$$Z = R + sL + \frac{1}{sC} = R + j(\omega L - \frac{1}{\omega C})$$

$$I = \left|\frac{V}{Z}\right| = \frac{V}{\sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2}}$$

Resonance

$$I = \left|\frac{V}{Z}\right| = \frac{V}{\sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2}}$$

- I is a maximum at resonance

$$\omega L = \frac{1}{\omega C}$$

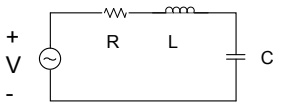
$$X_L = j\omega L$$ inductive reactance

$$\omega = \frac{1}{\sqrt{LC}} = 2\pi f$$

$$X_C = \frac{1}{j\omega C}$$ capactive reactance

$$f = \frac{1}{2\pi\sqrt{LC}}$$

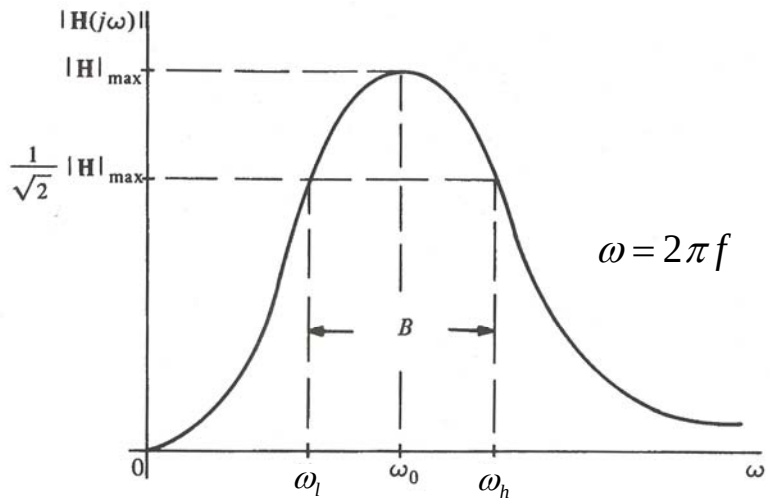
Resonance (Series RLC) – Key points



$$Z = R + sL + \frac{1}{sC} = R + j(\omega L - \frac{1}{\omega C})$$

- Applies to more complex RLC circuits
- At resonance: power is maximum
- At resonace: phase angle zero, i.e. capacitive reactance = inductive reactance, or impedance is real

Bandwidth – 3dB Point



$$\omega = 2\pi f$$

Bandwith - BW

- BW (radians) = $\omega_h - \omega_l$ where ω_h, ω_l are the half power points
- Peak power is at resonance $P = \frac{V^2}{R}$
- Half power points $I = \frac{V}{\sqrt{2}R}$ $I = \left|\frac{V}{Z}\right| = \frac{V}{\sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2}}$

$$\sqrt{2}R = \sqrt{R^2 + (wL - \frac{1}{wc})^2} \Rightarrow \omega_1 = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}} \quad \omega_2 = \frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

- Note: $\omega^2 = \omega_1\omega_2$

Bandwidth and Q (Series RLC)

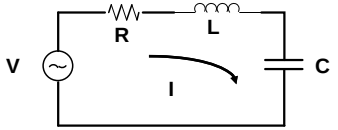
- BW (hertz) = $\frac{\omega_h - \omega_l}{2\pi} = \frac{R}{2\pi L}$
- Q* (quality factor) $\frac{resonant\ \ frequency}{bandwidth}$

$$Q = \frac{1}{R}\sqrt{\left(\frac{L}{C}\right)}$$

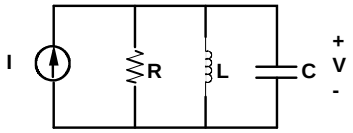
- Higher Q implies more selectivity

*Agarwal/Lang Foundation of Analog Digital Elect Circuits equation 14.47, p 794

Series Parallel Duality



$$V = I\left[R + jwL + \frac{1}{jwC}\right]$$



$$I = V\left[\frac{1}{R} + jwC + \frac{1}{jwL}\right]$$

Series		Parallel
V	⟷	I
R	⟷	1/R
L	⟷	C
C	⟷	L

Summary – Parallel Series RLC

Parallel

$$f_O = \frac{1}{2\pi\sqrt{LC}}$$

$$Q = 2\pi\ f_o RC$$

$$BW = (f_h - f_l) = \frac{1}{2\pi RC}$$

Series

$$f_O = \frac{1}{2\pi\sqrt{LC}}$$

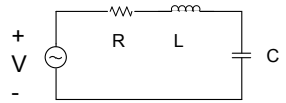
$$Q = \frac{2\pi\ f_O L}{R}$$

$$BW = (f_h - f_l) = \frac{R}{2\pi L}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} = 2\pi f_0$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Observations & Bode Plots



$$Z = R + sL + \frac{1}{sC} = R + j(\omega L - \frac{1}{\omega C})$$

$$\frac{I(s)}{V(s)} = \frac{1}{Z(s)} = \frac{\frac{1}{L}s}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

- Pole at DC or zero frequency
- Magnitude of Z is minium at resonance
- Bode plots are graphs of the transfer function: magnitude and phase angle

TABLE 32.1 *Analogies Between Electrical and Mechanical Systems*

Electric Circuit		One-Dimensional Mechanical System
Charge	$Q \leftrightarrow x$	Position
Current	$I \leftrightarrow v_x$	Velocity
Potential difference	$\Delta V \leftrightarrow F_x$	Force
Resistance	$R \leftrightarrow b$	Viscous damping coefficient
Capacitance	$C \leftrightarrow 1/k$	(k = spring constant)
Inductance	$L \leftrightarrow m$	Mass
Current = time derivative of charge	$I = \frac{dQ}{dt} \leftrightarrow v_x = \frac{dx}{dt}$	Velocity = time derivative of position
Rate of change of current = second time derivative of charge	$\frac{dI}{dt} = \frac{d^2Q}{dt^2} \leftrightarrow a_x = \frac{dv_x}{dt} = \frac{d^2x}{dt^2}$	Acceleration = second time derivative of position
Energy in inductor	$U_L = \frac{1}{2}LI^2 \leftrightarrow K = \frac{1}{2}mv^2$	Kinetic energy of moving object
Energy in capacitor	$U_C = \frac{1}{2}\frac{Q^2}{C} \leftrightarrow U = \frac{1}{2}kx^2$	Potential energy stored in a spring
Rate of energy loss due to resistance	$I^2R \leftrightarrow bv^2$	Rate of energy loss due to friction
RLC circuit	$L\frac{d^2Q}{dt^2} + R\frac{dQ}{dt} + \frac{Q}{C} = 0 \leftrightarrow m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = 0$	Damped object on a spring

*https://web.njit.edu/~levyr/Physics_121/chapter32.**ppt***

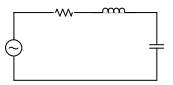
MATLAB Functions bode, freqs

- BODE(SYS,W) uses the vector W of frequencies (in radians/TimeUnit) to evaluate the frequency response
- [MAG,PHASE] = BODE(SYS,W) and [MAG,PHASE,W] = BODE(SYS) return the response magnitudes and phases in degrees (along with the frequency vector W if unspecified).
- SYS is the transfer function expressed as numerator and denominator in the form

$$SYS = \frac{d + es}{as^2 + bs + c}$$

- bode(num,denom,range)
  num=[d e], denom=[a b c], range= desired freqencies in radians
- freqs(num,denom,range) plots frequency response and phase angle

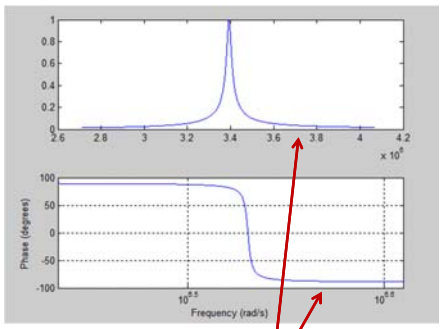
Bode vs Freqs Plots

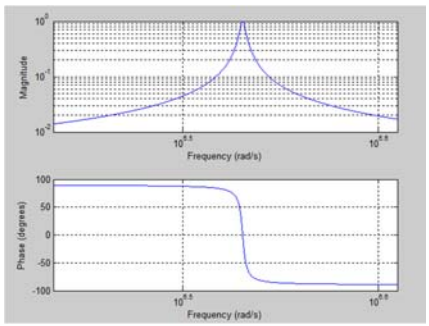


$$\frac{I(s)}{V(s)} = \frac{1}{Z(s)} = \frac{\frac{1}{L}s}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

R=1 L=47uh C=1.8nf f=540khz

```
num=[1/L 0]
denom=[1 R/L 1/(L*C)]
f=1/(2*pi*sqrt(L*C))
w=2*pi*f
w_range = [.8*w:20:1.2*w]
h=bode(num,denom,w_range)
magh=abs(h)
plot(w_range,magh)
shg
freqs(num,denom,w_range)
```

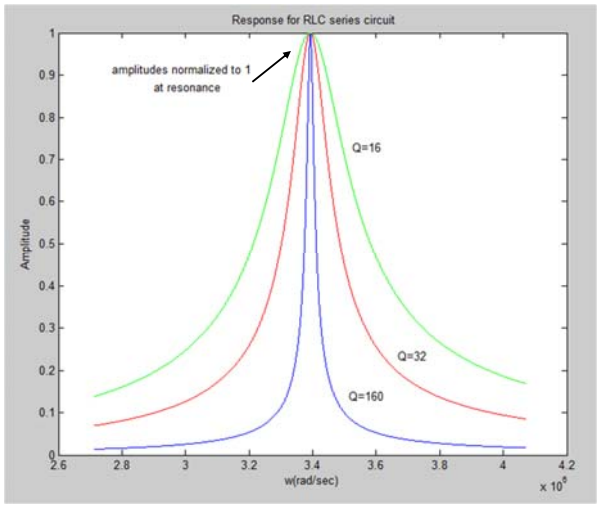




not same scale

bode freqs

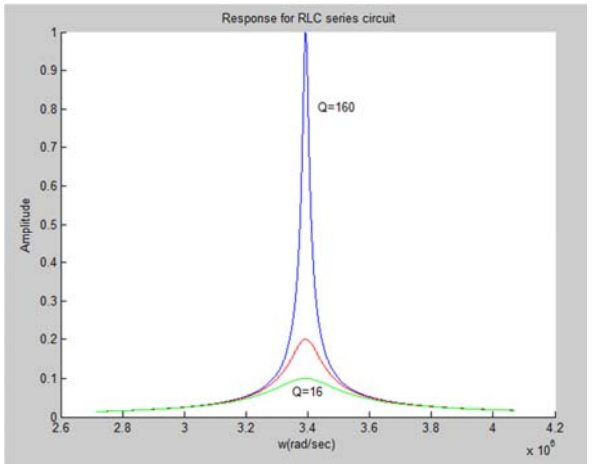
Selectivity and Q



L=47uh
C=1.8nf
f=540khz

R	Q
1	160
5	32
10	16

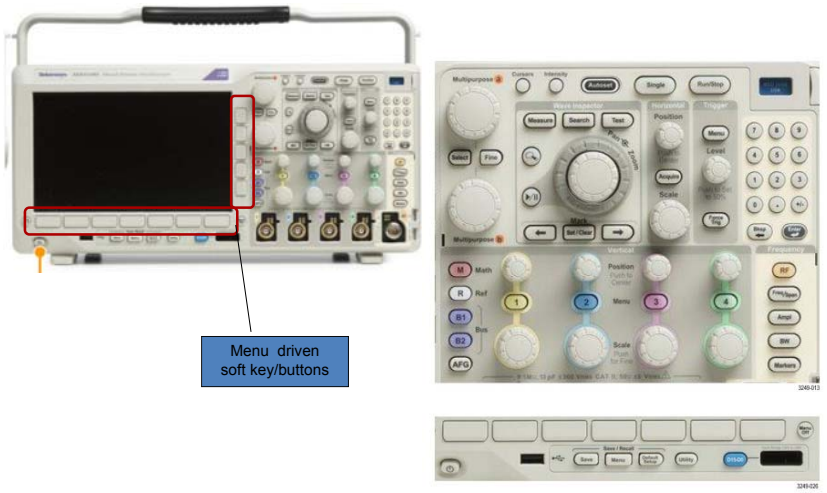
Selectivity and Q



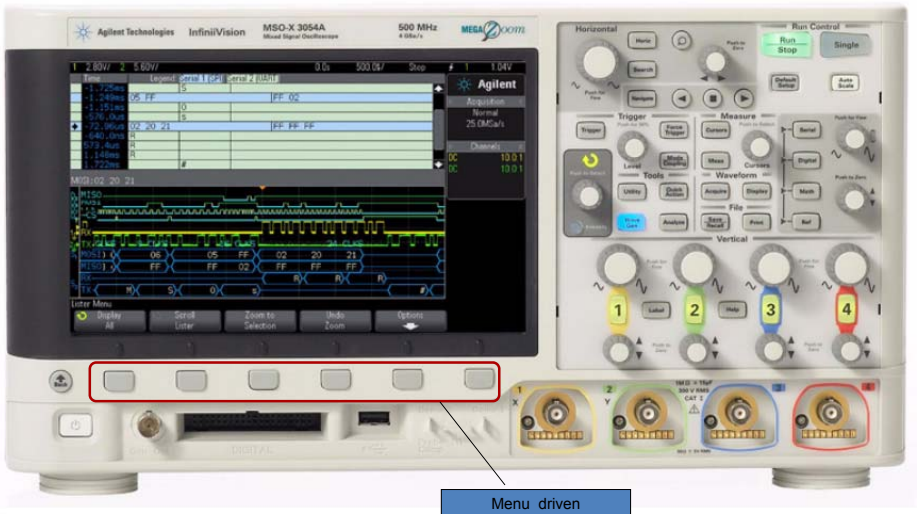
L=47uh
C=1.8nf
f=540khz

R	Q
1	160
5	32
10	16

Tektronix Oscilloscope



Agilent Oscilloscope



Lab 1 Topics

- Resonance, Q, bandwidth
- Transformers and impact on load and bandwidth
- Diode detector, demodulation
- Simple AM transmitter and receiver