

# 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,  $1V = 1 J/s$
- Kirkoff 1:  $\sum_{loop} V_i = 0$  (Conservation of energy)
- Kirkoff 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:  $P_a = \int_0^{1/f} V(t)I(t)dt = V_p I_p \int_0^{2\pi/\omega} \cos^2(\omega t)dt = \frac{V_p I_p}{2}$
- 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:  $G = 10 \log_{10}(P_{out}/P_{in})$
- 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	$V(t) = V_c \cos(\omega_1 t)$ , if 1 $V(t) = V_c \cos(\omega_0 t)$ , if 0
PSK	$V(t) = +V_p \cos(\omega t)$ , if 1 $V(t) = -V_p \cos(\omega t)$ , if 0

# Resistors, capacitors, inductors

- Resistors

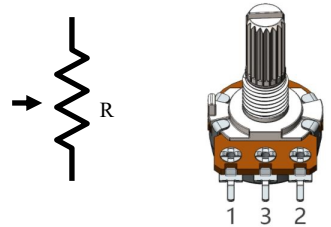
- Analytic model:  $IR = V$
- Energy dissipated:  $E = \int_{t_i}^{t_f} IV \, dt = \int_{t_i}^{t_f} I^2 R \, dt$

- 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

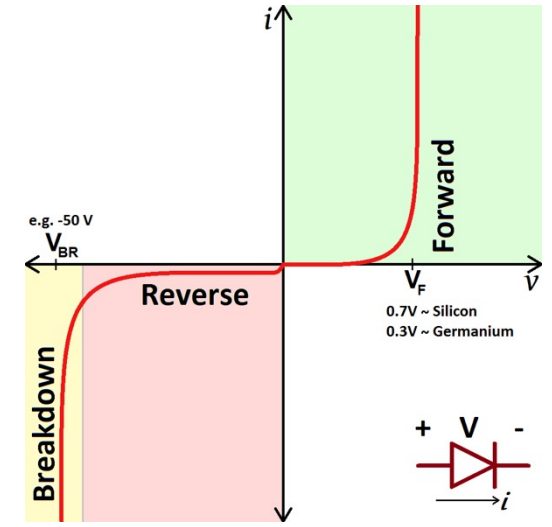
- Analytic model:  $V = L \frac{di}{dt}$
- Inductor Energy stored:  $E = \int_{t_i}^{t_f} IV \, dt = \int_{t_i}^{t_f} LI \frac{dI}{dt} \, dt = \frac{1}{2} LI^2$



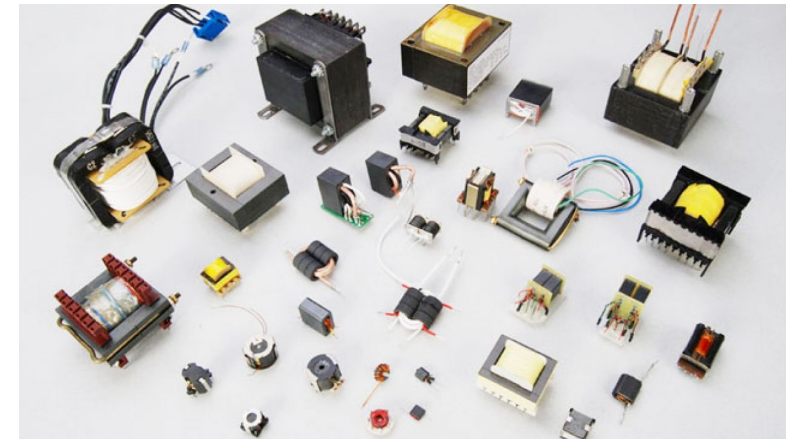
Credit: Make Electronics

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



Credit: Make Electronics



# 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  $\frac{d(V_1)}{dt}$ , 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
- $L_{eq} \frac{di}{dt} = V_1$ ,  $L_1 \frac{di_1}{dt} = V_1 - V_2$ ,  $L_2 \frac{di_2}{dt} = V_2$
- $V_1 = L_{eq} \frac{di}{dt} = L_1 \frac{di}{dt} + L_2 \frac{di}{dt}$  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

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



- RL behavior: charging

- $V_0 - V_2 = i_1 R = V_R$
- $V_L = V_2 = L \frac{di_2}{dt}$
- $i_1 = i_2, V_R = V_0 - V_L, \text{ so } L \frac{d}{dt} \frac{V_0 - V_L}{R} = V_L$
- $\frac{L}{R} \frac{dV_L}{dt} + V_L = 0$
- 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.
- $V(t) = \text{Re}(e^{j(\omega t + \theta)})$ , and  $I(t) = \text{Re}(e^{j(\omega t + \phi)})$
- Now define  $V = Ae^{j\theta}$  and  $I = Be^{j\phi}$ , so  $|V| = A$ ,  $|I| = B$ ,  $\angle V = \theta$ , and  $\angle I = \phi$ .  $V$  and  $I$  are called phasors and do not include time. Note that  $V(t) = \text{Re}(Ve^{j\omega t})$  and  $I(t) = \text{Re}(Ie^{j\omega t})$ .
- Note that  $I = CVj\omega$ , for a capacitor and  $V = LIj\omega$ , 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  $P = \frac{V\bar{I}}{2} = Z \frac{I\bar{I}}{2} = R \frac{|I|^2}{2} + jX \frac{|I|^2}{2}$ ; 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  $Q = \frac{X}{R} = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR}$ .
- 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.



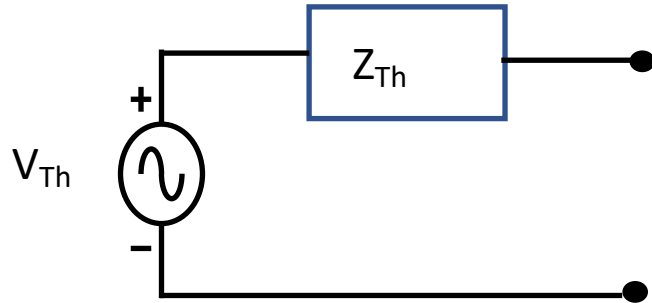
# Phasors, impedance and power

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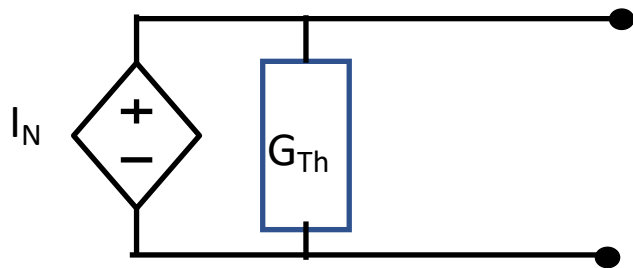


# Thevenin and Norton

- 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



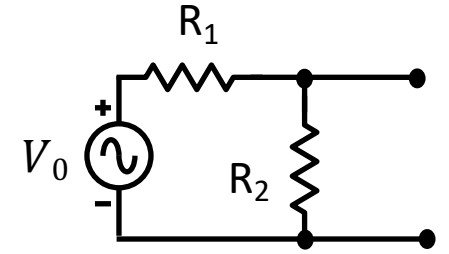
- Norton: Any combination of linear sources and passive elements terminating in two terminals is equivalent to a pure current source in parallel with a conductance



- Similar theorems for 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  $R_s = R_1 || R_2$
- 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 fore (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 fore (C).

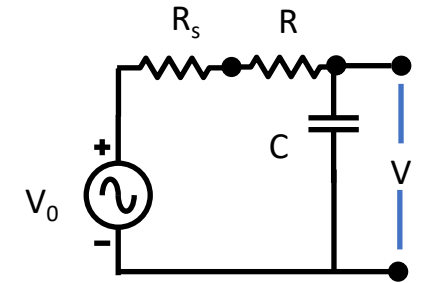
- $V_{Th} = \frac{R_3}{R_2 + R_3} V_0$
- $R_{Th} = R_2 || R_3$





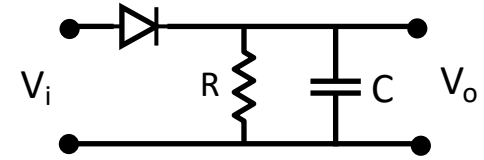
# Exercise 3: Capacitors

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  $C = 10\text{ nF}$ . Period is 50 *millisec*
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  $t_2$ .
  - $\tau = 3 \times 10^5 \times 10^{-8}\text{ sec} = 3\text{ millisec}$
  - $t_{12} \approx 1.5\text{ms}$
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  $R_p$ .
  - $C_0 = 100\text{pf}/m$ ,  $C_o = 50\text{pF}$ ,  $C_p = 10\text{pF}$
6. Now calculate the new  $t_{12}$ .
  - $\tau = 6\mu\text{-sec}$



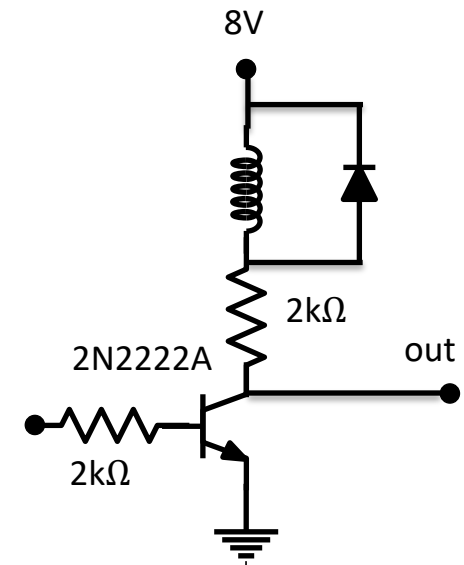
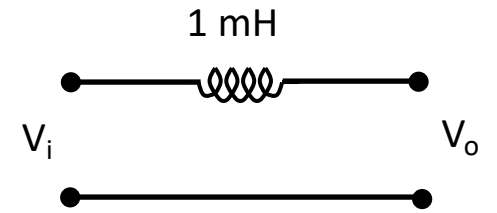
# Exercise 4: Diode detectors

- 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,  $R = 3k\Omega$ ,  $C = 10\text{ nF}$
- Set function generator for  $f_c = 1\text{MHz}$ ,  $V_{c,pp} = 5\text{V}$ ,  $f_m = 1\text{kHz}$ ,  $m = .7$ 
  1. Calculate  $\tau$  for the RC circuit.  $\tau \ll a(t)$
  2. Compare the max voltage of the AM signal to the max of  $V_0$ .  $\tau \gg \frac{c}{f_c}$
  3. What happens when we make  $m = 1.0$



# Exercise 5: Inductors

- Set function generator for 5V  $V_{pp}$ , 1kHz. Connect a 50Ω load
  1. Observe square wave with rounded corners, measure the time,  $t_2$  to decay to 0
  2. Calculate pp inductor current and the expected delay,  $t_2$
  3. Use 2 scope channels: one at input, one at output

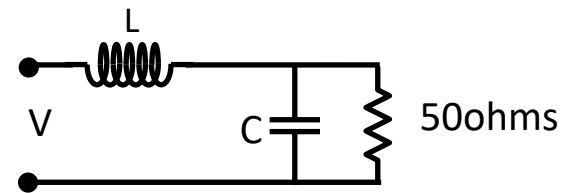
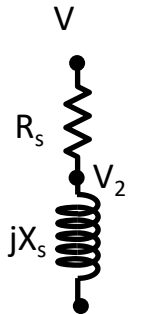
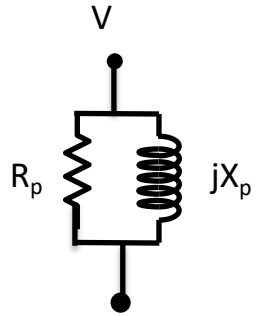


# Exercise 6: Diodes and snubbers

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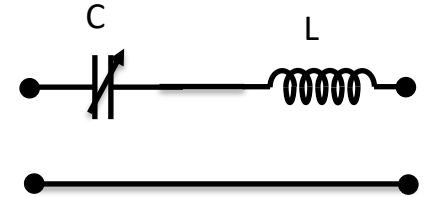
# Exercise 7: Parallel to Series conversion

- For series:  $Z_s = R_s + j\omega L$ ,  $Q_s = \frac{\omega L}{R_s}$
- 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  $Q_p = \frac{R_p}{\omega L}$



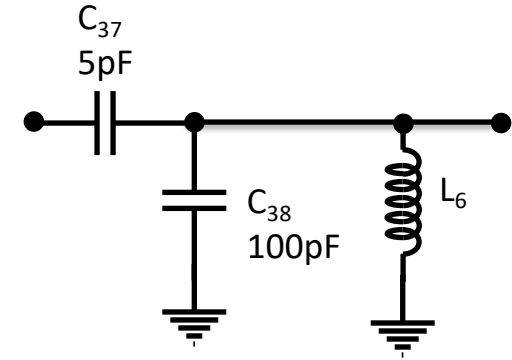
# Exercise 8: Series resonance

- For the circuit on the right,  $C = 8 - 50\text{pf}$ ,  $L = 15\mu\text{H}$  forming a bandpass filter.
- If  $C = 35\text{pf}$ , the resonant frequency is  $\omega = \frac{1}{\sqrt{35 \times 10^{-12} \times 15 \times 10^{-6}}} = \frac{10^9}{\sqrt{525}} \approx 43.6$ , so the resonant frequency is  $\frac{43.6}{2\pi} \approx 6.9\text{MHz}$
- Tune the resonant frequency to  $7\text{MHz}$  and find  $f_u$ ,  $f_l$  and  $\Delta f$  and thus  $Q$ .
- Compute what these values should be



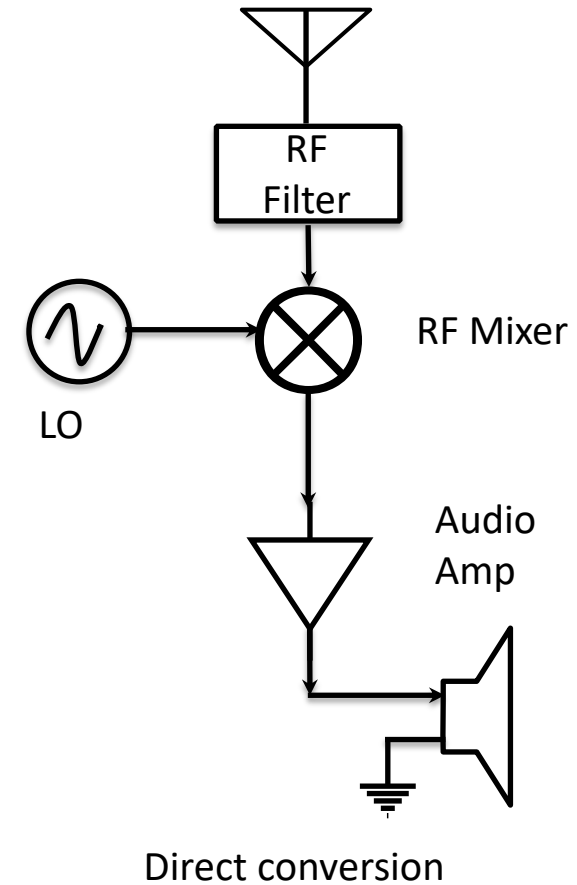
# Exercise 9: Parallel resonance

- $L = A_l N^2, A_l = 4 \frac{nH}{turn^2}$  for T37-2 core so for 28 turns,  $L_6 = 3.1\mu H$
- 1. Again, find the resonant frequency, the frequencies corresponding to a 3db fall off, the bandwidth and the Q of this circuit. This circuit is in the transmit oscillator



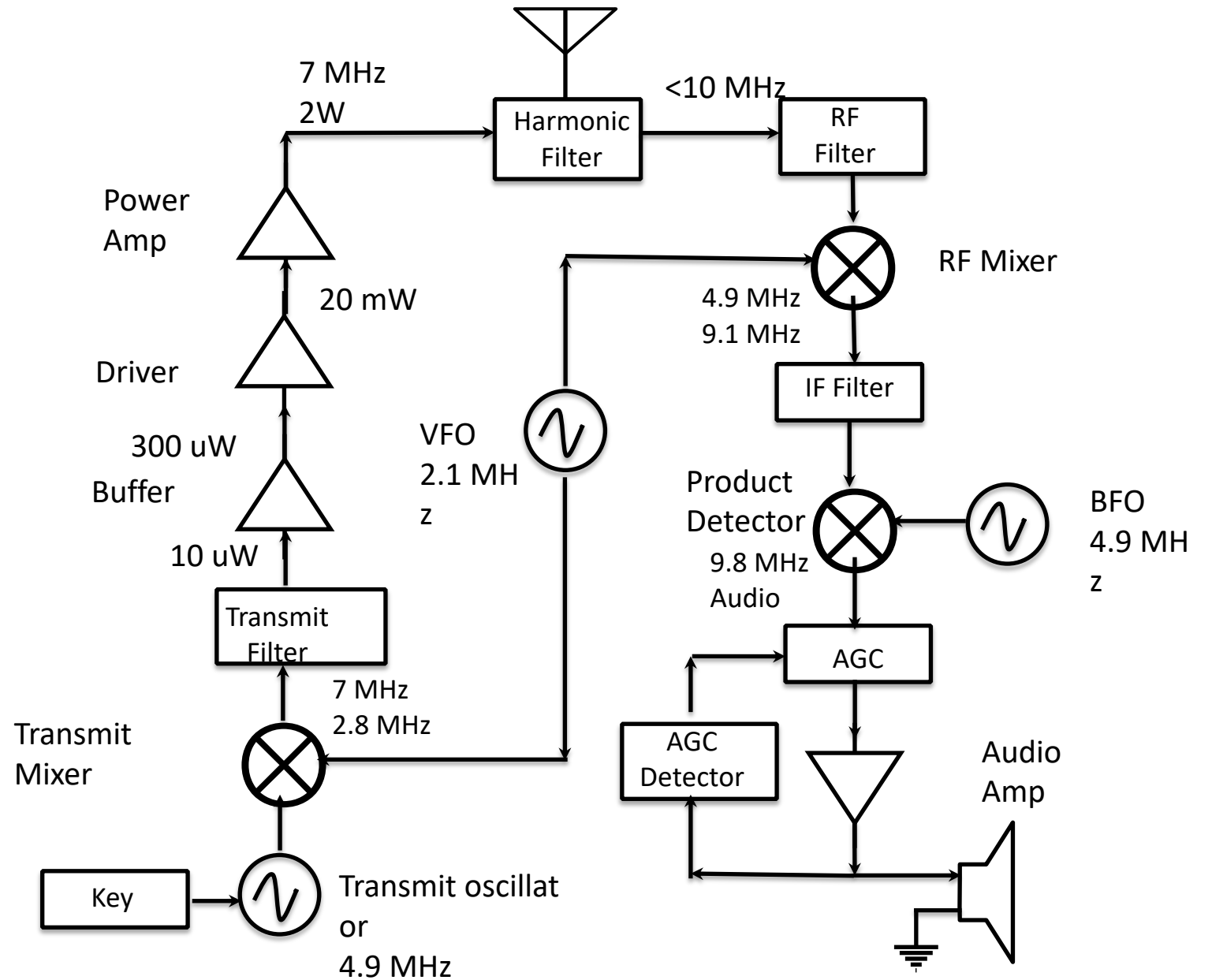
# Direct conversion and superhet receivers

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



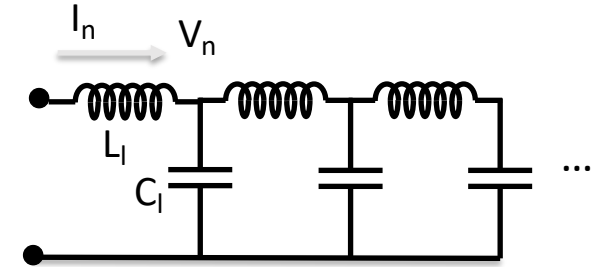


# Norcal 40A



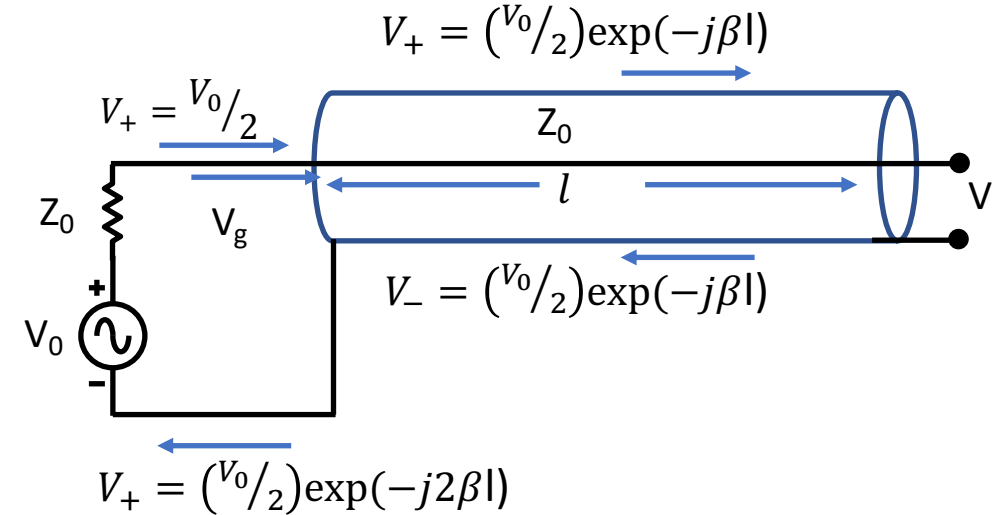
# Transmission Lines

- $V_{n+1} - V_n = -L_l \frac{\partial I_{n+1}}{\partial t}, L = \frac{L_l}{l}$
- $I_{n+1} - I_n = -C_l \frac{\partial V_n}{\partial t}, C = \frac{C_l}{l}$
- $\frac{\partial^2 V}{\partial z^2} = LC \frac{\partial^2 V}{\partial t^2}$  and  $\frac{\partial^2 I}{\partial z^2} = LC \frac{\partial^2 I}{\partial t^2}$
- Solution is  $V(z - vt), v = \frac{1}{\sqrt{LC}}$ , for forward wave
- $V' = vLI', \frac{V}{I} = \sqrt{\frac{L}{C}}, Z_0 = \sqrt{\frac{L}{C}}$
- Another solution is  $V(z + vt), v = \frac{1}{\sqrt{LC}}$ , for reverse wave
- $Z_0 = \frac{V_+}{I_+}, -Z_0 = \frac{V_-}{I_-}, V = V_+ + V_-$
- $P_+(t) = \frac{V_+^2}{Z_0}, P_-(t) = -\frac{V_-^2}{Z_0}$
- $\rho = \frac{V_-}{V_+}, Z = \frac{V}{I} = \frac{V_+ + V_-}{I_+ + I_-} = \frac{V_+}{I_+} \frac{1 + \frac{V_-}{V_+}}{1 + \frac{I_-}{I_+}} = Z_0 \frac{1 + \rho}{1 - \rho}$
- $\rho = \frac{Z - Z_0}{Z + Z_0}$
- $\rho_i = \frac{i_-}{i_+} = -\rho$



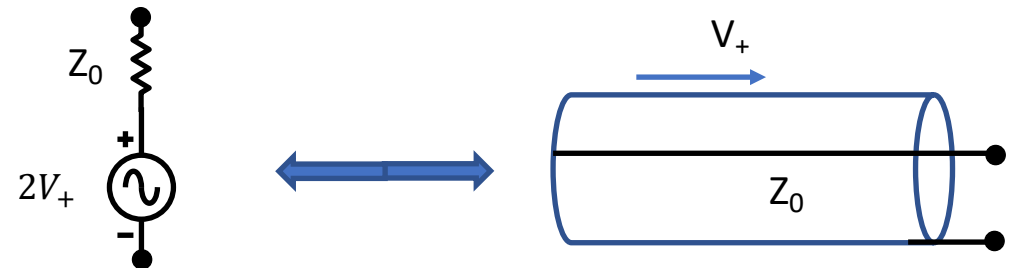
# Transmission Lines - continued

- Phasor:  $V(z - vt) = A \cos(\omega t - \beta z)$
- $\frac{dV}{dz} = -ZI, \frac{dI}{dt} = -YV'$
- $jk = \alpha + \beta j, jk = \sqrt{ZY}, Z_0 = \sqrt{\frac{Z}{Y}}$
- $jk = \sqrt{(j\omega L + R)(j\omega C + G)}, Z_0 = \sqrt{\frac{j\omega L + R}{j\omega C + G}}$
- $\alpha = \sqrt{\frac{\omega RC}{2}}, v = \sqrt{\frac{2\omega}{R}}$



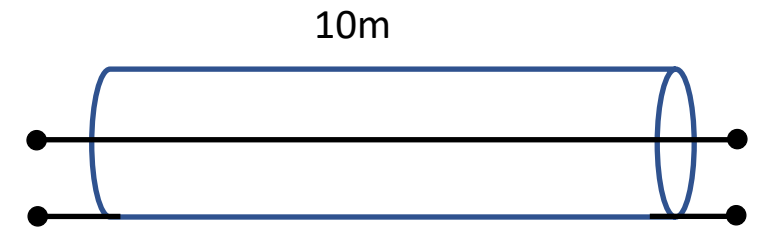
## Power

- $\tau = \frac{V}{V_+} = 1 + \rho = \frac{2Z}{Z + Z_0}, V = 2V_+$
- Lookback resistance is  $R_s = Z_0$
- $P_+ = \frac{V_+^2}{2Z_0} = \frac{V_0^2}{8Z_0}$ , This is the total available power



# Exercise 10: Coax

- Use  $50\Omega$  scope probe

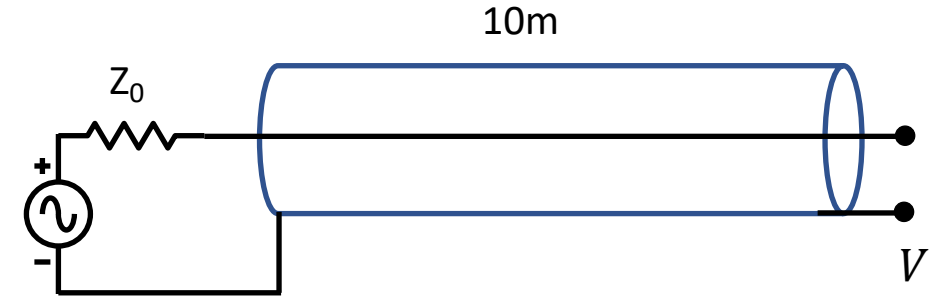


# Exercise 11: Waves

- Use  $50\Omega$  scope probe

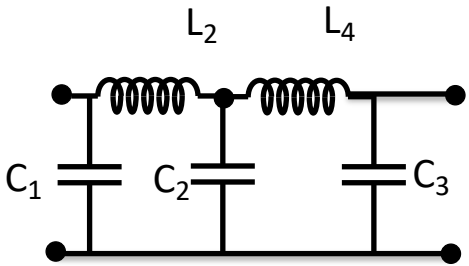
# Exercise 12: Resonance

- *RG58U* has a capacitance of about  $100 \text{ pF/m}$
- Let  $\alpha$  be the attenuation constant and  $\beta$  be the phase
- Derive an expression for  $|\frac{V_g}{V}|$  and use it to calculate  $\alpha$
- Find the wave velocity by calculating the resonant frequency and noting the time delay with a scope on the input and output
- Find, as usual,  $f_u$ ,  $f_u$ , and  $Q$ .
- Confirm  $Q = \frac{\alpha}{2\beta}$

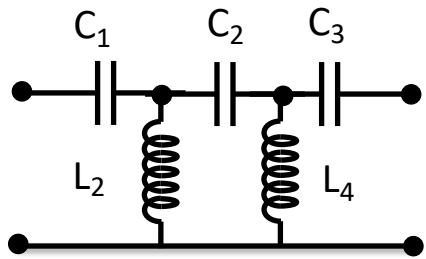


# Filters

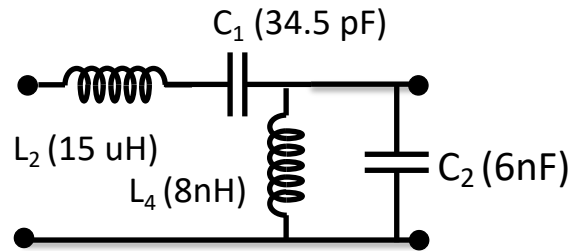
Low pass



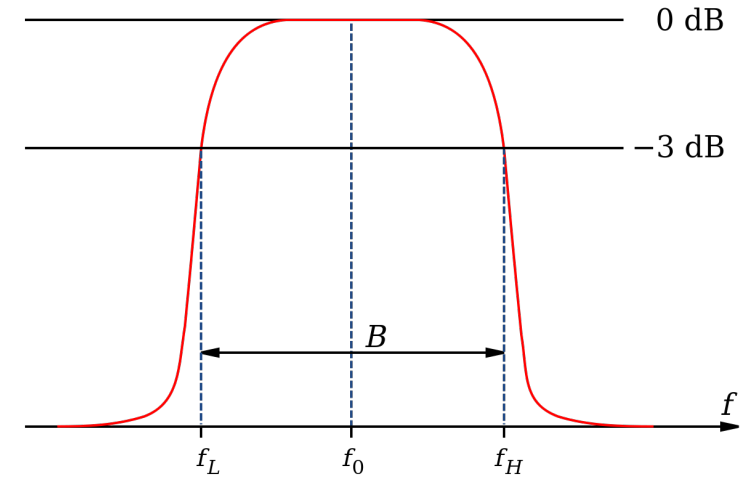
High pass



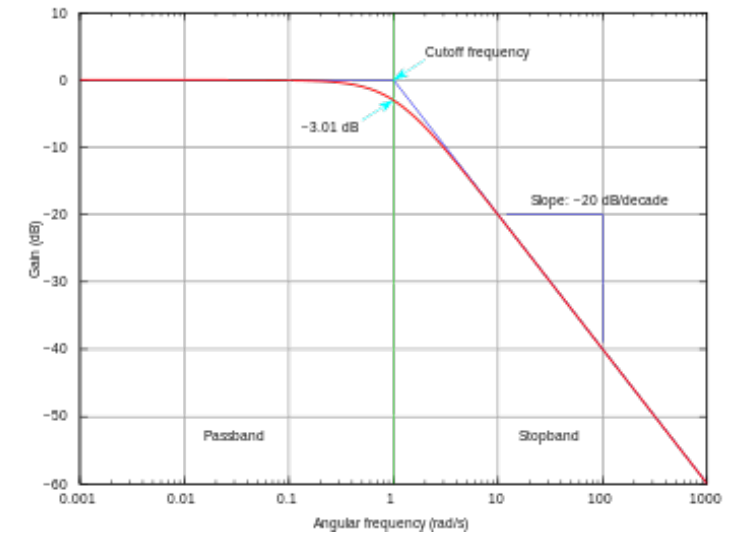
7 MHz bandpass



- Filters



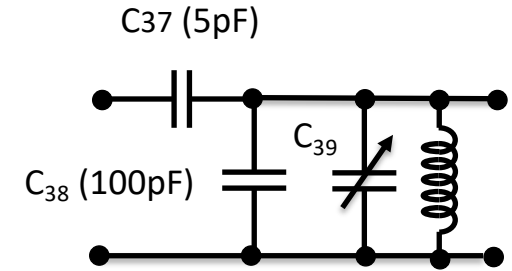
Bandpass - Wikipedia



Lowpass - Wikipedia

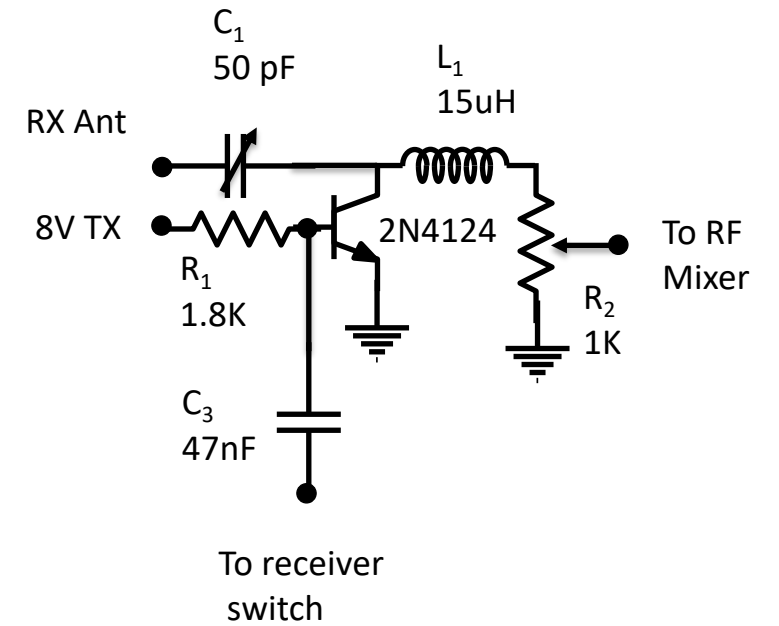
# Norcal transmit bandpass filter

- $C_{39} = 50\text{pF}$ ,
- $L_6$  is 36 turns #28 on T37-2 which has  $A_l = 4 \frac{\text{nH}}{\text{turn}^2}$
- $L_6 = A_l \cdot 36^2 = 3.1\mu\text{H}$
- $Z_2 = -\frac{j}{(C_{38}+C_{39})\omega_o}$ ,  $Z_3 = jL_6\omega_o$ ,  $Z_1 = \frac{j}{C_{37}\omega_o}$
- $Z_{2,3-eq} = \frac{jL_6\omega_o}{L_6(C_{38}+C_{39})\omega_o^2 - 1}$   $L_6$
- Resonance is when  $Z_{2,3-eq} \rightarrow \infty$ ,  $\omega_o^2 = \frac{1}{(C_{38}+C_{39})L_6} \approx \frac{10^{18}}{465}$ , when almost all the voltage drop is across  $Z_{2,3-eq}$   $\omega_o = \frac{10^9}{\sqrt{465}} \approx 50.8 \times 10^6$ ,  $f_0 = \frac{\omega_o}{2\pi} \approx 7.1 \text{ MHz}$
- 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



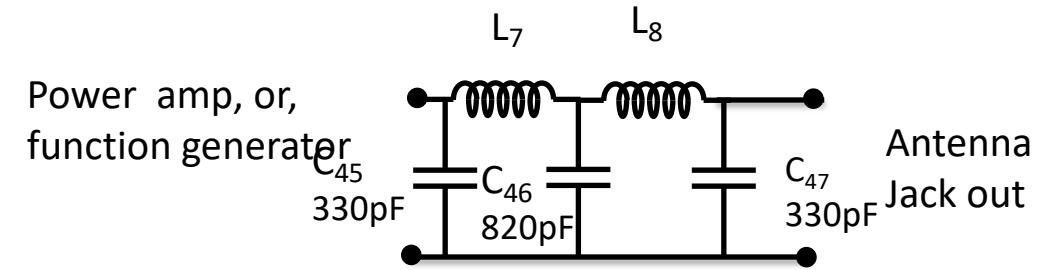


# Norcal RF Filter



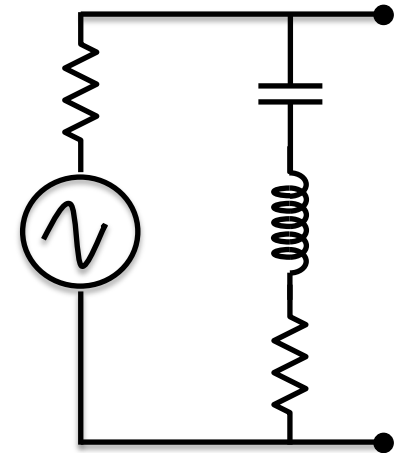
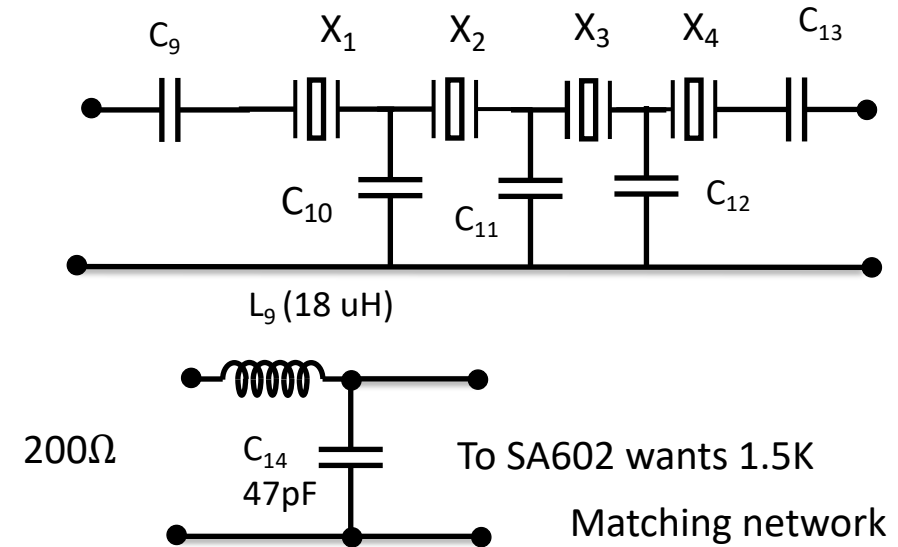
# Exercise 13: Norcal Harmonic Filter

- $L_7$ ,  $L_8$  use T37-2 core, 18 turns, 1.3uH
- Compare loss at 7MHz and 14MHz



# 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



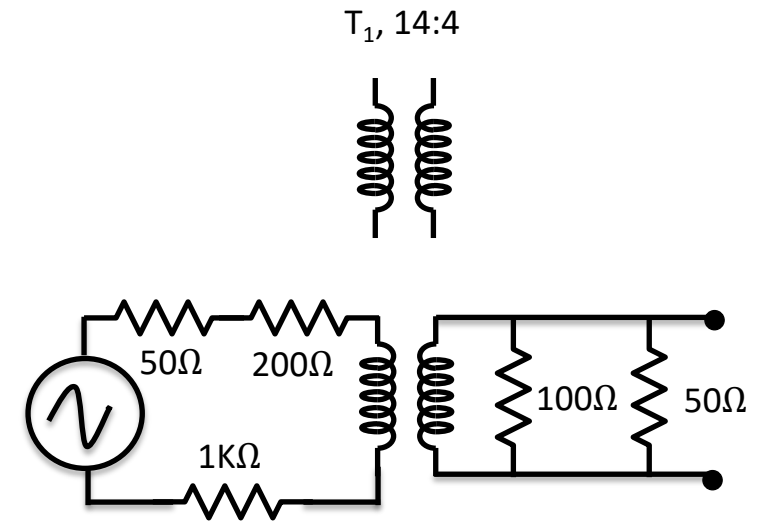
Equivalent circuit for crystal and generator

# Transformers

- $V_s = \frac{N_s}{N_p} V_p$

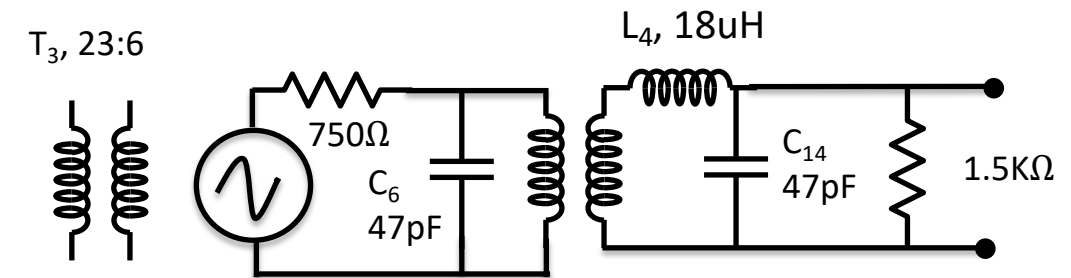
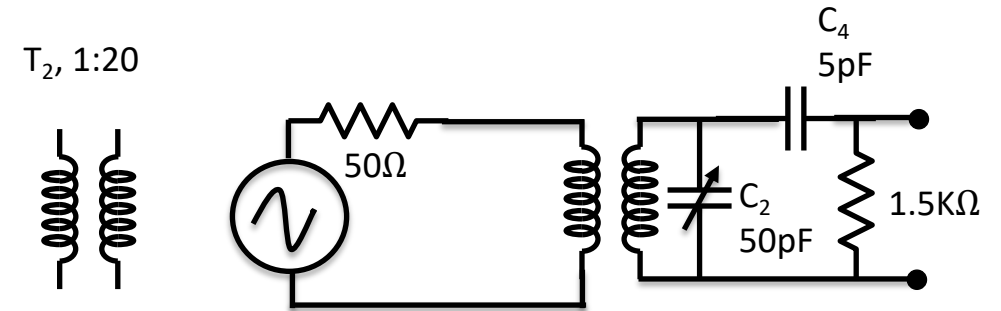
# Exercise 15: Norcal Driver Transformers

- $T_1$  is driver matcher uses FT 37-43
- Measurement circuit below



# Exercise 16: Norcal Tuned Transformers

- $T_2, T_3$  are IF matchers using FT 37-61
- Measurement circuit below



# Acoustics

- Section of air of length  $l$ ,  $U$  is average velocity,  $P$  is the pressure
- $\frac{\partial P}{\partial z} l = -\rho l \frac{\partial U}{\partial t}$
- $\frac{dl}{dt} = l \frac{\partial U}{\partial z}$
- $PV^\gamma = C$
- $\frac{\partial^2 P}{\partial t^2} = \frac{\gamma P}{\rho} \frac{\partial^2 P}{\partial x^2}$
- $v = \sqrt{\frac{\gamma P}{\rho}} = 332 \frac{m}{s}$
- $SWR = \frac{\lambda^2}{2\pi A}$ ,  $A$  is the area of the tube

Sound	L <sub>p</sub>	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>

# Exercise 17: Tuned Speaker

- $x$

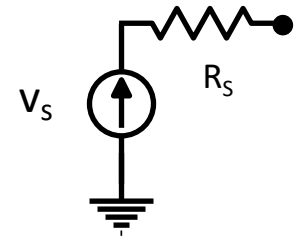
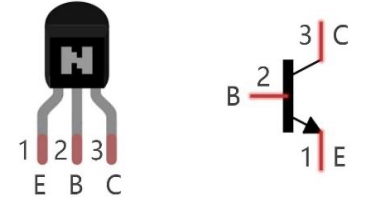


# Exercise 18: Acoustic Standing Wave

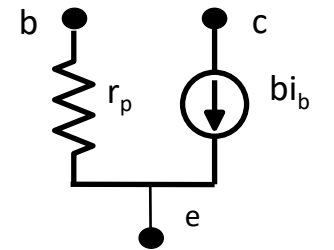
- $x$

# Bipolar Transistors

- NPN, PNP
- Model
- $i_C = \alpha i_E$
- $i_C = \beta i_B$
- $\beta = \alpha / (1 - \alpha)$
- $\beta \sim 100$



Bipolar source model



Bipolar equivalent circuit

# Bipolar Switches

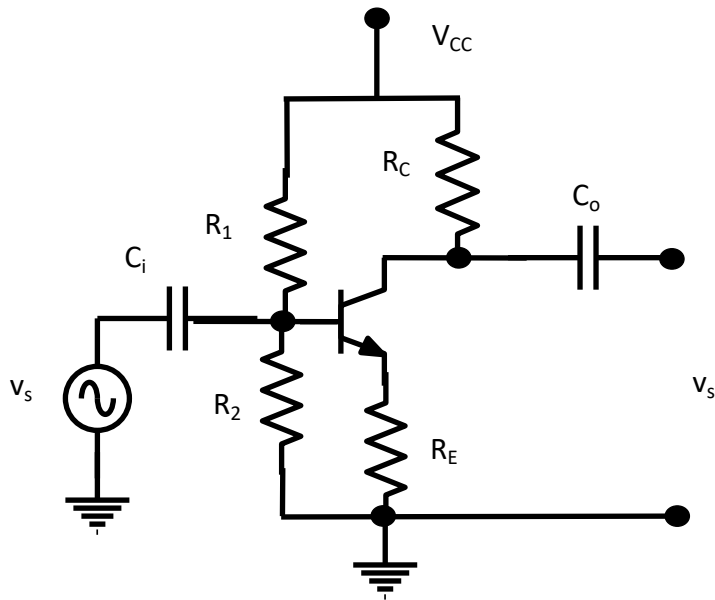
# BJT common emitter amplifier



Common emitter amp

- 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).
  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  $R_C= 1.5k\Omega$ .

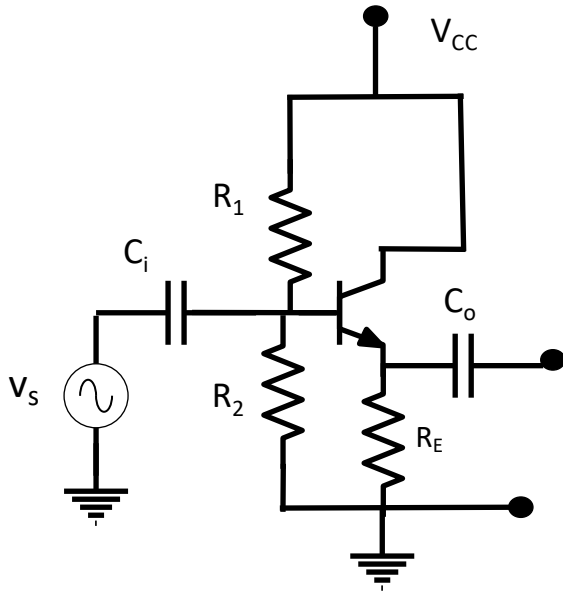
# BJT common emitter amplifier continued



Common emitter amp

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. We insert a voltage divider consisting of  $R_1$  and  $R_2$ , so that  $R_1 = (12-1.8)/270 \mu\text{A} \sim 39 \text{ k}\Omega$ .
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.

# BJT common collector amplifier



1. d

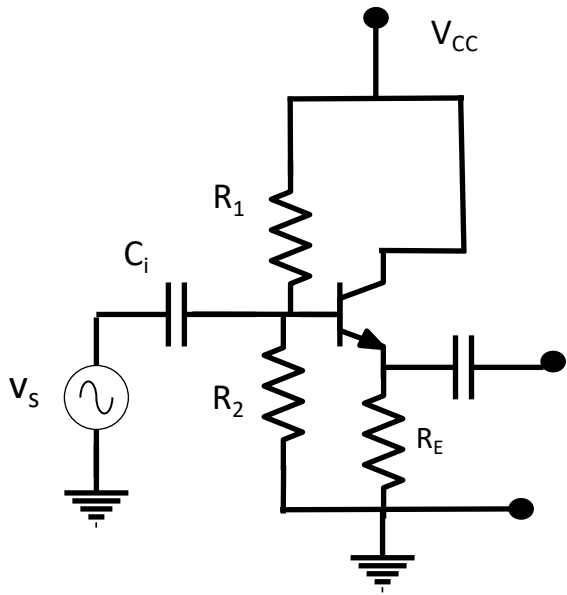
Common collector amp (Emitter Follower)

Common collector amp

Credit: Ward, Hands on Radio.

# BJT common collector amplifier continued

6. x

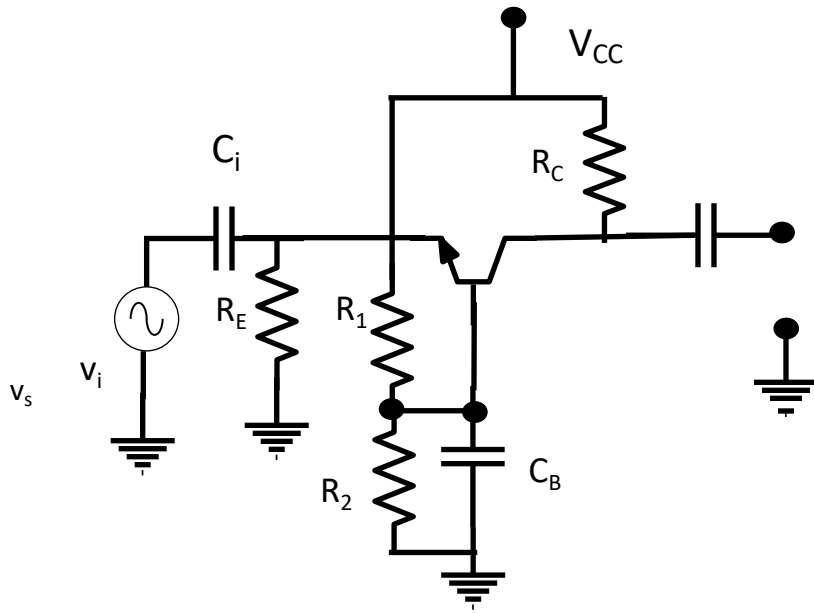


Common collector amp (Emitter Follower)

Credit: Ward, Hands on Radio.

# BJT common base amplifier

- X

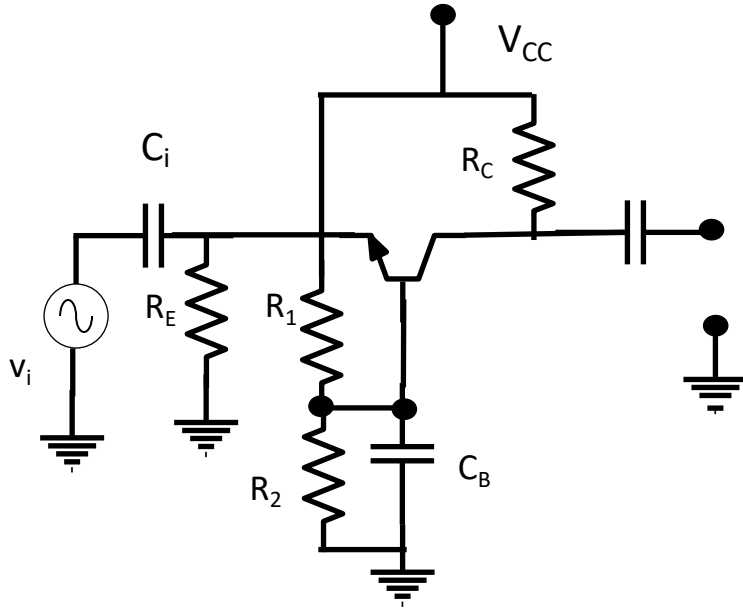


Common base amp



# BJT common base amplifier continued

6. x

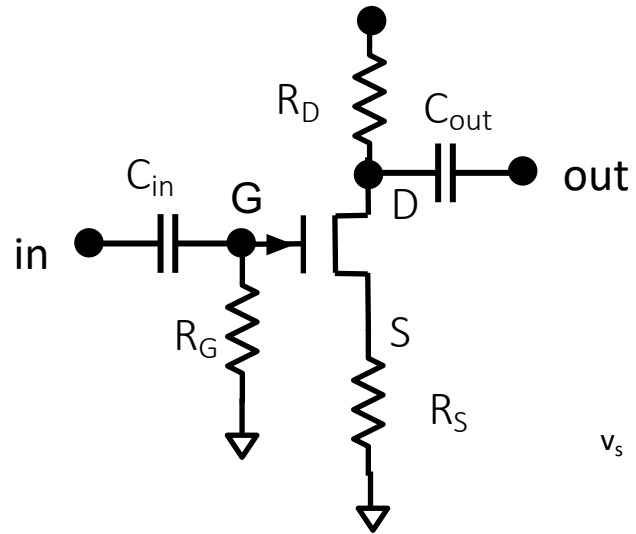


Common base amp

# JFETs

- JFET circuit model:  $I_{ds} = V_{ds}(\frac{2I_{dss}}{V_c^2})(V_{gs} - V_c - \frac{V_{ds}}{2})$
- Op amp:  $V_{out} = A_{OL}(V_+ - V_-)$ , input resistance is very high

# JFET Common Emitter Amplifier

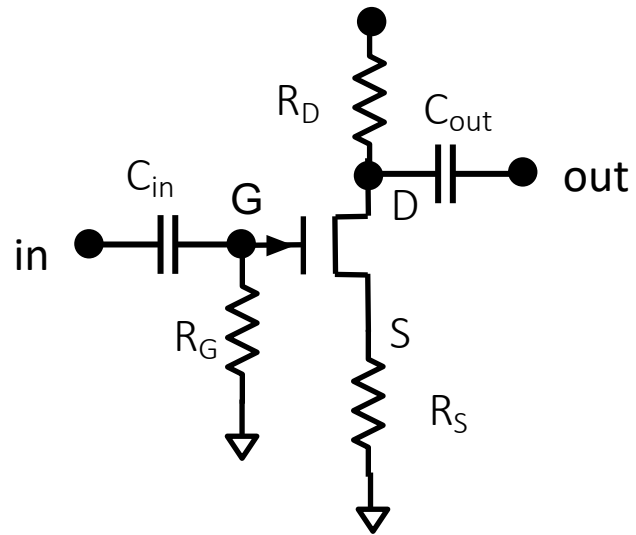


• X

# JFET common emitter amplifier continued

6. x

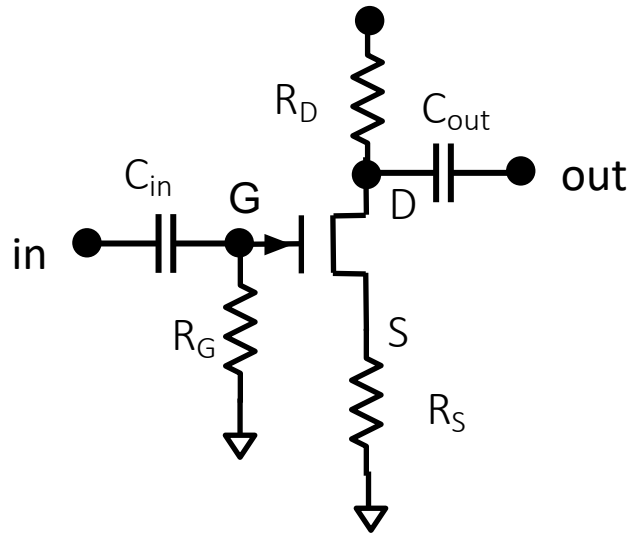
# JFET common source amplifier



1. d

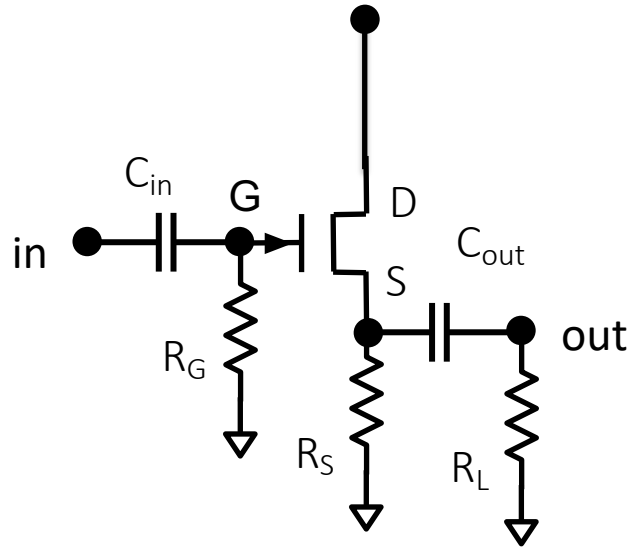
# JFET Common Source Amplifier continued

6. x



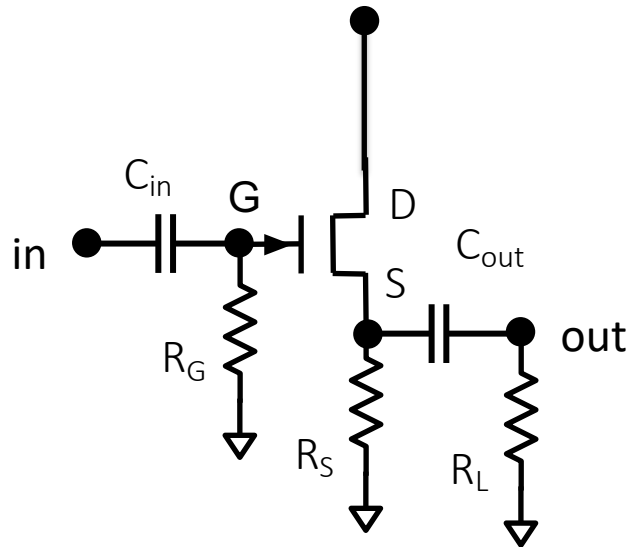
# JFET common drain amplifier

- X



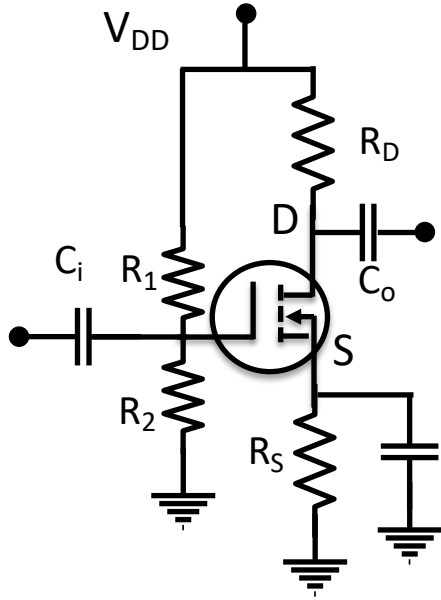
# JFET common drain amplifier continued

6. x





# CMOS common emitter amplifier



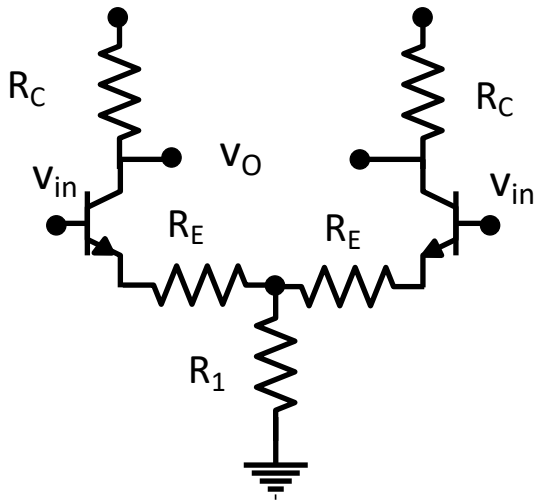
- Pick power
- $V_{DD} = i_D R_D + V_{DS} + i_D R_S$
- $V_{GS} = V_G - i_S R_S$
- $V_G = V_{DD} \frac{R_1}{R_1 + R_2}$
- $i_D = k(V_G - V_{TH})^2$
- Bias around  $\frac{V_{DD}}{3}$
- Pick gain,  $A = \frac{R_D}{R_S + \frac{1}{g_m}}$

# Differential Amplifier

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

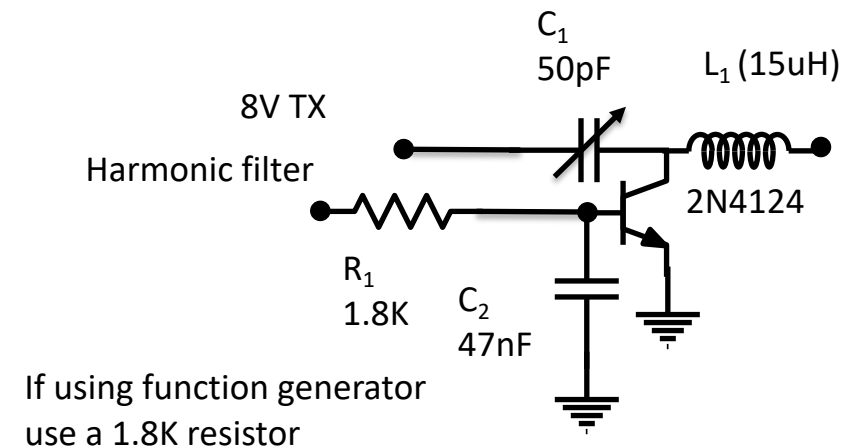
- Pick power  $\overline{P}_{12}$
- Choose collector current (2mA) by picking  $R_1$
- Pick gain,  $A = \frac{R_C}{2R_E}$

Differential amplifier



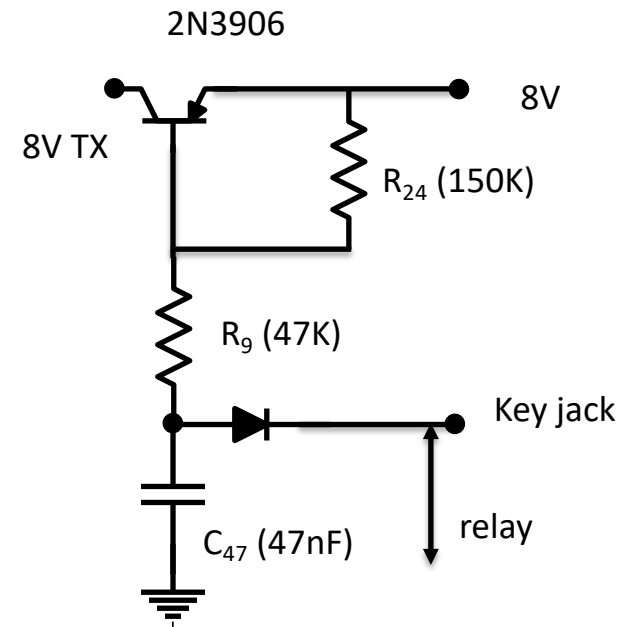
# Exercise 19: Norcal receiver switch

- Receiver mixer or an oscilloscope with  $50\Omega$
- When transistor conducts the receiver filter shorts



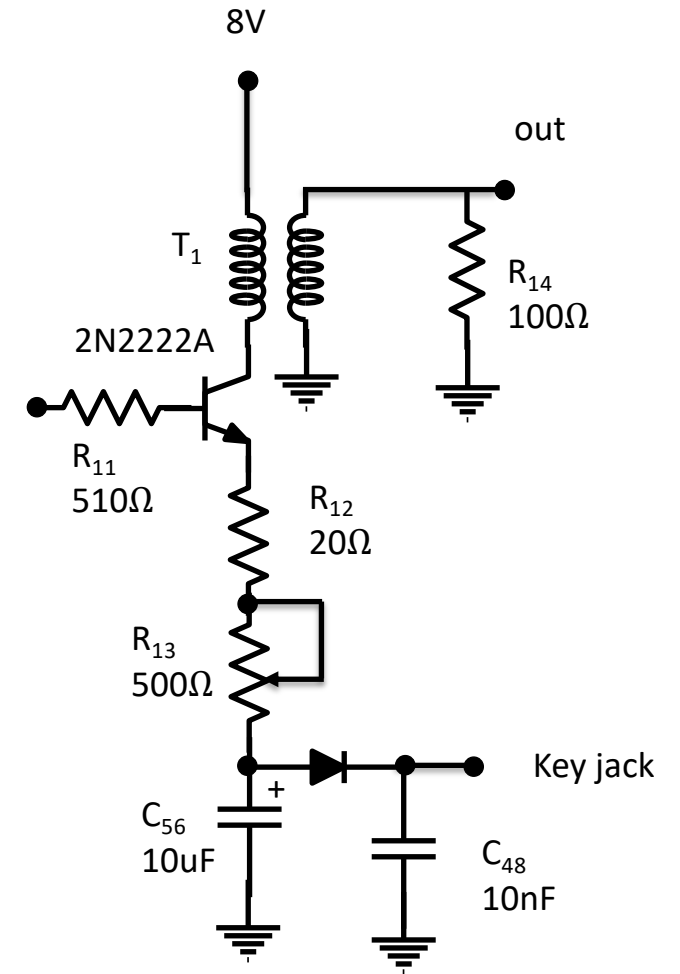
# Exercise 20: NorCal transmitter switch

- When key is down, transistor conducts



# Exercise 21: Norcal Driver

- Use 50 $\Omega$  scope probe

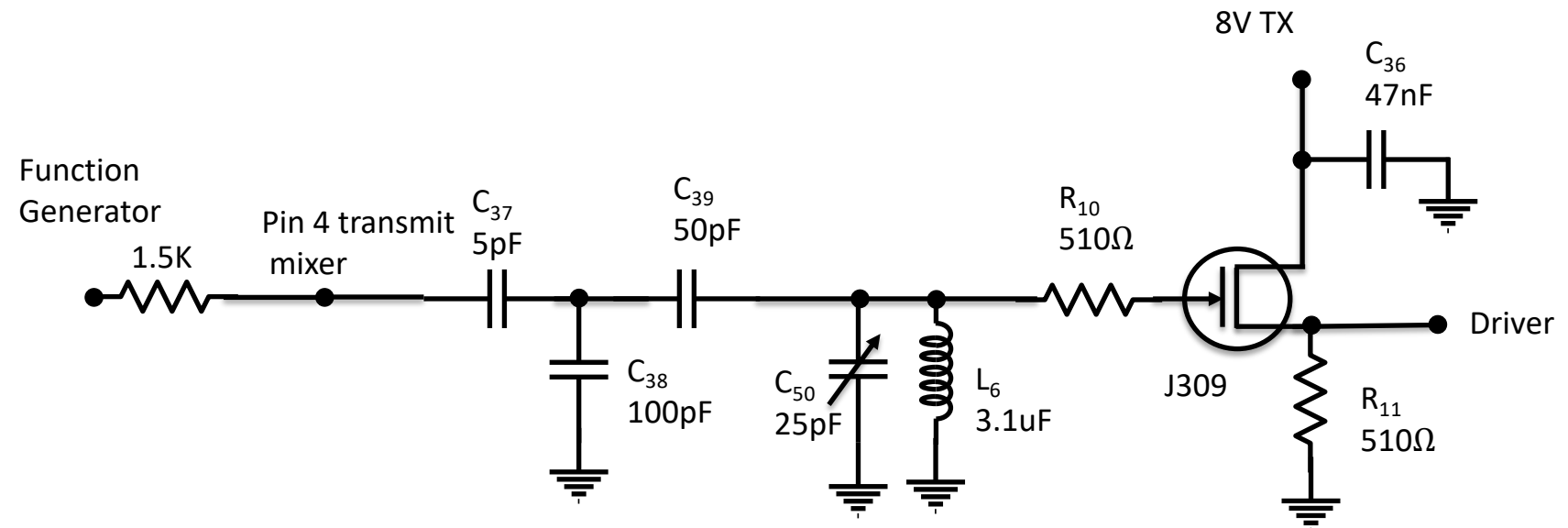


# Exercise 22: Emitter degeneration

- Use  $50\Omega$  scope probe

# Exercise 23: Norcal Buffer amplifier

$$G_V = \frac{V}{V_i}$$

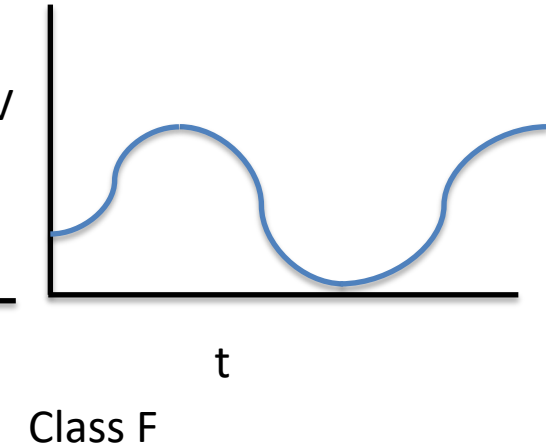
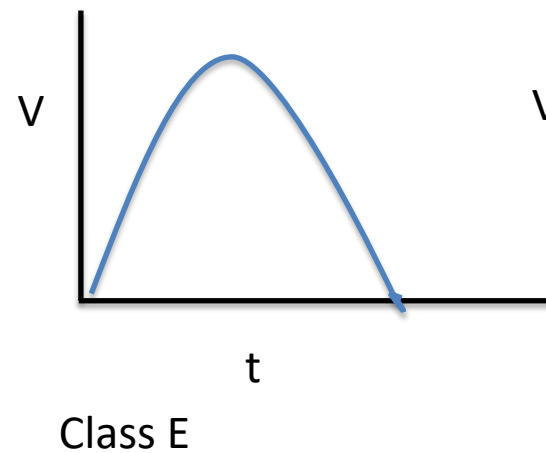
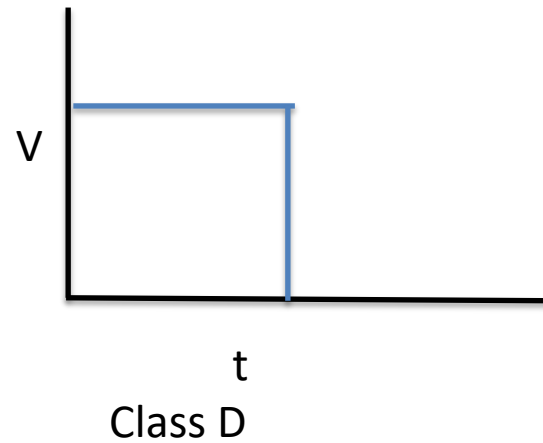
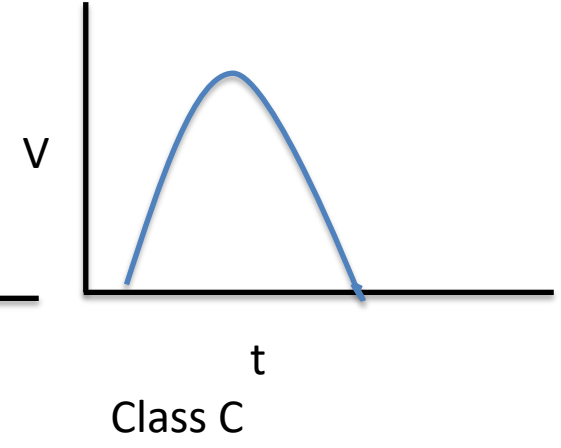
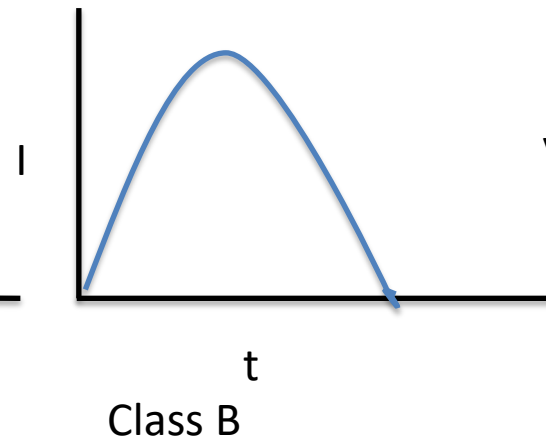
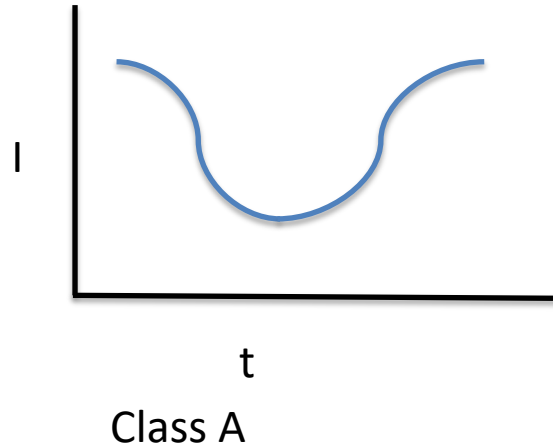


# Amplifier classes

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

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

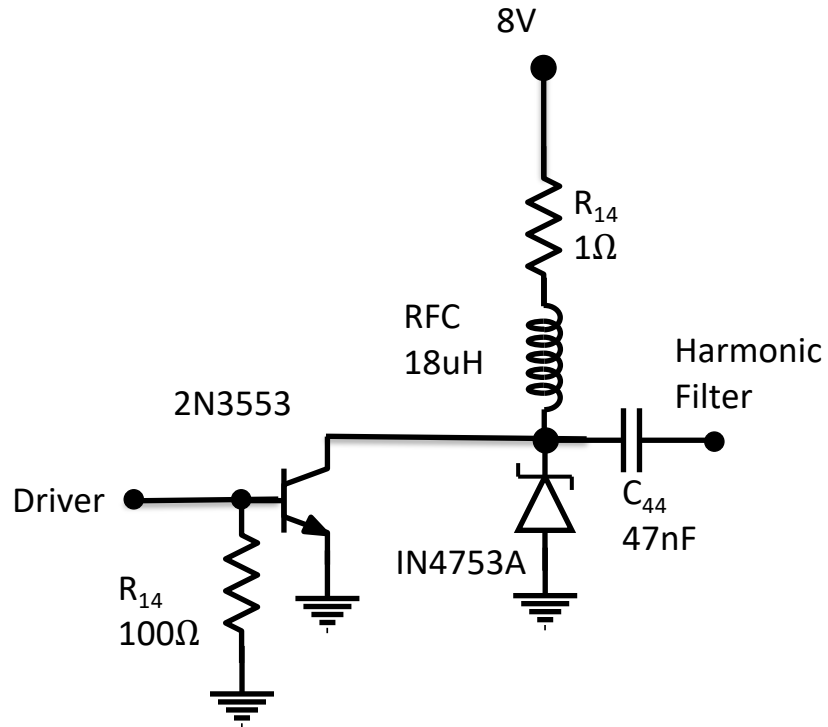
$$P_d = P_a + P_{on}$$



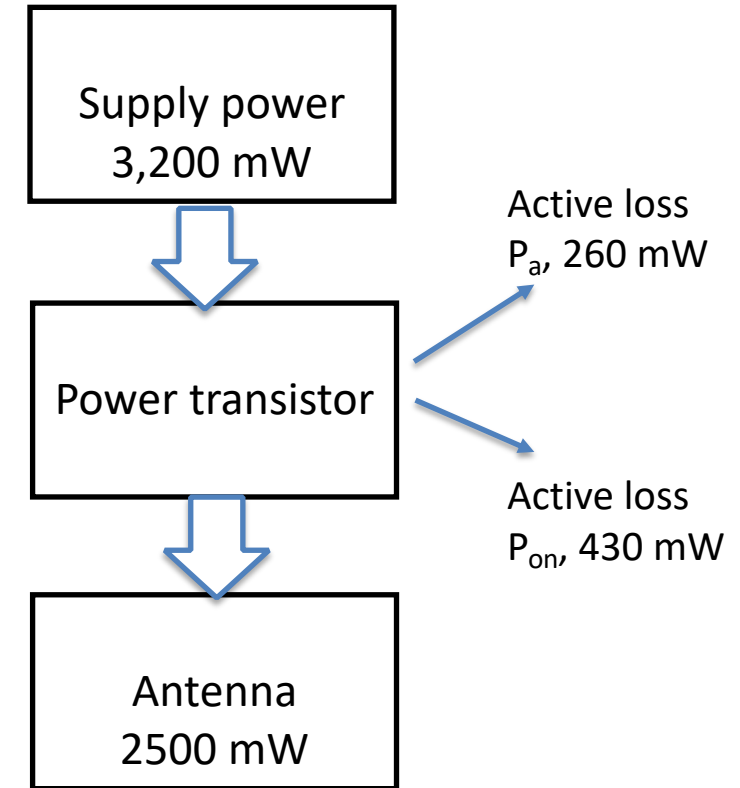


# Exercise 24: Norcal Power Amp

Norcal-40 Power amp is class C



- $R_t = \frac{T - T_0}{P_d}$
- $T_0$  is ambient temperature,  $T$  is heat sink temperature

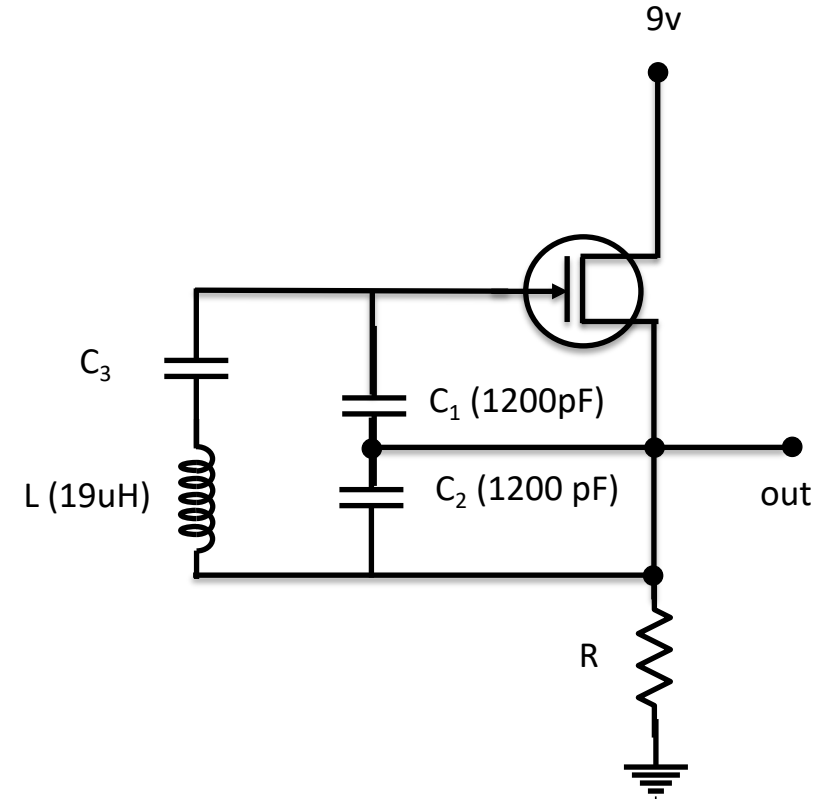


# Exercise 25: Power modelling

- Use 50 $\Omega$  scope probe

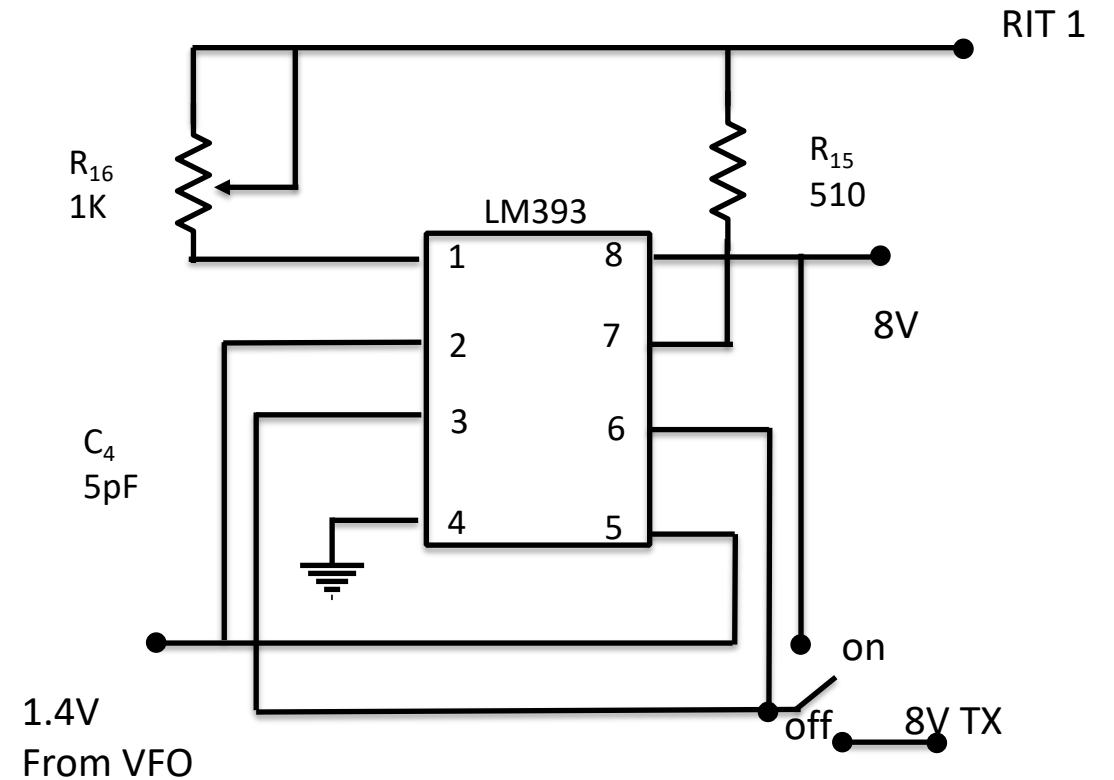
# Clapp oscillator

- $i_d = g_m v_{gs}$
- 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,  $v_{gs} = R i_d \frac{C_1}{C_2}, L = \frac{C_1}{RC_2}$
- Oscillation continues if  $g_m > \frac{C_1}{RC_2}$
- $v_{gs} = 2v_s$



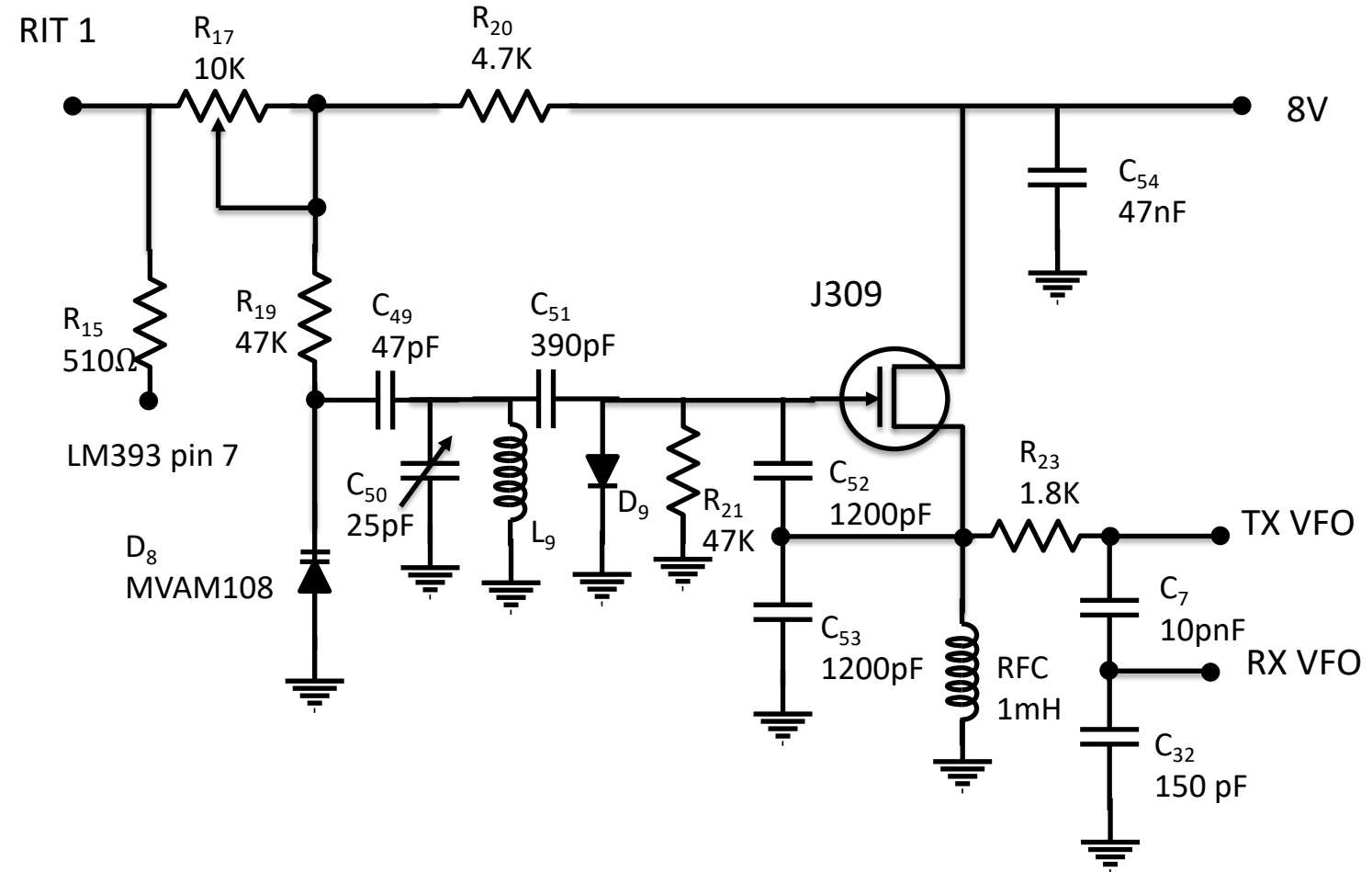
# Norcal Receiver Incremental Tuning (RIT)

- LM393 is a comparator
- For function generator connect through 1.5K



# Exercise 26: Norcal VFO

- L9: T68-7 62 turns
- 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  $g_m > 1/R$



# Exercise 27: Gain limiting

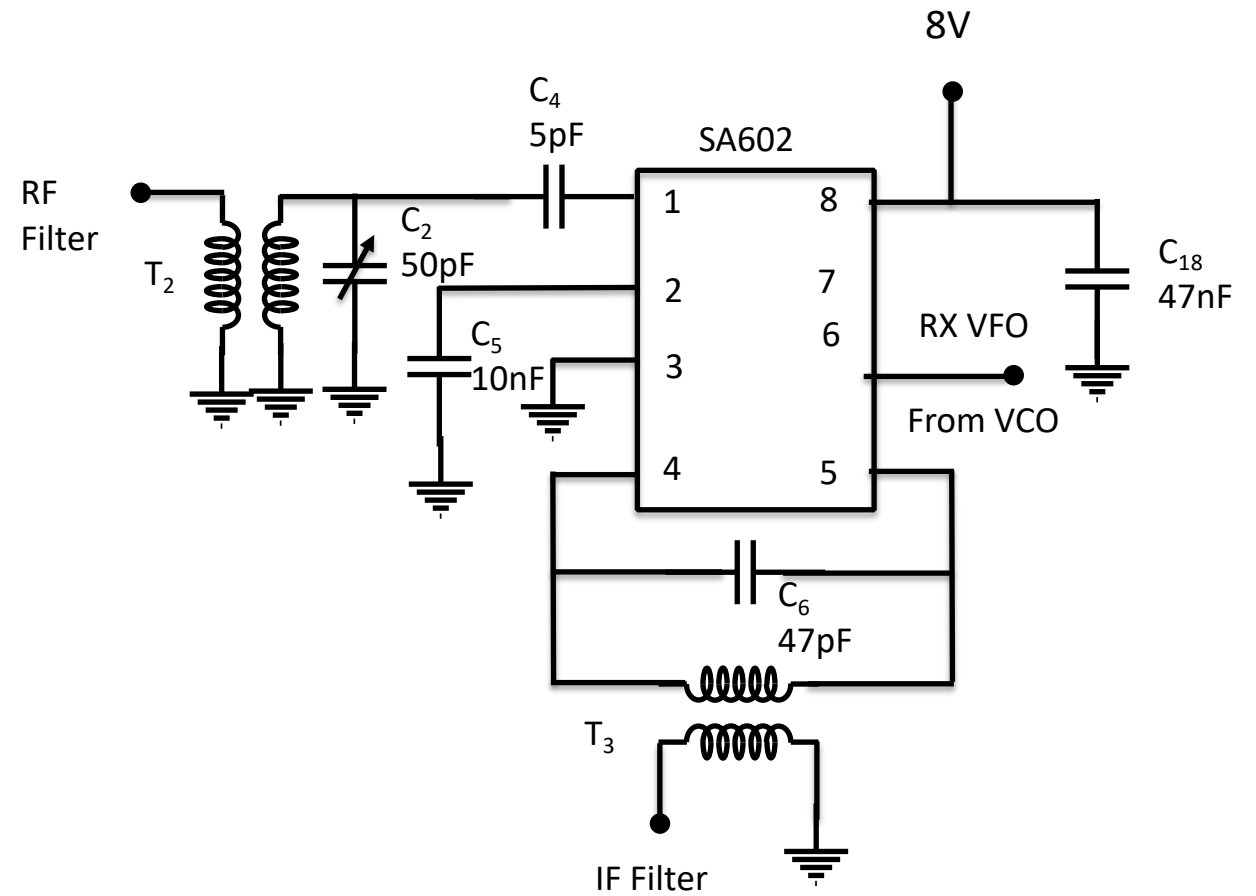
- $x$

# Mixers

- $x$

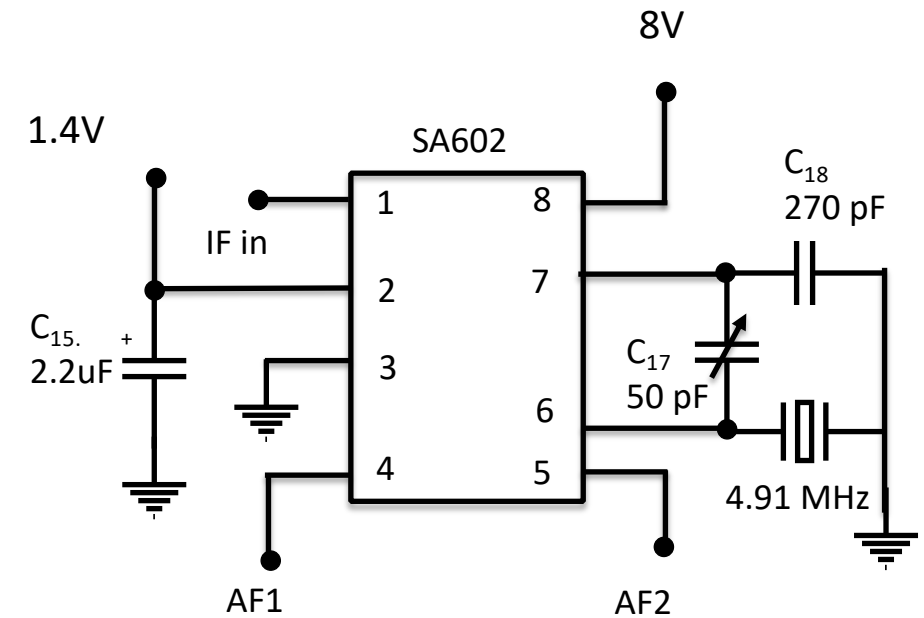
# Exercise 28: Norcal RF Mixer

- 50mVpp if using function generator



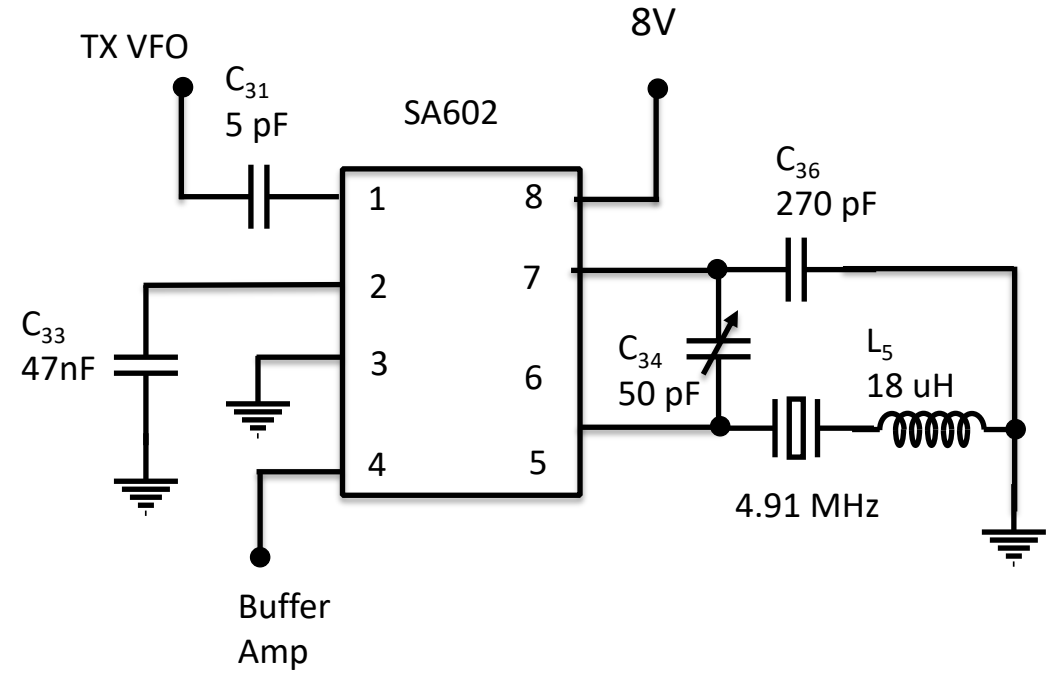


# Exercise 29: Norcal Product Detector

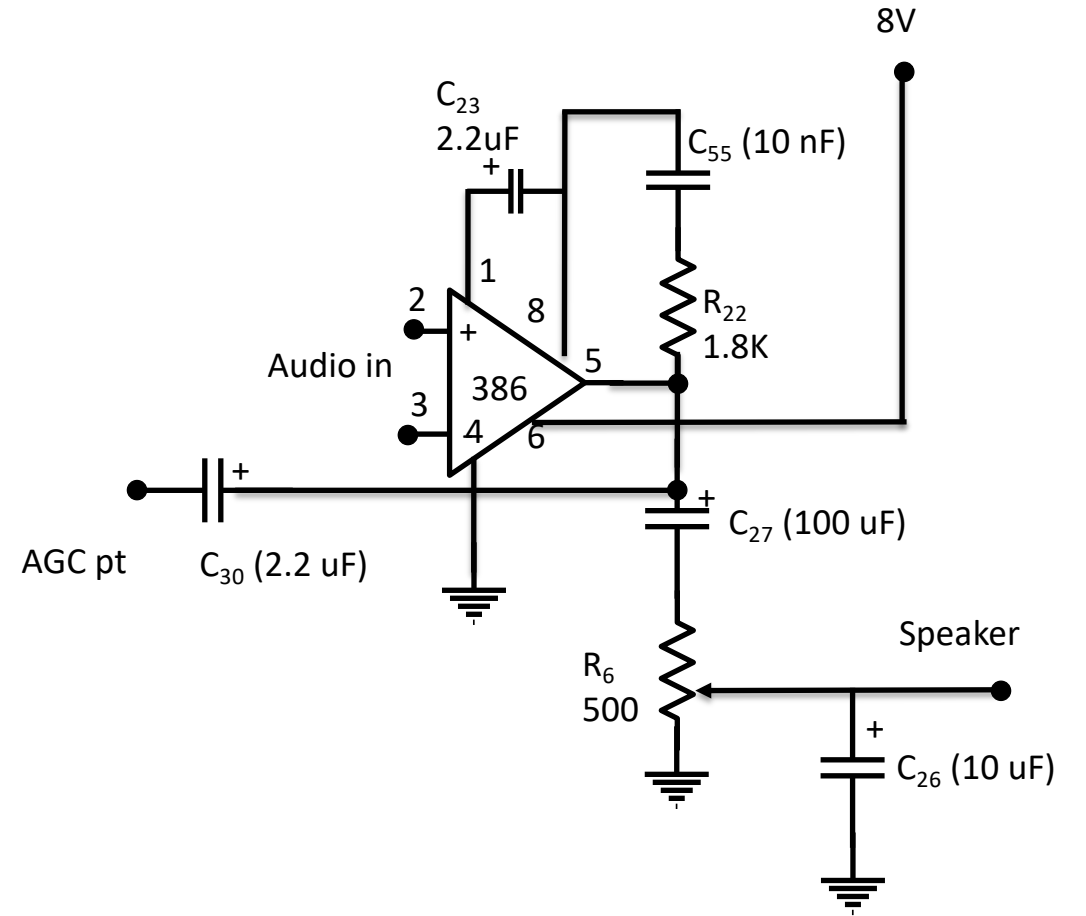


- 620 Hz output through AF1 and AF2

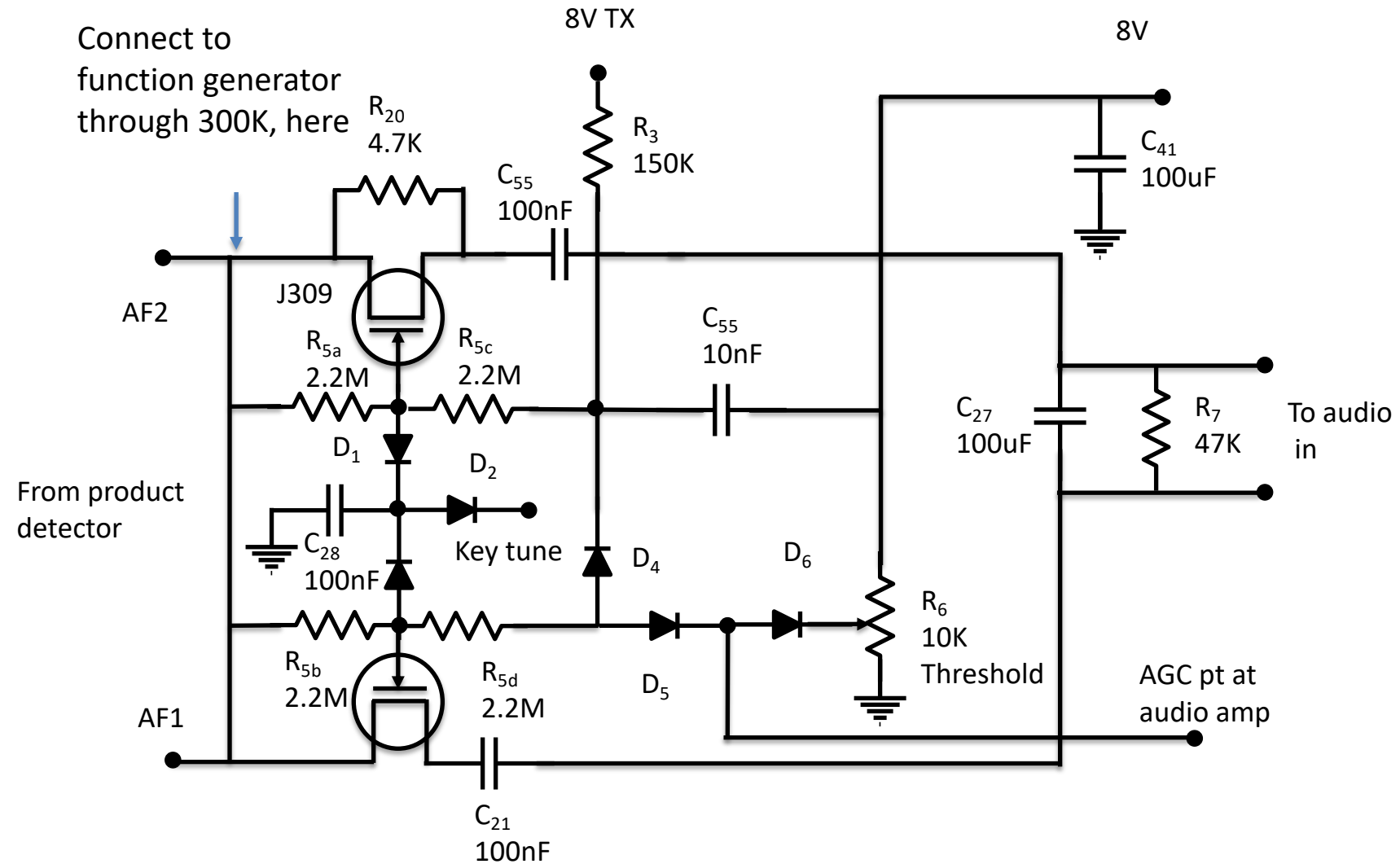
# Exercise 30: Norcal transmit mixer and oscillator



# Exercise 31: Norcal Audio Amp



# Exercise 32: Norcal AGC



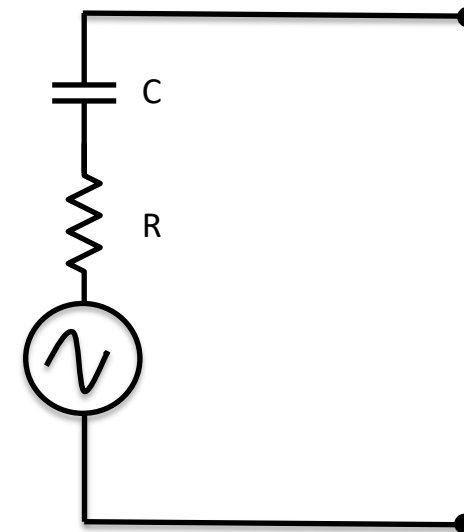
# Exercise 33: Alignment

- $x$

# Antennas and propagation

- 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 restricted cross products, we get:  $\beta E_x = \omega\mu_0 \frac{\omega\epsilon_0}{\beta}$ , so  $\beta = \omega\sqrt{\mu_0\epsilon_0}$
- Power density:  $S = \text{Re} \left( \frac{E_x \overline{H_y}}{2} \right) = \frac{(|E_x|)^2}{2\eta_0}$
- $\eta_0 = \frac{E_x}{H_y} = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377\Omega$
- 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
- For isotropic reference,  $G = \frac{4\pi r^2 S}{P_t}$

Receiving antenna Thevenin



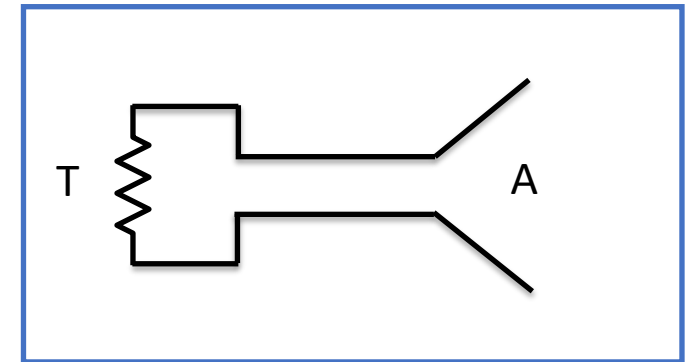
# Antennas and propagation

- Receiving antenna:
- $V_0 = hE$ ,  $h$  is effective antenna length ( $h = \frac{l}{2}$  for short antenna)
- For dipole:  $V_0 = \frac{l}{2} E \sin(\theta)$
- $A(\theta, \phi) = \frac{P_r}{S(\theta, \phi)}$ . 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
- $P_r = \frac{h^2 S \eta_0}{4R}$
- $A = \frac{h^2 \eta_0}{4R}$

# Antennas and propagation

- Antenna theorem:  $\oint A d\Omega = \lambda^2$
- For cavity on right, T is constant at thermodynamic equilibrium and the same power is transmitted and emitted, the Johnson noise is  $kT$ . The energy received is  $E = \frac{4\pi kT}{c\lambda^2}$ . Set  $B = \frac{kT}{\lambda^2}$ .  $kT = \oint BA d\Omega = \oint A \frac{kT}{\lambda^2} d\Omega$ , which gives the antenna theorem
- 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  $\frac{G_1}{A_1} = \frac{G_2}{A_2} = \frac{4\pi}{\lambda^2}$
- Friis formulas
- $S = \frac{P_t G}{4\pi r^2}, P_r = SA = \frac{P_t G A}{4\pi r^2}$

Insulated cavity

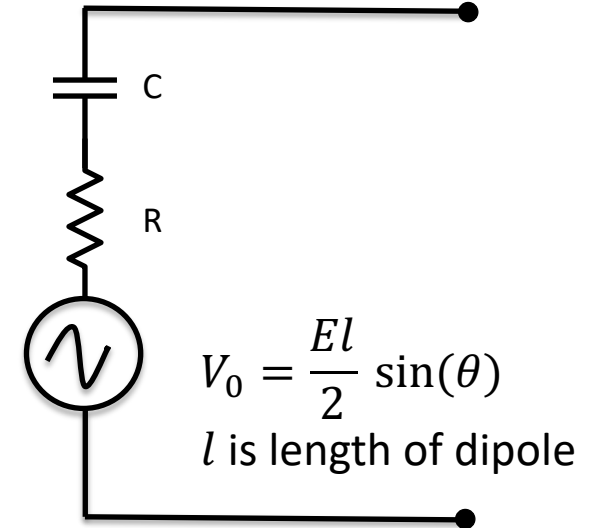




# Reciprocity and dipole

- For dipole (Length:  $l = \frac{\lambda}{2}$ )
- $\lambda^2 = \int A d\Omega = \int \frac{h^2 \eta_0}{4R_r} d\Omega$ , so
- $R_r = \frac{l^2 \eta_0}{16\lambda^2} \int \sin^2(\theta) d\Omega = \eta_0 \frac{\pi}{6} \left(\frac{l}{\lambda}\right)^2$
- $A = \frac{3\lambda^2}{8\pi} \sin^2(\theta)$  and  $G = 1.5 \sin^2(\theta)$ . . Note we used  $h = \frac{l}{2} \sin(\theta)$
- For Norcal,  $G = 1$ ,  $A = 150 \text{ m}^2$ , for  $r = 2000 \text{ m}$ ,  $P_r = 6 \text{ pW}$

Dipole Thevenin equivalent circuit



# Noise

- $V_{n(rms)} = \sqrt{\frac{1}{\tau} \int_0^\tau V(t)^2 dt}$
- $P_n = \frac{V_{n(rms)}^2}{R}$ ,  $R$  is load resistance
- $SNR = \frac{P}{P_n}$
- $MDS = \frac{P_n}{G}$
- 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 energy at resonance is  $kT = \frac{C}{2} \int_0^\infty |V_C|^2 df$
- $\int_0^\infty \frac{1}{|1 - \omega^2 LC + j\omega RC|^2} df = \frac{1}{4RC}$
- So,  $\overline{|V_C|^2} = 8kTR$

# Exercise 35: Intermodulation

- $x$

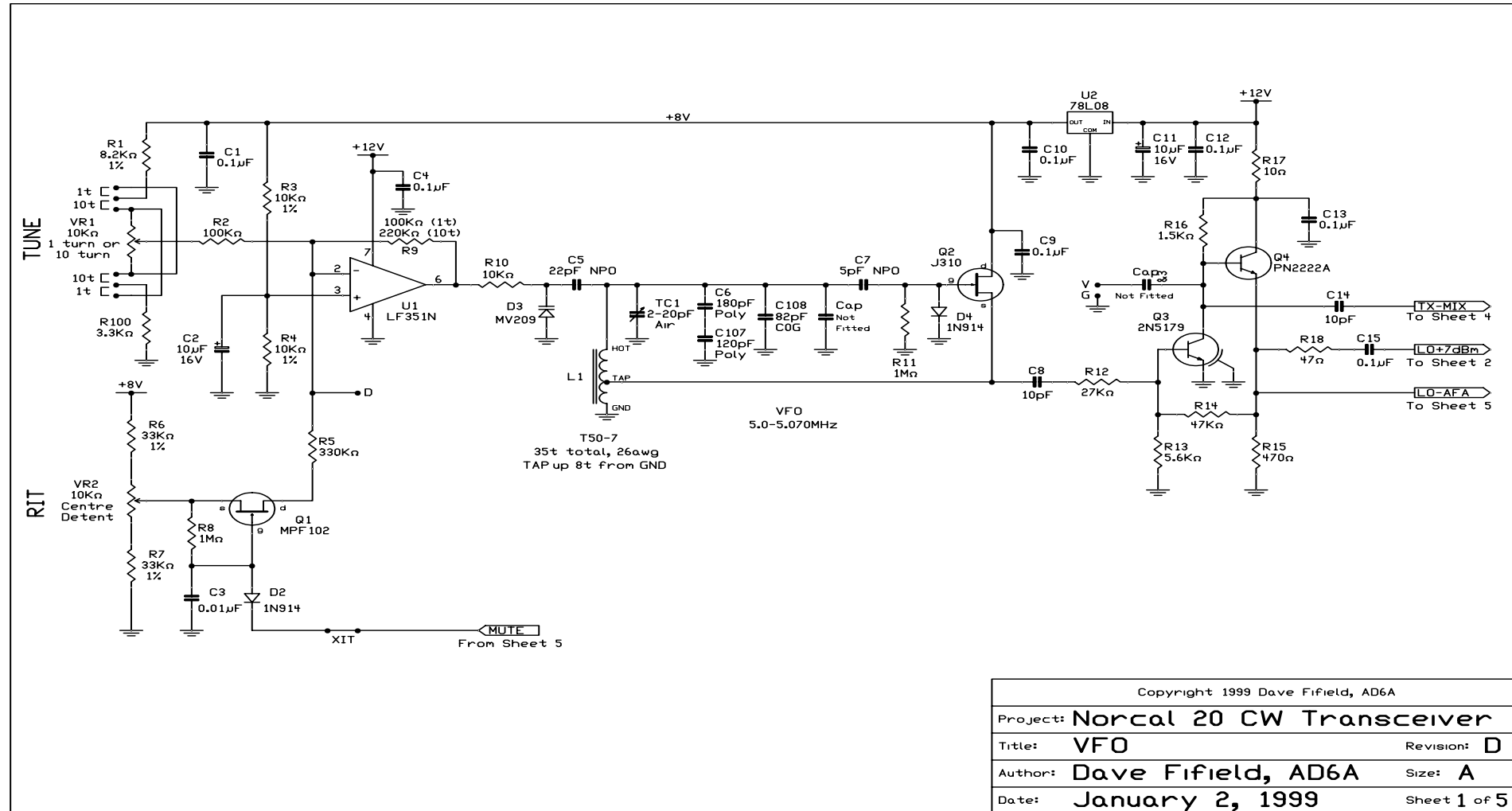
# Exercise 37: Antennas

- $x$

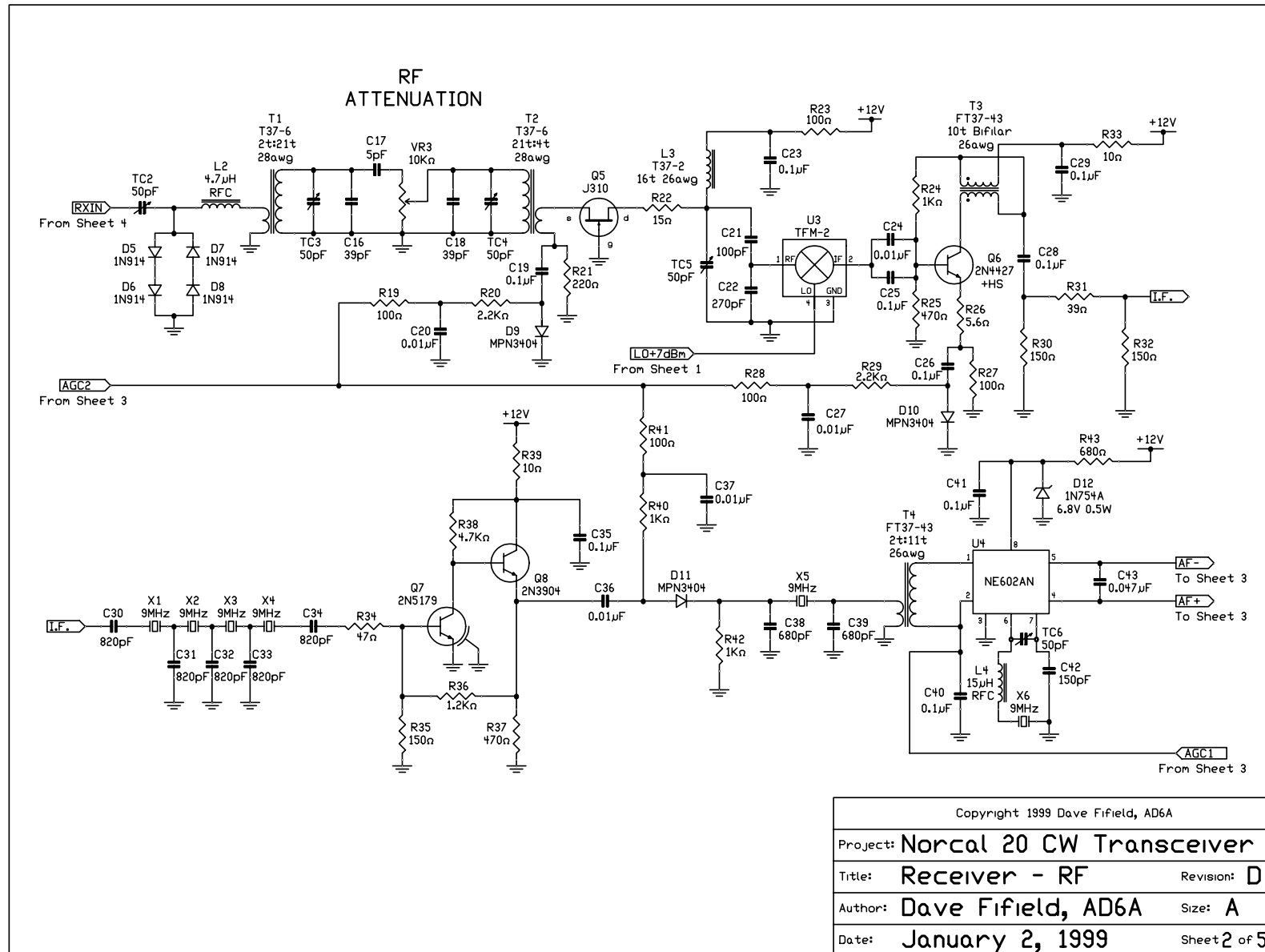
# Exercise 38: Propagation

- $x$

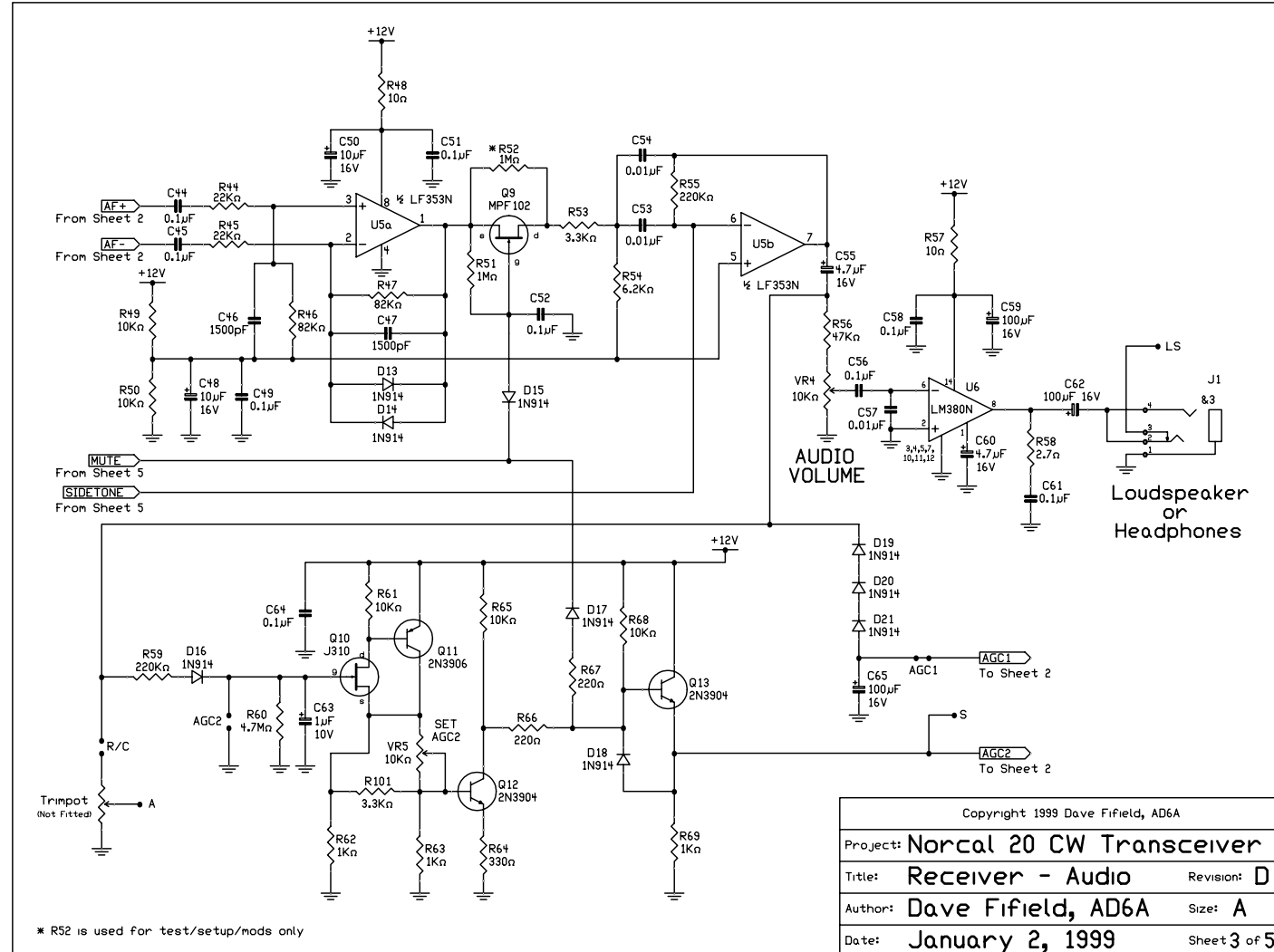
# Norcal circuit diagram, 1



# Norcal circuit diagram, 2

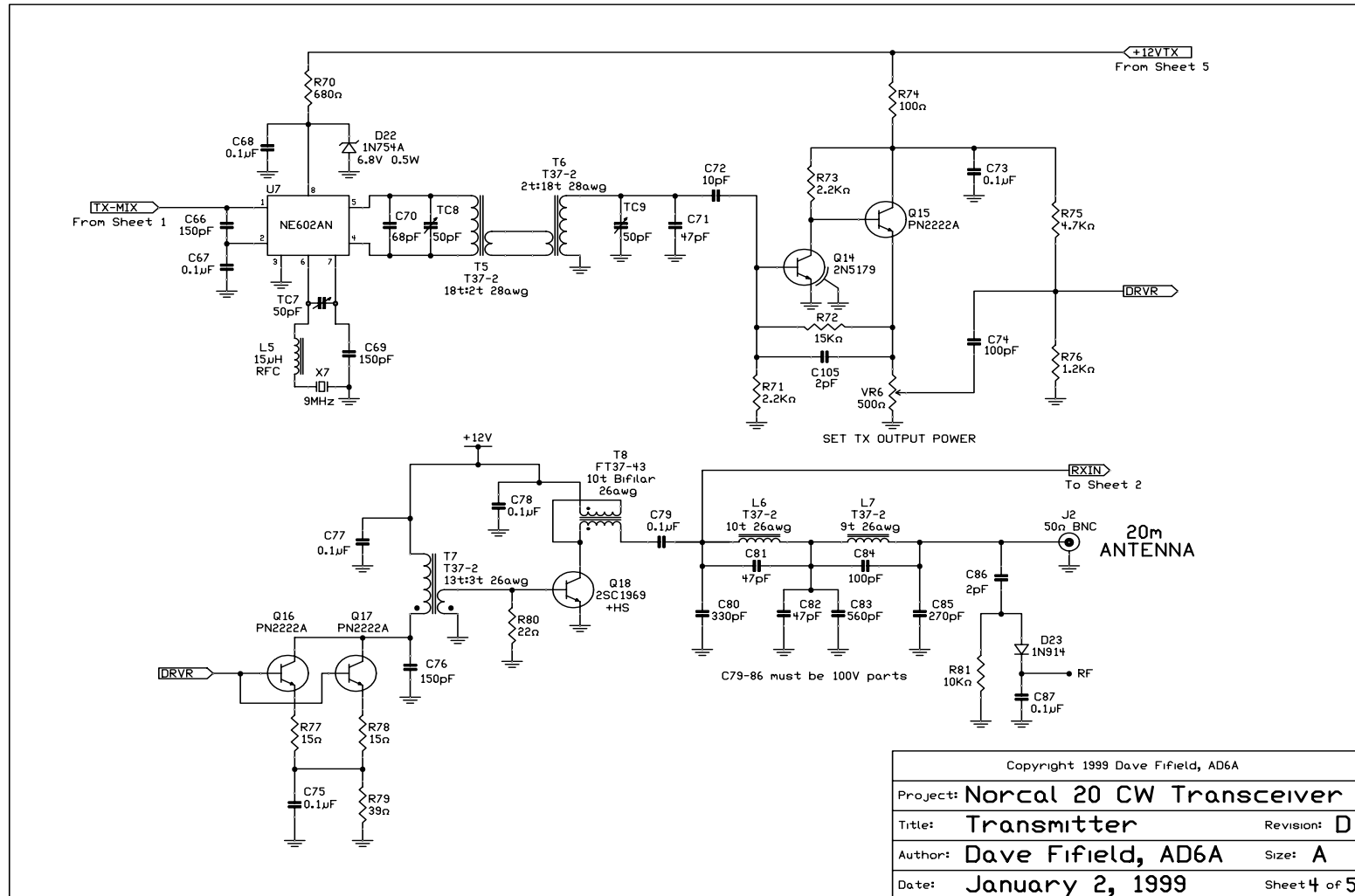


# Norcal circuit diagram, 3

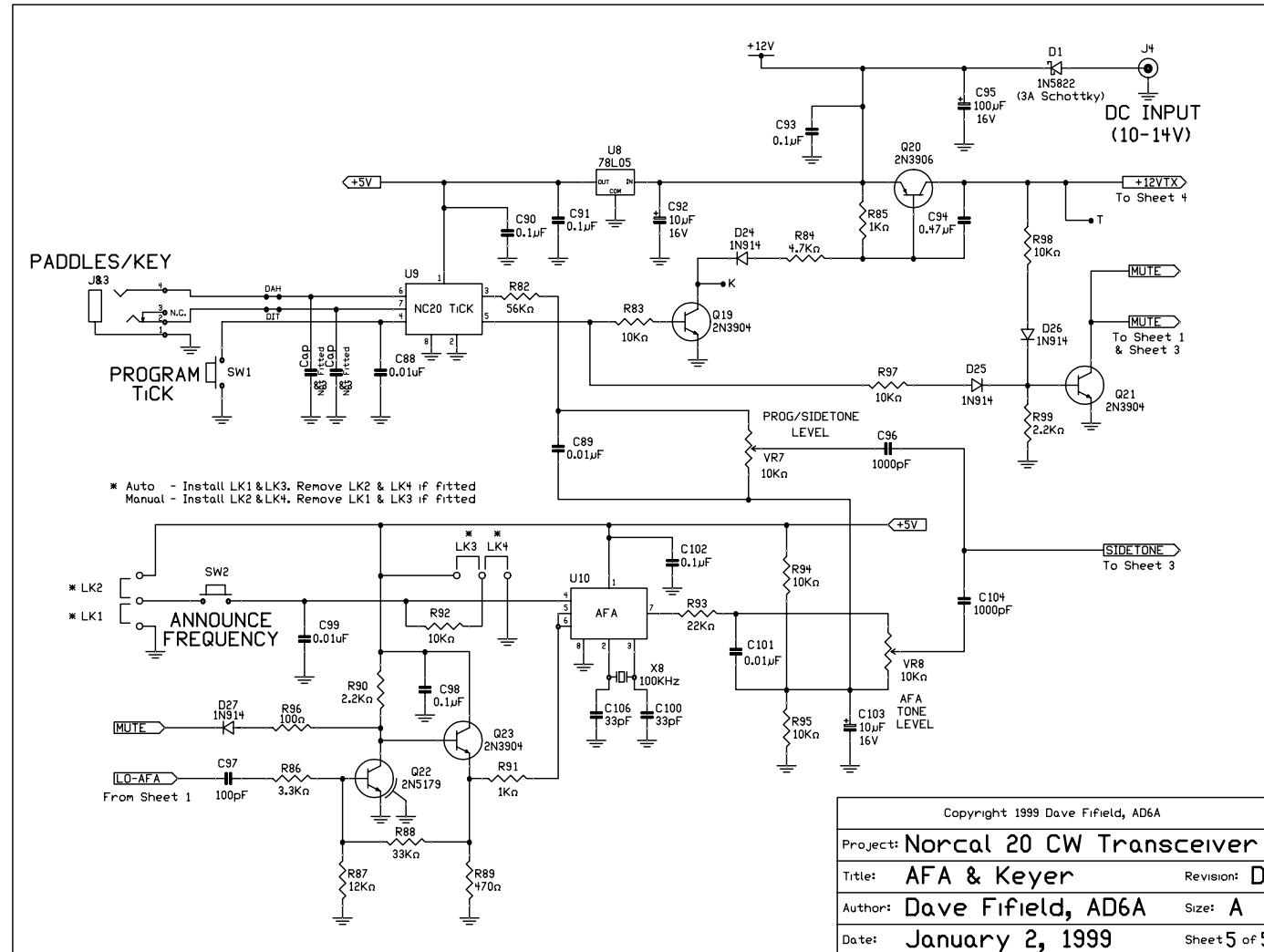




# Norcal circuit diagram, 4



# Norcal circuit diagram, 5

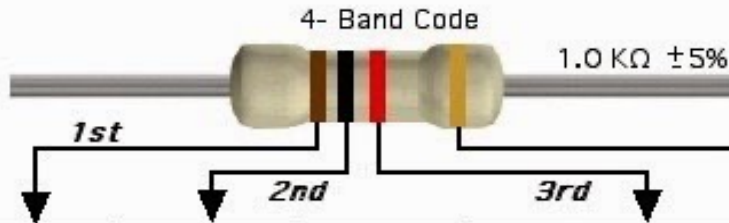


# Morse

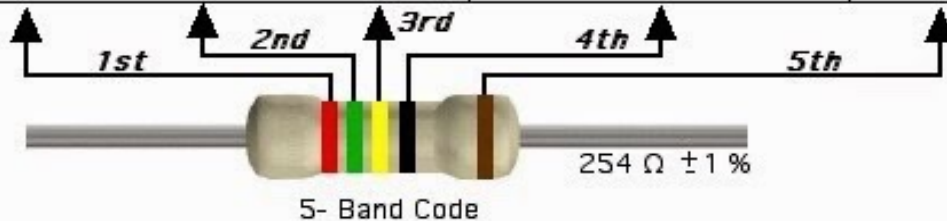
Symbol	Code	Symbol	Code	Symbol	Code
a	._	m	__	y	_.
b	__...	n	_.	z	__..
c	_.	o	___	0	_____
d	_.	p	_.	1	_.
e	.	q	___.	2	..
f	..	r	_.	3	..._
g	__.	s	...	4	...._
h	....	t	_	5	.....
i	..	u	..	6	_....
j	_.	v	..._	7	__...
k	_.	w	_.	8	____..
l	_.	x	_.	9	____.

# Color codes

## RESISTOR COLOR CODE GUIDE



Color	1st Band	2nd Band	3rd Band	Decimal Multiplier		Tolerance
Black	0	0	0	1	1	
Brown	1	1	1	10	10	$\pm$ 1 %
Red	2	2	2	100	100	$\pm$ 2 %
Orange	3	3	3	1K	1,000	
Yellow	4	4	4	10K	10,000	
Green	5	5	5	100K	100,000	
Blue	6	6	6	1M	1,000,000	
Violet	7	7	7	10M	10,000,000	
Gray	8	8	8		100,000,000	
White	9	9	9		1,000,000,000	
Gold					0.1	$\pm$ 5 %
Silver					0.01	$\pm$ 10 %
None						$\pm$ 20 %



- Resistors: ohms
- Capacitors: picoFards
- Inductors: milliHenries