Electronics of Radio

Notes on David Rutledge's book

John Manferdelli
johnmanferdelli@hotmail.com

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)
- $\mathrm{V}(t) = V_p \cos(\omega t)\,, \omega = 2\pi f$, $\mathrm{I}(t) = I_p \cos(\omega t)\,, \omega = 2\pi f$
- Instantaneous power: $P(t) = V(t)I(t) = V_p I_p\, cos^2(\omega t)$
- Average power: $P_a = \int_0^{1/f} V(t)I(t)dt = V(t)I(t) = \int_0^{2\pi/\omega} V_p I_p\, cos^2(\omega t)dt = \frac{V_p I_p}{2}$
- Band names:

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

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

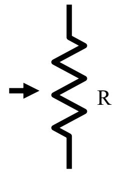
Signals

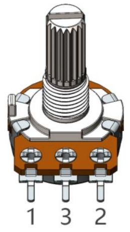
- Gain (G) expressed in decibels: $G = 10\ log_{10}(^{P_{out}}/_{P_{in}})$
- Mixer:
  - $V(t) = \cos(\omega_1 t)\cos(\omega_2 t) = \frac{1}{2}[\cos(\omega_+ t) + \cos(\omega_- t)],\ \omega_+ = \omega_1 + \omega_2,\ \omega_- = \omega_1 - \omega_2$
- Modulation

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

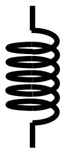

- Resistors
  - Analytic model: $IR = V$
  - Energy dissipated: $E = \int_{t_i}^{t_f} IV\,\mathrm{dt} = \int_{t_i}^{t_f} I^2 R dt$





- Capacitors
  - Analytic model: $CV = q, C\frac{dV}{dt} = i$
  - Capacitor Energy stored: $E = \int_{t_i}^{t_f} CV\frac{dV}{dt}\,\mathrm{dt} = \frac{1}{2}CV^2$

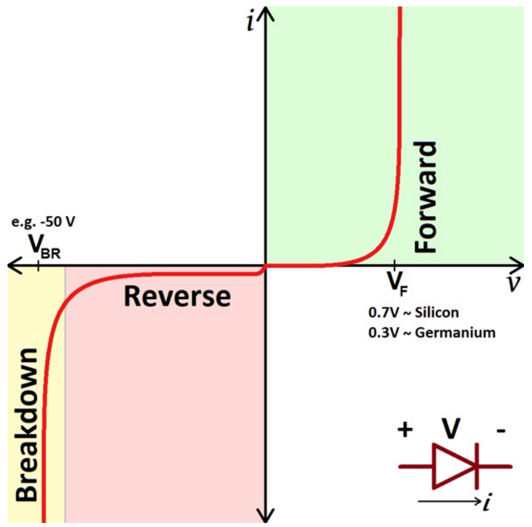
- Inductors
  - Analytic model: $V = L\frac{di}{dt}$
  - Inductor Energy stored: $E = \int_{t_i}^{t_f} IV\,\mathrm{dt} = \int_{t_i}^{t_f} LI\frac{dI}{dt}dt = \frac{1}{2}LI^2$




Credit: Make Electronics

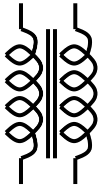
Diodes, transformers

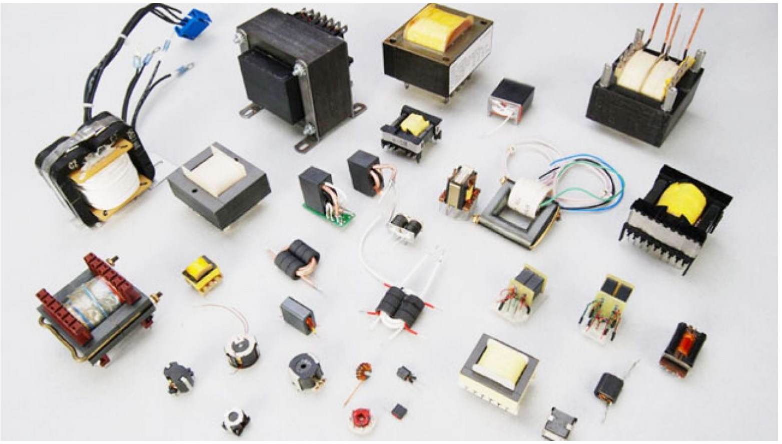
- Diodes
  - Devices that allow current to flow only in one direction
  - Silicon diodes, for example have, essentially infinite resistance if V_{ac}<0, that is if the cathode is at a higher potential than the anode and very low resistance if V_{ac}> .7V.
  - The cathode is usually labelled with a band



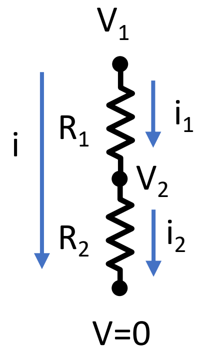
Credit: Make Electronics

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

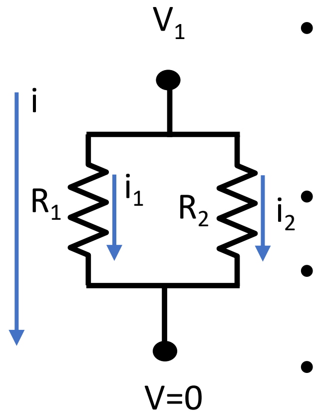




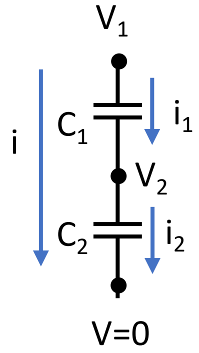
Simple circuit analysis with Kirchhoff



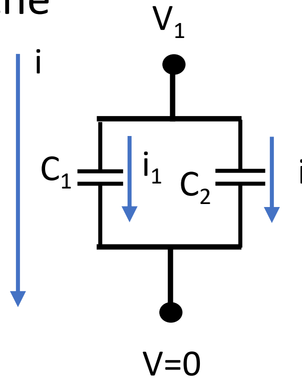
- R_{eq} is the equivalent resistance, replacing the top left circuit with a single resistance.
- By Kirchhoff's node rule, $i_1 = i_2 = i$, so
- $\frac{V_1-V_2}{R_1} = \frac{V_2}{R_2} = \frac{V_1}{R_{eq}}$ thus $\frac{R_1}{R_{eq}} V_1 = V_1 - V_2$ and $\frac{R_2}{R_{eq}} V_1 = V_2$. Adding, we get $\frac{R_1}{R_{eq}} V_1 + \frac{R_2}{R_{eq}} V_1 = V_1$. Dividing by V_1 and solving, we get $R_1 + R_2 = R_{eq}$



- Again let R_{eq} is the equivalent resistance, replacing the bottom left circuit with a single resistance.
- By Kirchhoff's node rule, $i_1 + i_2 = i$, so
- $\frac{V_1}{R_1} + \frac{V_1}{R_2} = \frac{V_1}{R_{eq}}$.
- Solving, we get. $\frac{R_1 R_2}{R_1+R_2} = R_{eq}$

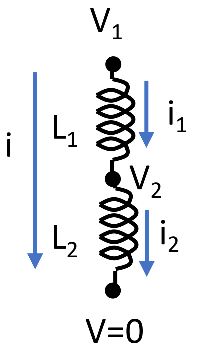


- C_{eq} is the equivalent capacitance, replacing the top right circuit with a single capacitor.
- By Kirchhoff's node rule, $i_1 = i_2 = i$, so
- $C_1 \frac{d\,(V_1-V_2)}{dt} = C_2 \frac{d\,(V_2)}{dt} = C_{eq} \frac{dV_1}{dt}$
- $\frac{C_{eq}}{C_1} \frac{d\,(V_1)}{dt} = \frac{d\,(V_1-V_2)}{dt}$ and $\frac{C_{eq}}{C_2} \frac{d\,(V_1)}{dt} = \frac{d\,(V_2)}{dt}$
- Adding and cancelling the $\frac{d\,(V_1)}{dt}$, we get
- $\frac{C_{eq}}{C_1} + \frac{C_{eq}}{C_2}$ =1 and solving, we get. $\frac{C_1 C_2}{C_1+C_2} = C_{eq}$

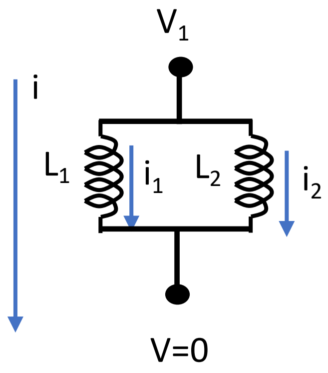


- C_{eq} is the equivalent capacitance, replacing the bottom right circuit with a single capacitor.
- By Kirchhoff's node rule, $i_1 + i_2 = i$
- $C_{eq} \frac{dV_1}{dt} = C_1 \frac{dV_1}{dt} + C_2 \frac{dV_1}{dt}$, so
- $C_{eq} = C_1 + C_2$

Simple circuit analysis with Kirchhoff

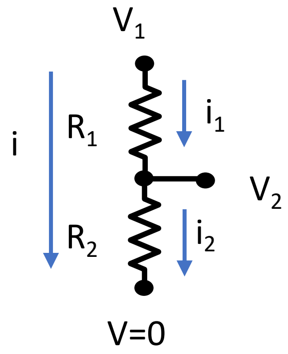


- Let L_{eq} be the equivalent inductance, replacing the top left circuit with a single inductor.
- By Kirchhoff's node rule, $i_1 = i_2 = i$, so
- $L_{eq}\frac{di}{dt} = V_1, L_1\frac{di_1}{dt} = V_1 - V_2, L_1\frac{di_2}{dt} = V_2$
- $V_1 = L_{eq}\frac{di}{dt} = L_1\frac{di}{dt} + L_2\frac{di}{dt}$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

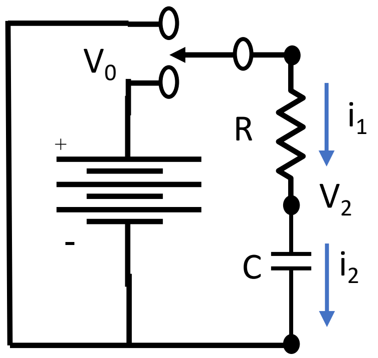


- Let L_{eq} be the equivalent inductance, replacing the bottom left circuit with a $\frac{di}{dt} = \frac{V_1}{L_{eq}}, \frac{di_1}{dt} = \frac{V_1}{L_1}, \frac{di_2}{dt} = \frac{V_1}{L_2},$
- single inductor.
- By Kirchhoff's node rule, $i_1 + i_2 = i$, so
- $\frac{V_1}{L_{eq}} = \frac{V_1}{L_1} +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

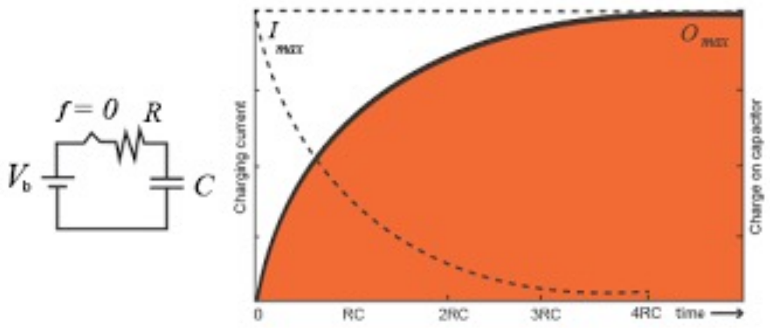
- The circuit on the right, is useful and is called a *voltage divider*.
- $i = i_1 = i_2$ so $\frac{V_1 - V_2}{R_1} = \frac{V_2}{R_2}, V_1 - V_2 = \frac{R_1}{R_2}V_2$
- Thus, $V_1 = (1 + \frac{R_1}{R_2})V_2$ and so
- $V_2 = \frac{R_2}{R_1 + R_2}V_1$

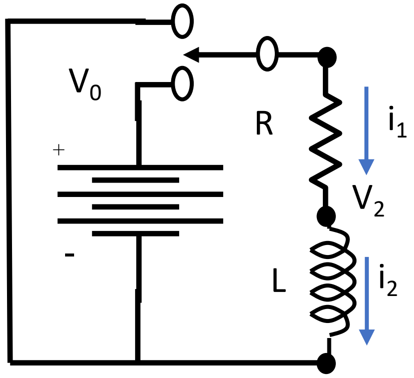


RC/RL circuit analysis with Kirchhoff

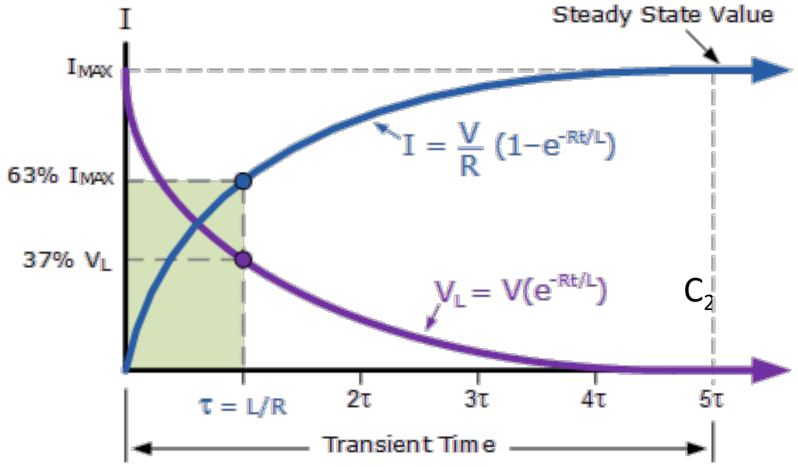


- RC behavior: charging
  - $V_0 - V_2 = i_1 R = V_R, i_1 = \frac{V_R}{R}$
  - $i_2 = C\frac{dV_2}{dt}, V_C = V_2$
  - $i_1 = i_2, V_C = V_0 - V_R$
  - $\frac{V_R}{R} = C\frac{dV_C}{dt}$, RC $\frac{dV_C}{dt} = V_0 - V_C$, or RC $\frac{dV_C}{dt} + V_C = V_0$
  - Solution is $V_C = V_0 - V_0 e^{-\frac{t}{RC}}$





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



Phasors

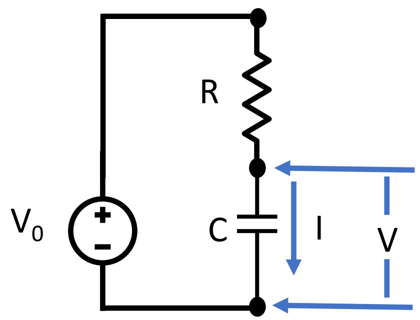
- $V(t) = RI(t)$
- $V(t) = L\dot{I}(t)$
- $I(t) = C\dot{V}(t)$
- Suppose $V(t) = Acos(\omega t + \theta)$ and $\mathrm{I}(t) = Bcos(\omega t + \phi)$. If $\phi > \theta$, we say the current leads the voltage.
- $V(t) = Re(e^{j(\omega t+\theta)})$, and $\mathrm{I}(t) = Re(e^{j(\omega t+\phi)})$
- Now 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 $V(t) = Re(Ve^{j\omega t})$ and $\mathrm{I}(t) = Re\left(Ie^{j\omega t}\right)$.
- Note that $I = CVj\omega$, for a capacitor and $V = LIj\omega$, for an inductor

Circuit analysis and impedance

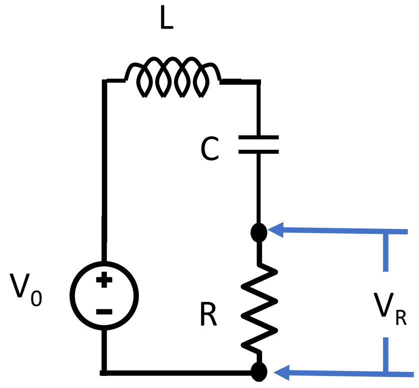
- Impedance unifies the “simple” ohms law with capacitance and inductance.
- $Z = R$, for resistors, $Z = j\omega L$, for inductors and $Z = \frac{1}{j\omega C}$, for capacitors.
- In general, $Z = R + jX$ and all the ohm like laws hold for resistors, capacitors and inductors .
  - $Z_{eq} = Z_1 + Z_2$ for two components with impedance Z_1, Z_2 connected in series
  - $Z_{eq} = \frac{Z_1 2}{Z_1 + Z_2}$ 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 $|V| = \frac{|I|}{|j\omega C|} = |\frac{V_0}{1+j\omega RC}|$
- For phasors V, I, define the complex power as $P = \frac{V\bar{I}}{2} = Z\frac{I\bar{I}}{2} = \mathrm{R}\frac{|I|^2}{2} + j\mathrm{X}\frac{|I|^2}{2}$; the first term is the real power, the second is called the *reactive* power.
- The average power is $P_a = Re(P) = Re(\frac{V\bar{I}}{2})$. We define the reactive power as $P_r = Im(P)$.
- $P_r = \omega(E_L - E_C)$, 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

- 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 $|V| = \frac{|I|}{|j\omega C|} = |\frac{V_0}{1+j\omega RC}|$
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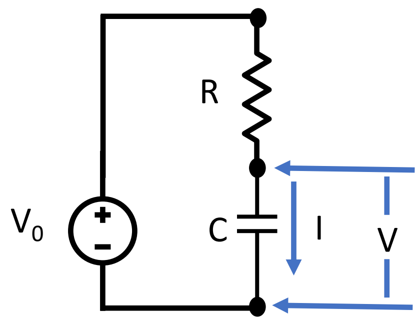
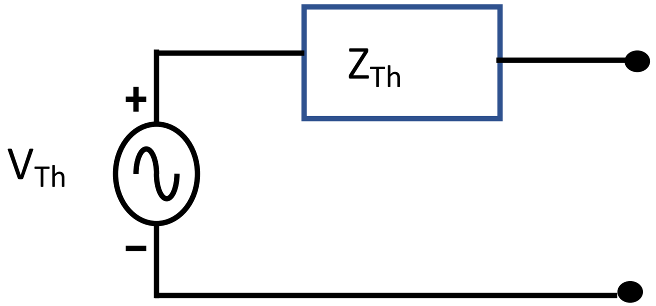
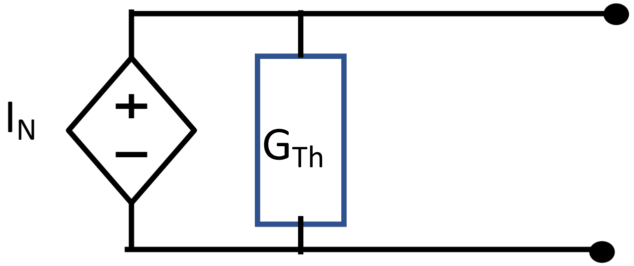


Thevenin and Norton

- 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



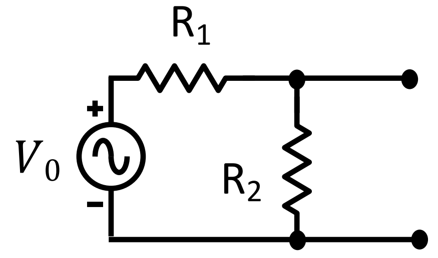
- Norton: Any combination of linear sources and passive elements terminating in two terminals is equivalent to a pure current source in parallel with a conductance



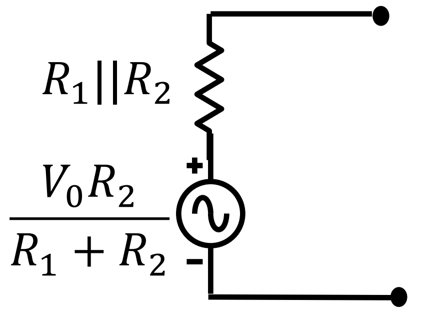
- Similar theorems for two terminal input and output devices (with transfer function)

Thevenin and Norton

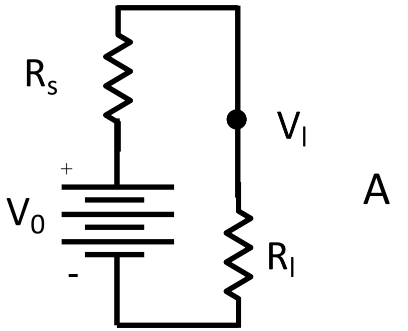
- We can use lookback resistance to calculate the Thevenin equivalent resistance and ideal source.
- To find the lookback resistance, short the source and apply the usual laws.
  - Here $R_s = R_1||R_2$
- To find the new ideal source, notice R_1 and R_2 form a voltage divider.
  - The new source voltage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



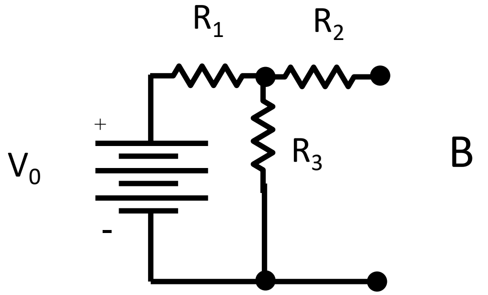
Is equivalent to

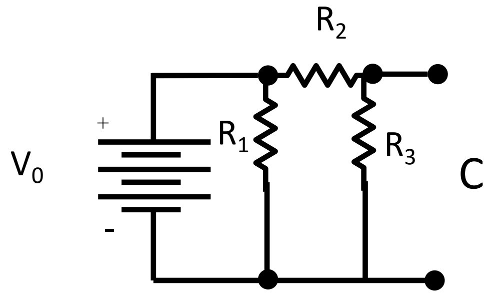


Exercise 1: Resistors

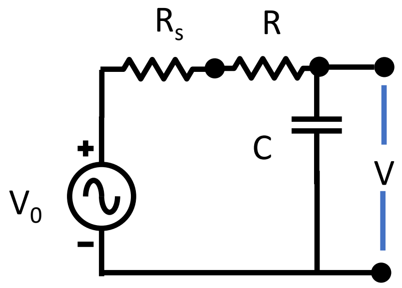


1. Consider (A). Find the formula for power in the load. Find the R_l that maximizes the power to the load.
   - $V_l = \frac{R_l}{R_s+R_l} V_0, I_l = \frac{V_0}{R_s+R_l}$.
   - $P_l = V_l I_l = \frac{R_l}{(R_s+R_l)^2} {V_0}^2$, which is maximum when $R_l = R_s$
2. Find the Thevenin and Norton parameters 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).
   - $V_{Th} = \frac{R_3}{R_2+R_3} V_0$
   - $R_{Th} = R_2 || R_3$

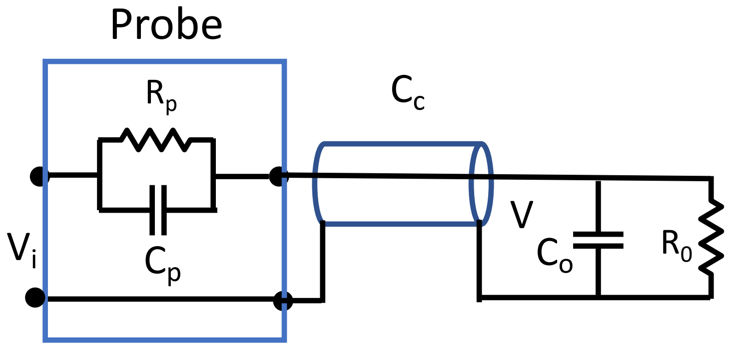




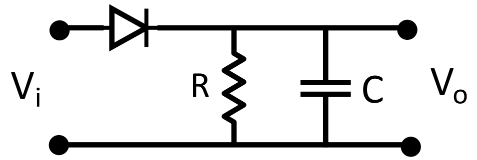
Exercise 3: Capacitors



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 $C = 10\ nF$. 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 τ and t_2.
   - $\tau = 3\times10^5\times10^{-8}\ sec = 3\ millisec$
   - $t_{12} \approx 1.5ms$
4. Capacitance on the scope prevents the delay from being 0. Measure the new t_2 with these changes.
5. Given C_0 and C_p and $R_{p.}$
   - $C_0 = 100pf/m, C_o = 50pF, C_p = 10pF$
6. Now calculate the new t_{12}.
   - $\tau = 6\mu$-sec

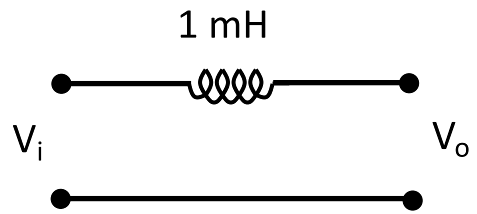


Exercise 4: Diode detectors

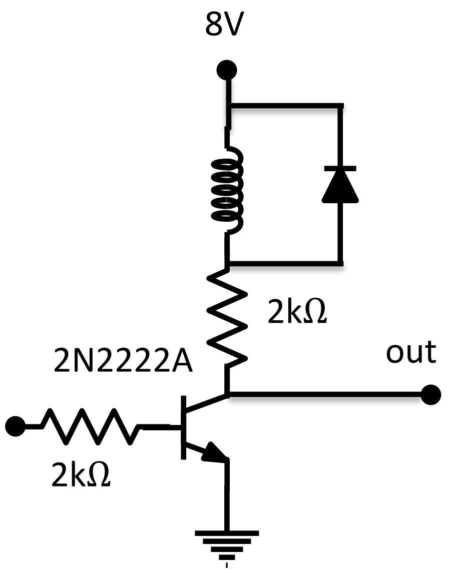


- For AM, $V(t) = V_c \cos(\omega_c t) + a(t) \cos(\omega_c t)$, Define the modulation depth $m = \frac{a_p}{V_c}$
- In circuit on the right, $R = 3k\Omega$, $C = 10\ nF$
- Set function generator for $f_c = 1MHz$, $V_{c,pp} = 5V$, $f_m = 1kHz$, $m = .7$
  1. Calculate τ for the RC circuit. $\tau \ll a(t)$
  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

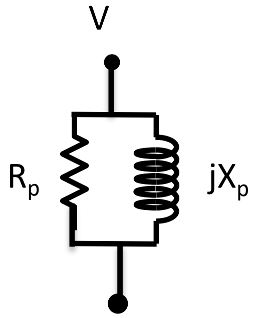


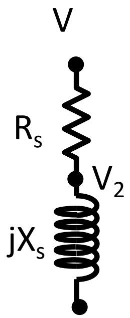
Exercise 6: Diodes and snubbers

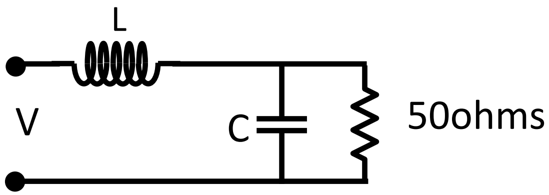
x

Exercise 7: Parallel to Series conversion

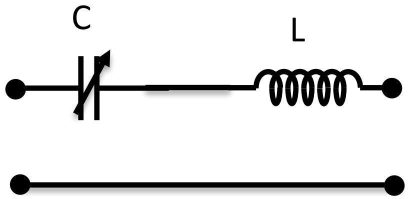
- For series: $Z_s = R_s + j\omega L$, $Q_s = \frac{\omega L}{R_s}$
- For parallel: $\frac{1}{Z_p} = \frac{1}{R_p} + \frac{1}{j\omega L}$, so $Z_p = \frac{j\omega L R_p}{R_p + j\omega L}$ and $Q_p = \frac{R_p}{\omega L}$







Exercise 8: Series resonance

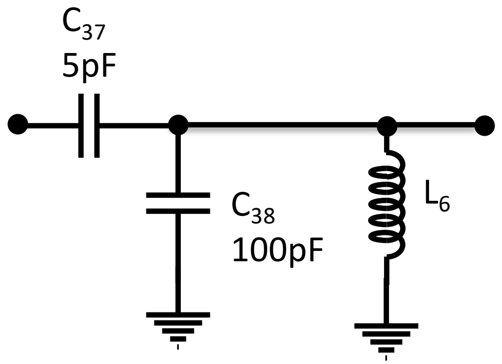


- For the circuit on the right, C$= 8 - 50pf$, $L = 15\mu H$forming a bandpass filter.
- If $C = 35pf$, the resonant frequency is $\omega = \frac{1}{\sqrt{35\times10^{-12}\times15\times10^{-6}}} = \frac{10^9}{\sqrt{525}} \approx 43.6$, so the resonant frequency is $\frac{43.6}{2\pi} \approx 6.9MHz$
- Tune the resonant frequency to $7MHz$ and find f_u, f_l and Δf and thus Q.
- Compute what these values should be

Exercise 9: Parallel resonance

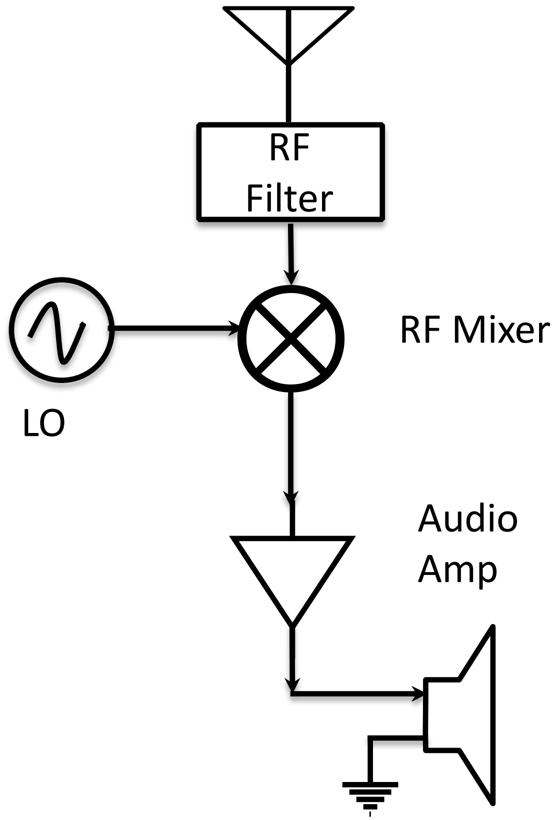
- $L = A_l N^2, A_l = 4\frac{nH}{turn^2}$ for T37-2 core so for 28 turns, $L_6 = 3.1\mu H$

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 oscill ator



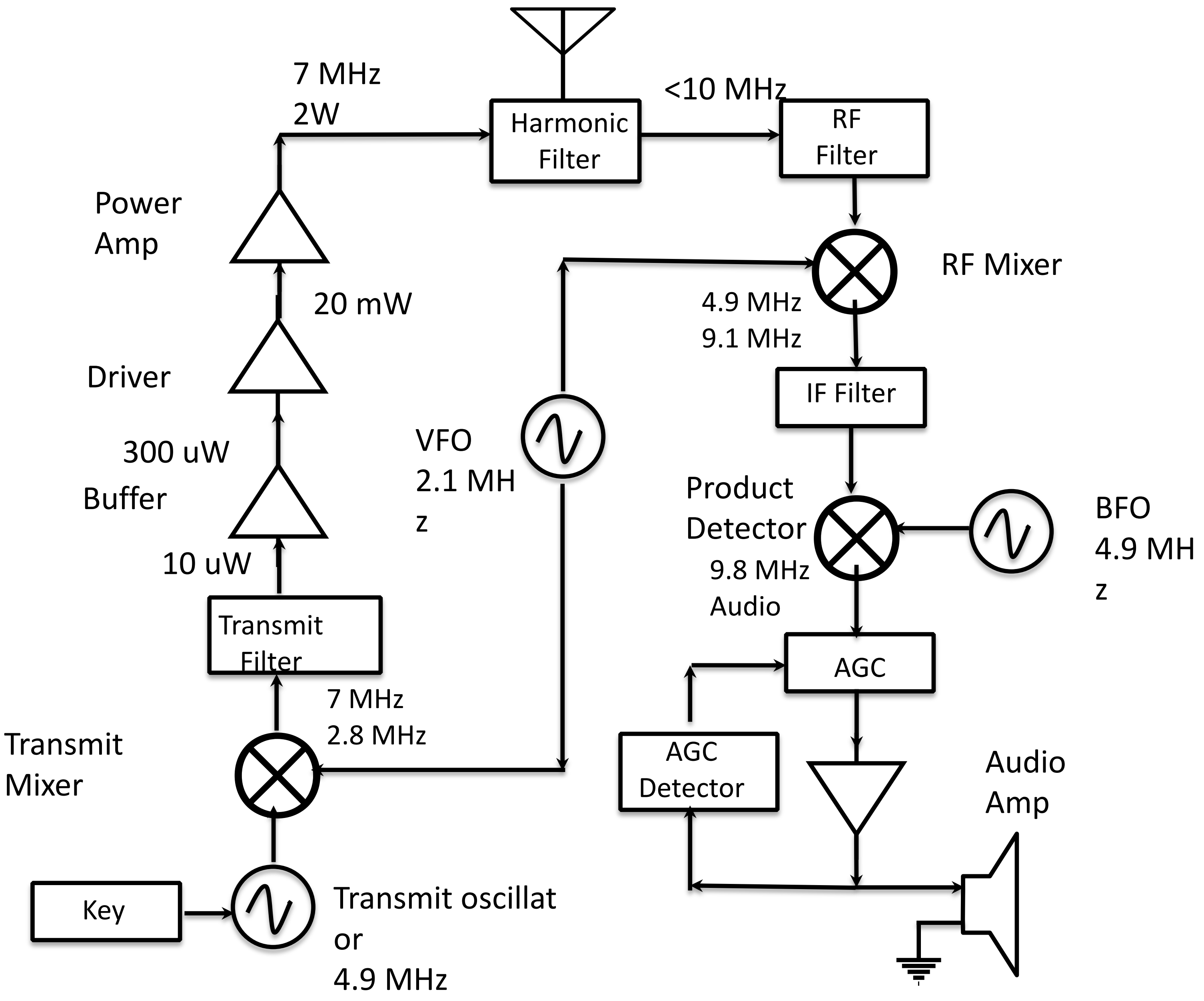
Direct conversion and superhet receivers

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

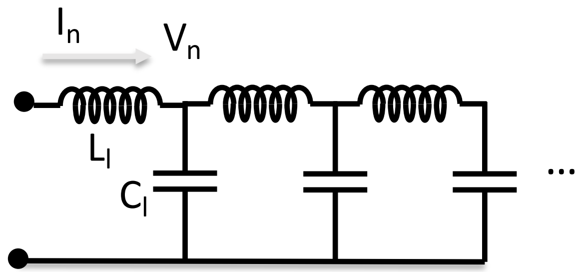


Direct conversion

Norcal 40A


7 MHz
2W
Harmonic Filter
<10 MHz
RF Filter
Power Amp
RF Mixer
20 mW
4.9 MHz
9.1 MHz
Driver
IF Filter
300 uW
VFO
2.1 MH
z
Buffer
Product Detector
BFO
4.9 MH
z
10 uW
9.8 MHz
Audio
Transmit Filter
AGC
7 MHz
2.8 MHz
Transmit Mixer
AGC Detector
Audio Amp
Key
Transmit oscillat
or
4.9 MHz

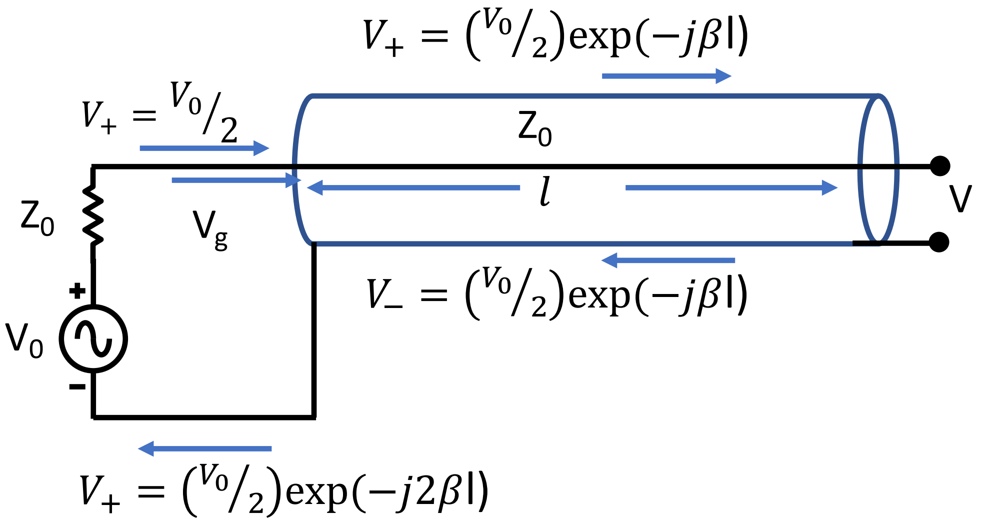
Transmission Lines



- $V_{n+1} - V_n = -L_l \frac{\partial I_{n+1}}{\partial t},\ L = \frac{L_l}{l}$
- $I_{n+1} - I_n = -C_l \frac{\partial V_n}{\partial t},\ C = \frac{C_l}{l}$
- $\frac{\partial^2 V}{\partial z^2} = LC \frac{\partial^2 V}{\partial t^2}$ 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
- $Z_0 = \frac{V_+}{I_+}, -Z_0 = \frac{V_-}{I_-}, V = V_+ + V_-$
- $P_+(t) = \frac{{V_+}^2}{Z_0},\ P_-(t) = -\frac{{V_-}^2}{Z_0}$
- $\rho = \frac{V_-}{V_+},\ \mathrm{Z} = \frac{V}{I} = \frac{V_+ + V_-}{I_+ + I_-} = \frac{V_+}{I_+} \frac{1+\frac{V_-}{V_+}}{1+\frac{I_-}{I_+}} = Z_0 \frac{1+\rho}{1-\rho}$
- $\rho = \frac{Z - Z_0}{Z + Z_0}$
- $\rho_i = \frac{i_-}{i_+} = -\rho$

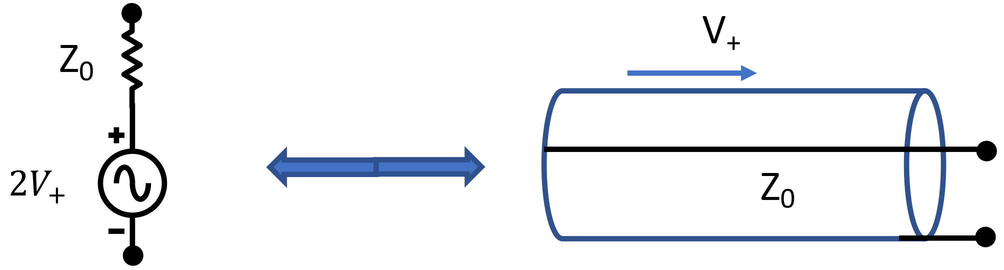
Transmission Lines - continued

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



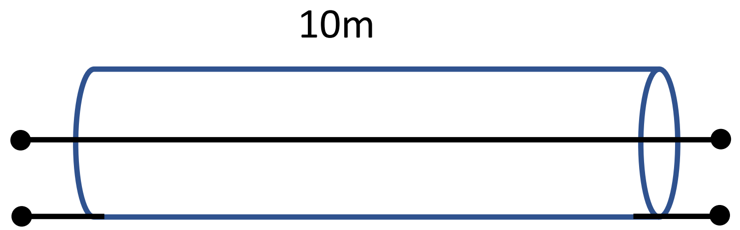
Power

- $\tau = \frac{V}{V_+} = 1 + \rho = \frac{2Z}{Z+Z_0}, V = 2V_+$
- 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 50Ω scope probe

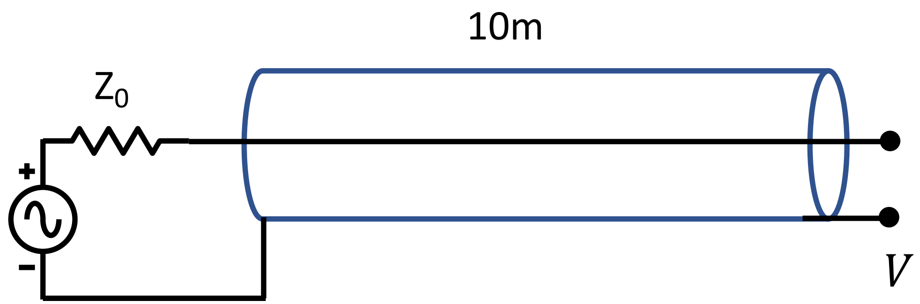


Exercise 11: Waves

- Use 50Ω scope probe

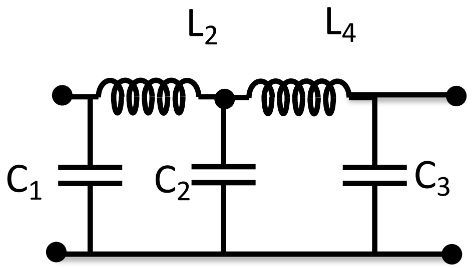
Exercise 12: Resonance

- $RG58U$ has a capacitance of about $100\ pF/m$
- Let α be the attenuation constant and β be the phase
- Derive an expression for $|\frac{V_g}{V}|$ and use it to calculate α
- 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 $Q = \frac{\alpha}{2\beta}$

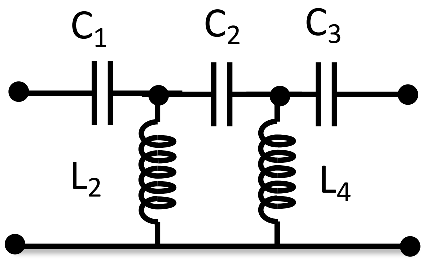


Filters

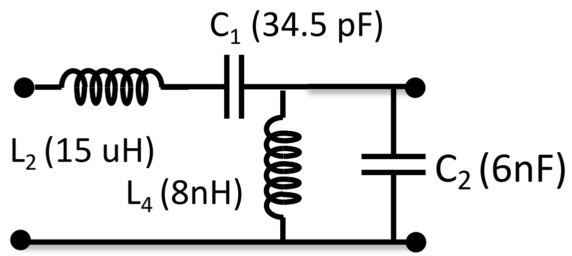
Low pass



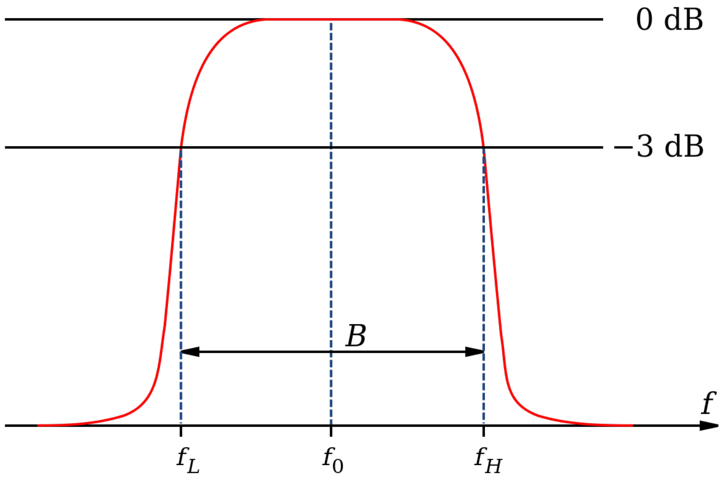
High pass



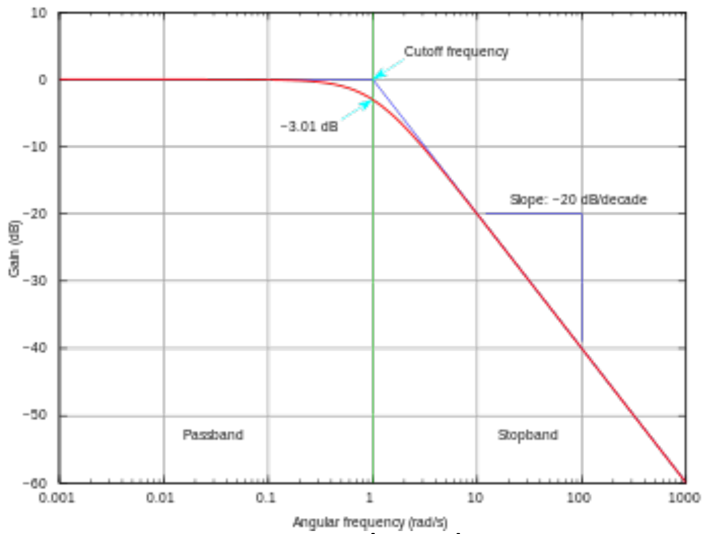
7 MHz bandpass



- Filters

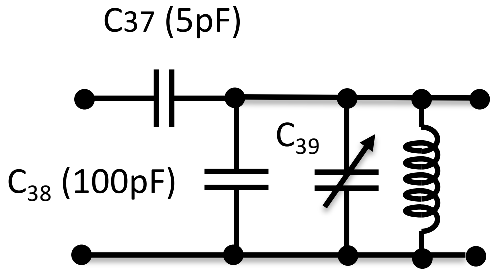


Bandpass - WIkipedia



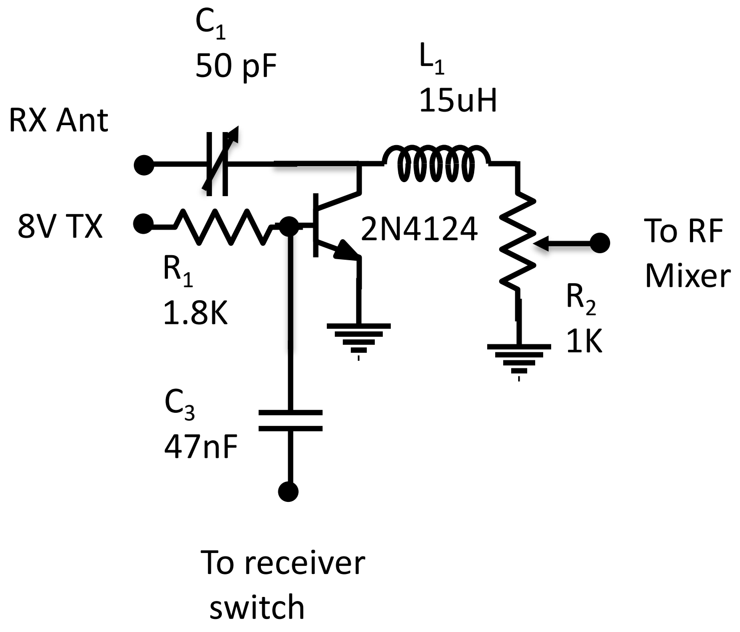
Lowpass - WIkipedia

Norcal transmit bandpass filter

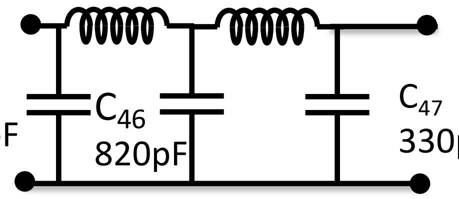


- $C_{39} = 50pF,$
- L_6 is 36 turns #28 on T37-2 which has $A_l = 4\frac{nH}{turn^2}$
- $L_6 = A_l \cdot 36^2 = 3.1\mu H$
- $Z_2 = -\frac{j}{(C_{38}+C_{39})\omega_o}, \; Z_3 = jL_6\omega_o, Z_1 = \frac{j}{C_{37}\omega_o}$
- $Z_{2,3-eq} = \frac{jL_6\omega_0}{L_6(C_{38}+C_{39})\omega_0{}^2-1}$ L$_6$
- Resonance is when $Z_{2,3-eq} \to \infty, {\omega_o}^2 = \frac{1}{(C_{38}+C_{30})L_6} \approx \frac{10^{18}}{465}$, when almost all the voltage drop is across $Z_{2,3-eq}$ $\omega_o = \frac{10^9}{\sqrt{465}} \approx 50.8\times10^6, f_0 = \frac{\omega_o}{2\pi} \approx 7.1\ MHz$
- 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



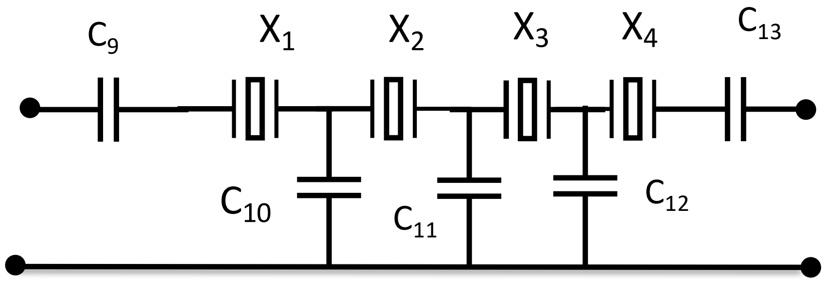
Exercise 13: Norcal Harmonic Filter

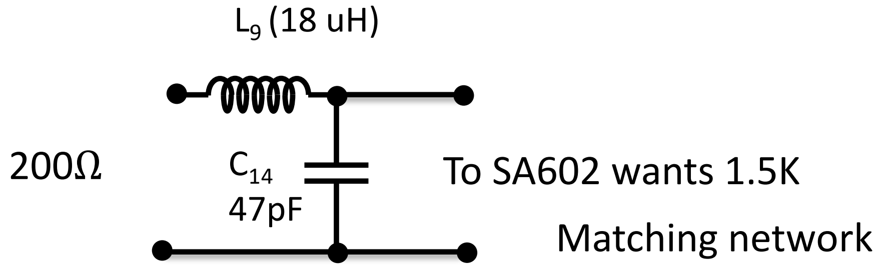


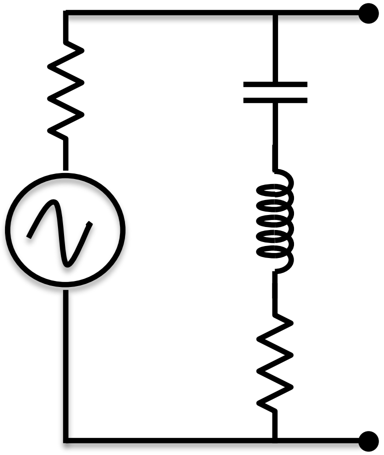
- L_7, L_8 use T37-2 core, 18 turns, 1.3uH
- Compare loss at 7MHz and 14MHz

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

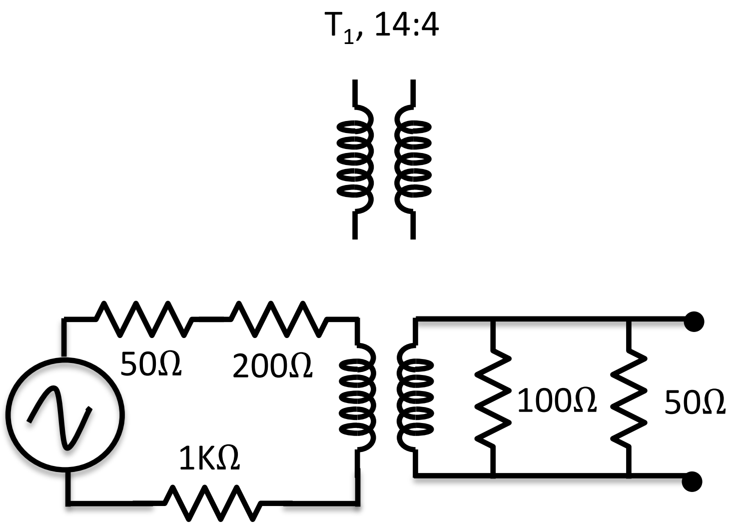
Transformers

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

Exercise 15: Norcal Driver Transformers

- T_1 is driver matcher uses FT 37−43

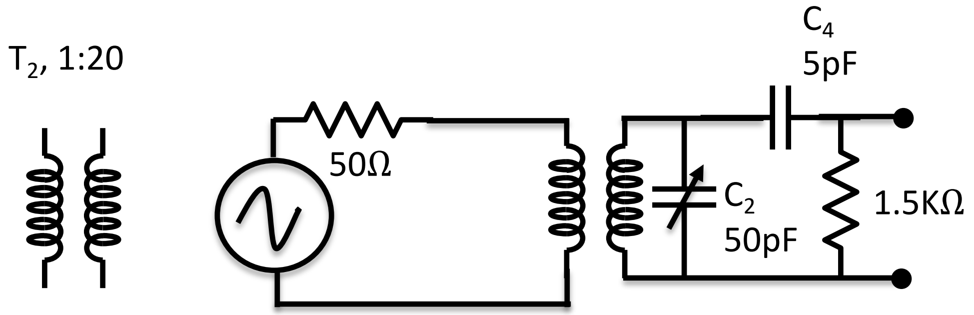
1. Measure the output V.
2. Calculate V
3. Measure the 3dB cutoff, f_c.
4. Use f_c to calculate A_l

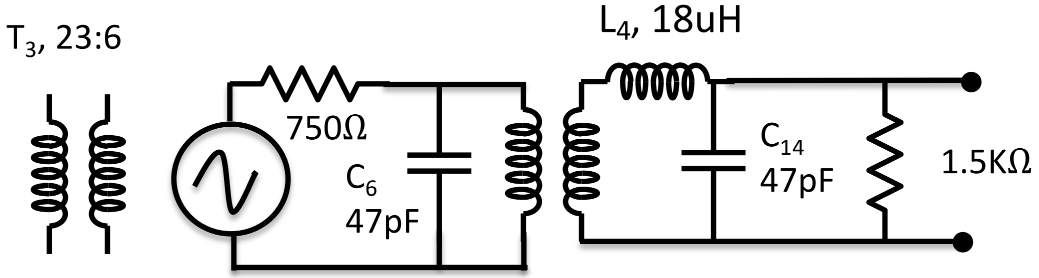


Exercise 16: Norcal Tuned Transformers

- $T_{2,}$ T_3 are IF matchers using FT 37−61
- .5Vpp sine at 7MHz

1. Measure 3dB bandwidth
2. Find P/P_+





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_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

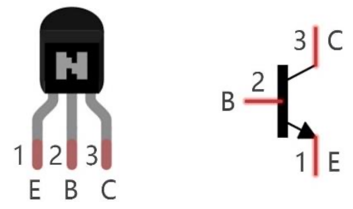
- Connect speaker to function generator 600Hz, 25mVrms.

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

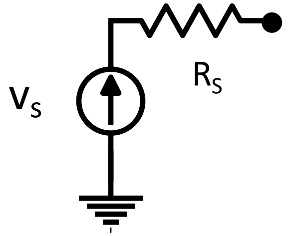
Exercise 18: Acoustic Standing Wave

- x

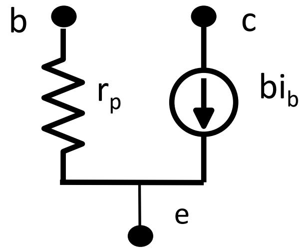
Bipolar Transistors



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



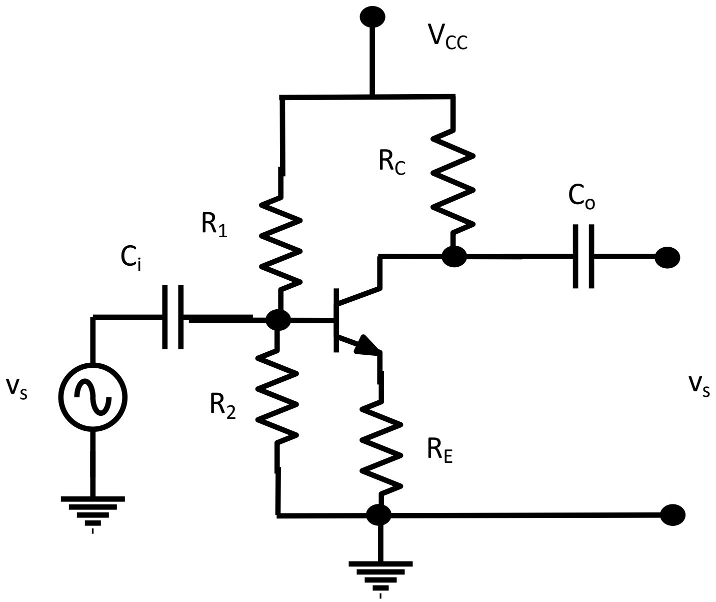
Bipolar source model



Bipolar equivalent circuit

Bipolar Switches

BJT common emitter amplifier



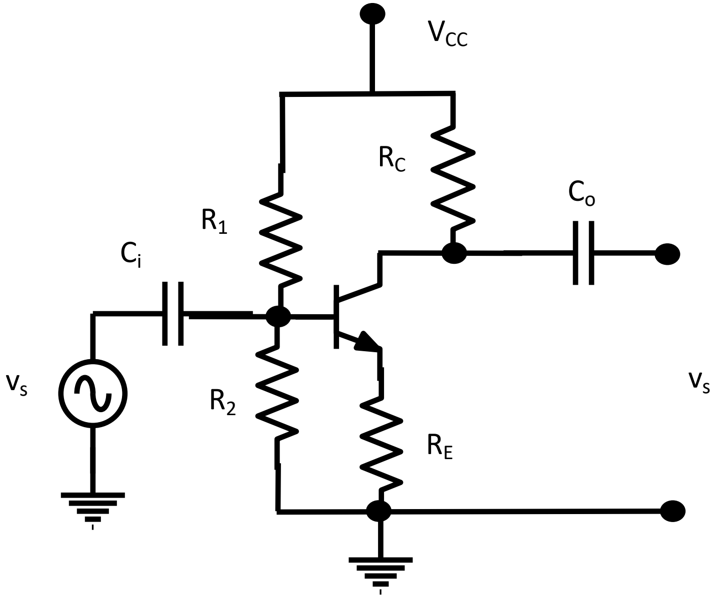
Common emitter amp

- Here's how to design a common emitter amplifier. We use a 2n3904 transistor with β=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$\boldsymbol{\Omega}$.
5. Since A = 5 and $A=R_C/R_E$, $R_C = 5 R_E$ so $R_E \sim 270$ $\boldsymbol{\Omega}$ (this is a standard resistor value) and R_C= 1.5k$\boldsymbol{\Omega}$.

Credit: Ward, Hands on Radio.

BJT common emitter amplifier continued



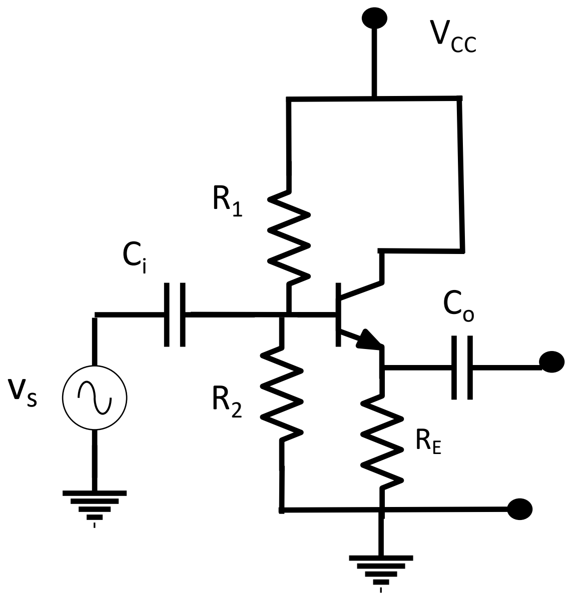
Common emitter amp

Credit: Ward, Hands on Radio.

6. i_b = 4mA/β = 27 μA.
7. Since V_{be} must be greater than .7V throughout the input signal range, we want the voltage across R_2 to satisfy $V_{be} + i_c R_E$ = 1.8V.
8. We insert a voltage divider consisting of R_1 and R_2, so that R_1= (12-1.8)/270 μA ~ 39 kΩ.
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 μF.

- 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



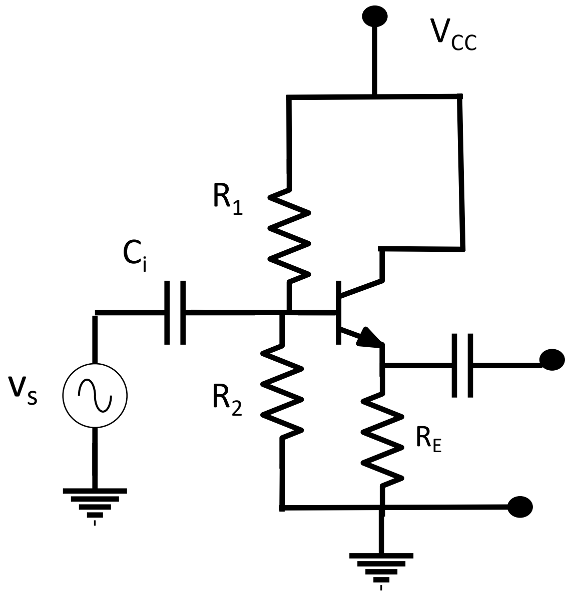
Common collector amp (Emitter Follower)

Common collector amp

Credit: Ward, Hands on Radio.

1. d

BJT common collector amplifier continued

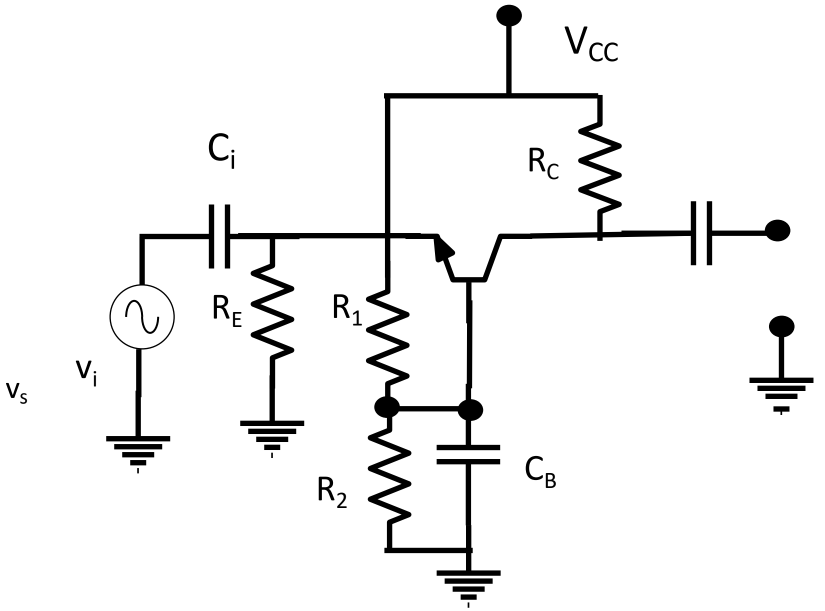


Common collector amp (Emitter Follower)

6. x

Credit: Ward, Hands on Radio.

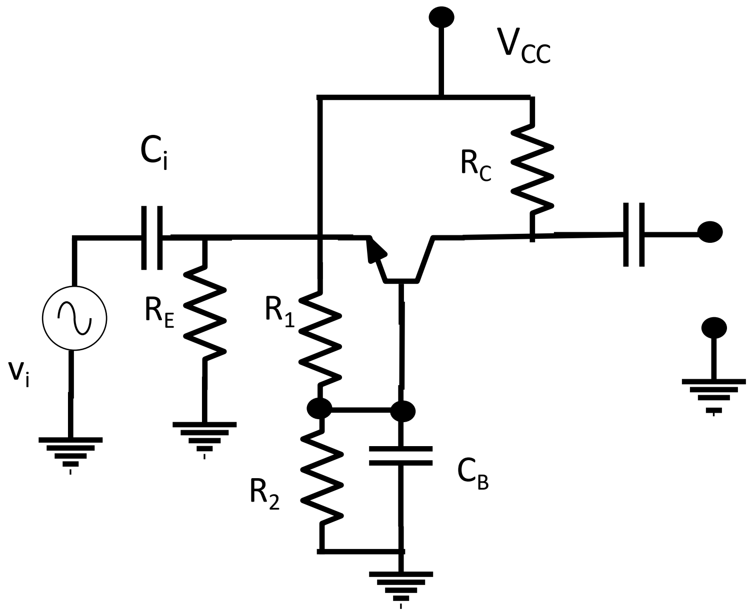
BJT common base amplifier



Common base amp

- x

BJT common base amplifier continued



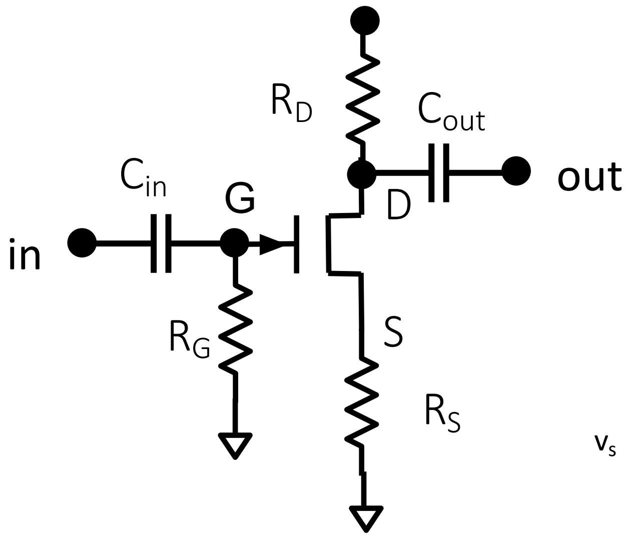
Common base amp

6. x

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



v_s

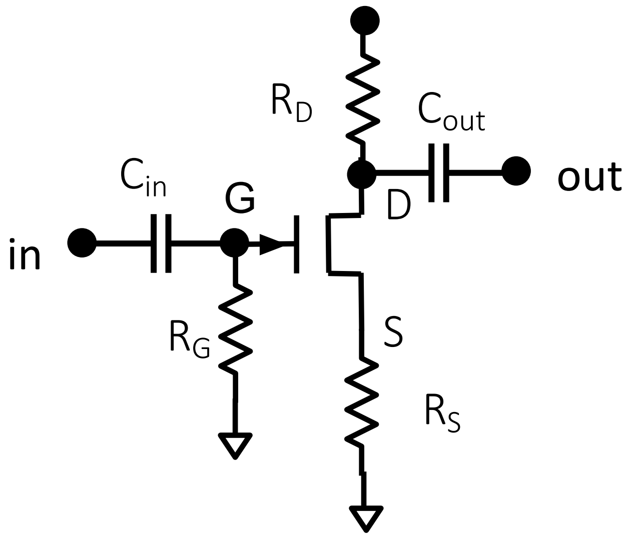
v_s

- x

JFET common emitter amplifier continued

6. x

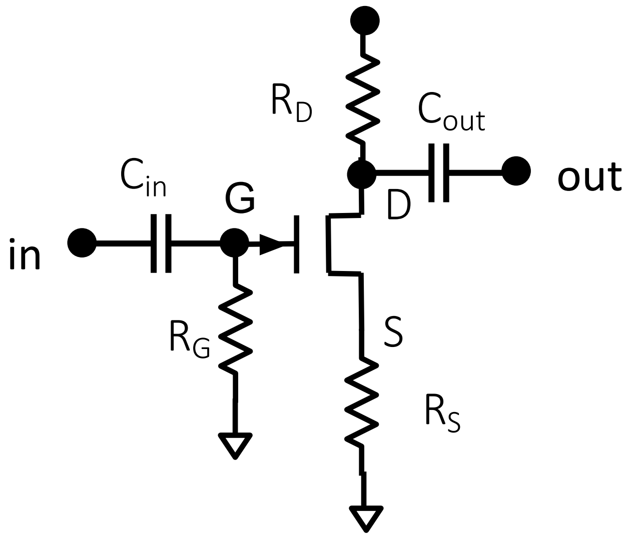
JFET common source amplifier



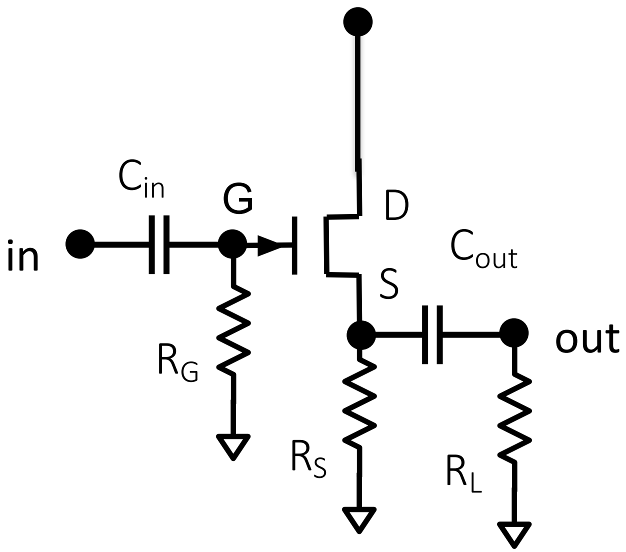
1. d

JFET Common Source Amplifier continued

6. x



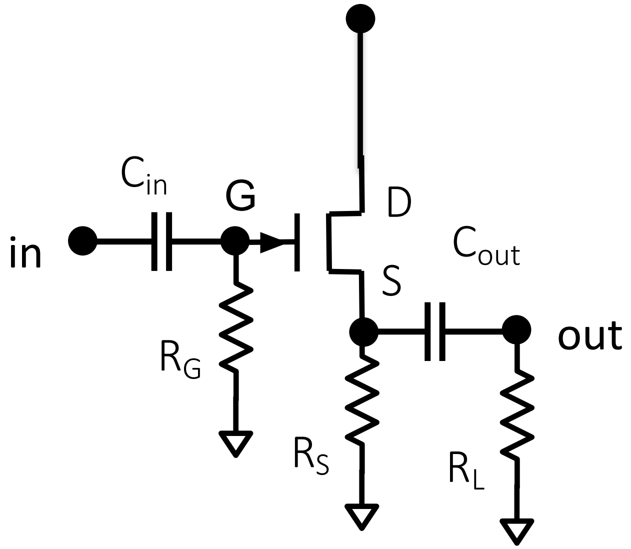
JFET common drain amplifier



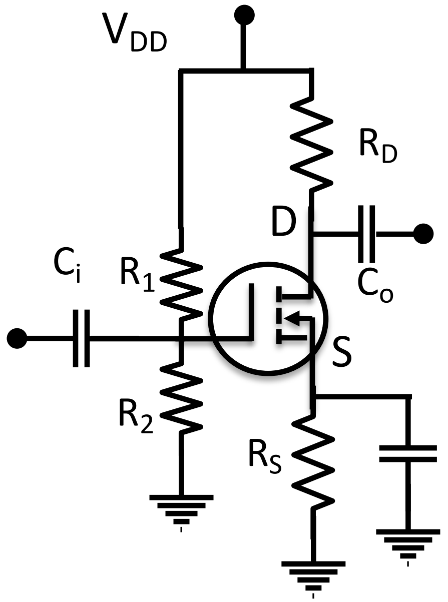
- x

JFET common drain amplifier continued

6. x



CMOS common emitter amplifier

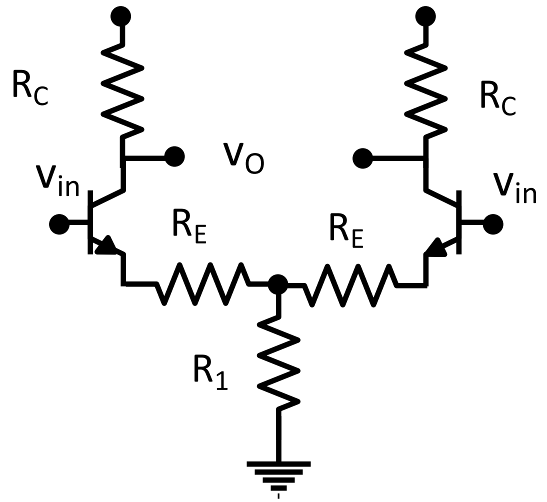


- Pick power
- $V_{DD} = i_D R_D + V_{DS} + i_D R_S$
- $V_{GS} = V_G - i_S R_S$
- $V_G = V_{DD} \frac{R_1}{R_1 + R_2}$
- $i_D = k(V_G - V_{TH})^2$
- Bias around $\frac{V_{DD}}{3}$
- Pick gain, $A = \frac{R_D}{R_S + \frac{1}{g_m}}$

Differential Amplifier

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

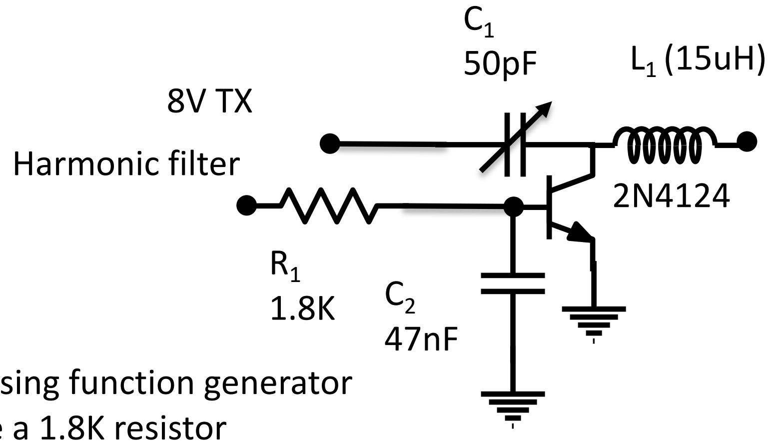
Differential amplifier



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

Exercise 19: Norcal receiver switch

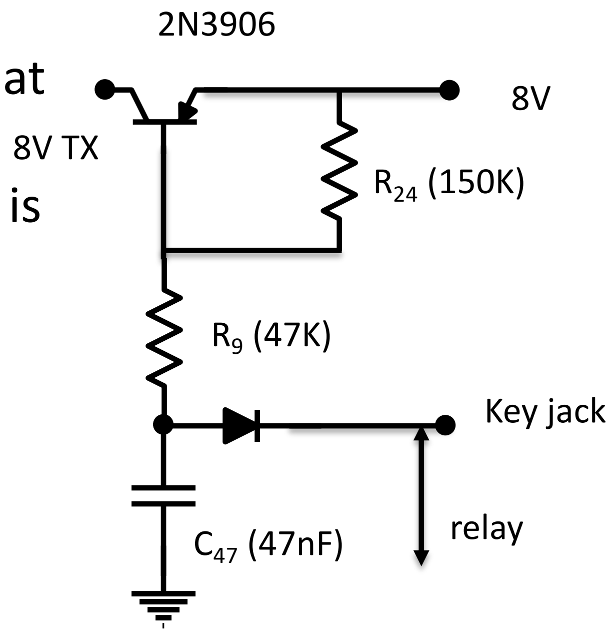
1. Consider the rising part of the base voltage waveform. Calculate slope.
2. Do the same for the falling part for voltage below .6V. Calculate t_2.
3. Measure switch attenuation
4. Measure the voltage with the switch on. Measure output voltage and calculate on-off rejection ratio $R=20 \log(V_{off}/V_{on})$
5. Find the saturation resistance R_s.
6. Calculate the expected attenuation



If using function generator use a 1.8K resistor

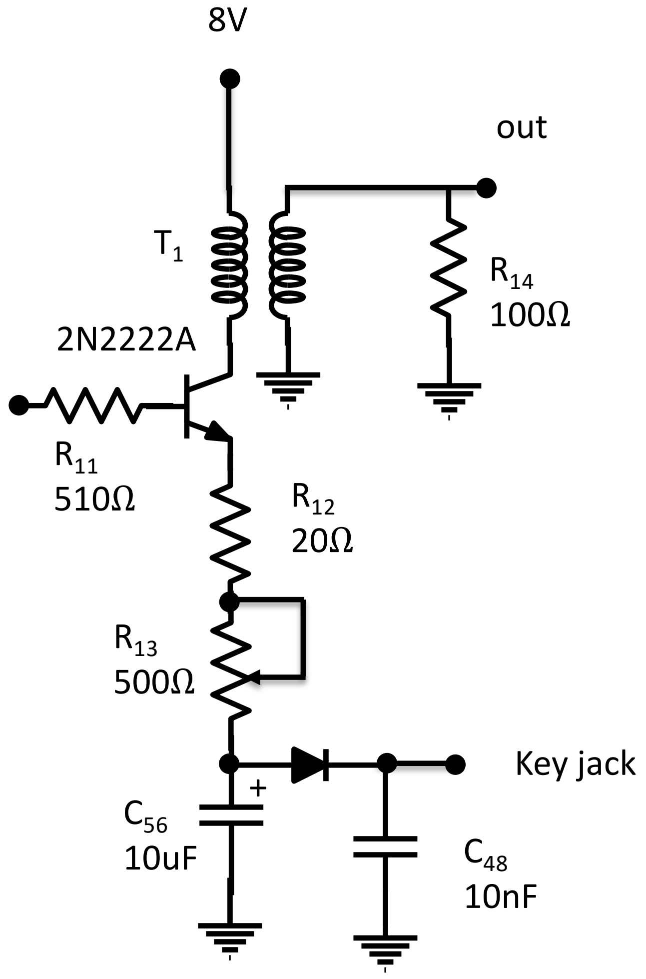
Exercise 20: NorCal transmitter switch

1. Calculate voltage on C_{57}.   Measure time for capacitor to charge half-way. Cal culate what the time should be.
2. Calculate the approximate current ic when Q4 is on. Assume base voltage on Q1 is700 mV. Neglect saturation voltage on Q4. Calculate base current i_b req uired to produce this collector current assuming $\beta = 100$.
3. Calculate i_b at key down assuming a 700 mV dropin base-emitter of Q4 and at 600mV at D11
4. Sketch collector voltage at Q4 showing where transistor is saturated. What is the delay in going active?
5. Use the delay to measure β.



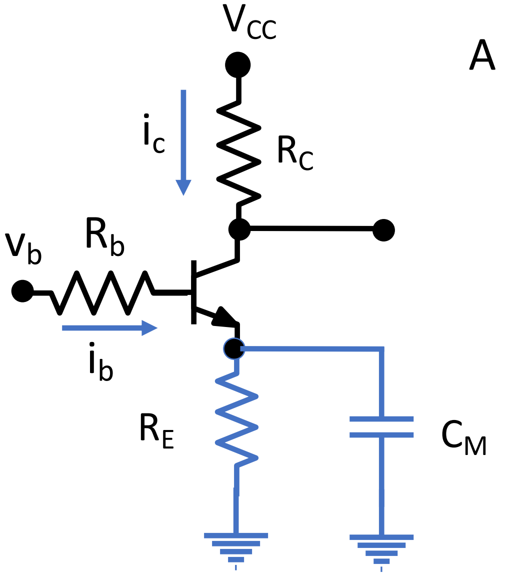
Exercise 21: Norcal Driver

1. Measure the voltage gain $G_v = \frac{v}{v_i}$ with R13 at minimum and maximun gain.
2. Calculate expected voltage gain at each setting.
3. 560ohm source resistance $V_o = 2V$

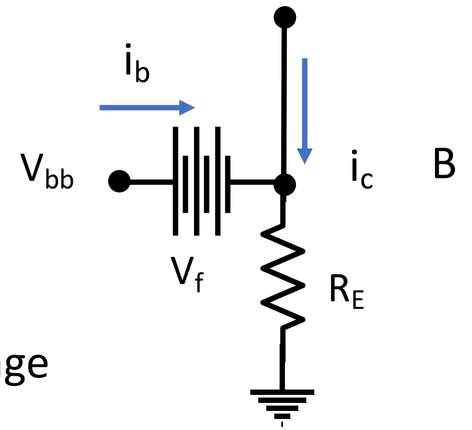


Emitter degeneration

- To the usual transistor circuit (A), on the right, we add R_E. (B) is an equivalent circuit.
- $V_{bb} \approx V_f + i_c R_E$. Let V be the output AC and V_i be the input AC, then the gain is $G = \frac{V}{V_i}$.
- $V_i = i_b R_b + i_E R_E \approx i_C R_E$, so $G_v = -\frac{R_C}{R_E}$ (Doesn't depend on β)
- $V = i_b R_b + i_C R_C \approx i_C R_C$, $Z_i = \beta R_E$, $Z_i = \frac{V}{i_b}$
- C_M is called a Miller capacitor. With it, $Z_i = \beta R_E || (1 + |G_v|) C_M$
- $r_c = \frac{V_{early}}{i_c}$
- $R_s{}' = R_S + R_b$
- $Z_C = r_C || C_C$, $Z_o = \frac{V}{i_C}$, C_c is specified in data sheet (8pF)
- $i = i_c - \beta i_b$, $i_b = -\frac{i_C R_s}{R_s{}' + R_E}$, $i = i_c(1 + \frac{\beta R_E}{R_s{}' + R_E})$
- $V = i z_c + i_C\,(R_s{}' || R_C)$, z_C is the collector impedance
- $Z_o = \frac{V}{i_C} = z_C \left(1 + \frac{\beta R_E}{R_s{}' + R_E}\right) + R_s{}' || R_E$
- $Z_o = Z_C \left(1 + \frac{\beta R_E}{R_s{}' + R_E}\right)$



Adding R_E (and (C_M)



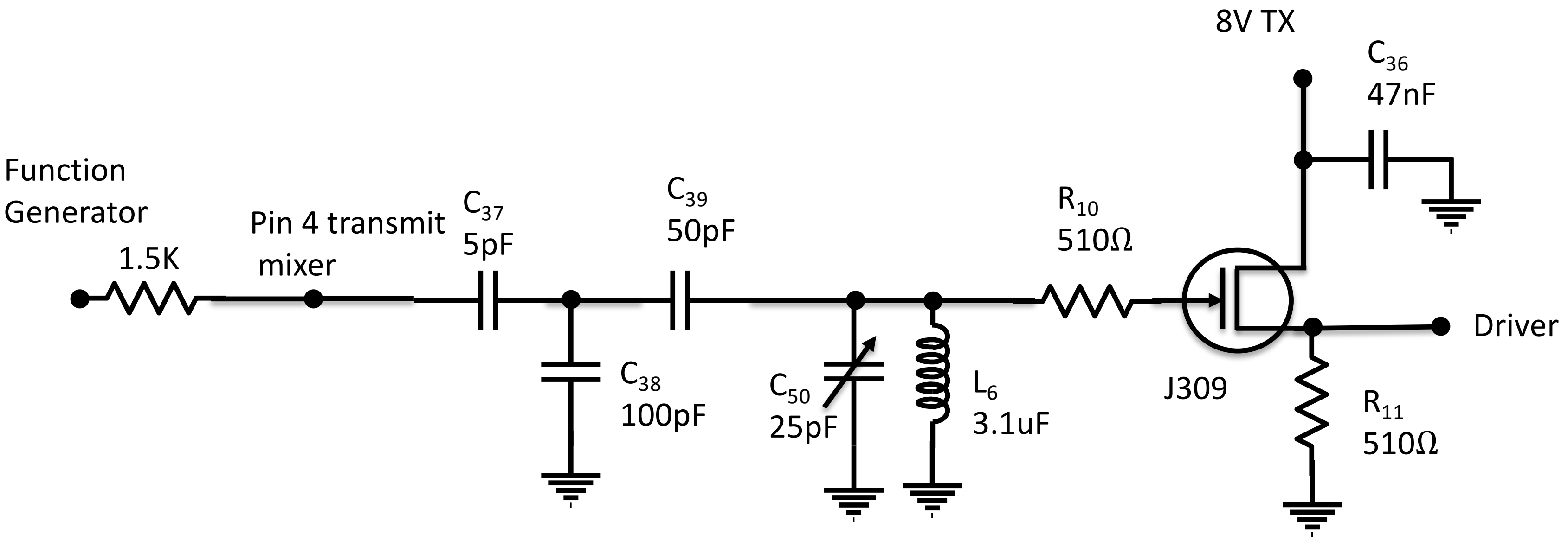
Bias voltage

Exercise 22: Emitter degeneration

- Use 50Ω scope probe

Exercise 23: Norcal Buffer amplifier

1. Measure the DC voltage at source of the JFET
2. Calculate the source and drain voltages you should expect
3. Measure the voltage gain
4. Find the transconductance you should expect
5. Calculate the available power P_+ from the function generator through a 1.5Kohm load. Calcul ate gain in in dB

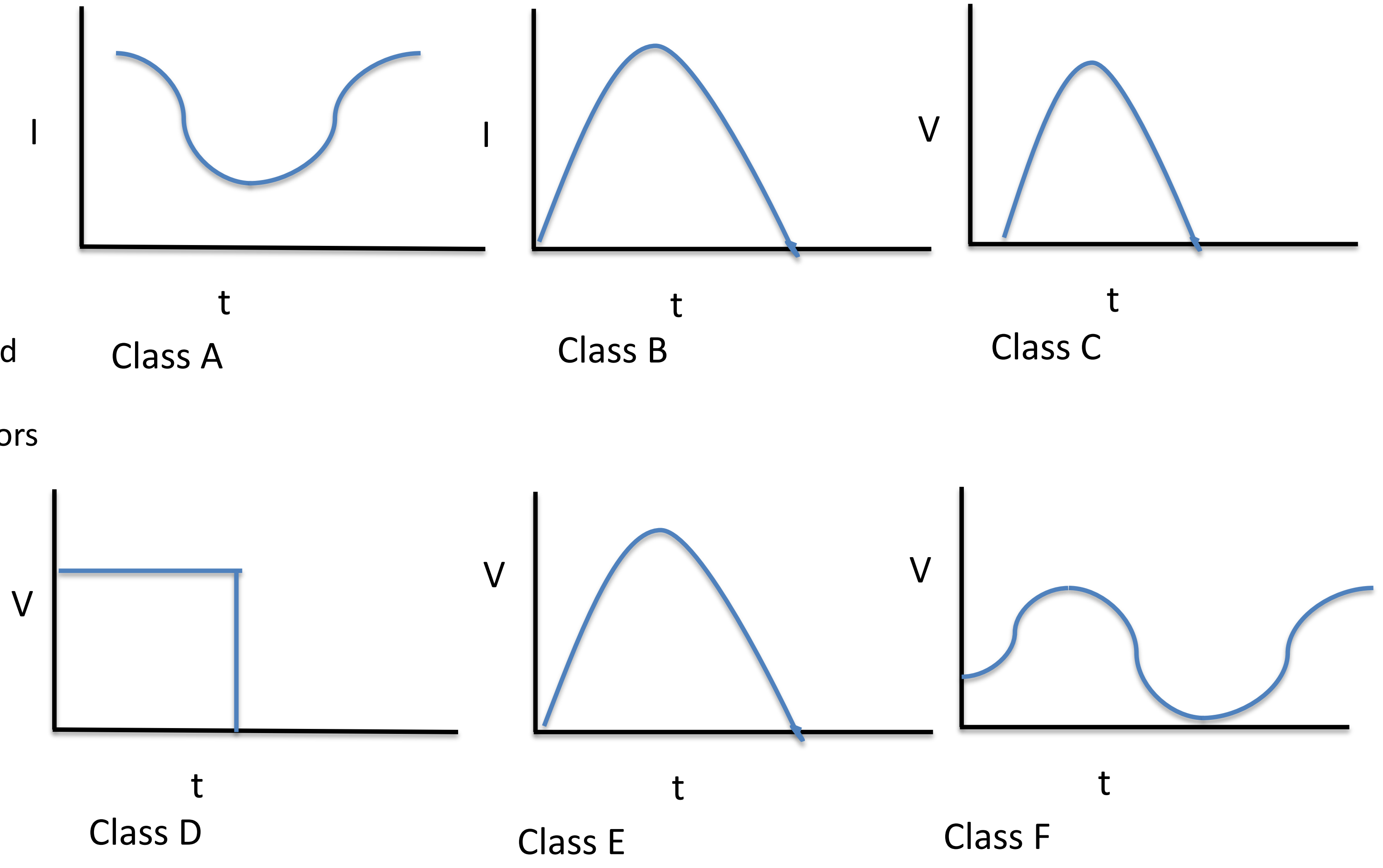


Amplifier classes

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

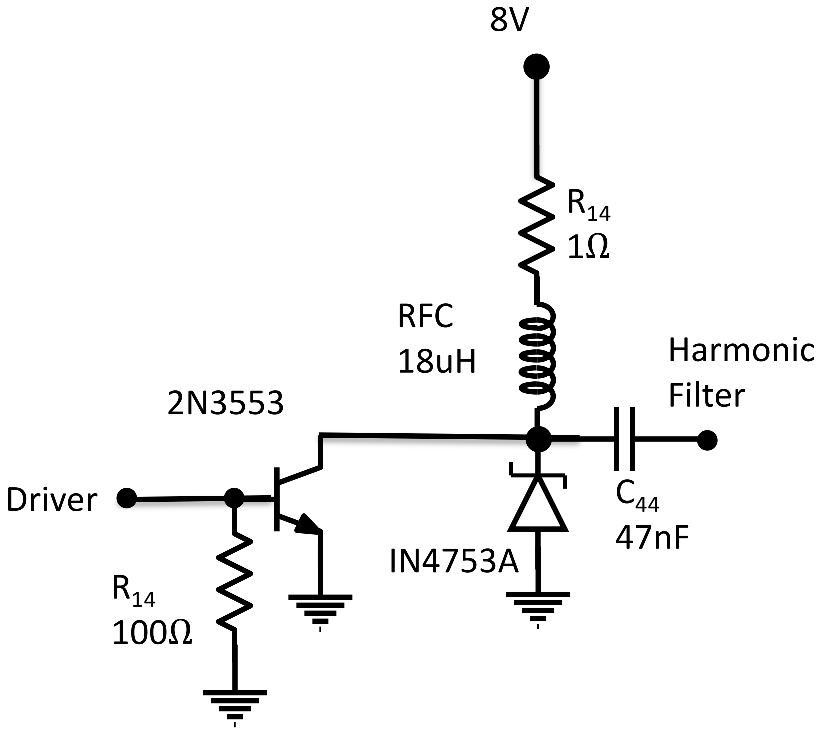
$$\eta = \frac{P}{P_0}, P_d = P_0 - P_i$$

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



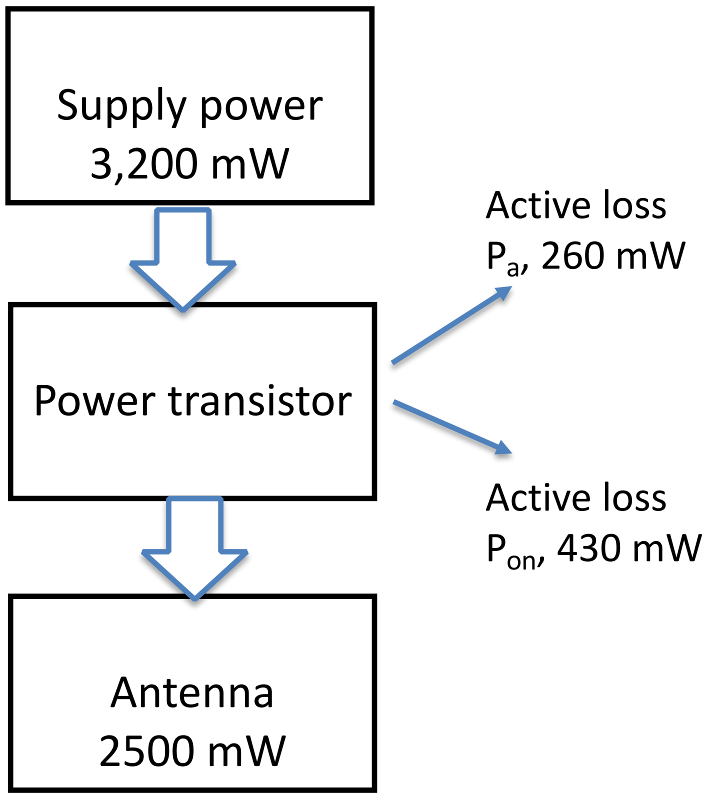
Exercise 24: Norcal Power Amp

Norcal-40 Power amp is class C



- $R_t = \frac{T - T_0}{P_d}$
- T_0 is ambient temperature, T is heat si nk temperatureType equation here.

1. Calculate pp across 50ohm load requir ed for output of 2W
2. Find pp output voltages or 5, 10, 15, 2 0, 25 and 30V. Calculate power supply current subtracting 2mA for regulator
3. Plot efficiency $\eta = \frac{P}{P_0}$. Plot dissipated power $P_d = P_o - P_i$



Thermal modelling

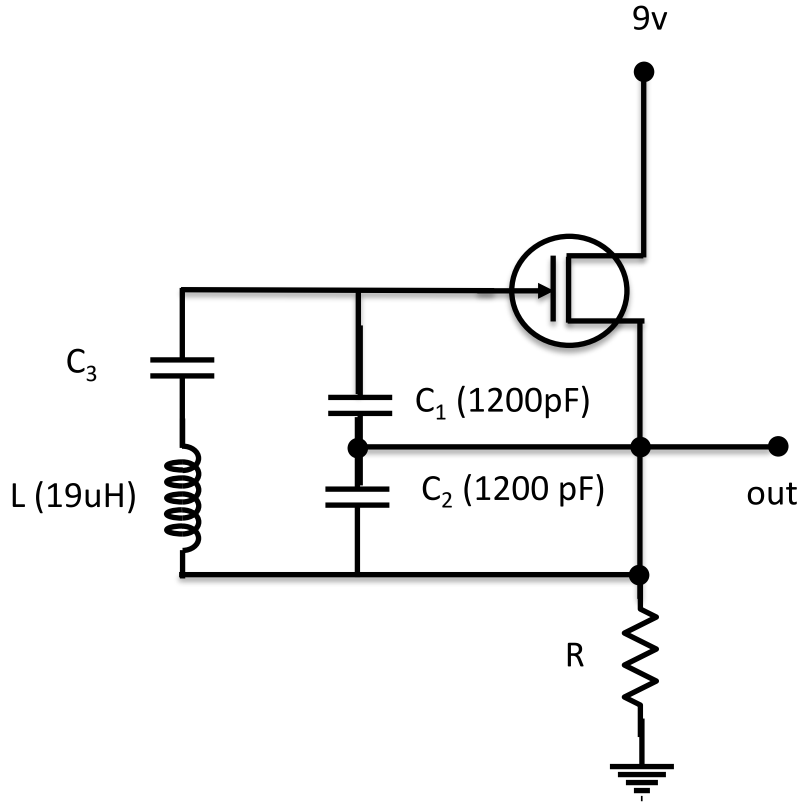
- T is heat sink temperature, T_0 is ambient temperature, P_d is power dissipated.
- $R_t = \frac{T - T_0}{P_d}$, R_t is the thermal resistance
- $C_t \dot{T} = P_d$, $R_j = \frac{T_j - T}{P_d}$, C_t is the thermal capacitance, T_j is the junction temperature
- $f(t) + \tau \dot{f(t)} = f_\infty$, $f(t) = f_0 e^{-\frac{t}{\tau}}$
- $P_d = \frac{T(t) - T_0}{R_t} + C_t \dot{T(t)}$, $\tau = C_t R_t$, $T_\infty = P_d R_t + T_0$
- $T(t) = T_\infty - P_d R_t e^{-\frac{t}{\tau}}$
- $T_j(t) = T(t) + R_j P_d$

Exercise 25: Thermal modelling

- Use 50Ω scope probe

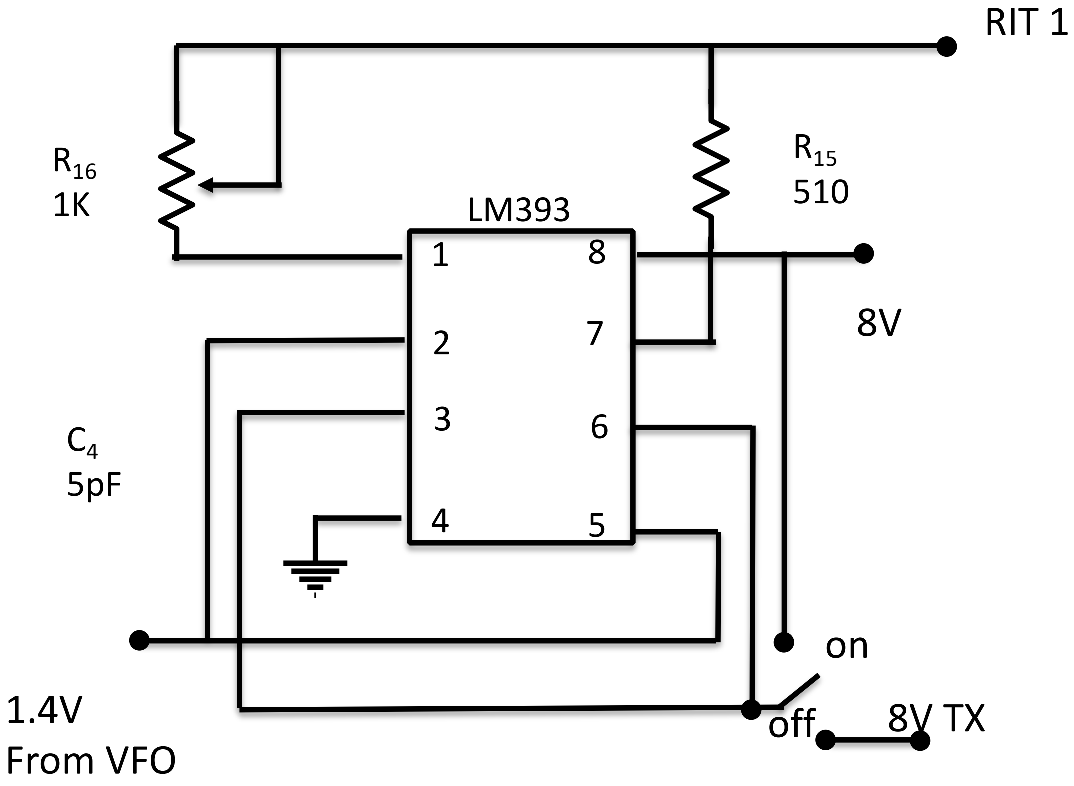
Clapp oscillator

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



Norcal Receiver Incremental Tuning (RIT)

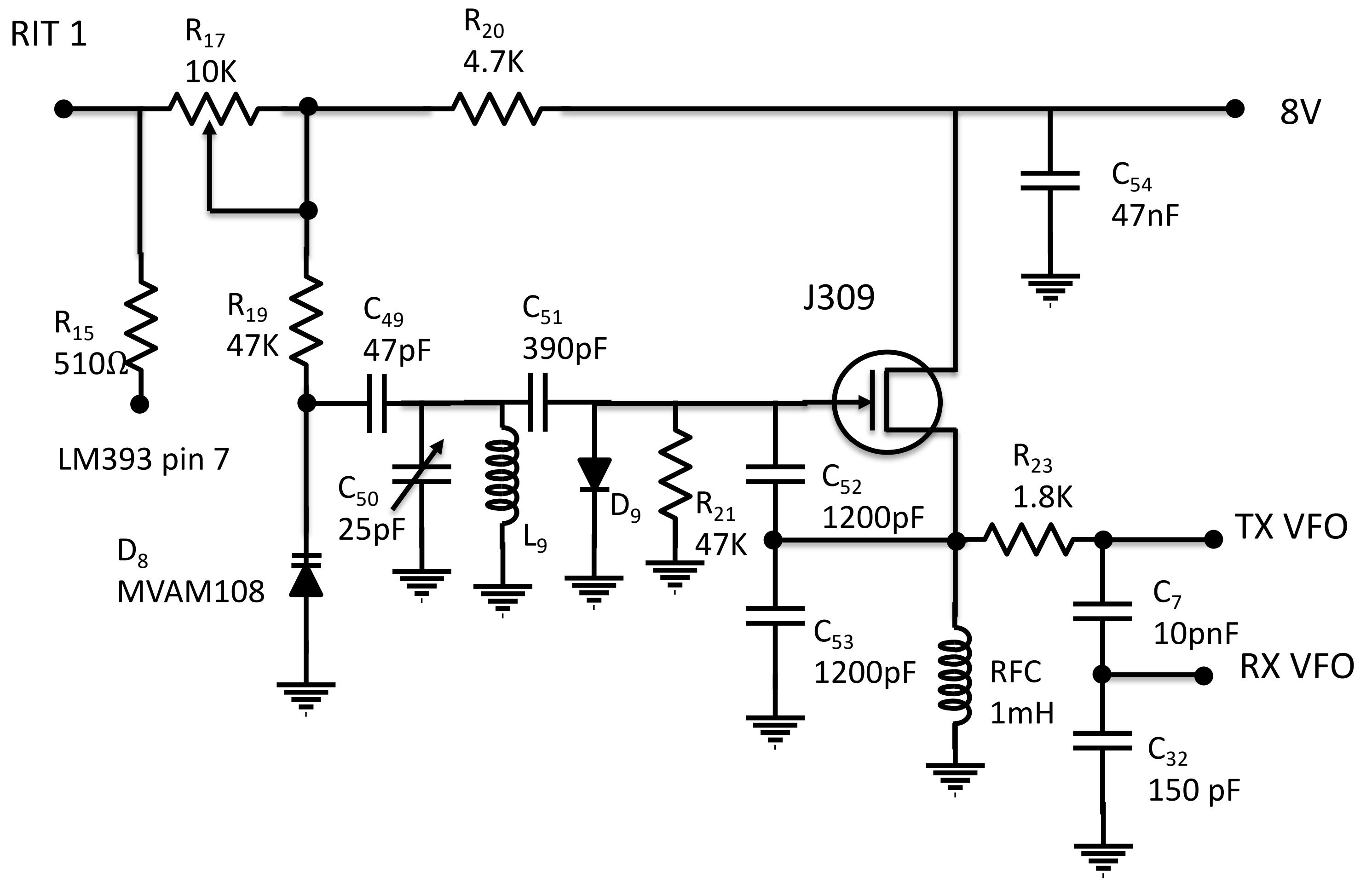
- LM393 is a comparator
- For function generator connect through 1.5K



Exercise 26: Norcal VFO

- L9: T68-7 62 turns
- Check MVAM108 capacitor when R_{17} is high an d low
- Start resistor (R_{21}) 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

1. Measure DC voltage across wiper in R17
2. Calculate expected V for large signal oscillation
3. How does this change if we consider the induc tor and source-drain resistance
4. How does the frequency change as R17 change s?
5. Callculate the oscillation frequency and the los s ratio $|V/V_I|$



Exercise 27: Gain limiting

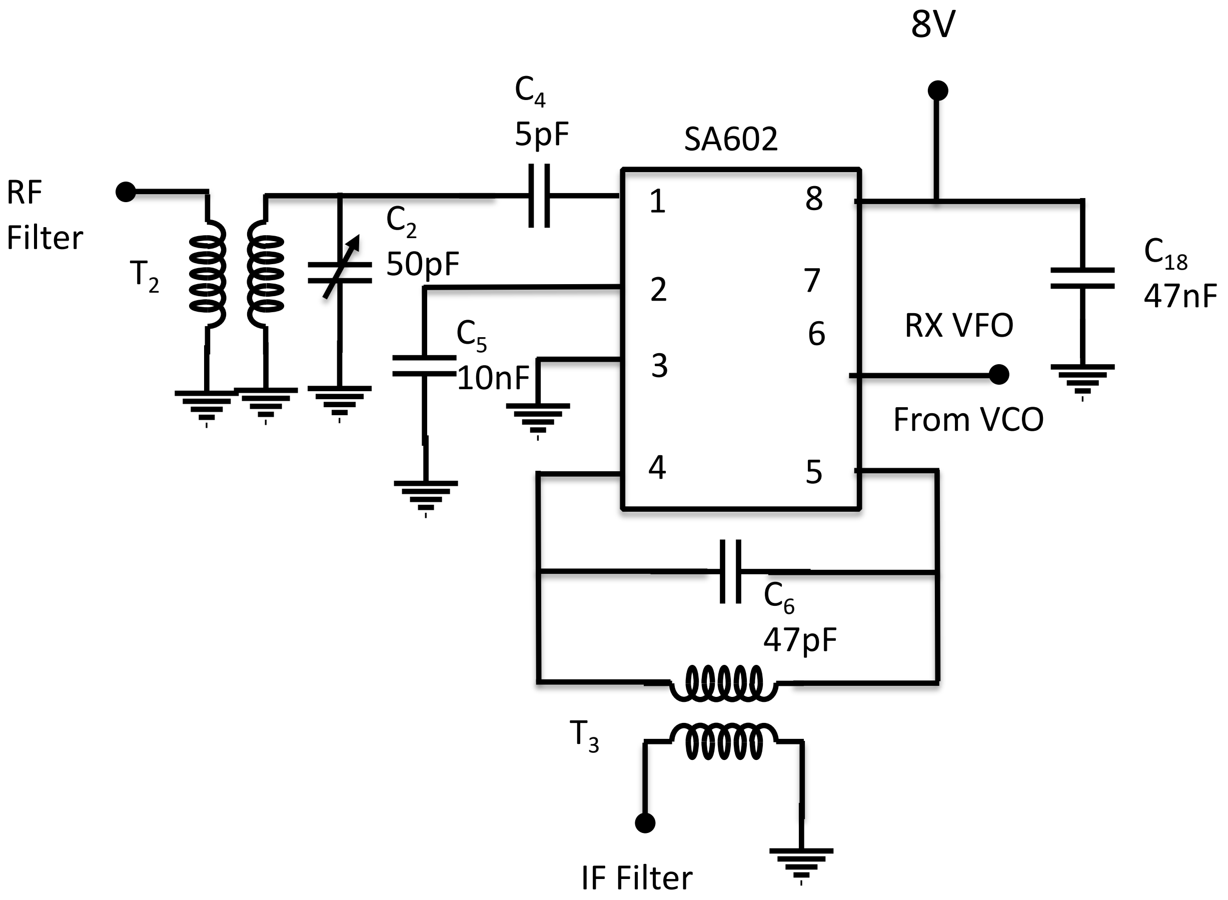
- x

Mixers

- x

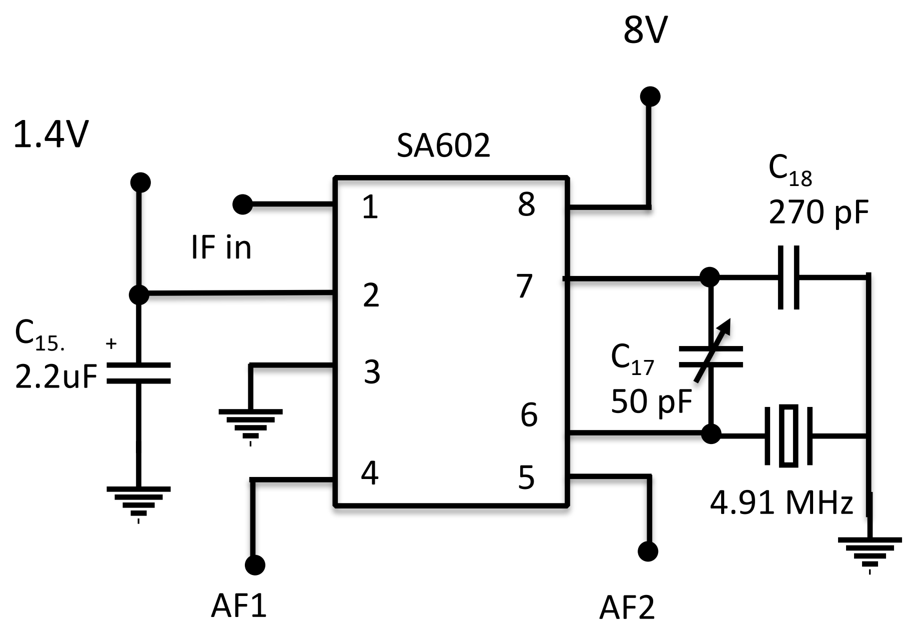
Exercise 28: Norcal RF Mixer

1. Measure conversion gain of the Mixer.
2. How much attenuation is provided by pot?
3. By how many dB is the image response surpressed



Exercise 29: Norcal Product Detector

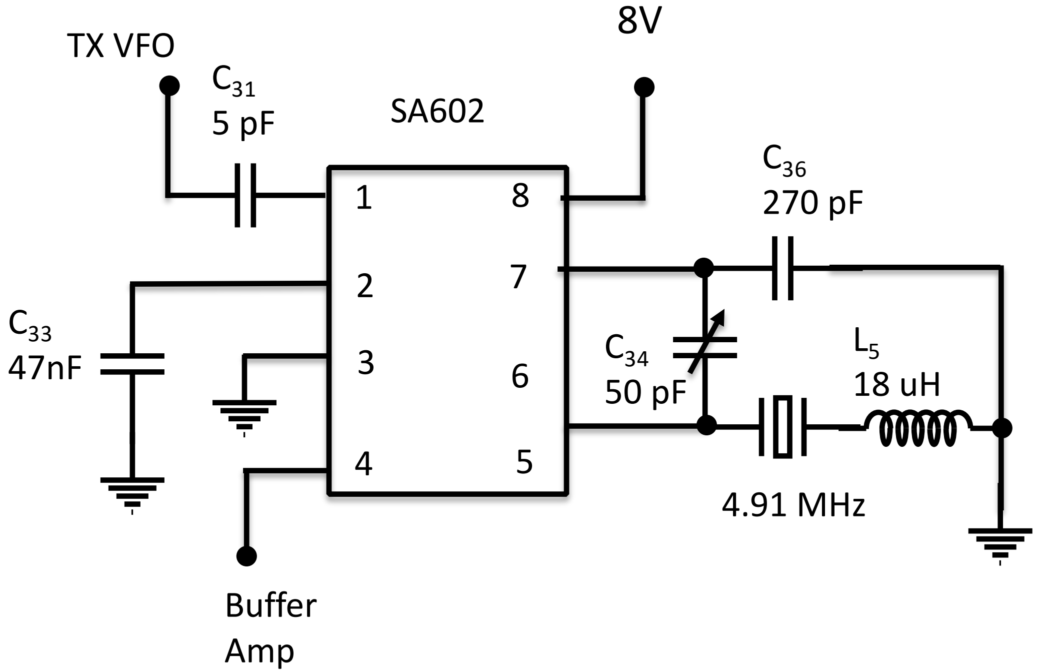
1. Adjust C17 for minimum oscillation frequency and recor d it
2. Calculate the minimum oscillation frequency you'd expe ct
3. Measure the temperature coefficient for the BFO
4. Measure the gain through the receiver from the antenna through the product detector
5. Find the f5 spur calculate the expected f3
6. By how much is the if spur surpressed



- 620 Hz output through AF1 and AF2

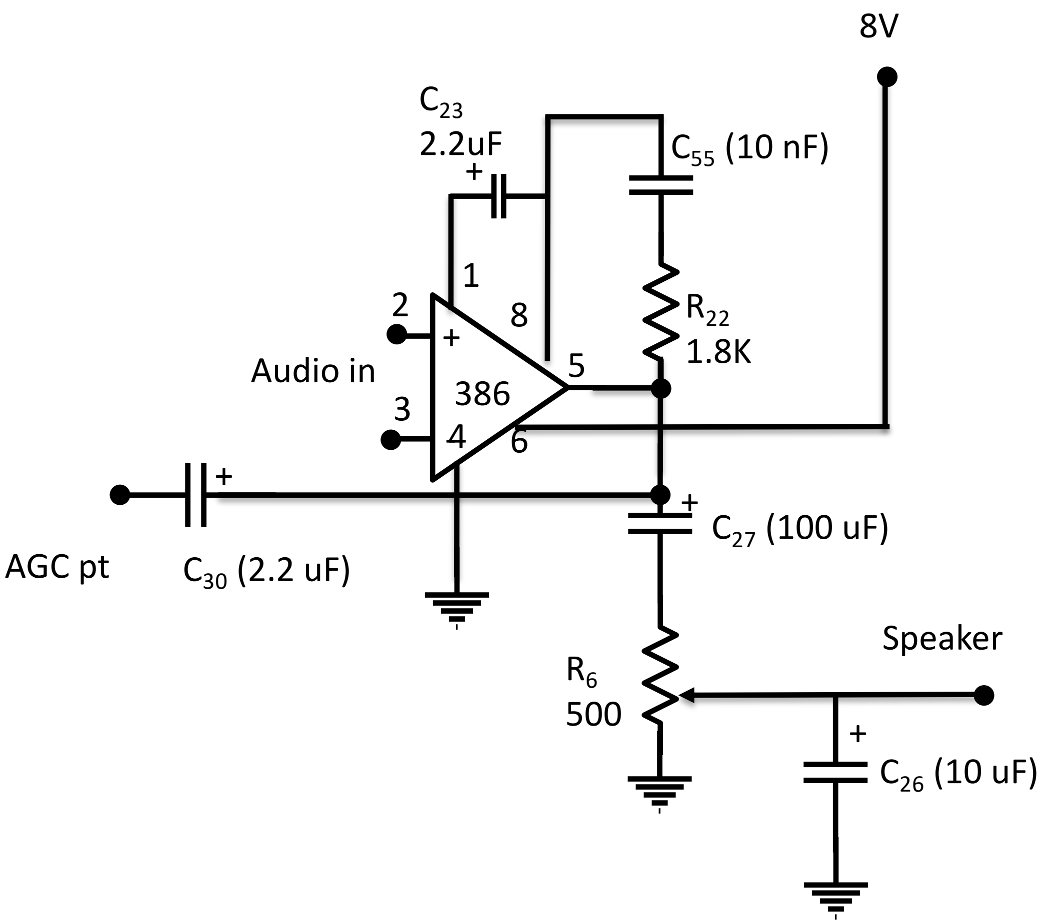
Exercise 30: Norcal transmit mixer and oscillator

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

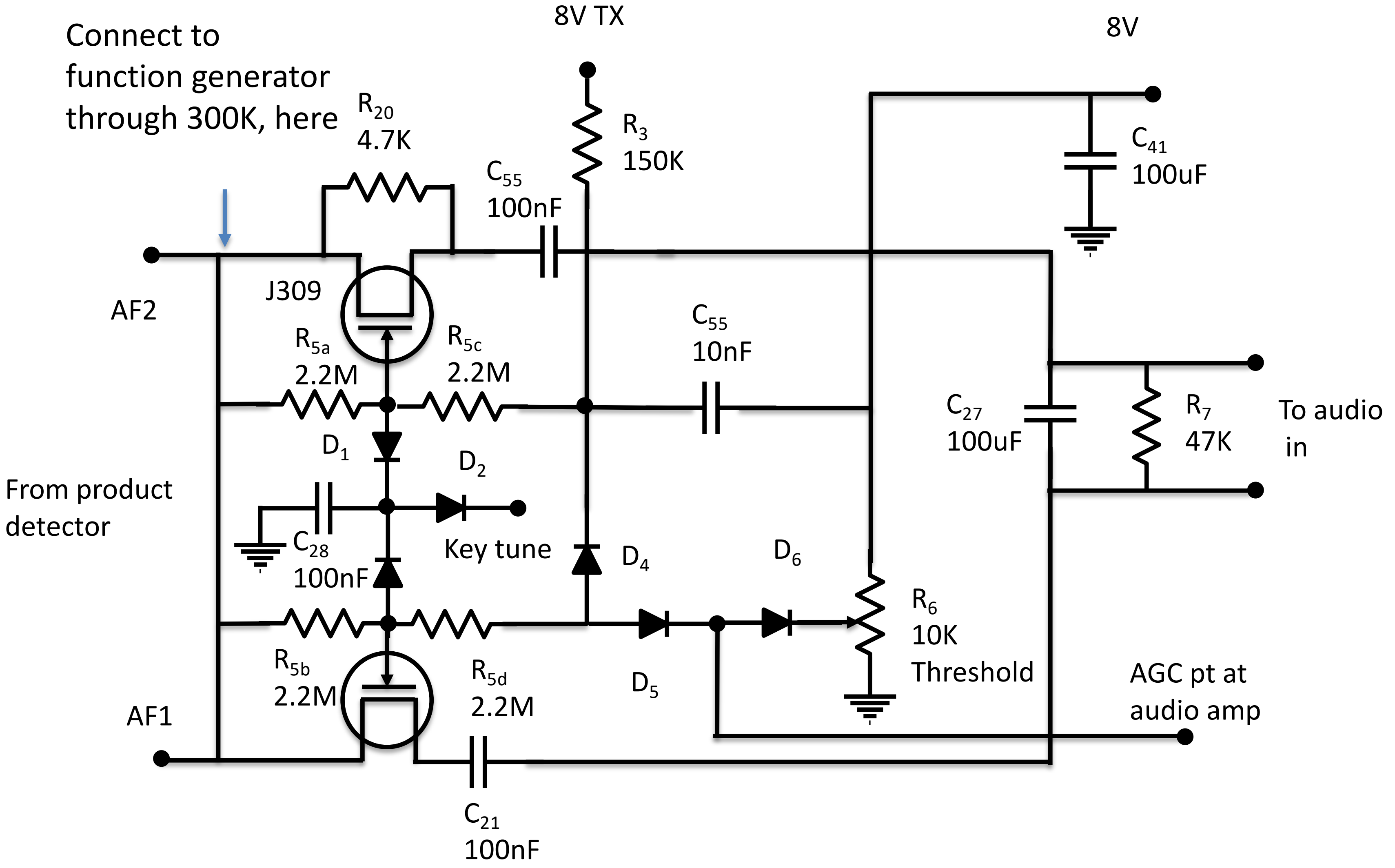


Exercise 31: Norcal Audio Amp

1. Calculate input V_i assuming very high input impedance
2. Measure the voltage gain Gv at high frequency and 3dB rolloff



Exercise 32: Norcal AGC



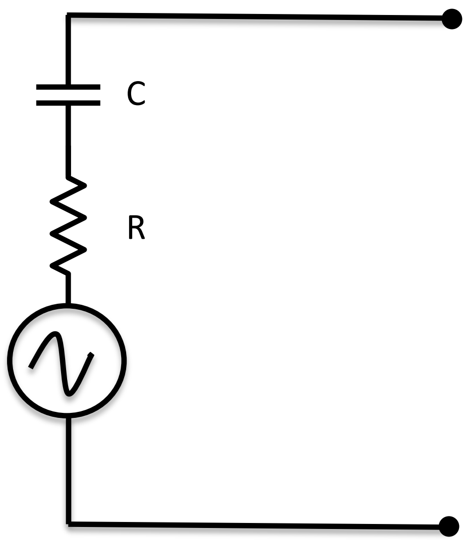
Exercise 33: Alignment

- 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: $S = Re\left(\frac{E_x \overline{H_y}}{2}\right) = \frac{(|E_x|)^2}{2\eta_0}$
- $\eta_0 = \frac{E_x}{H_y} = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377\Omega$
- 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



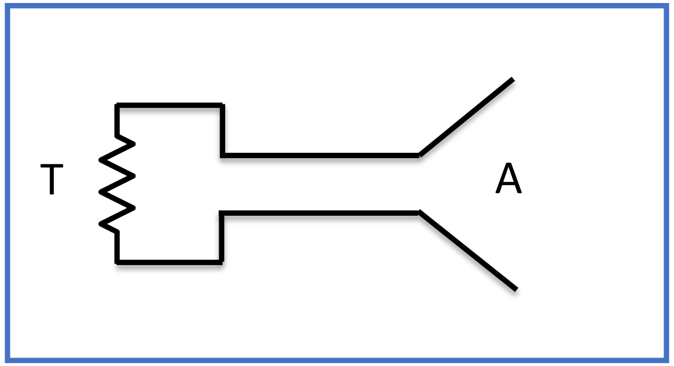
Antennas and propagation

- 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

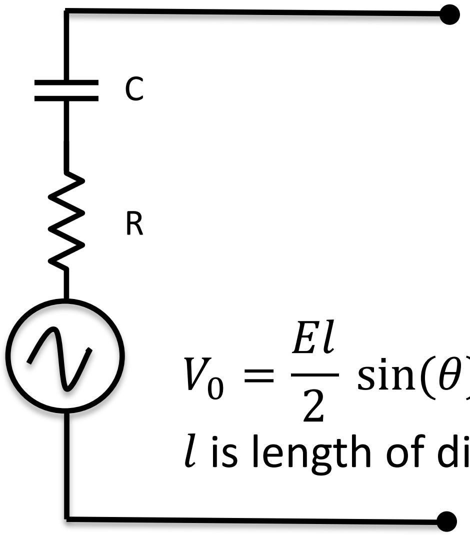


Reciprocity and dipole

- 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, $G = 1,\ A = 150m^2$, for $r = 2000 \, m, P_r = 6pW$

Dipole Thevenin equivalent circuit



$$V_0 = \frac{El}{2} \sin(\theta)$$

l is length of dipole

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, $\overline{|V_c|^2} = 8\mathrm{kTR}$

Exercise 35: Intermodulation

1. Find coefficients and frequencies for $[\cos(\omega_1 t) + [\cos(\omega_2 t)]^5$

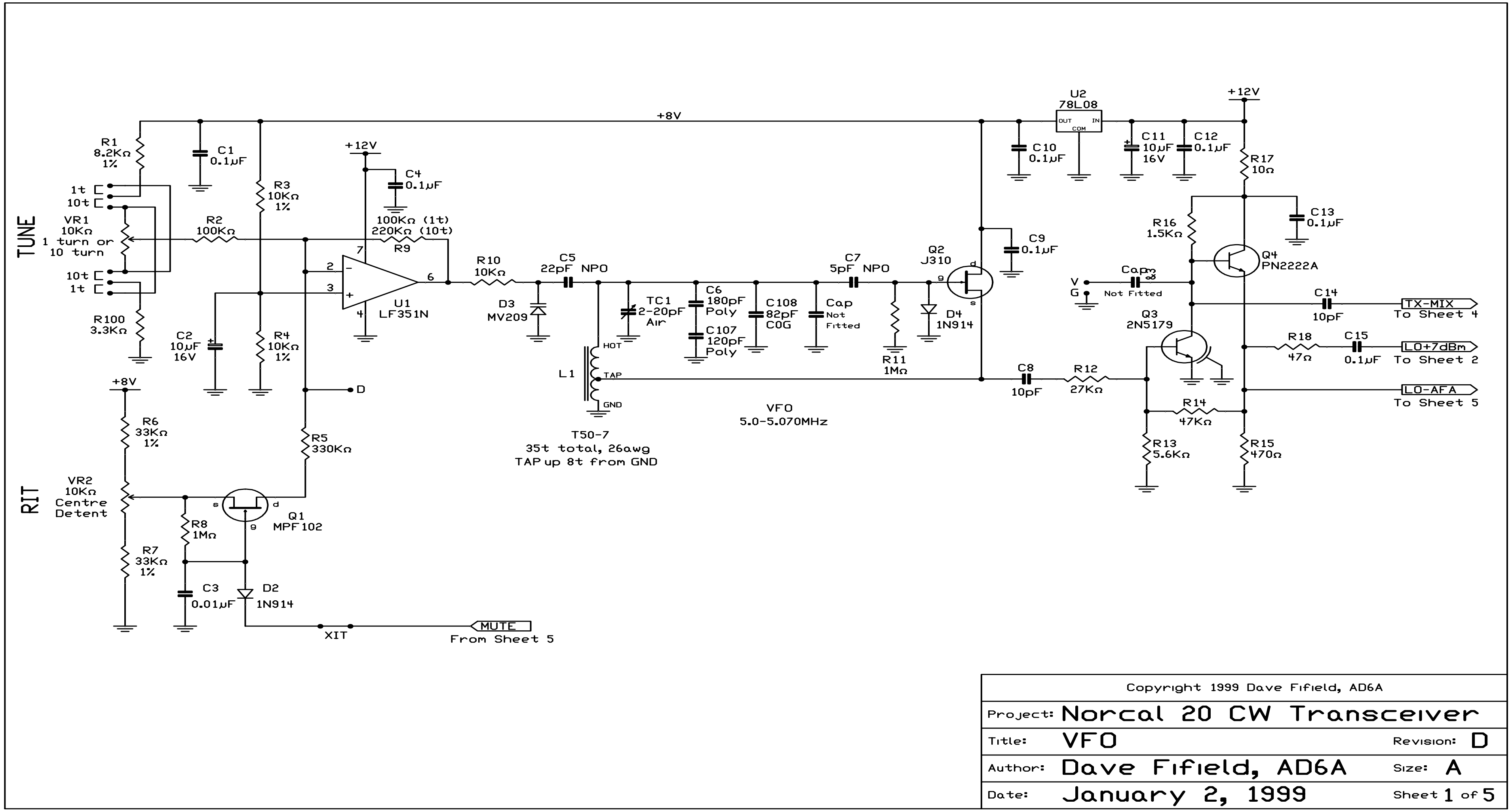
Exercise 37: Antennas

1. Use the relation between gain and effective area to rewrite the Friis transmission formula in terms of gain only. Consider UHF for airplanes. If the frequency makes the quarter length stub antenna have g ain 2, find the maximum possible LOS at 10km height. Required receiver power is –dBm. Find the mi nimum transmission power.
2. Find the inductance to resonate with a 3m whip. Assuming the Q of the coil is 200, find the turns rati o required to give a transceiver a 50 ohm load. What is the radiation efficiency?
3. Repeat 2 with a capacitive end koading, assuming the capacitance doubles.

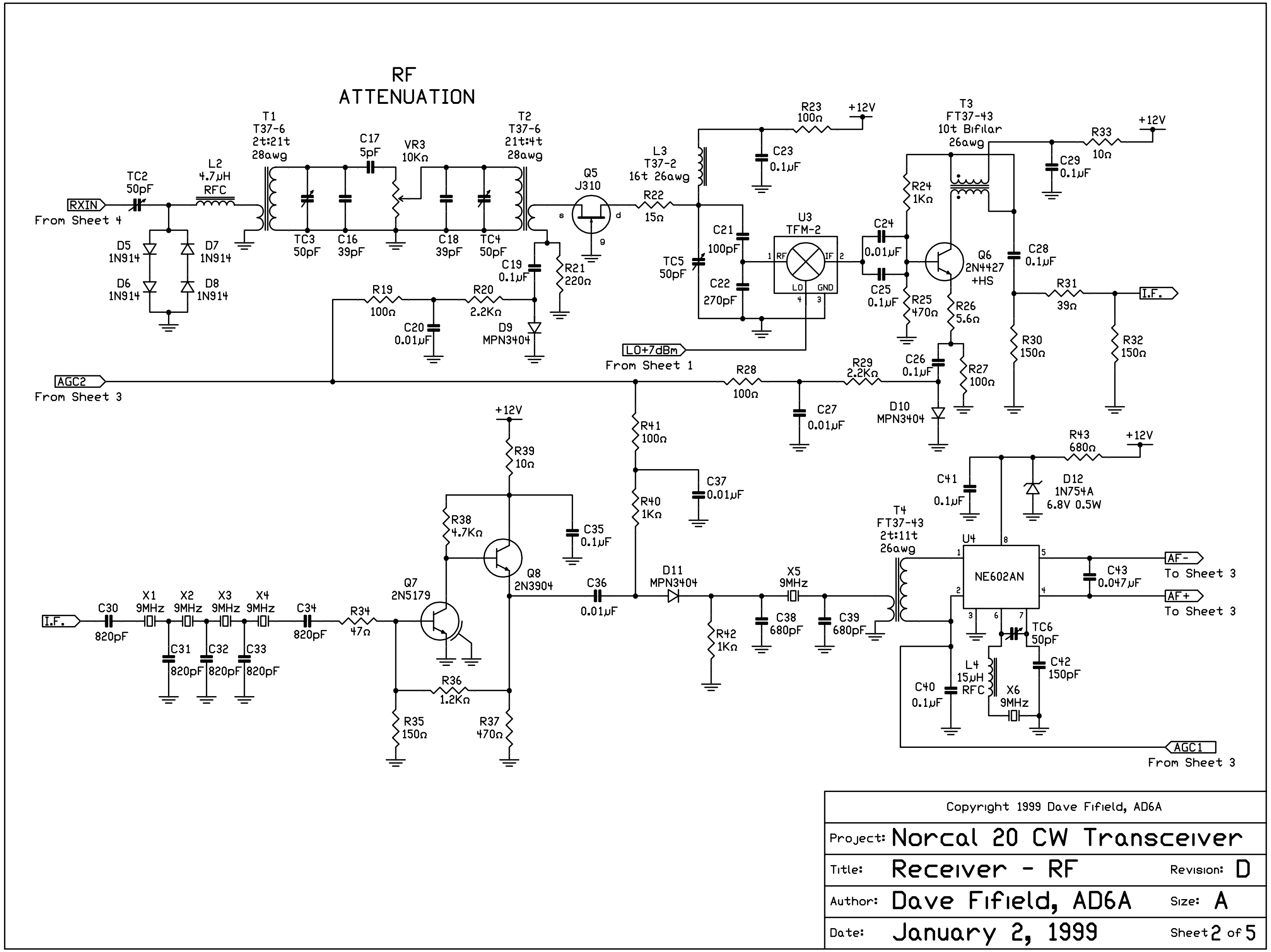
Exercise 38: Propagation

- x

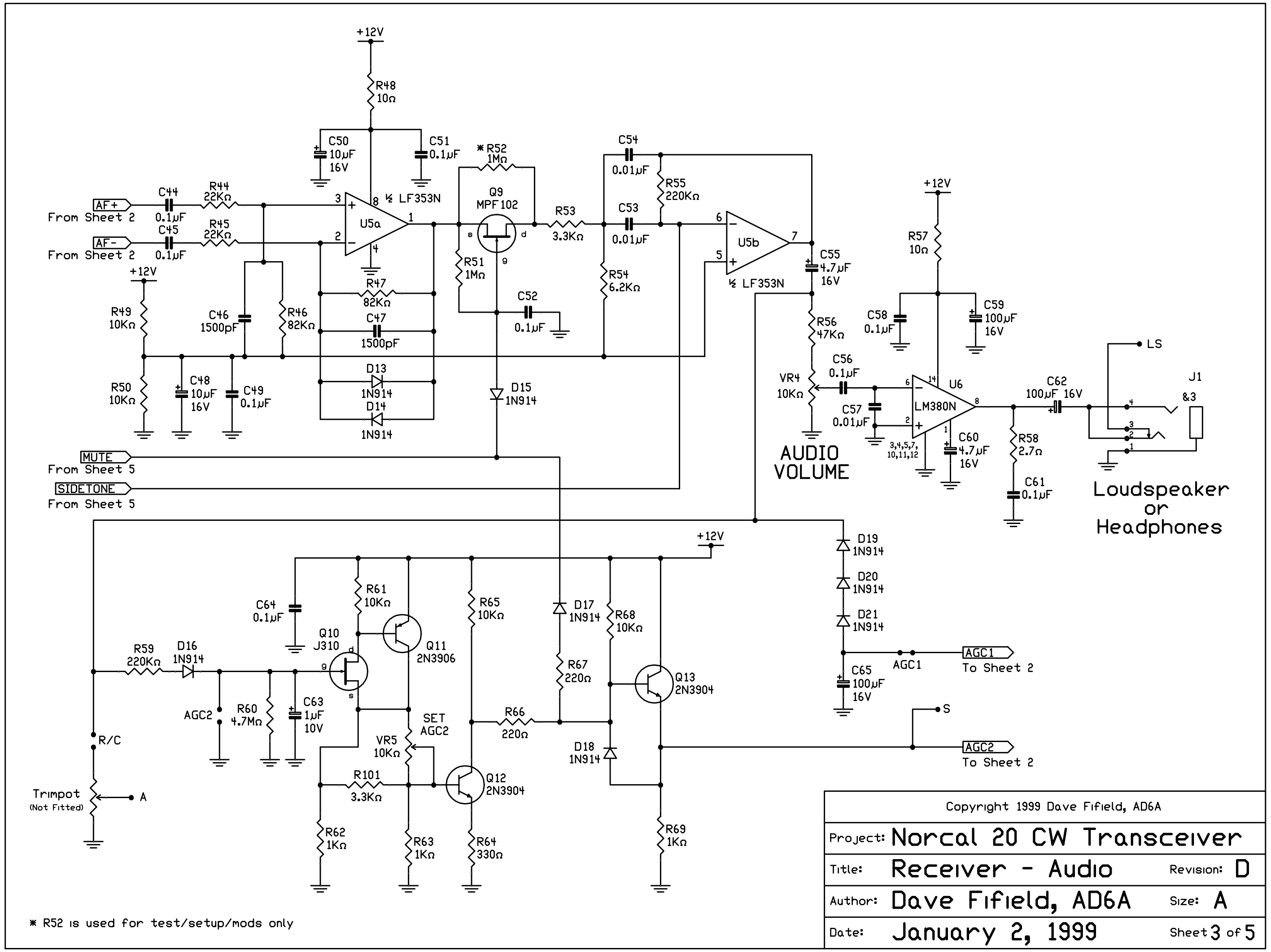
Norcal circuit diagram, 1



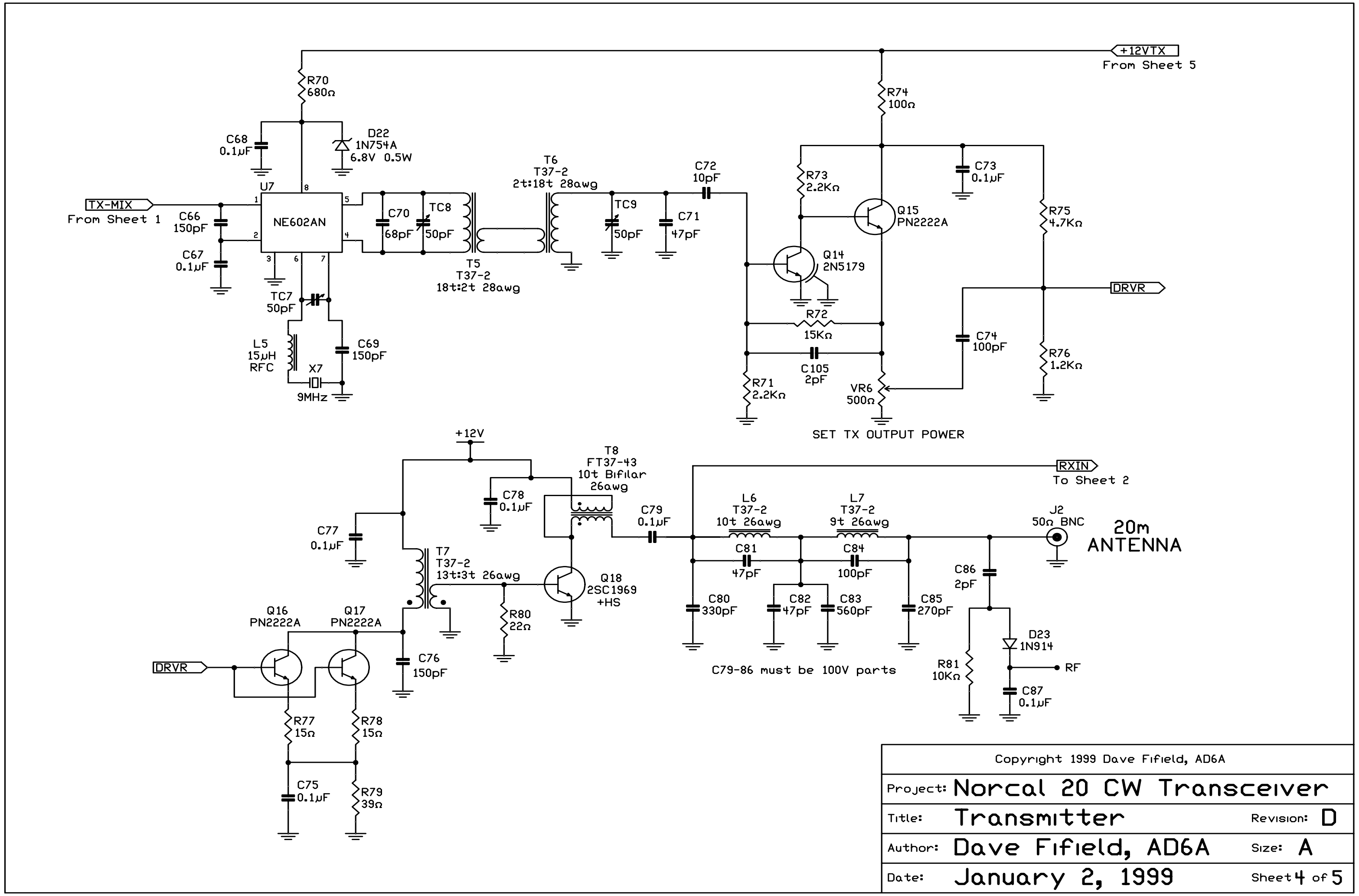
Norcal circuit diagram, 2



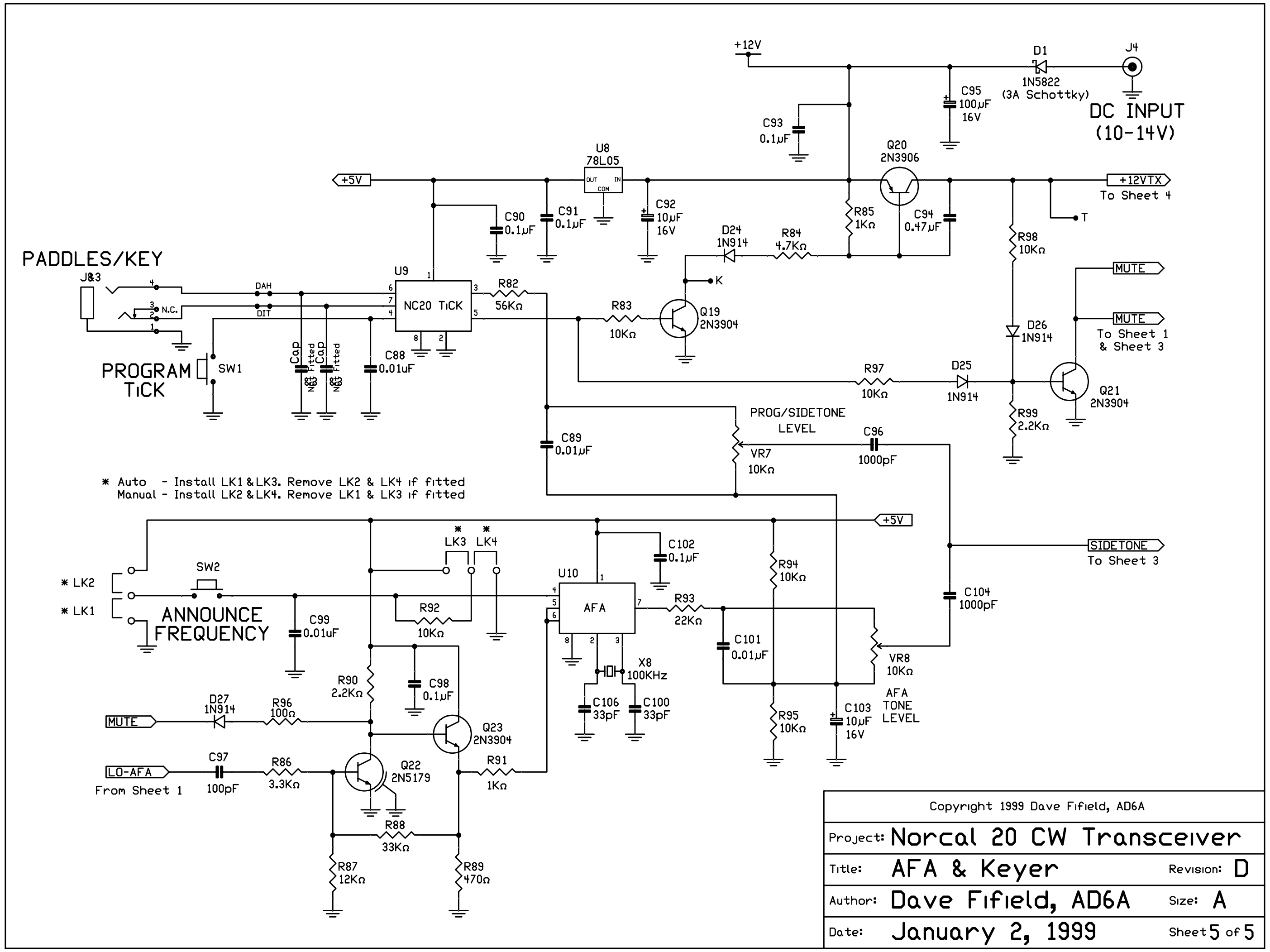
Norcal circuit diagram, 3



Norcal circuit diagram, 4



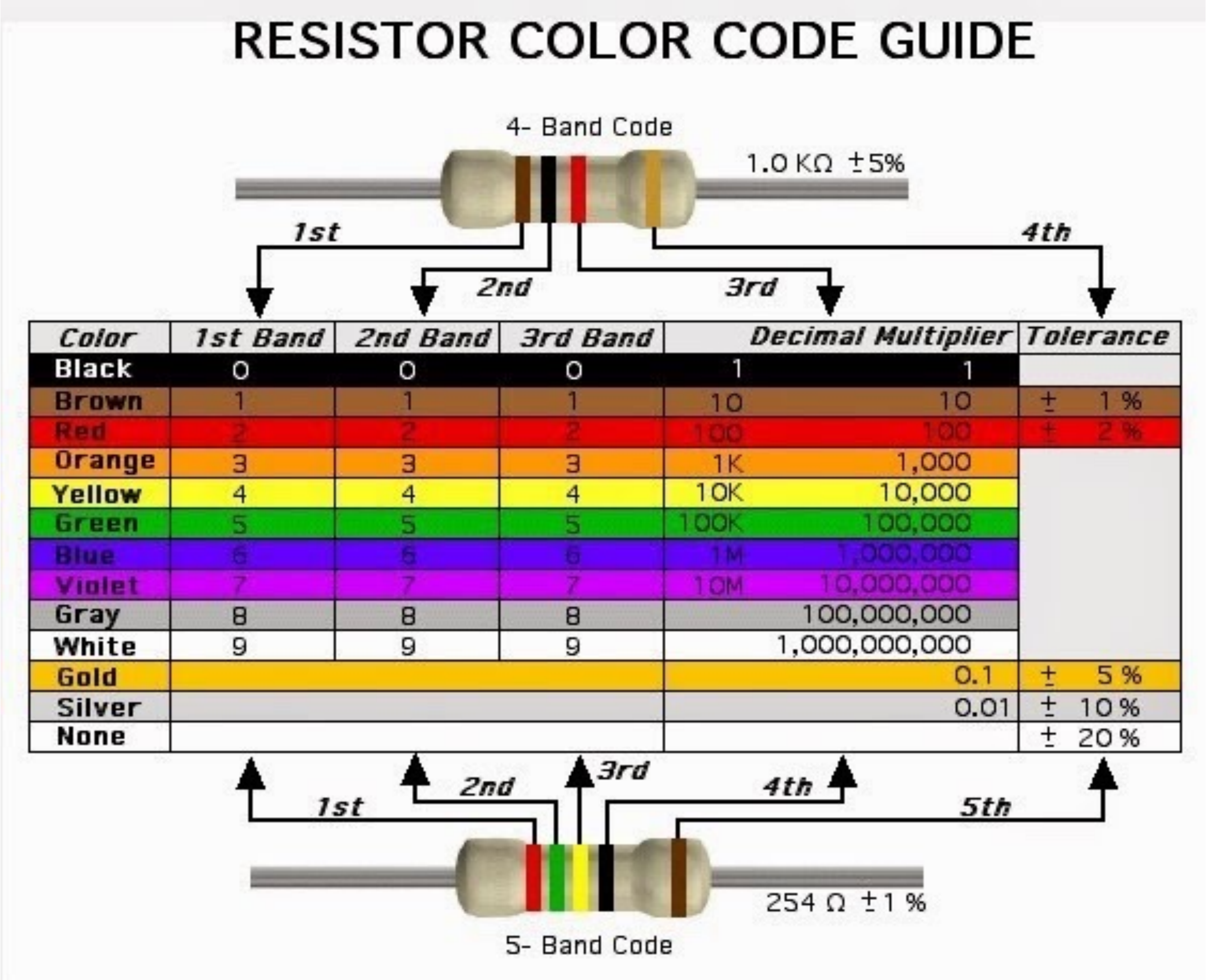
Norcal circuit diagram, 5



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



Color	1st Band	2nd Band	3rd Band	Decimal Multiplier		Tolerance
Black	0	0	0	1	1	
Brown	1	1	1	10	10	± 1 %
Red	2	2	2	100	100	± 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	± 5 %
Silver					0.01	± 10 %
None						± 20 %

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