

Electronics of Radio

Notes on David Rutledge's book

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Basic concepts

- Potential difference (V, ϕ): $\phi = \int_a^r E \cdot ds$, 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

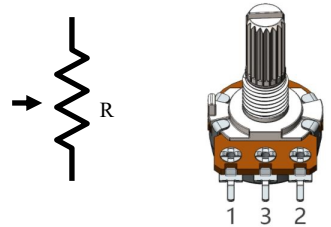
- Analytic model: $IR = V$
- Energy dissipated: $E = \int_{t_i}^{t_f} IV \, dt = \int_{t_i}^{t_f} I^2 R \, dt$

- 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

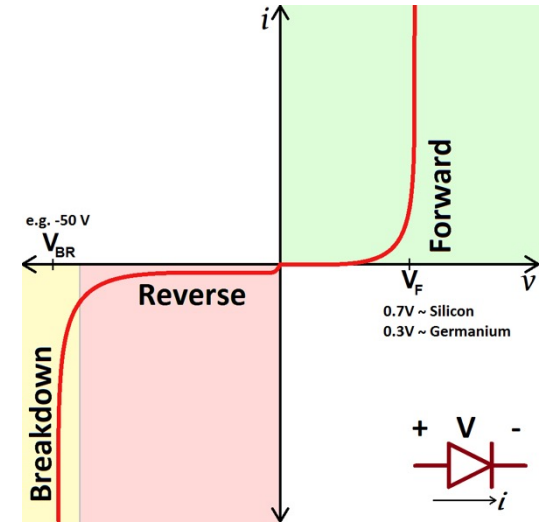
- Analytic model: $V = L \frac{di}{dt}$
- Inductor Energy stored: $E = \int_{t_i}^{t_f} IV \, dt = \int_{t_i}^{t_f} LI \frac{dI}{dt} \, dt = \frac{1}{2} LI^2$



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
- $L_{eq} = L_1 + L_2$

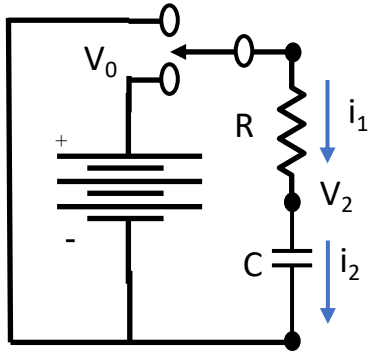


- Let L_{eq} be the equivalent inductance, replacing the bottom left circuit with a $\frac{di}{dt} = \frac{V_1}{L_{eq}}$, $\frac{di_1}{dt} = \frac{V_1}{L_1}$, $\frac{di_2}{dt} = \frac{V_1}{L_2}$, single inductor.
- By Kirchhoff's node rule, $i_1 + i_2 = i$, so
- $\frac{V_1}{L_{eq}} = \frac{V_1}{L_1} + \frac{V_1}{L_2}$ 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
- $V_2 = \frac{R_2}{R_1 + R_2} V_1$

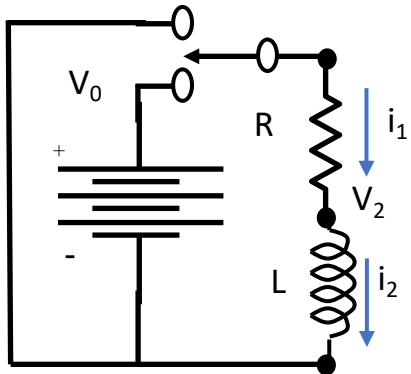


RC/RL circuit analysis with Kirchhoff



- 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 ω_u and ω_l , where $\omega_u > \omega_l$.
- We define $Q = \frac{X}{R} = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR}$.
- Solving for ω_u and ω_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.



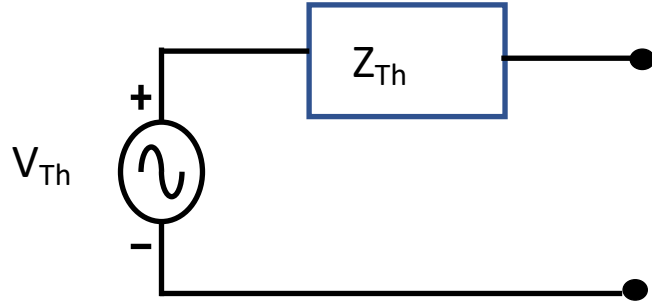
Phasors, impedance and power

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- 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*.
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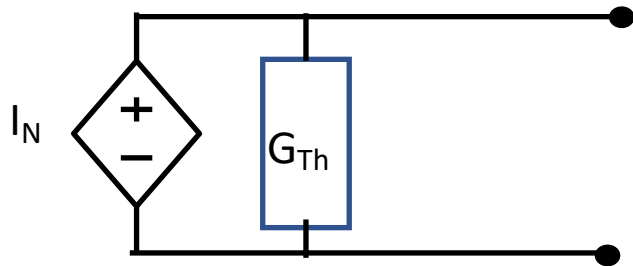


Thevenin and Norton

- 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



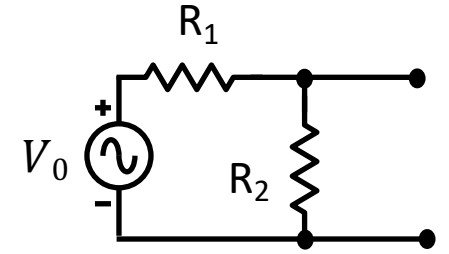
- Norton: Any combination of linear sources and passive elements terminating in two terminals is equivalent to a pure current source in parallel with a conductance



- 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).

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

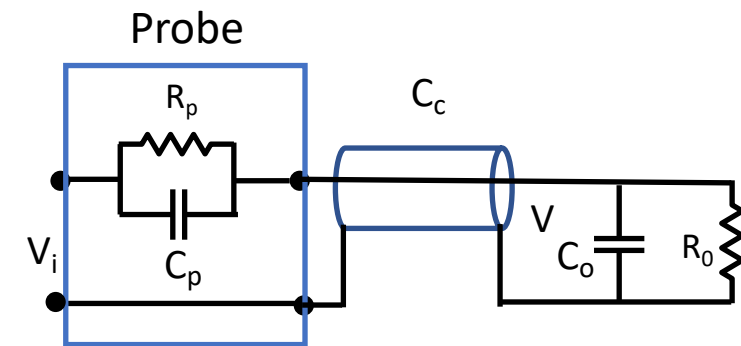
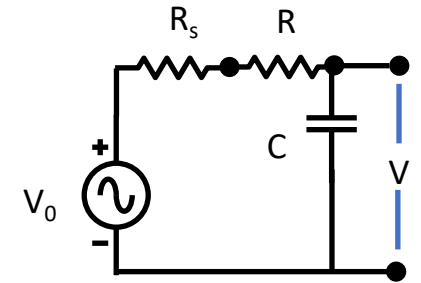


Exercise 2: Sources

Skip

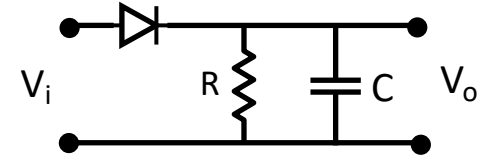
Exercise 3: Capacitors

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 $1M\Omega$.
3. Let t_2 , the time to discharge to 0V. Calculate τ and t_2 .
 - $\tau = 3 \times 10^5 \times 10^{-8} \text{ sec} = 3 \text{ millisec}$
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
6. Now calculate the new t_2 .



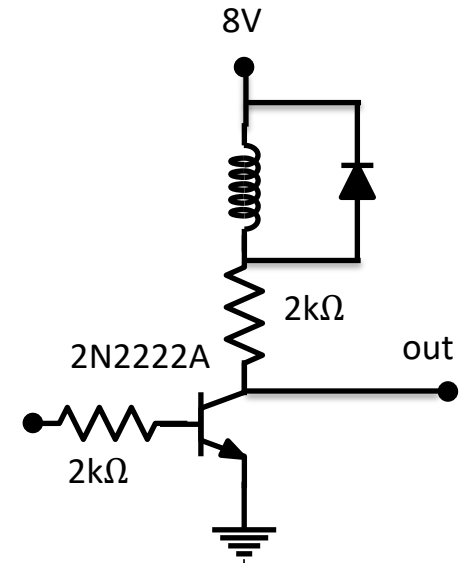
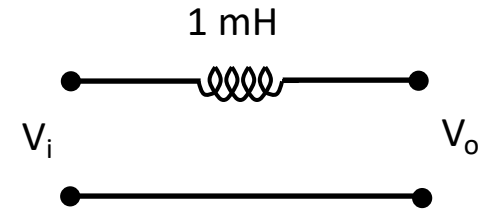
Exercise 4: Diode detectors

- 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 τ 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

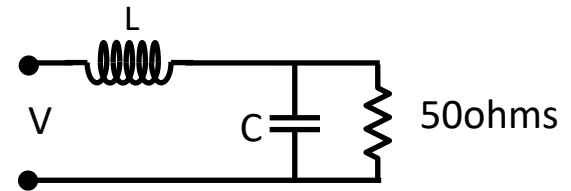
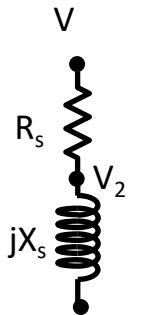
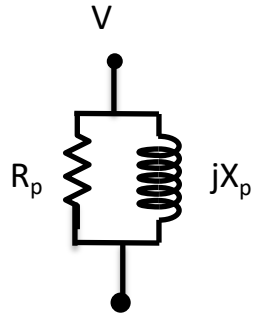
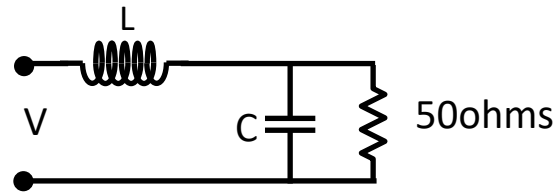


Exercise 6: Diodes and snubbers

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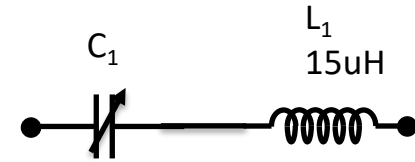
Exercise 7: Parallel to Series conversion

- $Q_s = \frac{X_s}{R_s}$
- $Q_p = \frac{X_p}{R_p}$



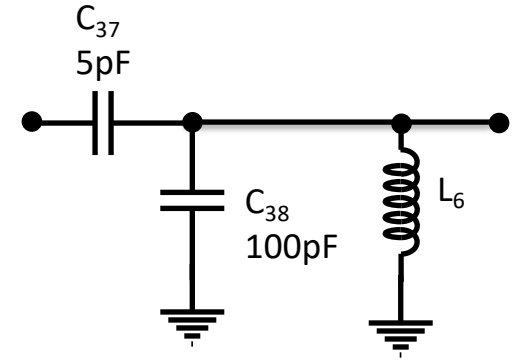
Exercise 8: Series resonance

- $C_1 = 8 - 50pf$



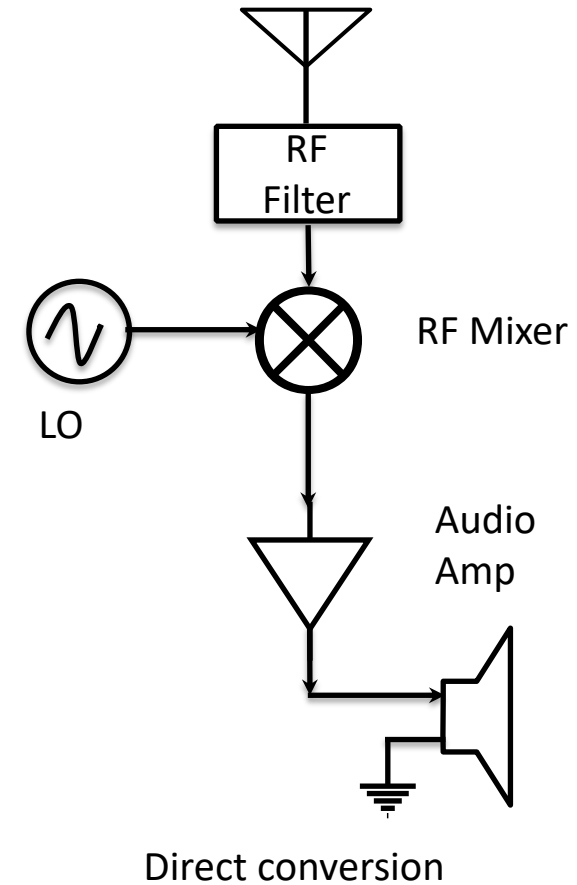
Exercise 9: Parallel resonance

- $L = A_l N^2, A_l = 4 \frac{\mu H}{turn^2}$

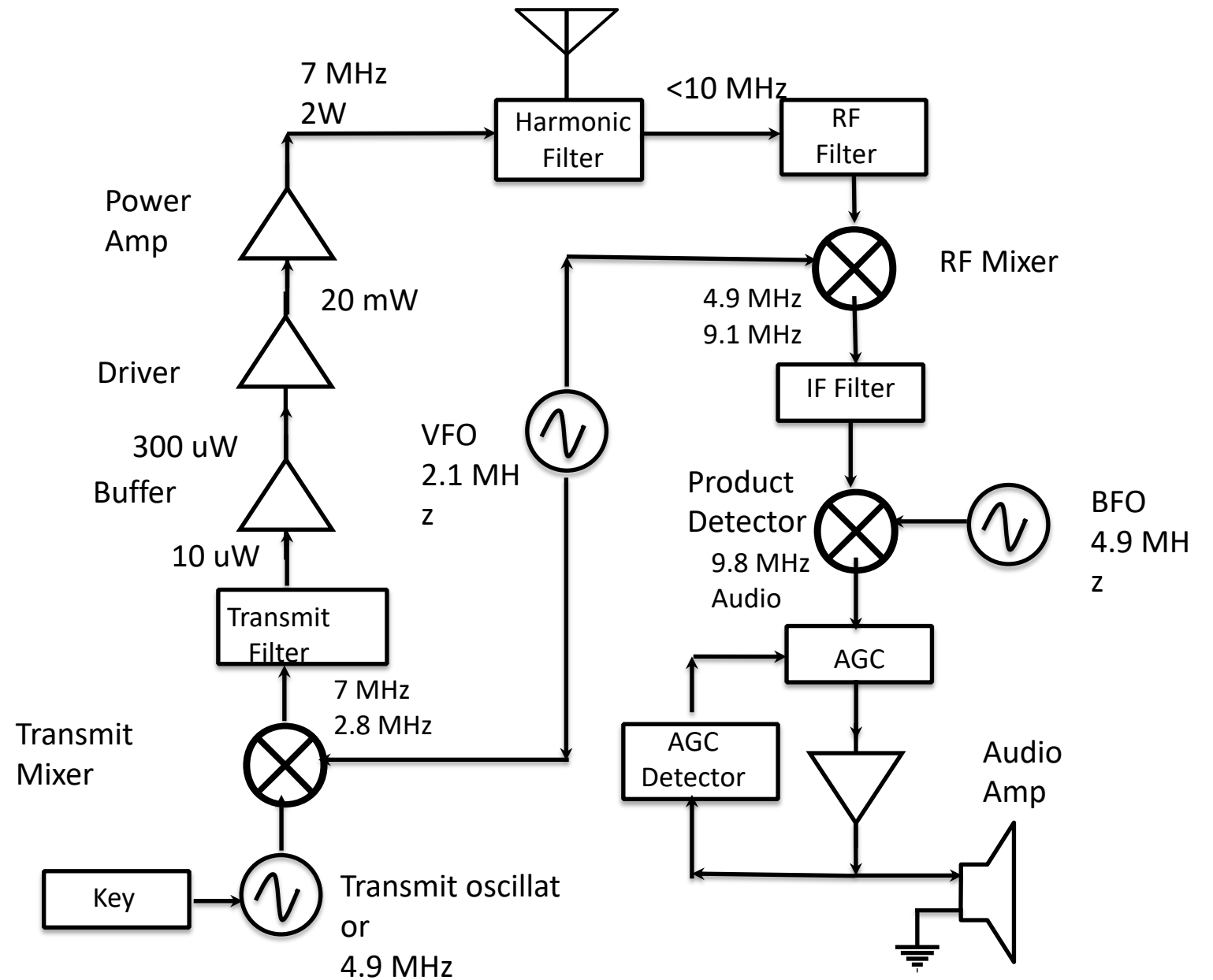


Direct conversion and superhet receivers

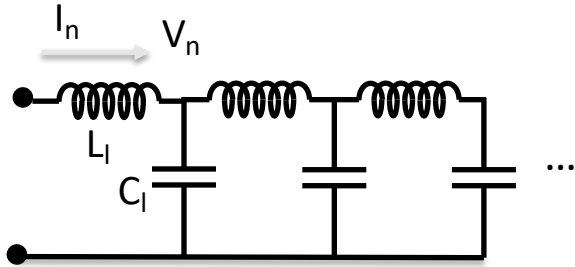
- Image frequency
 - $\omega_{rf} = \omega_{LO} - \omega_a$
 - $\omega_i = \omega_{LO} + \omega_a$
- Superheterodyne designs
 - $\omega_{rf} = \omega_{IF} + \omega_{VFO}$
 - $\omega_{vi} = \omega_{IF} - \omega_{VFO}$
 - $\omega_{IF} = \omega_{BFO} - \omega_a$
 - $\omega_{bi} = \omega_{BFO} + \omega_a$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



Norcal 40A



Transmission Lines



Power

$$\tau = \frac{V}{V_+} = 1 + \rho = \frac{2Z}{Z + Z_0}, V = 2V_+$$

Lookback resistance is $R_s = Z_0$

$$P_+ = \frac{V_+^2}{2Z_0} = \frac{V_0^2}{8Z_0}, \text{ This is the total available power}$$

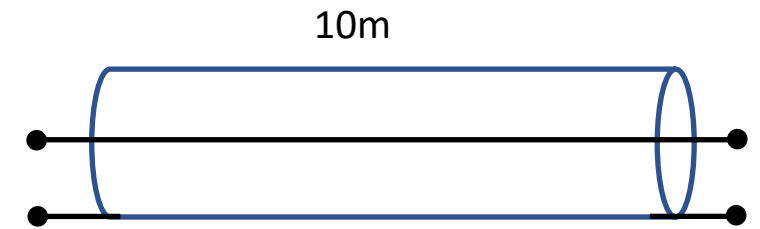
- $V_{n+1} - V_n = -L_l \frac{\partial I_{n+1}}{\partial t}, L = \frac{L_l}{l}$
- $I_{n+1} - I_n = -C_l \frac{\partial V_n}{\partial t}, C = \frac{C_l}{l}$
- $\frac{\partial^2 V}{\partial z^2} = LC \frac{\partial^2 V}{\partial t^2}$ and $\frac{\partial^2 I}{\partial z^2} = LC \frac{\partial^2 I}{\partial t^2}$
- 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

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Exercise 10: Coax

- Use 50Ω scope probe

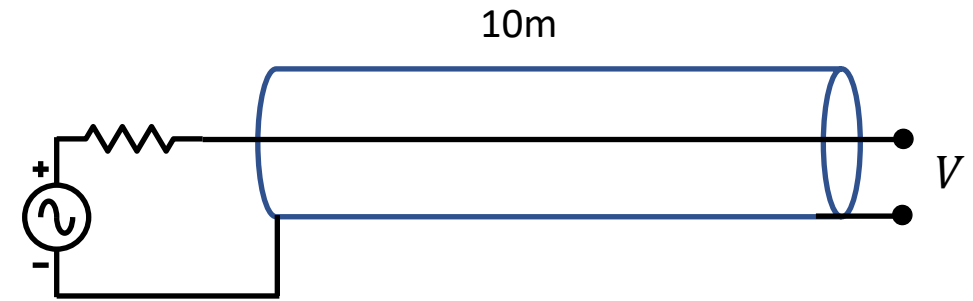


Exercise 11: Waves

- Use 50Ω scope probe

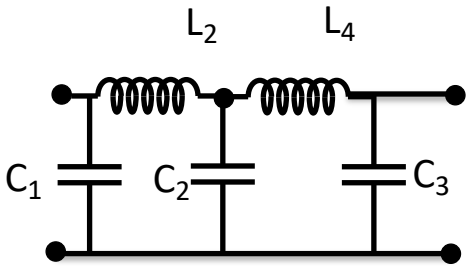
Exercise 12: Resonance

- Use 50Ω scope probe

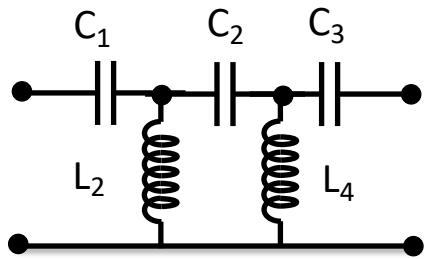


Filters

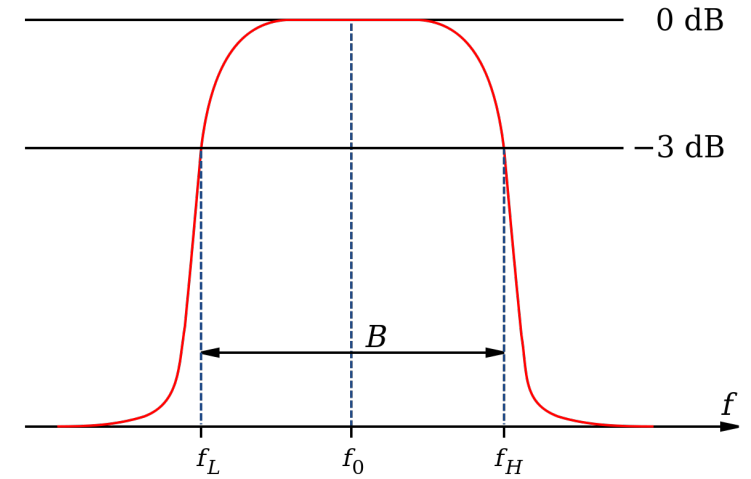
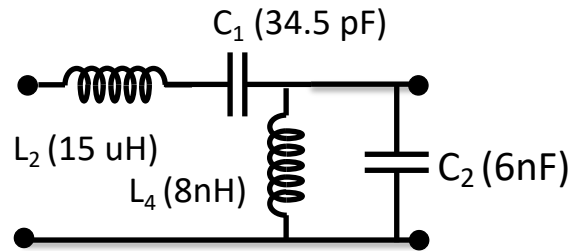
Low pass



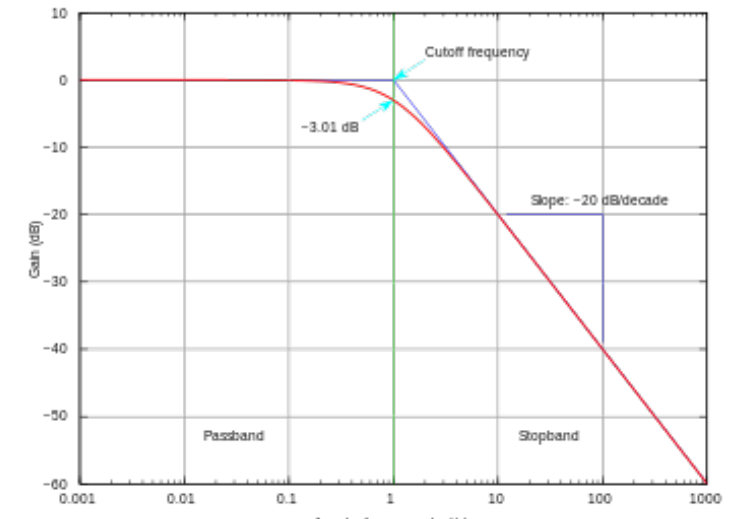
High pass



7 MHz bandpass

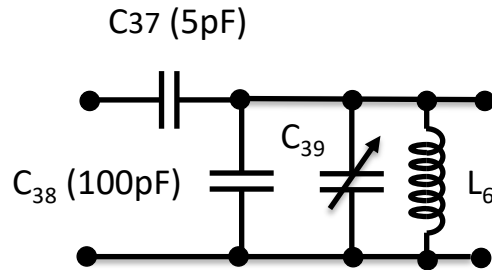


Bandpass - Wikipedia



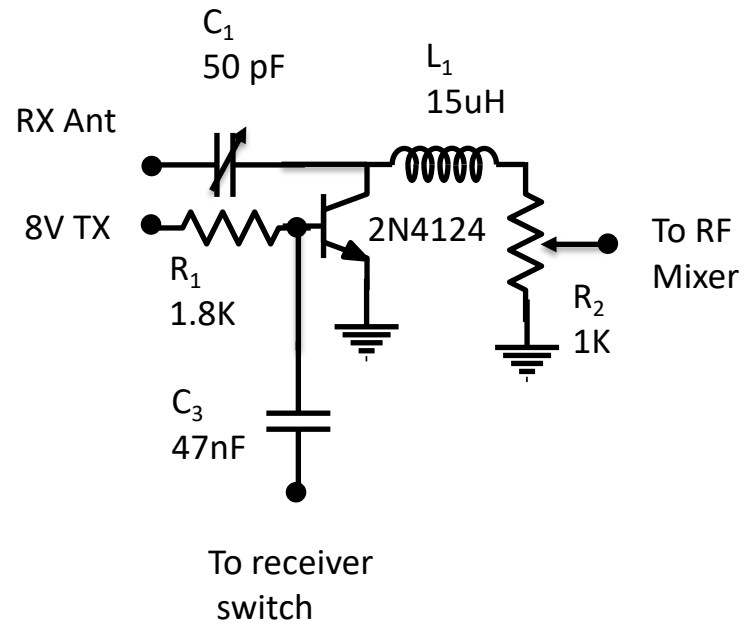
Bandpass - Wikipedia

Norcal transmit bandpass filter

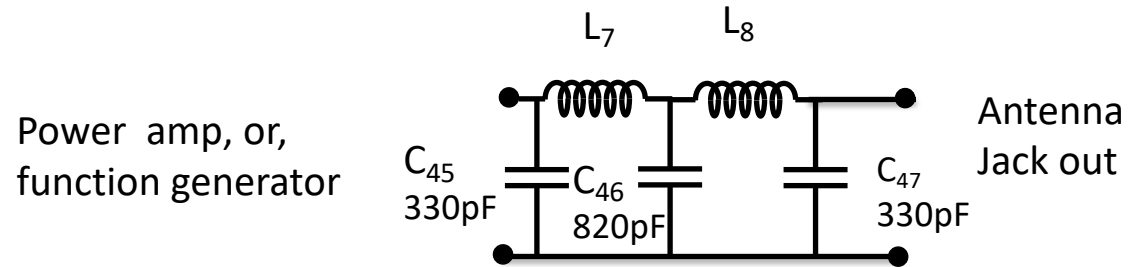


- $C_{39} = 50\text{pF}$,
- L_6 is 36 turns #28 on T37-2 which has $A_l = 4 \frac{\text{nH}}{\text{turn}^2}$
- $L_6 = A_l \cdot 36^2 = 3.1\mu\text{H}$
- $Z_2 = -\frac{j}{(C_{38}+C_{39})\omega_o}$, $Z_3 = jL_6\omega_o$, $Z_1 = \frac{j}{C_{37}\omega_o}$
- $Z_{2,3-eq} = \frac{jL_6\omega_o}{L_6(C_{38}+C_{39})\omega_o^2 - 1}$
- 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

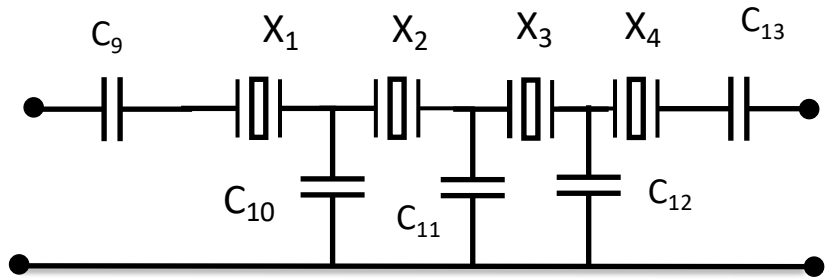


Exercise 13: Norcal Harmonic Filter

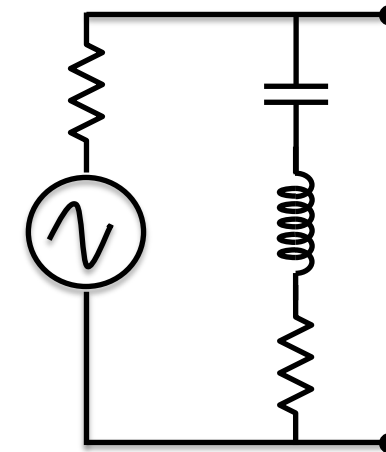
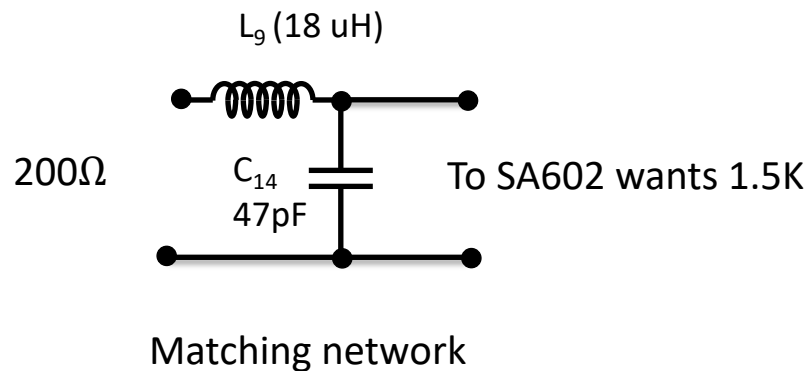


- L_7 , L_8 use T37-2 core, 18 turns, 1.3uH
- Compare loss at 7MHz and 14MHz

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_{pp} from function generator
- Calculate R and X for filter



Equivalent circuit for crystal and generator

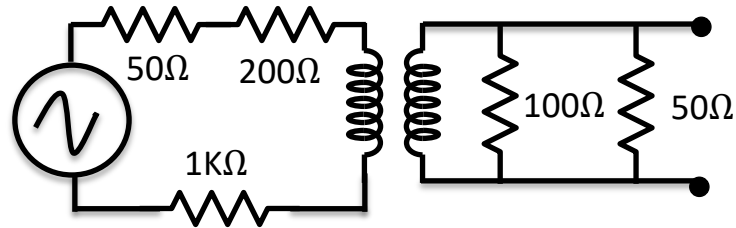
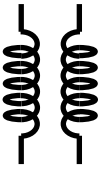
Transformers

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

Norcal matching transformers

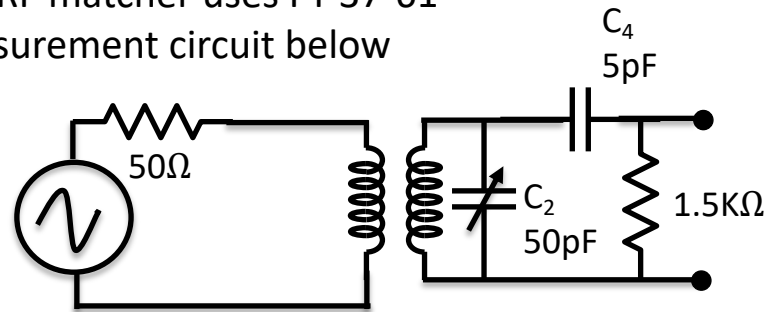
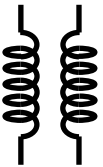
- T_1 is driver matcher uses FT 37-43
- Measurement circuit below

T_1 , 14:4

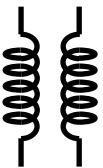


- T_2 is RF matcher uses FT 37-61
- Measurement circuit below

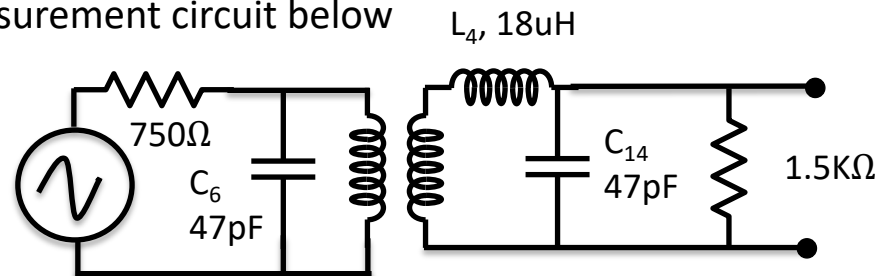
T_2 , 1:20



T_3 , 23:6



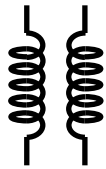
- T_3 is IF matcher uses FT 37-61
- Measurement circuit below



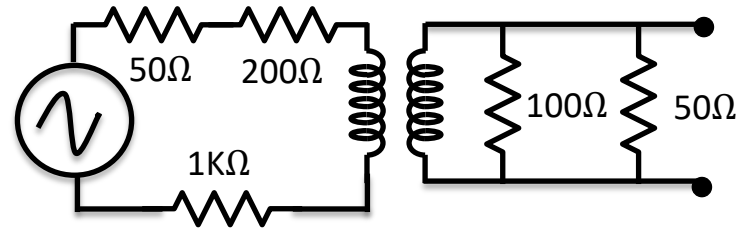
Exercise 15: Norcal Driver Transformers

- x

T_1 , 14:4



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

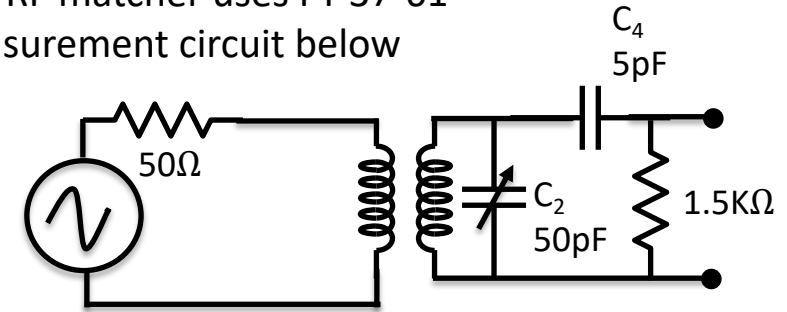
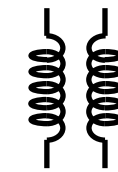


Exercise 16: Norcal Tuned Transformers

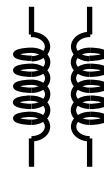
- x

- T_2 is RF matcher uses FT 37-61
- Measurement circuit below

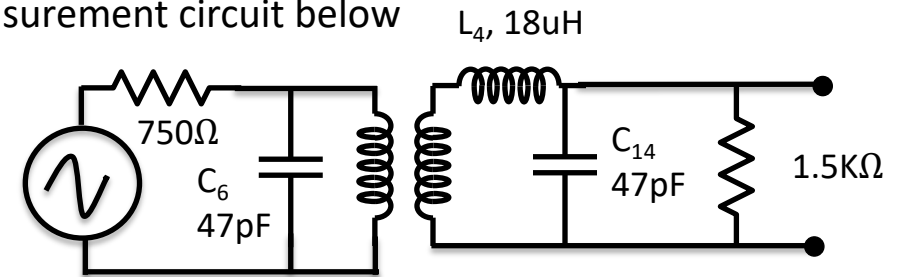
$T_2, 1:20$



$T_3, 23:6$



- T_3 is IF matcher uses FT 37-61
- Measurement circuit below



Acoustics

- $\frac{\partial^2 P}{\partial t^2} = \frac{\gamma P}{\rho} \frac{\partial^2 P}{\partial x^2}, v = \sqrt{\frac{\gamma P}{\rho}} = 332 \frac{m}{s}$
- $SWR = \frac{\lambda^2}{2\pi A}$, A is the area of the tube

| Sound | L _p | Power density |
|--------------------|----------------|----------------------|
| rustling leaves | 10dB | 1pW/m ² |
| broadcast studio | 20dB | 1pW/m ² |
| classroom | 50dB | 10nW/m ² |
| heavy truck | 90dB | 1nW/m ² |
| Shout at 1m | 100dB | 10mW/m ² |
| jackhammer | 110db | 100mW/m ² |
| jet takeoff at 50m | 120dB | 1W/m ² |

Exercise 17: Tuned Speaker

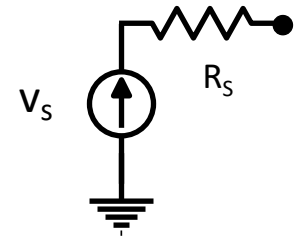
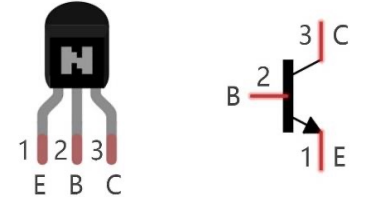
- x

Exercise 18: Acoustic Standing Wave

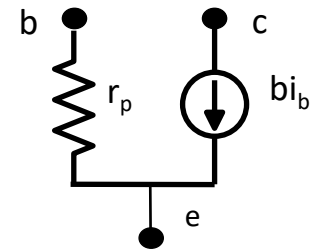
- x

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

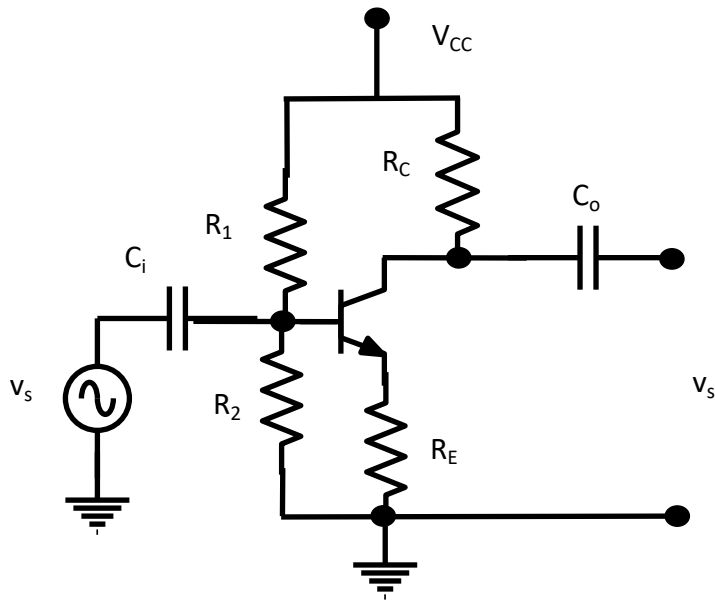


Bipolar equivalent circuit

Bipolar Switches

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

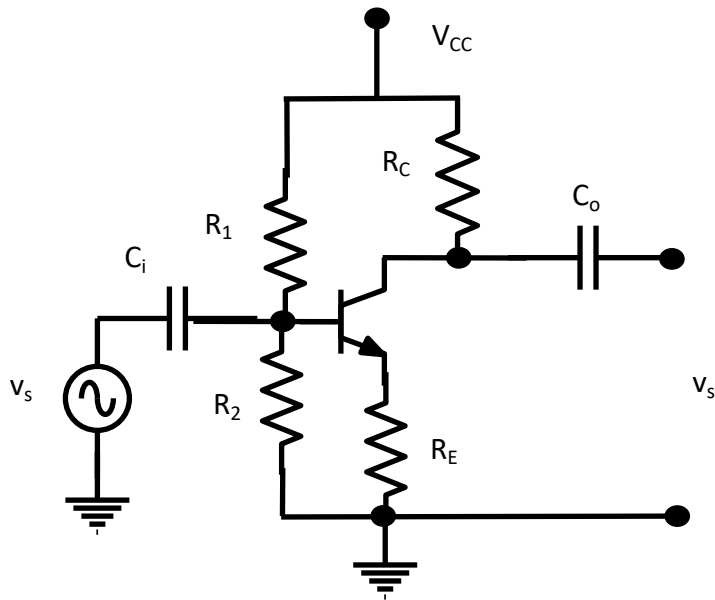
BJT common emitter amplifier



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 $R_C= 1.5k\Omega$.

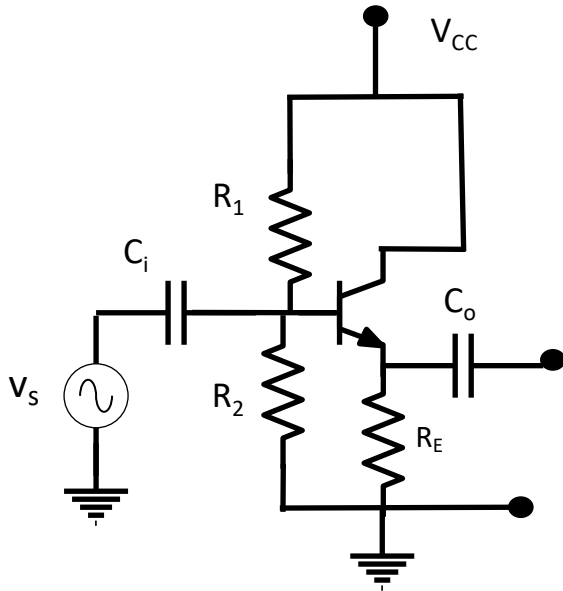
BJT common emitter amplifier continued



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

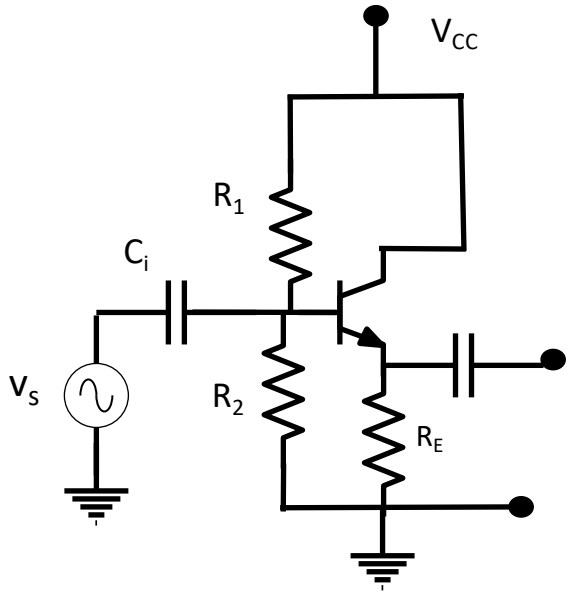
Common collector amp (Emitter Follower)

Common collector amp

Credit: Ward, Hands on Radio.

BJT common collector amplifier continued

6. x

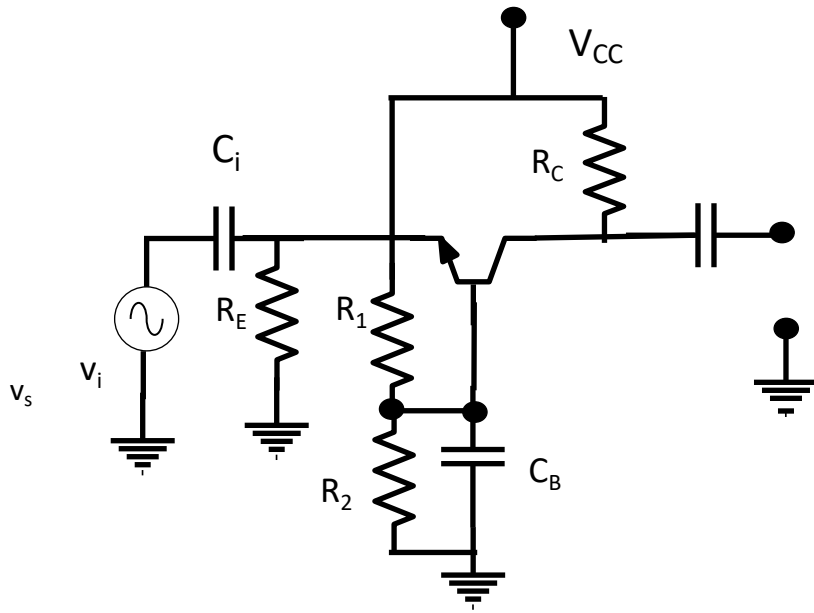


Common collector amp (Emitter Follower)

Credit: Ward, Hands on Radio.

BJT common base amplifier

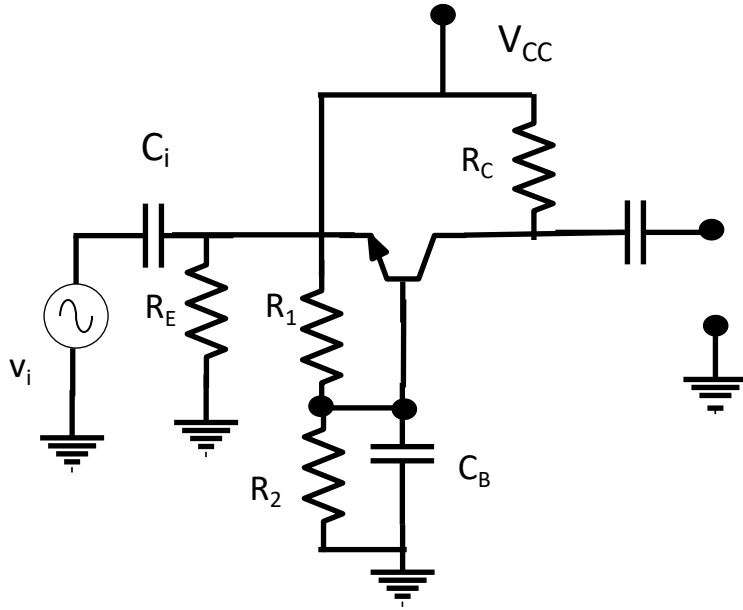
- X



Common base amp

BJT common base amplifier continued

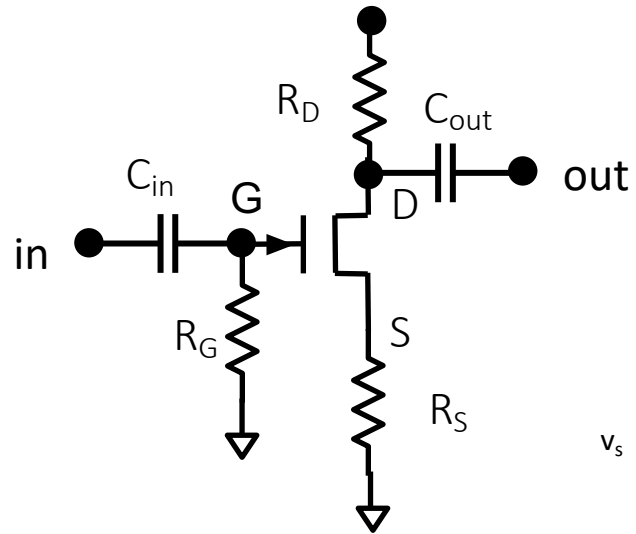
6. x



Common base amp

JFETs

JFET Common Emitter Amplifier

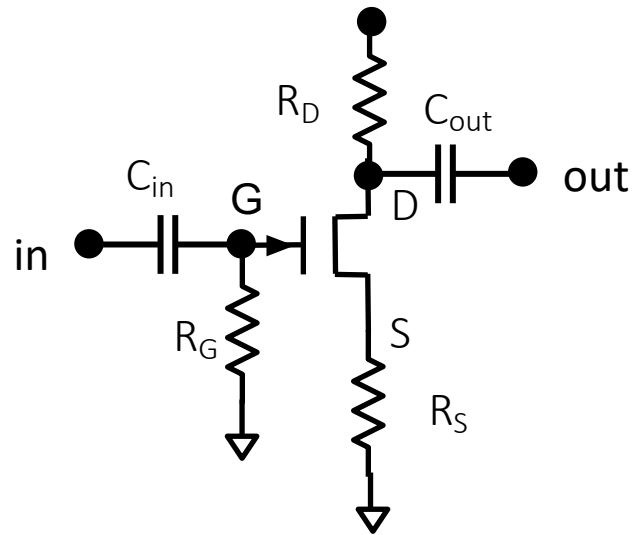


• X

JFET common emitter amplifier continued

6. x

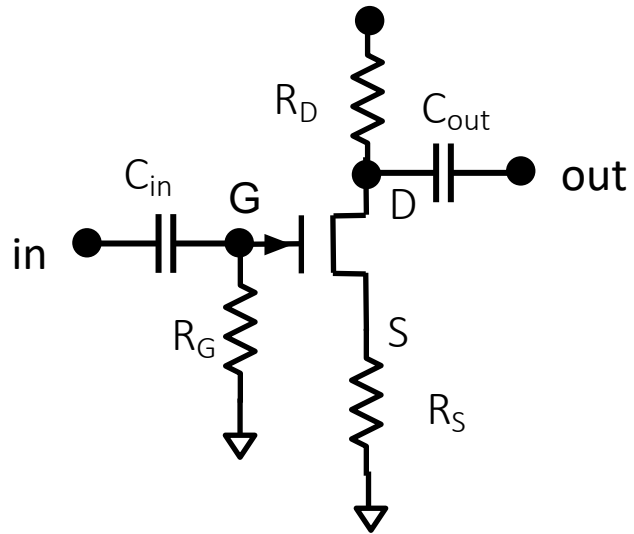
JFET common source amplifier



1. d

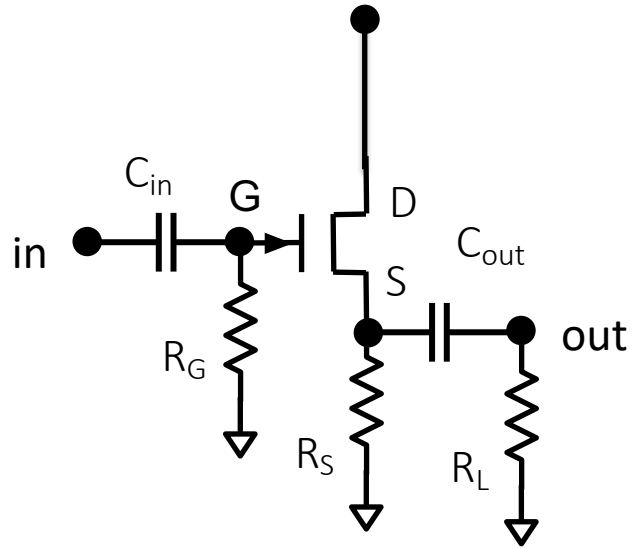
JFET Common Source Amplifier continued

6. x



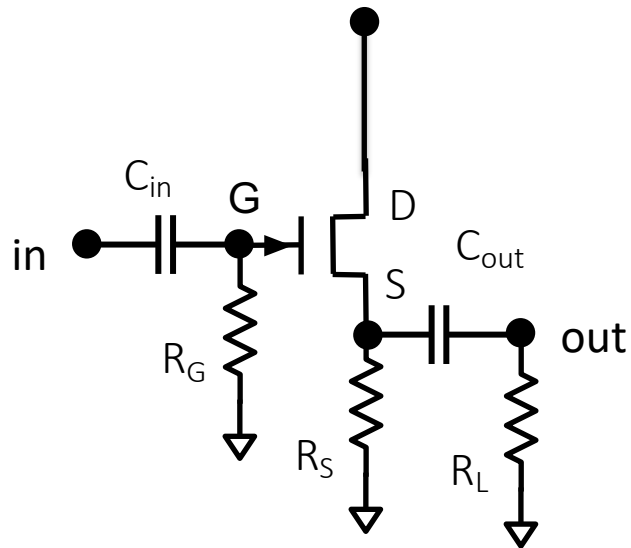
JFET common drain amplifier

- X



JFET common drain amplifier continued

6. x



CMOS common emitter amplifier



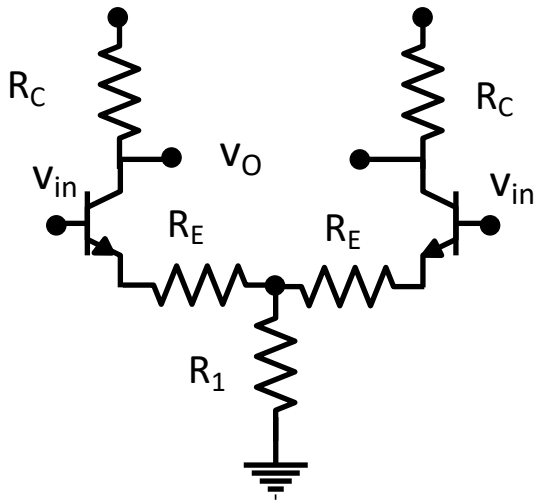
- Pick power
- $V_{DD} = i_D R_D + V_{DS} + i_D R_S$
- $V_{GS} = V_G - i_S R_S$
- $V_G = V_{DD} \frac{R_1}{R_1 + R_2}$
- $i_D = k(V_G - V_{TH})^2$
- Bias around $\frac{V_{DD}}{3}$
- Pick gain, $A = \frac{R_D}{R_S + \frac{1}{g_m}}$

Differential Amplifier

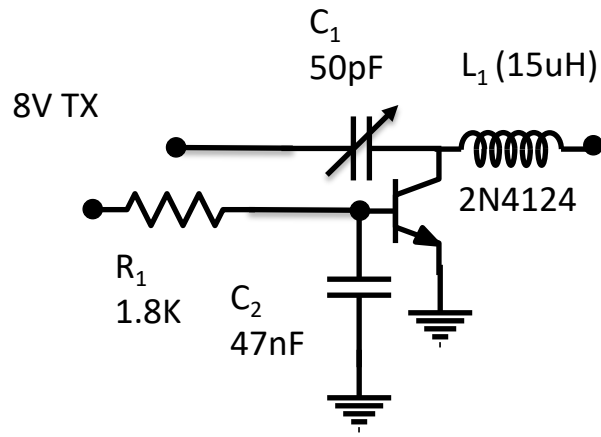
- Two port model
- $\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}$

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

Differential amplifier



Exercise 19: Norcal receiver switch



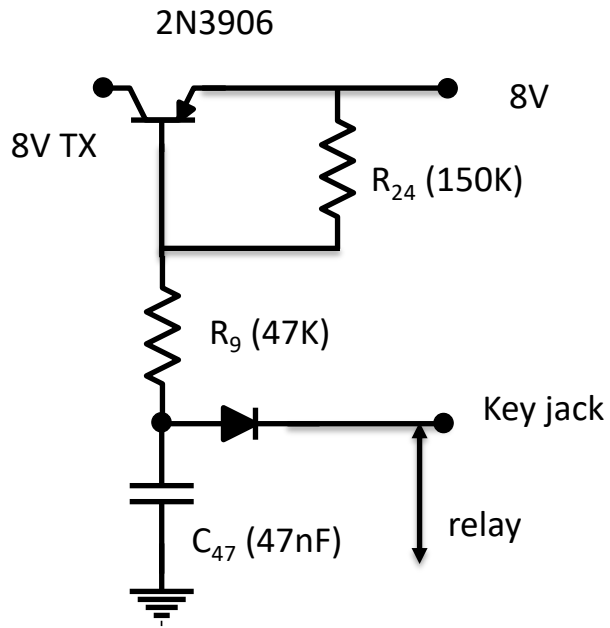
- Receiver mixer or an oscilloscope with 50Ω
- When transistor conducts the receiver filter shorts

Harmonic filter

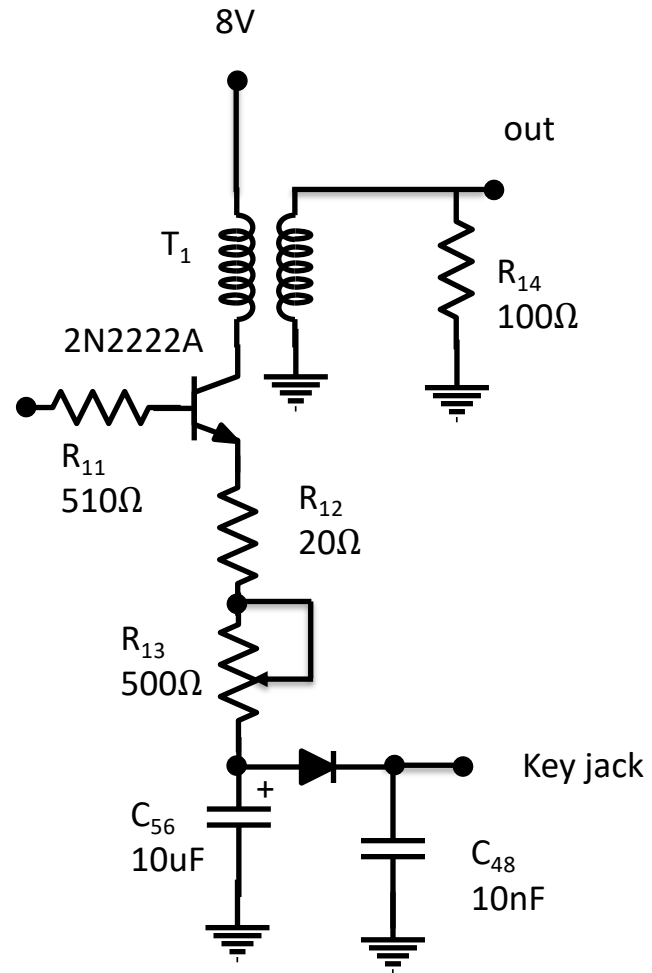
If using function generator
use a 1.8K resistor

Exercise 20: NorCal transmitter switch

- When key is down, transistor conducts



Exercise 21: Norcal Driver

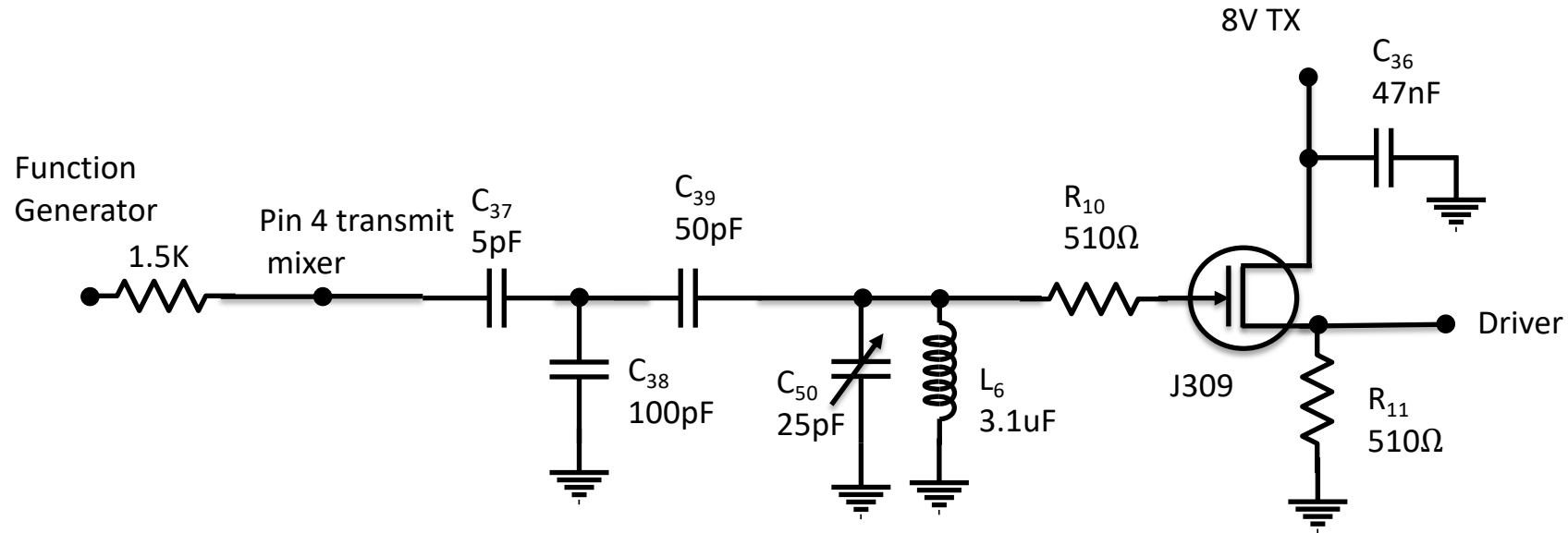


- Use 50 Ω scope probe

Exercise 22: Emitter degeneration

- Use 50Ω scope probe

Exercise 23: Norcal Buffer amplifier



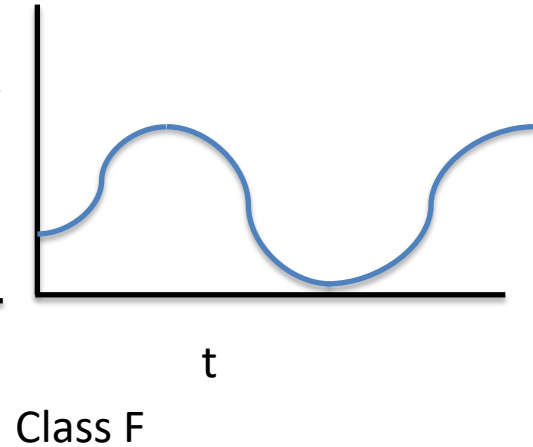
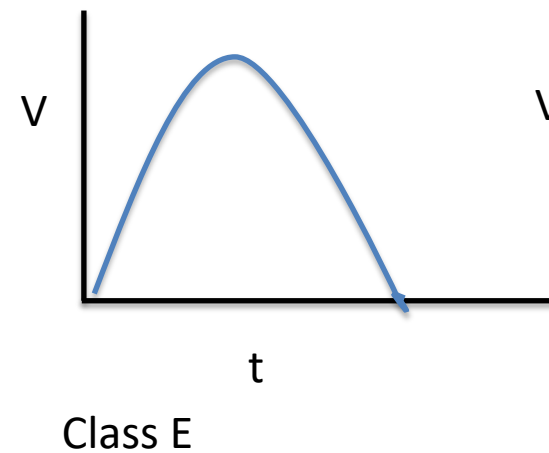
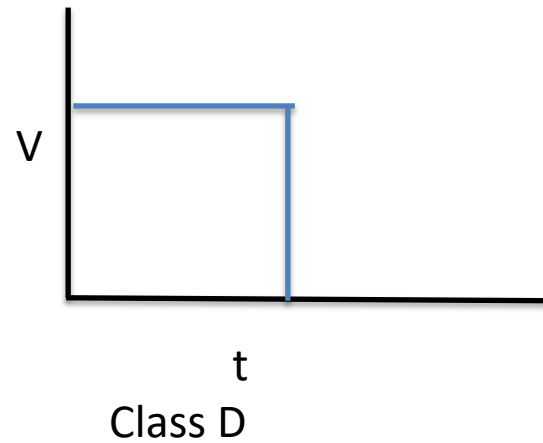
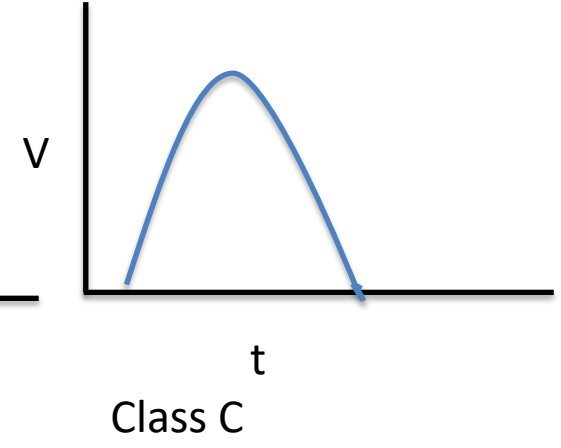
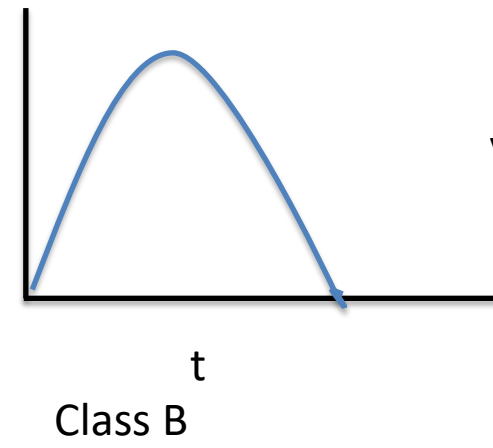
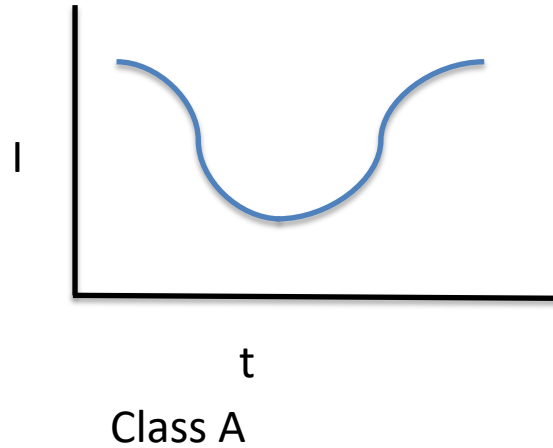
$$G_V = \frac{V}{V_i}$$

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 |

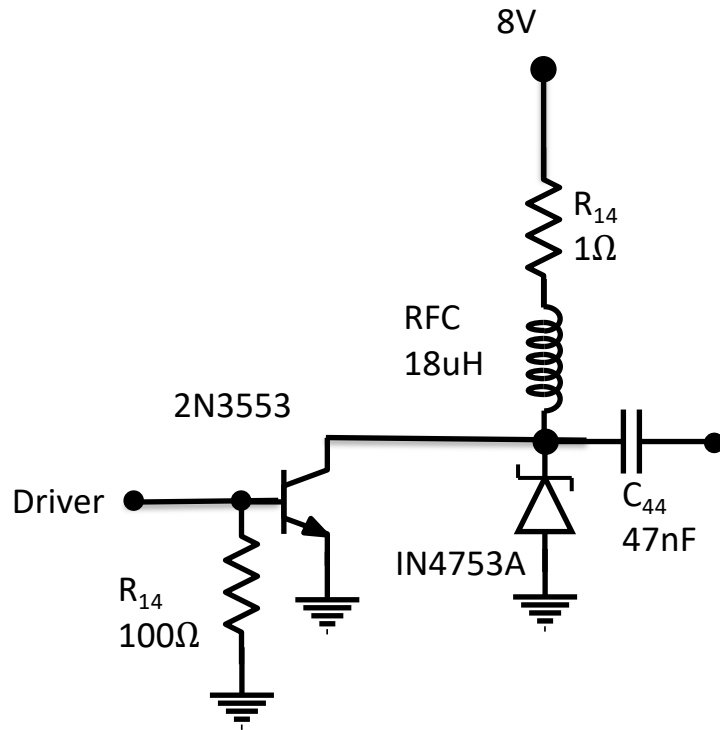
$$\eta = \frac{P}{P_0}, P_d = P_0 - P_i$$

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

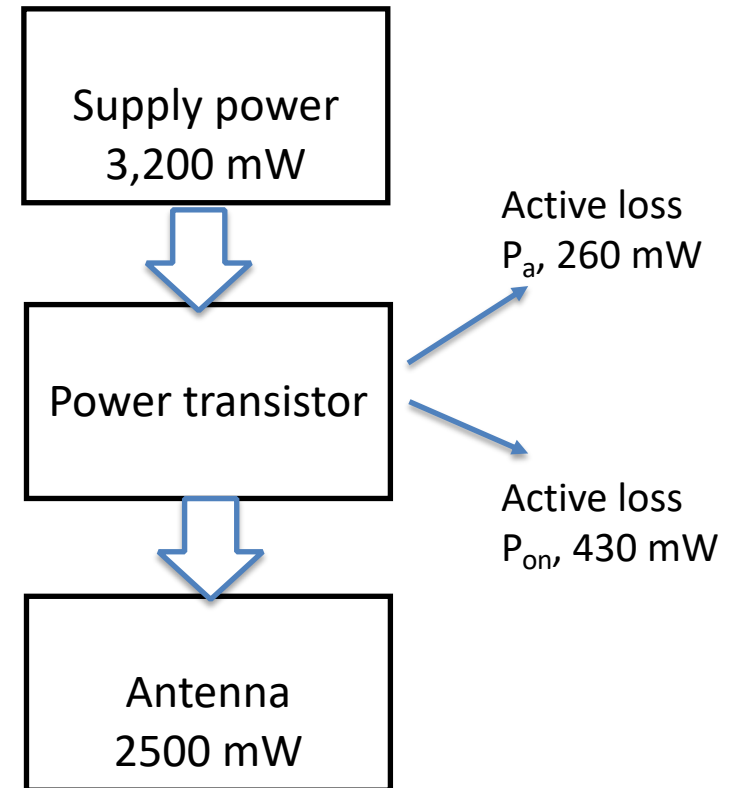


Exercise 24: Norcal Power Amp

Norcal-40 Power amp is class C



Harmonic
Filter

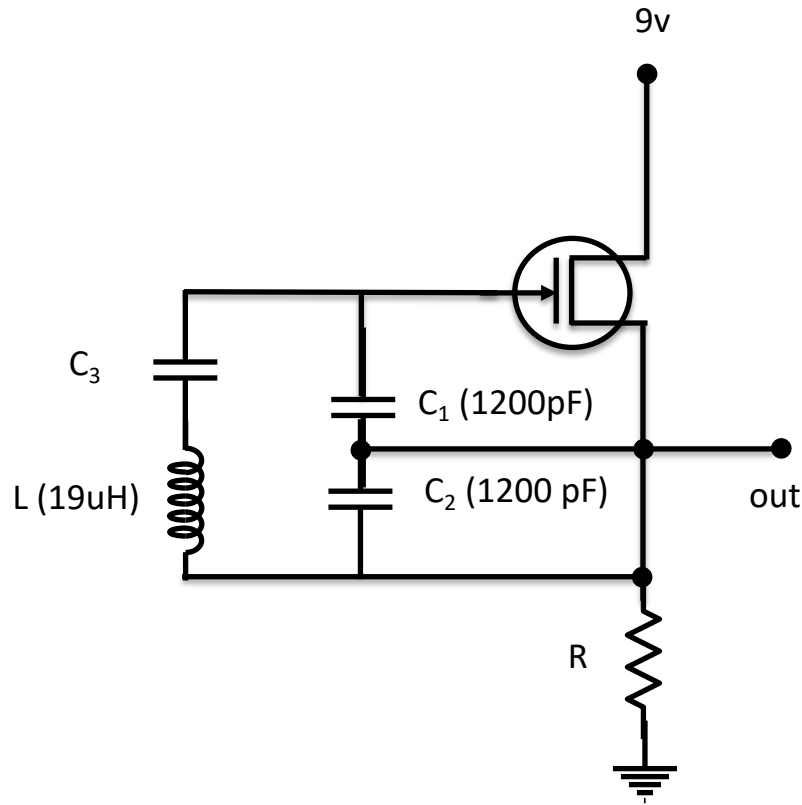


- $R_t = \frac{T - T_0}{P_d}$
- T_0 is ambient temperature, T is heat sink temperature

Exercise 25: Power modelling

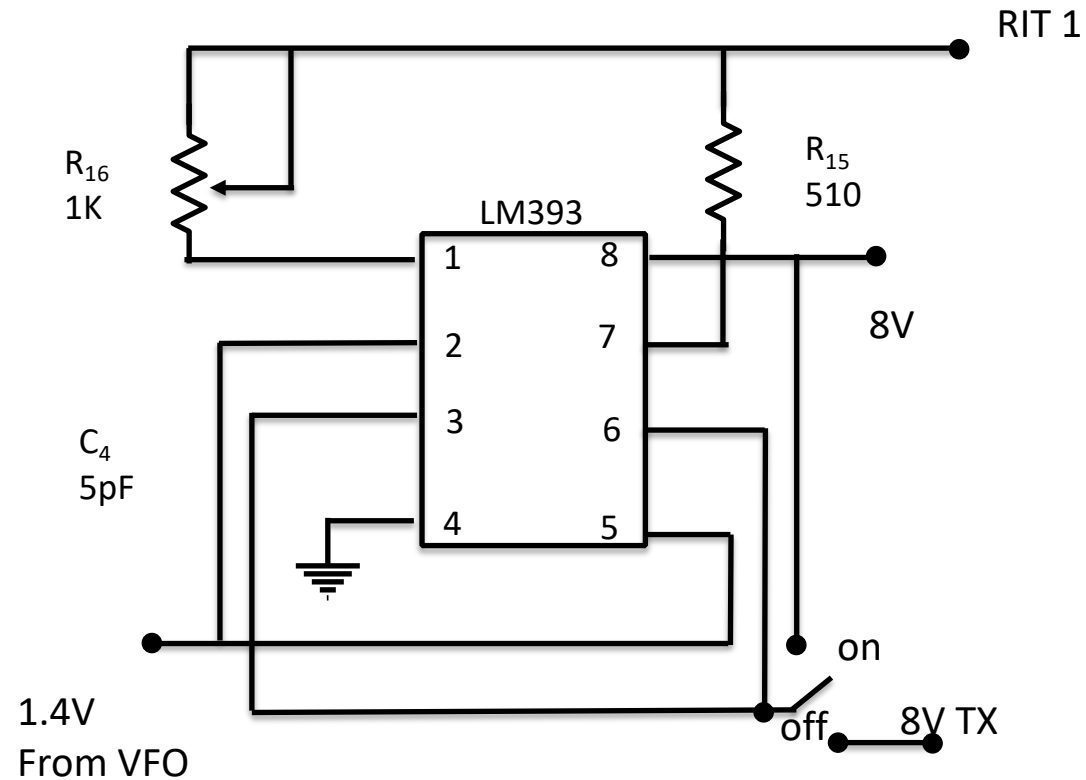
- Use 50 Ω scope probe

Clapp oscillator



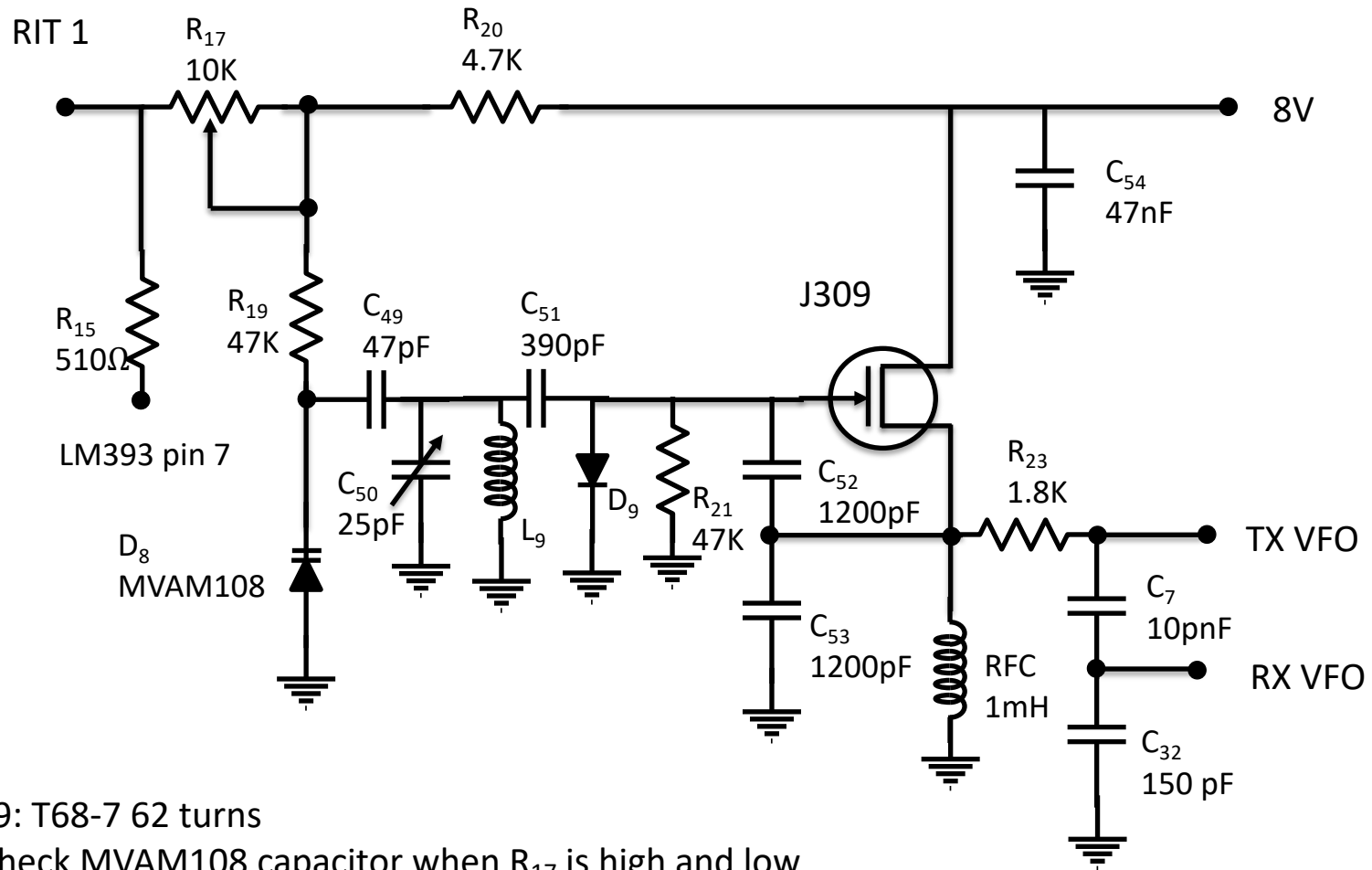
- $i_d = g_m v_{gs}$
- Resonance: $-\frac{1}{j\omega_0 C_2} = j\omega_0 L + \frac{1}{j\omega_0 C_3} + \frac{1}{j\omega_0 C_1}$
- $\omega_0 = \frac{1}{\sqrt{LC}}, C = C_1 || C_2 || C_3$
- At resonance, $v_{gs} = R i_d \frac{C_1}{C_2}, L = \frac{C_1}{RC_2}$
- Oscillation continues if $g_m > \frac{C_1}{RC_2}$
- $v_{gs} = 2v_s$

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 R₁₇ is high and low
- Start resistor (R₂₁) pulls gat to ground at start
- When gain limiting diode (D9) conducts, it pulls gate negative
- Oscillator keeps growing as long as $g_m > 1/R$

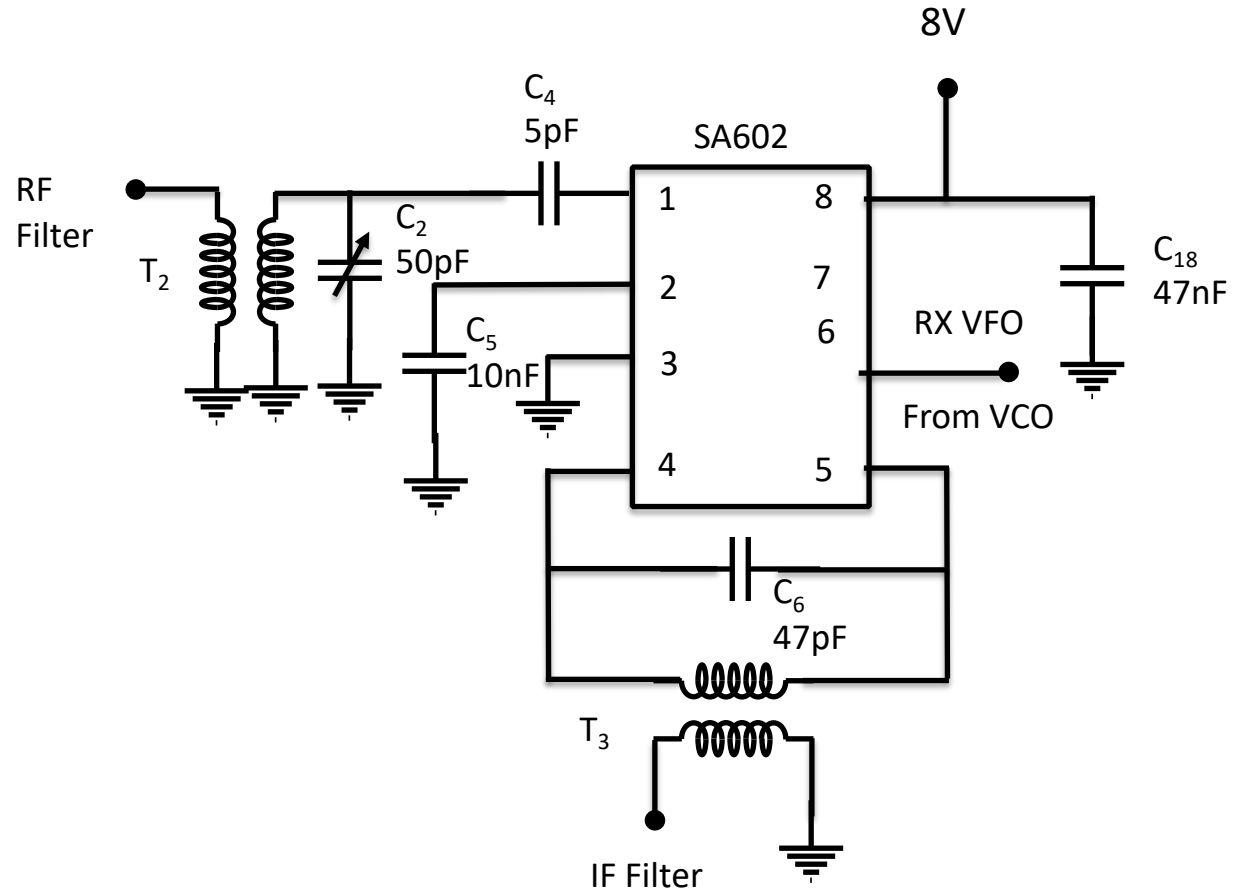
Exercise 27: Gain limiting

- x

Mixers

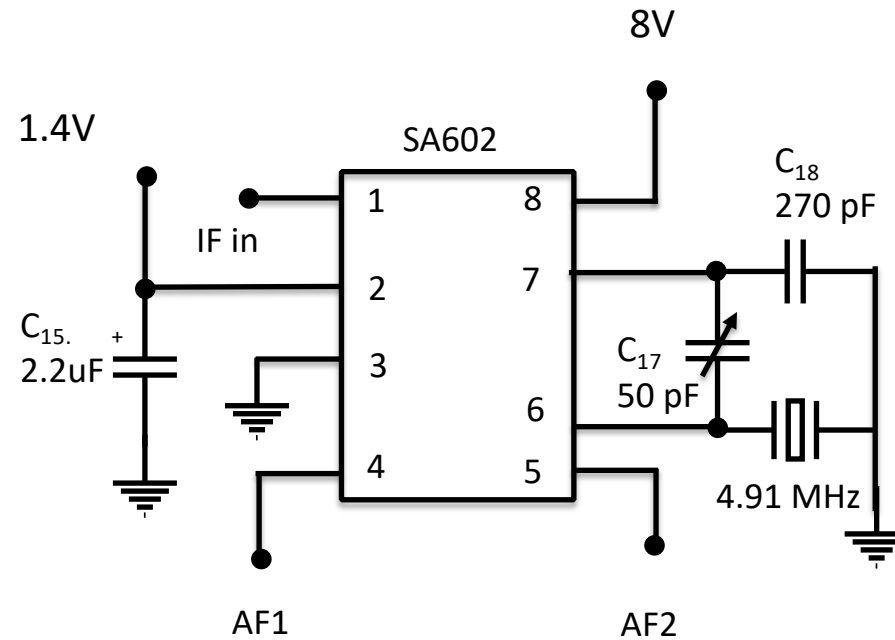
- x

Exercise 28: Norcal RF Mixer



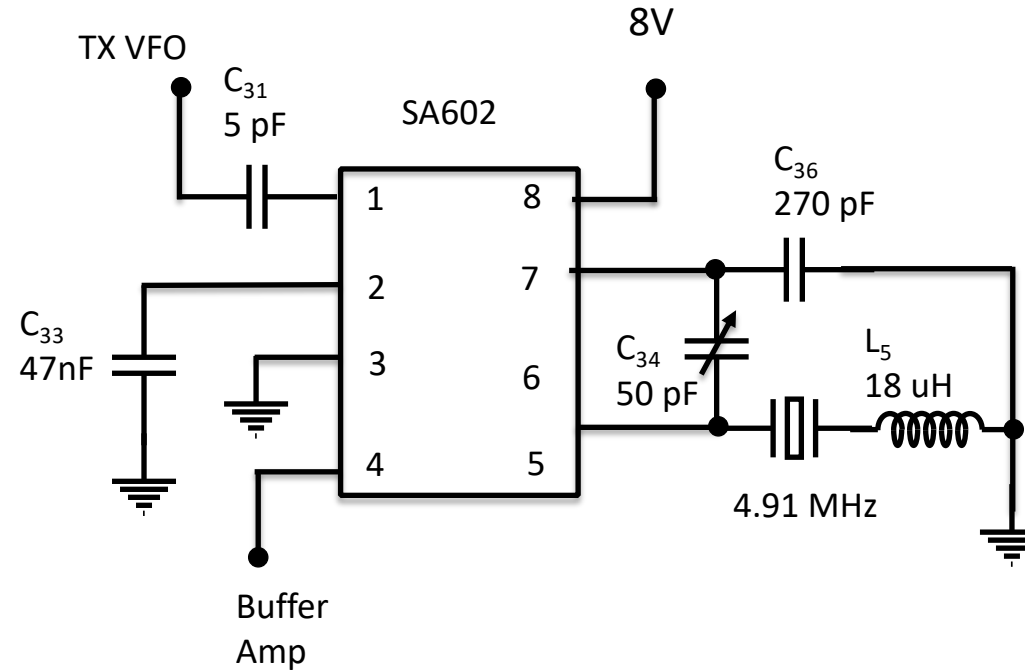
50mVpp if
using function
generator

Exercise 29: Norcal Product Detector

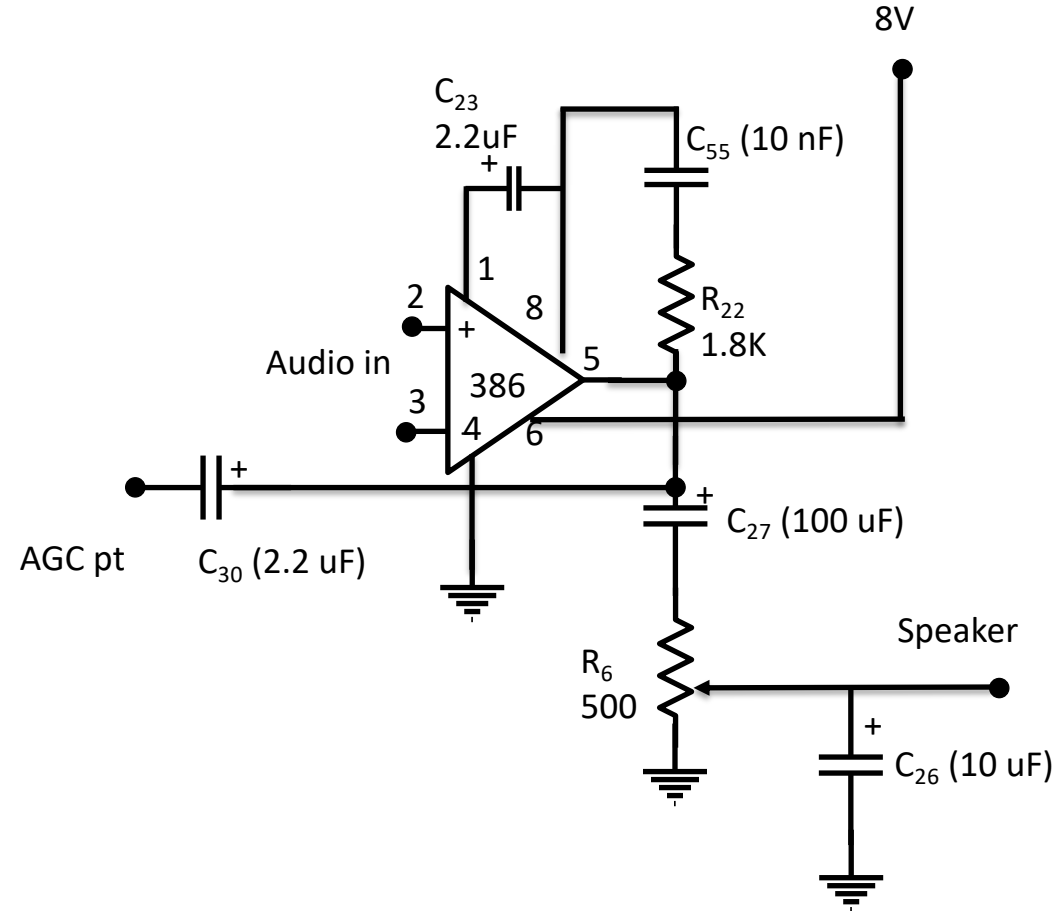


- 620 Hz output through AF1 and AF2

Exercise 30: Norcal transmit mixer and oscillator

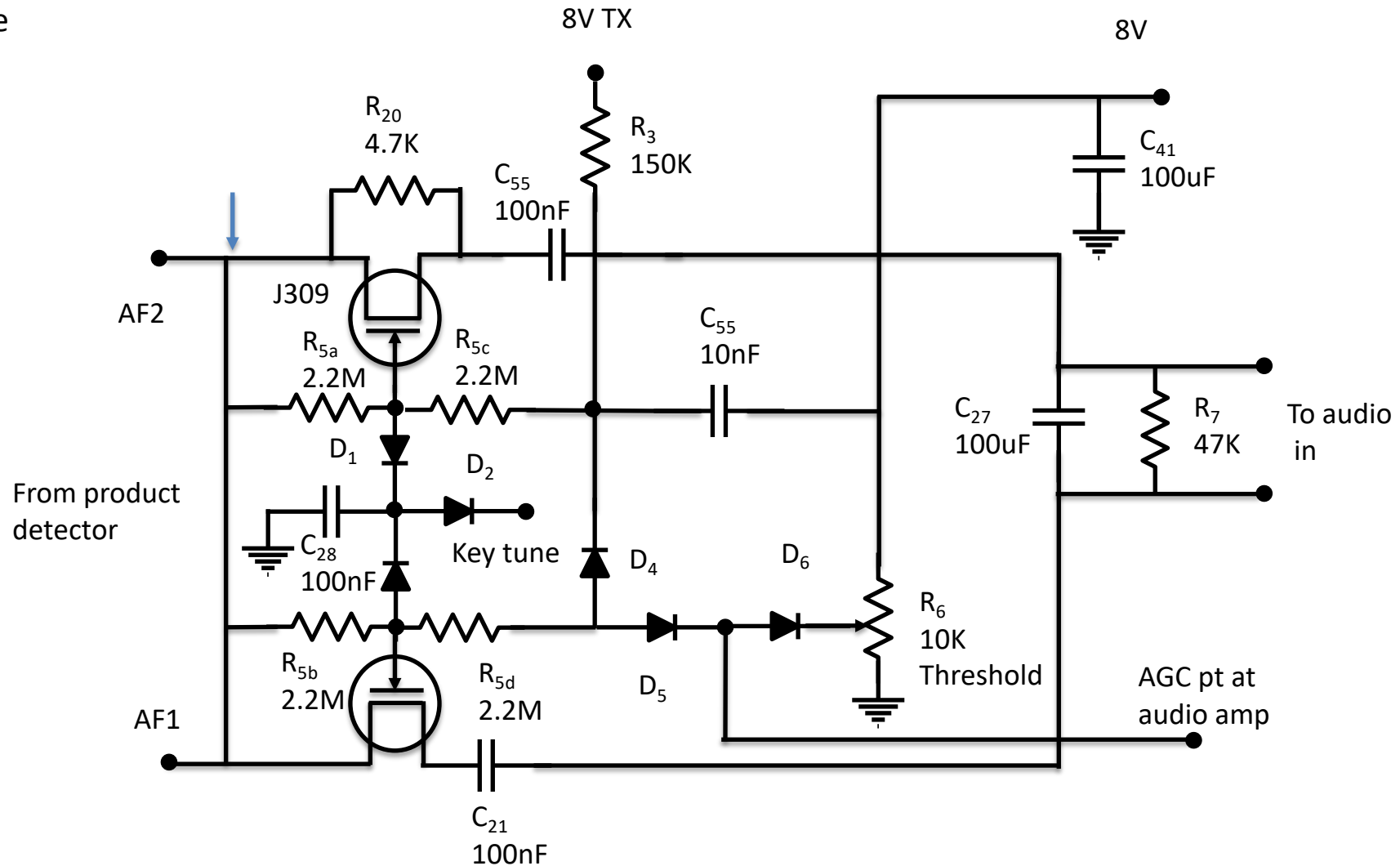


Exercise 31: Norcal Audio Amp



Exercise 32: Norcal AGC

Connect to
function generator
through 300K, here



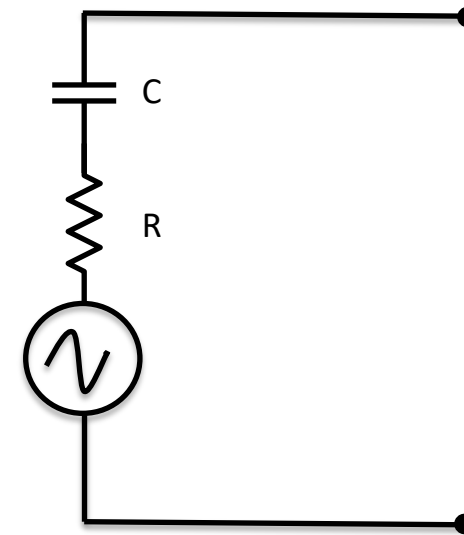
Exercise 33: Alignment

- 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

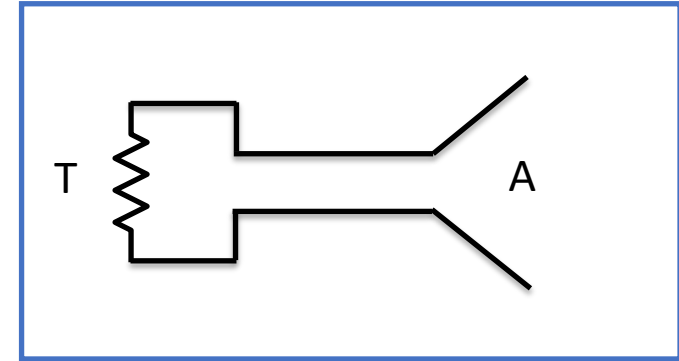


Antennas and propagation

- 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

Insulated cavity

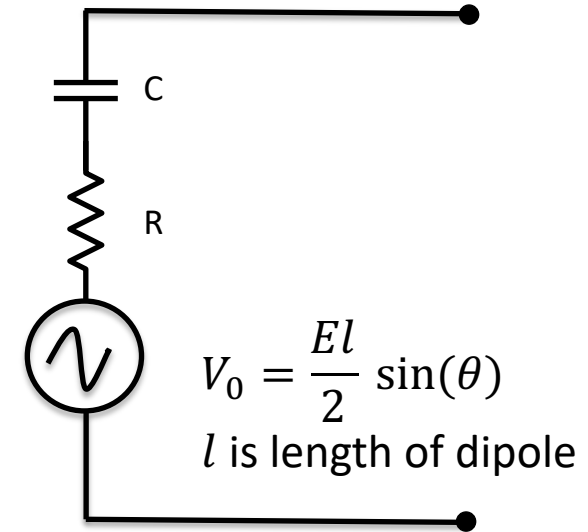


- Antenna theorem: $\oint A d\Omega = \lambda^2$
- For cavity on right, T is constant at thermodynamic equilibrium and the same power is transmitted and emitted, the Johnson noise is kT . The energy received is $E = \frac{4\pi kT}{c\lambda^2}$. Set $B = \frac{kT}{\lambda^2}$. $kT = \oint BA d\Omega =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

Reciprocity and dipole

Dipole Thevenin equivalent circuit

- 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 $r = 2000 \text{ m}$, $P_r = 6 \text{ pW}$



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

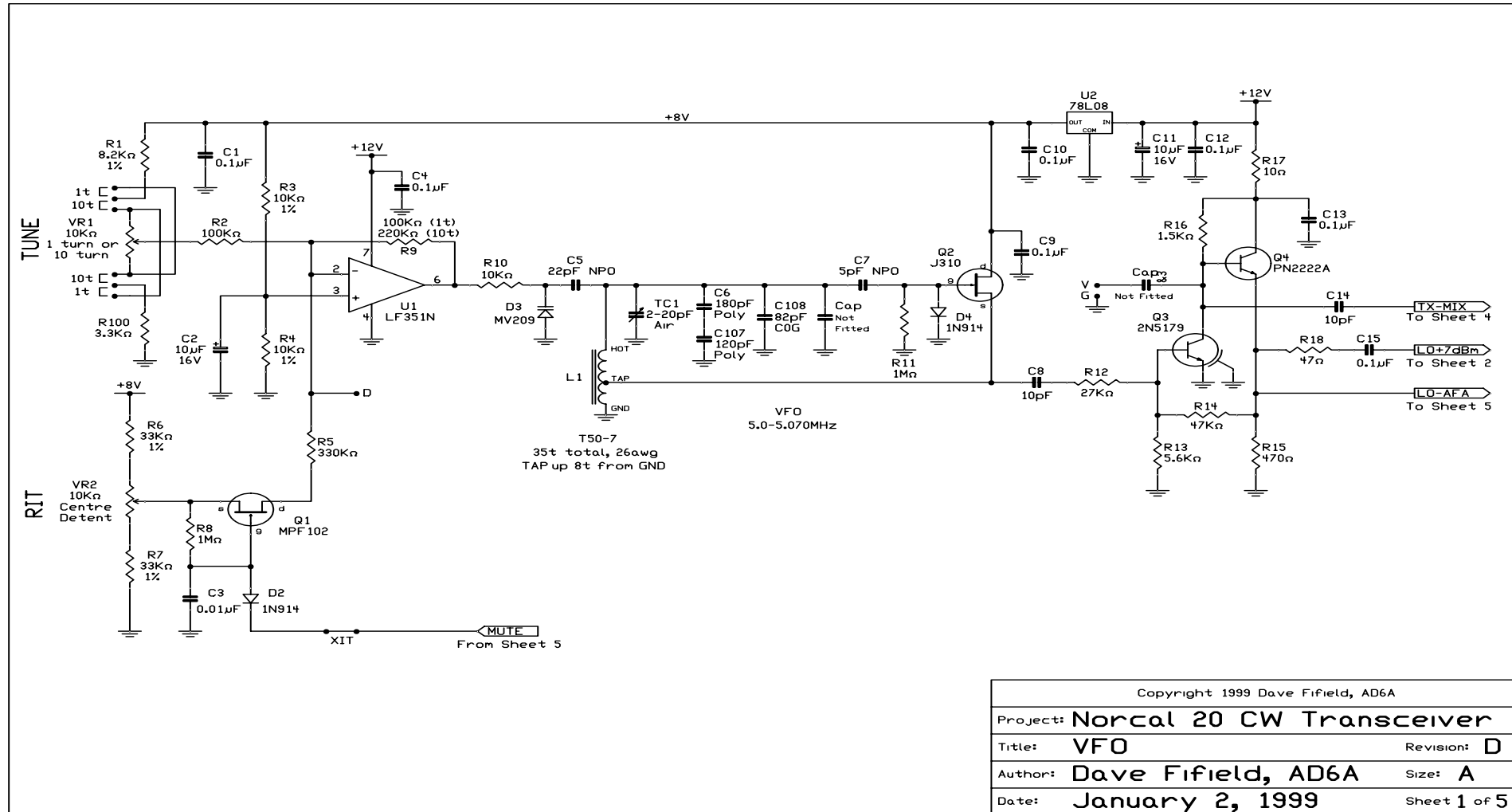
Exercise 37: Antennas

- x

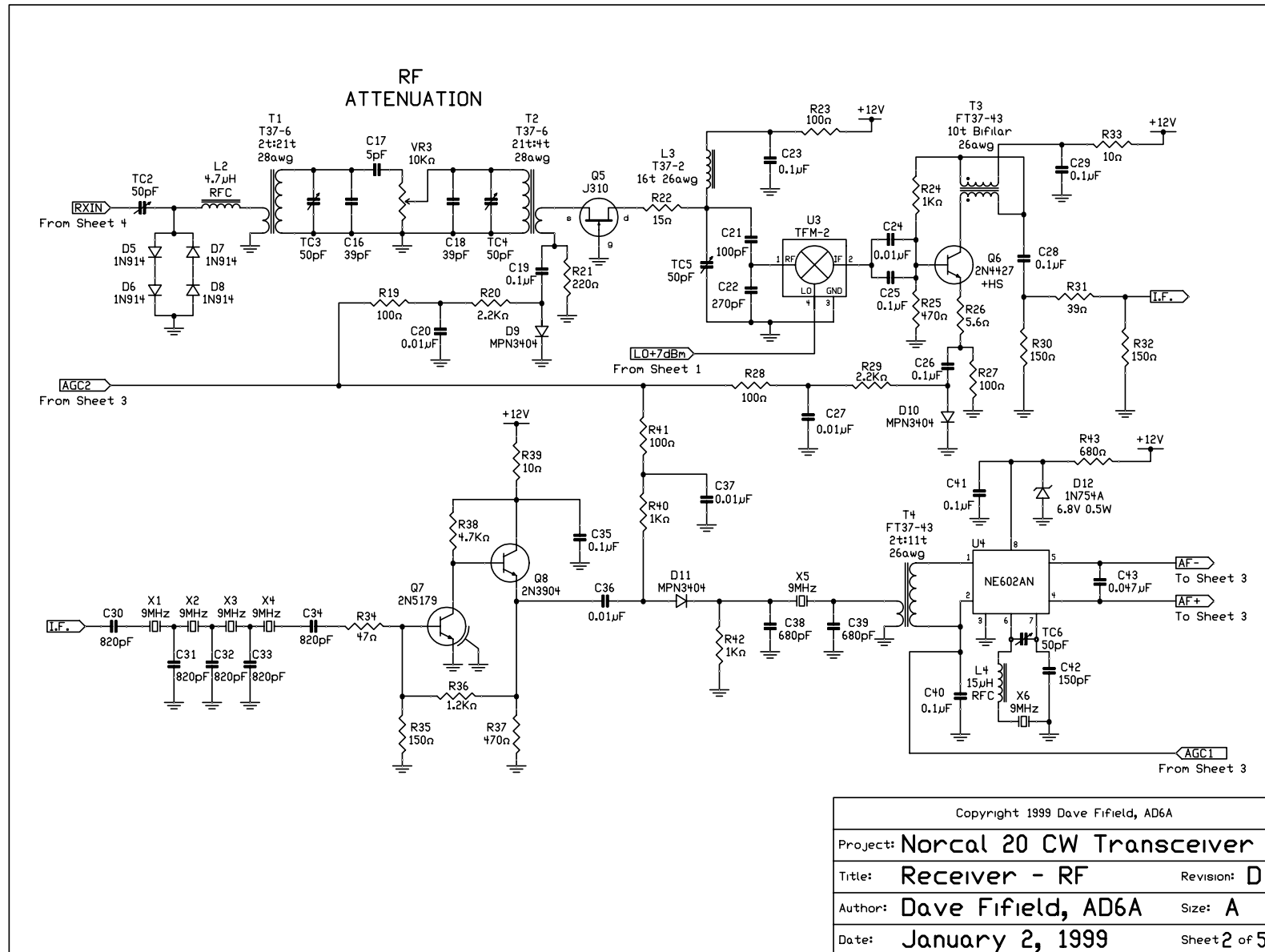
Exercise 38: Propagation

- x

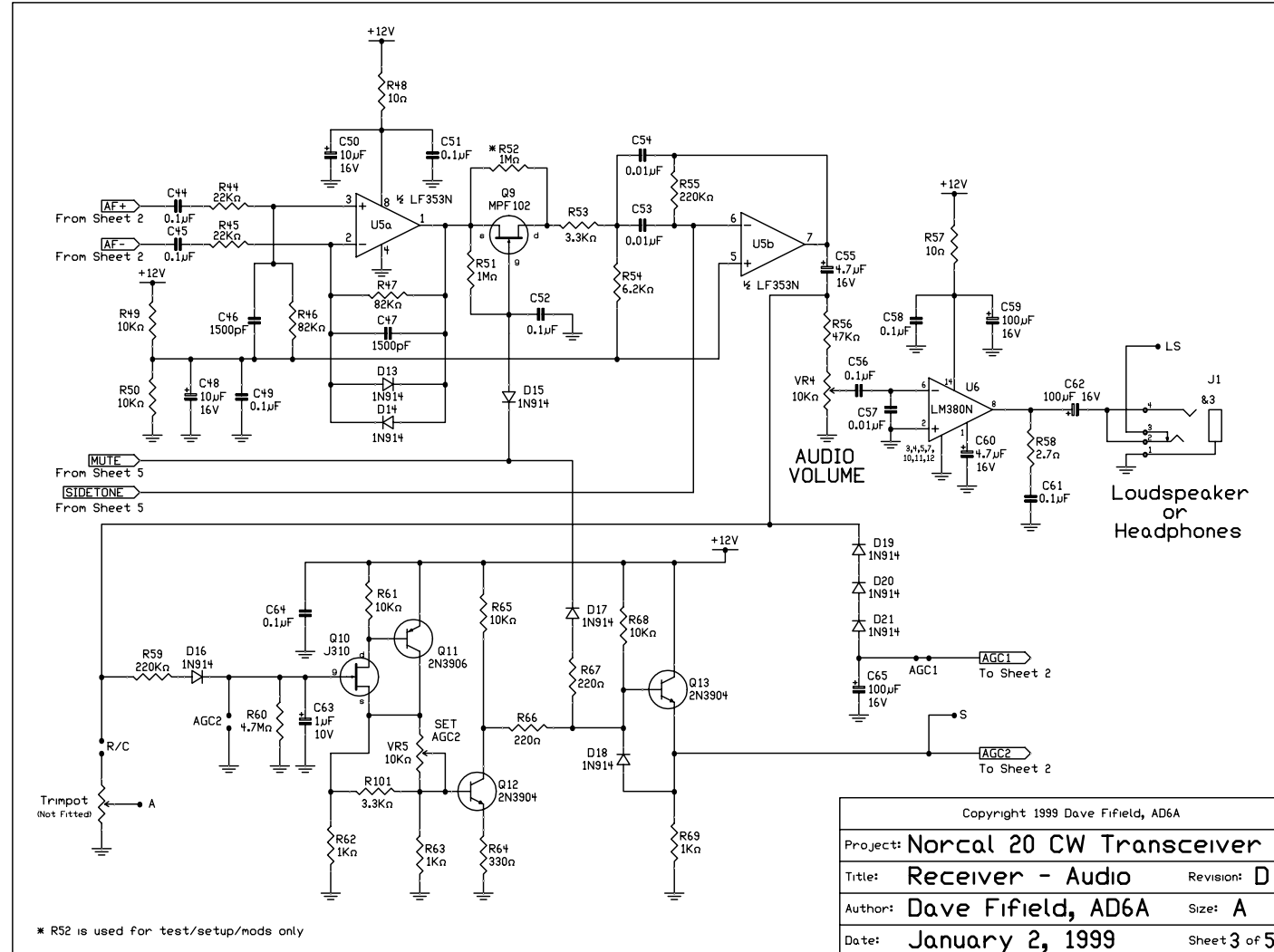
Norcal circuit diagram, 1



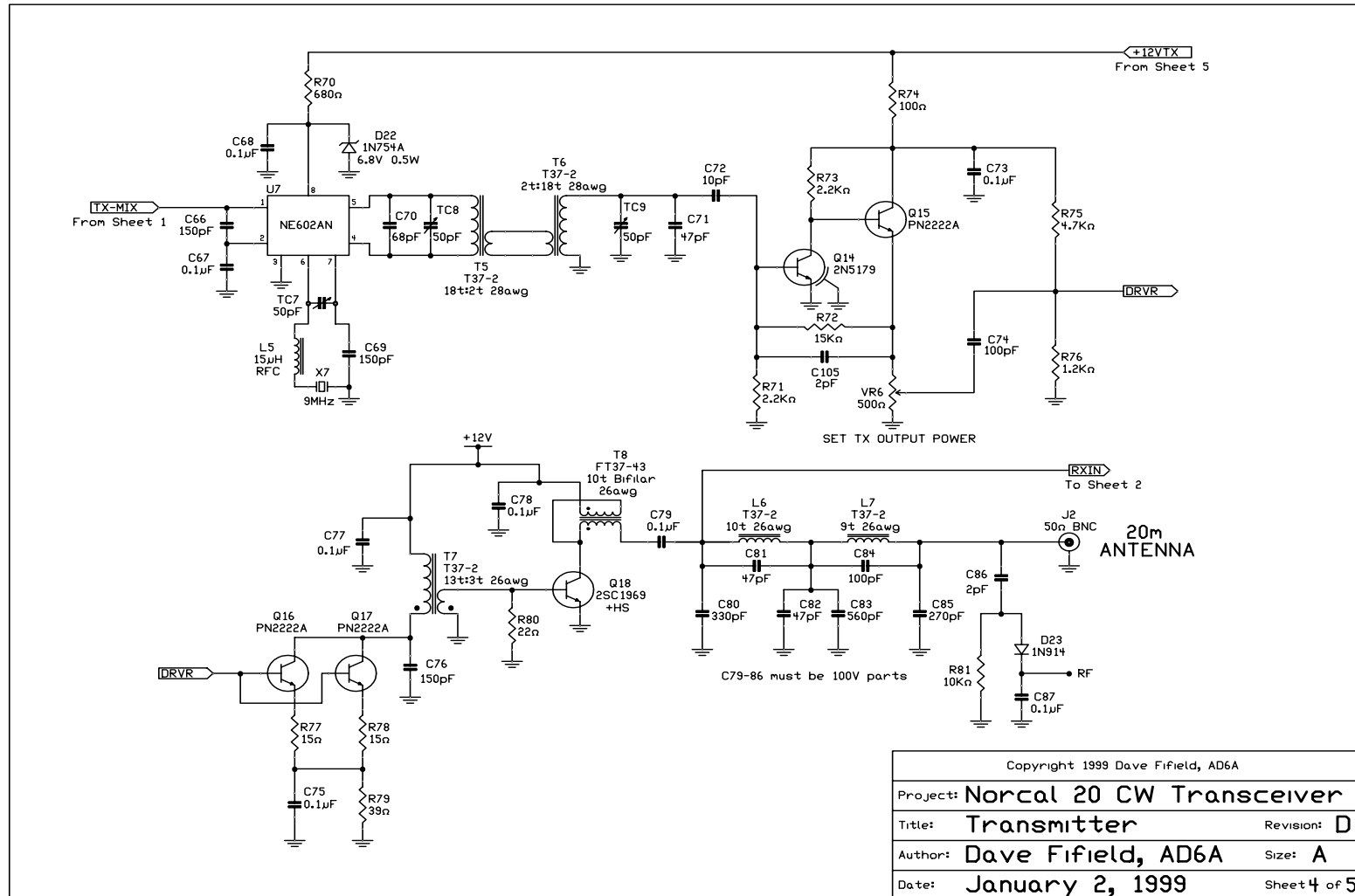
Norcal circuit diagram, 2



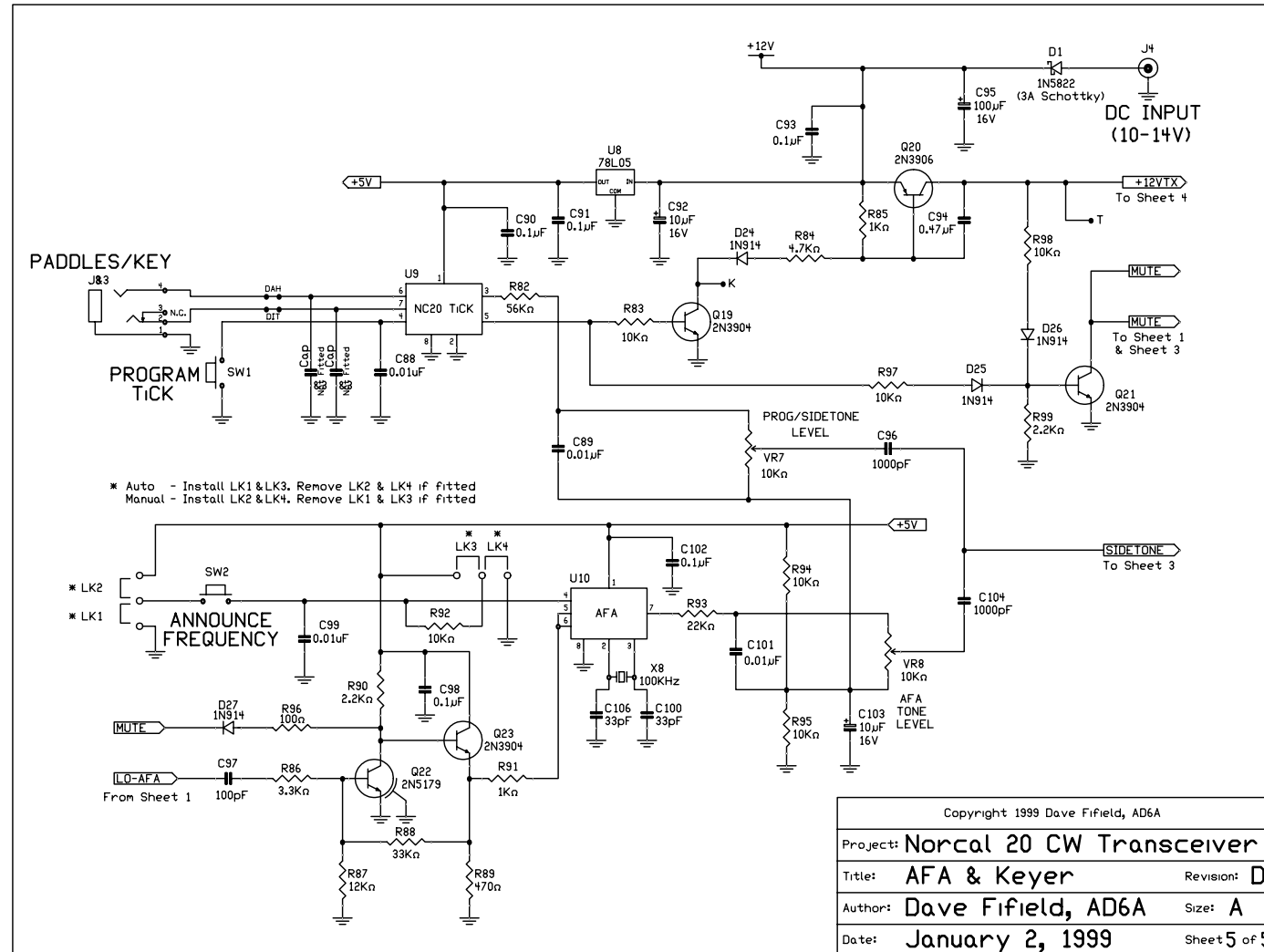
Norcal circuit diagram, 3



Norcal circuit diagram, 4



Norcal circuit diagram, 5

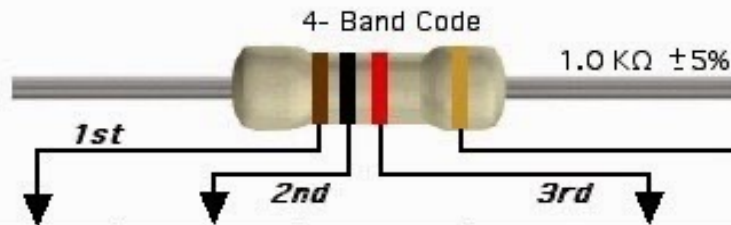


Morse

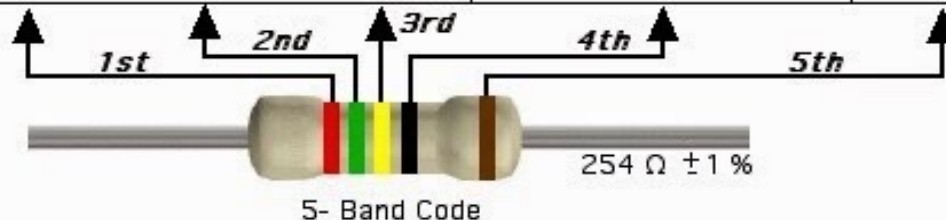
| Symbol | Code | Symbol | Code | Symbol | Code |
|--------|------|--------|------|--------|-------|
| a | ._ | m | — | y | —._ |
| b | —... | n | —. | z | —.. |
| c | —._. | o | —— | 0 | ———— |
| d | —.. | p | ._—. | 1 | ._—— |
| e | . | q | —._ | 2 | ..—— |
| f | .._. | r | —._. | 3 | ...— |
| g |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

Color codes

RESISTOR COLOR CODE GUIDE



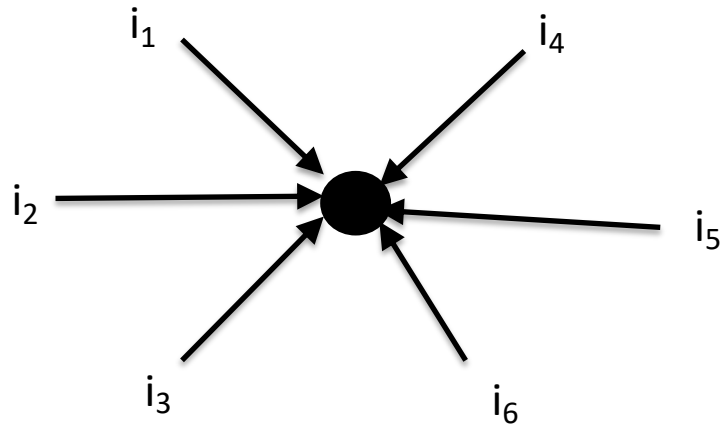
| Color | 1st Band | 2nd Band | 3rd Band | Decimal Multiplier | | Tolerance |
|--------|----------|----------|----------|--------------------|------------|------------|
| Black | 0 | 0 | 0 | 1 | 1 | |
| Brown | 1 | 1 | 1 | 10 | 10 | \pm 1 % |
| Red | 2 | 2 | 2 | 100 | 100 | \pm 2 % |
| Orange | 3 | 3 | 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 % |



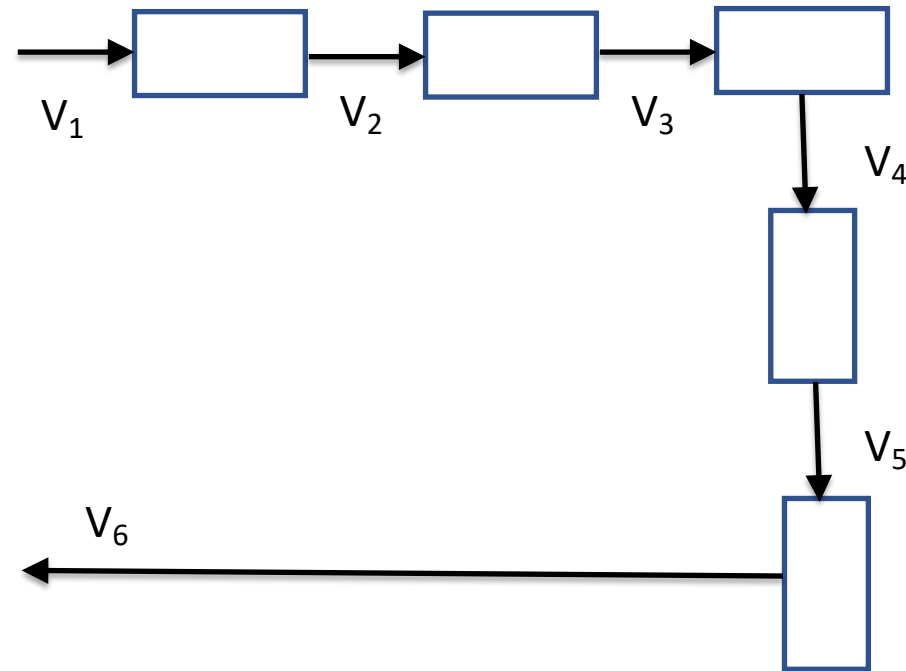
- Resistors: ohms
- Capacitors: picoFards
- Inductors: milliHenries

Kirchhoff

- There are two Kirchhoff's laws, one describes voltages the other describes currents.



$$i_1 + i_2 + i_3 + i_4 + i_5 + i_6 = 0$$



$$(V_2 - V_1) + (V_3 - V_2) + (V_4 - V_3) + (V_5 - V_4) + (V_6 - V_1) + (V_1 - V_6) = 0$$