

# Electronics of Radio

Notes on David Rutledge's book

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# Basic concepts

- Potential difference ( $V, \phi$ ):  $\phi = \int_a^r E \cdot ds$ , energy per charge,  $1V = 1 \text{ J/s}$
- Kirhhoff loop:  $\sum_{loop} V_i = 0$  (Conservation of energy)
- Kirhhoff node:  $\sum_{node} I_i = 0$  (Conservation of charge)
- $V(t) = V_p \cos(\omega t), \omega = 2\pi f, I(t) = I_p \cos(\omega t), \omega = 2\pi f$
- Instantaneous power:  $P(t) = V(t)I(t) = V_p I_p \cos^2(\omega t)$
- Average power:  $P_a = \int_0^{1/f} V(t)I(t)dt = \int_0^{2\pi/\omega} V_p I_p \cos^2(\omega t)dt = \frac{V_p I_p}{2}$
- Band names:

Name	Frequency
VLF	3-30kHz
LW	20-300kHz
MW	300kHz-3MHz
HF	3MHz-30MHz
VHF	30-300MHz

Name	Frequency
UHF	300MHz-1GHz
uW	1-30GHz
milliW	30-300GHz
submilliF	>300GHz

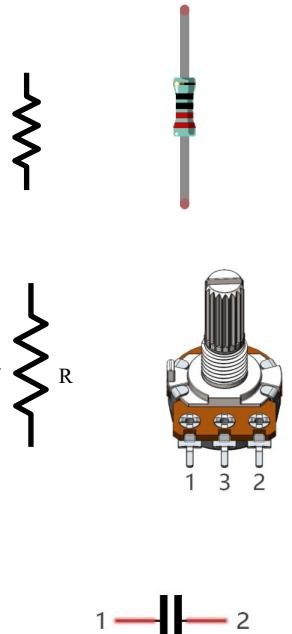
# Signals

- Gain (G) expressed in decibels:  $G = 10 \log_{10}(\frac{P_{out}}{P_{in}})$
- Mixer:
  - $V(t) = \cos(\omega_1 t) \cos(\omega_2 t) = \frac{1}{2}[\cos(\omega_+ t) + \cos(\omega_- t)], \omega_+ = \omega_1 + \omega_2, \omega_- = \omega_1 - \omega_2$
- Modulation

Name	Equation
AM	$V(t) = a(t)\cos(\omega_c t)$
FM	$V(t) = V_c\cos((\omega_c + a(t))t)$
FSK	$V(t) = V_c\cos(\omega_1 t), \text{ if } 1$ $V(t) = V_c\cos(\omega_0 t), \text{ if } 0$
PSK	$V(t) = +V_p\cos(\omega t), \text{ if } 1$ $V(t) = -V_p\cos(\omega t), \text{ if } 0$

# Resistors, capacitors, inductors

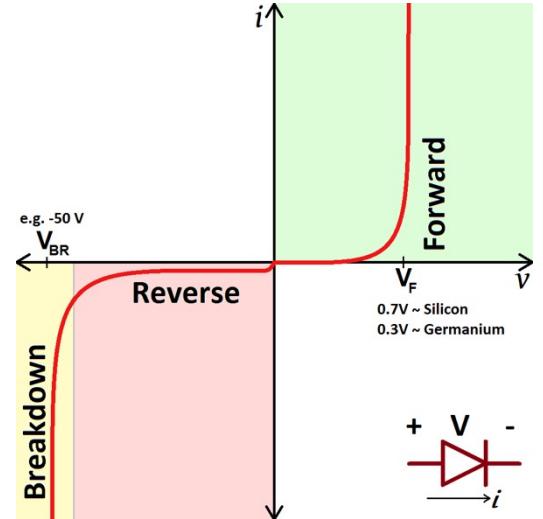
- Resistors
  - Analytic model:  $IR = V$
  - Energy dissipated:  $E = \int_{t_i}^{t_f} IV dt = \int_{t_i}^{t_f} I^2 R dt$
- Capacitors
  - Analytic model:  $CV = q, C \frac{dV}{dt} = i$
  - Capacitor Energy stored:  $E = \int_{t_i}^{t_f} CV \frac{dV}{dt} dt = \frac{1}{2} CV^2$
- Inductors
  - Analytic model:  $V = L \frac{di}{dt}$
  - Inductor Energy stored:  $E = \int_{t_i}^{t_f} IV dt = \int_{t_i}^{t_f} LI \frac{dI}{dt} dt = \frac{1}{2} LI^2$



Credit: Make Electronics

# Diodes, transformers

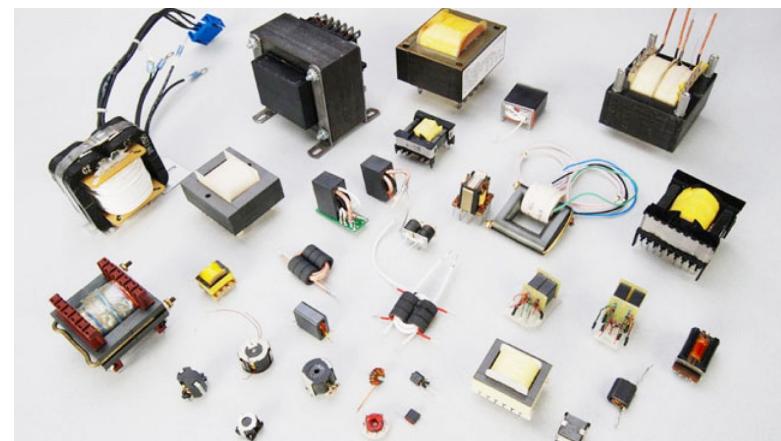
- Diodes
  - Devices that allow current to flow only in one direction
  - Silicon diodes, for example have, essentially infinite resistance if  $V_{ac} < 0$ , that is if the cathode is at a higher potential than the anode and very low resistance if  $V_{ac} > .7V$ .
  - The cathode is usually labelled with a band



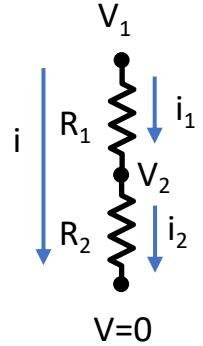
Credit: Make Electronics

- Transformers

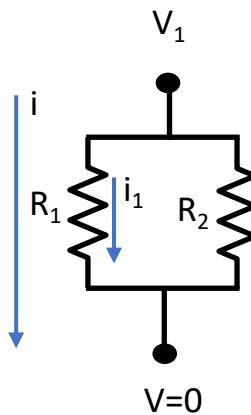
- AC only:  $\frac{N_2}{N_1} = \frac{V_2}{V_1}$



# Simple circuit analysis with Kirchhoff

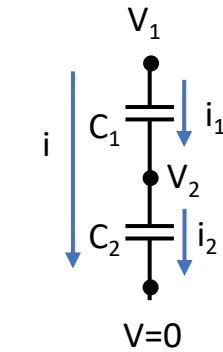


- \$R\_{eq}\$ is the equivalent resistance, replacing the top left circuit with a single resistance.
- By Kirchhoff's node rule, \$i\_1 = i\_2 = i\$, so
- $\frac{V_1 - V_2}{R_1} = \frac{V_2}{R_2} = \frac{V_1}{R_{eq}}$  thus  $\frac{R_1}{R_{eq}} V_1 = V_1 - V_2$  and  $\frac{R_2}{R_{eq}} V_1 = V_2$ . Adding, we get  $\frac{R_1}{R_{eq}} V_1 + \frac{R_2}{R_{eq}} V_1 = V_1$ . Dividing by \$V\_1\$ and solving, we get \$R\_1 + R\_2 = R\_{eq}\$

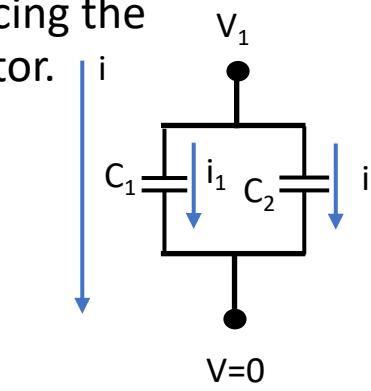


- Again let \$R\_{eq}\$ is the equivalent resistance, replacing the bottom left circuit with a single resistance.
- By Kirchhoff's node rule, \$i\_1 + i\_2 = i\$, so
- $\frac{V_1}{R_1} + \frac{V_1}{R_2} = \frac{V_1}{R_{eq}}$ .
- Solving, we get.  $\frac{R_1 R_2}{R_1 + R_2} = R_{eq}$

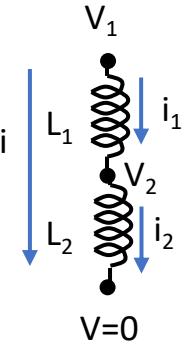
- \$C\_{eq}\$ is the equivalent capacitance, replacing the top right circuit with a single capacitor.
- By Kirchhoff's node rule, \$i\_1 = i\_2 = i\$, so
- $C_1 \frac{d(V_1 - V_2)}{dt} = C_2 \frac{d(V_2)}{dt} = C_{eq} \frac{dV_1}{dt}$
- $\frac{C_{eq}}{C_1} \frac{d(V_1)}{dt} = \frac{d(V_1 - V_2)}{dt}$  and  $\frac{C_{eq}}{C_2} \frac{d(V_1)}{dt} = \frac{d(V_2)}{dt}$
- Adding and cancelling the  $\frac{d(V_2)}{dt}$ , we get
- $\frac{C_{eq}}{C_1} + \frac{C_{eq}}{C_2} = 1$  and solving, we get.  $\frac{C_1 C_2}{C_1 + C_2} = C_{eq}$



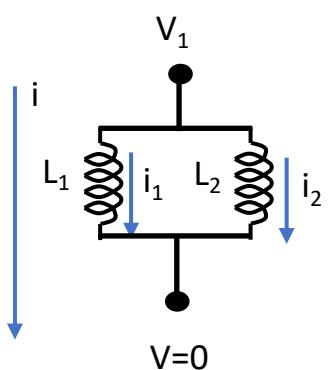
- \$C\_{eq}\$ is the equivalent capacitance, replacing the bottom right circuit with a single capacitor.
- By Kirchhoff's node rule, \$i\_1 + i\_2 = i\$
- $C_{eq} \frac{dV_1}{dt} = C_1 \frac{dV_1}{dt} + C_2 \frac{dV_1}{dt}$ , so
- $C_{eq} = C_1 + C_2$



# Simple circuit analysis with Kirchhoff

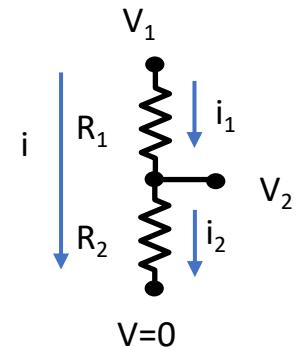


- Let  $L_{eq}$  be the equivalent inductance, replacing the top left circuit with a single inductor.
- By Kirchhoff's node rule,  $i_1 = i_2 = i$ , so
- $L_{eq} \frac{di}{dt} = V_1$ ,  $L_1 \frac{di_1}{dt} = V_1 - V_2$ ,  $L_1 \frac{di_2}{dt} = V_2$
- $V_1 = L_{eq} \frac{di}{dt} = L_1 \frac{di}{dt} + L_2 \frac{di}{dt}$  and
- $L_{eq} = L_1 + L_2$

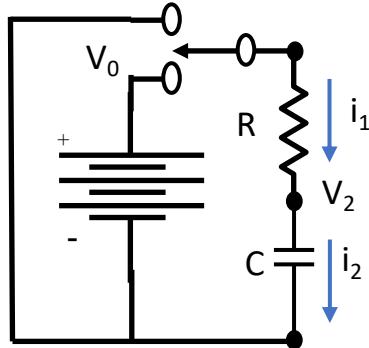


- Let  $L_{eq}$  be the equivalent inductance, replacing the bottom left circuit with a  $\frac{di}{dt} =$
- $\frac{V_1}{L_{eq}}$ ,  $\frac{di_1}{dt} = \frac{V_1}{L_1}$ ,  $\frac{di_2}{dt} = \frac{V_1}{L_2}$ ,
- single inductor.
- By Kirchhoff's node rule,  $i_1 + i_2 = i$ , so
- $\frac{V_1}{L_{eq}} = \frac{V_1}{L_1} + \frac{V_1}{L_2}$  and
- $L_{eq} = \frac{L_1 L_2}{L_1 + L_2}$

- The circuit on the right, is useful and is called a *voltage divider*.
- $i = i_1 = i_2$  so  $\frac{V_1 - V_2}{R_1} = \frac{V_2}{R_2}$ ,  $V_1 - V_2 = \frac{R_1}{R_2} V_2$
- Thus,  $V_1 = (1 + \frac{R_1}{R_2})V_2$  and so
- $V_2 = \frac{R_2}{R_1 + R_2} V_1$

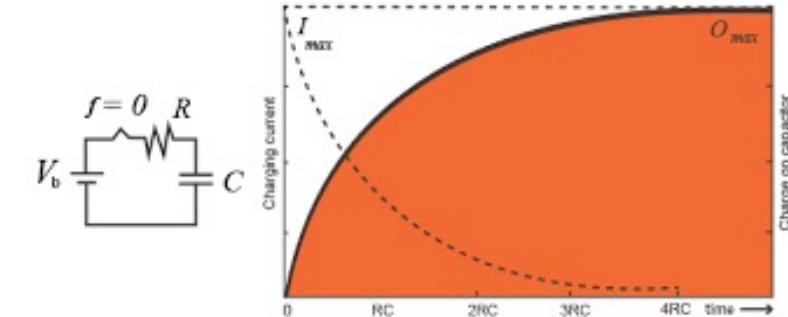


# RC/RL circuit analysis with Kirchhoff



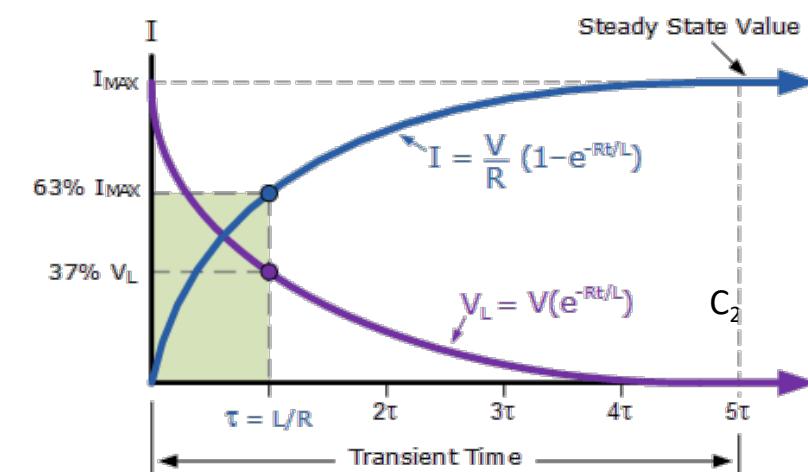
- RC behavior: charging

- $V_0 - V_2 = i_1 R = V_R, i_1 = \frac{V_R}{R}$
- $i_2 = C \frac{dV_2}{dt}, V_C = V_2$
- $i_1 = i_2, V_C = V_0 - V_R$
- $\frac{V_R}{R} = C \frac{dV_C}{dt}, RC \frac{dV_C}{dt} = V_0 - V_C$ , or  $RC \frac{dV_C}{dt} + V_C = V_0$
- Solution is  $V_C = V_0 - V_0 e^{-\frac{t}{RC}}$



- RL behavior: charging

- $V_0 - V_2 = i_1 R = V_R$
- $V_L = V_2 = L \frac{di_2}{dt}$
- $i_1 = i_2, V_R = V_0 - V_L$ , so  $L \frac{d}{dt} \frac{V_0 - V_L}{R} = V_L$
- $\frac{L}{R} \frac{dV_L}{dt} + V_L = 0$
- Solution is  $V_L = V_0 e^{-\frac{Rt}{L}}$



# Phasors

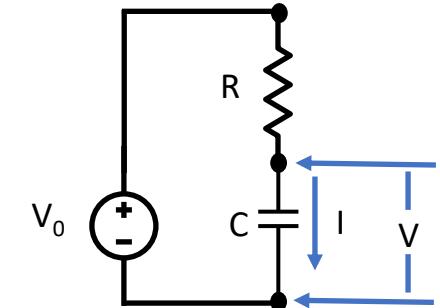
- $V(t) = RI(t)$
- $V(t) = L\dot{I}(t)$
- $I(t) = C\dot{V}(t)$
- Suppose  $V(t) = A\cos(\omega t + \theta)$  and  $I(t) = B\cos(\omega t + \phi)$ . If  $\phi > \theta$ , we say the current leads the voltage.
- $V(t) = \operatorname{Re}(Ae^{j(\omega t + \theta)})$ , and  $I(t) = \operatorname{Re}(Be^{j(\omega t + \phi)})$
- Now define  $\hat{V} = V = Ae^{j\theta}$  and  $\hat{I} = Be^{j\phi}$ , so  $|V| = A$ ,  $|I| = B$ ,  $\angle V = \theta$ , and  $\angle I = \phi$ .  $\hat{V}$  and  $\hat{I}$  are called phasors and do not include time. Note that  $V(t) = \operatorname{Re}(\hat{V}e^{j\omega t})$  and  $I(t) = \operatorname{Re}(\hat{I}e^{j\omega t})$ .
- Note that  $\hat{I} = C\hat{V}j\omega$ , for a capacitor and  $\hat{V} = L\hat{I}j\omega$ , for an inductor

# Circuit analysis and impedance

- Impedance unifies the “simple” ohms law with capacitance and inductance.
- $Z = R$ , for resistors,  $Z = j\omega L$ , for inductors and  $Z = \frac{1}{j\omega C}$ , for capacitors.
- In general,  $Z = R + jX$  and all the ohm like laws hold for resistors, capacitors and inductors .
  - $Z_{eq} = Z_1 + Z_2$  for two components with impedance  $Z_1, Z_2$  connected in series
  - $Z_{eq} = \frac{Z_1 Z_2}{Z_1 + Z_2}$  for two components with impedance  $Z_1, Z_2$  connected in parallel
- For example, for a resistor and capacitor in series has impedance  $Z = R + \frac{1}{j\omega C}$

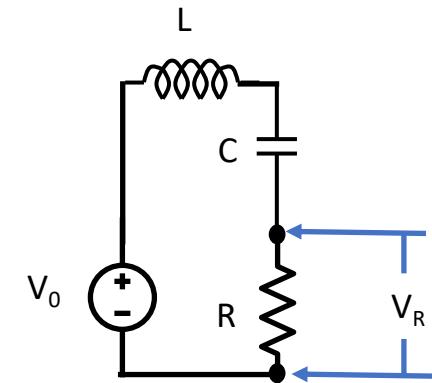
# Phasors, impedance and power

- For the circuit on the right,  $Z = R + \frac{1}{j\omega C}$  is the impedance for the resistor and capacitor in series.
- The phasor  $I = \frac{V_0}{Z}$  and the phasor  $V = \frac{I}{j\omega C} = \frac{V_0}{1+j\omega RC}$
- Further,  $|I| = \frac{V_0}{|Z|}$ ,  $\angle I = \angle \frac{V_0}{|Z|}$  and  $|V| = \frac{|I|}{|j\omega C|} = \left| \frac{V_0}{1+j\omega RC} \right|$
- For phasors  $V, I$ , define the complex power as  $P_{av} = \frac{V\bar{I}}{2} = Z \frac{I\bar{I}}{2} = R \frac{|I|^2}{2} + jX \frac{|I|^2}{2}$ ; the first term is the real power, the second is called the *reactive* power.
- The average power is  $P_a = \text{Re}(P) = \text{Re}\left(\frac{V\bar{I}}{2}\right)$ . We define the reactive power as  $P_r = \text{Im}(P)$ .
- $P_r = \omega(E_L - E_C)$ , where  $E_L$  and  $E_C$  are respectively, the energy stored in the inductor and capacitor respectively.



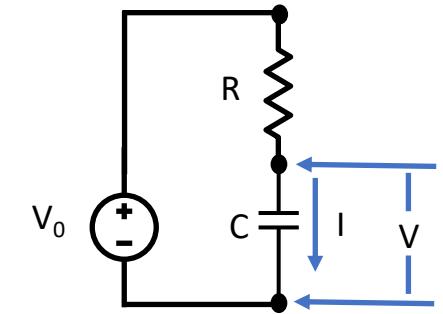
# Q and phasors

- Consider the series resonance on the right.  $Z_{LCR} = R + j \left( \omega L - \frac{1}{\omega C} \right)$
- The phasor,  $I = \frac{V_0}{Z_{LCR}}$ , and the phasor  $V_R = \frac{V_0}{Z_{LCR}} Z_R$ , where  $Z_R = R$ .
- So  $V_R = \frac{RC\omega V_0}{RC\omega + j(LC\omega^2 - 1)}$ .
- $|V_R|$  is maximum when  $\omega^2 LC = 1$ . Put  $\omega_0 = \frac{1}{\sqrt{LC}}$ . When  $\omega = \omega_0$ ,  $|V_R| = V_R = V_0$ .
- $|V_R| = \frac{V_0}{\sqrt{2}}$ , when  $X = R$ . Note that the power through R when  $X = R$  is half the power through R when  $X = 0$  or  $\omega = \omega_0$ .
- Let the frequencies where  $R = \pm X$  be denoted  $\omega_u$  and  $\omega_l$ , where  $\omega_u > \omega_l$ .
- We define  $Q = \frac{X}{R} = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 C R}$ .
- Solving for  $\omega_u$  and  $\omega_l$ , we get  $\frac{L\omega_u}{\omega_0} - \frac{\omega_0}{C\omega_u} = R$  and  $\frac{L\omega_l}{\omega_0} - \frac{\omega_0}{C\omega_l} = -R$ , or, in terms of  $Q$ ,
- $\frac{\omega_u}{\omega_0} - \frac{\omega_0}{\omega_u} = \frac{1}{Q}$  and  $\frac{\omega_l}{\omega_0} - \frac{\omega_0}{\omega_l} = -\frac{1}{Q}$ . In fact,  $\omega_0 = \sqrt{\omega_u \omega_l}$ , and so  $\frac{\omega_u}{\omega_0} - \frac{\omega_l}{\omega_0} = \frac{1}{Q}$ .
- Thus  $Q = \frac{\omega_0}{\omega_u - \omega_l} = \frac{\omega_0}{\Delta\omega}$
- From the definition of  $P_a$ , earlier,  $Q = \omega_0 \frac{E}{P_a}$ , where  $E$  is the total energy stored in  $L$  and  $C$ , which is in turn the peak  $E_L$  and peak  $E_C$  at resonance.



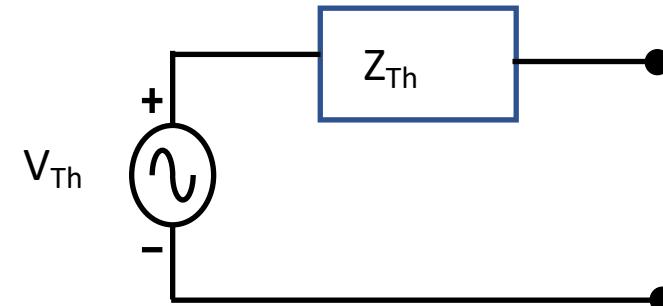
# Phasors, impedance and power

- For the circuit on the right,  $Z = R + \frac{1}{j\omega C}$  is the impedance for the resistor and capacitor in series.
- The phasor  $I = \frac{V_0}{Z}$  and the phasor  $V = \frac{I}{j\omega C} = \frac{V_0}{1+j\omega RC}$
- Further,  $|I| = \frac{V_0}{|Z|}$ ,  $\angle I = \angle \frac{V_0}{|Z|}$  and  $|V| = \frac{|I|}{|j\omega C|} = \left| \frac{V_0}{1+j\omega RC} \right|$
- For phasors  $V, I$ , define the complex power as  $P_{av} = \frac{V\bar{I}}{2} = Z \frac{\bar{I}\bar{I}}{2} = R \frac{|I|^2}{2} + jX \frac{|I|^2}{2}$ ; the first term is the real power, the second is called the *reactive* power.
- The average power is  $P_a = \text{Re}(P_{av}) = \text{Re}(\frac{V\bar{I}}{2})$ . We define the reactive power as  $P_r = \text{Im}(P_{av})$ .
- $P_r = \omega(E_L - E_C)$ , where  $E_L$  and  $E_C$  are respectively, the energy stored in the inductor and capacitor respectively.

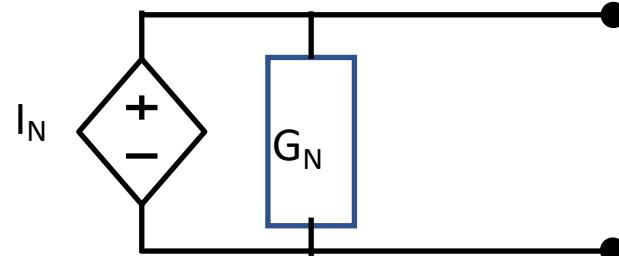


# Thevenin and Norton

- **Thevenin:** Any combination of *linear* sources and passive elements terminating in two terminals is equivalent to a pure voltage source in series with an impedance



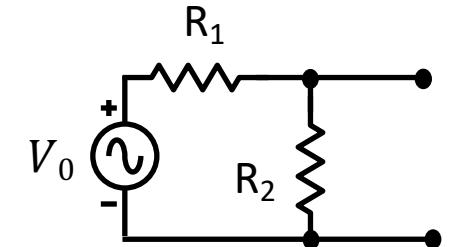
- **Norton:** Any combination of *linear* sources and passive elements terminating in two terminals is equivalent to a pure current source in parallel with a conductance



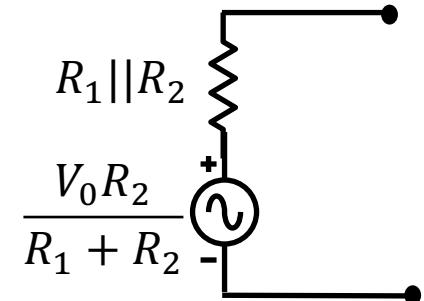
- Above,  $G_N = \frac{1}{Z_{Th}}$
- Similar theorems for *linear* two terminal input and output devices (with transfer function)

# Thevenin and Norton

- We can use lookback resistance to calculate the Thevenin equivalent resistance and ideal source.
- To find the lookback resistance, short the source and apply the usual laws.
  - Here  $R_s = R_1 \parallel R_2$
- To find the new ideal source, notice  $R_1$  and  $R_2$  form a voltage divider.
  - The new source voltage is  $\frac{V_0 R_2}{R_1 + R_2}$



is equivalent to



# Exercise 1: Resistors

1. Consider (A). Find the formula for power in the load. Find the  $R_l$  that maximizes the power to the load.

- $V_l = \frac{R_l}{R_s + R_l} V_0, I_l = \frac{V_0}{R_s + R_l}$ .

- $P_l = V_l I_l = \frac{R_l}{(R_s + R_l)^2} V_0^2$ , which is maximum when  $R_l = R_s$

2. Find the Thevenin and Norton parameters for (B).

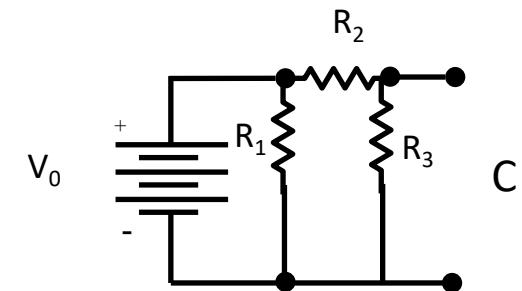
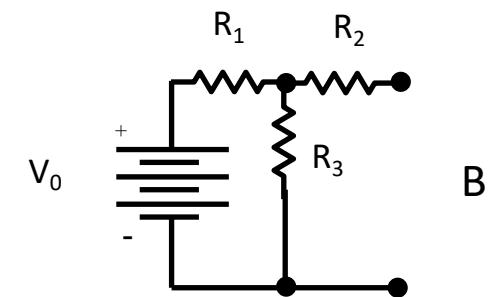
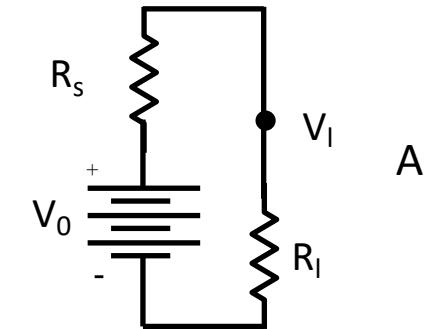
- $V_{Th} = \frac{R_3}{R_1 + R_3} V_0$

- $R_{Th} = R_2 + R_1 || R_3$

3. Find the Thevenin and Norton parameters for (C).

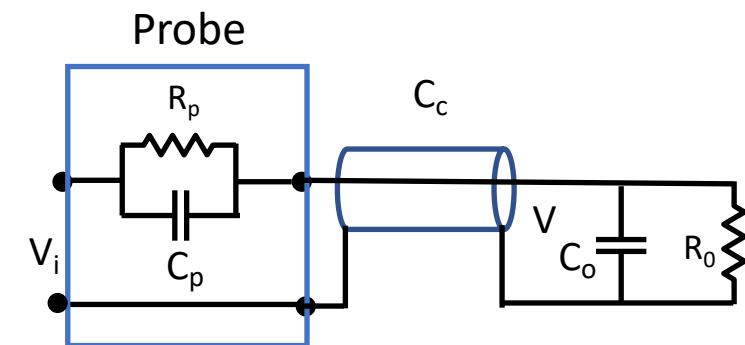
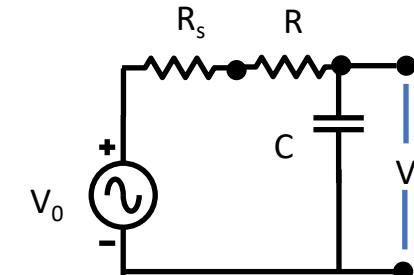
- $V_{Th} = \frac{R_3}{R_2 + R_3} V_0$

- $R_{Th} = R_2 || R_3$

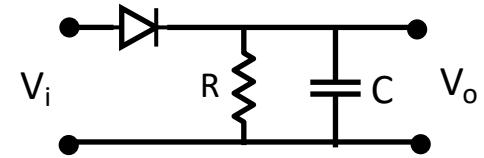


# Exercise 3: Capacitors

1. In the circuit on the right,  $V_0$  is a 2 volt pp ideal square wave source of frequency 20Hz,  $R_s = 50\Omega$ ,  $R = 300k\Omega$  and  $C = 10 nF$ . Period is 50 msec
2. What is the voltage,  $V$ , at the output? The scope has an input resistance of  $1M\Omega$ .
  - About a volt at peak
3. Let  $t_2$ , the time to discharge to 0V. Calculate  $\tau$  and  $t_2$ .
  - $\tau = 3 \times 10^5 \times 10^{-8} \text{ sec} = 3 \text{ msec}$
  - $t_{12} \approx 1.5ms$
4. Capacitance on the scope prevents the delay from being 0. Measure the new  $t_2$  with these changes.
5. Given  $C_0$  and  $C_p$  and  $R_p$ .
  - $C_0 = 100pf/m$ ,  $C_o = 50pF$ ,  $C_p = 10pF$
6. Now calculate the new  $t_{12}$ .
  - $\tau = 6\mu\text{-sec}$



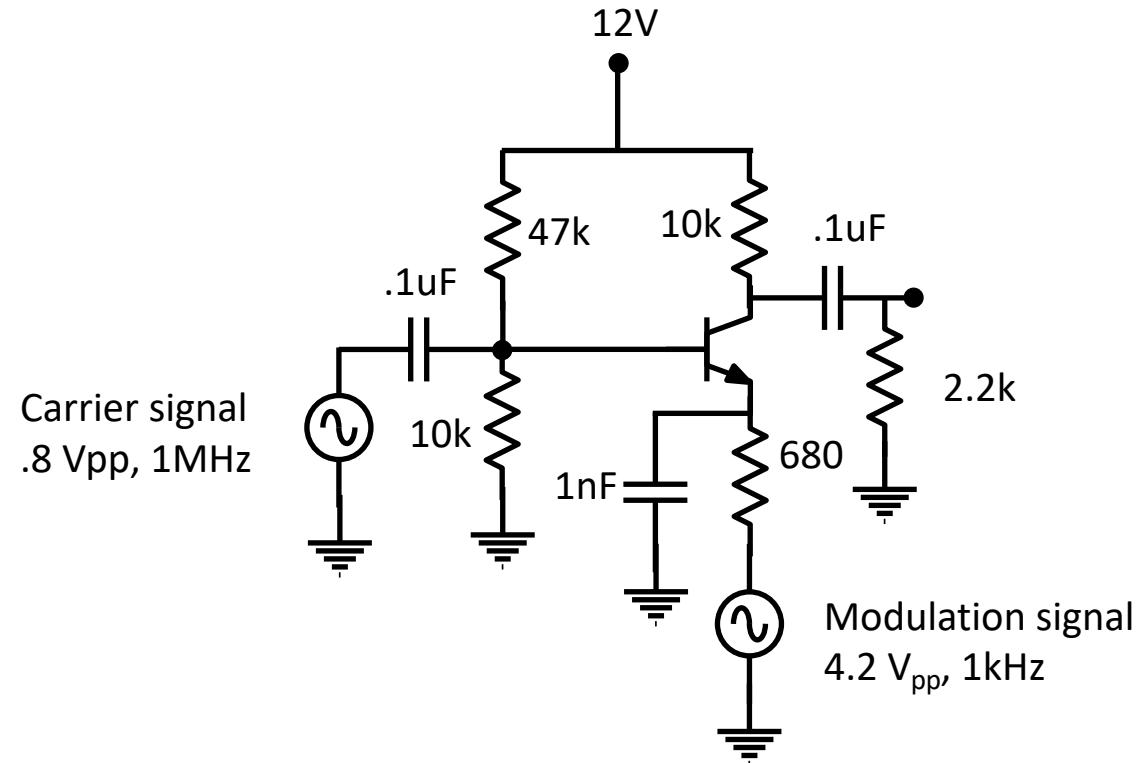
# Exercise 4: Diode detectors



- For AM,  $V(t) = V_c \cos(\omega_c t) + a(t) \cos(\omega_c t)$ , Define the modulation depth  $m = \frac{a_p}{V_c}$
- In circuit on the right,  $R = 10k\Omega$ ,  $C = 10 nF$
- Set function generator for  $f_c = 1MHz$ ,  $V_{c,pp} = 5V$ ,  $f_m = 1kHz$ ,  $m = .7$ 
  1. Calculate  $\tau$  for the RC circuit.  $\tau = 10^4 \times 10^{-8} \text{ sec} = .1ms$ .
    - $T_m$  is period of modulating signal.  $T_m = 10^{-3} \text{ sec} = 1ms$ . So  $\tau \ll T_m$
    - $T_c$  is period of modulating signal.  $T_c = 10^{-6} \text{ sec} = 1\mu s$ .  $\tau \gg T_c$
    - As you change  $f_m$  does the frequency of  $V_o$  track it? (It better)
  2. Compare the max voltage of the AM signal to the max of  $V_o$ .
    - $V_0, p \approx .8V$ ,  $V_{i,p} \approx 1.4V$
  3. What happens when we make  $m = 1.0$

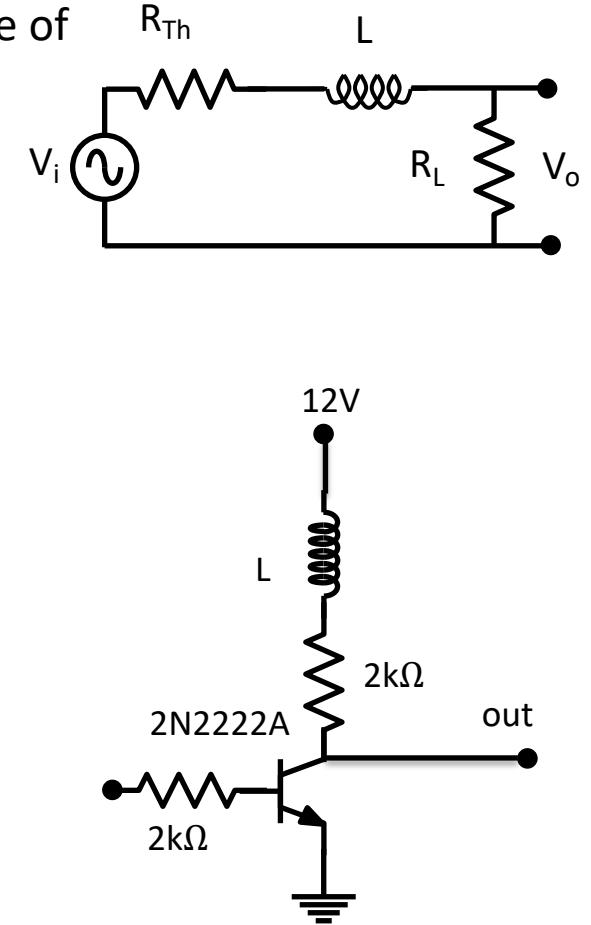
# AM Modulator for previous exercise

- I didn't have a signal generator that produced an AM signal, so I used the modulator on the right with the indicated inputs to produce the AM needed for the detector in the previous exercise.



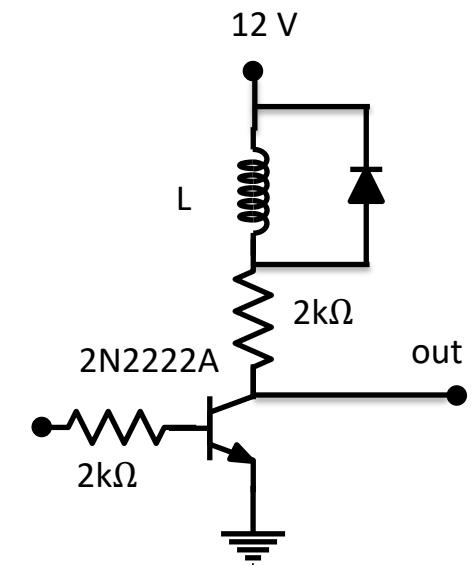
# Exercise 5: Inductors

- Set function generator for square wave with 5V  $V_{pp}$ , a Thevenin equivalent source resistance of  $R_{Th} = 50\Omega$  and frequency 1kHz. Connect a load,  $R_L = 100\Omega$  load, L=1mH
  - Observe square wave with rounded corners, measure the time,  $t_2$  to decay to 0
    - About 20 $\mu$ sec
  - In the top circuit, calculate inductor current and the expected delay,  $t_2$ 
    - $Z_{eq} = 150 + jL\omega$ ,  $\omega = 2\pi \times 10^3$ ,  $V_i = Re(V_{i,p}e^{j\omega t})$
    - As phasors,  $iZ_{eq} = V_i$ ,  $|i| \sqrt{150^2 + (\omega L)^2} = V_{i,p}$ ,  $|i| = \frac{V_{i,p}}{\sqrt{150^2 + (2\pi)^2}}$ ,  $\theta = \angle i = \arctan(-\frac{2\pi}{150})$ ,  $\theta \approx -2.4 \text{ rad} = -15^\circ$
    - $V_o = Re\left(\frac{100V_{i,p}}{\sqrt{150^2 + (2\pi)^2}} e^{j(\omega t + \theta)}\right)$ ,  $|V_o| = 1.6V$ ,
    - $\tau_{RL} = \frac{10^{-3}}{100} \text{ sec} \approx 10 \mu\text{sec}$
  - In the second circuit, use 2 scope channels: one at input, one at output.
    - 1 $\mu$  sec rise time. Ringing at 10MHz.  $\frac{1}{\sqrt{LC}} = 62.8 \times 10^6$ .  $C = \frac{10^3}{(62.8 \times 10^6)^2} \approx .25 \mu\text{F}$
    - Note: I made the pull-up 100K.



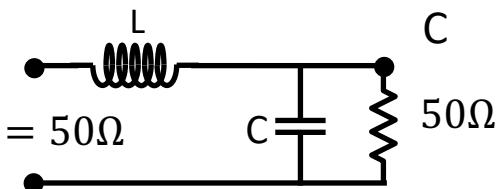
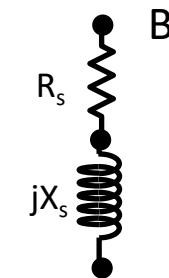
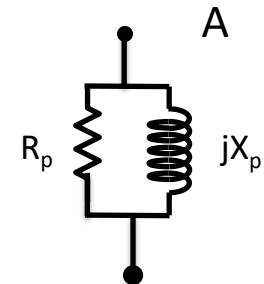
# Exercise 6: Diodes and snubbers

- Add indicated snubber diode.
  - 1. Swing up is nearly immediate with snubber
  - 2. Ringing at 10MHz.  $\frac{1}{\sqrt{LC}} = 62.8 \times 10^6$ .  $C = \frac{10^3}{(62.8 \times 10^6)^2} \approx .25 \mu F$
  - 3. What is its effect on ringing?
    - Ringing is uniform at 5 MHz
  - 4. Diode should be on when transistor is off.
- 
- Note: I made the pull-up 100K.



# Exercise 7: Parallel to Series conversion

- For series:  $Z_s = R_s + j\omega L$ ,  $Q_s = \frac{X_s}{R_s}$
  - For parallel:  $\frac{1}{Z_p} = \frac{1}{R_p} + \frac{1}{j\omega L}$ , so  $Z_p = \frac{j\omega L R_p}{R_p + j\omega L}$  and  $Q_p = \frac{R_p}{X_p}$
  - If  $Q_p = Q_s$ ,  $X_p X_s = R_p R_s$
- If circuits (A) and (B) have the same impedance, what is the relationship between  $R_p, X_p$  and  $R_s, X_s$ ?
    - $\frac{1}{Z_p} = \frac{1}{R_p} + \frac{1}{jX_s}$ ,  $Z_p = \frac{jR_p X_p}{R_p + jX_p} = \frac{X_p^2 R_p + jR_p^2 X_p}{R_p^2 + X_p^2}$ ,  $Z_s = R_s + jX_s$
    - $R_s = \frac{X_p^2 R_p}{R_p^2 + X_p^2}$ ,  $X_s = \frac{R_p^2 X_p}{R_p^2 + X_p^2}$ ,  $R_s = X_p \frac{X_p R_p}{R_p^2 + X_p^2}$ ,  $X_s = R_p \frac{X_p R_p}{R_p^2 + X_p^2}$ , set  $\rho = \frac{X_p R_p}{R_p^2 + X_p^2}$  for later reference
    - This shows the Q's must be equal as stated above.
  - Find a formula for  $X_s$ , for large  $Q = Q_p = Q_s$  and small  $Q = Q_p = Q_s$
  - Use circuit (C) to transfer a  $50\Omega$  load (circuit C) to a  $5\Omega$  load. What is  $X_C$  at 7 MHz?  $Z_i = 50\Omega$ . What are C and L in that model?
    - Use the parallel to series conversion to make a series equivalent circuit consisting of C and the  $50\Omega$  with  $R_s = 5\Omega$



# Exercise 8: Series resonance

- For the circuit on the right,  $C = 8 - 50\text{pf}$ ,  $L = 15\mu\text{H}$  forming a bandpass filter.  $R = 100\Omega$
- If  $C = 34\text{pf}$ , the resonant frequency is  $\omega = \frac{1}{\sqrt{35 \times 10^{-12} \times 15 \times 10^{-6}}} = \frac{10^9}{\sqrt{525}} \approx 44.2$ , so the resonant frequency is  $\frac{44.2}{2\pi} \approx 7.07\text{MHz}$

1. Tune the resonant frequency to  $7\text{MHz}$  and find  $f_u$ ,  $f_l$  and  $\Delta f$  and thus  $Q$ .

- $f_u = 7.67\text{MHz}$ ,  $f_l = 6.47\text{MHz}$ ,  $Q = \frac{f}{\Delta f} = \frac{7}{1.2} = 5.8$

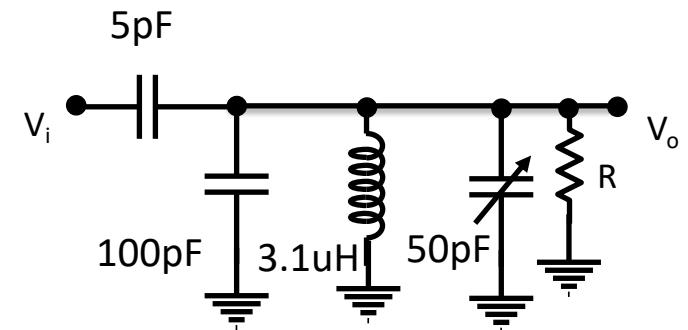
2. Compute what these values should be

- $Z_{eq} = R + j(\omega L - \frac{1}{\omega C})$
- As phasors,  $i = |i|e^{j\theta}$ ,  $|i| = \frac{V_{i,0}}{\sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2}}$ ,  $\theta = -\arctan(\frac{\omega L - \frac{1}{\omega C}}{R})$
- $V_0 = iR$ , Power through R at  $\omega$  is  $P(\omega) = |i|^2|R = \frac{|V_{i,0}|^2 R}{R^2 + (\omega L - \frac{1}{\omega C})^2}$ . At resonance,  $P(\omega_r) = \frac{|V_{i,0}|^2}{R}$ . To find half power, set  $\frac{1}{2} = (\frac{|V_{i,0}|^2 R}{R^2 + (\omega L - \frac{1}{\omega C})^2}) / (\frac{|V_{i,0}|^2}{R})$ , or  $R = \omega L - \frac{1}{\omega C}$ .
- Solving gives  $f_u = 7.67\text{MHz}$ ,  $f_l = 6.53\text{MHz}$ ,  $Q = 6.1$
- General formulas:  $\omega_u = \frac{R}{2L} + \sqrt{(\frac{R}{2L})^2 + \frac{1}{LC}}$ ,  $\omega_l = -\frac{R}{2L} + \sqrt{(\frac{R}{2L})^2 + \frac{1}{LC}}$



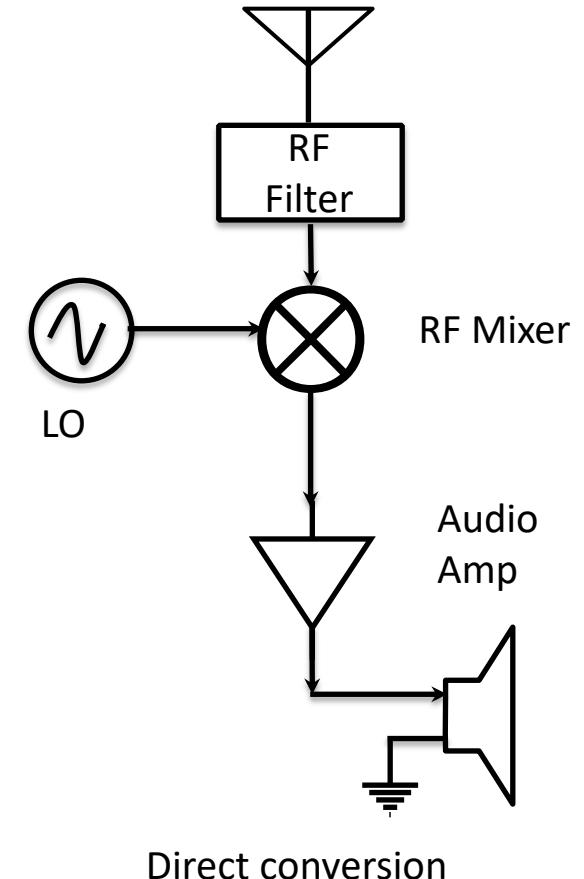
# Exercise 9: Parallel resonance

- $L = A_l N^2, A_l = 4 \frac{nH}{turn^2}$  for T37-2 core so for 28 turns,  $L = 3.1\mu H$
1. Find the resonant frequency, the frequencies corresponding to a 3db falloff, the bandwidth and the Q of this circuit. This circuit is in the transmit oscillator.
    - At tuned resonance (7MHz), effective capacitance is about 167 pF
    - $Q_p = \omega_0 RC$
    - For  $R = 1500\Omega$ , network:  $Q = 1500 \times 44 \times 10^6 \times 1.67 \times 10^{-10} = 11$
    - $BW = \frac{f_r}{Q} = \frac{7MHz}{11} = .636MHz$ .  $f_u = f_r + \frac{BW}{2} = 7.318MHz$ ,  $f_l = f_r - \frac{BW}{2} = 6.682MHz$ . This is 3dB cutoff.
    - General formulas:  $BW = \frac{f_r}{Q}, f_u = f_r + \frac{BW}{2}, f_l = f_r - \frac{BW}{2}$

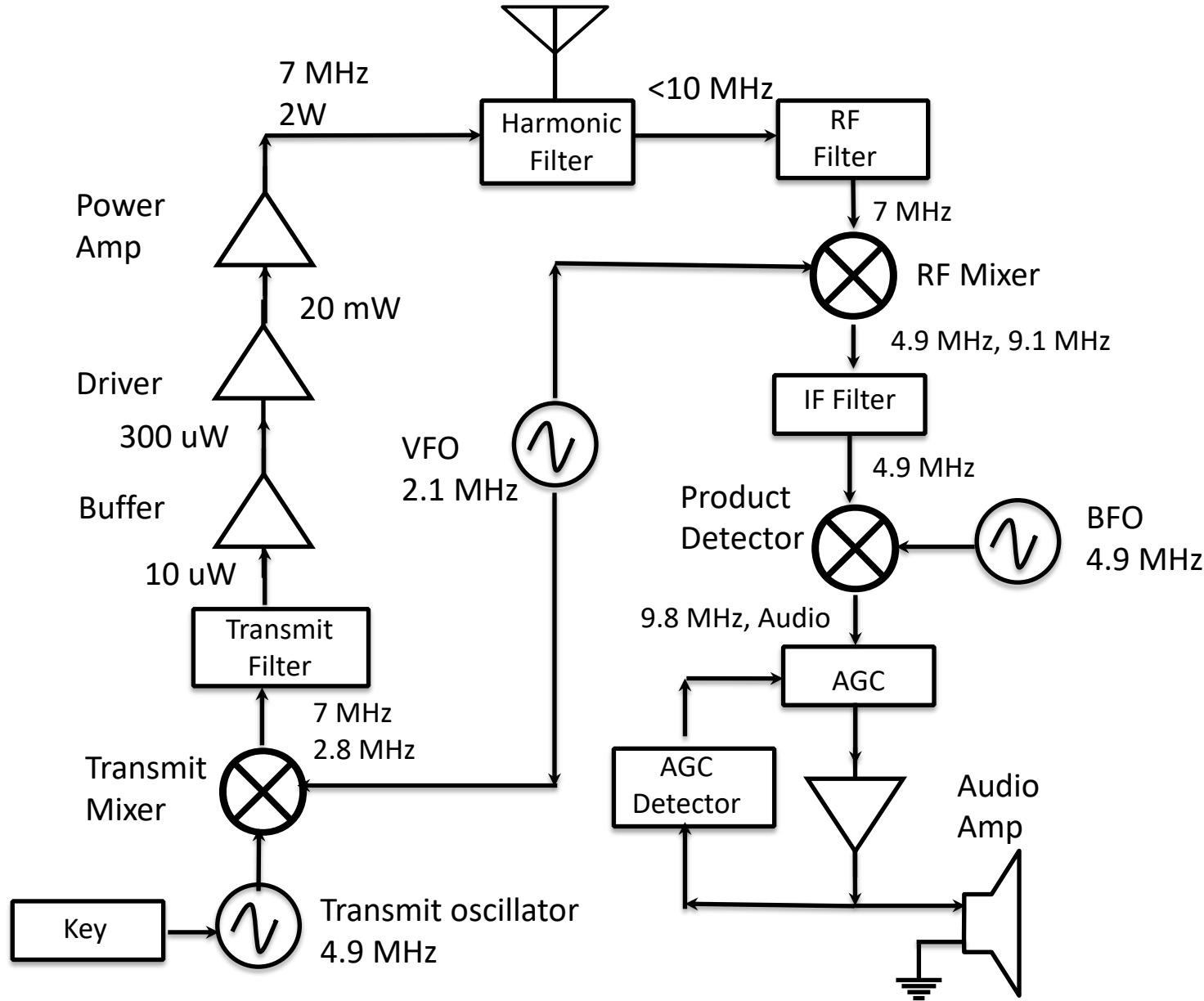


# Direct conversion and superhet receivers

- Image frequency
  - $\omega_{rf} = \omega_{LO} - \omega_a$
  - $\omega_i = \omega_{LO} + \omega_a$
- Superheterodyne designs
  - $\omega_{rf} = \omega_{IF} + \omega_{VFO}$
  - $\omega_{vi} = \omega_{IF} - \omega_{VFO}$
  - $\omega_{IF} = \omega_{BFO} - \omega_a$
  - $\omega_{bi} = \omega_{BFO} + \omega_a$
  - $\omega_{usb} = \omega_{VFO} + \omega_{BFO} + \omega_a$
  - $\omega_{lsb} = \omega_{VFO} + \omega_{BFO} - \omega_a$

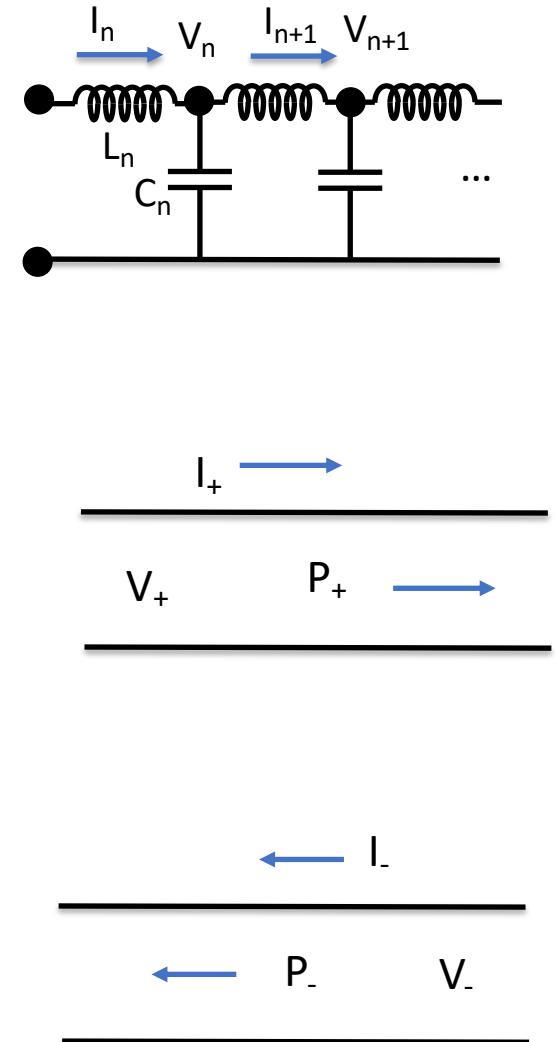


# Norcal 40A



# Transmission Lines

- $V_{n+1} - V_n = -L_l \frac{\partial I_{n+1}}{\partial t}, L = \frac{L_l}{l}$
- $I_{n+1} - I_n = -C_l \frac{\partial V_n}{\partial t}, C = \frac{C_l}{l}$
- $\frac{\partial^2 V}{\partial z^2} = LC \frac{\partial^2 V}{\partial t^2}$  and  $\frac{\partial^2 I}{\partial z^2} = LC \frac{\partial^2 I}{\partial t^2}$
- Solution is  $V(z - vt), v = \frac{1}{\sqrt{LC}}$ , which is the velocity for the forward wave
- $\frac{\partial V}{\partial z} = -L \frac{\partial I}{\partial t}$  and  $\frac{\partial I}{\partial z} = -C \frac{\partial V}{\partial t}$  implies
- $V' = vLI'$ ,  $\frac{V}{I} = \sqrt{\frac{L}{C}}$ ,  $Z_0 = \sqrt{\frac{L}{C}}$ ,  $Z_0$  is the forward or “characteristic” impedance
- Another solution is  $V(z + vt), v = \frac{1}{\sqrt{LC}}$  which is the velocity for the reverse wave
- $Z_0 = \frac{V_+}{I_+}$ ,  $-Z_0 = \frac{V_-}{I_-}$ ,  $V = V_+ + V_-$ ,  $-Z_0$  is the backwards looking impedance
- $P_+(t) = \frac{V_+^2}{Z_0}$ ,  $P_-(t) = -\frac{V_-^2}{Z_0}$



# Transmission Lines - continued

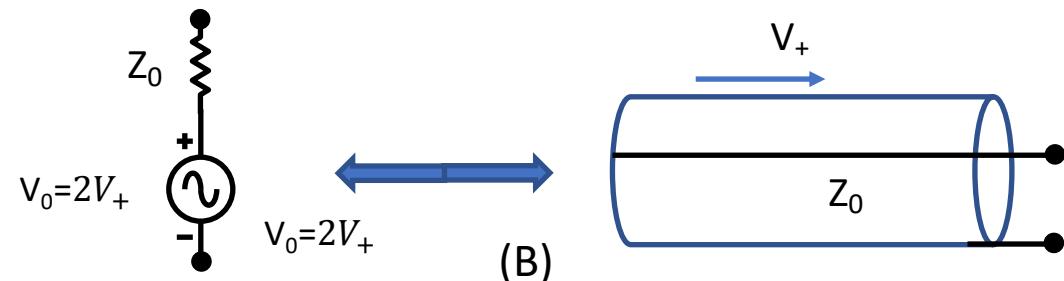
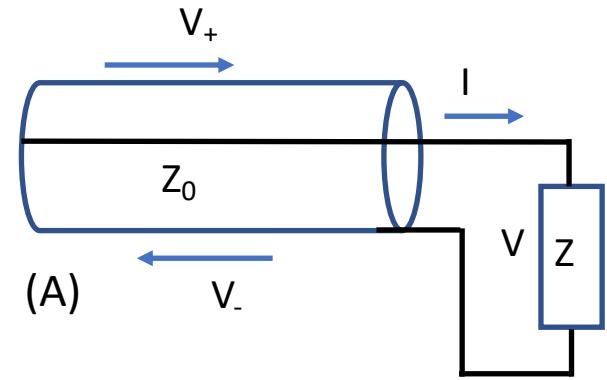
- $V(z - vt) = A \cos(\omega t - \beta z)$ ,  $v = \frac{\omega}{\beta}$ ; in phasor notation,  $V = Ae^{-j\beta z}$ .
- To compute power, let  $V_+ = Ae^{-j\beta z}$ ,  $V_- = Ae^{j\beta z}$
- Complex power is  $P_{av} = \frac{V\bar{I}}{2}$ ,  $P_+ = \frac{V_+\bar{I}_+}{2} = \frac{|V_+|^2}{2Z_0}$ ,  $P_- = \frac{V_-\bar{I}_-}{2} = -\frac{|V_-|^2}{2Z_0}$ , with  $\frac{V}{I} = Z_0$
- Suppose over a transmission line,  $Z$  is the distributed impedance/m,  $Y$  is the distributed admittance/m and suppose the forward wave is  $Ae^{j(\omega t - jk)}$ , and its phasor is  $V = Ae^{-jkz}$ . Let  $Z = \frac{V}{I}$ ,
- $\frac{dV}{dz} = -ZI$ ,  $\frac{dI}{dt} = -YV$ . ... (1)
- Put  $jk = \alpha + \beta j$  (to account for attenuation), then  $jk = \sqrt{ZY}$  and the forward phasor becomes  $e^{(-\alpha z - j\beta z)}$ .  $\alpha_{dB/m}$  is a transmission loss.  $\alpha_{dB/m} = 8.686\alpha_{nepers/m}$ . By differentiating (1), we get  $jkV = ZI$ ,  $-jkI = YV$ . Solutions are  $jk = \sqrt{ZY}$ ,  $Z_0 = \frac{V}{I} = \sqrt{\frac{Z}{Y}}$ , all complex
- Example: If  $Z = R + j\omega L$ ,  $Y = j\omega C + G$  for the transmission line, then  $jk = \sqrt{(j\omega L + R)(j\omega C + G)}$  and  $Z_0 = \sqrt{\frac{(j\omega L + R)}{(j\omega C + G)}}$  (positive real root)

# Transmission Lines - dispersion

- $\alpha$  and  $v$  can vary with frequency; this is dispersion.
- Heaviside: Adjust parameters so  $\frac{R}{L} = \frac{G}{C}$ , then  $\alpha$  and  $v$  are constants and we get:
  - $jk = j\omega\sqrt{LC}(1 + \frac{R}{j\omega L})$  and  $v = \frac{\omega}{\beta} = \frac{1}{\sqrt{LC}}$ ,  $\alpha = \sqrt{RG}$
  - We also get  $Z_0 = \sqrt{\frac{L}{C}}$  as with a lossless line.
  - If  $\omega L \gg R$ 
    - $G = 0$  and  $Z_0 = \sqrt{\frac{(j\omega L+R)}{j\omega C}} \approx \sqrt{\frac{L}{C}}$
    - If  $R \gg \omega L$ 
      - $jk = \sqrt{\frac{(j\omega L+R)}{j\omega C}} \approx \sqrt{j\omega RC}$ , and  $\alpha = \sqrt{\frac{\omega RC}{2}}$ ,  $\alpha = \sqrt{\frac{2\omega}{RC}}$
- For first transatlantic cable,  $L = 460 \frac{nH}{m}$ ,  $C = 75 \frac{pF}{m}$ ,  $f = 12Hz$ ,  $R = 7 \frac{m\Omega}{m}$ ,  $l = 3600 km$ ,  $\alpha = \sqrt{\frac{\omega RC}{2}} = 4.4 \times 10^{-3} nepers/m$ ,  $\alpha l = 140dB$ 
  - $\alpha l \approx 140dB$  and highly dispersive

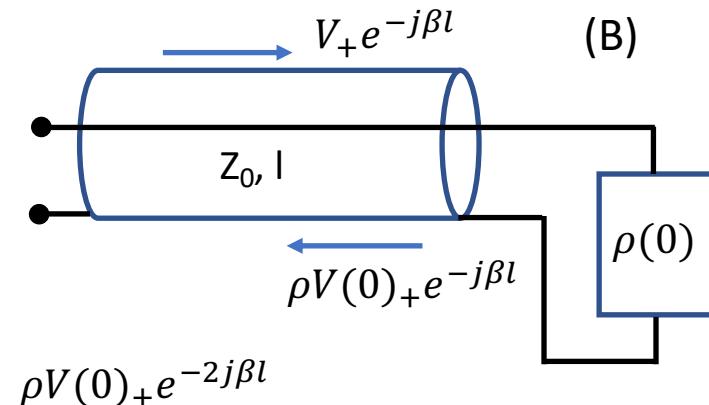
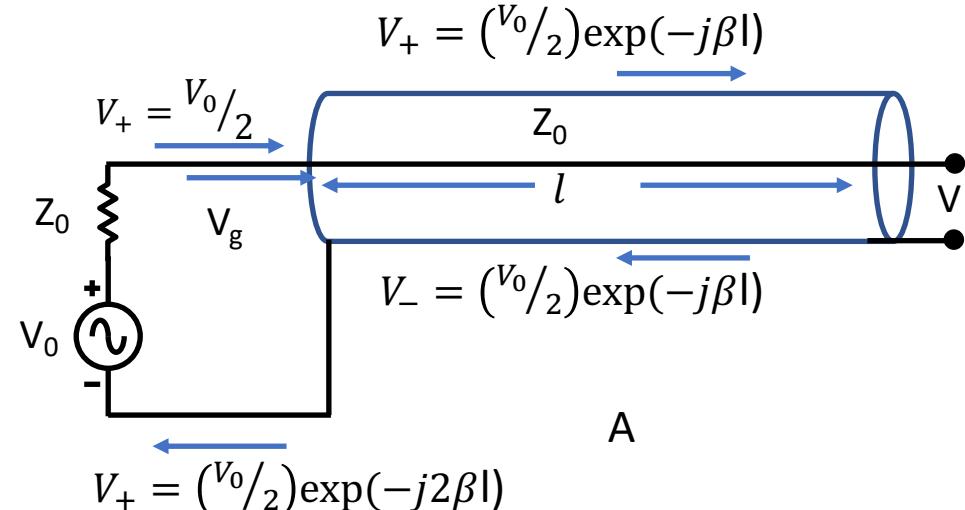
# Transmission Lines-reflections

- $\rho = \frac{V_-}{V_+}$ ,  $\rho V_+ = V_-$ ,  $V = V_+ + V_- = (1 + \rho)V_+$
- $\rho_i = \frac{i_-}{i_+} = -\rho$
- $\tau = \frac{V}{V_+} = 1 + \rho = \frac{2Z}{Z+Z_0}$ ,  $V = 2V_+$
- Consider the circuit in the upper right (A):  $V = V_+ + V_-$ ,  $I = I_+ + I_-$ ,  $Z = \frac{V}{I}$
- $Z = \frac{V}{I} = \frac{V_+ + V_-}{I_+ + I_-}$
- $\frac{Z}{Z_0} = \frac{1+\rho}{1-\rho}$ ,  $\rho = \frac{Z-Z_0}{Z+Z_0}$ ,  $\rho_{open-circuit} = 1$ .
  
- For (B):
- Lookback resistance is  $R_s = Z_0$ , short circuit for (B) is  $i_s = \frac{V_0}{Z_0}$
- Thevenin equivalent for open circuit is (B)
- $P_+ = \frac{V_+^2}{2Z_0} = \frac{V_0^2}{8R_s}$ , This is the total available power



# Transmission Lines – resonance and Q

- For (A) on right,  $V_+ = \frac{V_0}{2}$ ,  $V = V_+ + V_- = V_0 e^{-j\beta l}$ ,  $V_- = \frac{V_0}{2} e^{-2j\beta l}$ 
  - $V_g = V_0 e^{-j\beta l} \cos(\beta l) = \frac{V_0}{2} (1 + e^{-2j\beta l})$ ,  $V_g(\frac{\lambda}{4}) = 0$
  - $I_g = \frac{V_+ - V_-}{Z_0} = jI_s e^{-j\beta l} \sin(\beta l)$ .
  - $X = \frac{V_g}{jI_g} = \frac{Z_0}{\tan(\beta l)}$
- $Q = \omega \frac{E}{P_a}$ ,  $E = \frac{lP_+}{v}$ ,  $P_a = P_+ - P_+ e^{-2\alpha l} \rho(0) \approx 2\alpha l P_+$ ,  $Q = \frac{\beta}{2\alpha}$
- In (B) to the right, the coefficient of reflection is  $\rho(0)$  and the generator absorbs the reverse wave.  $V = V_+ + V_- = V_0 e^{-j\beta l}$ .
  - $V_f = \rho(0)V_+e^{-j\beta l}$ ,  $V_r = \rho(0)V_+e^{-2j\beta l}$
  - $\rho(l) = \frac{V_-}{V_+} = \rho(0)e^{-2j\beta l}$  is the reflection coefficient at generator.
  - $\rho(\frac{\lambda}{2}) = \rho(0)$ ,  $\rho(\frac{\lambda}{4}) = -\rho(0)$
  - $\frac{Z(\lambda/4)}{Z_0} = \frac{Z_0}{Z(0)}$ ,  $Z = \frac{Z}{Z_0}$ ,  $y = \frac{1}{z}$ ,  $Z(\frac{\lambda}{4}) = -\frac{1}{z(0)}$
  - Normalized:  $Z(\lambda/4) = \frac{1}{z(0)}$
  - $Z_0 = \sqrt{Z(\lambda/4)Z(0)}$ ,  $Z_0 = \sqrt{R_S R_L}$



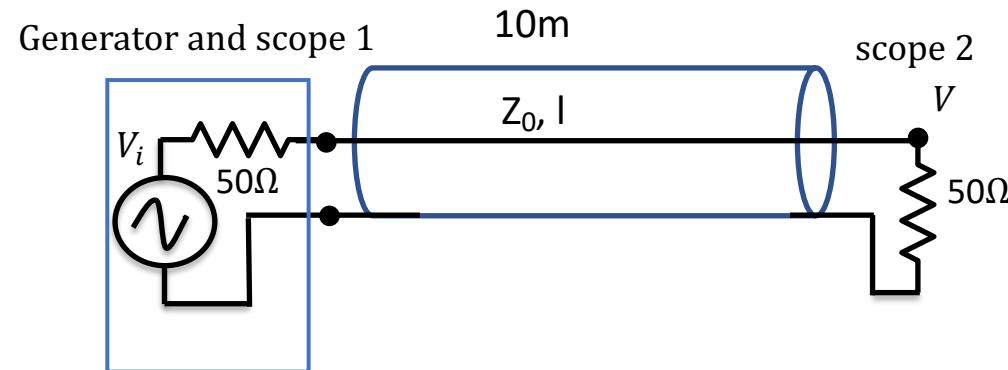
# Exercise 10: Coax

- We'll measure the velocity of waves in RG58U by connecting one channel of the scope to the input and one to the output.

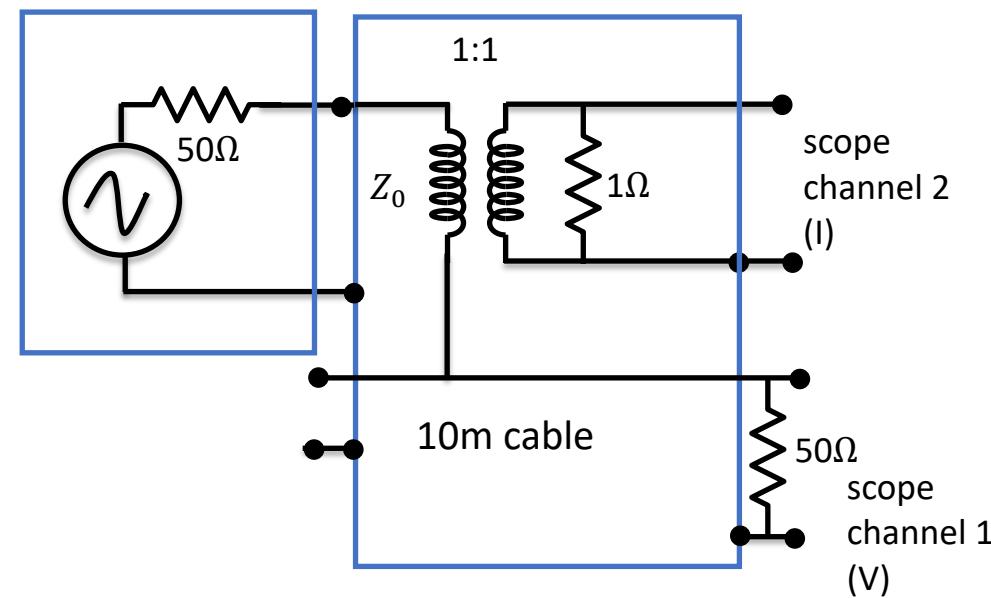
- Measure the velocity,  $v$ , in 10m coax at 7MHz. Try different frequencies. Use  $50\text{ns}$ ,  $5V_{pp}$  using square waves at 20kHz.

Ans: about  $\frac{2}{3}c$

- Do the same with an antenna.
- Calculate  $Z_0$  with  $50\Omega$  termination for the circuit on the right.
- Remove the  $50\Omega$  and measure the  $V$  and use it and  $Z_0$  to calculate  $L$ , and  $C$  for the coax
  - Measured speed is  $v = 2 \times 10^8 \text{ m/s}$ .  $Z_0 = 50\Omega$ . For high impedance,  $Z_0 = \sqrt{\frac{L}{C}}$  and  $v = \frac{1}{\sqrt{LC}}$ . So,  $Z_0^2 C = L$  and  $v^2 = \frac{1}{LC}$ , so  $Z_0^2 C^2 v^2 = 1$ .  $C = \frac{1}{Z_0 v} = 10^{-10} \text{ F}$ .  $2500 \times 10^{-10} \text{ F} = L = 250 \text{ nH}$ , which is what we use in the next problem.

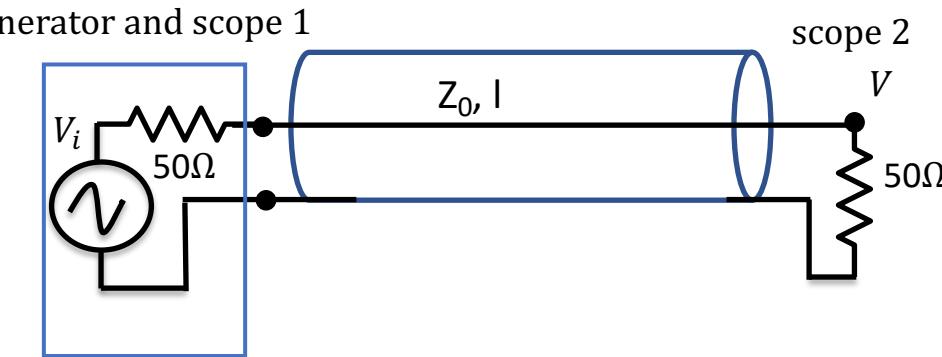


Function generator



# Exercise 11: Waves

- Suppose we want to send voice over 100km of coax,  $Z_L = 50\Omega$ ,  $l = 100\text{km}$ .
- Measure the SWR which is the ratio of the maximum to minimum output
    - $V = V_+ + V_-$ ,  $\rho = \frac{Z - Z_0}{Z + Z_0}$ ,  $Z = 50\Omega$ , we get  $Z_0$  from the previous exercise.
    - $|V_{max}| = |V_f| + |V_r| = (1 + \rho)|V_f|$ ,  $|V_{min}| = (1 - \rho)|V_f| = |V_f|$ .  $SWR = \frac{|V_{max}|}{|V_{min}|} = \frac{1 + \rho}{1 - \rho}$ ,
  - If  $L = 250 \frac{nH}{m}$ ,  $C = 100\text{pf}/m$  and the distributed resistance at voice is  $50 \text{ m}\Omega/m$ , calculate total dB loss at 500, 1000 and 2000Hz using the high frequency approximation.
    - $Z(f) = j\omega L + R = 50 \times 10^{-3} + j \cdot 2\pi f \cdot 250 \times 10^{-9}$
    - $Y(f) = j\omega C + \frac{1}{R} = \frac{1}{50 \times 10^{-3}} + j 2\pi f \cdot 10^{-10}$
    - $Z_0(f) = \sqrt{\frac{Z(f)}{Y(f)}}$
    - $Z_0(500) = 400\Omega$ ,  $Z_0(1000) = 282\Omega$ ,  $Z_0(500) = 200\Omega$ ,
    - High resistance approximation:  $\alpha(f) = \sqrt{\frac{\omega RC}{2}}$ ,
    - $\alpha(500) = 8.8 \times 10^{-5}$ ,  $\alpha(1000) = 12.6 \times 10^{-5}$
    - $\alpha(2000) = 17.6 \times 10^{-5} \times 10^5$
    - For 100km, loss is  $\alpha \times 10^5$



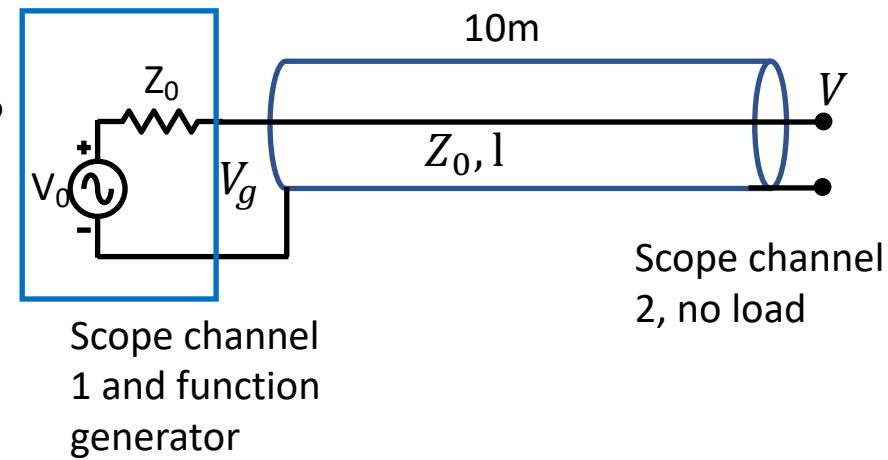
# Exercise 11: Waves

3. Add a 100mH inductor every 1km. Now what's the loss?

- $Z(f) = j\omega L + R = 50 \times 10^{-3} + j \cdot 2\pi f \cdot 10^{-4}$ ,  $Z_0(f) = \sqrt{\frac{Z(f)}{Y(f)}}$
- $Z_0(f) = \sqrt{\frac{Z(f)}{Y(f)}}$
- $Z_0(500) = 318\Omega$ ,  $Z_0(1000) = 317\Omega$ ,  $Z_0(2000) = 316\Omega$
- High reactance approximation:  $\alpha(f) = \frac{R}{2Z_0}$ ,  $Z_0 = \sqrt{\frac{L}{C}} = 1000\Omega$
- $\alpha(f) = \frac{R}{2Z_0(f)}$ ,  $\alpha(500) = \alpha(1000) = \alpha(2000) = \frac{5 \times 10^{-2}}{2000} = 5.5 \times 10^{-5}$  nepers/m
- For 100km, loss is  $\alpha \times 10^5 = 5.5$  or  $5.5 \times 8.868 \approx 49dB$

# Exercise 12: Resonance

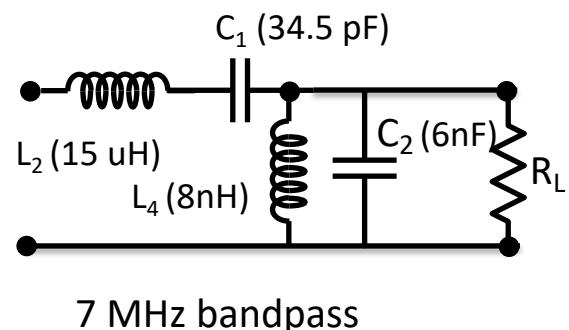
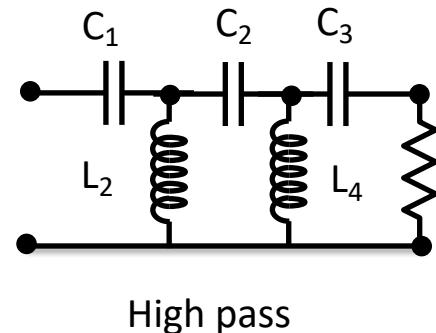
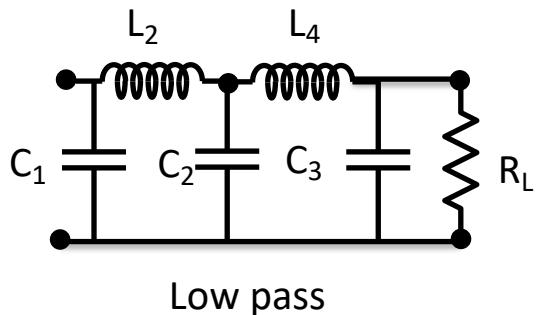
- RG58U has a capacitance of about  $100 \frac{pF}{m}$ . Let  $\alpha$  be the attenuation constant and  $\beta$  be the phase
1. Derive an expression for  $|\frac{V_g}{V}|$  and assuming  $\alpha$  is small by finding the first resonance where  $V_g$  is minimum.
    - $V_g = V_0 e^{-j\beta l} \cos(\beta l)$ ,  $V = V_0 \exp(-j\beta l)$ .  $|\frac{V_g}{V}| = \cos(\beta l)$ . So, at  $l = \frac{\lambda}{2}$ ,  $|V_g| = |V|$
  2. Find  $\alpha$  and the wave velocity by finding the resonant frequency (without the load,  $1V_{pp}$ ) and noting the time delay with a scope on the input and output. Use  $|\frac{V_g}{V}|$  to calculate  $\alpha$ .
    - $|V|$  will be maximum at resonant frequency with unterminated line.
    - $|V_g(l)|$  is minimum when  $l = \frac{\lambda_r}{4}$  and  $\beta l = \frac{\pi}{4}$ . This gives  $\beta$ .
    - At  $l = \frac{\lambda}{2}$ ,  $|\frac{V_g}{V}| = e^{-\alpha(\lambda/2)}$
  3. Use this to calculate the velocity,  $v$ . How large is the frequency shift caused?
    - $v = \frac{\omega_r}{\beta}$ . [ $v$  should be about  $2 \times 10^8$  m/s]
  4. Find, as usual,  $f_u$ ,  $f_l$ , and  $Q$ .
    - $Q = \frac{\beta}{2\alpha}$
    - $Q = \frac{f_r}{BW}$ , so  $BW = \frac{f_r}{Q}$ .  $f_u = f_r + \frac{BW}{2}$ , and  $f_l = f_r - \frac{BW}{2}$



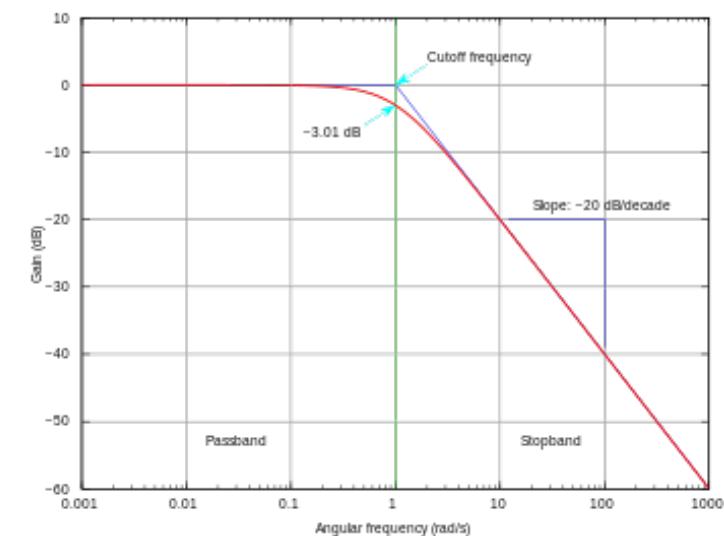
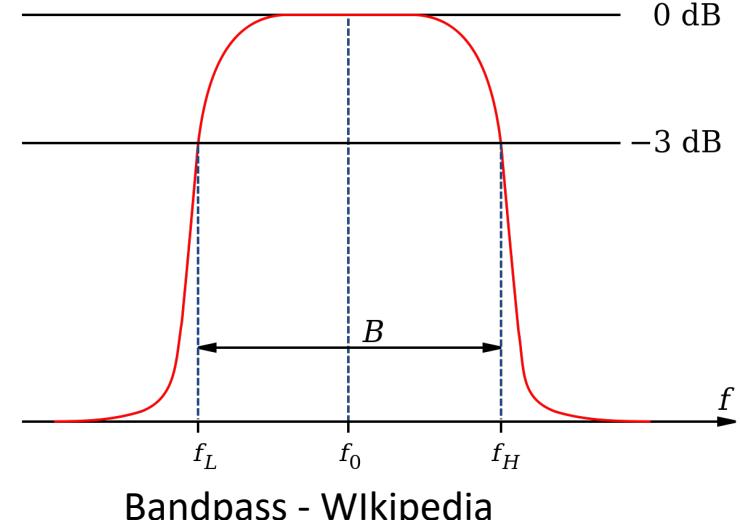
Scope channel  
1 and function  
generator

Scope channel  
2, no load

# Filters

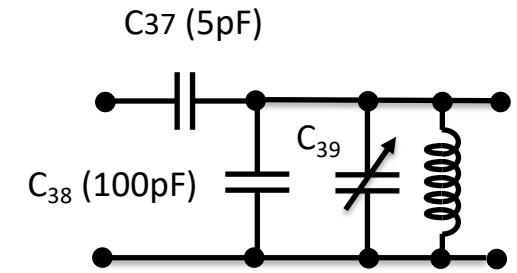


- Circuits on the left are called ladder filters.
- Low pass (Butterworth equivalent): Tabled values for inductors and capacitors based on frequency and dB drop-off.
- Can convert low pass into bandpass.
- For low pass to high pass
- Butterworth:  $L = \frac{P_i}{P} = 1 + (\frac{f}{f_c})^{2n}$ ,  $f_c$  is 3dB cutoff
- Chebyshev:  $L = 1 + \alpha C_n^2 (\frac{f}{f_c})^{2n}$ ,  $f_c$  is 3dB cutoff
- Normalized reactance's:  $a_i = \sin(\frac{(2i-1)\pi}{2n})$
- Ripple loss:  $1 + \alpha = 10^{\frac{L_r}{10}}$
- $\beta = \sinh(\frac{\tanh^{-1}(1/\sqrt{1+\alpha})}{n})$ ,  $c_i = \frac{a_i a_{i-1}}{c_{i-1}(\beta^2 + \sin^2((i-1)\pi/n))}$
- Example: cutoff at 10MHz, 4<sup>th</sup> order, 50ohm output, 3dB cutoff,  $L(20MHz) = 6n = 24dB$ ,  $a_1 = 0.765$ ,  $X_1 = x_1 Z_0 = 38\Omega$ ,  $L_1 = \frac{X_1}{\omega_c} = 610nH$ ,  $b_2 = a_2 = 1.848$ ,  $B_2 = b_2/Z_0$ ,  $C_2 = B_2/\omega_c$
- Yuck!



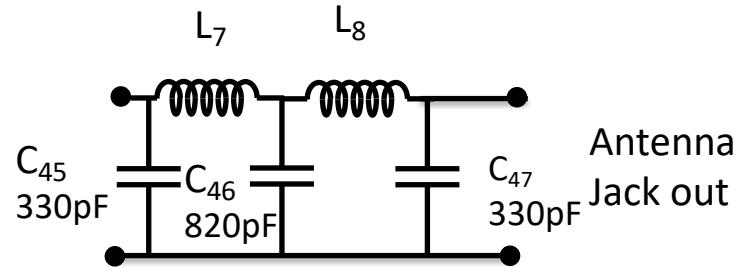
# Norcal transmit bandpass filter

- $C_{39} = 50\text{pF}$ ,
- $L_6$  is 36 turns #28 on T37-2 which has  $A_l = 4 \frac{nH}{\text{turn}^2}$ ,  $L_6 = A_l \cdot 36^2 = 3.1\mu\text{H}$
- $Z_2 = -\frac{j}{(C_{38}+C_{39})\omega_0}$ ,  $Z_3 = jL_6\omega_0$ ,  $Z_1 = \frac{j}{C_{37}\omega_0}$
- $Z_{2,3-eq} = \frac{jL_6\omega_0}{L_6(C_{38}+C_{39})\omega_0^2-1}$
- Resonance is when  $Z_{2,3-eq} \rightarrow \infty$ ,  $\omega_0^2 = \frac{1}{(C_{38}+C_{39})L_6} \approx \frac{10^{18}}{465}$ , when almost all the voltage drop is across  $Z_{2,3-eq}$   $\omega_0 = \frac{10^9}{\sqrt{465}} \approx 50.8 \times 10^6$ ,  $f_0 = \frac{\omega_0}{2\pi} \approx 7.1 \text{ MHz}$
- Q of filter is:  $Q_s = \frac{X_s}{R_s}$ .  $R_s$  comes from the other components and must be measured
- Note that  $Z_{2,3-eq}$  is small for the other modulation product



# Exercise 13: Norcal Harmonic Filter

- $L_7, L_8$  use T37-2 core, 18 turns,  $1.3\mu\text{H}$ . Use  $50\Omega$  termination and set function generator at  $10V_{\text{pp}}$ .
  1. Compute and compare loss at 7MHz and 14MHz.
  2. From  $A_l = 5nH/\text{turn}^2$ , calculate  $L_7$  and  $L_8$ .
  3. What is the spur strength at 7, 14 and 28MHz? Measure and calculate.
- Need Puff (a simulator) to get losses. However, answer is there is a 6dB drop-off at every frequency doubling

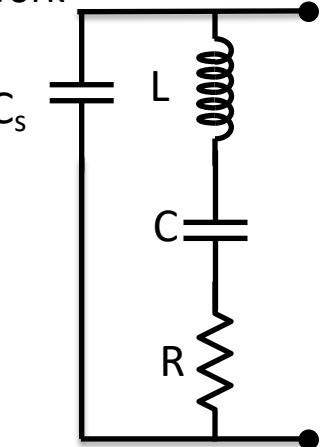
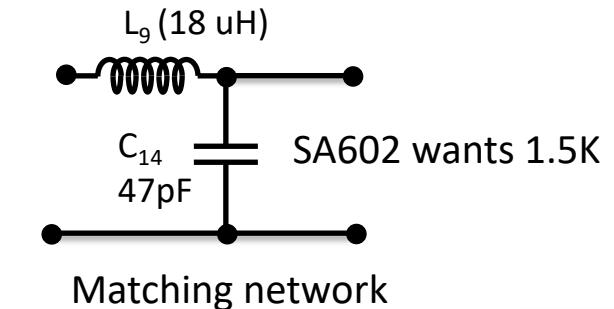
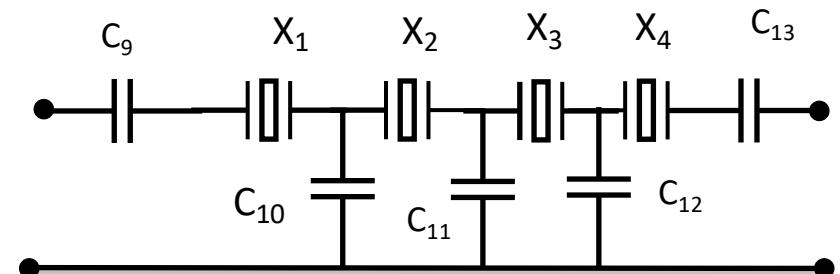


# Exercise 14: Norcal IF Cohn Filter

- $X_1$  through  $X_4$  are 4.91 MHz
- $C_{10}, C_{11}, C_{12}$  are 270 pF
- Set function generator to 50mV<sub>pp</sub> from function generator
- Calculate R and X for filter

1. Measure the resonant frequency of one of the crystals
  - Duh
2. Calculate the parameters of the crystal. Omitting  $C_s$

- $f_r = \frac{1}{2\pi\sqrt{LC}}$  and  $Q = \frac{1}{R} \sqrt{\frac{L}{C}}$ . We can measure  $f_r$  and find Q using the 3dB bandwidth.  $R$  is the resistance at resonance.
- $Q \approx 80$
- $25\Omega < R < 100\Omega$
- If  $R = 50$ ,  $C = 8.1\text{pF}$ ,  $L = 130\mu\text{H}$



Equivalent circuit for crystal

# Transformers

- For solenoid,  $\oint B \cdot ds = \mu_0 nI$  inside
- $LI = \Phi_B$ . Since there are  $n$  turns in the solenoid, over the solenoid,  $LI = \mu_0 n^2 I$ , so  $L = \mu_0 n^2$ .
- This is the source of  $L = A_l n^2$
- $V_s = \frac{N_s}{N_p} V_p$
- $Z_p = \left(\frac{N_p}{N_s}\right)^2 Z_s$

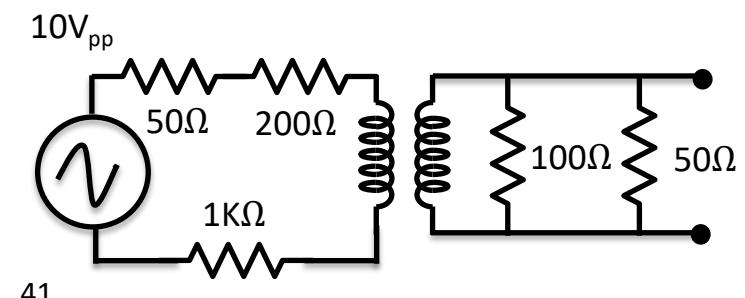
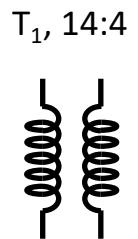
# Exercise 15: Norcal Driver Transformers (1)

- $T_1$  uses FT 37-43.  $L(\mu H) = \frac{A_L t^2}{1000}$ ,  $A_L = 350$ .  $f_r = 7 \times 10^6 MHz$ ,  $n_p = 14$ ,  $n_s = 4$ ,  $\omega_r = 2\pi \times 7 \times 10^6 MHz = 4.4 \times 10^7$

1. Measure the output  $V_{out}$ .

2. Calculate  $V_{out}$

- $L_p = 68.6 \mu H$ ,  $L_s = 5.6 \mu H$
- $Z_{eq,in}(\omega) = 1250 + j(\omega L_p)$ ,  $Z_{eq,in}(\omega_r) = 1250 + 3016j$ ,  $|Z_{eq,in}(\omega_r)| = 3264$
- $Z_{eq,out}(\omega) = 33 + j\omega L_s$ ,  $Z_{eq,out}(\omega_r) = 33 + j246$ ,  $|Z_{eq,out}(\omega_r)| = 248$
- $V_{t,in} = \frac{3016}{3264} V_{in}$
- $V_{out} = V_{t,out} = \frac{n_s}{n_p} V_{t,in} = .29 V_{t,in} = .29 \times \frac{3016}{3264} \times 5 = 1.3V$
- $i_p(\omega) = \frac{V_{in}}{|Z_{eq,in}|} e^{j\theta_p(\omega)}$ ,  $\theta_p(\omega) = \arctan\left(\frac{\omega L_p}{1250}\right)$ ;  $i_s(\omega) = \frac{V_{out}}{|Z_{eq,out}|} e^{j\theta_s(\omega)}$ ,  $\theta_s(\omega) = \arctan\left(\frac{\omega L_s}{33}\right)$ .
- $P_{in,a} = Re\left(\frac{V_{in}\overline{I_{in}}}{2}\right) = Re\left(\frac{V_{in}^2}{2|Z_{eq,in}(\omega)|}\right) e^{j\theta_p(\omega)}$
- $P_{out,a} = Re\left(\frac{V_{out}\overline{I_{out}}}{2}\right) = Re\left(\frac{V_{out}^2}{2|Z_{eq,out}(\omega)|}\right) e^{j\theta_s(\omega)}$

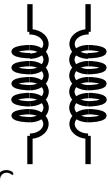


# Exercise 15: Norcal Driver Transformers (2)

- $\cos(\theta_s(\omega_r)) = .13, \cos(\theta_p(\omega_r)) = .38,$
  - $\frac{P_{out,a}(\omega_r)}{P_{in,a}(\omega_r)} = \left(\frac{V_{out}}{V_{in}}\right)^2 \frac{|Z_{eq,in}(\omega_r)|}{|Z_{eq,out}(\omega_r)|} \frac{\cos(\theta_s(\omega_r))}{\cos(\theta_p(\omega_r))} = \left(\frac{1.3}{5}\right)^2 \times \frac{3264}{248} \times \frac{.13}{.38} = .3$
3. Measure the 3dB cutoff,  $f_c$ .
- $\frac{P_{out,a}(\omega)}{P_{in,a}(\omega)} = \left(\frac{V_{out}}{V_{in}}\right)^2 \frac{|Z_{eq,in}(\omega)|}{|Z_{eq,out}(\omega)|} \frac{\cos(\theta_s(\omega))}{\cos(\theta_p(\omega))} = .15$

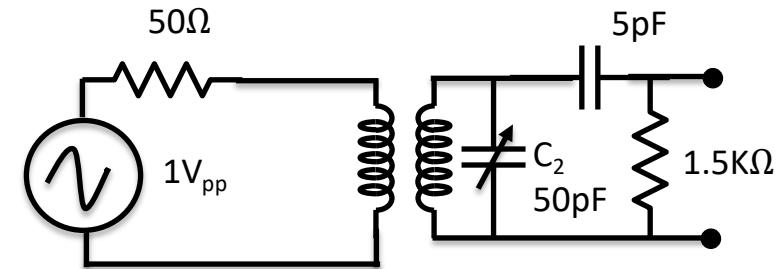
# Exercise 16: Norcal Tuned Transformers

$T_2, 1:20$



- $T_2, T_3$  are IF matchers using FT 37-61.  $A_L = 55 \text{ nH/turn}^2$ .

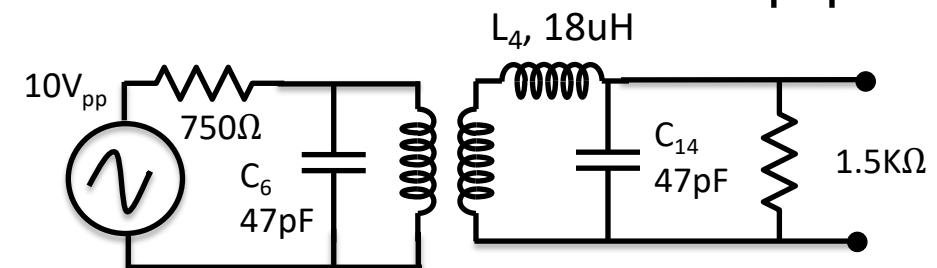
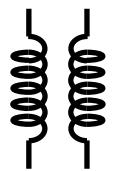
- Measure 3dB bandwidth
- Find  $P/P_+$



$T_2$

- $P_a = Re\left(\frac{VI}{2}\right)$ ,  $V = V_+ + V_-$ ,  $\rho = \frac{V_+}{V_-} = \frac{Z - Z_0}{Z + Z_0}$ ,  $Z$  is look forward,  $Z_0$  is look back resistance.  $P_+ = \frac{V_+^2}{2Z_0}$ .  $L_{in} = 55\text{nH}$ ,  $L_{out} = 22\mu\text{H}$ ,  $\omega = 4.4 \times 10^7$
- $Z = 50 + 2.4j$ ,  $Z_0 = 203 - 4030j$ ,  $\rho = 1$ , so  $V_+ = V_-$ ,  $V = 2V_+$
- $\frac{P}{P_+} = \frac{1}{4}$
- Similar calculation for  $T_3$ .

$T_3, 23:6$



# Acoustics

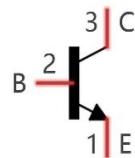
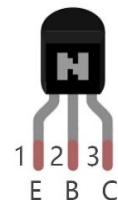
- $P = P_0 + P_e, \rho = \rho_0 + \rho_e$
- 1. Gas moves and changes density: Displacement of undisturbed air is  $x$ . At time  $t$ , it's at  $x + \chi(x, t)$ , so  $\rho_0 \Delta x = \rho(x + \Delta x + \chi(x + \Delta x, t) - x - \chi(x, t))$ , or  $\rho_0 \Delta x = \rho(\frac{\partial \chi(x, t)}{\partial x} \Delta x + \Delta x)$ . So,  $\rho_e = -\rho_0 \frac{\partial \chi}{\partial x}$
- 2. Change in density causes change in pressure:  $P = f(\rho), P_0 + P_e = f(\rho_0 + \rho_e) = f(\rho_0) + \rho_e f'(\rho_0), f'(\rho_0) = \kappa = (\frac{dP}{d\rho})_0$ , or  $P_e = \kappa \rho_e$
- 3. Pressure differences cause motion:  $P(x, t) - P(x + \Delta x, t) = -\frac{\partial P_e}{\partial x} \Delta x$ , Newton's law gives  $\rho_0 \frac{\partial^2 \chi}{\partial t^2} = -\frac{\partial P_e}{\partial x} = -\kappa \frac{\partial \rho_e}{\partial x}$
- Substituting (1) into (3) gives  $\frac{\partial^2 \chi}{\partial t^2} = \kappa \frac{\partial^2 \chi}{\partial x^2}$ , put  $\kappa = \frac{1}{c_s^2}$
- Solution is  $\chi(x, t) = f(x - vt)$  [Different  $f$  than above].
- To find,  $\kappa = (\frac{dP}{d\rho})_0$ , note that the flow is adiabatic so  $PV^\gamma = C'$  and  $\rho$  varies inversely as  $V$ , so  $P = \rho^\gamma C$ , and finally, using  $PV = Nkt$ ,  $\kappa = (\frac{dP}{d\rho})_0 = \frac{\gamma k T}{n}$
- $L_p = 20 \log(\frac{P}{P_0}), P_0 = 20 \mu Pa$

Sound	$L_p$	Power density
rustling leaves	10dB	1pW/m <sup>2</sup>
broadcast studio	20dB	1pW/m <sup>2</sup>
classroom	50dB	10nW/m <sup>2</sup>
heavy truck	90dB	1nW/m <sup>2</sup>
Shout at 1m	100dB	10mW/m <sup>2</sup>
jackhammer	110db	100mW/m <sup>2</sup>
jet takeoff at 50m	120dB	1W/m <sup>2</sup>

# Bipolar Transistors - I

- NPN Model

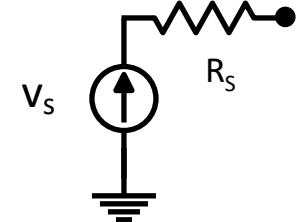
- $V_f \approx .7V, V_s \approx .2V$
- Conducts when  $V_{be} > V_f$
- $i_c = \beta i_b$
- $i_c = \alpha i_e$
- $\beta = \frac{\alpha}{1-\alpha}$  [=  $h_{fe}$ , small signal]
- $\beta \approx 100, \beta_r \approx 10$
- $r_e i_e = 25mV, r_b = (1 + \beta)r_e, r_e \approx 33\Omega$
- $i_b = \frac{v_{be}}{(1+\beta)r_e}$
- $g_m v_{be} = g_m r_b i_b$



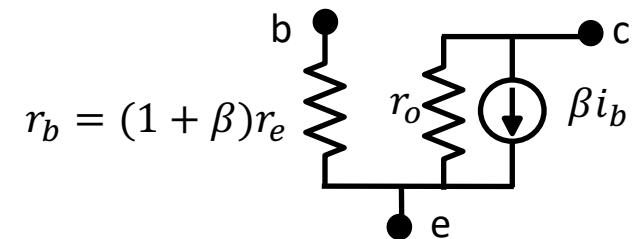
- Switch

- $G_s = \frac{i_b}{15mV}$
- $R_s = 2\Omega$

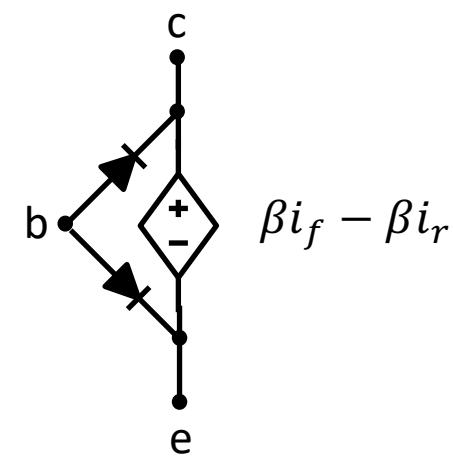
	$V_{be}$	$V_{bc}$	$V_{ce}$	$i_c$
active	$V_f$	$< V_f$	$> V_s$	$\beta i_b$
rev saturated	$< V_f$	$V_f$	$< -V_s$	$-(\beta_r + 1)i_b$
saturated	$V_f$	$V_f$	$V_s > V_{ce} > -V_s$	$> -(\beta_r + 1)i_b$ $< \beta i_b$
cutoff	$< V_f$	$< V_f$	*	0



Bipolar source model



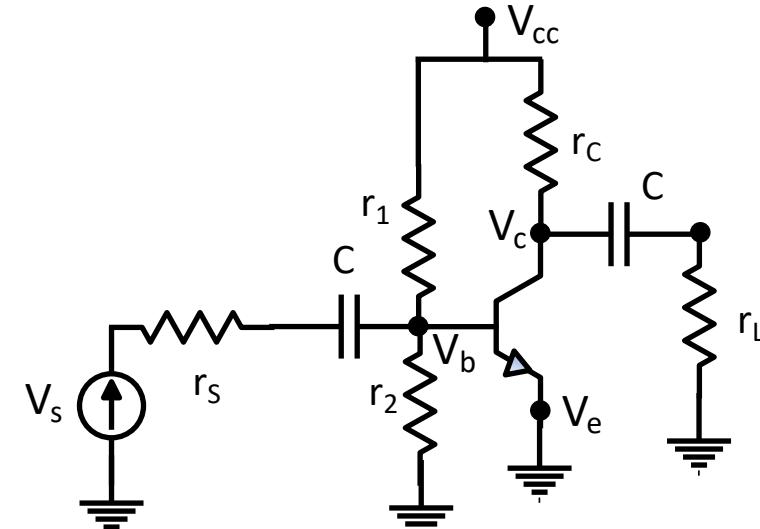
Bipolar equivalent circuit



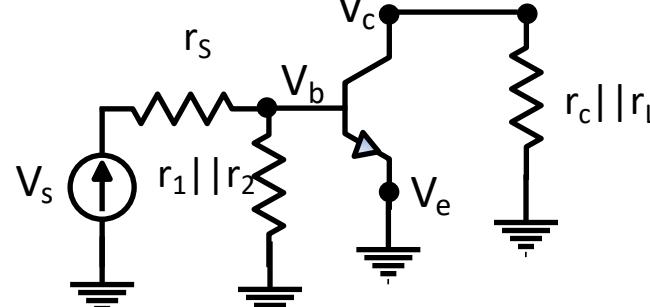
Bipolar model

# Bipolar Transistors - II

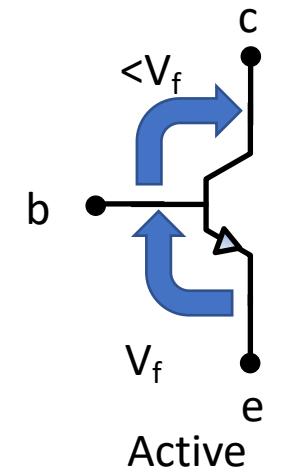
- NPN Mode
  - $V_f = .7V$
  - $\beta = g_m r_\pi$
  - $g_b = \frac{i_b}{V_t}, V_t \approx 25mV, g_m = \frac{i_c}{V_t}$
- DC
  - $\frac{V_{cc}-2V_f}{R_C} < i_c, \beta i_b = i_c$
  - $V_c = V_{cc} - i_c R_C$
  - $\frac{V_{cc}-V_b}{R_B} = i_b$
- Small signal
  1. Convert to AC only and simplify
  2. Thevenize circuit
  3. Replace transistor with model



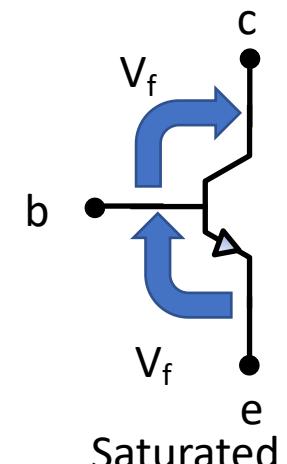
Small signal - original  
Step 1



Small signal



Active



Saturated

# Bipolar Transistors - III

- Small signal
  1. Convert to AC only and simplify
  2. Thevenize

- $V_{th,in} = V_s \frac{r_1 || r_2}{r_1 || r_2 + r_s}$

- $r_{th,in} = r_s || r_1 || r_2$

- $r_{th,out} = r_c || r_L$

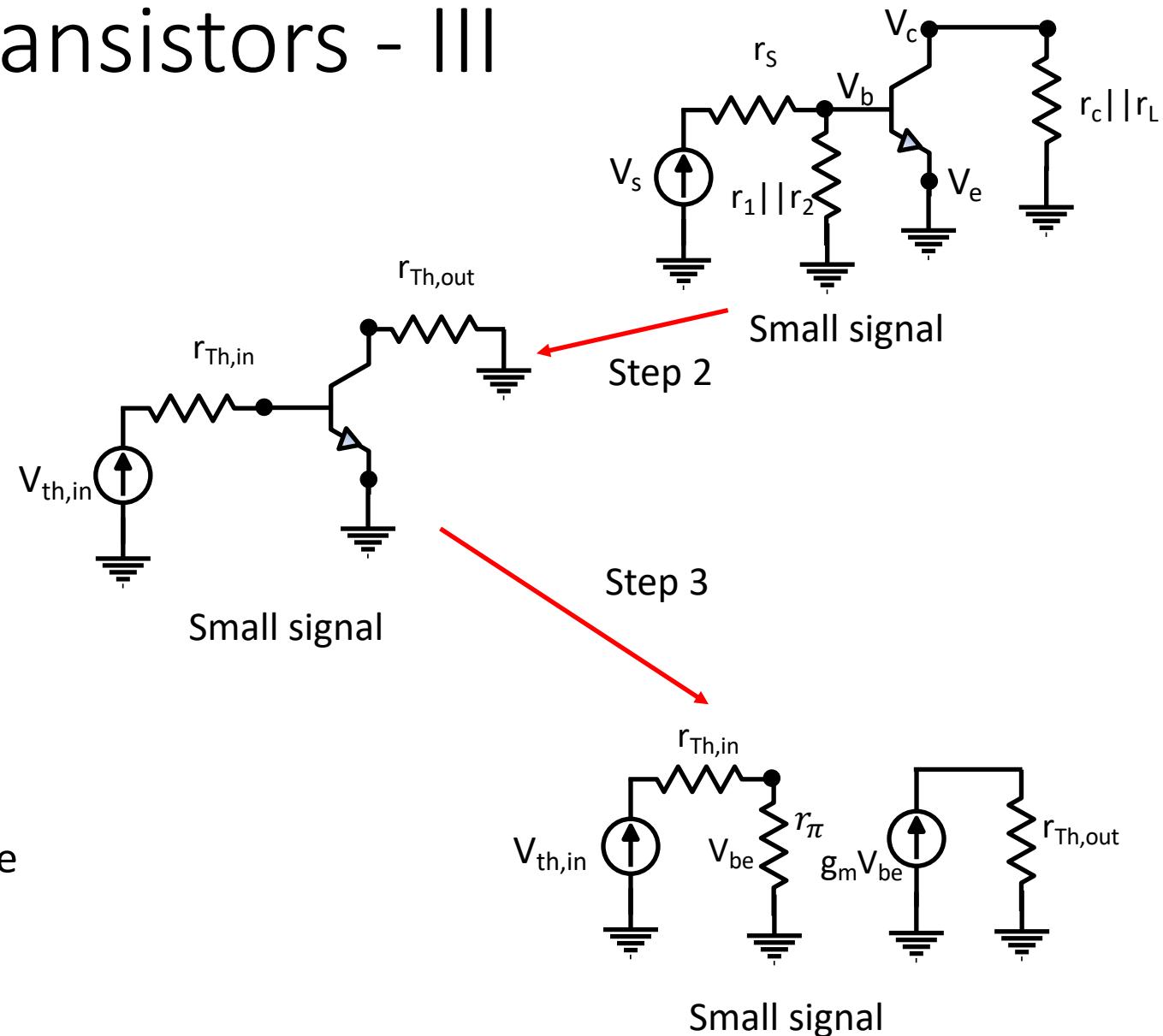
- 3. Replace transistor with model

- $\frac{V_{be}}{V_{Th,in}} = \frac{r_\pi}{r_\pi + r_{Th,in}}$

- $\frac{V_{out}}{V_{be}} = -g_m r_0 || r_c || r_L$

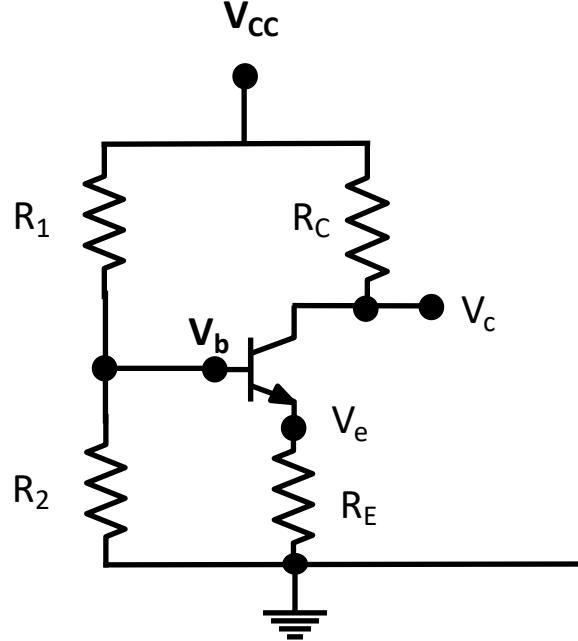
- $r_0$  is the transistor model resistance between b and c

- $A_{gain} = \frac{V_{out}}{V_s}$



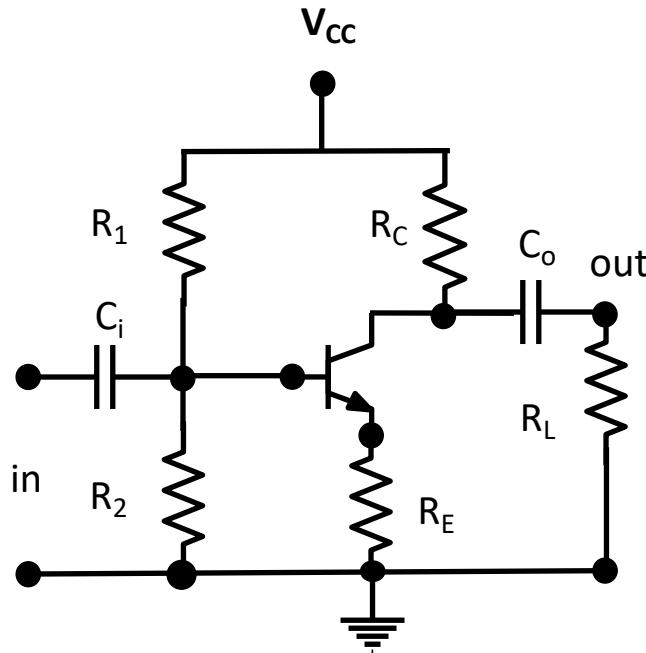
# Transistor experiment

## Experiment A



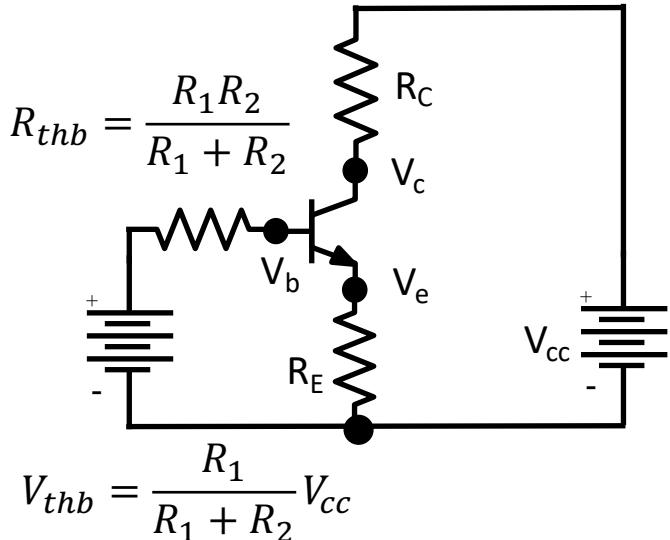
- $V_{cc} = 9V, R_1 = 22.8k\Omega, R_2 = 7.2k\Omega, R_c = 1k\Omega, R_E = 220k\Omega$ . 2n3904 transistor,  $\beta = 150$ .
- With no transistor,  $R_2$  adjusted so  $V_b = 2.36V$ .  $V_b = 2.24V, V_e = 1.54V, V_c = 1.89V$ .  $i_c = 7mA, i_b = 46\mu A$ .
- Experiment B
  - Again,  $V_{cc} = 9V, R_1 = 20k\Omega, R_2 = 10k\Omega, R_c = 1k\Omega, R_E = 220k\Omega$ . 2n3904 transistor,  $\beta = 150$ . With no transistor,  $R_2$  adjusted so  $V_b = 5.8V$ . Put transistor in and  $V_b = 2.4V$ .
  - With transistor,  $V_b = 2.4V, V_e = 1.7V, V_c = 1.74V$ .  $i_c = 7mA, i_b = 46\mu A$ .
  - Analyze these with our transistor model.
  - Now use the Thevenin equivalents to analyze them.

# Turn the transistor experiment into a CE amplifier



- Add  $C_i$  and  $C_o$ . Component values are:
  - $C_i = C_o = 1\mu F$
  - $R_1 = 20k\Omega, R_2 = 10k\Omega$
  - $R_C = 1k\Omega, R_E = 220\Omega$
  - $V_{cc} = 9V$
- 1. Use a function generator to generate a  $V_{pp} = 800mV, 10\text{kHz}$ .
- 2. The input impedance is  $Z_{in} = R_1 || R_2 || (\beta + 1)R_E$ , and the output impedance is  $Z_{out} = R_C$ . Add a load  $R_L$  whose value is  $Z_{out}$ .
- 3. Now connect a scope to the output and measure the gain. Calculate what it should be and compare them. How do the input and output waveforms compare?

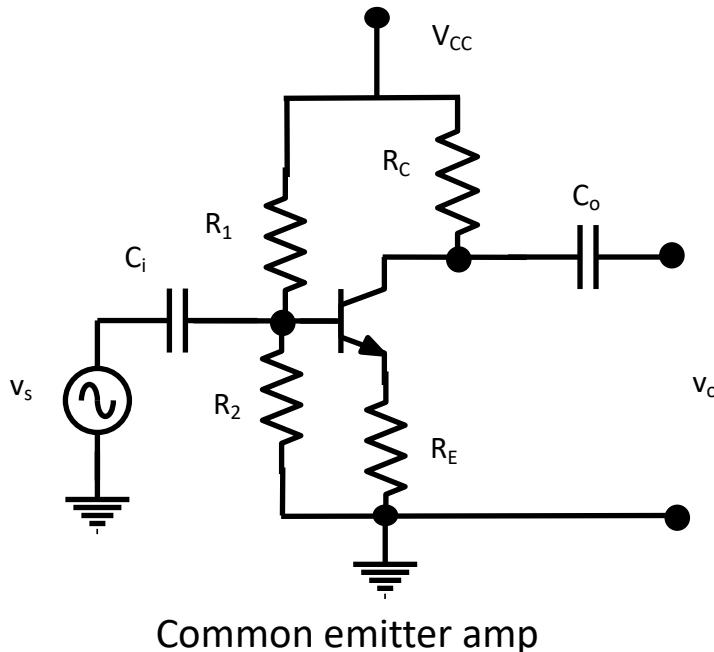
# Transistor experiment - Thevenin equivalent DC



- In Experiment A
  - $R_1 = 22.8k\Omega, R_2 = 7.2k\Omega, V_{thb} = 2.16V, R_{th} = 5.5k\Omega.$
  - If  $r_e \approx 33\Omega, r_b \approx 5k\Omega, i_b = \frac{2.16 - 1.54}{11500} = 53\mu A$ , which is close.
- In Experiment B
  - $R_1 = 22k\Omega, R_2 = 8k\Omega, V_{thb} = 2.4V, R_{th} = 5.9k\Omega.$
  - If  $r_e \approx 33\Omega, r_b \approx 5k\Omega, i_b = \frac{2.4 - 1.7}{10900} = 64\mu A$ , which is also close, but a little high.
- Turn this into a CE amplifier by adding 1uF input and output capacitors. Measure and calculate the voltages and gains.

# BJT common emitter amplifier

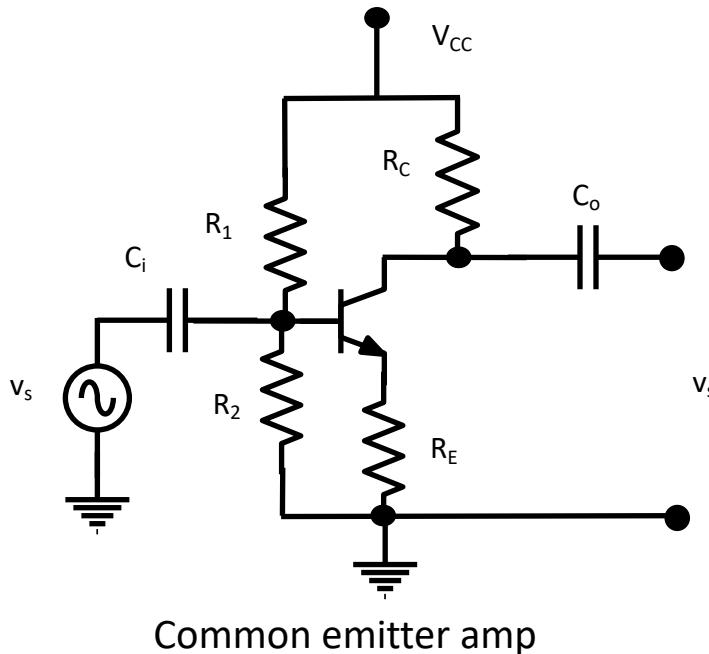
- Here's how to design a common emitter amplifier. We use a 2n3904 transistor with  $\beta=150$ . This circuit will work! Build it.



1. Pick the supply voltage  $V_{cc}=12V$ .
2. Choose a gain (amplification factor),  $A = 5$ .
3. Choose the “Q point” of the conducting transistor (4mA) and  $V_{ce,q} = 5V$ .
4.  $V_{cc} = (i_c \cdot R_C) + V_{ce} + i_e R_E \sim i_e \cdot (R_C + R_E) + V_{ce}$  with  $i_c=4mA$ . We get  $(R_C + R_E) = (V_{cc} - V_{ce})/(4mA) = 1.75 k\Omega$ .
5. Since  $A = 5$  and  $A=R_C/R_E$ ,  $R_C= 5 R_E$  so  $R_E \sim 270 \Omega$  (this is a standard resistor value) and  $R_C= 1.5k\Omega$ .

Credit: Ward, Hands on Radio.

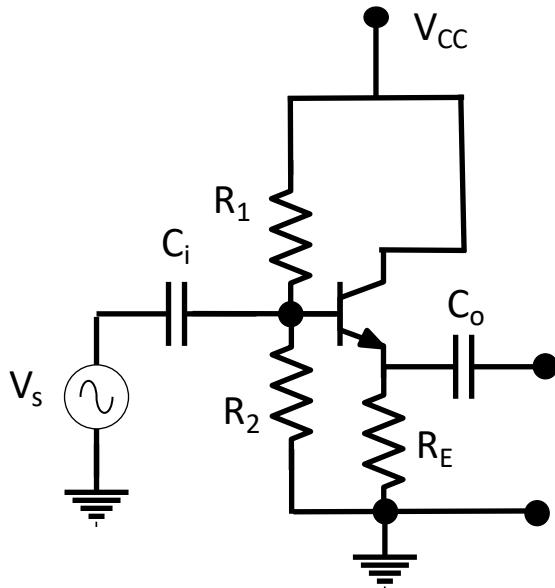
# BJT common emitter amplifier continued



6.  $i_b = 4\text{mA}/\beta = 27 \mu\text{A}$ .
7. Since  $V_{be}$  must be greater than .7V throughout the input signal range, we want the voltage across  $R_2$  to satisfy  $V_{be} + i_c R_E = 1.8\text{V}$ .
8. Rule of thumb is current through  $R_1$  and  $R_2$  is  $10i_b$ . We insert a voltage divider consisting of  $R_1$  and  $R_2$ , so that  $R_1 = (12-1.8)/270 \mu\text{A} \sim 39 \text{k}\Omega$ .  
 $R_2 = 6.7\text{k}\Omega$
9.  $C_o$  and  $C_i$  are picked to offer small resistance to the frequency range we're interested in and  $C_o = C_i = 5 \mu\text{F}$ .
  - I haven't explained why we want  $R_E$  but it provides thermal stability for the transistor over the range we care about. The fact that  $A=R_C/R_E$  can be calculated using Kirchhoff's laws.

Credit: Ward, Hands on Radio.

# BJT common collector amplifier

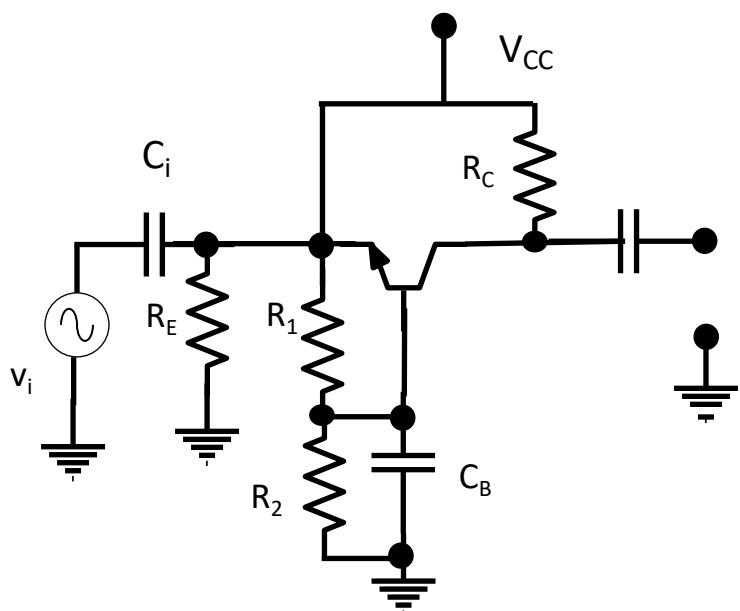


1.  $\beta = 150, A_V = 1, V_{cc} = 12V$
2. Q-pt:  $i_{ce} = 5mA, V_{ce,q} = 6V$  (rule of thumb),  $v_{be} = .7V$ .
3.  $i_{R_1 \rightarrow R_2} = 10i_b$  (ROT),  $V_{ce} = v_{be} + i_{ce,q}R_E, R_E = 1.2k\Omega, i_b = \frac{V_{ce,q}}{\beta} = 33\mu A$
4.  $V_{R_2} = V_{be} + i_C R_E = 6.7V, V_{R_1} = 5.3V$
5.  $R_2 = \frac{6.7}{330\mu A} = 20k\Omega, R_1 = \frac{5.3}{330\mu A} = 16k\Omega$
6.  $Z_{in} = R_1 || R_2 || (\beta + 1)R_E, R_{in} = 50\Omega, Z_{out} = 5\Omega$

Common collector amp (Emitter Follower)

Credit: Ward, Hands on Radio.

# BJT common base amplifier

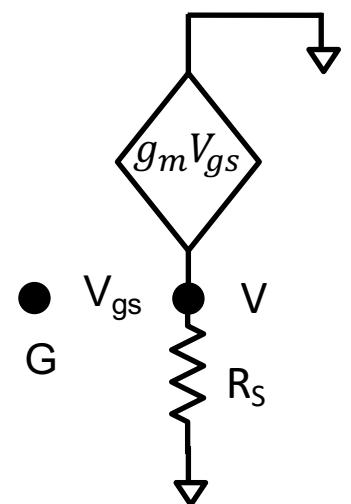
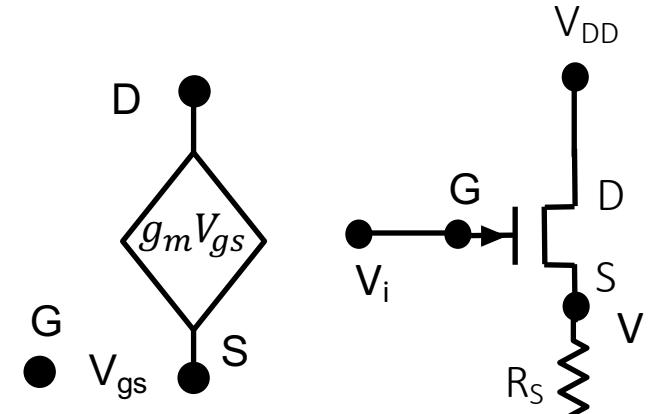


Common base amp

- $A_I = \frac{i_C}{i_E} = \frac{\beta}{\beta+1}, A_V = \frac{R_C||R_L}{r_e}, Z_{out} \approx R_C$
- 1.  $V_{CC} = 12V, V_{be} = .7V, R_E = 50\Omega, R_L = 1k\Omega, i_{ce,q} = 5mA, V_{ce,q} = 6V$
- 2.  $i_b = \frac{i_{ce,q}}{\beta} = 33\mu A, i_{R_1 \rightarrow R_2} = 10 i_b = 330\mu A$  (ROT)
- 3.  $V_{R_2} = V_{be} + i_C R_E = 6.7V, V_{R_1} = 5.3V$
- 4.  $R_1 = \frac{5.3}{330\mu A} = 16k\Omega, R_C = \frac{V_{cc}-i_{c,Q}R_E-V_{ce,Q}}{i_{c,Q}} = 1.35k\Omega$
- 5.  $A_V = \frac{R_C||R_L}{26/i_e} = 115$

# JFETs

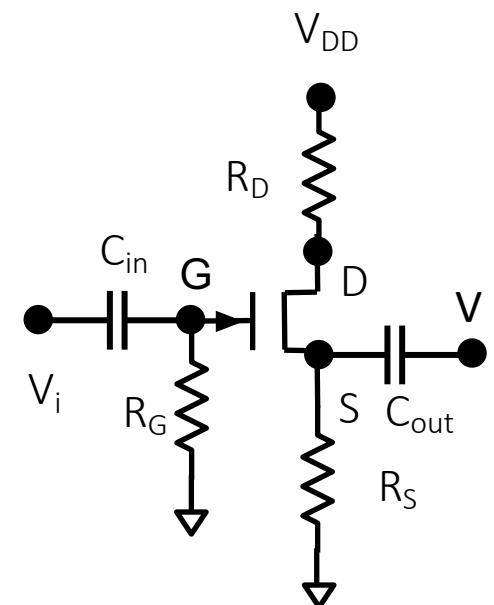
- JFET circuit model (active region):
  - $I_d = I_{dss} \left(1 - \frac{V_{gs}}{V_c}\right)^2$ , provided  $0 < V_{gs} < V_c$  and  $V_{ds} > V_{gs} - V_c$ .  $i_{dss}$  is drain to source current when gate is at 0.
  - $g_m = \frac{dI_d}{dV_{gs}} = \frac{\Delta i_{ds}}{\Delta v_{gs}} \approx -\frac{2I_{dss}}{V_c} \left(1 - \frac{V_{gs}}{V_c}\right)$
  - For circuit on right,  $g_m \Delta v_{gs} = \Delta i_{ds}$  and so  $g_m R_S \Delta v_{gs} = V$
  - $V_c$  is cutoff voltage. When  $V_{gs} < V_c$  there's no channel conduction. Some people call this  $V_T$  or  $V_P$ .
  - JFET input impedance is high ( $10^{10} \Omega$ ).
  - For J309,  $V_c \approx -2.6V$ ,  $i_{dss} \approx 23mA$ ,  $g_m \approx 12$ .
  - DC:  $V_b = -i_b R_S$
  - AC:  $V = R_S g_m V_{gs}$ ,  $v_{gs} = V_g - V$



AC model

# JFET common drain (follower) amplifier

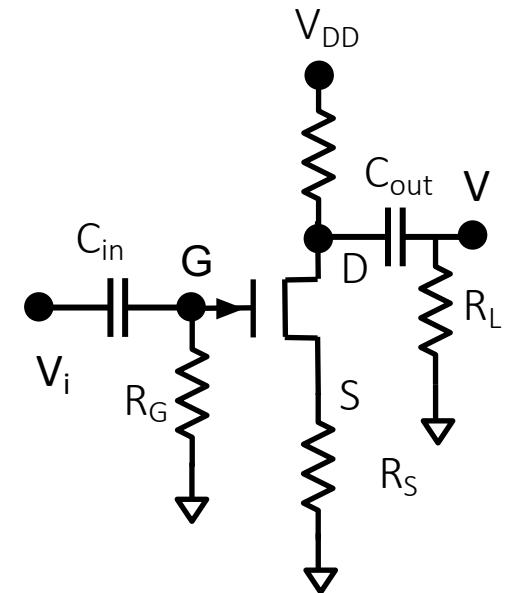
- $A_V = 1, Z_{out} = R_S \parallel \frac{1}{g_m} \approx \frac{1}{g_m}$  (if  $g_m R_S \gg 1$ )



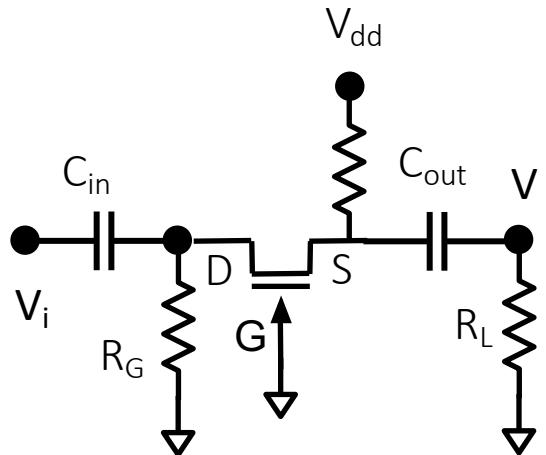
# JFET common source amplifier

- $A_V = -\frac{g_m R_D}{1+g_m R_S} = -\frac{R_D}{R_L}, Z_{in} = R_G, Z_{out} \approx R_D$
- $R_S = \frac{-V_P}{i_{dd}} \left(1 - \sqrt{\frac{i_{dq}}{i_{dss}}}\right), g_m \approx 15mA/V, Z_0 = \frac{1}{g_m}$

1.  $V_{dd} = 12V, i_{dss} = 35mA, V_P = 3.0V, A_V = 10, i_{dd} = 10mA$
2. From equation above,  $R_S = 139\Omega, R_D = 10R_S = 1390\Omega$
3.  $A_V = -g_m(R_D || R_L)$



# JFET common gate amplifier



- $A_V = g_m(R_D || R_L)$ ,  $Z_{out} \approx r_0(g_m R_S + 1) || R_D$ ,  $Z_{in} = R_S || \frac{1}{g_m}$
- $V_{DD} = 12V$ ,  $i_{dss} = 60mA$ ,  $V_P = -6$ ,  $A_V = 10$ ,  $R_L = 1k\Omega$ ,  $R_S = 50\Omega$
- $i_{d,q} = \frac{V_P}{2R_S^2 i_{dss}} \left( V_P + \sqrt{V_P^2 - 4R_S i_{dss} V_P} \right) - \frac{V_P}{R_S}$

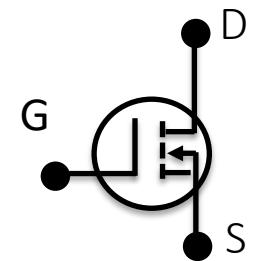
1. Solve for  $R_D$ :  $10 = g_m \times R_D || R_L$ ,  $R_D = 2k\Omega$
2. Find  $i_{d,q} = \frac{V_P}{2R_S^2 i_{dss}} \left( V_P + \sqrt{V_P^2 - 4R_S i_{dss} V_P} \right) - \frac{V_P}{R_S} = 10mA$

# MOSFETs

- MOSFET circuit model,  $V_{Th}$  is threshold voltage,  $W$  is channel width,  $L$  is channel length

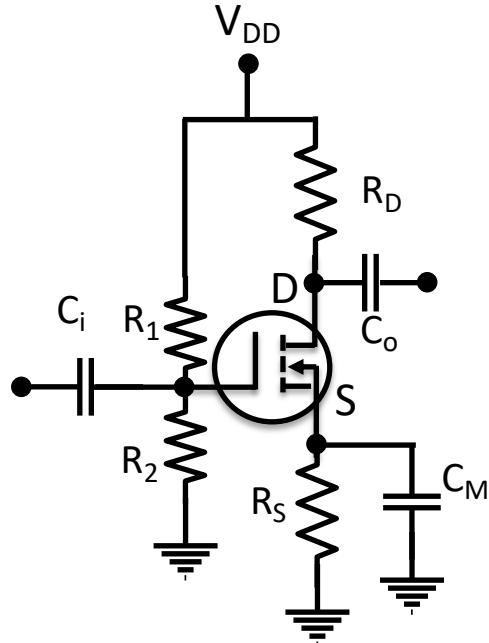
- Ohmic:  $I_D = k \left( \frac{W}{L} \right) [2(V_{GS} - V_T)V_{DS} - V_{DS}^2]$

- Saturation:  $I_D = k \left( \frac{W}{L} \right) (V_{GS} - V_T)^2 = I_{DS}$



N channel MOSFET

# CMOS common emitter amplifier



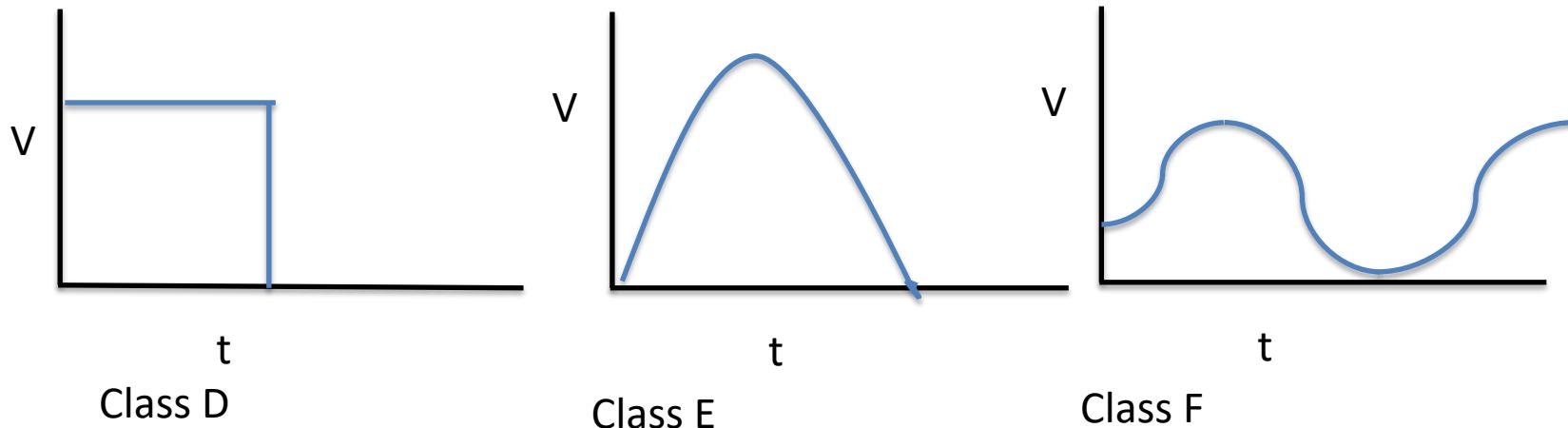
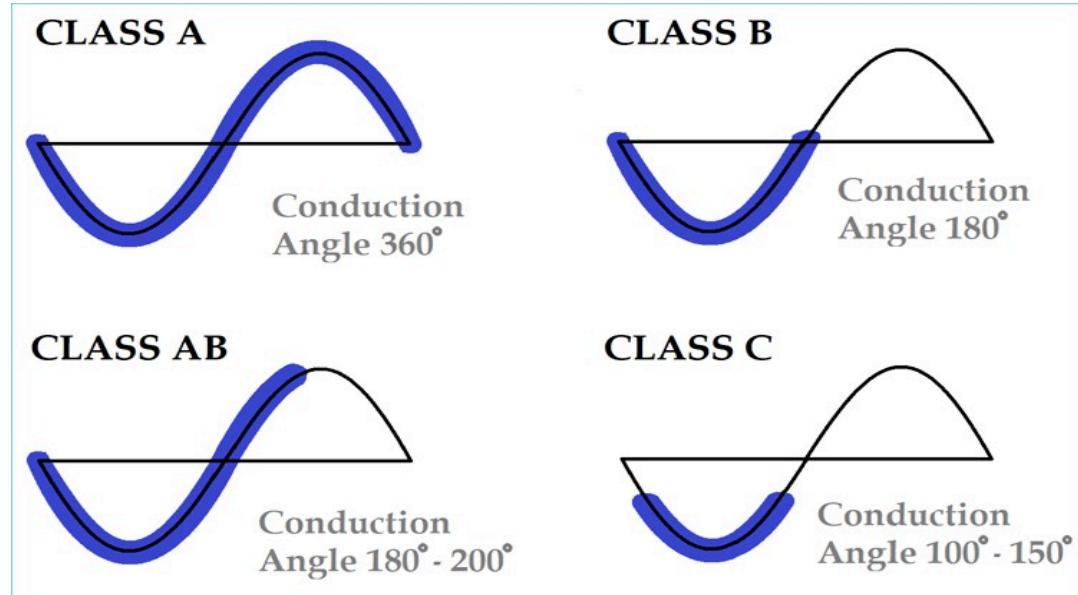
- Pick power
- $V_{DD} = i_D R_D + V_{DS} + i_D R_S$
- $V_{GS} = V_G - i_S R_S$
- $V_G = V_{DD} \frac{R_1}{R_1 + R_2}$
- $i_D = k(V_G - V_{TH})^2$
- Bias around  $\frac{V_{DD}}{3}$
- Pick gain,  $A = \frac{R_D}{R_S + \frac{1}{g_m}}$
- For 2N7000,  $g_m \approx 200$

# Amplifier classes

Class	Efficiency	Characteristics
A	35%	Full bias
B	60%	Low bias
C	75%	Saturating
D	75%	Switch in pass-band
E	90%	Voltage switch
F	80%	Harmonic resonators

$$\eta = \frac{P}{P_0}, P_d = P_0 - P_i$$

$$P_d = P_a + P_{on}$$

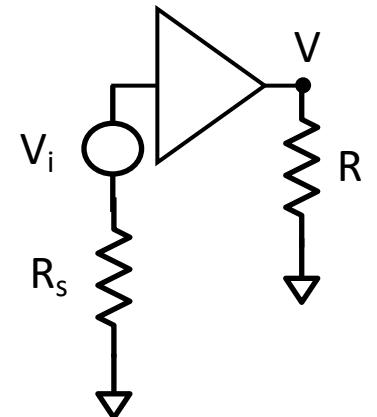


# Efficiency of class A amplifiers

- Here,  $P_o$  is the power from the supply,  $P_d$  is the dissipated power,  $P$  is the output power.  $R$  is the collector resistor.
- $\eta = \frac{P}{P_0}$ ,  $P_0$  is DC power
- $P_0 = V_{cc}I_0$ , where  $I_0 = \langle i_c \rangle$ , so  $I_0 = \frac{V_{cc}}{2R}$  ( $R$  is the collector resistance). Thus,  $P_o = \frac{V_{cc}^2}{2R}$ .
- AC load power is  $P = \frac{V_{pp}I_{pp}}{8} = \frac{V_{cc}^2}{8R}$ . So maximum efficiency  $\eta = \frac{P}{P_o} = 25\%$ .
- DC load power is  $\frac{V_{cc}^2}{4R}$  and so is transistor power.
- Half the power in a class A is lost to load resistance. If we replace resistance with transformer,  $P_0 = \frac{V_{cc}^2}{R'}$ , where  $R'$  is the effective load resistance and  $P = \frac{V_{pp}I_{pp}}{8} = \frac{V_{cc}^2}{2R'}$ , giving 50% efficiency. Transformer turns ratio controls peak-to-peak current. Maximum current is  $I_m = \frac{2V_{cc}}{R'} = \frac{2V_{cc}}{n^2R}$ , where  $n$  is the turns ratio.

# Amplifier gain

- Let  $P_+$  be the maximum input power (when load is matched) and  $V_+$  is the voltage at maximum power.  $V_+ = \frac{V_0}{2}$
- $G = 10\log\left(\frac{P}{P_+}\right)$
- $P = \frac{V_{pp}^2}{8R}$
- $P_+ = \frac{V_{+,pp}^2}{8R_s}$
- $G_s = 10\log\left(\frac{V}{V_+}\right)$

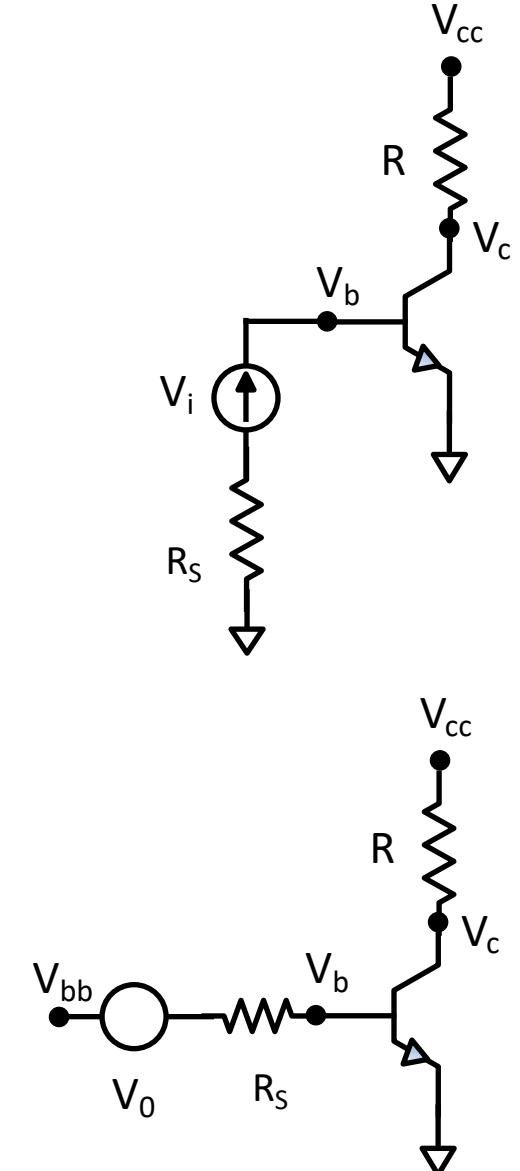
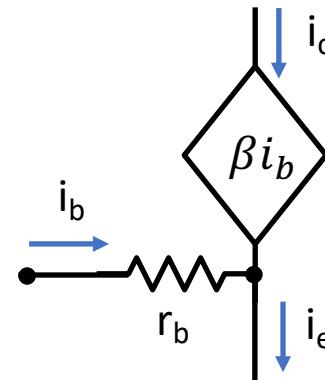


# Bipolar transistors - IV

- At saturation,  $v_{bc} < V_f$ , so there is conduction from the collector to the base.
- $i_b = i_{bs} \exp\left(\frac{V_b}{V_t}\right)$ ,  $V_t$  is the thermal voltage,  $V_t = 25mV$ ,  $i_{bs}$  is the base saturation current.
- $i_c = i_{cs} \exp\left(\frac{V_c}{V_t}\right)$ . Note  $i_{cs} = \beta i_{bs}$ . Both increase rapidly with temperature

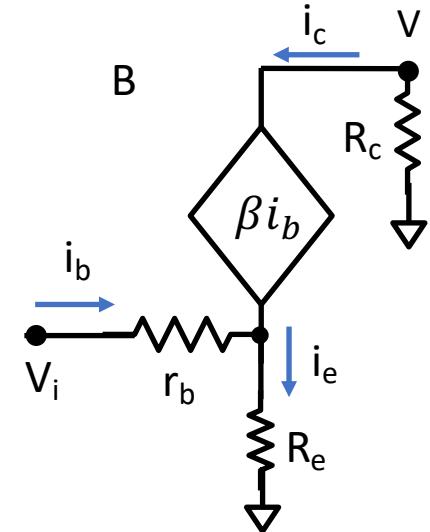
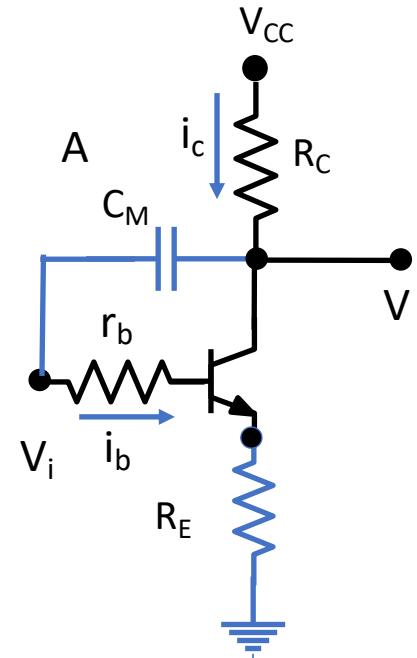
- Base resistance

- $g_b = \frac{i_b}{V_t} = \frac{di_b}{dV_b}$
- $r_b = \frac{25mV}{i_b}$
- $g_m = \frac{i_c}{V_t} = \frac{di_c}{dV_b}$
- $i_b = r_b V_b$



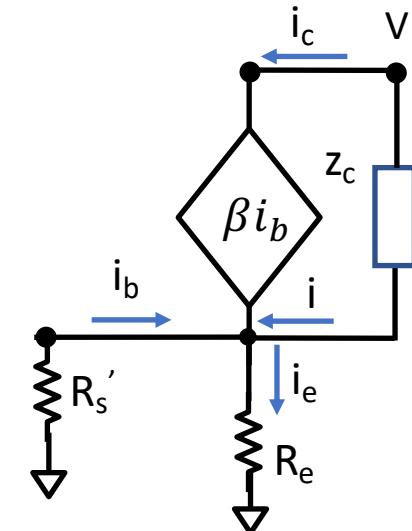
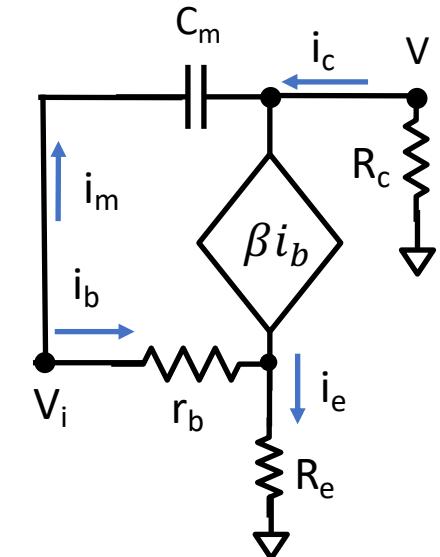
# Emitter degeneration

- To the usual transistor circuit (A), on the right, we add  $R_E$ . (B) is an equivalent circuit.
- $V_{bb} \approx V_f + i_c R_E$ . Let  $V$  be the output AC and  $V_i$  be the input AC.
- The gain is  $G_v = \frac{V}{V_i}$ .
- $V_i = i_b r_b + i_E R_E \approx i_C R_E$ ,  $Z_i = \frac{V_i}{i_b}$ ,
- $V = -i_c R_C$ .
- So  $G_v = -\frac{R_C}{R_E}$  (Doesn't depend on  $\beta$ ).
- $V_i \approx \beta i_b R_E$
- $Z_i = \frac{V_i}{i_b}$ , so  $Z_i = \beta R_E$ .



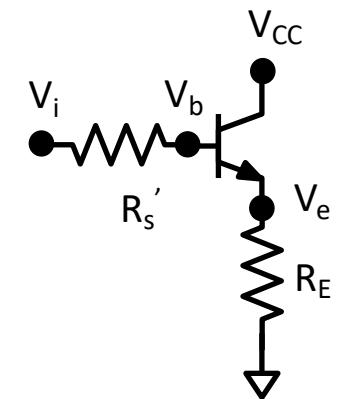
# Emitter degeneration

- $C_M$  is called a Miller capacitor and it arises from a capacitance,  $C_C$ , between the collector and emitter.  $i_m = j\omega C_C(V_i - V) = j\omega C_M(1 + |G_v|)V_i$ .  $i_m$  is the maximum current between base and emitter in the equivalent circuit on the right.
- With the Miller capacitor,  $Z_i = \beta R_E || (1 + |G_v|) C_M$
- $r_c \approx \frac{V_{early}}{i_c}$ ,  $r_c$  is the collector resistance
- $R_s' = R_S + r_b$ ,  $r_b$  is the base resistance.  $R_s'$  is the combined source resistance.
- $z_C$  is called the collector impedance and  $z_c = r_c || C_C$ ,  $C_c$  is specified in data sheet (8pF).
- $Z_o = \frac{V}{i_C}$ ,  $i = i_c - \beta i_b$ ,
- $i_b = -\frac{i_C R_S}{R_s' + R_E}$ ,
- $i = i_c \left(1 + \frac{\beta R_E}{R_s' + R_E}\right)$
- $V = i z_c + i_C (R_s' || R_E)$
- $Z_o = \frac{V}{i_C} = z_C \left(1 + \frac{\beta R_E}{R_s' + R_E}\right) + R_s' || R_E$ .
- $|z_c| \gg R_E$ , so  $Z_o = z_C \left(1 + \frac{\beta R_E}{R_s' + R_E}\right)$



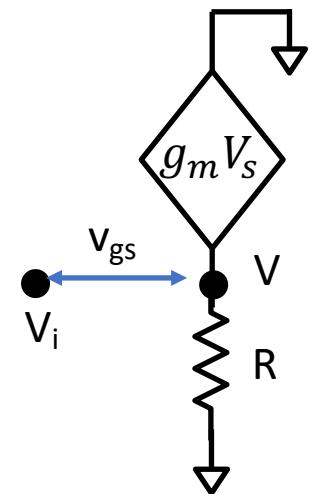
# More on emitter follower

- $Z_0 = \frac{v_e}{i_e}$
- $v_b = -R_s' i_b, R_s' = R_s + r_b$
- $i_e \approx \beta i_b$
- $Z_0 \approx \frac{R_s'}{\beta}$



# JFET follower

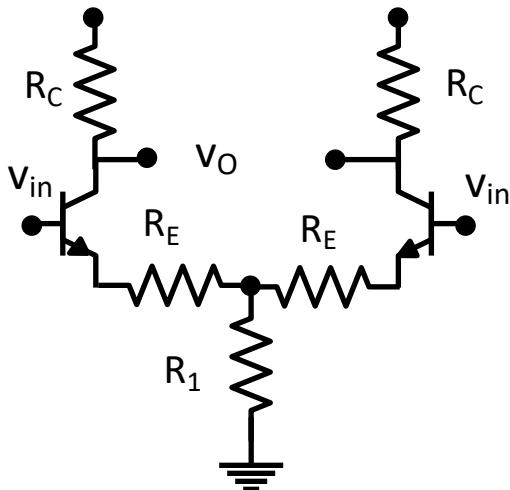
- $V = Rg_m v_{gs}$
- $v_{gs} = V_i - V$
- $V = \frac{RV_i}{R + \frac{1}{g_m}}$
- $Z_0 = \frac{1}{g_m}$
- $G_v = \frac{V}{V_i} = \frac{Rg_m}{1+Rg_m} \approx 1$



# Differential Amplifier

- Two port model
- $\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}$

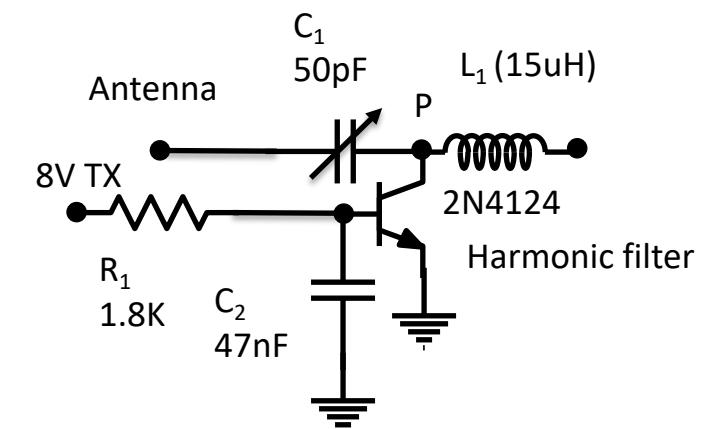
- Pick power 12
- Choose collector current ( $2mA$ ) by picking  $R_1$
- Pick gain,  $A = \frac{R_C}{2R_E}$
- $G_d = -\frac{R_c}{R_e}$
- $Z_d = 2R_c$



Differential amplifier

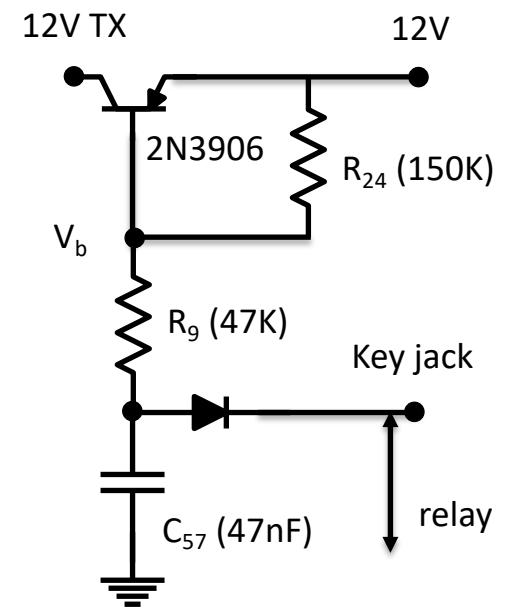
# Exercise 19: Norcal receiver switch

1. Consider the rising part of the base voltage waveform. Calculate slope.
2. Do the same for the falling part for voltage below .6V. Calculate  $t_2$ .
3. Measure the switch attenuation
  - When the transistor is saturated, the drop across ce is 1.4V. At full power,  $P = \frac{V_m^2}{8R}$  and  $V_m = 33.9V$ .  $\frac{P_{new}}{P_{original}} = \frac{1}{33.9^2}$ , so  $loss = 10 \log\left(\frac{1}{33.9^2}\right) = -31dB$ .
4. Measure the voltage with the switch on. Measure output voltage and calculate on-off rejection ratio  $R=20 \log(V_{off}/V_{on})$



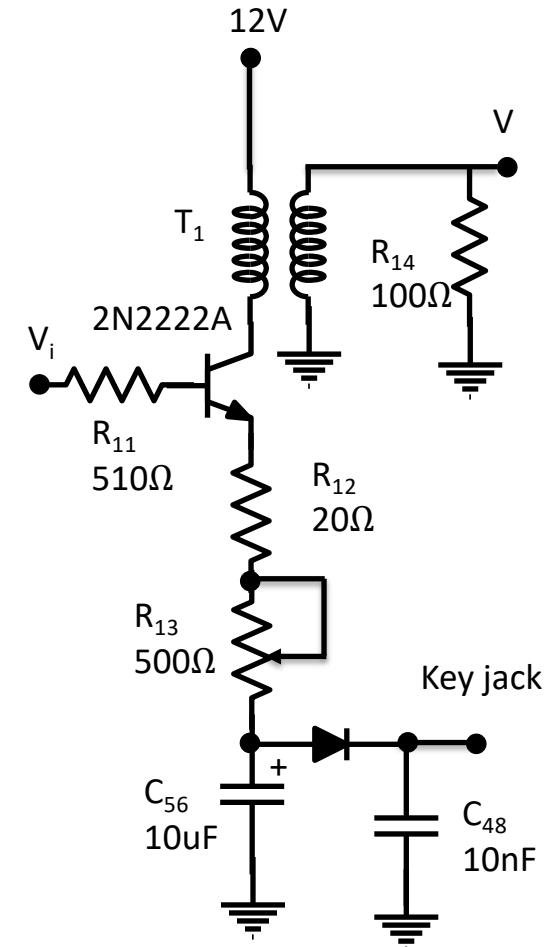
# Exercise 20: NorCal transmitter switch

- For transmitter switch, saturation resistance is  $\approx 2\Omega$ ,  $G_s = \frac{i_b}{15mV}$ .
  - $i$  is current into the load. In Norcal,  $i = 7mA$ . For 2n3906, to ensure saturation,  $i_b = \frac{2i}{100} = 140\mu A$ .
- Calculate voltage on  $C_{57}$ . Measure time for capacitor to charge half-way. Calculate what the time should be.
    - $\tau = 197 \times 10^4 \times 47 \times 10^{-9} = 9.2 \times 10^{-2} sec = 92 msec$ .
  - Calculate the approximate current  $i_c$  when  $Q_4$  is on. Assume base voltage on  $Q_1$  is 700 mV. Neglect saturation voltage on  $Q_4$ . Calculate base current  $i_b$  required to produce this collector current assuming  $\beta = 100$ .
  - Calculate  $i_b$  at key down assuming a 700 mV drop-in base-emitter of  $Q_4$  and at 600mV at  $D_{11}$ 
    - $V_b = \frac{R_9}{R_9 + R_{24}} (12) \approx 3V$ ,  $i_b = i_{bs} \exp(\frac{V_b}{V_t})$ ,
  - Sketch collector voltage at  $Q_4$  showing where transistor is saturated. What is the delay in going active?
  - Use the delay to measure  $\beta$ .



# Exercise 21: Norcal Driver

1. Measure the output voltage and calculate the power, P.
  2. Calculate the power from the power supply.
  3. Measure the voltage gain  $G_v = \frac{V}{V_i}$  with R13 at minimum and maximum gain.
- $\omega = 4.4 \times 10^7$ ,  $L_{p,T1} = 68.6 \mu H$ . This is a class A amplifier.
  - $R' = n^2 R$ ,  $n = \frac{14}{4}$ ,  $R' = 1225 \Omega$
  - $Z_{eq}(R) = (20 + R) + j\omega L_{p,T1}$ ,  $0 \leq R \leq 500$ .  $R = R_{13}$
  - $Z_{eq}(0) = 20 + 2992j$ ,
  - $i_c = \frac{V_{cc} - V_{ce}}{20 + R'}$ ,  $i_c = \beta i_b$ ,  $V_e = 20i_c$
  - From text,  $P = \frac{(V_{cc} - V_e)^2}{2R'}$
  - $P_o(R) = \frac{V_{cc}^2}{(20 + R + R')}$
  - Gain is between 2.5 and 60



# Exercise 22: Emitter degeneration

- In Driver amplifier, add probe to  $R_{11}$ , this allows us to measure the AC voltage,  $V_i$

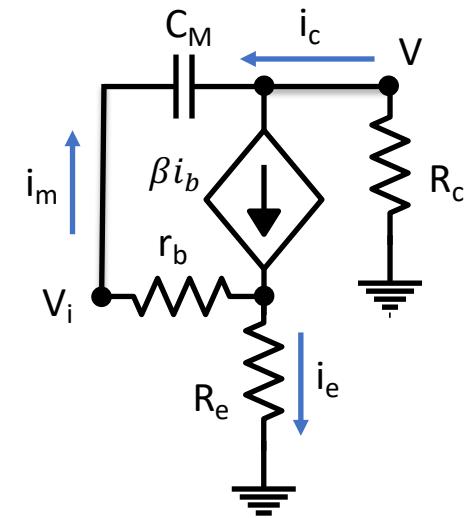
1. Measure  $G_v = \frac{V}{V_i}$  with  $R_{13}$  turned fully counterclockwise and then fully clockwise.

- $R' = 1225\Omega$
- When  $R_{13}$  is fully counter-clockwise  $R_{E, effective} = 520\Omega$ ,  $G_v = \frac{1225}{520} = 2.36$
- When  $R_{13}$  is fully clockwise  $R_{E, effective} = 20\Omega$ ,  $G_v = \frac{1225}{20} = 61$
- Calculate the expected voltage gain for each setting of  $R_{13}$

2. Measure  $V_i$  at the maximal gain setting

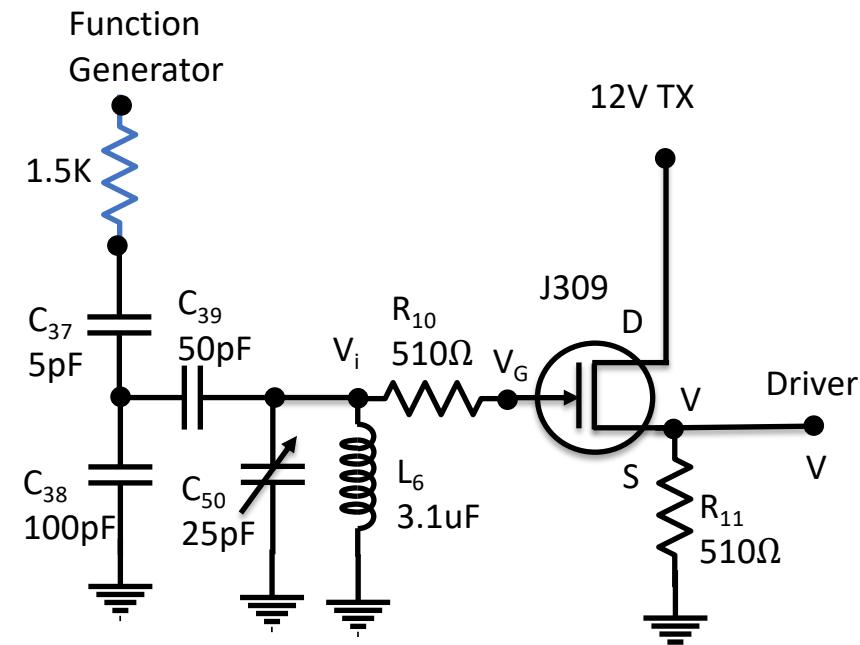
3. The open circuit voltage is  $V_0 = 2V$ , calculate  $V_i$  in terms of  $C_M$

- $Z_i = \beta R_E || (G_v + 1) C_M$ ,  $V_i = Z_i i_b$ ,  $V = -1225 i_c$  so  $\frac{V}{V_i} = -\frac{1225}{Z_i} \cdot \frac{i_c}{i_b} = -\beta \frac{1225}{Z_i}$



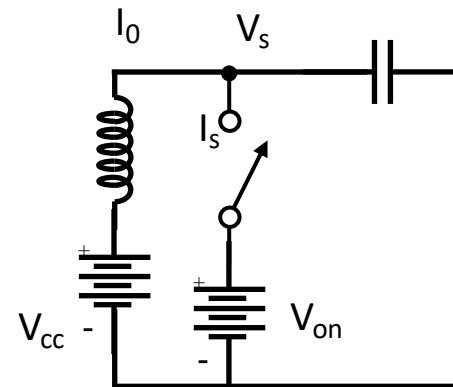
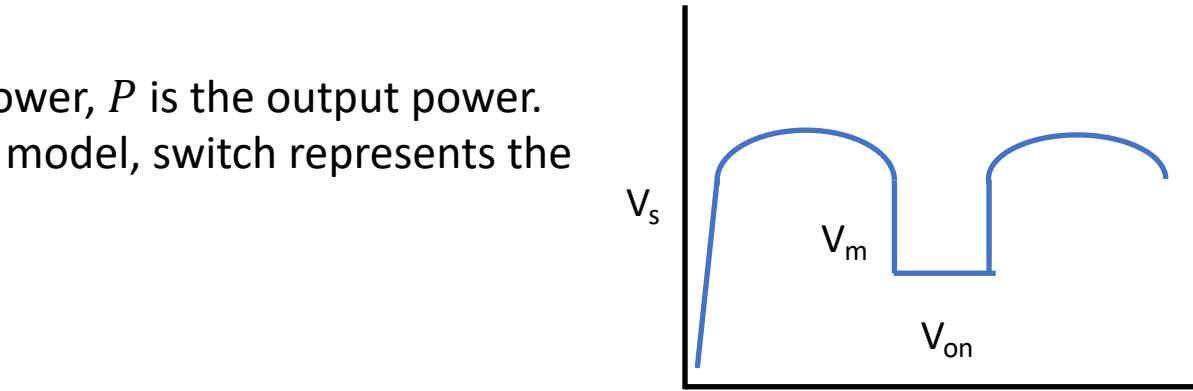
# Exercise 23: Norcal Buffer amplifier

1.  $R_{11}$  determines the bias. Measure the DC voltage at source of the JFET ( $V$ ).
2. Calculate the drain bias current. Calculate the source and drain voltages you should expect ( $R = R_{11}$ )
  - $V_{gs} = V_i - V$ ,  $i_d = i_{dss}(1 - \frac{V_{gs}}{V_C})^2$ ,  $V = g_m V_{gs} R$
  - $g_m \approx 12$ ,  $i_{dss} = 23mA$ ,  $V_C = -2.6V$
  - $V_{gs} = \frac{V_i}{1+g_m R}$ , substitute into  $i_d = i_{dss}(1 - \frac{V_{gs}}{V_C})^2$  to get  $i_d$ .  $i_s = \frac{V}{R}$
3. Calculate and measure the voltage gain of the buffer.
  - $G_V = \frac{V}{V_i} = \frac{1}{1 + \frac{1}{g_m R}}$ , or about 1 since  $g_m \approx 12$
4. Find the transconductance using the measured voltage gain.
5. Calculate the available power  $P_+$  from the function generator through a  $1.5k\Omega$  load. Calculate gain in dB.

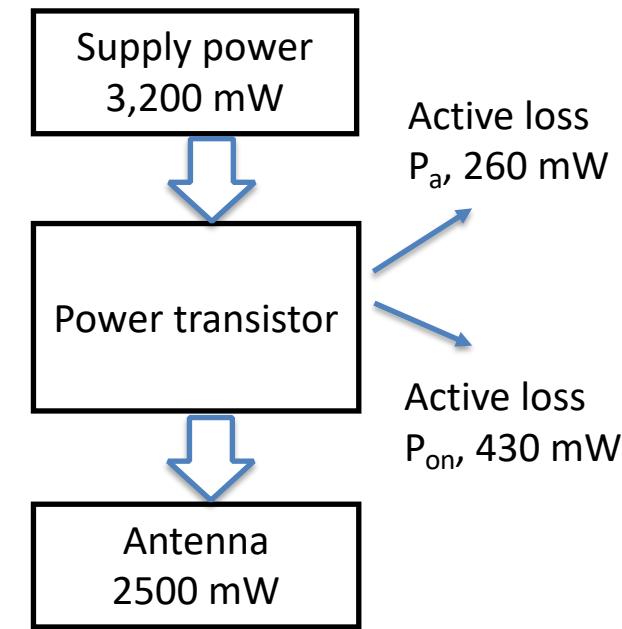


# Class C amplifiers and Norcal 40 Power amp

- Here  $P_o$  is the power from the supply,  $P_d$  is the dissipated power,  $P$  is the output power. The Norcal Power amplifier is a class C amplifier. For switch model, switch represents the transistor, when the transistor is on, the switch is open.
- $V_s = V_{on} + V_m \cos(\omega t)$ , (switch off),  $V_{on}$  (switch on)
- $V_{cc} = V_{on} + \frac{V_m}{\pi}$ ,  $V_m = \pi(V_{cc} - V_{on})$
- $P_0 = V_{cc}I_0$ ,  $P_d = V_{on}I_0$
- $P = P_o - P_d = \frac{(V_{cc}-V_{on})}{\pi}$
- $\eta = \frac{P}{P_0} = \frac{(V_{cc}-V_{on})}{V_{cc}}$
- $P = \frac{V_m^2}{8R}$ ,  $R$  is input filter impedance
- $P_d = P_0 - P = 3.2W - 2.5W = 700mW$
- Cap energy:  $E = \frac{CV^2}{8R} = 37nJ$
- $P_a = Ef = 260mW$
- $i_c = i_0 - i_s = 215mA$
- $P_{on} = V_{on}i_{on} = 430mW$
- $P_d = P_a + P_{on} = 690mW$

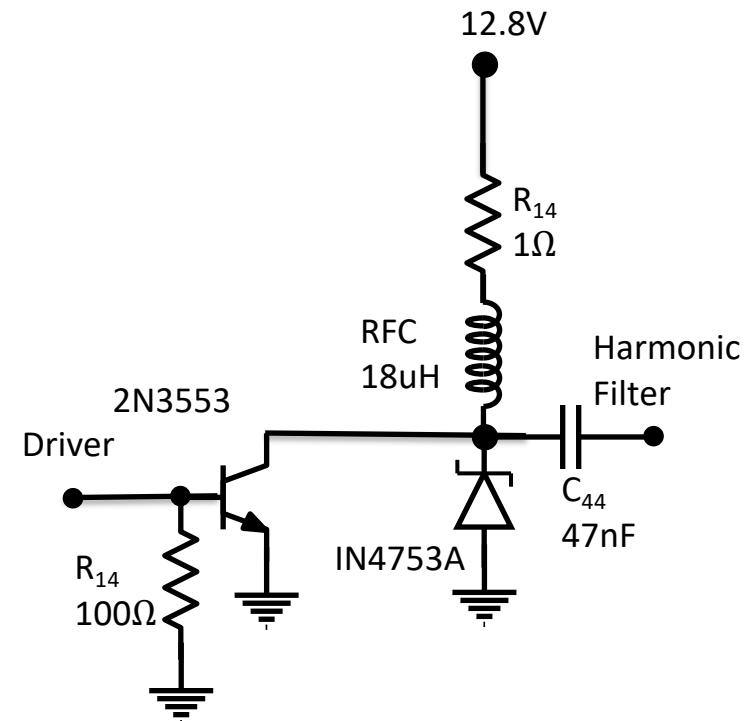


Switch model for class C amp



# Exercise 24: Norcal Power Amp

- Measure the peak-to-peak voltage across 50ohm load required for output of 2W. Calculate it and compare. Calculate the gain in dB
  - $V_{cc} = 12.8V, R \approx 50\Omega, I_0 = 250mA$
  - $P_{on} = V_{on}I_{on} = 430mW, P_a = Ef = 260mA, P_d = P_a + P_{on} = 690mW$
  - $P_o = V_{cc}I_0 = 3.2W.$
  - $P = \frac{\pi(V_{cc}-V_{on})^2}{8R} = 2.6W$
- Find pp output voltages of 5, 10, 15, 20, 25 and 30V. Calculate power supply current subtracting 2mA for regulator
- Calculate the output power, efficiency and dissipation power.
  - $P_d = P_0 - P = 3.2W - 2.5W$
  - $\eta = \frac{P}{P_0} = \frac{2.5}{3.2} = .78$



# Thermal modelling

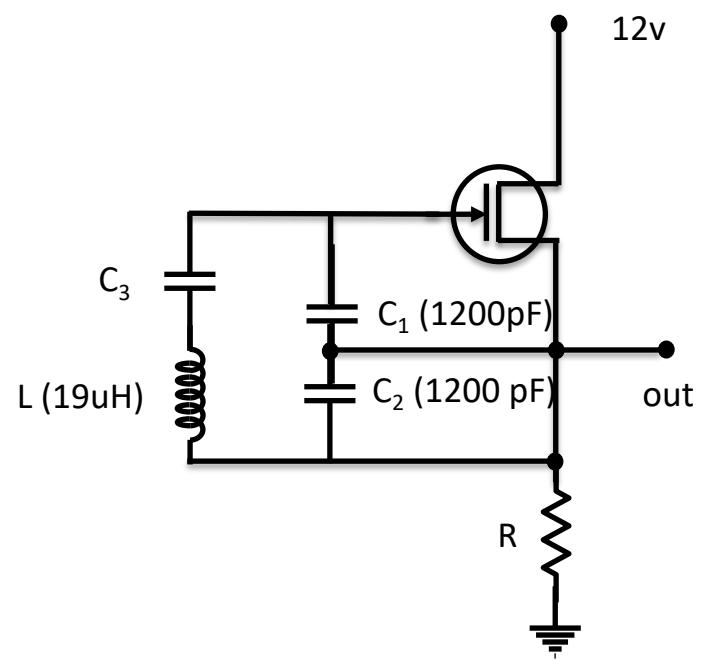
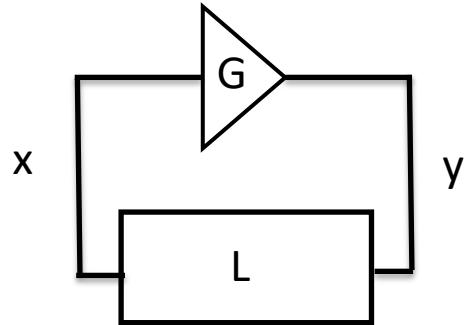
- $T$  is heat sink temperature,  $T_0$  is ambient temperature,  $P_d$  is power dissipated.
- $R_t = \frac{T-T_0}{P_d}$ ,  $R_t$  is the thermal resistance
- $C_t \dot{T} = P_d$ ,  $C_t$  is the thermal capacitance
- $R_j = \frac{T_j-T}{P_d}$ ,  $T_j$  is the junction temperature
- $f(t) + \tau f'(t) = f_\infty$ ,  $f(t) = f_0 e^{-\frac{t}{\tau}}$
- $P_d = \frac{T(t)-T_0}{R_t} + C_t T'(t)$ ,  $\tau = C_t R_t$ ,  $T_\infty = P_d R_t + T_0$
- $T(t) + \tau T'(t) = T_\infty$ ,  $\tau = C_t R_t$ .
- $T_\infty = P_d R_t + T_0$
- $T(t) = T_\infty - P_d R_t e^{-\frac{t}{\tau}}$
- $T_j(t) = T(t) + R_j P_d$

# Exercise 25: Thermal modelling

- For Motorola 2N3553,  $T_j = 25^{\circ}/W$ 
  1. Measure ambient temperature
  2. Turn function generator until output is  $30V_{pp}$
  3. After 20 minutes, measure  $T_\infty$ . Use this to calculate  $R_t$  and  $T_j$
  4. Plot heat sink temperature vs time. Measure  $t_2$  and calculate  $C_t$
- Need measurements

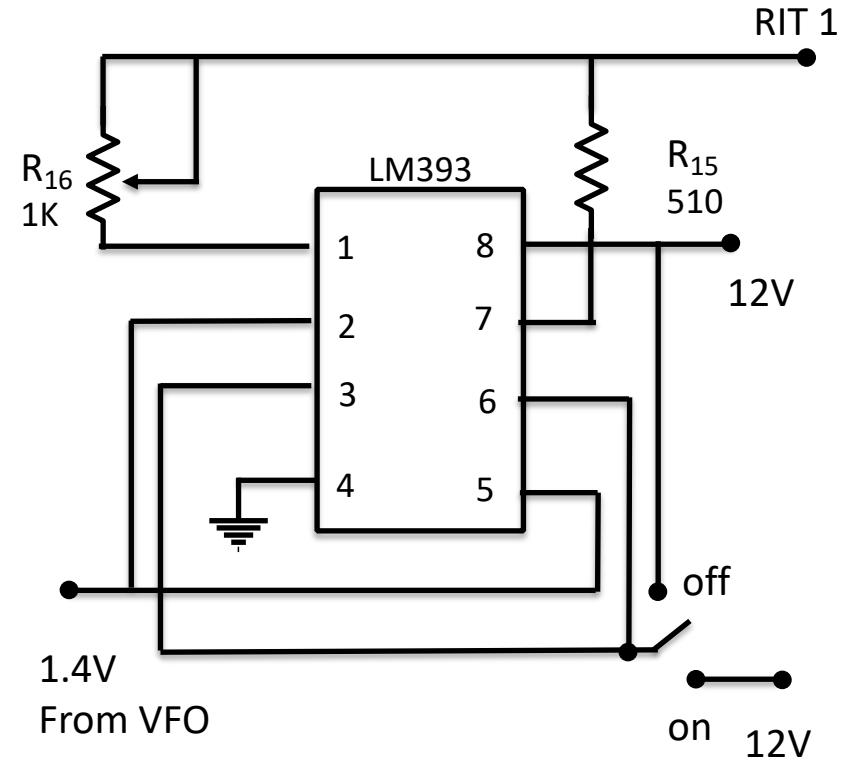
# Clapp oscillator

- Oscillation condition
  - $Gx = y$ ,  $Ly=x$
  - $|G| = |L|$  and  $\angle G = \angle L$
- Clapp (circuit on right)
  - $i_d = g_m v_{gs}$
  - Resonance:  $-\frac{1}{j\omega_0 C_2} = j\omega_0 L + \frac{1}{j\omega_0 C_3} + \frac{1}{j\omega_0 C_1}$
  - $\omega_0 = \frac{1}{\sqrt{LC}}$ ,  $C = C_1 || C_2 || C_3$
  - At resonance,  $v_{gs} = R i_d \frac{C_1}{C_2}$ ,  $L = \frac{C_1}{R C_2}$
  - Oscillation continues if  $g_m > \frac{C_1}{R C_2}$
  - $v_{gs} = 2v_s$



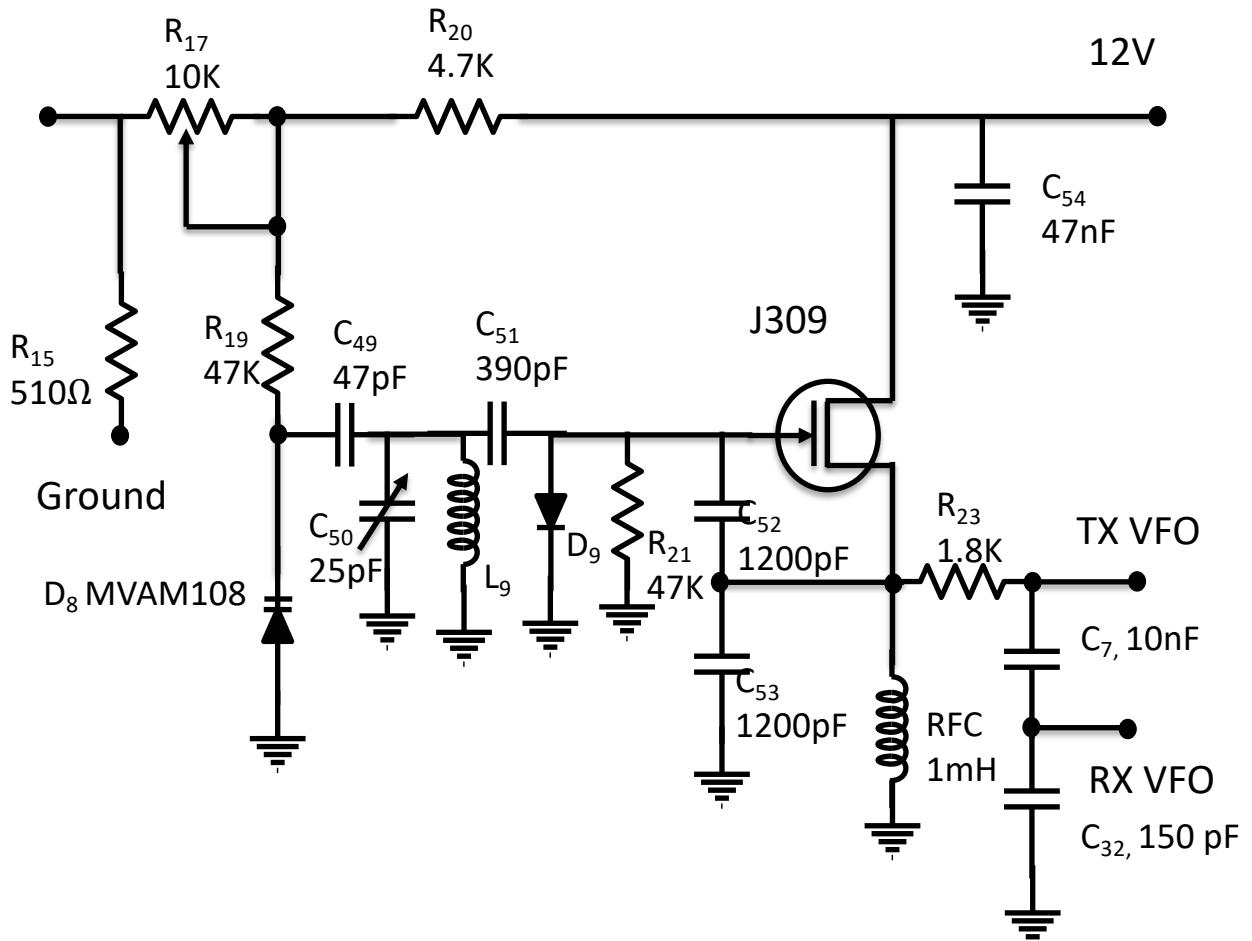
# Norcal Receiver Incremental Tuning (RIT)

- LM393 is a comparator
- RIT allows transmit and receive frequency to be offset.
- If transmitter is on, TX will be 8V and the left comparator will be off, the right one on and  $R_{15}$  will be grounded.
- For receiving, TX is <1.4V, disconnecting  $R_{15}$  and shorting  $R_{16}$  to ground.



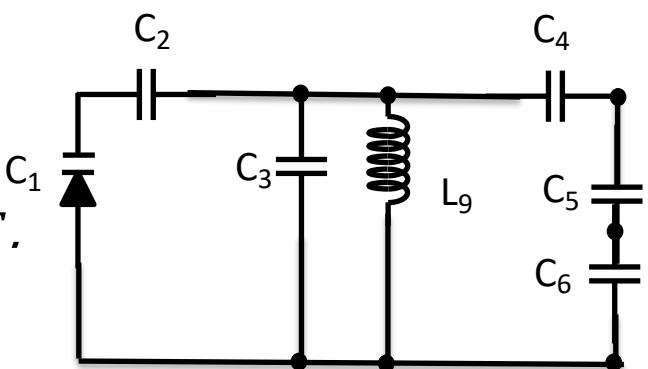
# Exercise 26: Norcal VFO

- Check MVAM108 capacitor when  $R_{17}$  is high and low
  - Start resistor ( $R_{21}$ ) pulls gate to ground at start
  - When gain limiting diode ( $D_9$ ) conducts, it pulls gate negative
  - Oscillator keeps growing as long as  $g_m > 1/R$
1. Measure p-p voltage,  $V$ . What should you expect?
  2. Measure DC voltage across wiper in  $R_{17}$
  3. Calculate expected  $V$  for large signal oscillation
  4. How does the frequency change as  $R_{17}$  changes?
  5. Calculate the oscillation frequency and the loss ratio  $|V/V_1|$
  6. How would this change if you took when  $L_9$  is turned off?



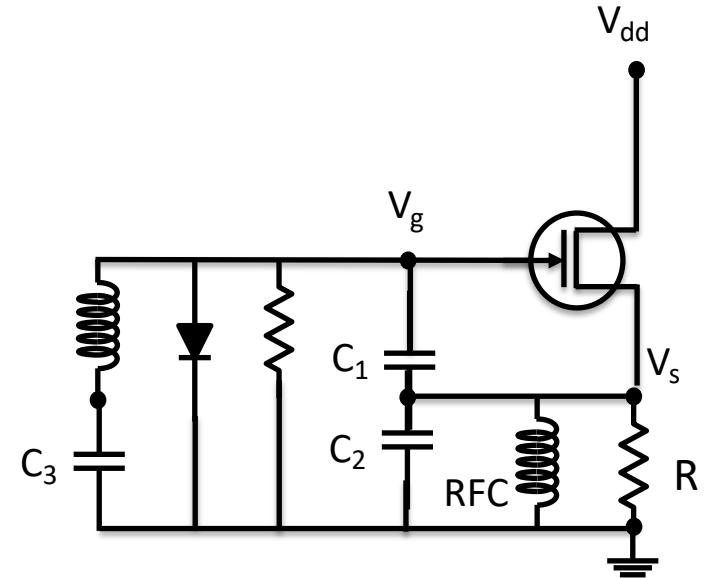
# VFO Problem

- The figure on the right is an equivalent circuit for the oscillator for the purpose of calculating resonant frequency. The varactor,  $C_1$  varies from 30 to 600 pF depending on the voltage.
- $C_2 = 47\text{pF}$ ,  $C_3 = 7\text{pF}$ ,  $C_4 = 390\text{pF}$ ,  $C_5 = C_6 = 1200\text{pF}$ ,  $L_9 = 19.2\mu\text{H}$
- The equivalent capacitance for  $C_4 - C_5 - C_6$  is  $C_{R,eq} = 236\text{pF}$ .
- When  $C_1 = 187\text{pF}$ , the equivalent capacitance for  $C_1 - C_2 - C_3$  is  $C_{L,eq} = 46.2\text{pF}$  and  $C_{osc} = 282\text{pF}$ . At the resonant frequency,  $\omega L_9 = \frac{1}{\omega C_{osc}}$ .  $\omega^2 = \frac{1}{L_9 C_{osc}}$ .  $f_r = 2.16\text{MHz}$
- When  $C_1 = 54\text{pF}$ , the equivalent capacitance for  $C_1 - C_2 - C_3$  is  $C_{L,eq} = 32\text{pF}$ .  $C_{osc} = 268\text{pF}$  At the resonant frequency,  $\omega L_9 = \frac{1}{\omega C_{osc}}$ .  $\omega^2 = \frac{1}{L_9 C_{osc}}$ .  $f_r = 2.22\text{MHz}$ .
- These values are what we want for the tunable VFO.



# Gain Limiting in Norcal 40

- The gain here is limited by the diode.  $C_1 = C_2$ .  $V_g = 2V_s$
- $V_g = V_f - V$ ,  $V_f$  is the forward voltage of the diode.
- $V_m = V_g + \frac{V}{2}$ , or  $V_m = V_g - \frac{V}{2}$
- $G_m = \frac{I}{V} = \frac{1}{R}$
- $I_d = I_{dss}(1 - \frac{V_{gs}}{V_c})^2$
- $I_o = \frac{I_m}{4}$ ,  $I \approx I_m$
- $G_m = \frac{I_m}{V}$
- Oscillation condition is  $G_m = \frac{1}{R}$



# Exercise 27: Gain limiting

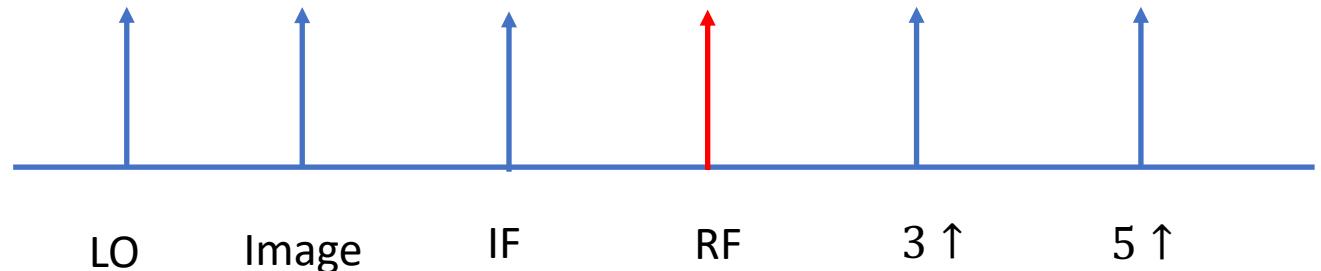
1. Measure the voltage,  $V$ , on  $R_{23}$
2. In deriving the oscillation condition, we neglected the inductor resistance and drain source resistance,  $r_d$ . How does this affect the conditions?  $L_9$  has a Q of 250 and  $r_d = 5k\Omega$ , now what is the predicted  $V$ ?
3. Calculate the loss ratio  $|\frac{V}{V_i}|$ .
4. Measure the temperature dependence of the VFO.
5. How much does the temperature have to change to cause a 100Hz shift?
6. What is the oscillation change if we remove one turn of the inductor?
7. What is the RIT tuning range?

# Gain limiting

- Need measurements

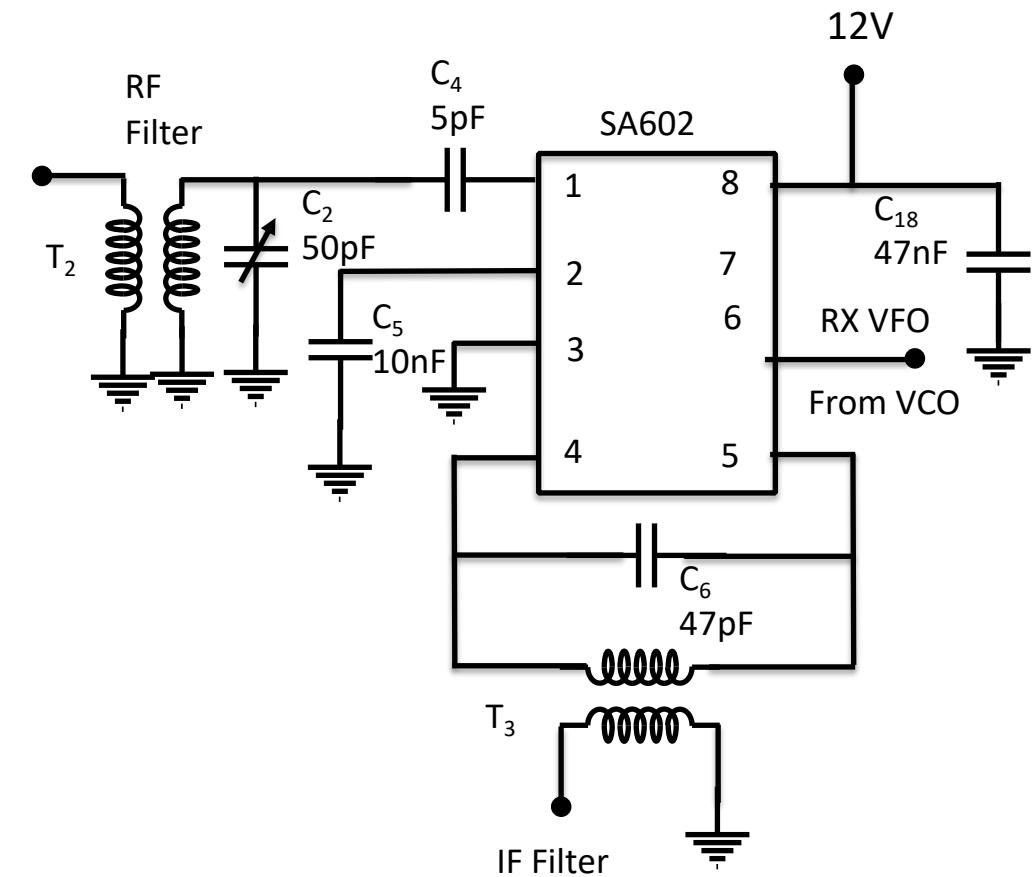
# Mixers

- $V_{lo}(t)$  is a square wave with period  $\omega_{lo}$ . Expanding this in a Fourier series, we get:
- $V_{lo}(t) = \frac{4}{\pi} \left( \cos(\omega_{lo}t) - \frac{\cos(3\omega_{lo}t)}{3} + \frac{\cos(5\omega_{lo}t)}{5} \dots \right)$ ,  $V_{rf}(t) = V_{rf} \cos(\omega_{rf}t)$
- $V_{lo}(t)V_{rf}(t) = \frac{2V_{rf}}{\pi} \left( \cos(\omega_- t) - \frac{\cos(3\omega_- t)}{3} + \frac{\cos(5\omega_- t)}{5} \dots \right) + \frac{2V_{rf}}{\pi} \left( \cos(\omega_+ t) - \frac{\cos(3\omega_+ t)}{3} + \frac{\cos(5\omega_+ t)}{5} \dots \right)$
- $\omega_+ = \omega_{lo} + \omega_{rf}$  and  $\omega_- = |\omega_{lo} - \omega_{rf}|$
- We define  $\omega_{k+} = (k\omega_{lo} + \omega_{rf})$  and  $\omega_{k-} = |k\omega_{lo} - \omega_{rf}|$  and  $V_{k+}(t) = \frac{2V_{rf}}{k\pi} \cos(\omega_{k+}t)$  and  $V_{k-}(t) = \frac{2V_{rf}}{k\pi} \cos(\omega_{k-}t)$
- $\omega_i = \omega_{if} - \omega_{lo}$  and  $\omega_{if} = \omega_{if} + \omega_i$ ,  $\omega_i$  is a spurious signal.  $\omega_{k+}$  and  $\omega_{k-}$  are the spurs from the  $k$ th harmonic



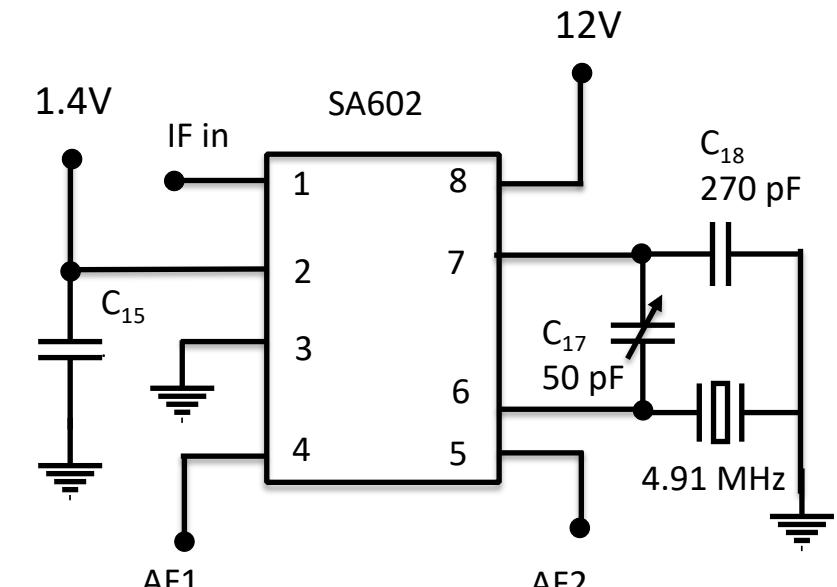
# Exercise 28: Norcal RF Mixer

1. Measure conversion gain of the Mixer.
  2. How much attenuation is provided by pot?
  3. By how many dB is the image response suppressed.  
Look at the spur  $f_{\downarrow 5}$
- Need measurements



# Exercise 29: Norcal Product Detector (1)

1. Adjust C<sub>17</sub> for minimum oscillation frequency and record it.
  2. Calculate the minimum oscillation frequency you'd expect.
  3. Measure the temperature coefficient for the BFO.
  4. Measure the gain through the receiver from the antenna through the product detector.
  5. Find the f<sub>5</sub> spur calculate the expected f<sub>3</sub>.
  6. By how much is the if spur suppressed?
- Need measurements



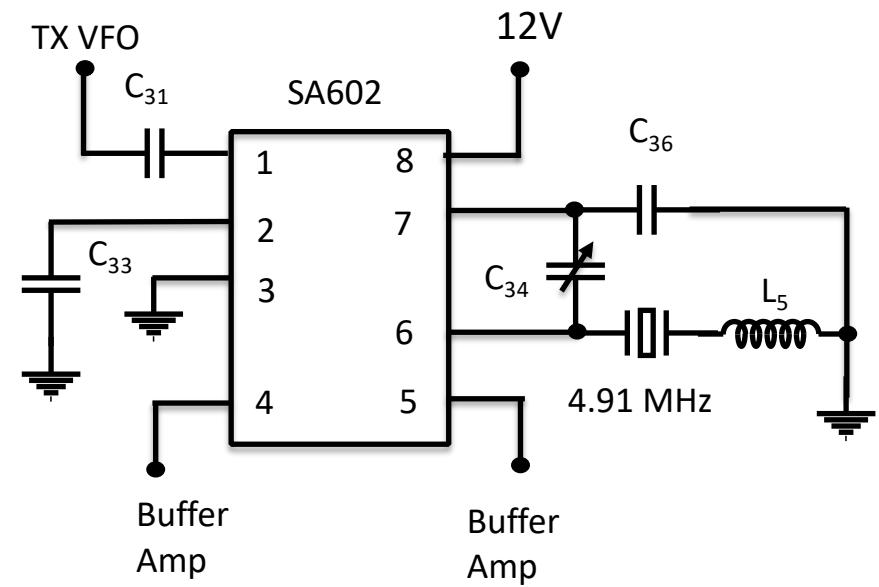
- 620 Hz output through AF1 and AF2

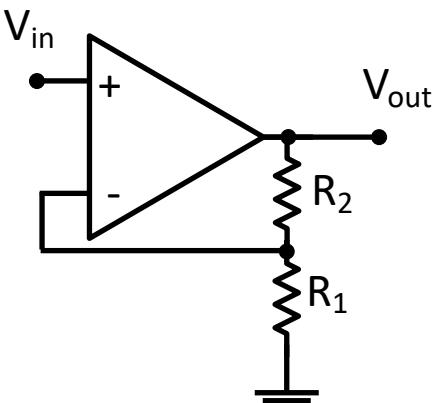
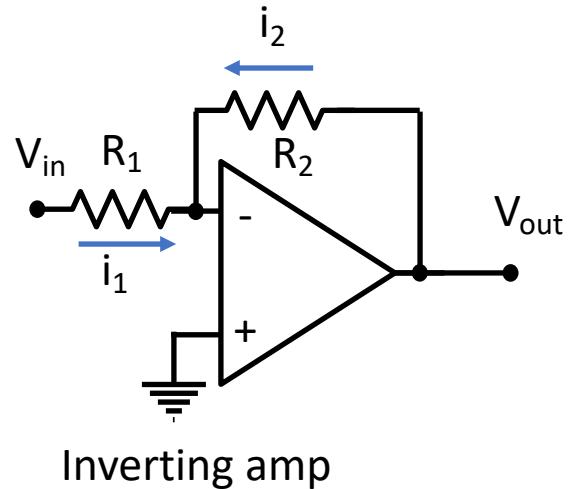
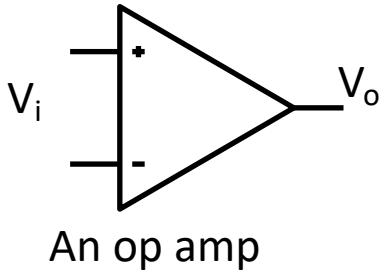
# Norcal Product Detector (2)

x.

# Exercise 30: Norcal transmit mixer and oscillator

1. How much would you expect the inductor to lower the oscillation frequency
  2. Use the TX VFO and the voltage attenuation to calculate the input power from the transmit mixer. Calculate the gain through the entire chain
  3. Measure the rise and fall time of keying response
  4. There is a spurious  $f_{mn} = mf_{vfo} + nf_{to}$ .
- Need measurements





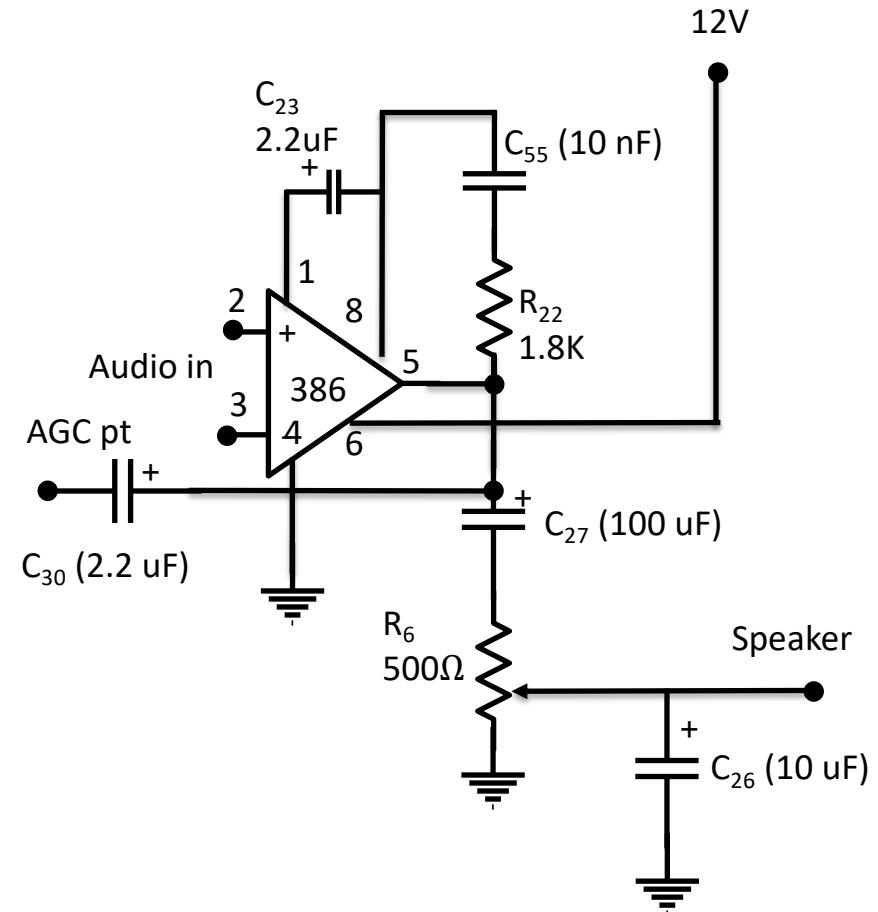
Noninverting amp

# Op Amps

- Ideal op amp
  - $Z_{in} = \infty$
  - $A_V = \frac{V_o}{V_{i,+} - V_{i,-}}$ ,  $A_V$  is an op amp parameter between  $10^4$  and  $10^6$ .
  - $V_- = V_+$  for negative feedback
- Example 1: Inverting amp, we'll show the gain is  $\frac{R_2}{R_1}$ 
  - $i_1 = \frac{V_{in}}{R_1}, i_2 = \frac{V_{out}}{R_2}$  since the op amp has infinite input impedance
  - By Kirchhoff,  $i_1 = -i_2$ , so  $V_{out} = \frac{R_2}{R_1} V_{in}$
  - $Z_{in} = R_1$
  - $Z_{out}$  is same as non-inverting.
- Example 2: Non-inverting amp
  - $V_- = V_+$ , so  $V_{out} = (1 + \frac{R_2}{R_1}) V_{in}$
  - $Z_{in} > 10^6 \Omega$
  - $Z_{out} = \frac{R_{o,Th}}{1+A_V\beta}, \beta = \frac{R_2}{R_1+R_2}$ ,  $R_{o,Th}$  is the Thevenin resistance of the op amp

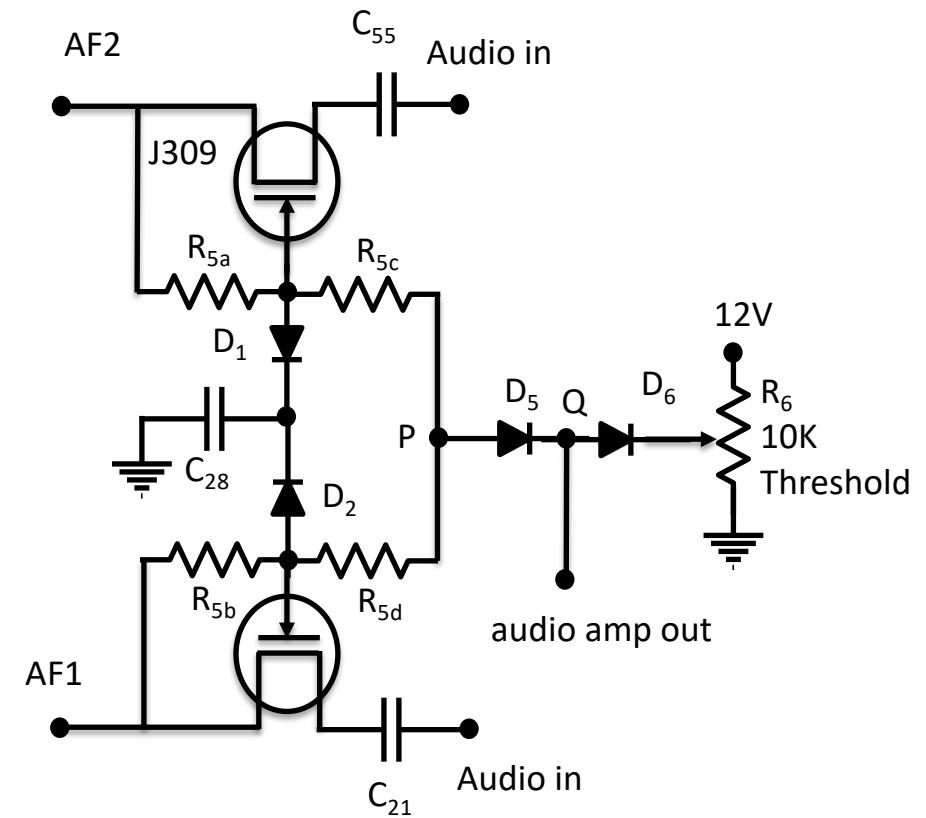
# Exercise 31: Norcal Audio Amp

1. Calculate input  $V_i$  assuming very high input impedance
  2. Measure the voltage gain  $G_v$  at high frequency and 3dB roll-off
- Input impedance is high.
  - The 386 acts like a non-inverting op amp. The internal feedback resistor is  $R_f = 15k\Omega$ .  $G = 2 \frac{R_f}{R_e}$ . With pins 1, 8 open,  $R_e = 1.5k\Omega$ , so  $G = 2 \frac{15}{1.5} = 20$ . pins 1 and 8 go across  $1.35k\Omega$  of  $R_e$ . So, shorting them (using the non-inverting gain circuit) results in a gain of  $G = 2 \frac{15}{.15} = 200$ .

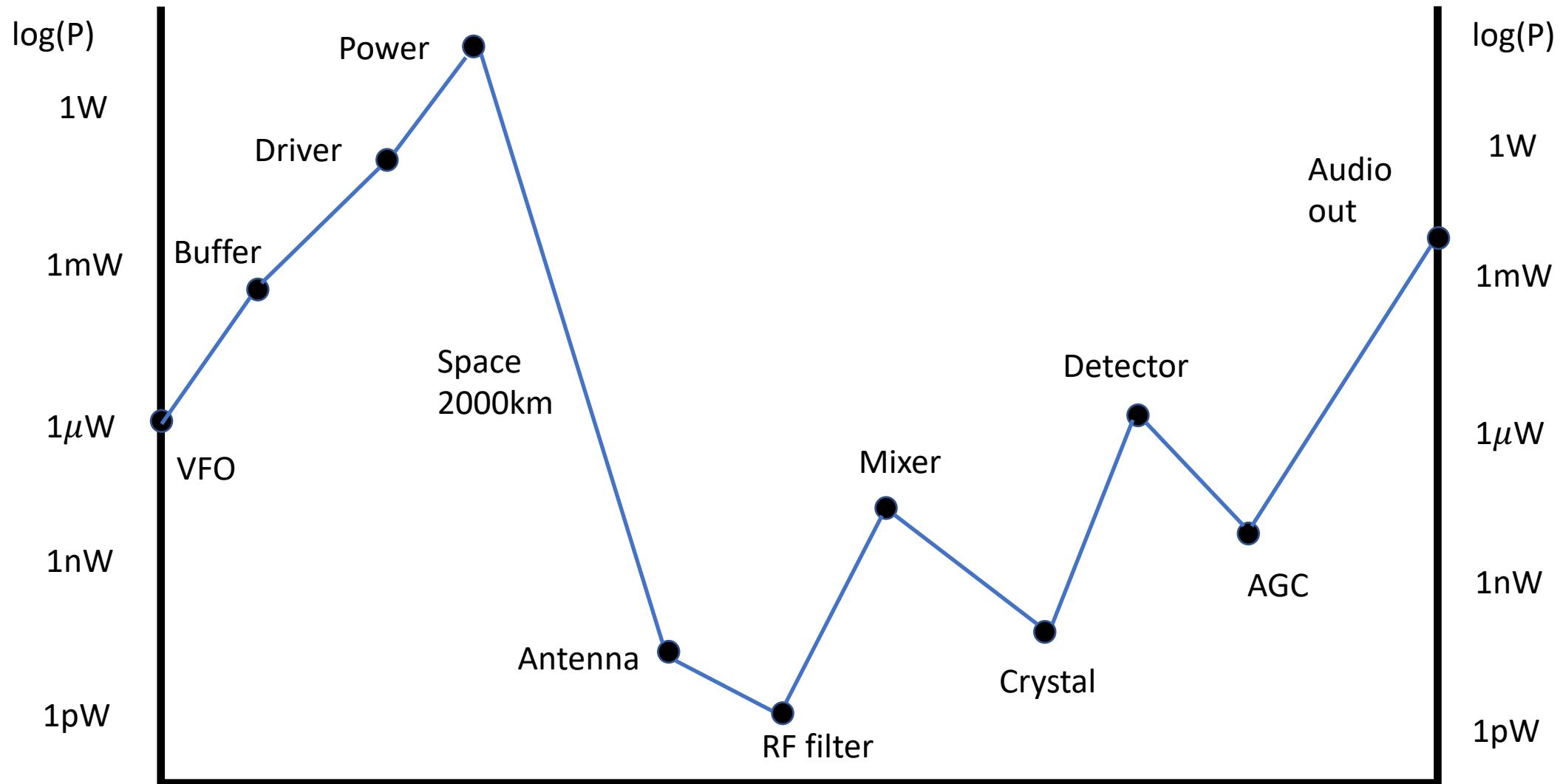


# Exercise 32: Norcal AGC

- Connect function generator through 300K resistor to AF2 (620Hz sine,  $R_6$  fully counterclockwise) and oscilloscope to audio output. Adjust input so output is 1V rms. Connect multimeter to P.
- 1. Plot audio output v dc control
- 2. What is the maximum control voltage we can measure? Infer cutoff voltage  $V_c$
- 3. What is the minimum control voltage?
- Need measurements



# NorCal power levels

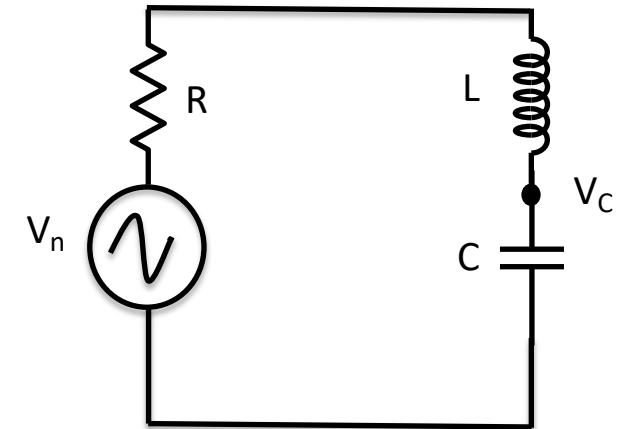


# Noise

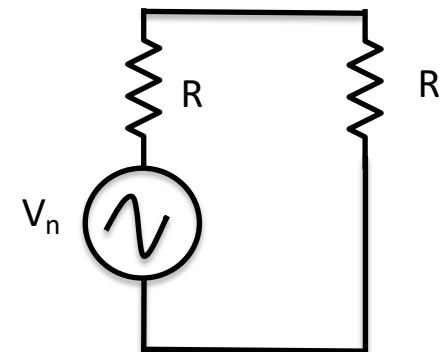
- $V_{n(rms)} = \sqrt{\frac{1}{\tau} \int_0^\tau V(t)^2 dt}$
- Average power:  $P_n = \frac{V_{n(rms)}^2}{R}$ ,  $R$  is load resistance
- $SNR = \frac{P}{P_n}$
- $MDS = \frac{P_n}{G}$
- $P_n = NB$ ,  $N$  is noise power density,  $B$  is bandwidth
- $NEP = \frac{N}{G}$  (Noise equivalent power)
- Noise phasors
  - $\overline{|V_n|^2} = \int |V_n|^2 p dA$
  - $N = \frac{\overline{|V_n|^2}}{2R}$

# Nyquist

- $V_C = \frac{1}{j\omega C} \frac{V_n}{R + j\omega L + \frac{1}{j\omega C}}$
- $\overline{|V_c|^2} = \frac{\overline{|V_n|^2}}{|1 - \omega^2 LC + j\omega RC|^2}$
- Expected the energy stored in C, at resonance is  $kT = \frac{C}{2} \int_0^\infty |V_c|^2 df$ , by equipartition theorem
- $\int_0^\infty \frac{1}{|1 - \omega^2 LC + j\omega RC|^2} df = \frac{1}{4RC}$
- So,  $\overline{|V_n|^2} = 8kTR$ ,  $V_{n(rms)} = \sqrt{4kTR}$
- $N = kT = \frac{\overline{|V_n|^2}}{2R}$  (Noise density)
- $T_e = \frac{N}{k}$
- $T_n = \frac{NEP}{k}$



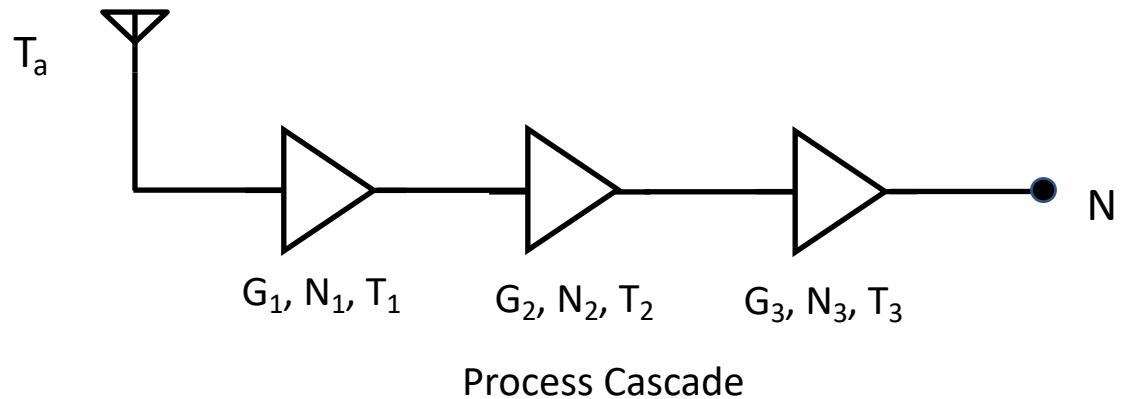
Noise model for R



Matched load

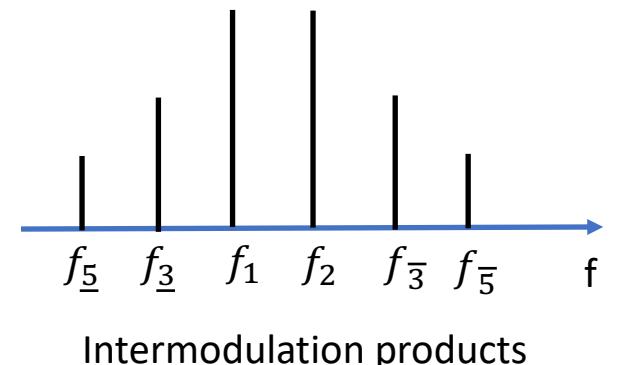
# System noise

- Attenuator (and filter) noise
  - $N_a = kT \left(1 - \frac{1}{L}\right), T_a = T(L - 1)$
- $N = G_3 G_2 G_1 kT_a + G_2 G_3 N_1 + G_3 N_2 + N_3$
- $T_r = T_a + T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2}$
- $\frac{T_n}{T_0} = F - 1, T_0 = 290 K$
- For NorCal,  $L = 3.2$ , each filter has  $T_f = 290(L - 1) = 630K$
- $T_r = T_f + LT_m + \frac{T_f L}{G} + T_m \frac{L^2}{G} = 2780K$
- Want receiver noise << Antenna noise
- For NorCal, antenna noise is at least 30 dB bigger than receiver noise
- To measure noise, inject a signal that doubles the Noise power



# Intermodulation

- If frequency components are  $k_1f_1 + k_2f_2 + \dots + k_nf_n$ , modulation order is  $|k_1| + |k_2| + \dots + |k_n|$
- Intermodulation response
  - $V = G_0V_i + G_2V_i^2 + G_3V_i^3 + \dots$
  - $V_i = V_1\cos(\omega_1t) + V_2\cos(\omega_2t)$
- MDS is where input power ( $P_i$ ) is  $2P_n$ . MDI is where intermodulation power is  $2P_n$ .
- Dynamic range = MDI-MDS.
- Good receivers have DR  $\sim 100dB$

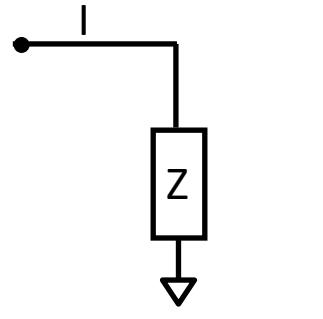


# Antennas

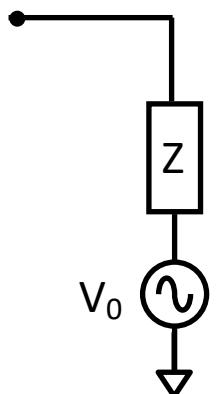
- From Maxwell, for a plane wave ( $E$  in  $x$  direction,  $H$  in  $y$  direction), wave is of form  $\exp(j\omega t - j\beta z)$
- $\nabla \times E = -j\mu_0 \omega H$
- $\nabla \times B = j\epsilon_0 \omega E$
- $\beta \hat{z} \times E = \mu_0 \omega H, \beta E_x \hat{y} = \mu_0 \omega H$
- Substituting and taking the cross product, we get:
  - $\beta E_x = \omega \mu_0 H_y$  and  $\beta H_y = -\omega \epsilon_0 E_x$
  - $\eta_0 = \frac{E_x}{H_y} = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377\Omega$
- Write  $\beta = \omega \sqrt{\mu_0 \epsilon_0}$
- Power density:  $S = \text{Re} \left( \frac{E_x \bar{H}_y}{2} \right) = \frac{(|E_x|)^2}{2\eta_0}$

# Transmitting Antennas

- Antenna Impedance:  $P_t = \frac{R|I|^2}{2}$ ,  $R$  is real part of  $Z$ ,
- $R = R_r + R_l, \eta = \frac{R_r}{R}$
- Power density for isotropic antenna:  $S_i = \frac{P_t}{4\pi r^2}$
- Define  $G(\theta, \phi) = \frac{S(\theta, \phi)}{S_r}$ .  $S(\theta, \phi)$  is just the Poynting vector
- $G = \frac{S}{S_i} = \frac{4\pi r^2 S}{P_t}$
- Note:  $r^2 d\Omega = dA, d\Omega = d\varphi d(\cos(\theta)) = \sin(\theta) d\varphi d\theta, \int d\Omega = 4\pi$
- $\int G d\Omega = \int S(\theta, \phi) \frac{4\pi r^2}{P_t} d\Omega = \frac{4\pi}{P_t} \int S(\theta, \phi) \frac{r^2}{P_t} d\Omega$ . But  $S_\Omega(\theta, \phi) = r^2 S(\theta, \phi)$ , so
- $\int G d\Omega = \frac{4\pi}{P_t} \int S_\Omega(\theta, \phi) d\Omega = 4\pi$



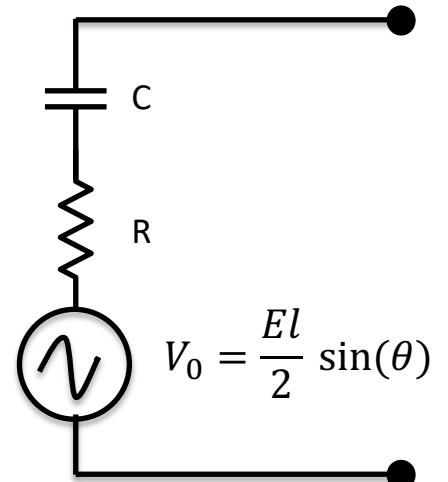
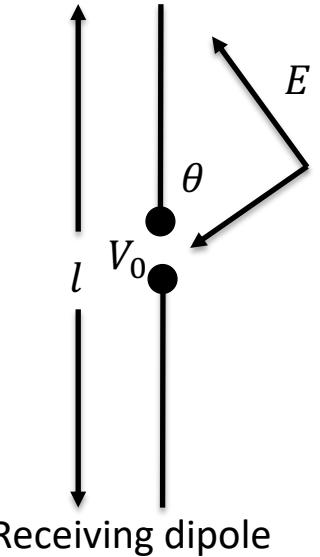
Transmitting Antenna



Receiving Antenna

# Receiving Antenna

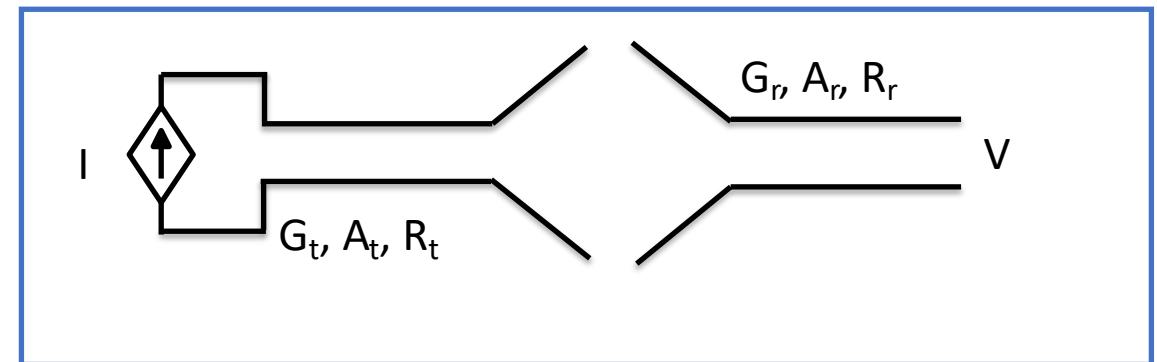
- $V_0 = hE$ ,  $h$  is effective antenna length ( $h = \frac{l}{2}$  for short antenna)
- For dipole:  $V_0 = \frac{l}{2} E \sin(\theta)$ ,  $h = \frac{l}{2} \sin(\theta)$
- $A(\theta, \phi) = \frac{P_r}{S(\theta, \phi)}$ . This is the definition of the effective area,  $A$ .
- By reciprocity,  $A(\theta, \phi) = \frac{\lambda^2}{4\pi} G(\theta, \phi)$
- $P_r = \frac{|V_0|^2}{8R_a} = \frac{|hE|^2}{8R_a}$ , so
- $P_r = \frac{h^2 S \eta_0}{4R}$
- $A = \frac{h^2 \eta_0}{4R}$



Dipole Thevenin equivalent circuit

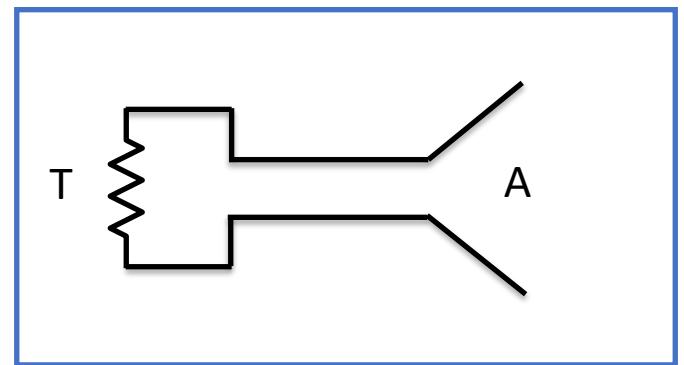
# Friis

- For transmitting/receiving antenna pairs:
  - $G_1 A_2 = \frac{|V|^2 \pi r^2}{|I|^2 R_1 R_2} = G_2 A_1.$
  - So  $\frac{G_1}{A_1} = \frac{G_2}{A_2} = \frac{4\pi}{\lambda^2}$
  - $S = \frac{P_t G}{4\pi r^2}$
  - $P_r = S A = \frac{P_t G A}{4\pi r^2}$ . --- Friis radiation formula
  - For us,  $G = 1, A = 150 \text{ m}^2, r = 2000 \text{ km}, P_t = 2 \text{ W}$
  - $P_r = 6 \text{ pW}$



# Antenna Theorem

- Antenna theorem:  $\oint A \cdot d\Omega = \lambda^2$
- For cavity on right, T is constant at thermodynamic equilibrium and the same power is emitted and absorbed, the Johnson noise is  $kT$ . The energy received is
  - $E = \frac{4\pi kT}{c\lambda^2}$ .
  - Set  $B = \frac{kT}{\lambda^2}$ .
  - $kT = \oint BA \cdot d\Omega = \oint A \frac{kT}{\lambda^2} d\Omega$ , which gives the antenna theorem



Insulated cavity

# Reciprocity

- *Reciprocity:* The position of an ideal voltmeter and ideal current source can be interchanged without changing the voltmeter reading.

- $P_t = |I|^2 \frac{R_1}{2}$

- $P_r = \frac{P_t G_1 A_2}{4\pi r^2}$ , by Friis

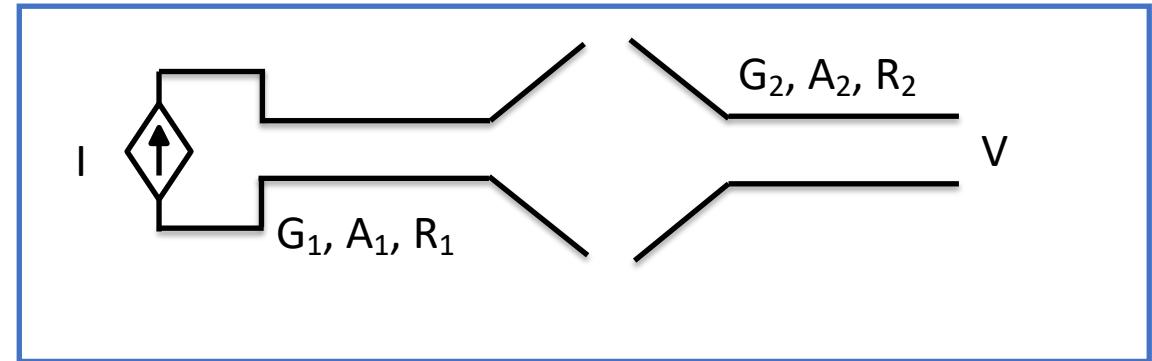
- $P_r = \frac{|V|^2}{8R_2}$

- $\frac{|V|^2}{8R_2} = \frac{|I|^2 R_1 G_1 A_2}{8\pi r^2}$

- $\frac{|V|^2 \pi r^2}{|I|^2 R_1 R_2} = G_1 A_2$ , so  $G_1 A_2 = G_2 A_1$  or  $\frac{G_1}{A_1} = \frac{G_2}{A_2} = \frac{G}{A}$

- $\int G d\Omega = 4\pi$  and by the Antenna theorem,  $\int A d\Omega = \lambda^2$ , so

- $\frac{G}{A} = \frac{4\pi}{\lambda^2}$



# Reciprocity and dipoles

- For dipole (Length:  $l = \frac{\lambda}{2}$ )
- $\lambda^2 = \int A d\Omega = \int \frac{h^2 \eta_0}{4R_r} d\Omega$ , so
- $R_r = \frac{l^2 \eta_0}{16\lambda^2} \int \sin^2(\theta) d\Omega = \eta_0 \frac{\pi}{6} \left(\frac{l}{\lambda}\right)^2$
- Put  $\eta_0 = 120\pi$ ,  $R_r = 20\pi^2 \frac{l^2}{\lambda^2}$  and  $A = \frac{3\lambda^2}{8\pi} \sin^2(\theta)$
- $G = 1.5 \sin^2(\theta)$ . Note we used  $h = \frac{l}{2} \sin(\theta)$

# Exercise 35: Intermodulation

- Only  $f_{3\uparrow} = 2f_1 - f_2, f_{3\downarrow} = 2f_2 - f_1, f_{5\uparrow} = 3f_1 - 2f_2$  and  $f_{5\downarrow} = 3f_2 + 2f_1$  are close enough to the rf frequency to matter for intermodulation
- 1. Find coefficients and frequencies for  $[\cos(\omega_1 t) + [\cos(\omega_2 t)]^5$
- 2. Find  $f_{3\uparrow}, f_{3\downarrow}, f_{5\uparrow}$  and  $f_1$
- 3. Find the MDS and the antenna limited MDR
- $MDS = \frac{P_n}{G}$ , MDI is input that gives output tone +  $2P_n$
- $MDR = MDI - MDS$
- This needs measurements to measure the minimum detectable signal.

# Exercise 37: Antennas

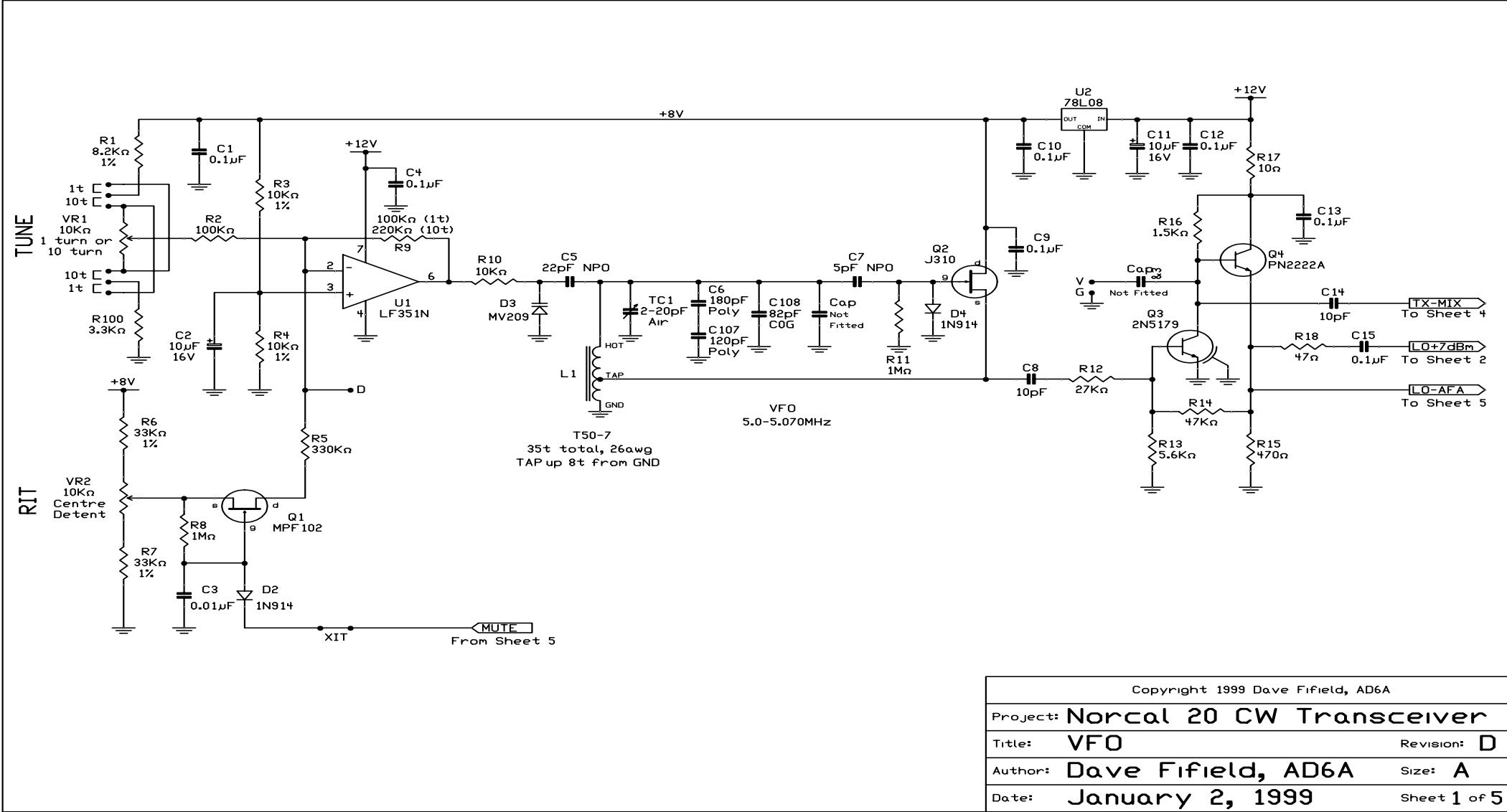
1. Use the relation between gain and effective area to rewrite the Friis transmission formula in terms of gain only. Consider UHF for airplanes. If the frequency makes the quarter length stub antenna have gain 2, find the maximum possible LOS at 10km height. Required receiver power is  $-90$  dBm. Find the minimum transmission power.

- Friis radiation formula is  $P_r = \frac{P_t G A}{4\pi r^2}$ ,  $\lambda = \frac{c}{f}$  and  $\frac{G}{A} = \frac{4\pi}{\lambda^2}$ , so  $P_r = P_t \left( \frac{G c}{4\pi r f} \right)^2$
- $P_r$  requires  $-90$  dBm power.  $-90 = 10 \log \left( \frac{P_r}{1mW} \right)$ , so  $P_r$  must be at least  $10^{-12} W$ .
- $P_t(f) = \left( \frac{4\pi r f}{G c} \right)^2 \times 10^{-12} W$ .  $P_t(10^8) = 4.4mW$ ,  $P_t(2 \times 10^8) = 19.24mW$ ,  $P_t(3 \times 10^8) = 40mW$  and  $P_t(10^9) = 440mW$ .

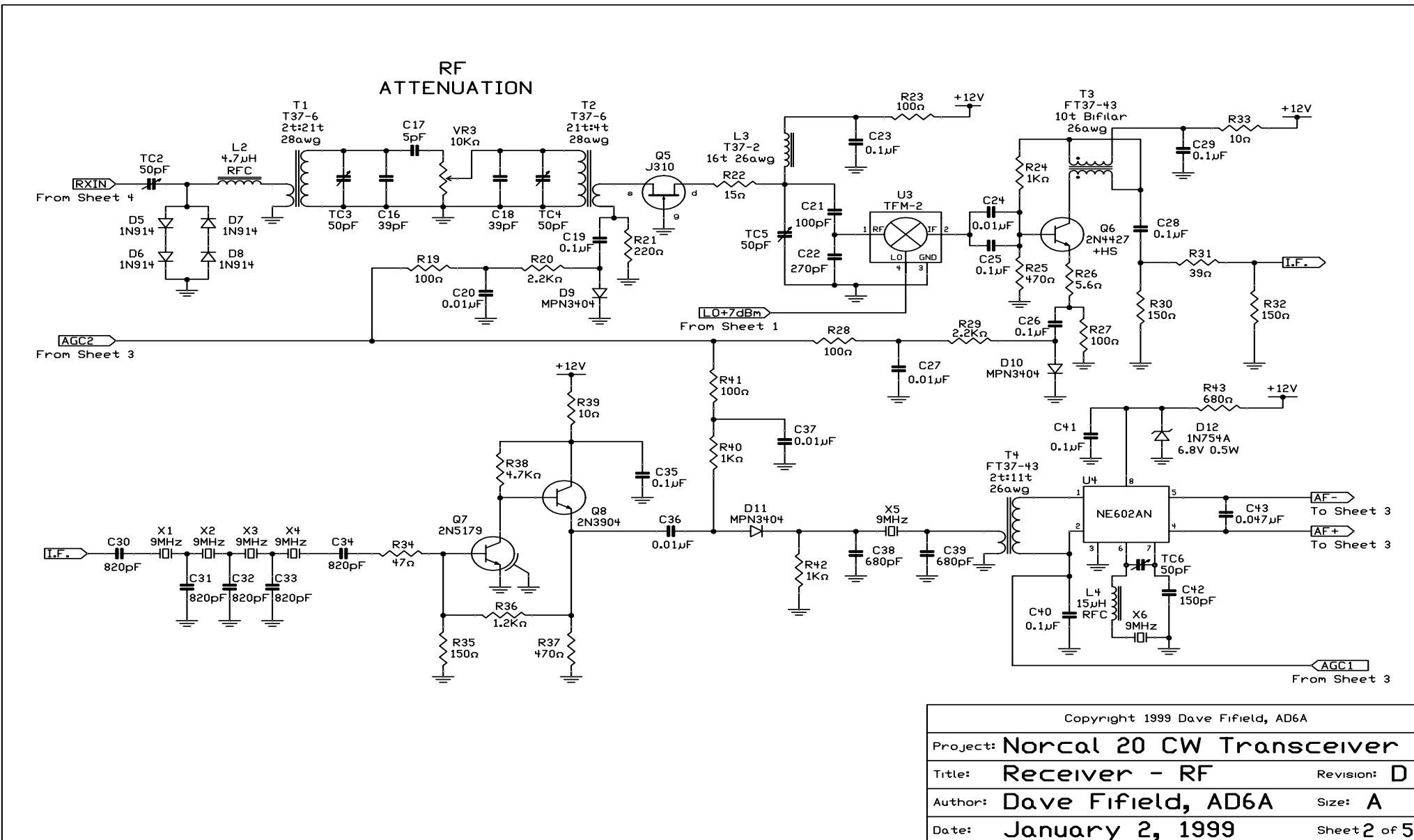
2. Find the inductance to resonate with a 3m whip. Assuming the Q of the coil is 200, find the turns ratio required to give a transceiver a 50 ohm load. What is the radiation efficiency?

- For whip,  $R_r = 160\pi^2 \left( \frac{l}{\lambda} \right)^2 \approx 7.8\Omega$ .  $Q = 200 = \frac{L}{7.8}$ .  $L = 1551\Omega$ .
- $Z_s = 7.8 + 1551j$ .  $L = 3.6\mu H$
- $\frac{1551}{50} = \frac{Z_p}{Z_s} = \left( \frac{N_p}{N_s} \right)^2$ ,  $\frac{N_p}{N_s} = \sqrt{31} = 5.2$ .
- Radiation efficiency is  $\frac{P_{radiated}}{P_{input}} = \frac{R_r}{R_r + R_L} = \frac{7.8}{57.8} \approx .14$

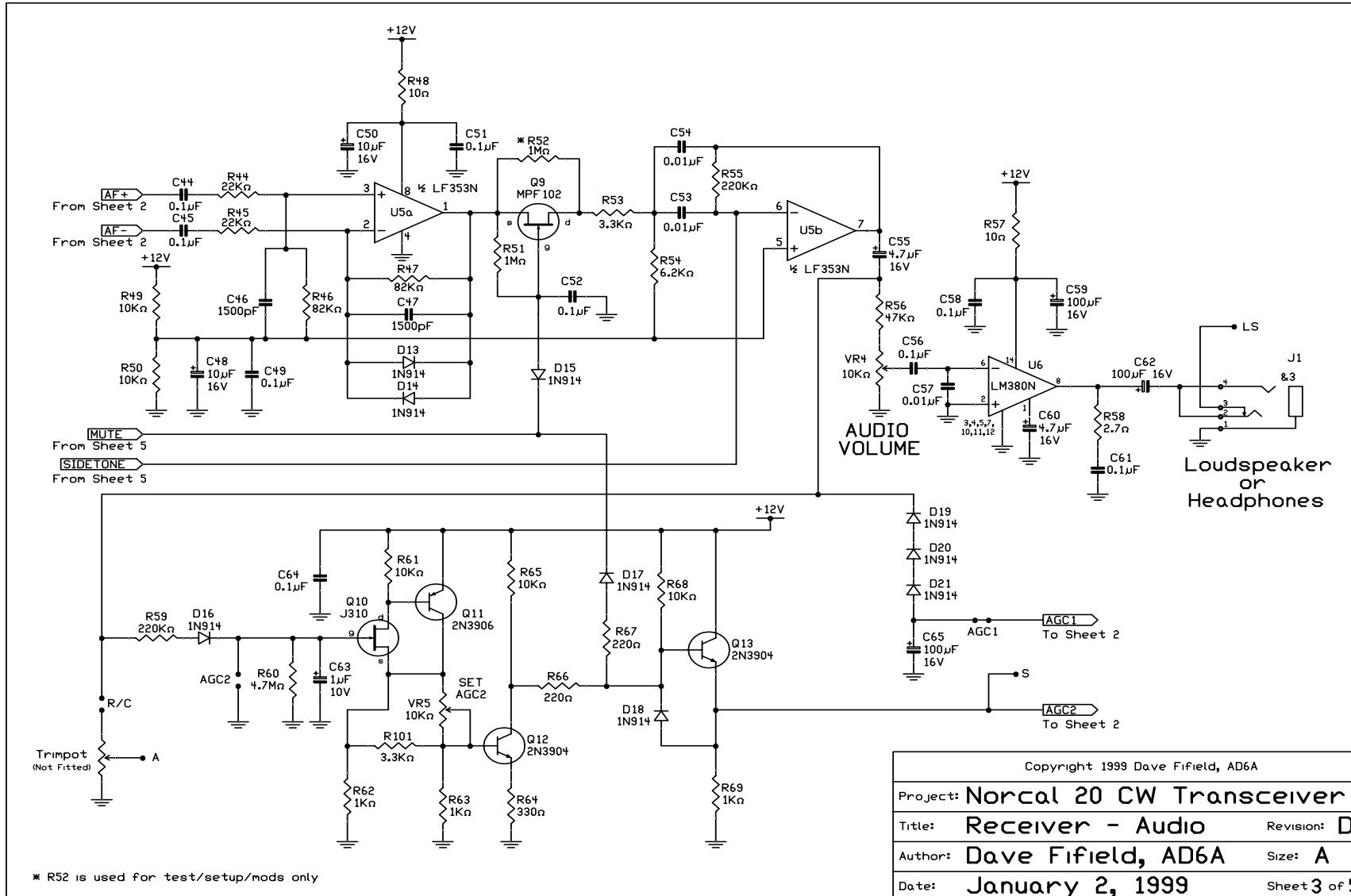
# Norcal circuit diagram, 1



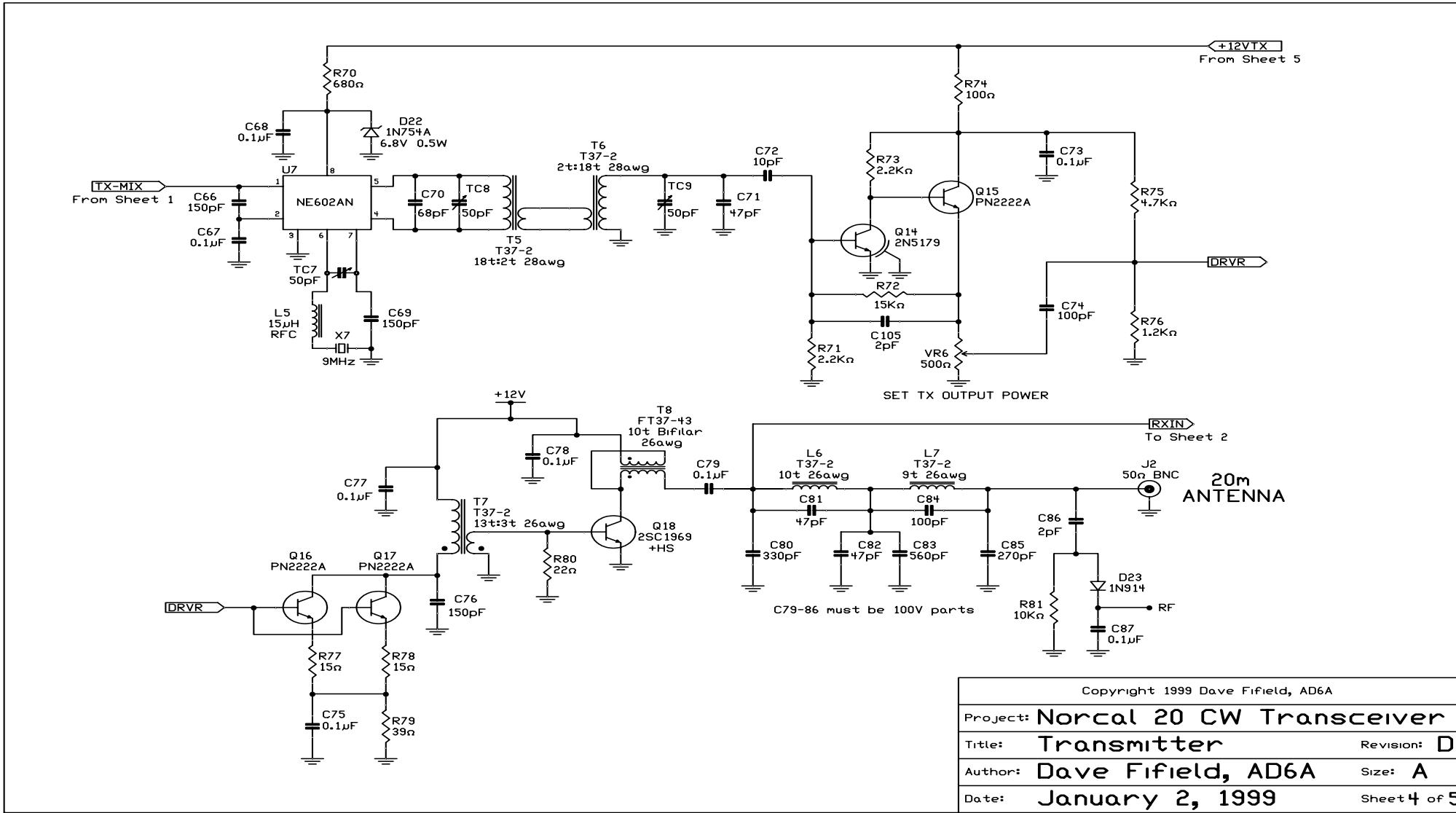
# Norcal circuit diagram, 2



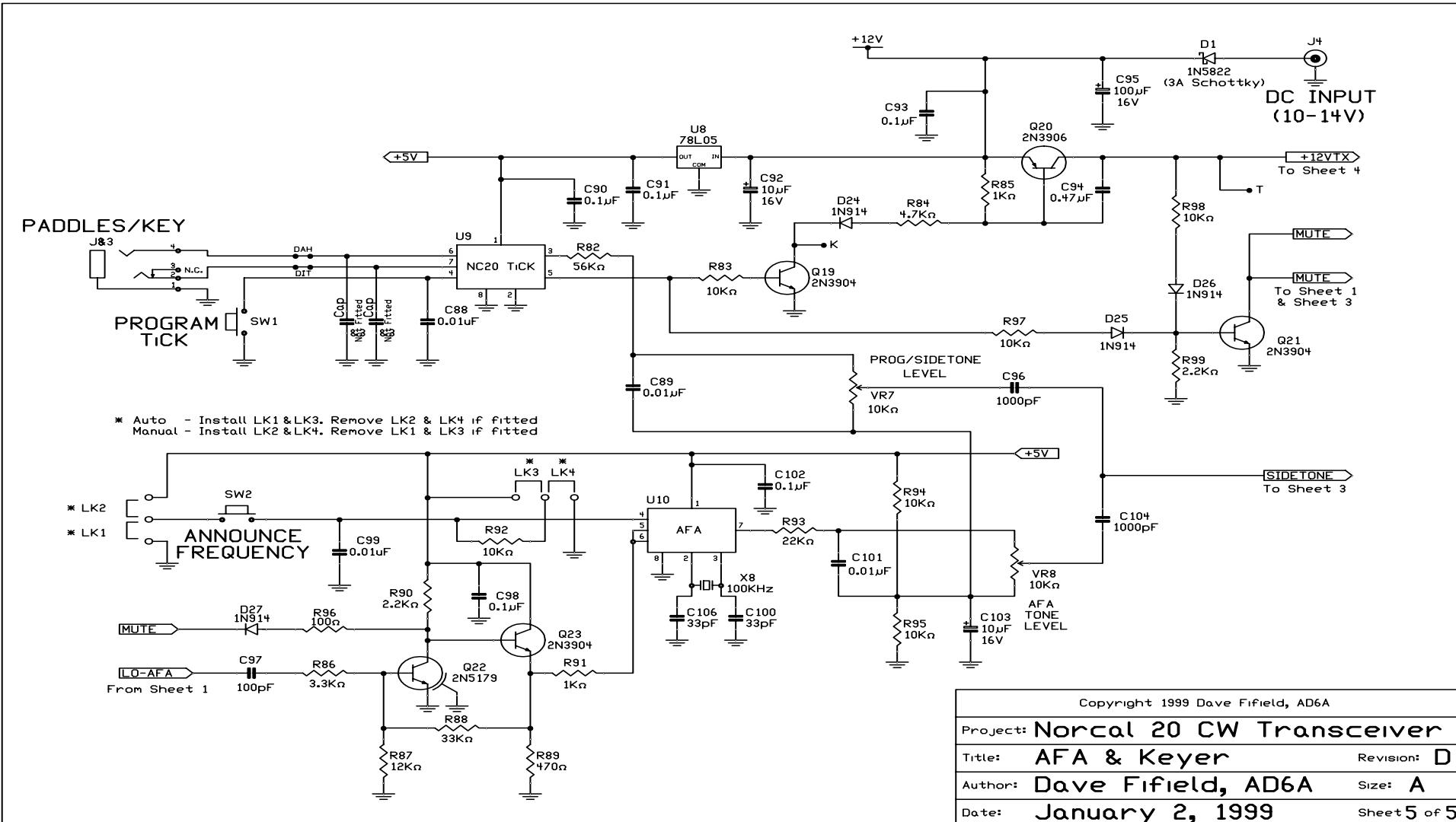
# Norcal circuit diagram, 3



# Norcal circuit diagram, 4



# Norcal circuit diagram, 5



# Appendix

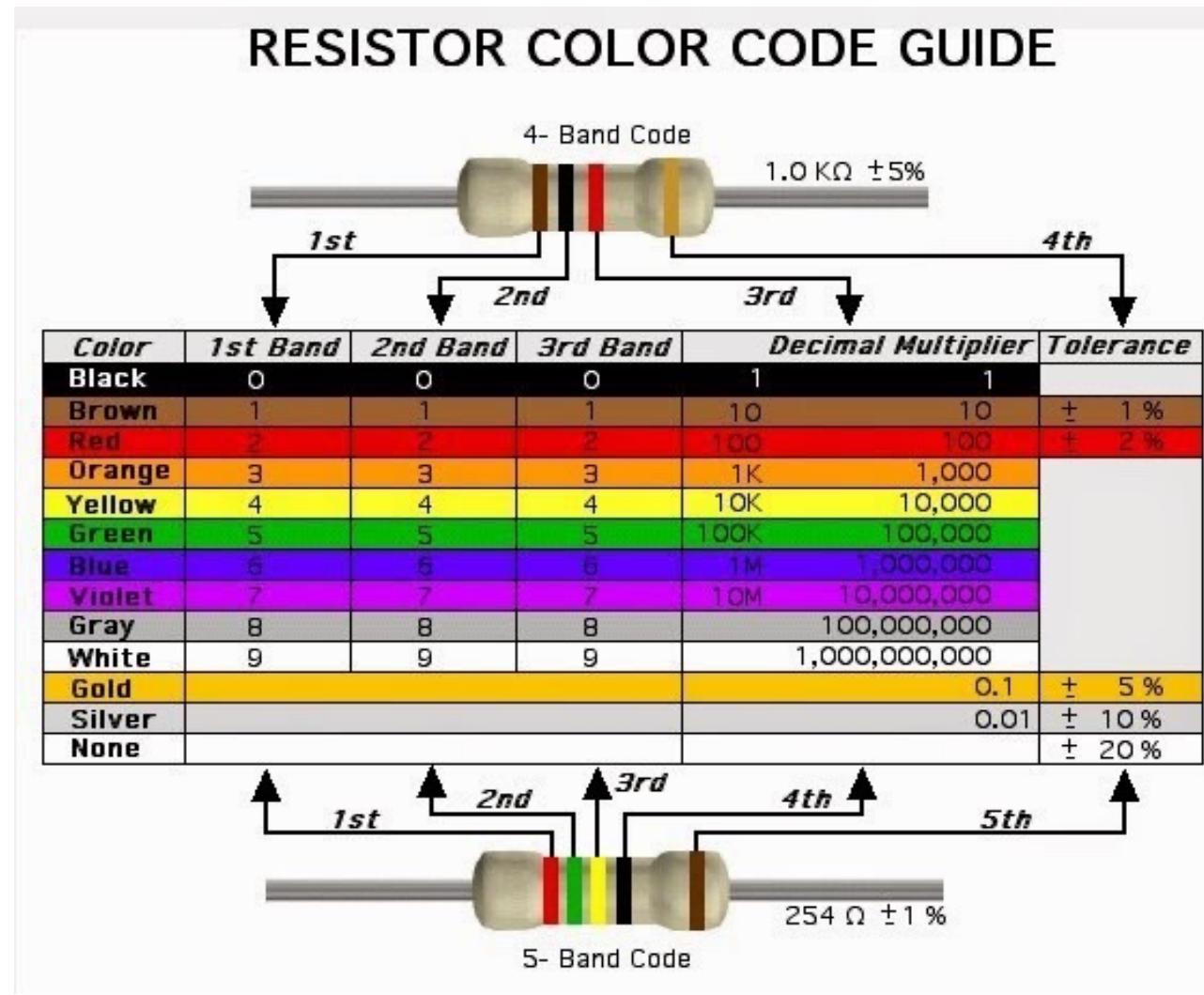
# Exercise 17: Tuned Speaker

- Connect speaker to function generator 600Hz, 25mVrms.
1. Sound peaks at resonance. Find resonant frequency  $L_p$ .
  2. Measure  $f_l$ ,  $f_u$  by noting the 3dB loss. Calculate Q.
  3. Use voltmeter to find resonance with speaker (nominally 8ohm) to calculate impedance
  4. Calculate the resonant frequency from a transmission line equivalent circuit.

# Morse

Symbol	Code	Symbol	Code	Symbol	Code
a	.—	m	—	y	—.—
b	—...	n	—.	z	—..
c	—.-	o	---	0	----
d	—..	p	.—.	1	.----
e	.	q	—.-	2	..----
f	..—.	r	—.	3	...--
g	—.	s	...	4	....-
h	....	t	—	5	.....
i	..	u	..—	6	—....
j	.—	v	...—	7	—...
k	—.-	w	—.	8	—..
l	—..	x	—..—	9	-----.

# Color codes



- Resistors markings in ohms
- Capacitors markings in picoFarads
- Inductors markings in microHenries

# Component data



Core Size	26	3	15	1	2	6	10	12/17	0
T-12-( )	*	60	50	48	20	17	12	7.5	2.4
T-16-( )	145	61	55	44	22	19	13	8	3
T-20-( )	185	76	65	52	25	22	16	10	3.5
T-25-( )	245	100	85	70	34	27	19	12	4.5
T-30-( )	335	140	93	85	43	36	25	16	6
T-37-( )	285	120	90	80	40	30	25	15	4.9
T-44-( )	370	180	160	105	52	42	33	18.5	6.5
T-50-( )	330	175	135	100	49	40	31	18	6.4
T-68-( )	435	195	180	115	57	47	32	21	7.5
T-80-( )	460	180	170	115	55	45	32	22	8.5
T-94-( )	600	248	200	160	84	70	58	*	10.6
T-106-( )	930	450	345	325	135	116	*	*	19
T-130-( )	810	350	250	200	110	96	*	*	15
T-157-( )	1000	420	*	320	140	115	*	*	*
T-184-( )	1690	720	*	500	240	195	*	*	*
T-200-( )	920	425	*	250	120	100	*	*	*
T-200A-( )	1600	*	*	*	218	*	*	*	*

## IRON POWDER TOROIDS - A, Values \*\*

\* size not available in this material

\*\* L =  $\mu\text{H}/100 \text{ turns}$

# In the beginning...

- The laws of EM according to Clerk Maxwell are:

$$1. \nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$2. \nabla \cdot \mathbf{B} = 0$$

$$3. \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$4. c^2 \nabla \times \mathbf{B} = \frac{\mathbf{j}}{\epsilon_0} + \frac{\partial \mathbf{E}}{\partial t}, \epsilon_0 = 8.854 \times 10^{-12} \frac{C^2}{N \cdot m^2}, \frac{1}{c^2} = \epsilon_0 \mu_0$$

$$5. \nabla \cdot \mathbf{j} = -\frac{\partial \rho}{\partial t}$$

- Here  $\mathbf{E}$  is the electric field,  $\mathbf{B}$  is the magnetic field,  $\mathbf{j}$  is the current density through a closed surface,  $c$  is the speed of light and  $\rho$  is the charge density at a point.
- In non-dispersive matter,  $B = \mu H = \mu_0(H + M)$ ,  $\mu = \mu_0(1 + \chi_m)$ ,
- $D = \epsilon E = \epsilon_0 E + P$ ,  $\epsilon = \kappa \epsilon_0$  and (1) becomes  $\nabla \cdot \mathbf{D} = \rho_f$ , (4) becomes  $\nabla \times \mathbf{H} = \mathbf{j}_f + \frac{\partial \mathbf{D}}{\partial t}$

- The rest of classical physics, including special relativity, is:

- Newton-Einstein:  $\mathbf{p} = m\mathbf{v}$ ,  $m = \frac{m_0}{\sqrt{1 - (\frac{v}{c})^2}}$ ,  $\mathbf{F} = m \frac{d\mathbf{p}}{dt}$ .

- Gravity:  $\mathbf{F} = -\frac{Gm_1 m_2}{r^2} \mathbf{u}_r$  where  $\mathbf{u}_r$  is the unit vector from  $m_1$  to  $m_2$  and  $\mathbf{F}$  is the force on  $m_2$ .

# Solutions to the wave equation

- The solution of  $\nabla^2\psi - \frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} = -s$  is  $\psi(x, y, z, t) = \frac{s(t-\frac{r}{c})}{4\pi r}$  where  $S = \int_V s dV$
- Later, we will use this to find the "general" solution to Maxwell's equations
  - $\phi(r_1, t) = \int_{V_2} \frac{\rho(r_2, t-\frac{|r_1-r_2|}{c})}{4\pi\epsilon_0|r_1-r_2|} dV_2$  and  $\mathbf{A}(r_1, t) = \int_{V_2} \frac{\mathbf{j}(r_2, t-\frac{|r_1-r_2|}{c})}{4\pi\epsilon_0 c^2|r_1-r_2|} dV_2$ , where
  - $B = \nabla \times A$ ,  $E = -\nabla\phi - \frac{\partial A}{\partial t}$ , and  $c^2\nabla \cdot A = -\frac{\partial \phi}{\partial t}$
- You are not expected to have guessed this answer
- To do this, we'll need the "BAC-CAB" identity:  $A \times (B \times C) = B(A \cdot C) - C(A \cdot B)$
- When we apply this to  $\nabla \times (\nabla \times \mathbf{A})$ , we get  $\nabla \times (\nabla \times \mathbf{A}) = \nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A}$

# General solution to Maxwell's equations

- Returning to the general Maxwell equations, from  $\nabla \cdot B = 0$ , we get  $B = \nabla \times A$
- Substituting into  $c^2 \nabla \times \mathbf{B} = \frac{\mathbf{j}}{\epsilon_0} + \frac{\partial \mathbf{E}}{\partial t}$ , we get  $c^2 \nabla \times (\nabla \times A) = \frac{\mathbf{j}}{\epsilon_0} + \frac{\partial \mathbf{E}}{\partial t}$
- Applying “BAC-CAB”, we get  $\nabla(\nabla \cdot A) - \nabla^2 A = \frac{\mathbf{j}}{c^2 \epsilon_0} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}$  (Equation 1)
- Now,  $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ , so substituting for  $\mathbf{B}$ , we get  $\nabla \times \left( \mathbf{E} + \frac{\partial \mathbf{A}}{\partial t} \right) = 0$  and so  $\mathbf{E} = -\nabla \phi - \frac{\partial \mathbf{A}}{\partial t}$
- Substituting into equation 1,  $\nabla(\nabla \cdot A) - \nabla^2 A = \frac{\mathbf{j}}{c^2 \epsilon_0} + \frac{1}{c^2} \frac{\partial}{\partial t} \left( -\nabla \phi - \frac{\partial \mathbf{A}}{\partial t} \right)$ , or
- $\nabla(\nabla \cdot A) - \nabla^2 A = \frac{\mathbf{j}}{c^2 \epsilon_0} - \frac{1}{c^2} \nabla \frac{\partial \phi}{\partial t} - \frac{1}{c^2} \frac{\partial^2 A}{\partial t^2}$ .
- $\nabla^2 A - \frac{1}{c^2} \frac{\partial^2 A}{\partial t^2} = -\frac{\mathbf{j}}{c^2 \epsilon_0} + \nabla \left[ \frac{1}{c^2} \frac{\partial \phi}{\partial t} + (\nabla \cdot A) \right]$
- Now if  $A$  and  $\phi$  give  $B = \nabla \times A$  and  $E = -\nabla \phi - \frac{\partial A}{\partial t}$ , then  $A' = A + \nabla \varphi$  and  $\phi' = \phi - \frac{\partial \varphi}{\partial t}$  give  $B = \nabla \times A'$  and  $E = -\nabla \phi' - \frac{\partial A'}{\partial t}$ , for any function  $\varphi$

# General solution to Maxwell's equations

- Thus, we can pick a solution  $(A, \phi)$  with  $\nabla \cdot A = -\frac{1}{c^2} \frac{\partial \phi}{\partial t}$ . Then we get
- $\nabla^2 A - \frac{1}{c^2} \frac{\partial^2 A}{\partial t^2} = -\frac{j}{c^2 \epsilon_0}$
- Substituting for  $E = -\nabla \phi - \frac{\partial A}{\partial t}$  into  $\nabla \cdot E = \frac{\rho}{\epsilon_0}$ , we get
- $\nabla \cdot (\nabla \phi) + \frac{\partial \nabla \cdot A}{\partial t} = -\frac{\rho}{\epsilon_0}$ , or  $\nabla \cdot (\nabla \phi) - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = -\frac{\rho}{\epsilon_0}$ , or  $\nabla^2 \phi - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = -\frac{\rho}{\epsilon_0}$
- The solutions are  $\phi(r_1, t) = \int_{V_2} \frac{\rho(r_2, t - \frac{|r_1 - r_2|}{c})}{4\pi\epsilon_0 |r_1 - r_2|} dV_2$  and
- $\mathbf{A}(r_1, t) = \int_{V_2} \frac{\mathbf{j}(r_2, t - \frac{|r_1 - r_2|}{c})}{4\pi\epsilon_0 c^2 |r_1 - r_2|} dV_2$  with  $\nabla \cdot A = -\frac{1}{c^2} \frac{\partial \phi}{\partial t}$ , with  $\nabla \cdot A = -\frac{1}{c^2} \frac{\partial \phi}{\partial t}$ .

# Solution to Maxwell's equations in free space

- Free space is defined by  $\rho = 0$  and  $j = 0$ , so our potentials satisfy
- $\nabla^2 A - \frac{1}{c^2} \frac{\partial^2 A}{\partial t^2} = 0$  and  $\nabla^2 \phi - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = 0$
- These have the usual wave equation solutions  $\phi(x, y, z, t) = f(k \cdot r - \omega t)$ , etc
- Thus, in free space  $\phi$  and  $\mathbf{A}$  and hence  $\mathbf{E}$  and  $\mathbf{B}$  propagate as waves.

# Solution to Maxwell's equations in conductors

- In conductors,  $\mathbf{j} = \sigma \mathbf{E}$ 
  - $c^2 \nabla \times \mathbf{B} = \frac{\mathbf{j}}{\epsilon} + \frac{\partial \mathbf{E}}{\partial t} = \frac{\sigma}{\epsilon} \mathbf{E} + \frac{\partial \mathbf{E}}{\partial t}$
  - This becomes  $c^2 \frac{\partial(\nabla \times \mathbf{B})}{\partial t} = \frac{\sigma}{\epsilon} \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial^2 \mathbf{E}}{\partial t^2}$
  - $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ , so we get  $c^2 \nabla \times \frac{\partial \mathbf{B}}{\partial t} = -c^2 \nabla \times (\nabla \times \mathbf{E}) = \frac{\sigma}{\epsilon} \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial^2 \mathbf{E}}{\partial t^2} = -c^2 [\nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E}] = c^2 \nabla^2 \mathbf{E}$   
(since  $\rho = 0$  in a conductor)
  - Applying the trial solution  $\mathbf{E} = E_0 \exp(i\omega t - kr)$ , we get  $-k^2 - i\omega\mu\sigma + \omega^2\mu\epsilon = 0$ .
  - Putting  $k = \alpha - \beta i$ ,  $\alpha = \frac{\omega}{2} \sqrt{\mu\epsilon} \left(1 + \sqrt{1 + \frac{\sigma^2}{\omega^2\epsilon^2}}\right)$  and  $\beta = \frac{\omega\mu\sigma}{2\alpha}$ .
  - For copper,  $\sigma = 5.78 \times 10^7 \Omega^{-1}\text{-m}$ . This explains the “skin effect” in conductors.

# Radiation, antennas

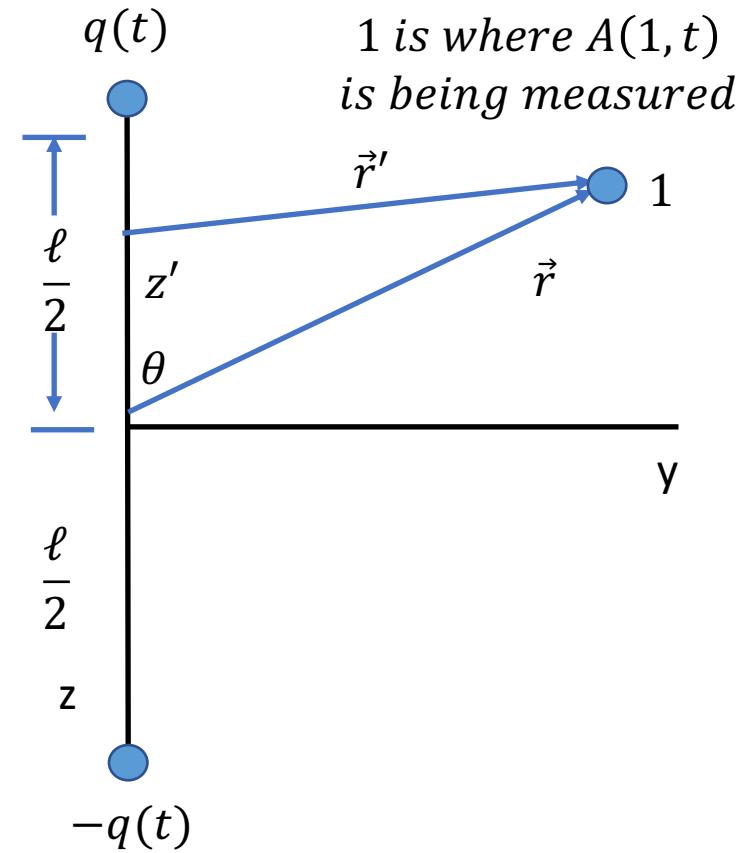
- Accelerating charges radiate energy in the form of electromagnetic waves (companion E and B fields).
- The radiation from accelerating charge  $q$  is  $\mathbf{E}_{rad} = -\frac{1}{4\pi\epsilon_0 c^2} \frac{q}{r} \mathbf{a}_\perp (t - \frac{r_{12}}{c})$ .
- Here,  $\mathbf{a}_\perp$  is the acceleration  $\perp$  to the line from  $\mathbf{r}_1$  to  $\mathbf{r}_2$ .
- For example, applying a time varying potential  $V_0 \sin(\omega t)$  to an antenna will cause the antenna to radiate power since the voltage and hence charges affected accelerate within the antenna, that is, their positions have a non-zero second derivative. That's how a transmitter "couples" to the antenna of a receiver. In the receiver, the radiated wave accelerates charges in the antenna replicating the original wave (at much reduced power).
- These simple radio waves are carrier waves of frequency  $\frac{\omega}{2\pi}$ . To transfer information (voice, images, binary data), we modulate carrier waves combining them with an "information source" signal. Receivers demodulate the incoming wave and recreate the original "information source" signal.

# Maxwell's equations in a non-dispersive media

- $B = \mu H, D = \epsilon E$
- $\nabla \cdot D = \rho$
- $\nabla \cdot B = 0$
- $\nabla \times E = -\frac{\partial B}{\partial t}$
- $\nabla \times H = j + \frac{\partial E}{\partial t}$
- $\nabla \cdot j = -\frac{\partial \rho}{\partial t}$

# Radiation from a small dipole

- $A(1, t) = \int \frac{\vec{j}(2, t - \frac{r_{12}}{c})}{4\pi\epsilon_0 c^2 r_{12}} dV_2$ . From figure on right,  $j_z dV_2 = I dz'$ .
- Note  $\vec{p}(t) = q(t)l\hat{k}$ ,  $k = \hat{z}$  and  $\dot{q}(t) = I$ .  $\phi$  is the angle from the x axis to the projection of  $r$  on the x-y plane.
- $\vec{r}' + z'\hat{k} = \vec{r}$  and  $|\vec{r} - z'\hat{k}| = r - z' \cos(\theta)$
- If  $l \ll cT = \lambda$ ,  $I\left(\vec{z}', t - \frac{r'}{c}\right) \approx I\left(0, t - \frac{r'}{c}\right)$  and we get:
- $A_z(r, t) = \frac{\mu_0}{4\pi} \int_{-\frac{l}{2}}^{\frac{l}{2}} \frac{I\left(\vec{z}', t - \frac{r'}{c}\right)}{4\pi\epsilon_0 c^2 r'} dz' = \frac{\mu_0}{4\pi} \frac{l}{r} I(0, t - \frac{r'}{c})$
- Choosing gauge,  $\nabla \cdot A + \frac{1}{c^2} \frac{\partial \phi}{\partial t} = 0$
- $\frac{\partial \phi}{\partial t} = -\frac{l}{4\pi\epsilon_0} \frac{\partial}{\partial z} \left( \frac{1}{r} I\left(t - \frac{r}{c}\right) \right) = \frac{z}{r^2} \left( \frac{q(t - \frac{r}{c})}{r} - \frac{I((t - \frac{r}{c}))}{c} \right)$
- Pick an oscillating dipole:  $q\left(t - \frac{r}{c}\right) = q_0 \cos\left(\omega\left[t - \frac{r}{c}\right]\right)$
- $I\left(t - \frac{r}{c}\right) = I_0 \sin\left(\omega\left[t - \frac{r}{c}\right]\right) = -\omega q_0 \sin\left(\omega\left[t - \frac{r}{c}\right]\right)$



# Radiation from a small dipole

- $\nabla^2 H - \epsilon\mu \frac{\partial^2 H}{\partial t^2} - \sigma\mu \frac{\partial H}{\partial t} = 0$
- $\nabla^2 E - \epsilon\mu \frac{\partial^2 E}{\partial t^2} - \sigma\mu \frac{\partial E}{\partial t} = 0$
- $A_r = \frac{\mu_0}{4\pi} \frac{I_0 l}{r} \cos(\theta) \sin(\omega [t - \frac{r}{c}])$
- $A_\phi = 0, A_\theta = -\frac{\mu_0}{4\pi} \frac{I_0 l}{r} \cos(\theta) \sin(\omega [t - \frac{r}{c}])$
- $B_\phi = \frac{1}{r} \frac{\partial}{\partial r} (r A_\theta) - \frac{1}{r} \frac{\partial A_r}{\partial \theta} = \frac{\mu_0}{4\pi} \frac{I_0 l}{r} \sin(\theta) [\frac{\omega}{r} \cos(\omega [t - \frac{r}{c}]) + \frac{1}{r} \sin(\omega [t - \frac{r}{c}])]$
- $E_r = -\frac{\partial \phi}{\partial t} - \frac{\partial A_r}{\partial t} = \frac{2l I_0 \cos(\theta)}{4\pi \epsilon_0} \left[ \frac{\sin(\omega [t - \frac{r}{c}])}{r^2 c} - \frac{\cos(\omega [t - \frac{r}{c}])}{\omega r^3} \right]$
- $E_\theta = \frac{-I_0 l \sin(\theta)}{4\pi \epsilon_0} \left( \left[ \frac{1}{r^3 \omega} - \frac{\omega}{rc^2} \right] \cos(\omega [t - \frac{r}{c}]) - \frac{1}{cr^2} \sin(\omega [t - \frac{r}{c}]) \right)$
- $E_\phi = -\frac{1}{r \sin(\theta)} \frac{\partial \phi}{\partial \phi} - \frac{\partial A_\phi}{\partial t} = 0$

# Radiation from a small dipole

- $\nabla \cdot (\mathbf{E} \times \mathbf{H}) = -\mathbf{H} \frac{\partial \mathbf{B}}{\partial t} - \mathbf{E} \frac{\partial \mathbf{D}}{\partial t} - \mathbf{E} \cdot \mathbf{j}$
- $\mathbf{S} = \mathbf{E} \times \mathbf{H}$ ,  $\nabla \cdot \mathbf{S} + \frac{\partial u}{\partial t} = -\mathbf{E} \cdot \mathbf{j}$  ( $u$  is energy density)
- $\int S \cdot dA = \frac{(l I_0 \omega)^2}{6\pi\epsilon_0 c^3} \cos(\omega [t - \frac{r}{c}])^2$
- $P_{av} = \frac{(l\omega)^2}{6\pi\epsilon_0 c^3} \frac{I_0^2}{2} = \frac{2\pi}{3} \sqrt{\frac{\mu_0}{\epsilon_0}} \left(\frac{l}{\lambda}\right)^2 \frac{I_0^2}{2}$
- $R_r = \frac{2\pi}{3} \sqrt{\frac{\mu_0}{\epsilon_0}} \left(\frac{l}{\lambda}\right)^2$

# Large half wave dipole

- For large half wave, add small dipoles to produce half wave antenna.

- $dE_\theta = I_0 \frac{\sin(\theta)}{4\pi\epsilon_0 R c^2} \omega \cos(\omega) \cos\left(\frac{2\pi z'}{\lambda}\right) dz'$

- $dB_\phi = I_0 \frac{\mu_0 \omega}{4\pi R c} \omega \cos\left(\omega \left[t - \frac{r}{c}\right]\right) \cos\left(\frac{2\pi z'}{\lambda}\right) dz'$

- Suffices to find:  $K = \int_{[-\frac{\pi}{2}, \frac{\pi}{2}]} \frac{1}{R} \cos\left(t - \frac{R}{c}\right) \cos(u) du = \frac{1}{2\pi\epsilon_0 r c} \cos\left(\omega \left[t - \frac{r}{c}\right]\right) \frac{\cos\left(\frac{\pi}{2}\cos(\theta)\right)}{\sin^2(\theta)}$ ,  $u = \frac{2\pi z'}{\lambda}$

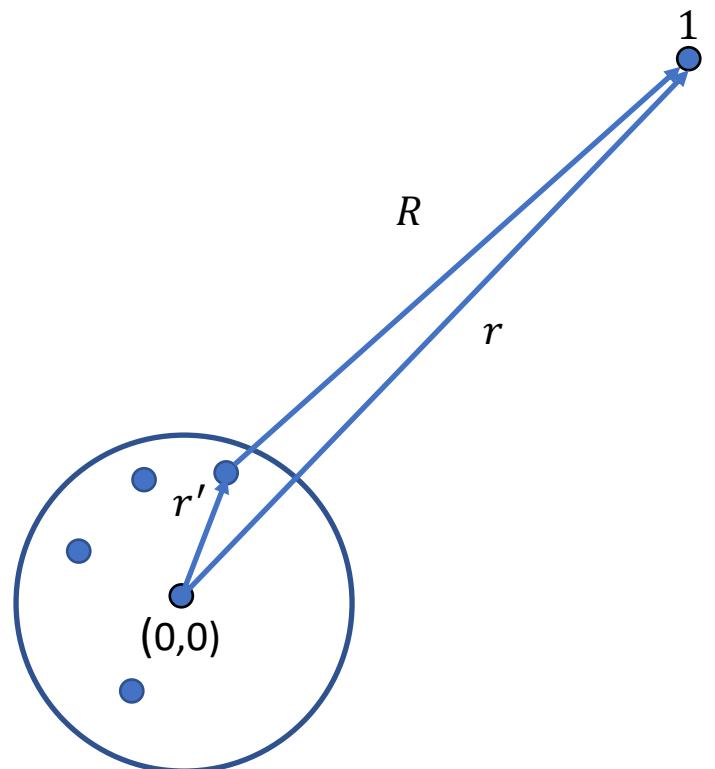
- $E_\theta = I_0 \frac{1}{2\pi\epsilon_0 r c} \cos\left(\omega \left[t - \frac{r}{c}\right]\right) \frac{\cos\left(\frac{\pi}{2}\cos(\theta)\right)}{\sin(\theta)}$

- $B_\phi = I_0 \frac{\mu_0}{2\pi r} \omega \cos\left(\omega \left[t - \frac{r}{c}\right]\right) \frac{\cos\left(\frac{\pi}{2}\cos(\theta)\right)}{\sin(\theta)}$

- $P_{av} = \frac{1}{4\pi} \sqrt{\frac{\mu_0}{\epsilon_0}} I_0^2 \int_{[0, \pi]} \frac{\cos^2\left(\frac{\pi}{2}\cos(\theta)\right)}{\sin^2(\theta)} \sin(\theta) d\theta = 73.1 \Omega \frac{I_0^2}{2}$

# Radiation from charge distribution

- $\mathbf{r}' + \mathbf{R} = \mathbf{r}, R = |\mathbf{r} - \mathbf{r}'|$
- $\varphi(r, t) = \frac{1}{4\pi\epsilon_0} \int_{V_1} \frac{\rho(r', t - \frac{R}{c})}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{v}' = \frac{1}{4\pi\epsilon_0} \left[ \frac{Q}{r} + \frac{r \cdot \mathbf{p}(t - \frac{r}{c})}{r^3} + \frac{r \cdot \frac{d\mathbf{p}}{dt}(t - \frac{r}{c})}{cr^2} \right]$
- $\mathbf{A}(r, t) = \frac{\mu_0}{4\pi} \int_{V_1} \frac{\mathbf{j}(r', t - \frac{R}{c})}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{v}' = \frac{\mu_0}{4\pi r} \frac{d}{dt} \mathbf{p}(t - \frac{r}{c})$
- $\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla \varphi$
- $\mathbf{B}(r, t) = \frac{-\mu_0}{4\pi c r^2} \mathbf{r} \times \ddot{\mathbf{p}}(t - \frac{r}{c})$
- $\mathbf{E}(r, t) = -\frac{c}{r} \mathbf{r} \times \mathbf{B}(r, t)$
- $\frac{d\mathbf{p}}{dt} = q \frac{d\mathbf{r}'}{dt} = q\mathbf{v}, \frac{d^2}{dt^2} \mathbf{p}(t - \frac{r}{c}) = q \frac{d\mathbf{v}}{dt}$
- $S = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B} = \frac{\ddot{\mathbf{p}}^2 \sin(\theta)^2}{16\pi^2 \epsilon_0 c^3 r^r} \frac{\vec{r}}{r}$
- $P_R = -\frac{dW}{dt} = \frac{2}{3} \frac{q^2}{4\pi\epsilon_0 c^3} \left( \frac{d\mathbf{v}}{dt} \right)^2$
- Compare to Feynman later



# Radiation from a single accelerating charge

- Near zone

- $\varphi(r, t) = \frac{q}{4\pi\epsilon_0} \left[ \frac{1}{R'(1 + \frac{v \cdot n'}{c})} \right]$

- $R^* = R' - \frac{v}{c}(x_0 - x'_1)$

- $E(r, t) = \frac{1}{4\pi\epsilon_0} \frac{1}{R^{*3}} \left[ \left( R' - \frac{R' v'}{c} \right) \left( 1 - \frac{v^2}{c^2} \right) + \frac{R'}{c^2} \left( R' - \frac{R' v'}{c} \right) \times \frac{dv'}{dt} \right]$

- $B = \frac{R' \times E}{R' c}$

- $S = \frac{q^2}{16\pi^2 c^3 \epsilon_0} \frac{R' (R' \times v')^2}{(R')^5}$

# Feynman's Treatment - 1

- Want to derive the Heaviside-Feynman equation:

- $E = \frac{q}{4\pi\epsilon_0} \left[ \frac{e_{r'}}{r'^2} + \frac{r'}{c} \frac{d}{dt} \frac{e_{r'}}{r'^2} + \frac{1}{c^2} \frac{d^2 e_{r'}}{dt^2} \right]$

- $cB = e_{r'} \times E$

- Solution to Maxwell:

- $E = -\nabla\phi - \frac{\partial A}{\partial t}, B = \nabla \times A$

- $\nabla^2\phi - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = -\frac{\rho}{\epsilon_0}, \nabla^2 A - \frac{1}{c^2} \frac{\partial^2 A}{\partial t^2} = -\frac{j}{c^2 \epsilon_0}$

- With gauge  $\nabla \cdot A = -\frac{1}{c^2} \frac{\partial \phi}{\partial t}$

- Consider solution to  $\nabla^2\psi - \frac{1}{c^2} \frac{\partial^2 \psi}{\partial t^2} = -s$

- First solve  $\nabla^2\psi - \frac{1}{c^2} \frac{\partial^2 \psi}{\partial t^2} = 0, \psi(x, t, z, t) = \frac{f(t - \frac{r}{c})}{r}$

- As  $r \rightarrow 0, \psi(x, t, z, t) = \frac{f(t)}{r}$ .

- Consider the electrostatic case where  $\nabla^2\phi = -\frac{\rho}{\epsilon_0}$  where  $\phi = \frac{q}{4\pi\epsilon_0 r}$ ; by analogy:
  - $f\left(t - \frac{r}{c}\right) = \frac{s(t - \frac{r}{c})}{4\pi}$
  - $S = \int s dV$
- So, solution is:  $\psi(x, t, z, t) = \frac{1}{4\pi} \frac{s(t - \frac{r}{c})}{r}$ . Thus,
  - $A(1, t) = \int \frac{j(2, t - \frac{r_{12}}{c})}{4\pi\epsilon_0 c^2 r_{12}} dV_2$
  - $\phi(1, t) = \int \frac{\rho(2, t - \frac{r_{12}}{c})}{4\pi\epsilon_0 r_{12}} dV_2$
  - $E = -\nabla\phi - \frac{\partial A}{\partial t}, B = \nabla \times A$
  - With gauge  $\nabla \cdot A = -\frac{1}{c^2} \frac{\partial \phi}{\partial t}$

# Feynman's Treatment - 2

- For small blob of charge moving with velocity  $v, j = v\rho$ .

- $A(1, t) = \int \frac{j(2, t - \frac{r_{12}}{c})}{4\pi\epsilon_0 c^2 r_{12}} dV_2 = \frac{1}{r} \int v \rho dV_2 = \frac{qv}{r}$

- So, for a dipole with  $\vec{p}(r, t) = qd\vec{k}, \frac{qv}{r} = \frac{\partial \vec{p}}{\partial t}$

- $A(1, t) = \frac{\dot{p}(t - \frac{r}{c})}{4\pi\epsilon_0 c^2 r}, B = \nabla \times A$  and  $B_z = 0$ .  $A$  is due to dipole current. If the dipole charges oscillate  $p(t) = p_0 \sin(\omega t)$ ,

$$A_z(1, t) = \frac{1}{4\pi\epsilon_0 c^2 r} p_0 \omega \cos(\omega[t - \frac{r}{c}])$$

- $B_x = \frac{\partial A_z}{\partial y} = \frac{1}{4\pi\epsilon_0 c^2 r} \frac{\partial \dot{p}(t - \frac{r}{c})}{\partial y}, B_y = -\frac{\partial A_z}{\partial x} = -\frac{1}{4\pi\epsilon_0 c^2 r} \frac{\partial \dot{p}(t - \frac{r}{c})}{\partial x}$

- $B_x = \frac{1}{4\pi\epsilon_0 c^2 r} \left[ -\frac{y(t - \frac{r}{c})}{r^3} - \frac{y\ddot{p}(t - \frac{r}{c})}{cr^2} \right], B_y = \frac{1}{4\pi\epsilon_0 c^2 r} \left[ \frac{x\dot{p}(t - \frac{r}{c})}{r^3} + \frac{x\ddot{p}(t - \frac{r}{c})}{cr^2} \right]$

- Rewrite this as

- $\vec{B} = \frac{1}{4\pi\epsilon_0 c^2 r^3} \left[ \dot{p} \left( t - \frac{r}{c} \right) + \frac{r}{c} \ddot{p} \left( t - \frac{r}{c} \right) \right] \times r$

- Compare this to Biot Savart:  $dB = \frac{1}{4\pi\epsilon_0 c^2} \frac{j \times r}{r^3} dV$

- Now suppose the dipole charges oscillate  $q(t) = q_0 \sin(\omega t)$

- When  $\frac{r}{c}$  is small,  $\dot{p} \left( t - \frac{r}{c} \right) = \dot{p}(t) - \frac{r}{c} \ddot{p}(t) + \dots$

- $E \perp B, E = cB$  and from  $\frac{\partial \phi}{\partial t} = -\nabla \cdot A$ , we get

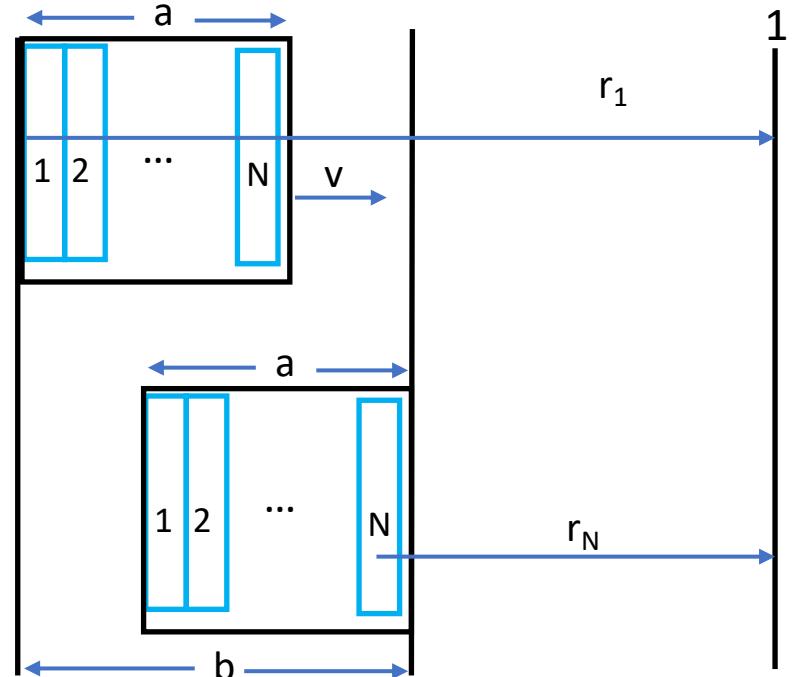
- $\phi = \frac{1}{4\pi\epsilon_0 r^3} \left[ p \left( t - \frac{r}{c} \right) + \frac{r}{c} \dot{p} \left( t - \frac{r}{c} \right) \right] \cdot r$ , and

- $E = -\nabla \phi - \frac{\partial A}{\partial t} = \frac{1}{4\pi\epsilon_0 c^2 r^3} \left[ \frac{3(p^* \cdot r) \vec{r}}{r^2} + \frac{1}{c^2} (\ddot{p} \left( t - \frac{r}{c} \right) \times r \times r) \right]$  where

- $p^* = p \left( t - \frac{r}{c} \right) + \frac{r}{c} \dot{p} \left( t - \frac{r}{c} \right)$

# Lienard-Wierchert

- $\phi(1, t) = \int \frac{\rho(2, t - \frac{r_{12}}{c})}{4\pi\epsilon_0 r_{12}} dV_2$
- $\phi(1, t) = \sum \frac{\rho_i \Delta V_i}{r_i} = \sum \frac{\rho w a^2}{r'} = \frac{\rho a^3}{r'} \frac{N w}{a} = \frac{q}{r'} \frac{b}{a}$
- $b = a + \frac{v}{c} b$
- So, we get
  - $\phi(1, t) = \frac{q}{4\pi\epsilon_0 [r - \frac{v \cdot r}{c}]_{ret}}$  and
  - $A(1, t) = \frac{qv_{ret}}{4\pi\epsilon_0 c^2 [r - \frac{v \cdot r}{c}]_{ret}}$
- Now we can compute  $E$  as above and verify the Heaviside formula



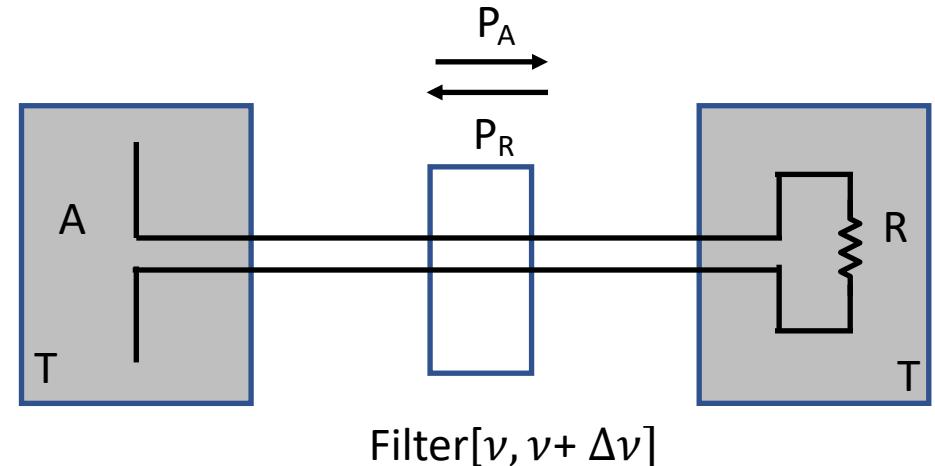
# Radiation loss and antenna aperture

- Spreading loss:  $L_s = 32 + \log(d) + 20 \log(f)$ 
  - d in kilometers
  - F in megahertz
- $W = A_e P_e, A_e = \frac{\lambda^2}{4\pi}$

# Antenna aperture

- Deriving antenna aperture uses thermodynamic argument: black body equilibrium

- $P_A = \frac{A_e}{2} B_v \Delta\nu \int_{[0,4\pi]} d\Omega = 2\pi A_e B_v \Delta\nu$
- $B_v = \frac{2\nu^2 kT}{c^2} = \frac{2kT}{\lambda^2}$  (Rayleigh-Jeans)
- $P_R = kT\Delta\nu$
- $P_A = P_R$
- $A_e = \frac{\lambda^2}{4\pi}$



# Impedance matching

- L networks,  $\pi$  and T networks
- Impedance and reflection coefficients

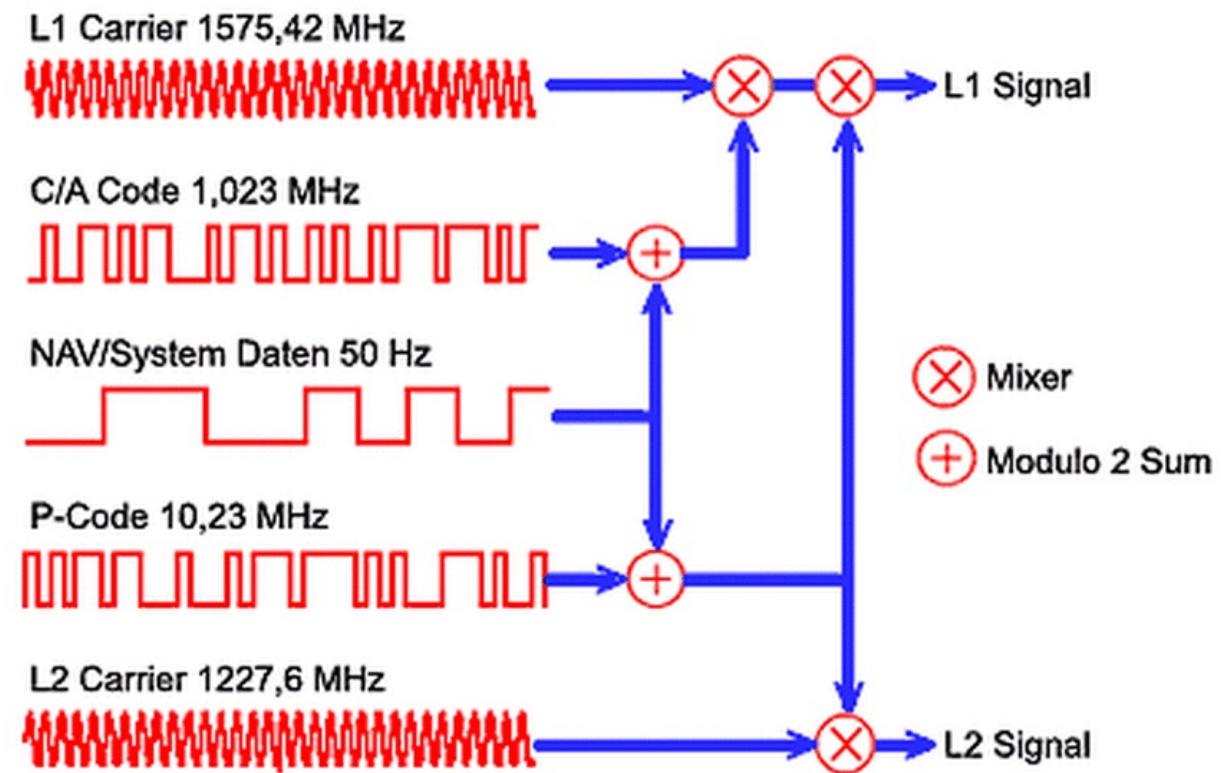
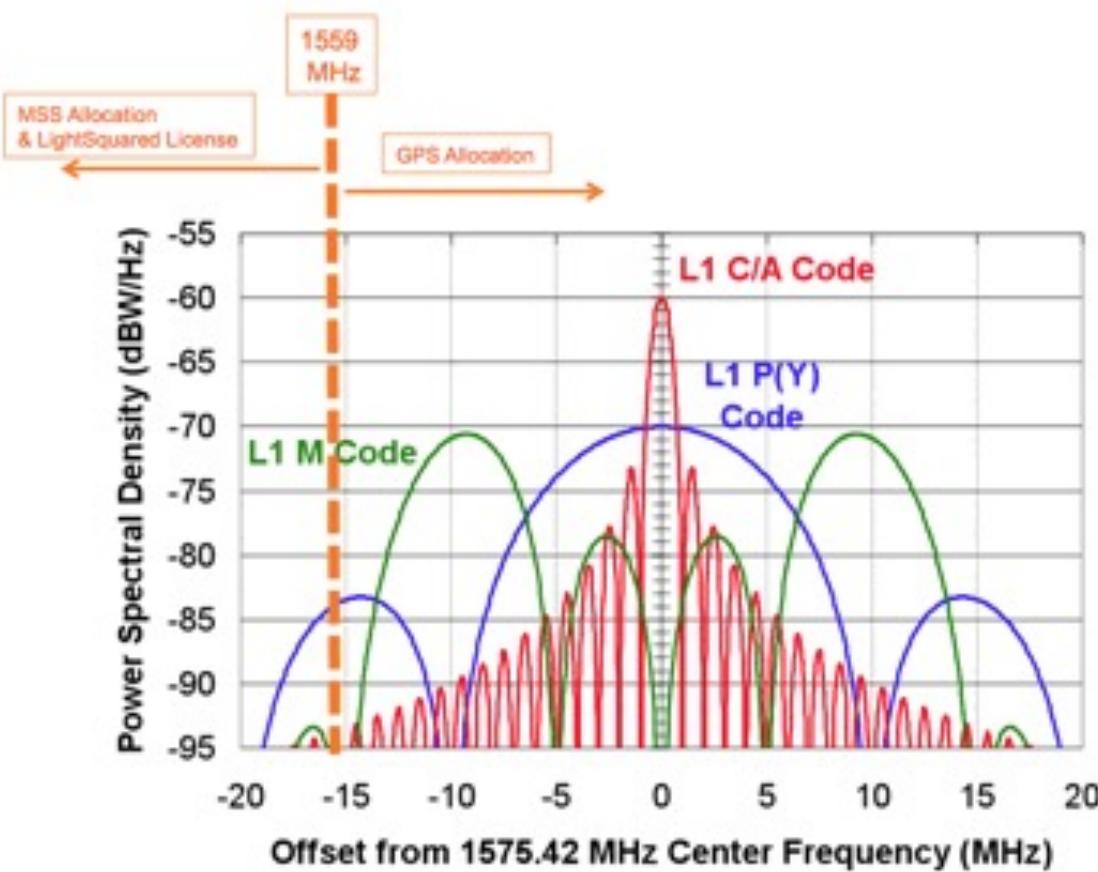
# GPS

- Space Segment
  - 31 operating satellites (Current generation: block IIIA – 2018)
  - 12 hour orbits MEO (21000km), 8-12 satellites in view
  - Transmitter power: 44.8 W,  $G_t = 12dBi$ . Clocks accurate to better than 10ns (no leap seconds).
- Control segment master at Schriever AFB (plus alternative master, 4 ground antennas and 6 ground stations). Ephemeris updates daily.
- User segment
  - Two bands: L1 (1575.42 MHz [2.046MHz BW]) civilian and military, L2 (1227.6MHz)], military only
  - Two signals: C/A (civilian) and P(Y) (military). C/A signal is Direct Sequence Spread Spectrum
  - Satellite identified by PRN (1-32).
  - L1 signal:  $s(t) = A_c C(t) D(t) \cos(\omega_c t + \theta_1) + A_p P(t) D(t) \sin(\omega_c t + \theta_2)$ 
    - $C(t)$  - coarse ranging code
    - $D(t)$  - navigation signal consists of (clock, ephemeris, almanac corrections) 37,500 bits. 50 bps transmission.
    - $P(t)$  - precision ranging (Y is encrypted)

# Some data and rough calculations

- $N = kTB$ ,  $k = 1.38 \times 10^{-23} J/K$ . BW:  $2.046 MHz$
- For comparison: laptop emission noise density is capped at  $10^{-7} \frac{W}{MHz}$
- Noise:  $1.38 \times 10^{-23} \frac{J}{K} \times 100 \times 2 \times 10^6 = 2.76 \times 10^{-15} W, (-145.6 dB)$
- Free space loss (@100K):  $P_r = \frac{P_t G A}{4\pi r^2} \cdot \int A d\Omega = \lambda^2 \cdot P_r = \frac{(44.7)10^{1.24}}{4\pi(21 \times 10^6)^2} \times \frac{3 \times 10^8}{1.575 \times 10^9} = 4 \times 10^{-15} W (-144 dB)$
- Final SNR:  $-144 + 145.6 + 43 = 44.6 dB$ .
  - Lower in practice since satellite not directly overhead, and there are shadowing and multipath losses. In addition, we have receiver loss (and receiver antenna gain) so  $P_r$  could be as small as  $-170 dB$  and final SNR is approximately  $-170 + 144 + 43 = 17 dB$
- Receiver modeled at  $G_r = 2 dBi$

# Signal Structure



# Signal Summary

<b>GNSS System</b>	GPS	GPS		GPS	GPS
<b>Service Name</b>	C/A	L1C		P(Y) Code	M-Code
<b>Centre Frequency</b>	1575.42 MHz	1575.42 MHz		1575.42 MHz	1575.42 MHz
<b>Frequency Band</b>	L1	L1		L1	L1
<b>Access Technique</b>	CDMA	CDMA		CDMA	CDMA
<b>Signal Component</b>	Data	Data	Pilot	Data	N.A.
<b>Modulation</b>	BPSK(1)	TMBOC(6,1,1/11)		BPSK(10)	BOC <sub>sin</sub> (10,5)
<b>Sub-carrier frequency [MHz]</b>	-	1.023	1.023 & 6.138	-	10.23
<b>Code frequency</b>	1.023 MHz	1.023 MHz		10.23 MHz	5.115 MHz
<b>Primary PRN Code length</b>	1023	10230		$6.19 \cdot 10^{12}$	N.A.
<b>Code Family</b>	Gold Codes	Weil Codes		Combination and short-cycling of M-sequences	N.A.
<b>Secondary PRN Code length</b>	-	-	1800	-	N.A.
<b>Data rate</b>	50 bps / 50 sps	50 bps / 100 sps	-	50 bps / 50 sps	N.A.
<b>Minimum Received Power [dBW]</b>	-158.5	-157		-161.5	N.A.
<b>Elevation</b>	5°	5°		5°	5°

# L1 Signal Structure

- $s_m(t) = C(t) \oplus D(t)$ .  $s(t) = A_c s_m(t) \cos(\omega_c t + \theta_1)$  [bspk]
  - D(t) - 50 bps transmission (20ms).
  - C(t) – 1 Mbps chipping rate. 300 meters,  $1\mu\text{s}/chip$ . Chipping code repeats 20 times for single navigation bit.
- C/A code is generated from two Gold codes and the PRN identifier (5 bits).
  - $g_1(x) = 1 + x^3 + x^{10}$ ,  $g_2(x) = 1 + x^2 + x^3 + x^8 + x^9 + x^{10}$
  - Phase selector takes PRN and uses it to select bits of the second Gold code.
- Signal Characteristics
  - Received power: -130dBm, Noise power: -111dBm
  - Spread spectrum contributes 43 dB to processing. Want SNR greater than 14 dB
  - SNR for C/A: -20dB

# Acquisition, tracking and navigation

- Acquisition
  - Receiver generates known C/A code and attempts to correlate with signal.
  - To generate C/A code, receiver needs to know which satellite it's attempting to acquire to determine code
- Tracking via delay loop to maintain C/A code alignment
- The Navigation Message includes the Ephemeris parameters, the Time parameters and Clock Corrections, the Service Parameters with satellite health information, Ionospheric parameters model, and the Almanacs, allowing the computation of the position of "all satellites in the constellation". The ephemeris and clocks parameters are usually updated every two hours, while the almanac is updated at least every six days.

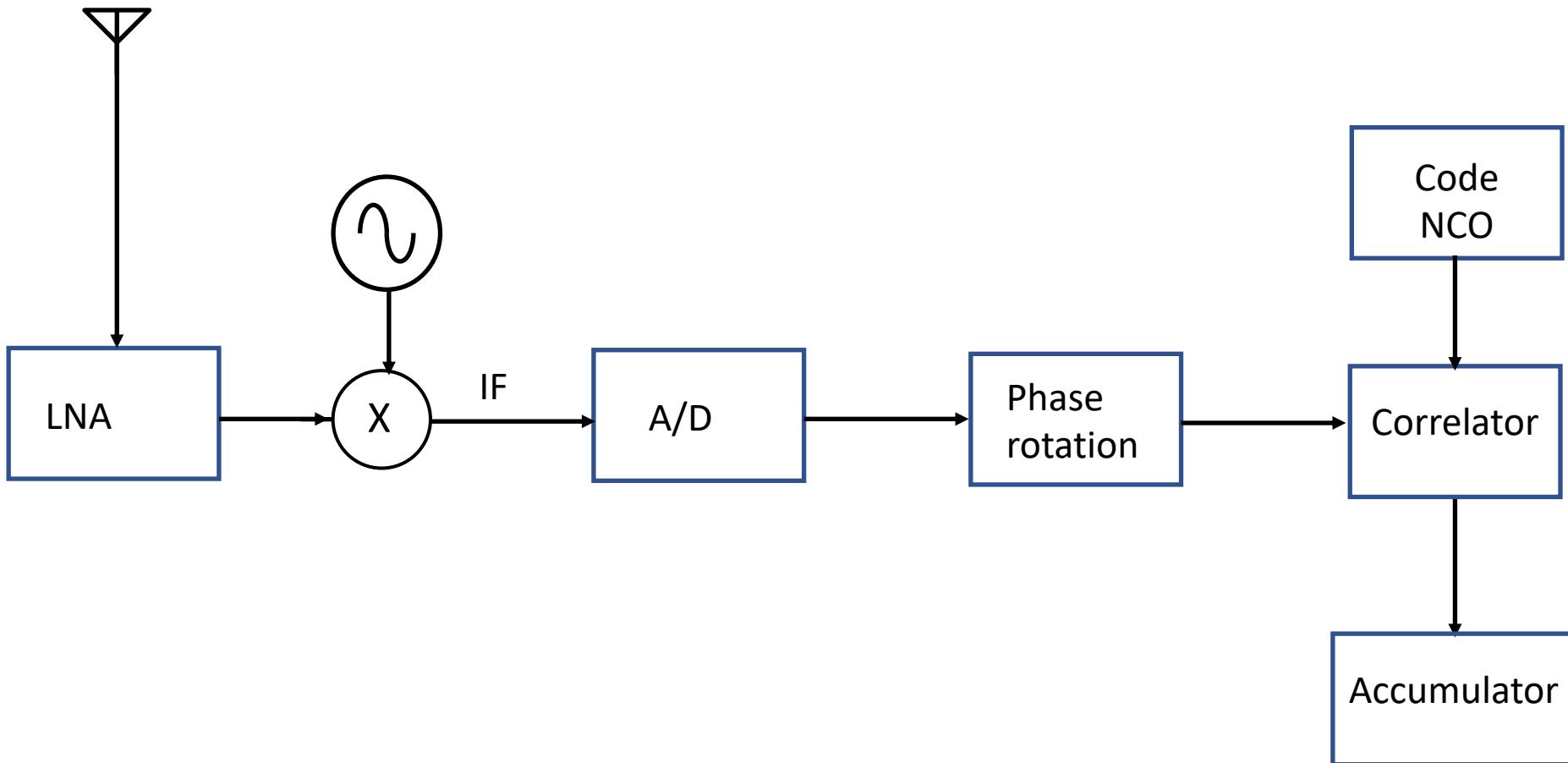
# Navigation Message

- The navigation message contains 25 pages ('frames') of 30 seconds each. Entire message takes 12.5 minutes to be transmitted. Every frame is subdivided into 5 sub-frames of 6 seconds each; every sub-frame consists of 10 words, with 30 bits per word.
- Every sub-frame starts with the telemetry word (TLM), needed for synchronism. Next, the transference word (HOW) which provides time information (seconds of the GPS week), allowing the receiver to acquire the week-long P(Y)-code segment.
  - Sub-frame 1: contains information the satellite clock. It also has information about satellite health condition.
  - Sub-frames 2 and 3: contain satellite ephemeris.
  - Sub-frame 4: provides ionospheric model parameters, UTC information (Universal Coordinate Time), part of the almanac, and indications whether the Anti-Spoofing, A/S, is activated.
  - Sub-frame 5: contains data from the almanac and the constellation status. It allows to quickly identify the satellite from which the signal comes. A total of 25 frames are needed to complete the almanac.
  - **Sub-frames 1, 2 and 3 are transmitted with each frame.** The content of sub-frames 4 and 5 is common for all satellites. So, the almanac data for all in orbit satellites can be obtained from a single tracked satellite.

# Processing and Accuracy

- For satellite k:  $\rho = \sqrt{(x^{(k)} - x)^2 + (y^{(k)} - y)^2 + (z^{(k)} - z)^2}$ 
  - Need to account for skew between satellite clocks and receiver clock. b is receivers clock bias
  - Four satellites required. More satellites increase precision with least squares.
- Doppler correction improves accuracy
- *Carrier-Phase Enhancement* corrects timing errors caused by non-zero PRN pulse transition.
  - It uses the L1 carrier wave, which has a period about one-thousandth of the C/A Gold code bit providing an additional clock.
  - The phase difference error in the normal GPS amounts to 2–3 m error. *Carrier-Phase Enhancement* reduces this to 3 cm (1.2 in).
- *Differential GPS*

# GPS receiver



# More careful estimates\*

Elevation	5°	40°	90°
Power at sat input	14.3dB	14.3dB	14.3dB
Sat antenna gain	12.1dB	12.9dB	10.2dB
EIRP	26.4dB	27.2dB	24.5dB
Range	25240km	22020km	20190km
Path loss	-159 dB/m <sup>2</sup>	-157.8 dB/m <sup>2</sup>	-157.1 dB/m <sup>2</sup>
Atmo loss	.5dB	.5dB	.5dB
Received power density	-133.1dB/m <sup>2</sup>	-131.1dB/m <sup>2</sup>	-133.1dB/m <sup>2</sup>

\*Misra and Enge, GPS

# More careful estimates\*

Elevation	5°	40°	90°
Received power density	$4.9 \times 10^{-14} \text{W/m}^2$	$7.8 \times 10^{-14} \text{W/m}^2$	$4.9 \times 10^{-14} \text{W/m}^2$
Effective area of receiver	$2.7 \times 10^{-3} \text{m}^2$	$2.7 \times 10^{-3} \text{m}^2$	$2.7 \times 10^{-3} \text{m}^2$
Isotropic receiver power	-158.5 dB	-156.5dB	-158.5dB
G <sub>r</sub>	-4 dBic	2 dBic	4dBoc
C/A received power	-162.5dB	-154.5dB	-154.5dB

\*Misra and Enge, GPS

# More careful estimates\*

Noise loss

Elevation	Ant cable	LNA	cable
Gain	-1dB	20dB	-10dB
F	1dB	2-3dB	10dB
T	75.4	290	2610

SNR

Elevation	5°	90°
Received C/A power (C)	-162.5dB	-154.5dB
$N_0$	-201 W/Hz	-201W/Hz
$C/N_0$	34.5 db-Hz	46.5 dBHz
$C/P_n$ 20MHz	-34.6 dB	-26.5dB
$C/P_n$ 2MHz	-24.5dB	-16.5dB

\*Misra and Enge, GPS

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