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)
- $\mathrm{V}(t) = V_p \cos(\omega t), \omega = 2\pi f, \mathrm{I}(t) = I_p \cos(\omega t), \omega = 2\pi f$
- 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

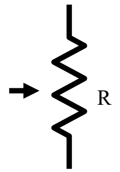
Signals

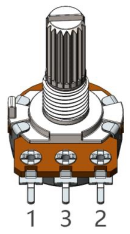
- Gain (G) expressed in decibels: $G = 10\ log_{10}({}^{P_{out}}/_{P_{in}})$
- Mixer:
  - $V(t) = \cos(\omega_1 t)\cos(\omega_2 t) = \frac{1}{2}[\cos(\omega_+ t) + \cos(\omega_- t)]$, $\omega_+ = \omega_1 + \omega_2$, $\omega_- = \omega_1 - \omega_2$
- Modulation

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

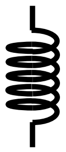

- Resistors
  - Analytic model: $IR = V$
  - Energy dissipated: $E = \int_{t_i}^{t_f} IV\,\mathrm{dt} = \int_{t_i}^{t_f} I^2 R dt$





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

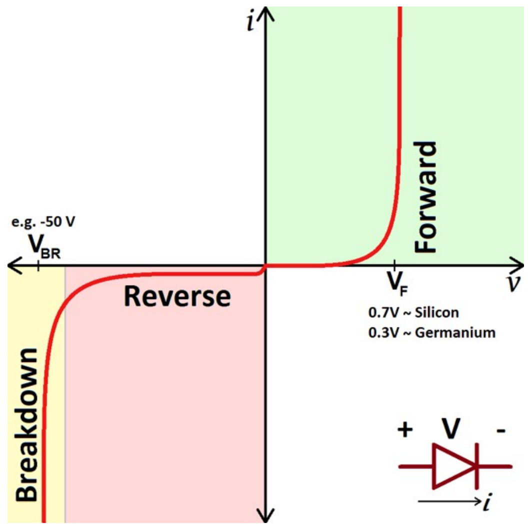
- Inductors
  - Analytic model: $V = L\frac{di}{dt}$
  - Inductor Energy stored: $E = \int_{t_i}^{t_f} IV\,\mathrm{dt} = \int_{t_i}^{t_f} LI\frac{dI}{dt}dt = \frac{1}{2}LI^2$




Credit: Make Electronics

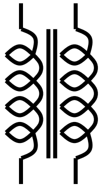
Diodes, transformers

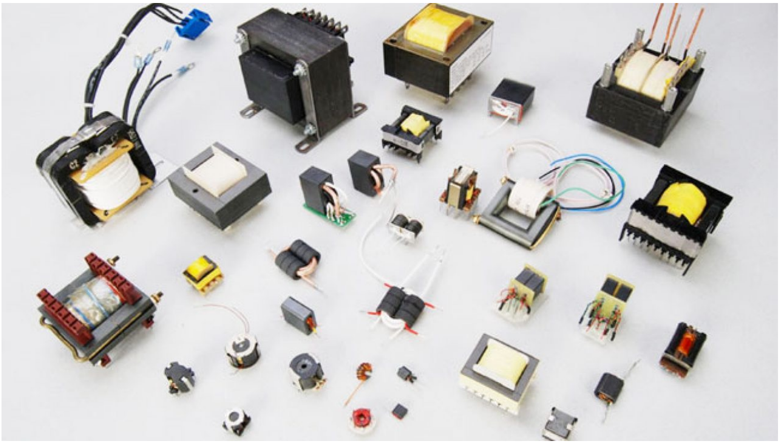
- Diodes
  - Devices that allow current to flow only in one direction
  - Silicon diodes, for example have, essentially infinite resistance if V_{ac}<0, that is if the cathode is at a higher potential than the anode and very low resistance if V_{ac}> .7V.
  - The cathode is usually labelled with a band



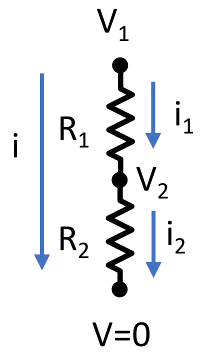
Credit: Make Electronics

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

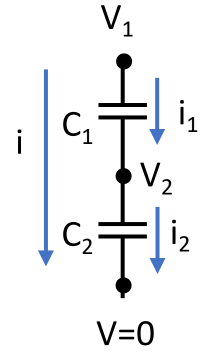




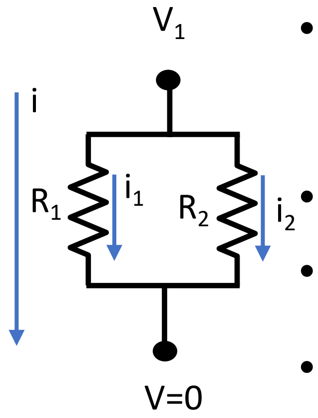
Simple circuit analysis with Kirchhoff



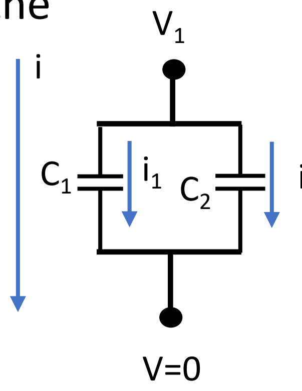
- R_{eq} is the equivalent resistance, replacing the top left circuit with a single resistance.
- By Kirchhoff's node rule, $i_1 = i_2 = i$, so
- $\frac{V_1 - V_2}{R_1} = \frac{V_2}{R_2} = \frac{V_1}{R_{eq}}$ thus $\frac{R_1}{R_{eq}} V_1 = V_1 - V_2$ and $\frac{R_2}{R_{eq}} V_1 = V_2$. Adding, we get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



- 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. $\frac{C_1 C_2}{C_1 + C_2} = C_{eq}$

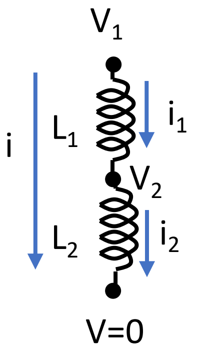


- Again let R_{eq} is the equivalent resistance, replacing the bottom left circuit with a single resistance.
- By Kirchhoff's node rule, $i_1 + i_2 = i$, so
- $\frac{V_1}{R_1} + \frac{V_1}{R_2} = \frac{V_1}{R_{eq}}$.
- Solving, we get. $\frac{R_1 R_2}{R_1 + R_2} = R_{eq}$

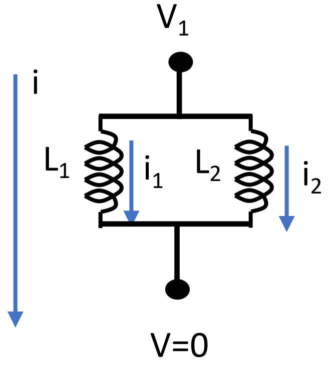


- C_{eq} is the equivalent capacitance, replacing the bottom right circuit with a single capacitor.
- By Kirchhoff's node rule, $i_1 + i_2 = i$
- $C_{eq} \frac{dV_1}{dt} = C_1 \frac{dV_1}{dt} + C_2 \frac{dV_1}{dt}$, so
- $C_{eq} = C_1 + C_2$

Simple circuit analysis with Kirchhoff

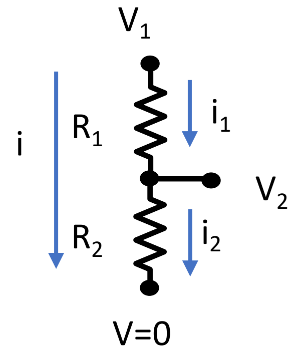


- Let L_{eq} be the equivalent inductance, replacing the top left circuit with a single inductor.
- By Kirchhoff's node rule, $i_1 = i_2 = i, \text{so}$
- $L_{eq}\frac{di}{dt} = V_1, L_1\frac{di_1}{dt} = V_1 - V_2, L_1\frac{di_2}{dt} = V_2$
- $V_1 = L_{eq}\frac{di}{dt} = L_1\frac{di}{dt} + L_2\frac{di}{dt}$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

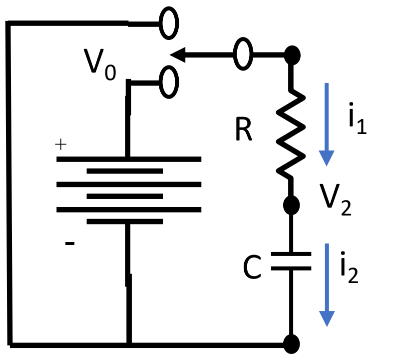


- Let L_{eq} be the equivalent inductance, replacing the bottom left circuit with a $\frac{di}{dt} = \frac{V_1}{L_{eq}}, \frac{di_1}{dt} = \frac{V_1}{L_1}, \frac{di_2}{dt} = \frac{V_1}{L_2},$
- single inductor.
- By Kirchhoff's node rule, $i_1 + i_2 = i, \text{so}$
- $\frac{V_1}{L_{eq}} = \frac{V_1}{L_1}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

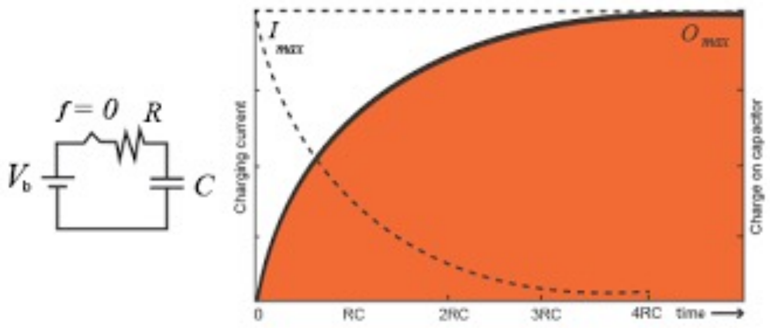
- The circuit on the right, is useful and is called a *voltage divider*.
- $i = i_1 = i_2$ so $\frac{V_1 - V_2}{R_1} = \frac{V_2}{R_2}, V_1 - V_2 = \frac{R_1}{R_2}V_2$
- Thus, $V_1 = (1 + \frac{R_1}{R_2})V_2$ and so
- $V_2 = \frac{R_2}{R_1 + R_2}V_1$

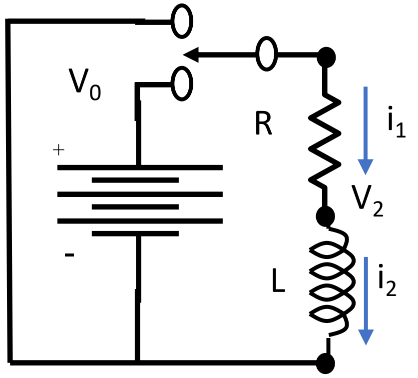


Simple circuit analysis with Kirchhoff

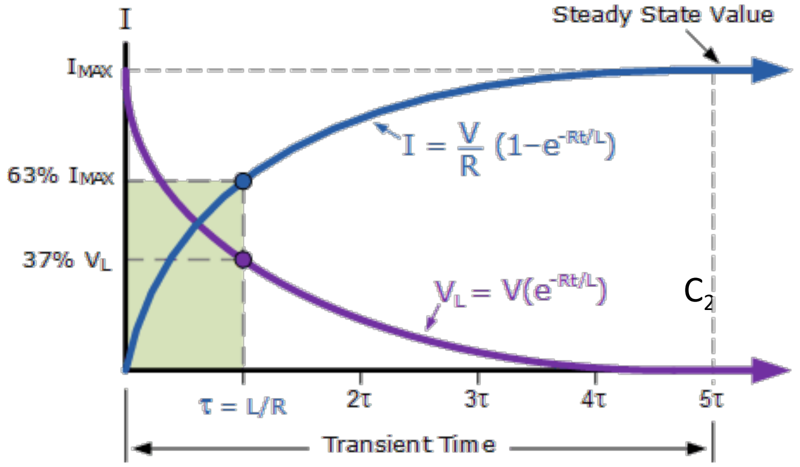


- RC behavior: charging
  - $V_0 - V_2 = i_1 R = V_R, i_1 = \frac{V_R}{R}$
  - $i_2 = C\frac{dV_2}{dt}, V_C = V_2$
  - $i_1 = i_2, V_C = V_0 - V_R$
  - $\frac{V_R}{R} = C\frac{dV_C}{dt}$, $\mathrm{RC}\frac{dV_C}{dt} = V_0 - V_C$, or $\mathrm{RC}\frac{dV_C}{dt} + V_C = V_0$
  - Solution is $V_C = V_0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





- 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 $\mathrm{L}\frac{d}{dt}\frac{V_0 - V_L}{R} = V_L$
  - $\frac{L}{R}\frac{d\,V_L}{dt} + V_L = 0$
  - Solution is $V_L = V_0 e^{-\frac{Rt}{L}}$



Phasors

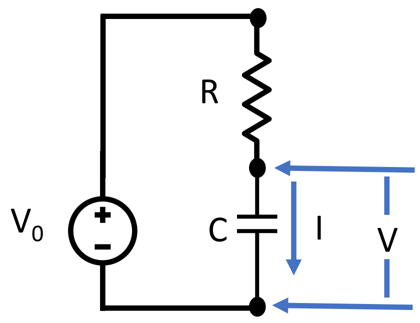
- $V(t) = RI(t)$
- $V(t) = L\dot{I}(t)$
- $I(t) = C\dot{V}(t)$
- Suppose $V(t) = Acos(\omega t + \theta)$ and $\mathrm{I}(t) = Bcos(\omega t + \phi)$. If $\phi > \theta$, we say the current leads the voltage.
- $V(t) = Re(e^{j(\omega t+\theta)})$, and $\mathrm{I}(t) = Re(e^{j(\omega t+\phi)})$
- Now 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 with Kirchhoff 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 $Z = R + \frac{1}{j\omega C}$

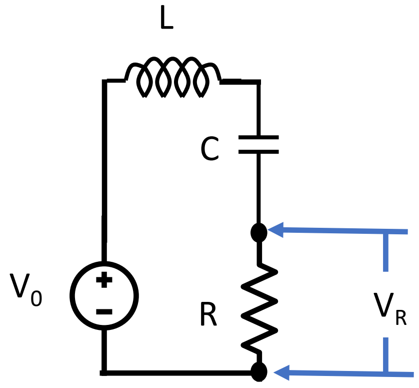
Phasors, impedance and power

- 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.

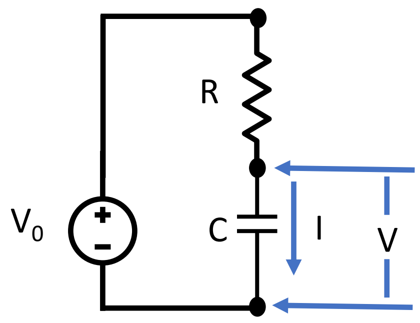


Q and phasors

- 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 $V = \frac{I}{j\omega C} = \frac{V_0}{1+j\omega RC}$
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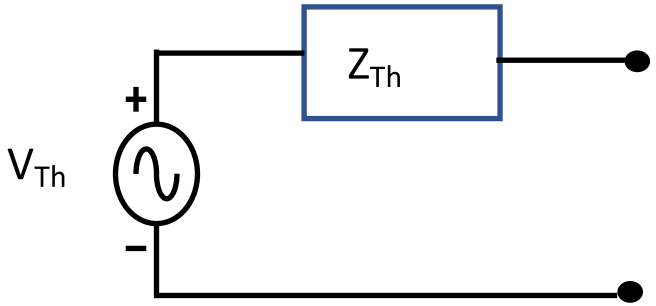
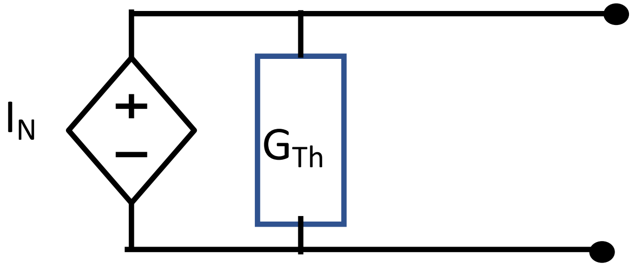
- The average power is $P_a = Re(P) = Re(\frac{V\bar{I}}{2})$. We define the reactive power as $P_r = Im(P)$.
- $P_r = \omega(E_L - E_C)$, where $E_L$and E_C are respectively, the energy stored in the inductor and capacitor respectively.

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



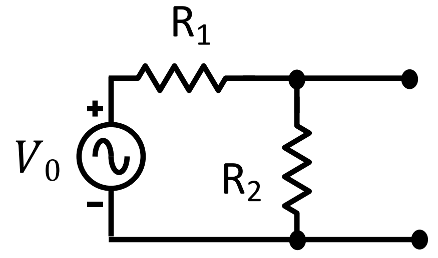
- Norton: Any combination of linear sources and passive elements terminating in two terminals is equivalent to a pure current source in parallel with an conductance



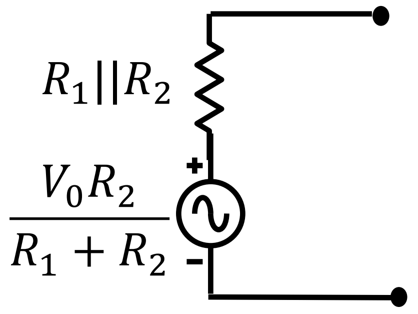
- Similar theorems for two terminal input and output devices (with transfer function)

Thevenin and Norton

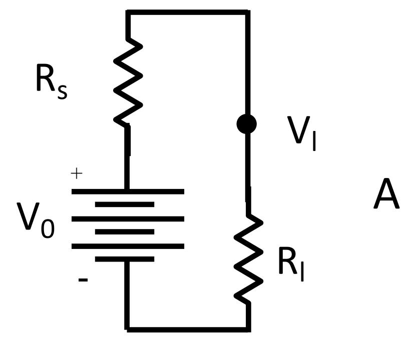
- We can use lookback resistance to calculate the Thevenin equivalent resistance and ideal source.
- To find the lookback resistance, short the source and apply the usual laws.
  - Here $R_s = R_1||R_2$
- To find the new ideal source, notice R_1 and R_2 form a voltage divider.
  - The new source voltage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



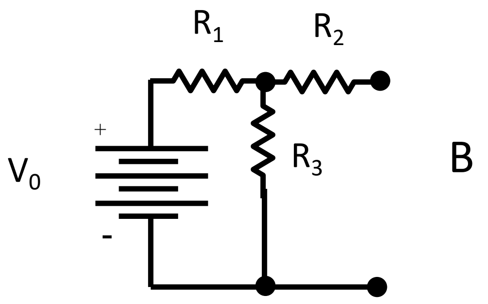
Is equivalent to



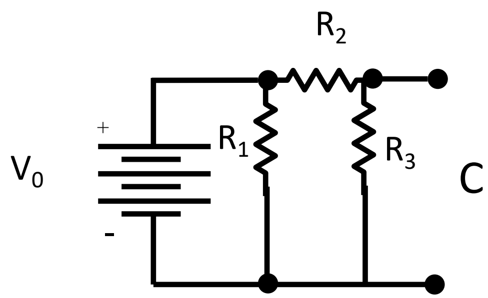
Exercise 1: Resistors



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

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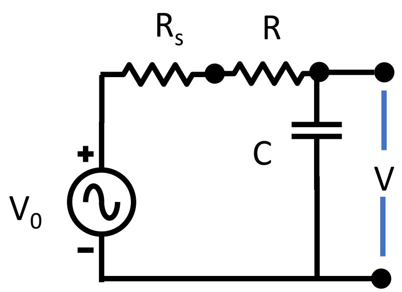
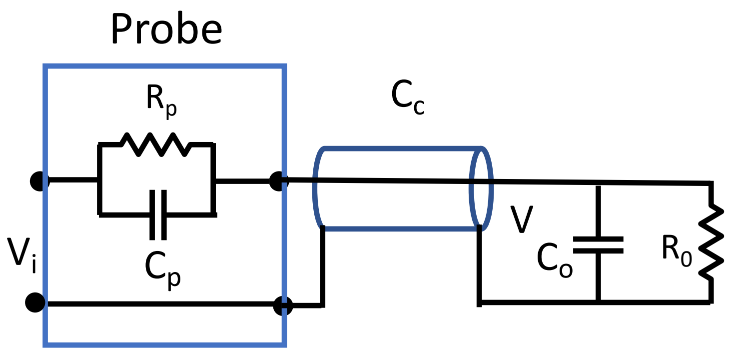
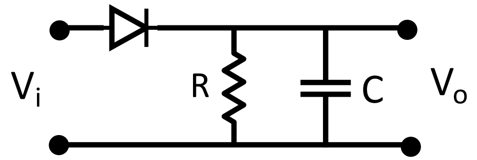
Exercise 3: Capacitors



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 $C = 10\ nF$.
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.
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.

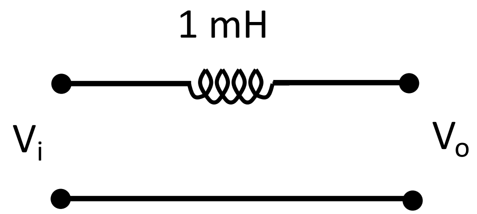


Exercise 4: Diode detectors



- 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, $R = 3k\Omega$, $C = 10\ nF$
- 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

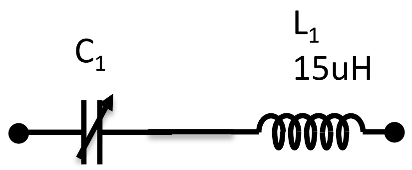
Exercise 6: Diodes and snubbers

x

Exercise 7: Parallel to Series conversion

- Use 50Ω scope probe

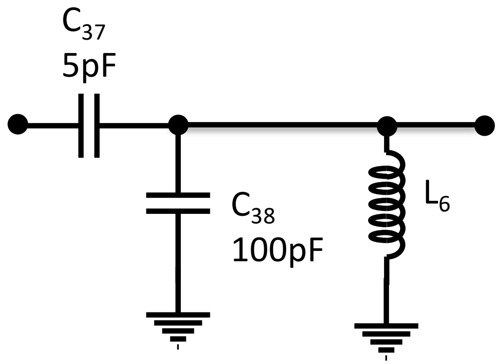
Exercise 8: Series resonance



- Use 50Ω scope probe

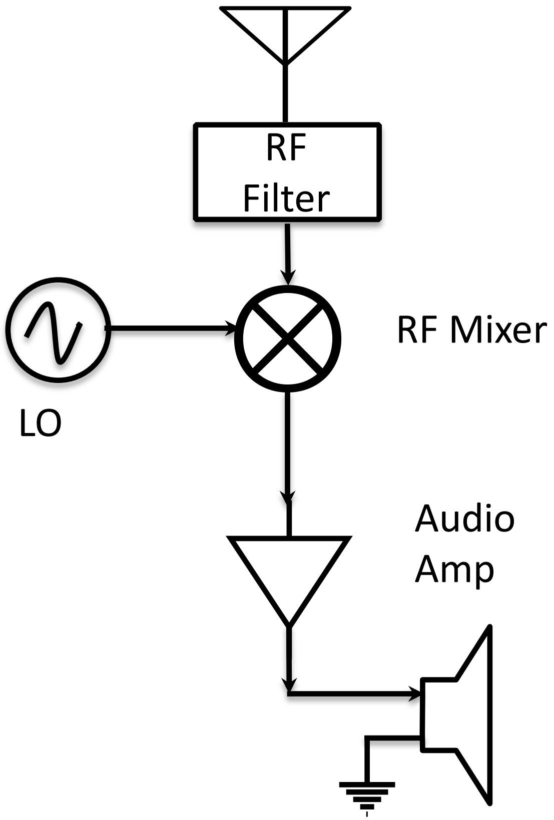
Exercise 9: Parallel resonance

- Use 50Ω scope probe



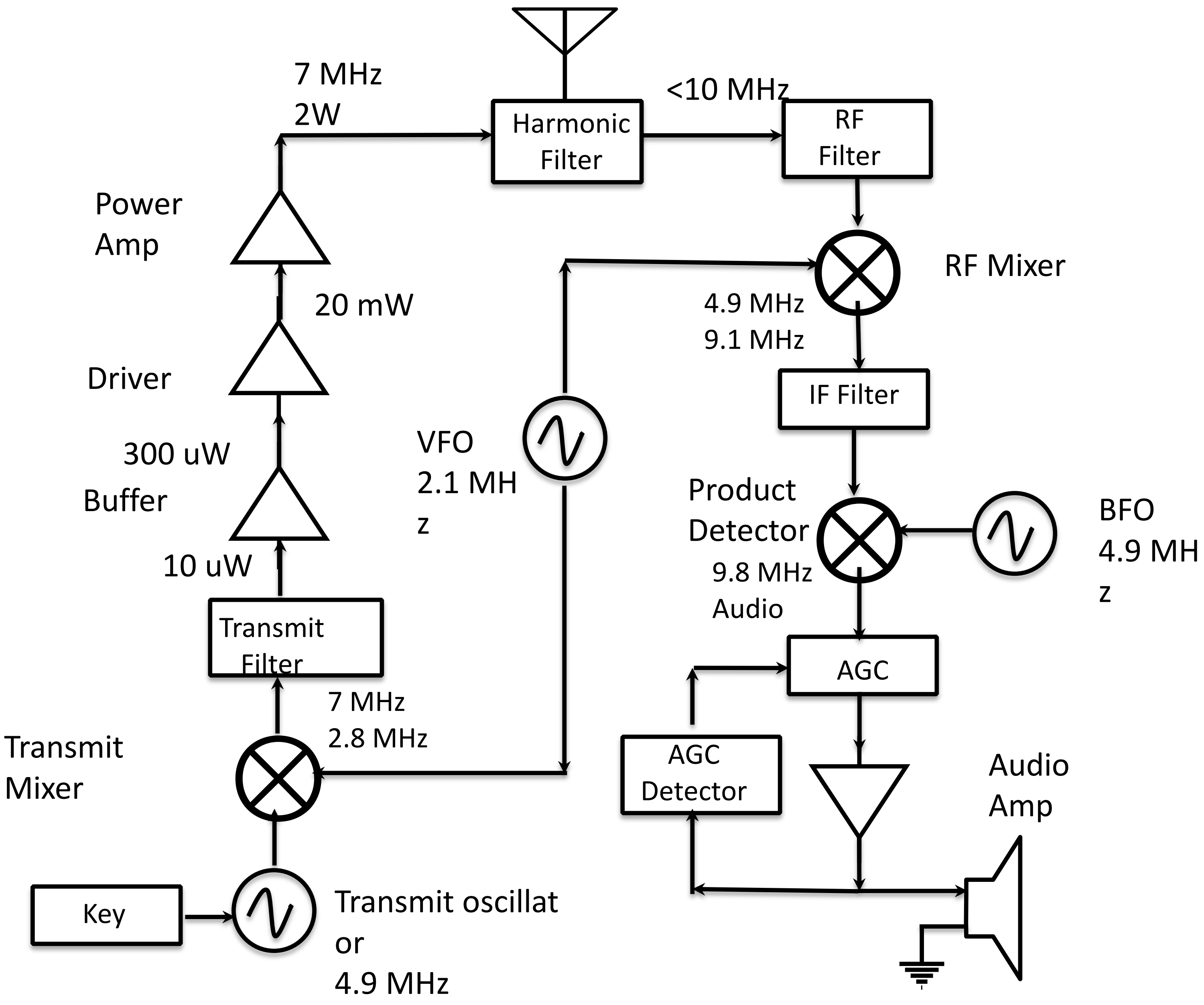
Direct conversion and superhet receivers

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

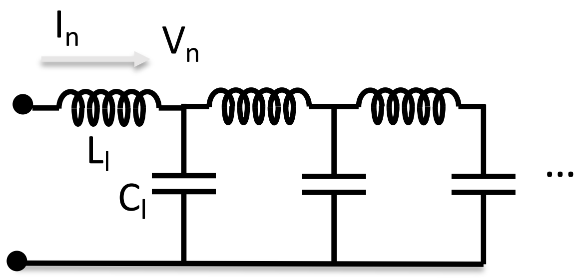


Direct conversion

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
VFO
2.1 MH
z
300 uW
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



Power

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

Lookback resistance is $R_s = Z_0$

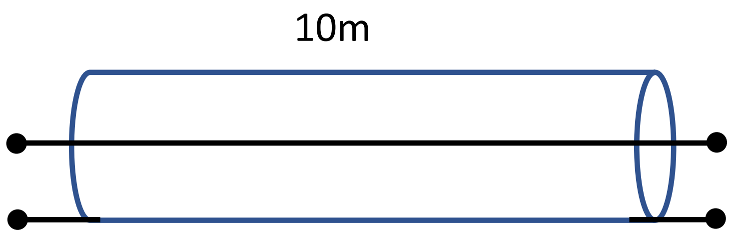
$P_+ = \frac{{V_+}^2}{2Z_0} = \frac{{V_0}^2}{8Z_0}$, This is the total available power

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

x

Exercise 10: Coax

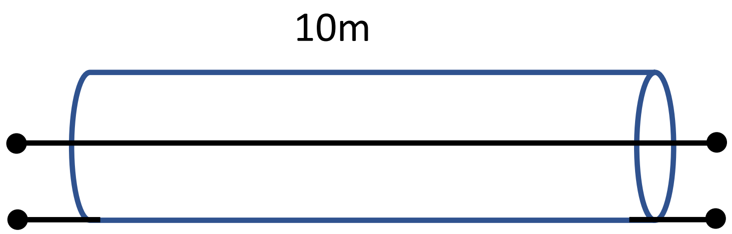


- Use 50Ω scope probe

Exercise 11: Waves

- Use 50Ω scope probe

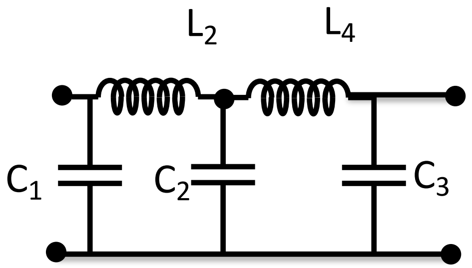
Exercise 12: Resonance



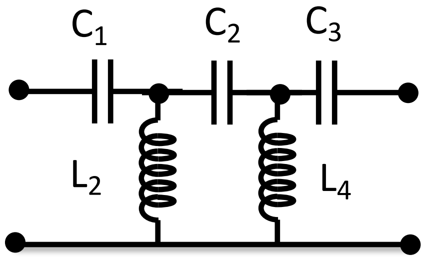
- Use 50Ω scope probe

Filters

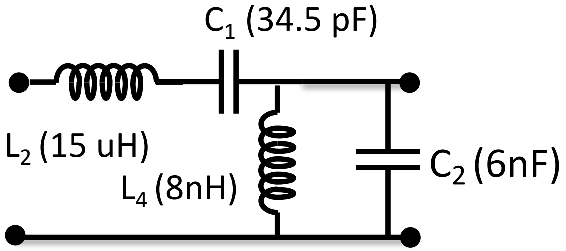
Low pass

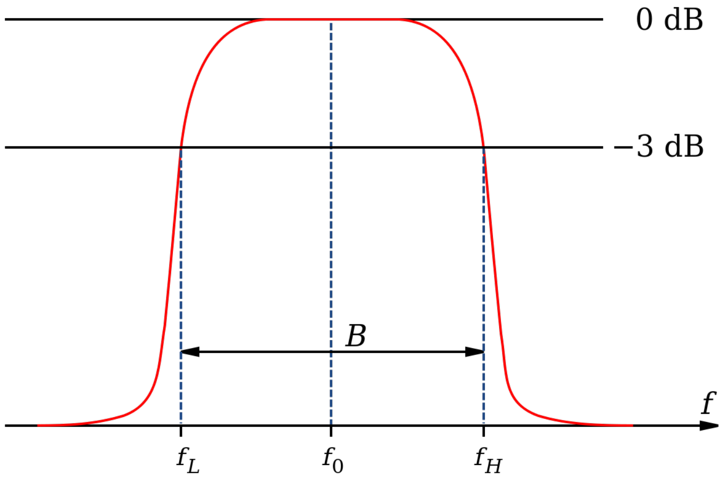


High pass

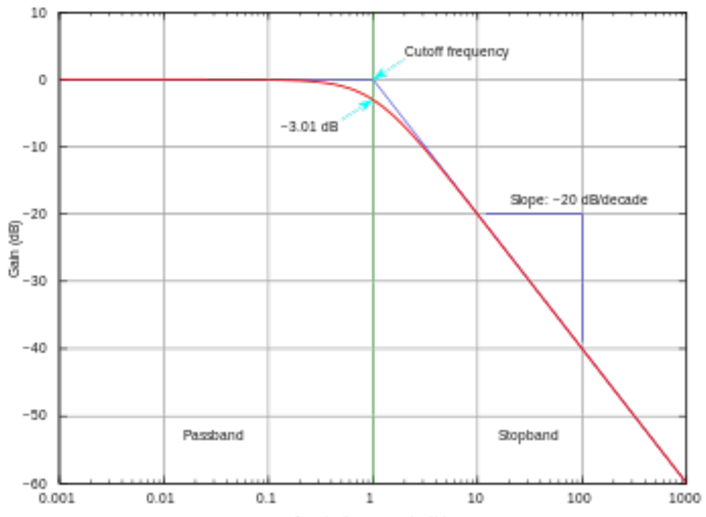


7 MHz bandpass



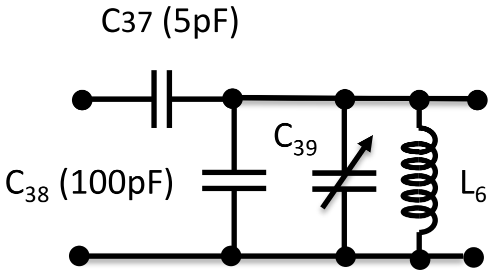


Bandpass - WIkipedia



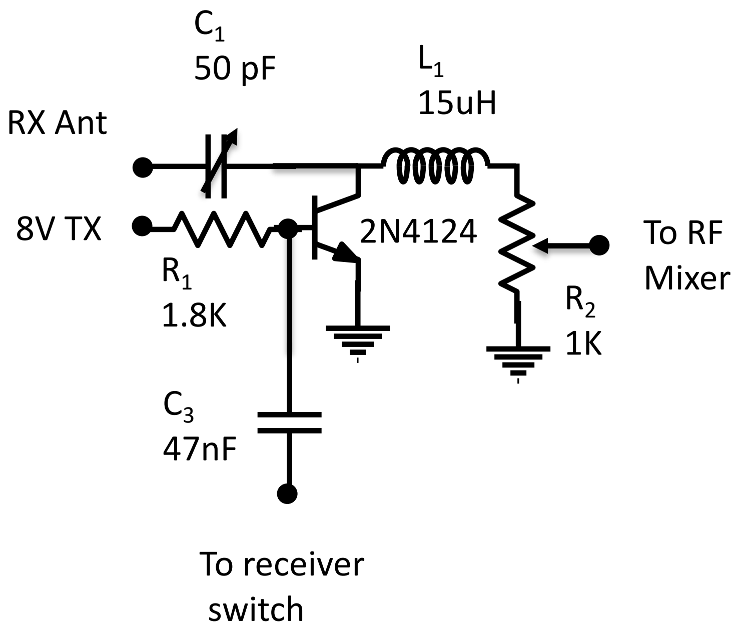
Bandpass - WIkipedia

Norcal transmit bandpass filter

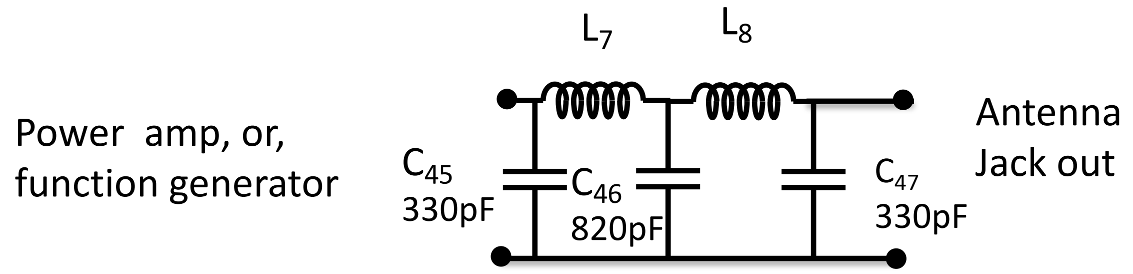


- $C_{39} = 50pF,$
- L_6 is 36 turns #28 on T37-2 which has $A_l = 4\frac{nH}{turn^2}$
- $L_6 = A_l \cdot 36^2 = 3.1\mu H$
- $Z_2 = -\frac{j}{(C_{38}+C_{39})\omega_o}$, $Z_3 = jL_6\omega_o, Z_1 = \frac{j}{C_{37}\omega_o}$
- $Z_{2,3-eq} = \frac{jL_6\omega_0}{L_6(C_{38}+C_{39})\omega_0{}^2-1}$
- Resonance 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 compon ents and must be measured
- Note that $Z_{2,3-eq}$ is small for the other modulation prod uct

Norcal RF Filter

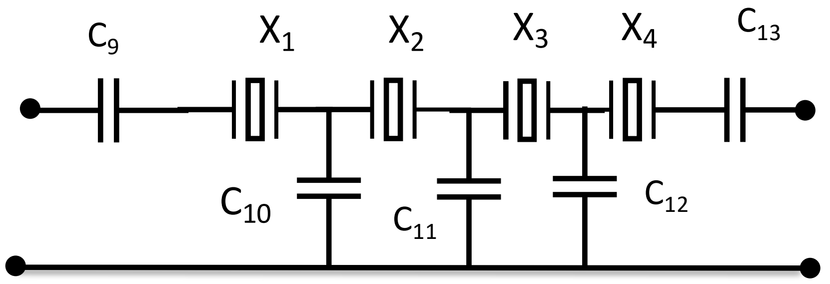


Exercise 13: Norcal Harmonic Filter

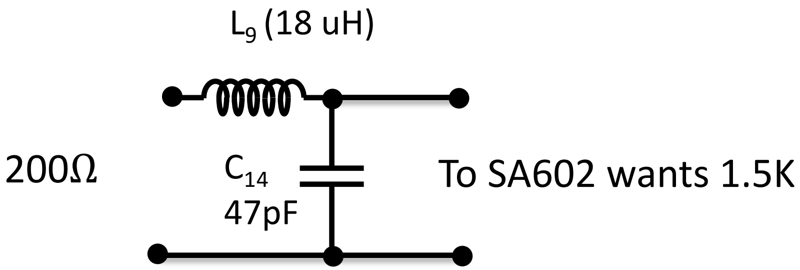


- L_7, L_8 use T37-2 core, 18 turns, 1.3uH
- Compare loss at 7MHz and 14MHz

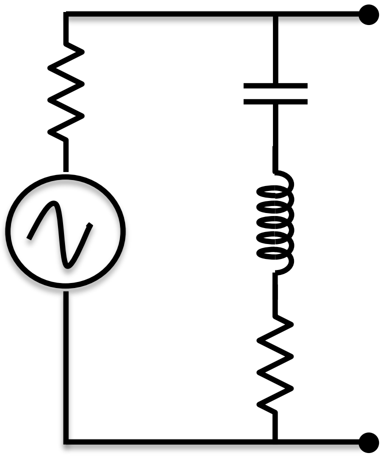
Exercise 14: Norcal IF Cohn Filter



- 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



Matching network



Equivalent circuit for crystal and generator

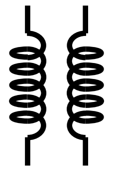
Transformers

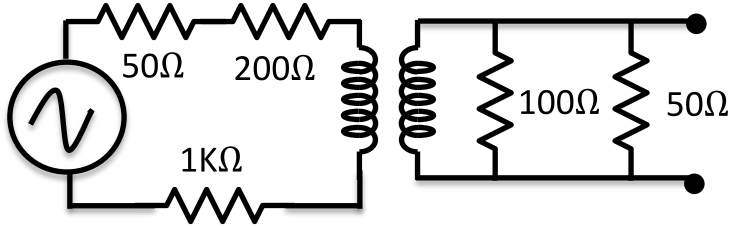
- x

Norcal matching transformers

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

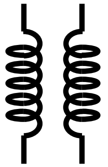
T_1, 14:4

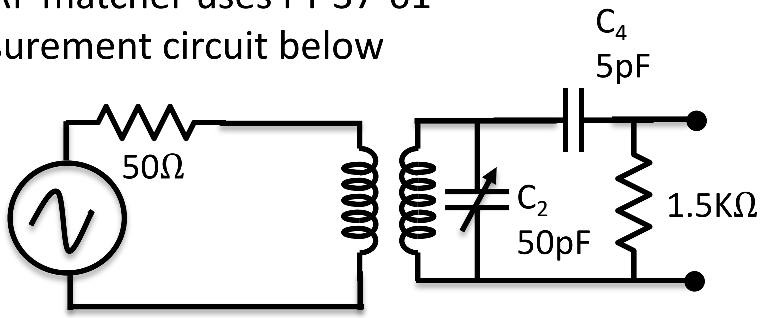




- T_2 is RF matcher uses FT 37-61
- Measurement circuit below

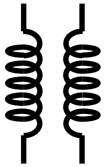
T_2, 1:20

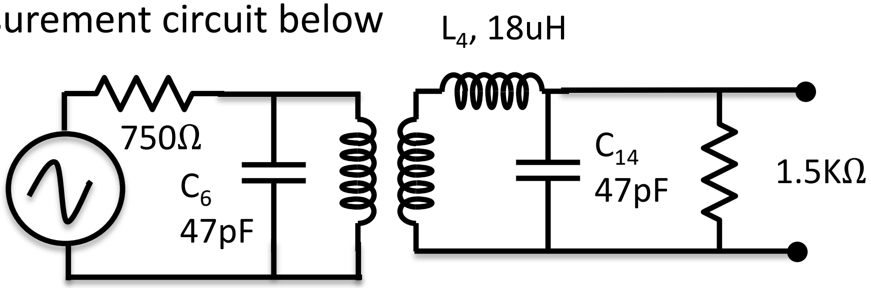




T_3, 23:6

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

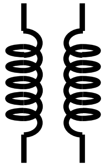




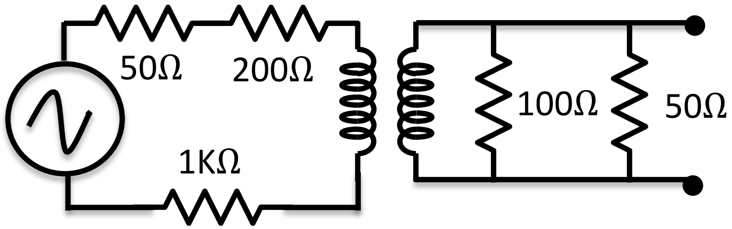
Exercise 15: Norcal Driver Transformers

- x

T$_1$, 14:4



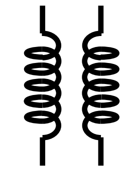
- T$_1$ is driver matcher uses FT 37-43
- Measurement circuit below

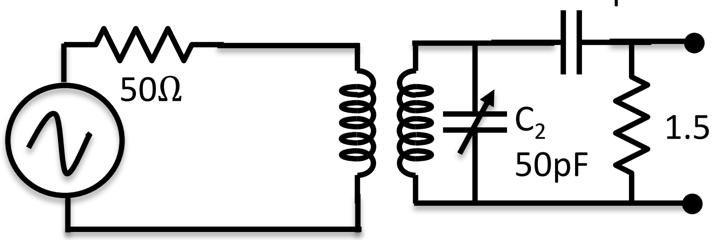


Exercise 16: Norcal Tuned Transformers

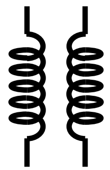
- x

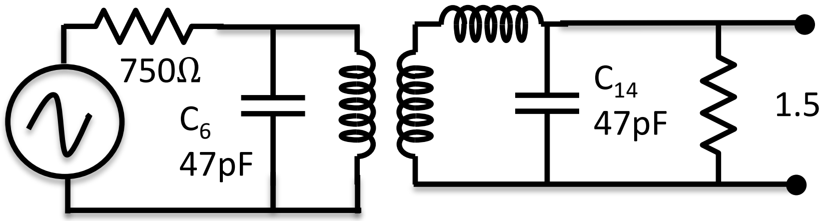
- T_2 is RF matcher uses FT 37-61
- Measurement circuit below





- T_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

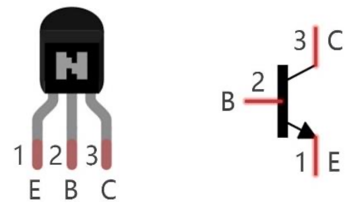
- x

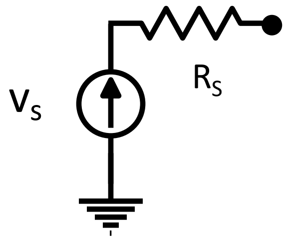
Exercise 18: Acoustic Standing Wave

- x

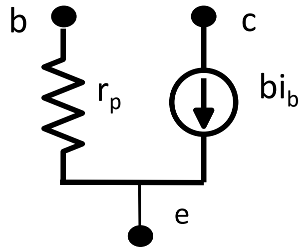
Bipolar Transistors

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





Bipolar source model

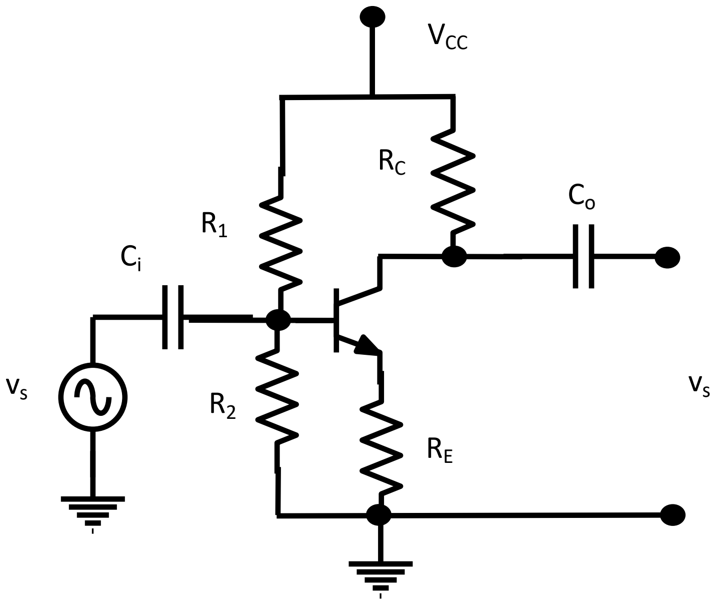


Bipolar equivalent circuit

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



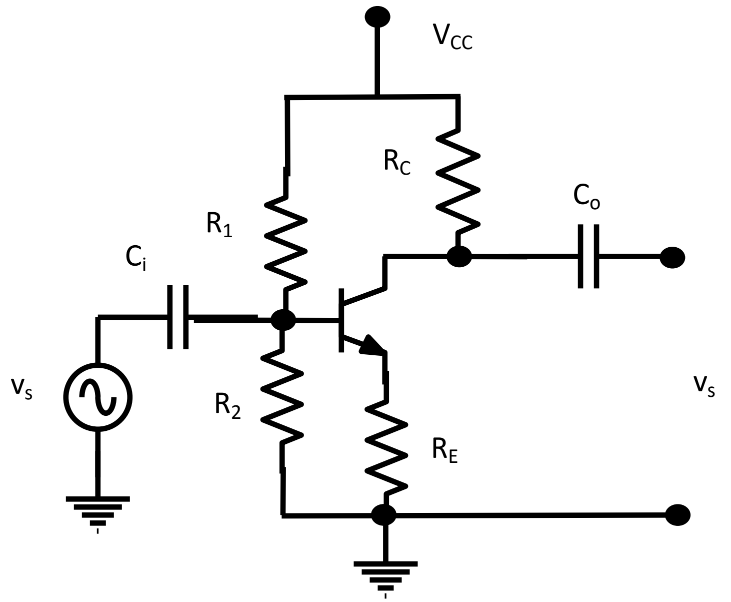
Common emitter amp

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

Credit: Ward, Hands on Radio.

BJT common emitter amplifier continued



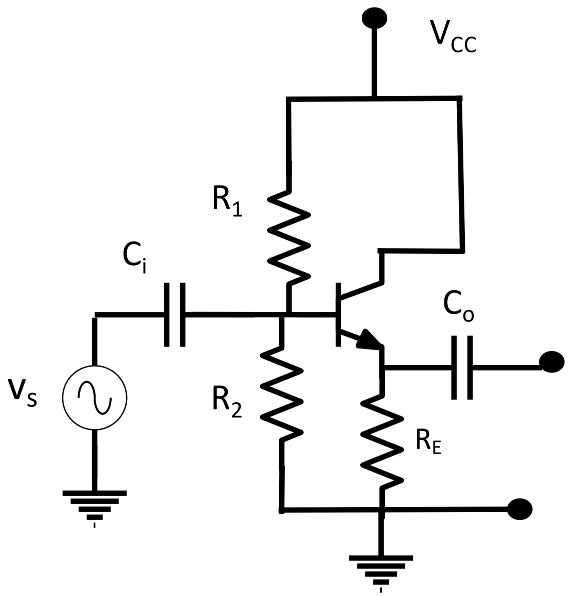
Common emitter amp

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_cR_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.

Credit: Ward, Hands on Radio.

BJT common collector amplifier



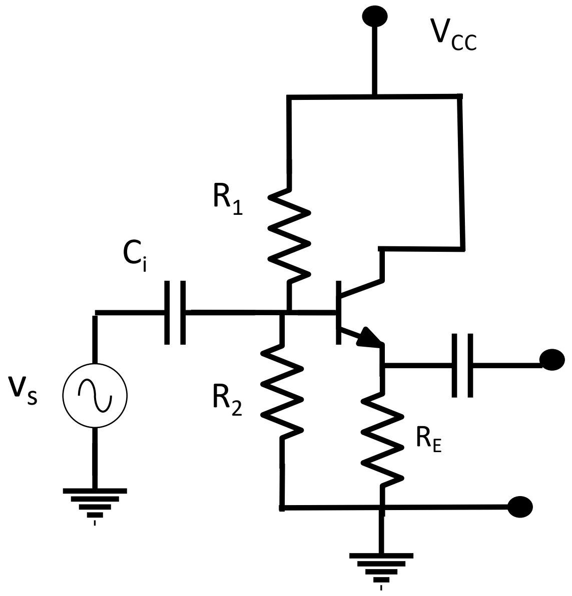
Common collector amp (Emitter Follower)

1. d

Common collector amp

Credit: Ward, Hands on Radio.

BJT common collector amplifier continued

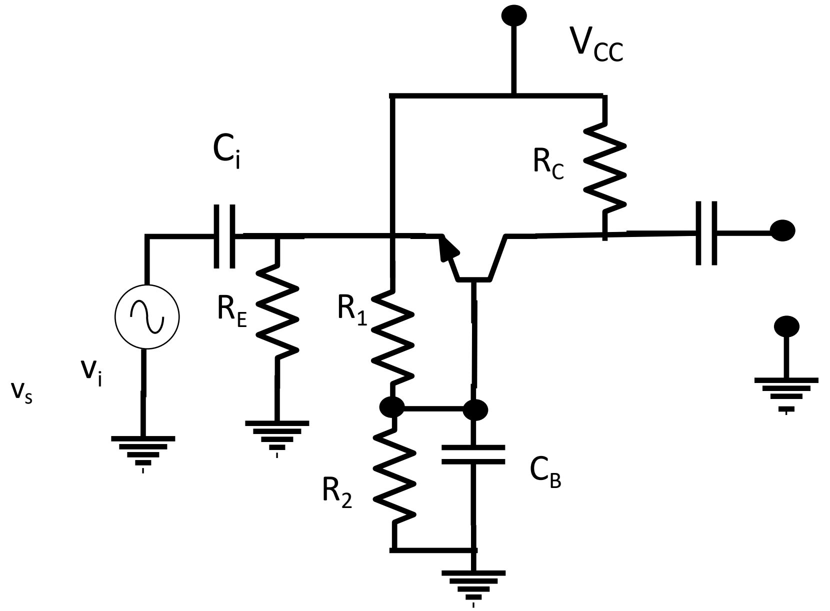


Common collector amp (Emitter Follower)

Credit: Ward, Hands on Radio.

6. x

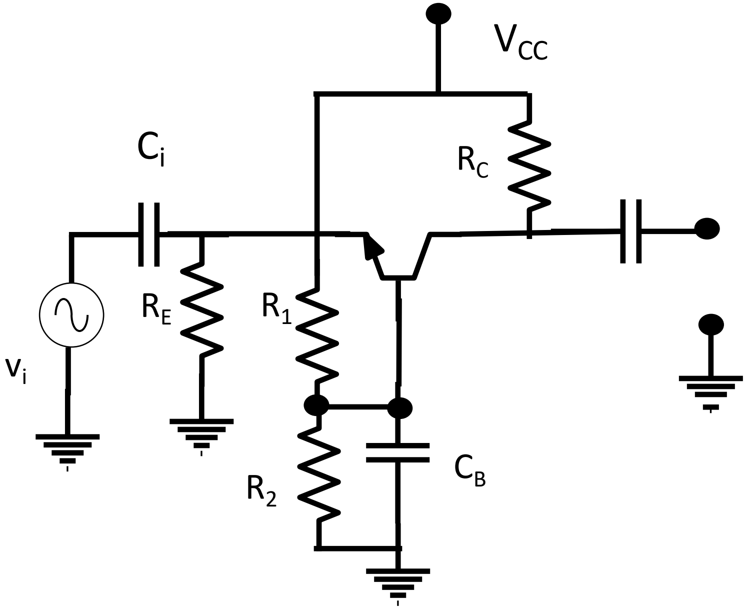
BJT common base amplifier



Common base amp

- x

BJT common base amplifier continued

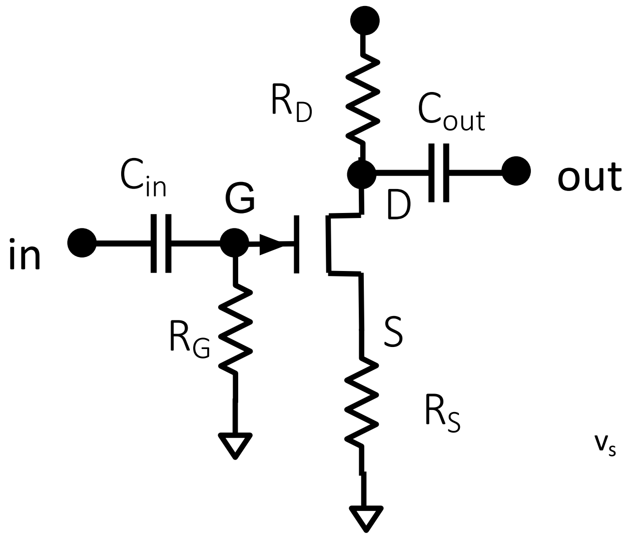


Common base amp

6. x

JFETs

JFET Common Emitter Amplifier



v_s

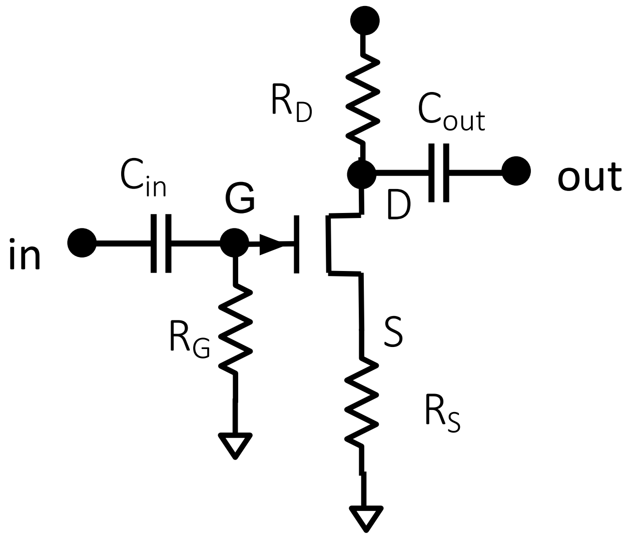
v_s

- x

JFET common emitter amplifier continued

6. x

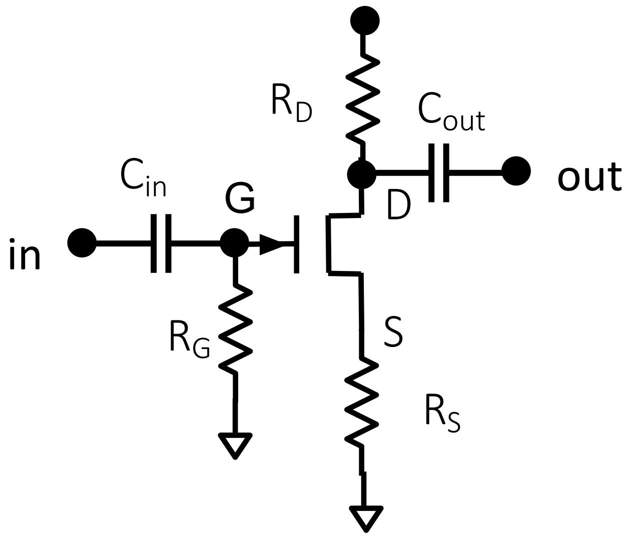
JFET common source amplifier



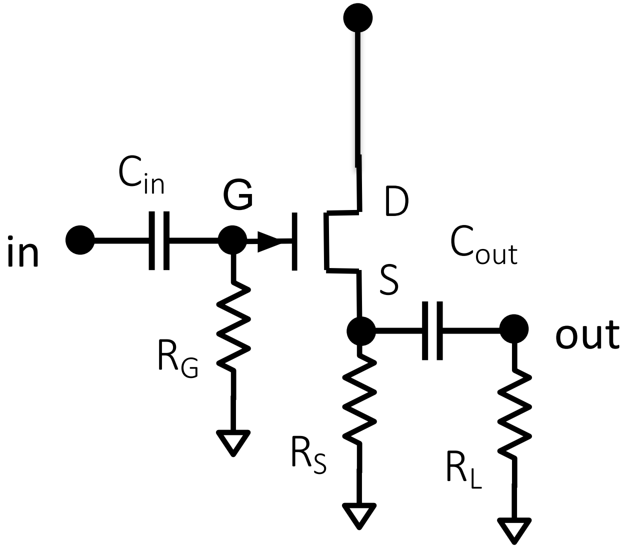
1. d

JFET Common Source Amplifier continued

6. x



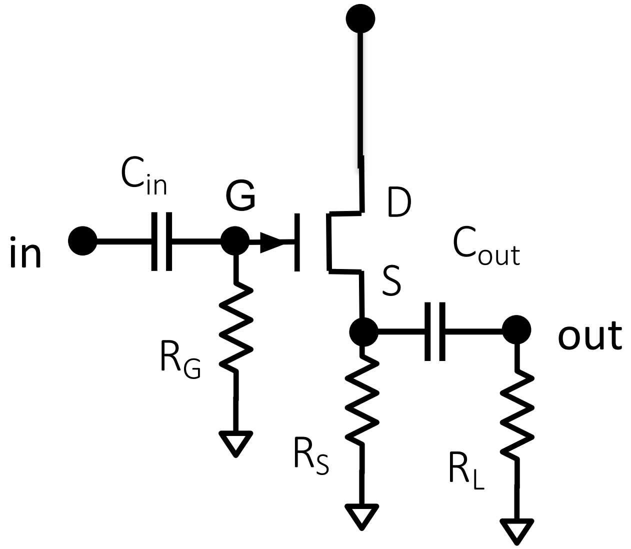
JFET common drain amplifier



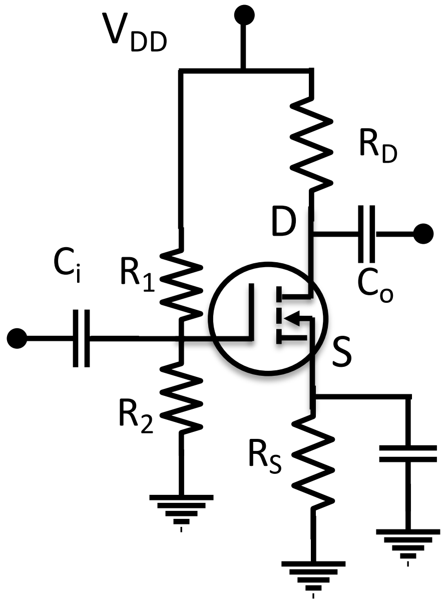
- x

JFET common drain amplifier continued

6. x



CMOS common emitter amplifier

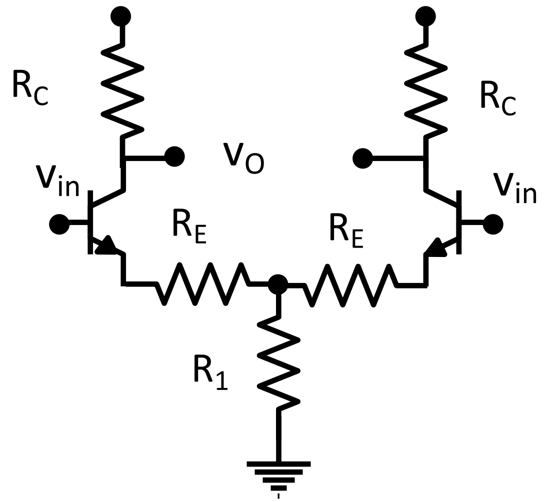


- Pick power
- $V_{DD} = i_D R_D + V_{DS} + i_D R_S$
- $V_{GS} = V_G - i_S R_S$
- $V_G = V_{DD} \frac{R_1}{R_1 + R_2}$
- $i_D = k(V_G - V_{TH})^2$
- Bias around $\frac{V_{DD}}{3}$
- Pick gain, $A = \frac{R_D}{R_S + \frac{1}{g_m}}$

Differential Amplifier

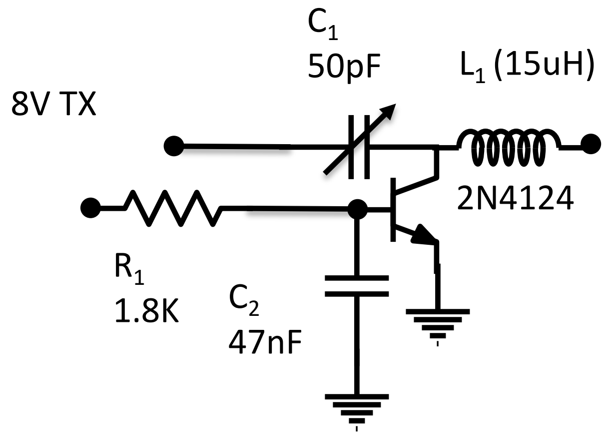
- Two port model
- $\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}$

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



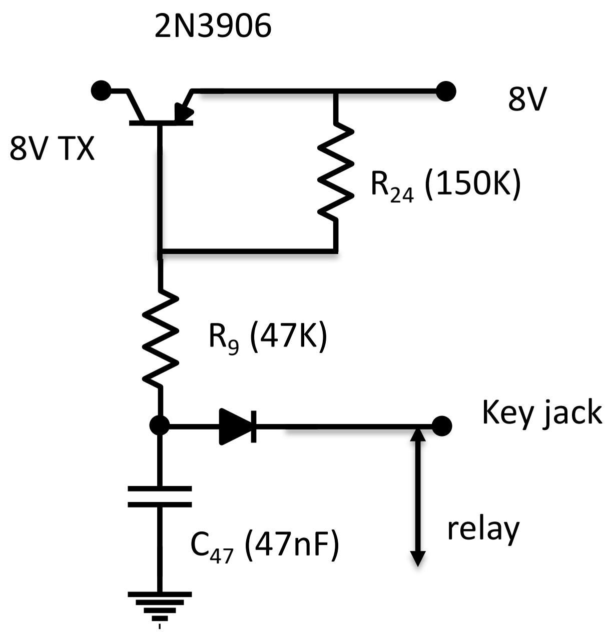
Harmonic filter

If using function generator
use a 1.8K resistor

- Receiver mixer or an oscilloscope with 50Ω

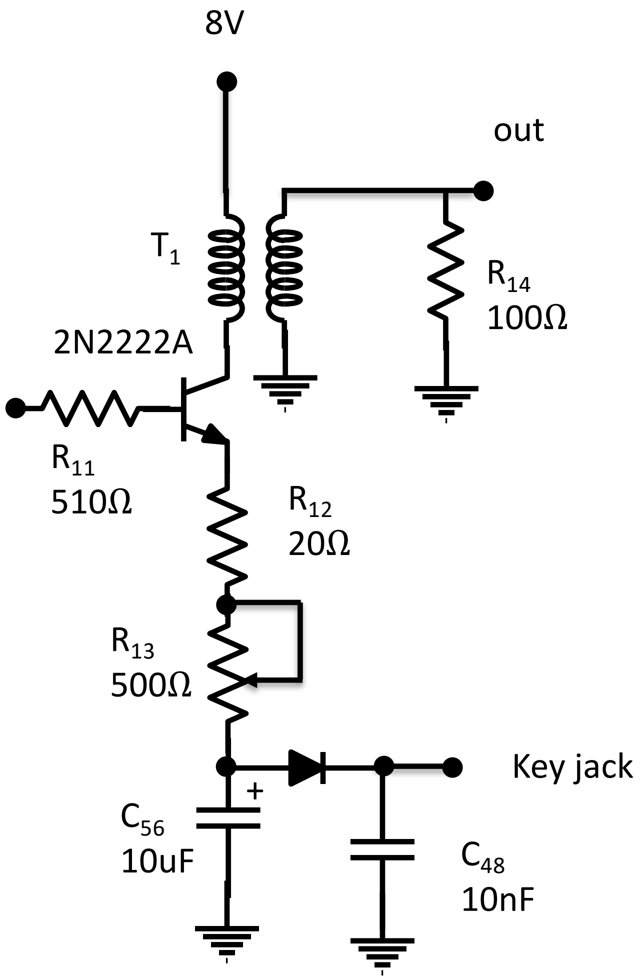
- When transistor conducts the receiver filter shorts

Exercise 20: NorCal transmitter switch



- When key is down, transistor conducts

Exercise 21: Norcal Driver

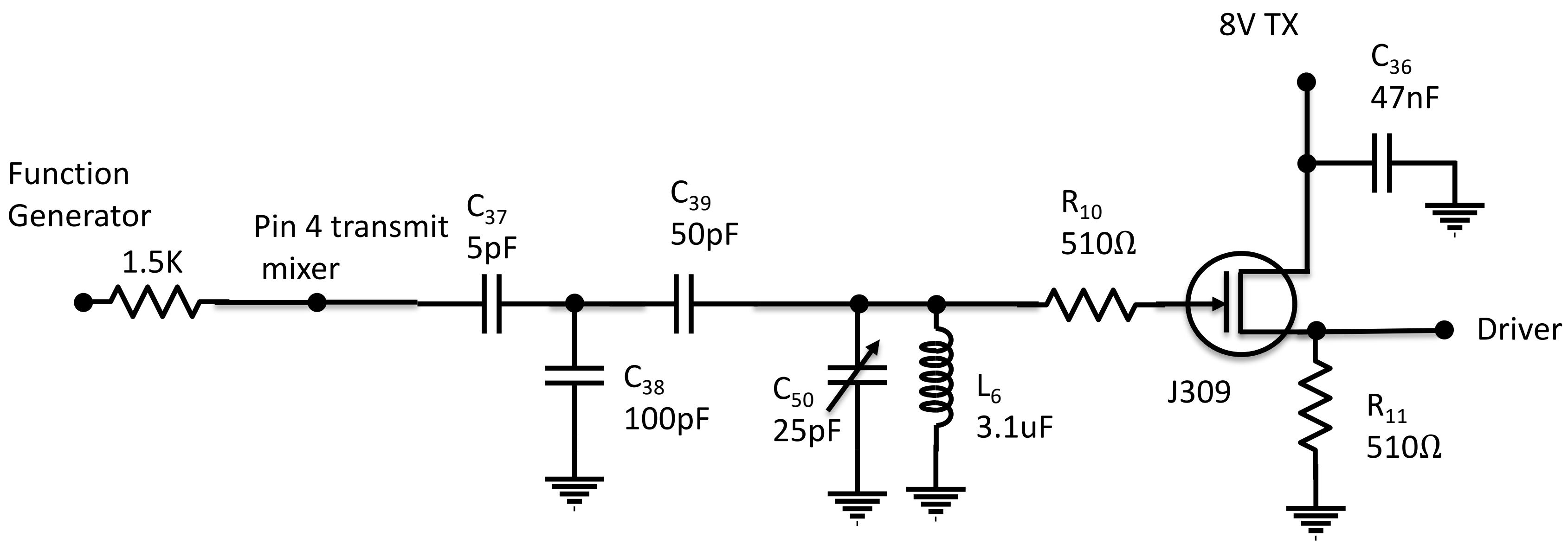


- Use 50Ω scope probe

Exercise 22: Emitter degeneration

- Use 50Ω scope probe

Exercise 23: Norcal Buffer amplifier



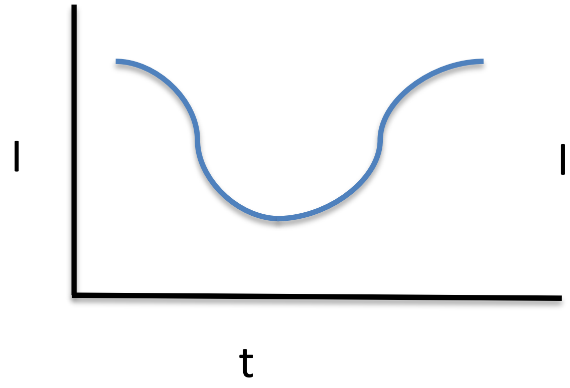
$$G_V = \frac{V}{V_i}$$

Amplifier classes

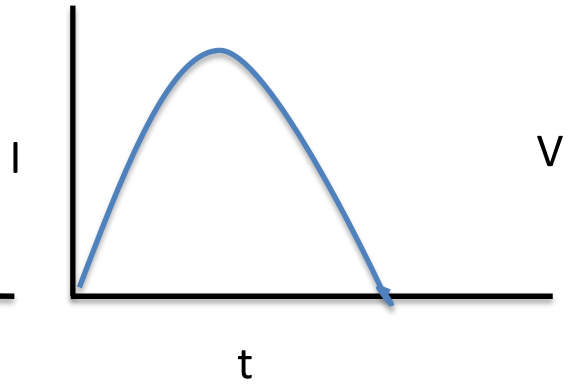
Class	Efficiency	Characteristics
A	35%	Full bias
B	60%	Low bias
C	75%	Saturating
D	75%	Switch in pass-band
E	90%	Voltage switch
F	80%	Harmonic resonators

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

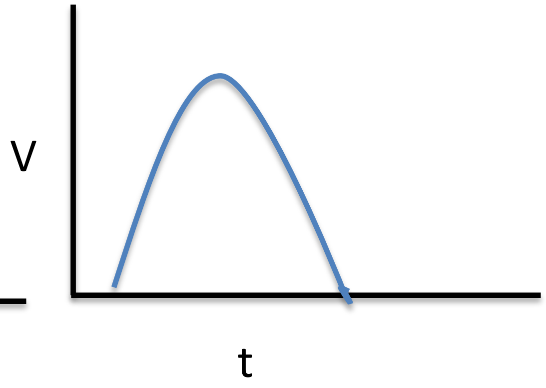
$$P_d = P_a + P_{on}$$



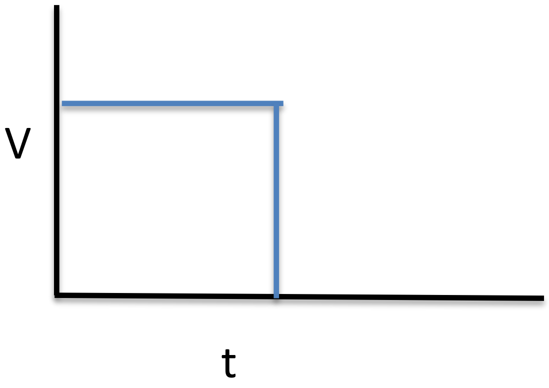
Class A



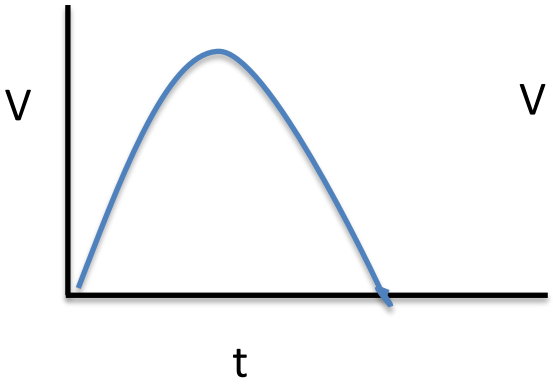
Class B



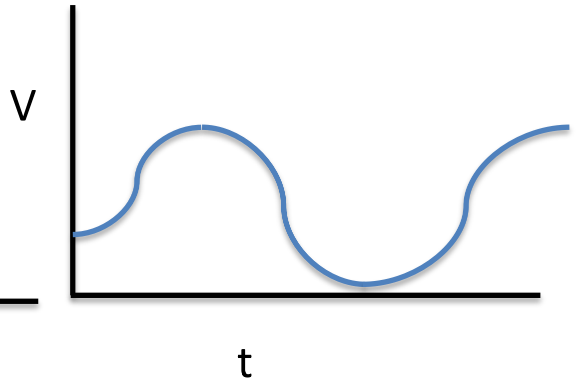
Class C



Class D



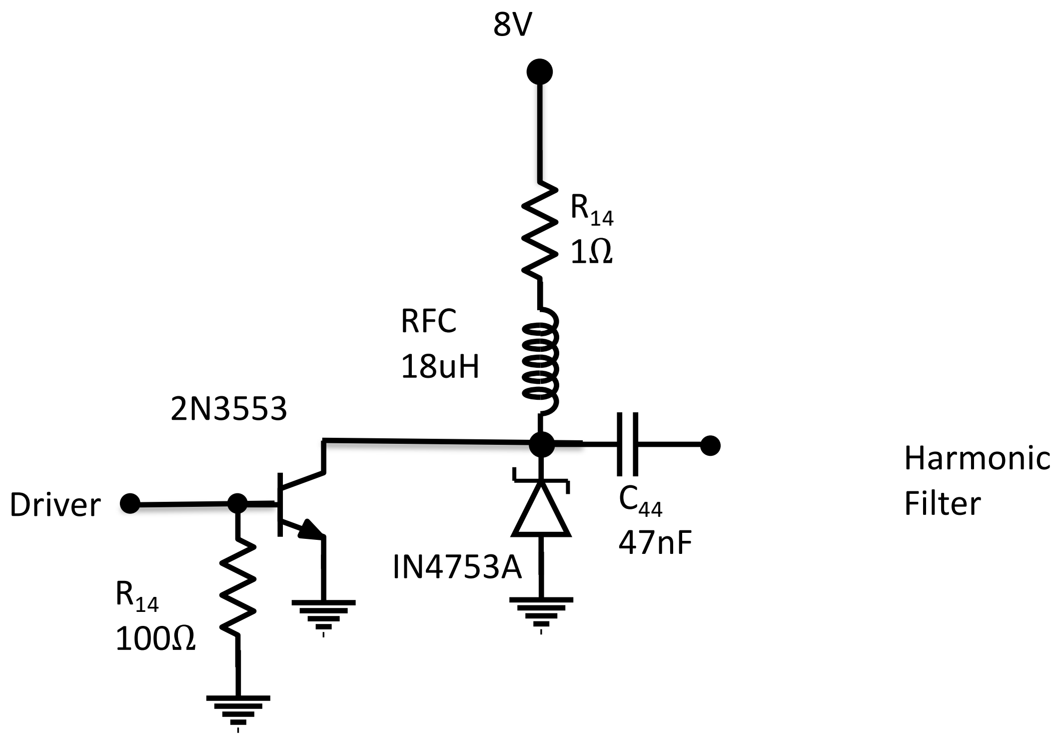
Class E

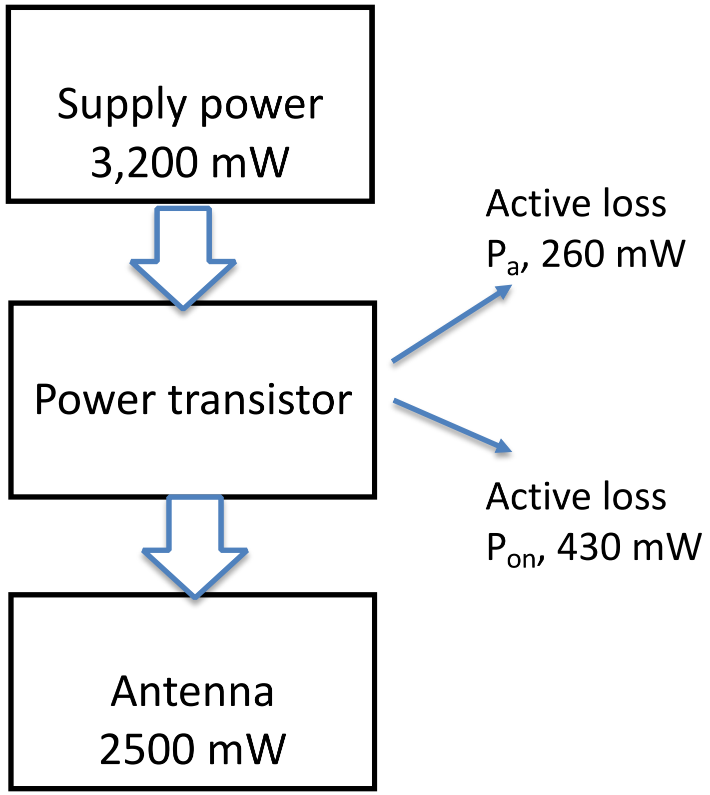


Class F

Exercise 24: Norcal Power Amp

Norcal-40 Power amp is class C



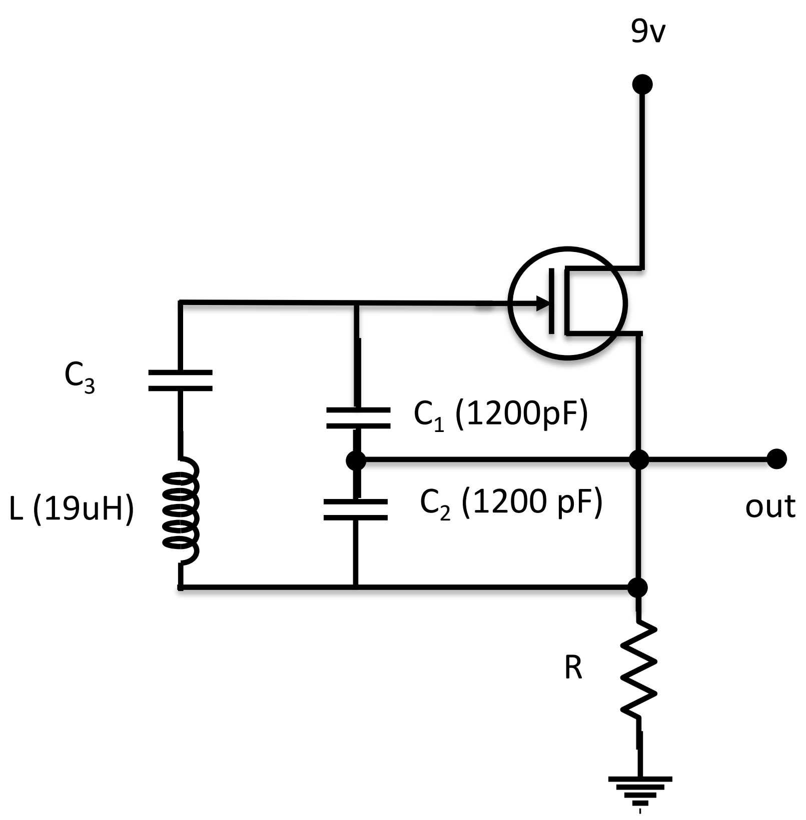


- $R_t = \frac{T - T_0}{P_d}$
- T_0 is ambient temperature, T is heat sink temperature

Exercise 25: Power modelling

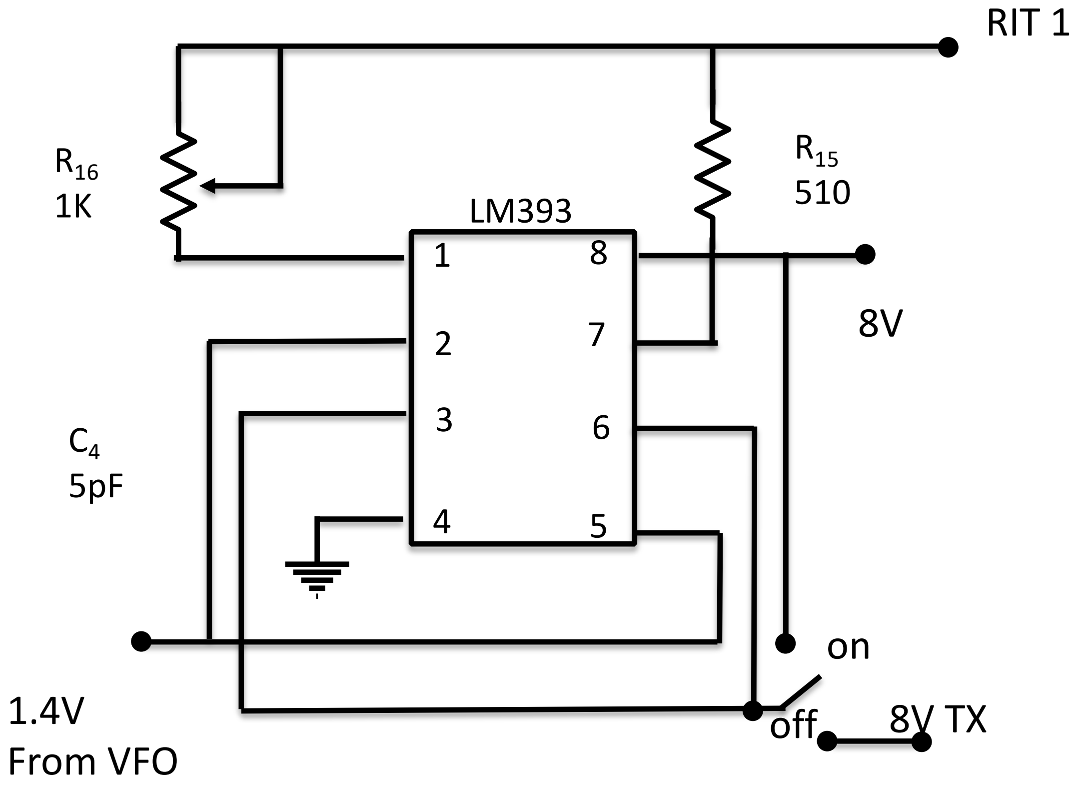
- Use 50Ω scope probe

Clapp oscillator



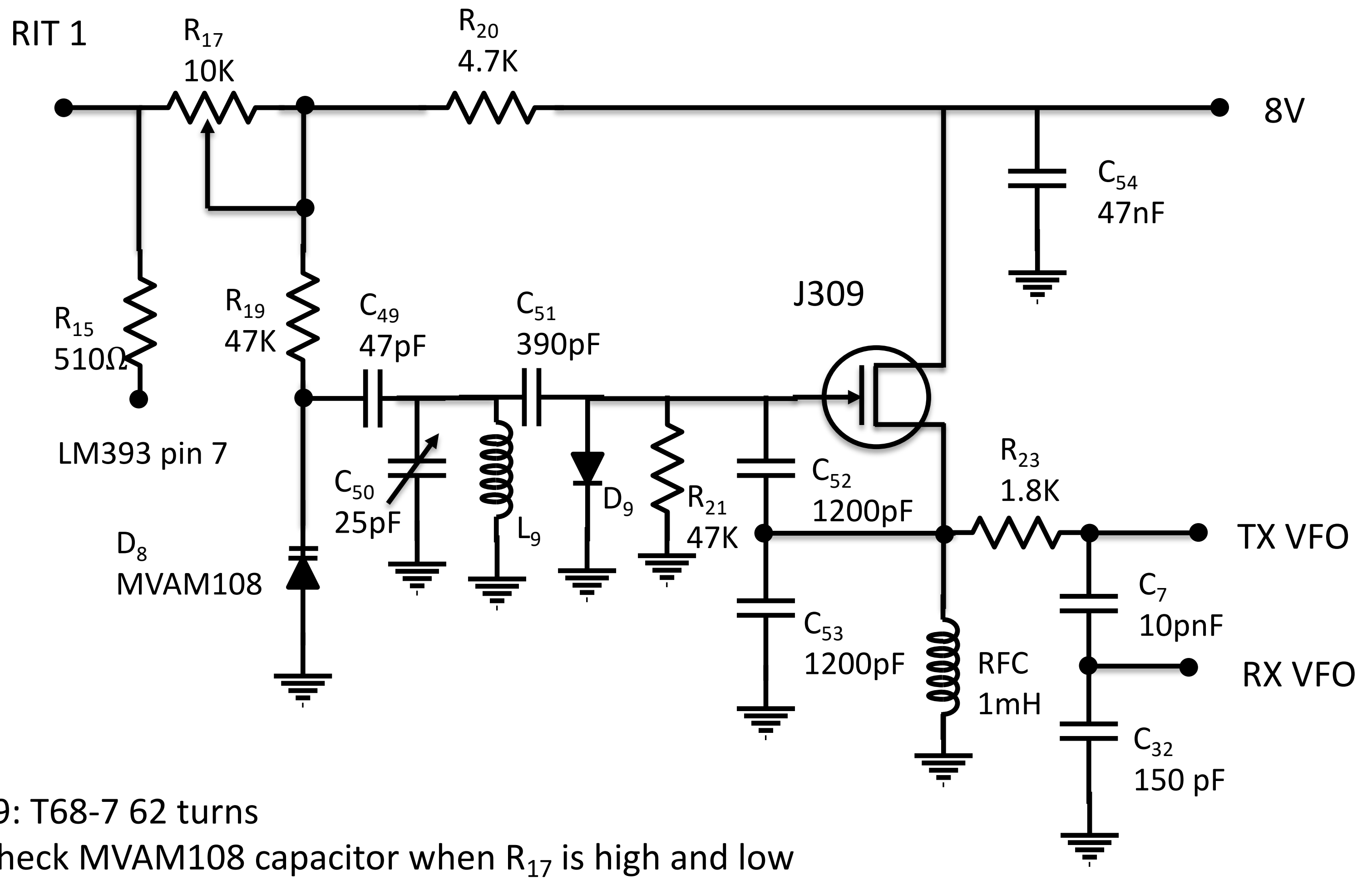
- $i_d = g_m v_{gs}$
- Resonance: $-\frac{1}{j\omega_0 C_2} = j\omega_0 L + \frac{1}{j\omega_0 C_3} + \frac{1}{j\omega_0 C_1}$
- $\omega_0 = \frac{1}{\sqrt{LC}}$, $C = C_1||C_2||C_3$
- At resonance, $v_{gs} = Ri_d \frac{C_1}{C_2}$, $L = \frac{C_1}{RC_2}$
- Oscillation continues if $g_m > \frac{C_1}{RC_2}$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

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 and 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

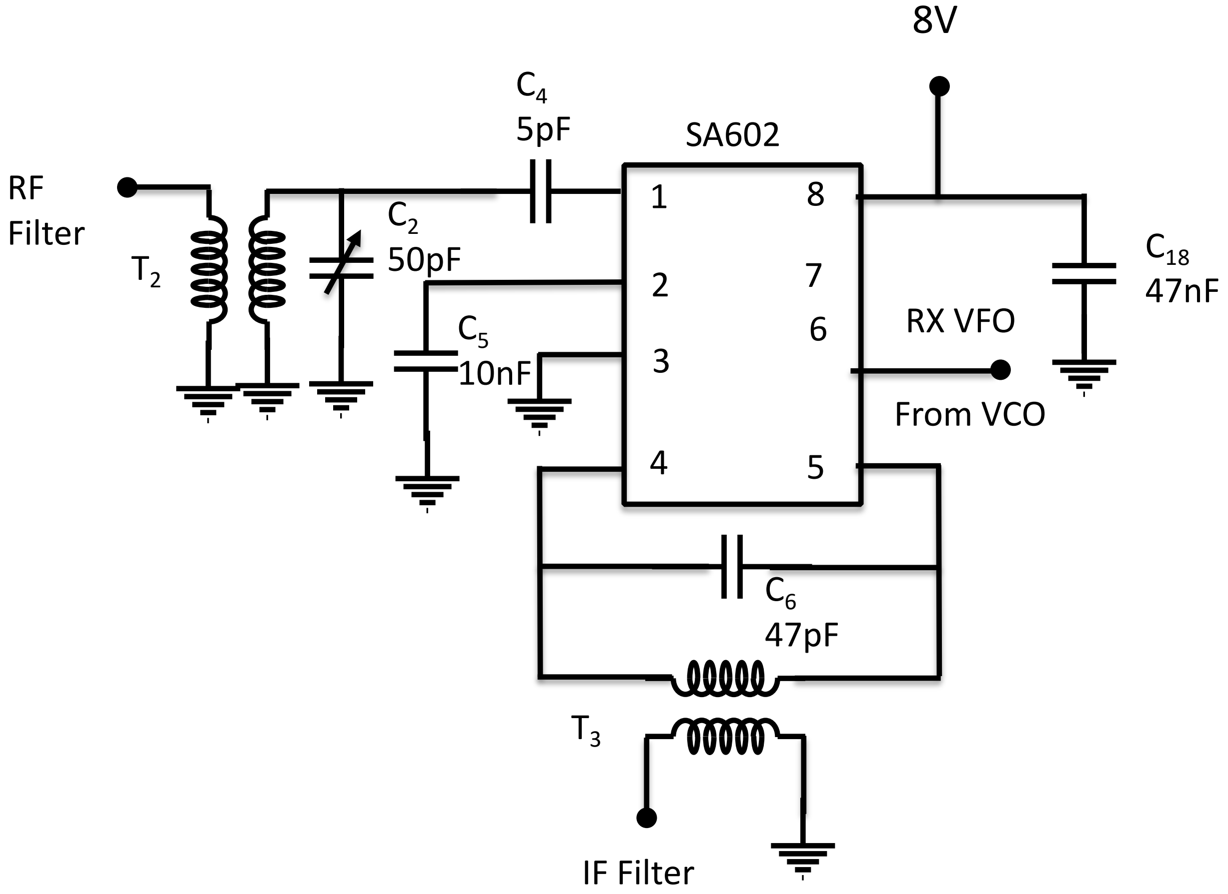
Exercise 27: Gain limiting

- x

Mixers

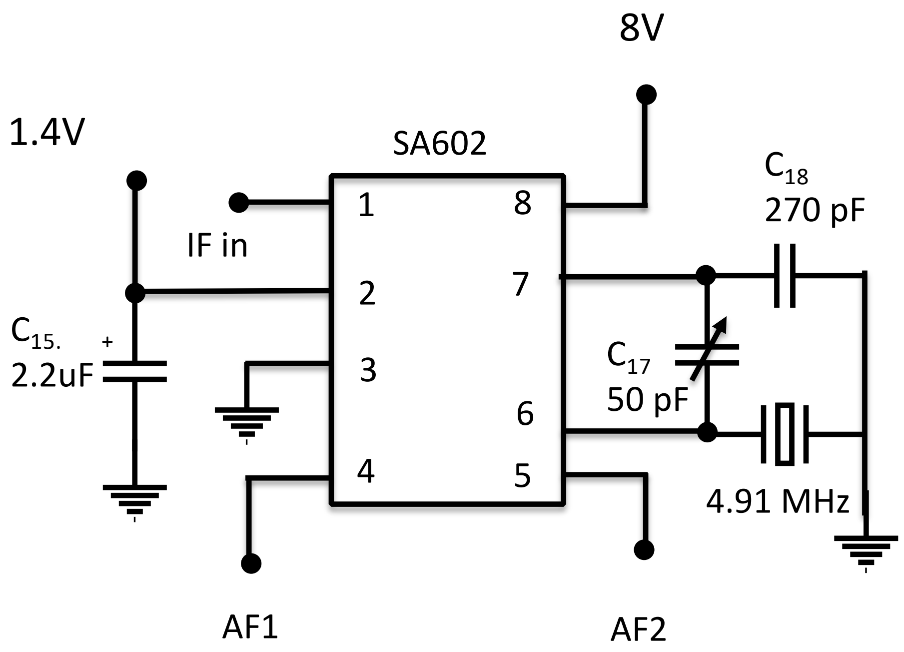
- x

Exercise 28: Norcal RF Mixer



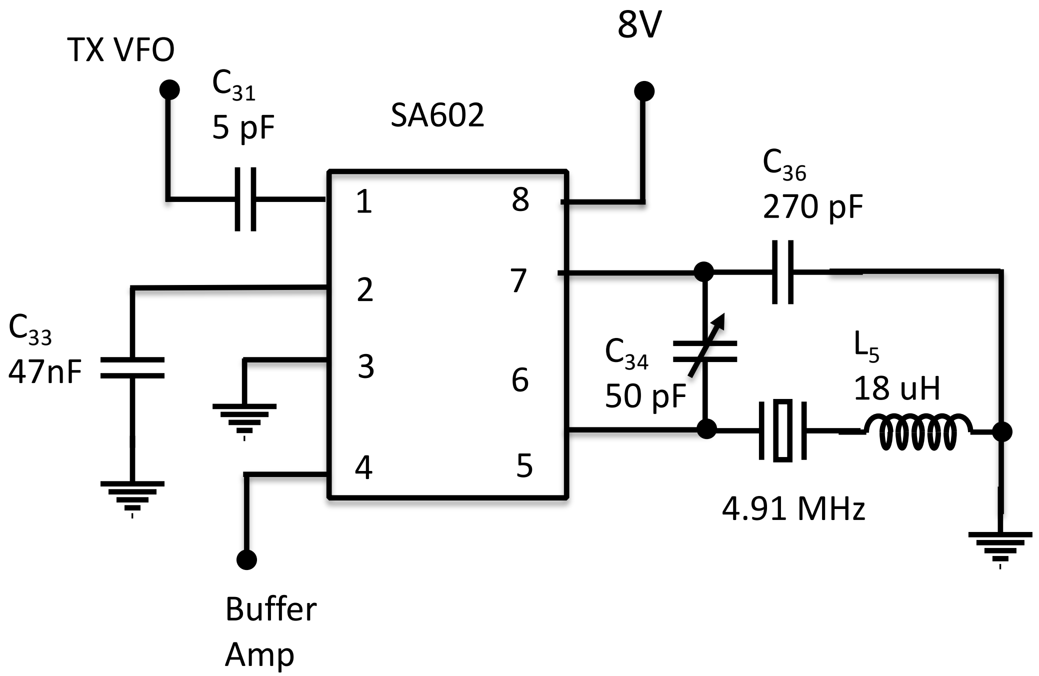
50mVpp if using function generator

Exercise 29: Norcal Product Detector

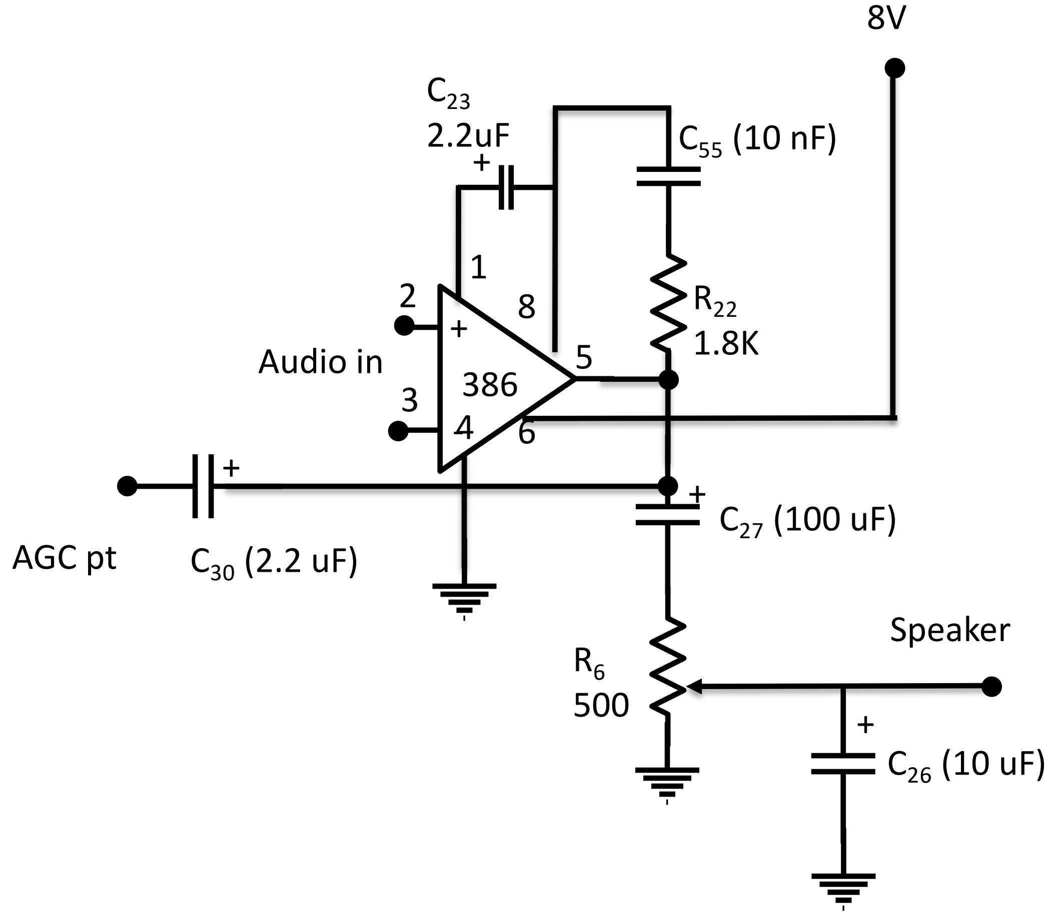


- 620 Hz output through AF1 and AF2

Exercise 30: Norcal transmit mixer and oscillator

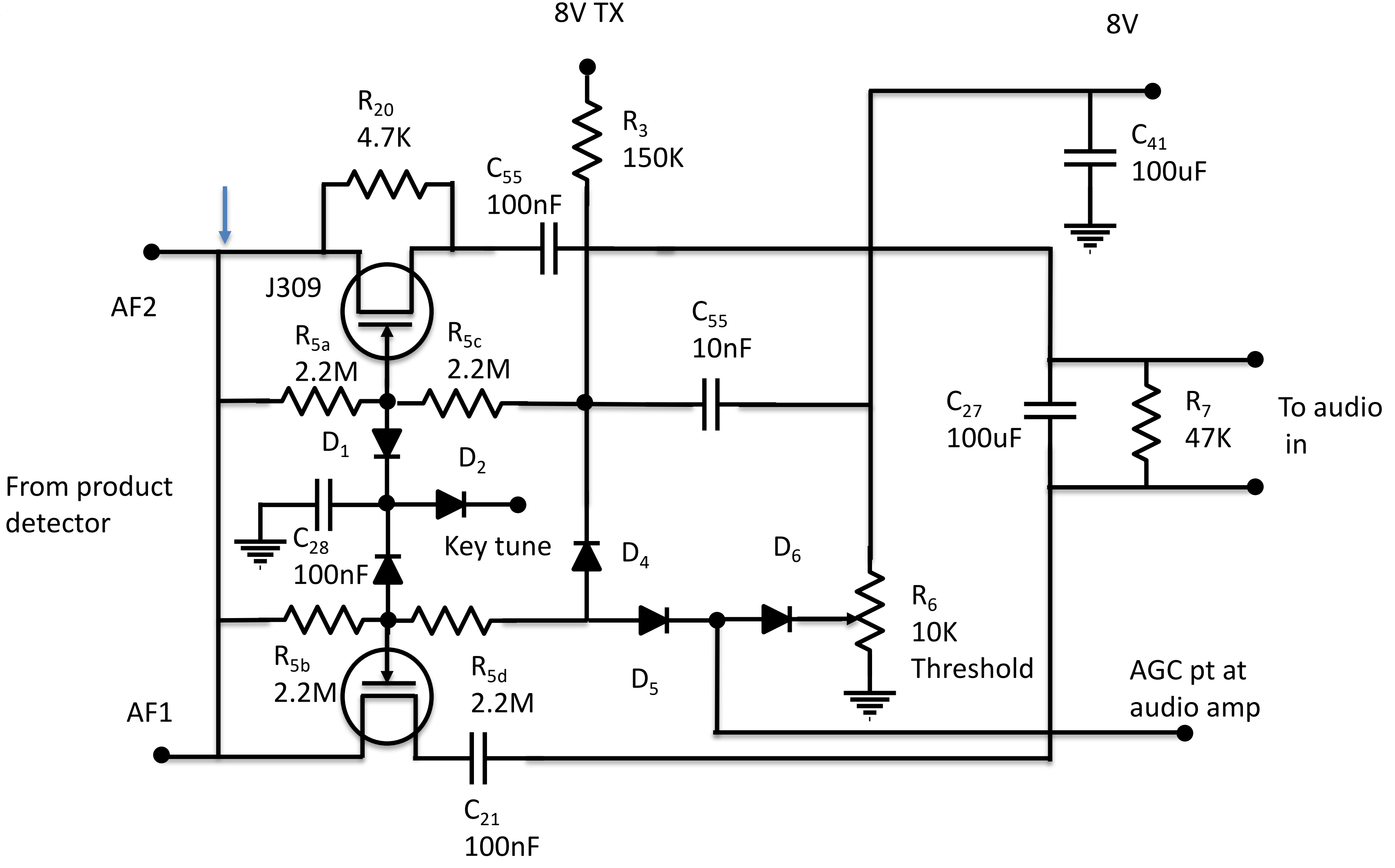


Exercise 31: Norcal Audio Amp



Exercise 32: Norcal AGC

Connect to
function generator
through 300K, here



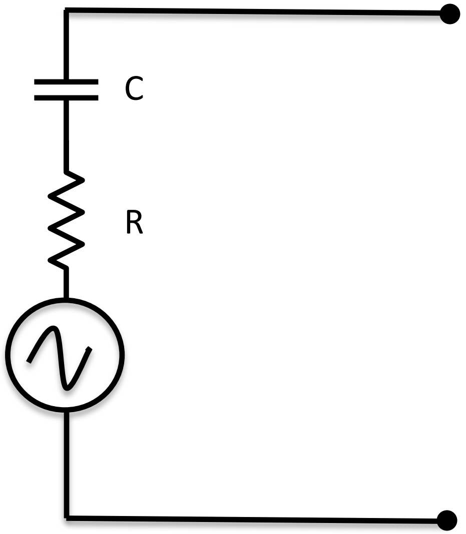
Exercise 33: Alignment

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

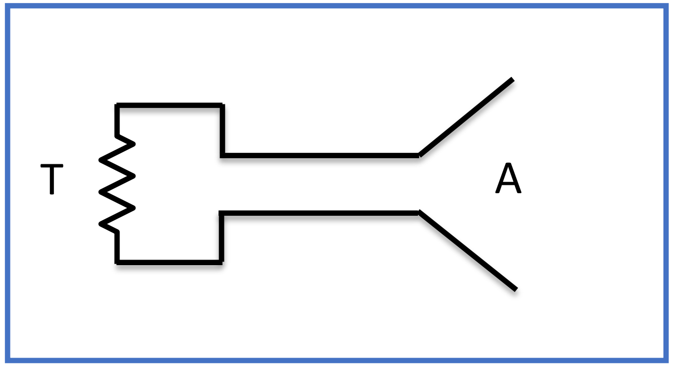


Antennas and propagation

- 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

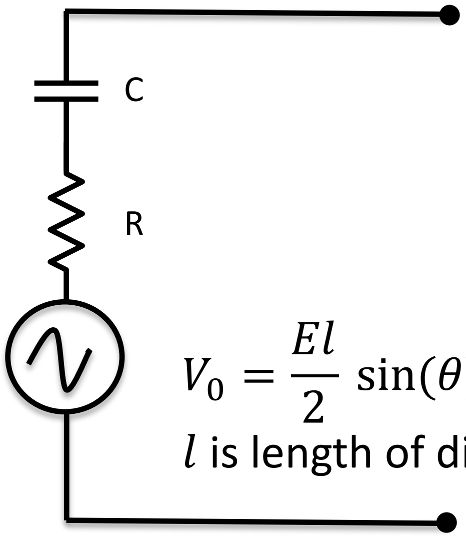
Insulated cavity



- 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



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

l is length of 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
- $R_r = \frac{l^2 \eta_0}{16\lambda^2} \int sin^2(\theta) d\Omega = \eta_0 \frac{\pi}{6} (\frac{l}{\lambda})^2$
- $A = \frac{3\lambda^2}{8\pi} sin^2(\theta)$ and $G = 1.5\, sin^2(\theta)$. . Note we used $h = \frac{l}{2}\sin(\theta)$

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

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

- x

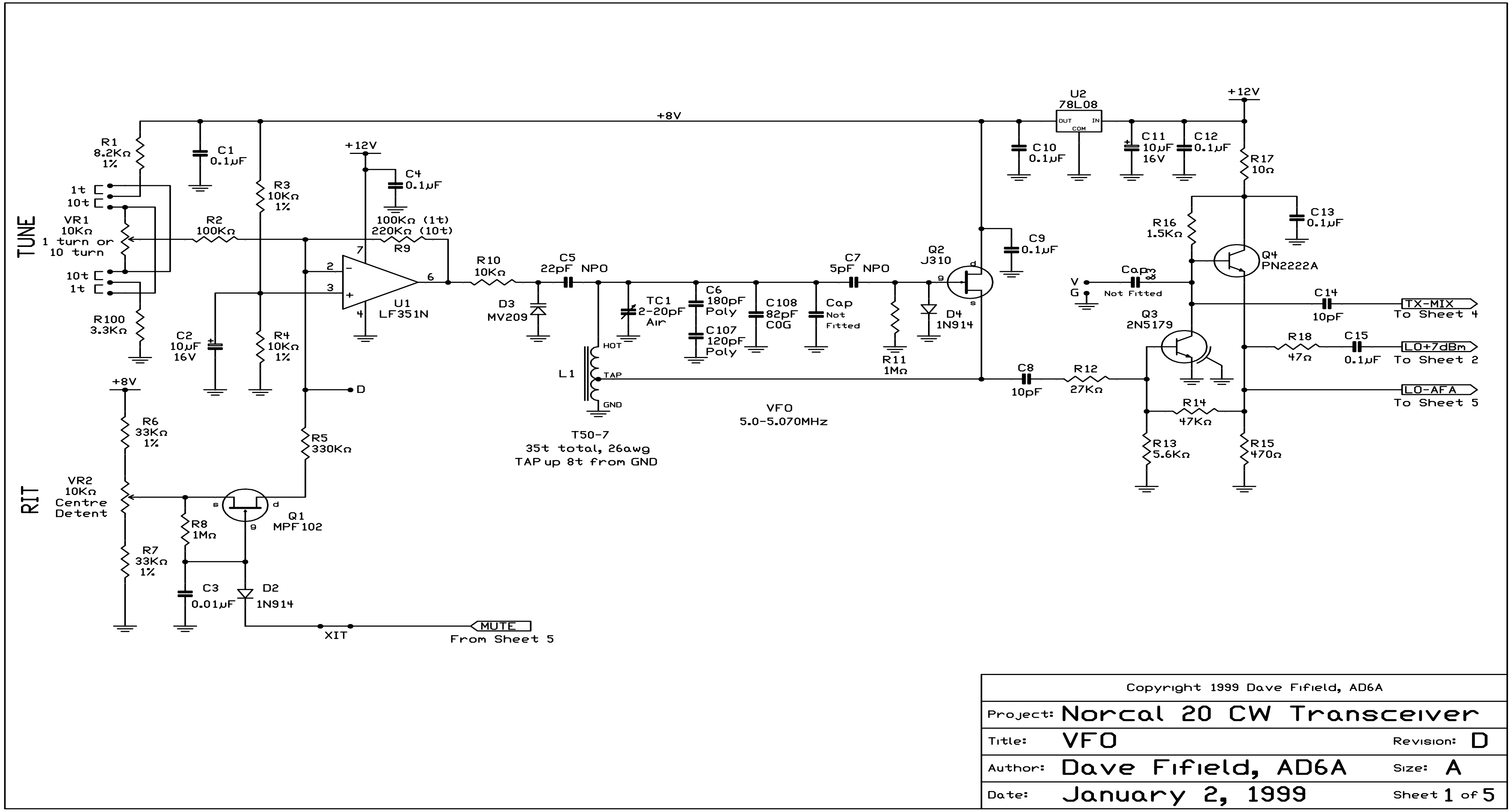
Exercise 37: Antennas

- x

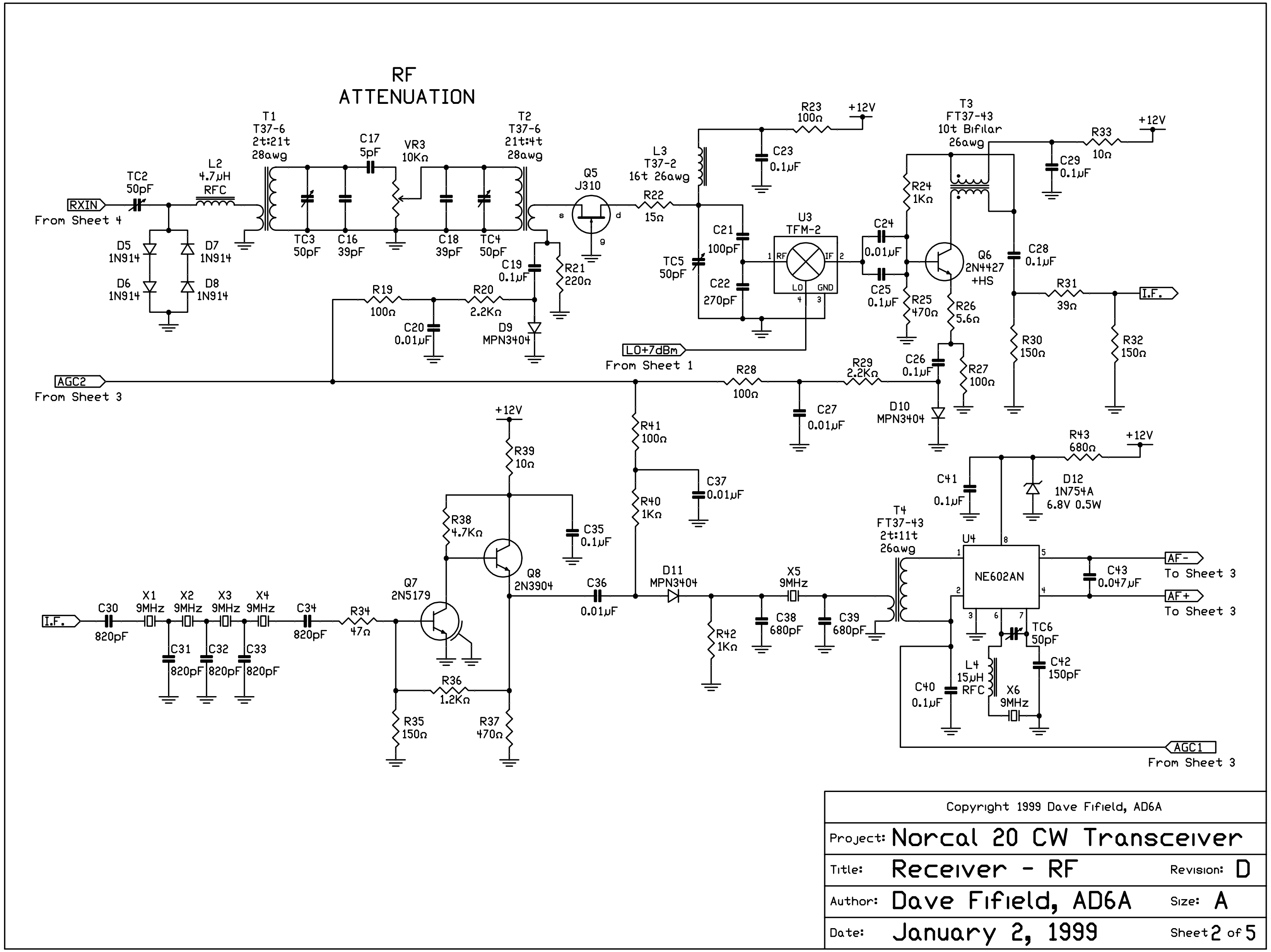
Exercise 38: Propagation

- x

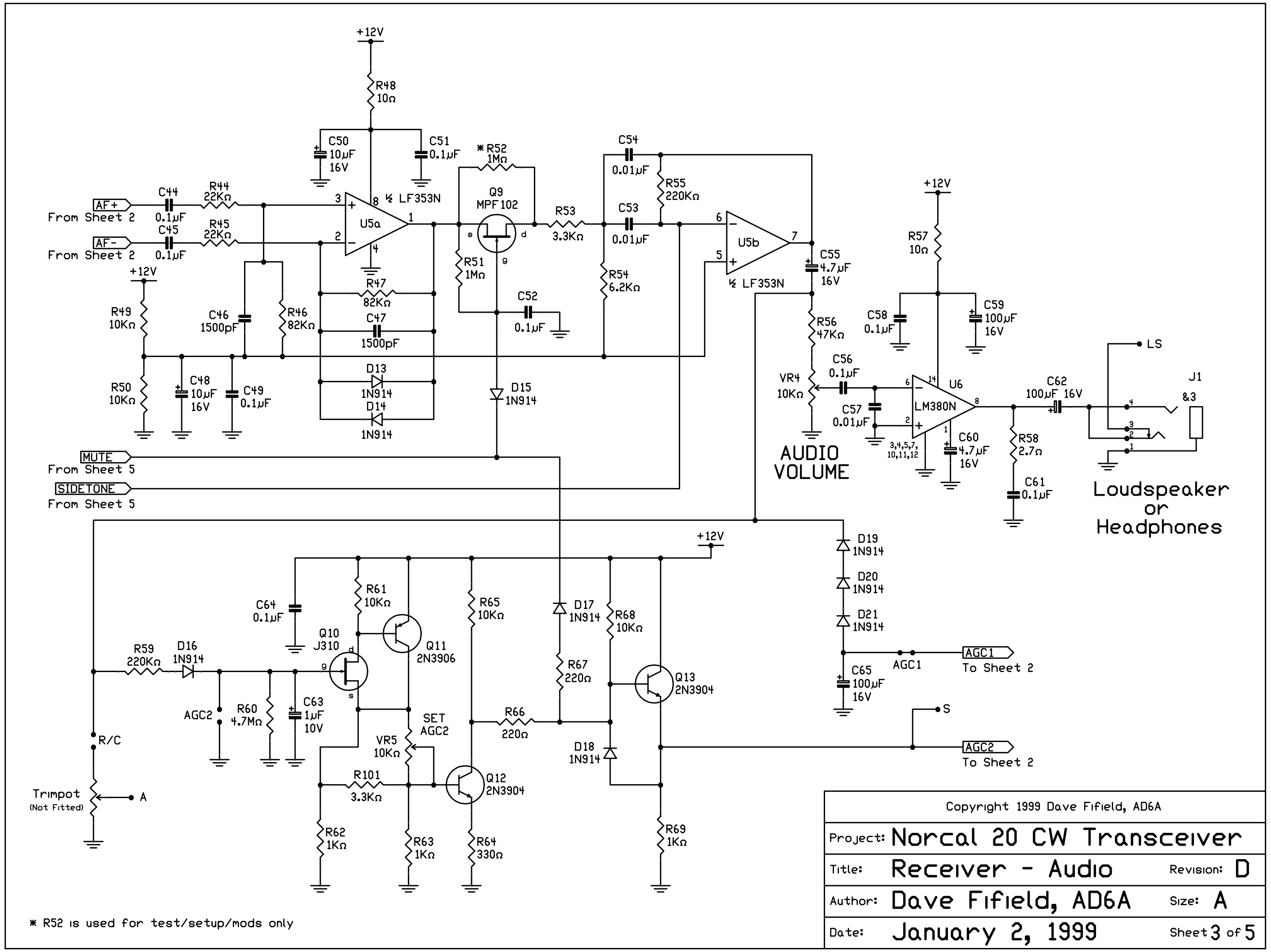
Norcal circuit diagram, 1



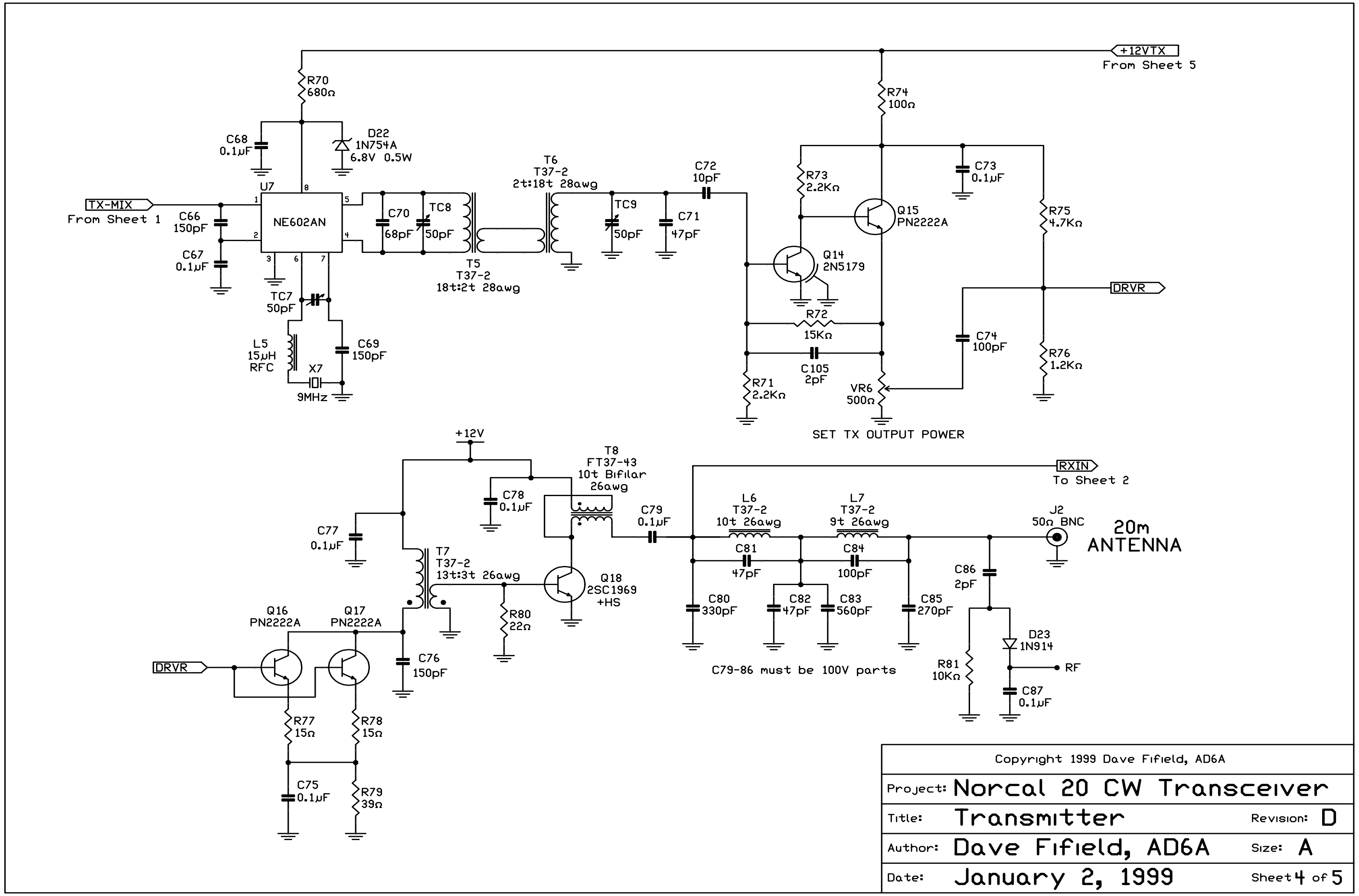
Norcal circuit diagram, 2



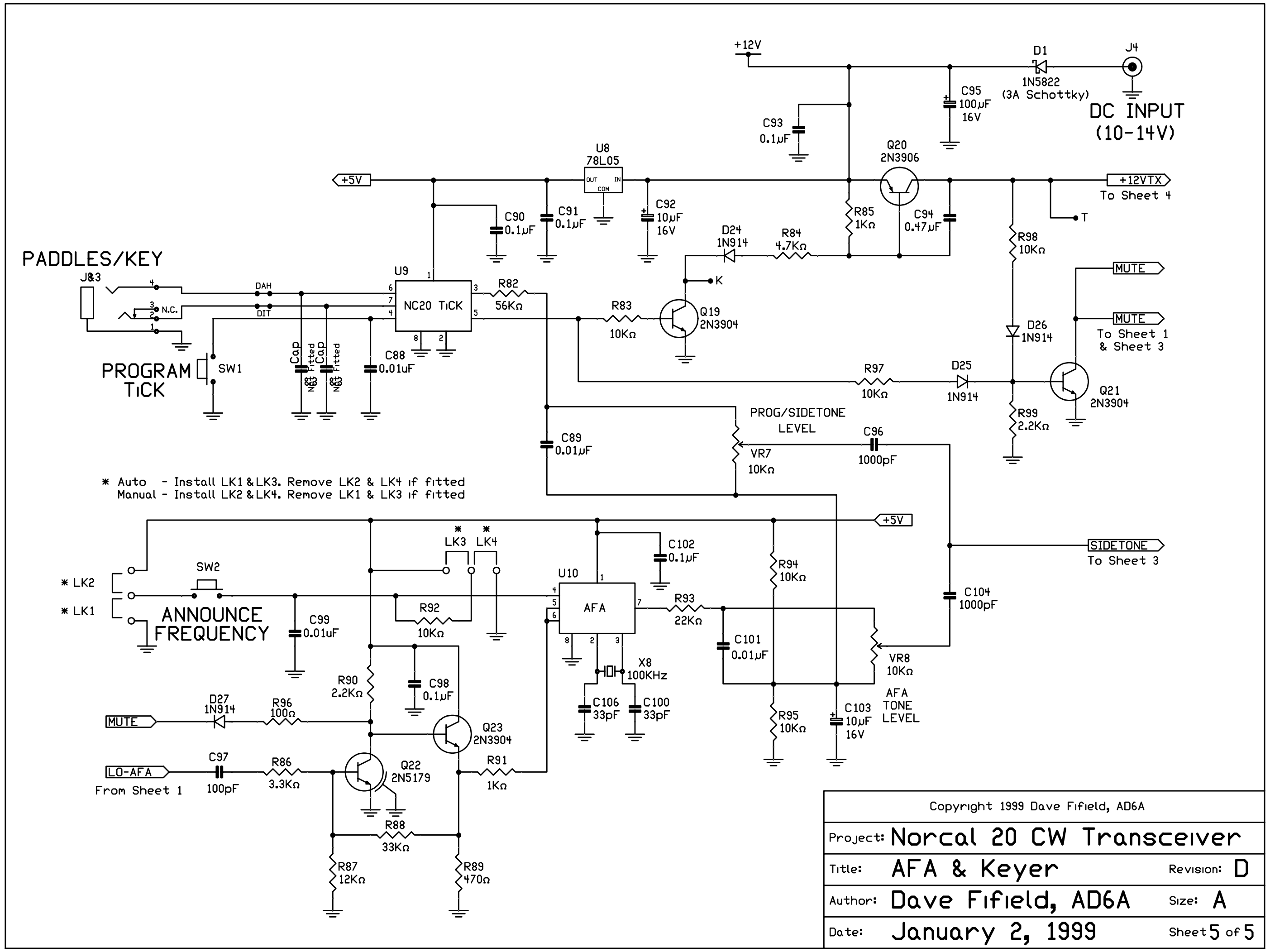
Norcal circuit diagram, 3



Norcal circuit diagram, 4



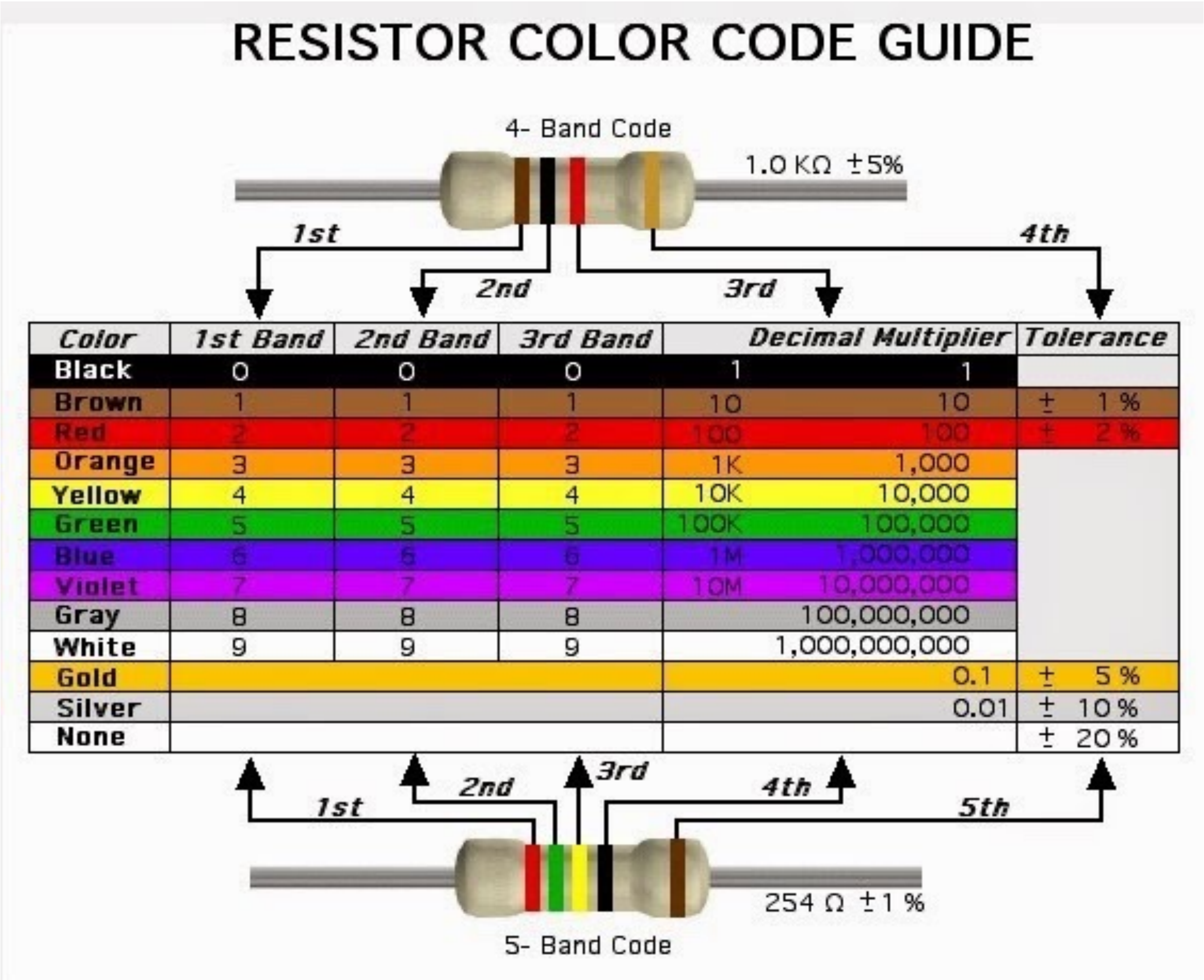
Norcal circuit diagram, 5



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

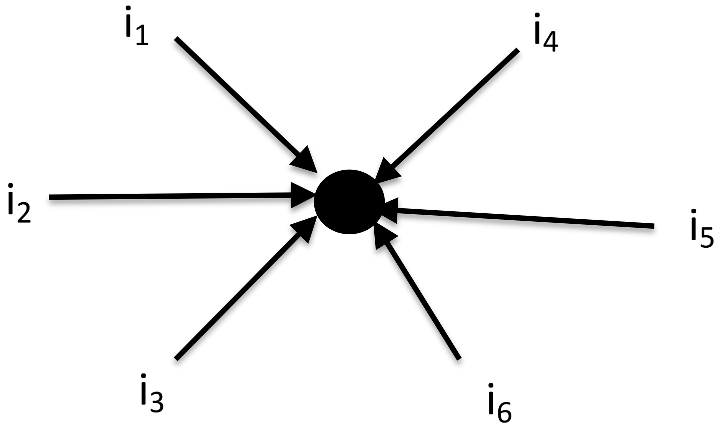


Color	1st Band	2nd Band	3rd Band	Decimal Multiplier		Tolerance
Black	0	0	0	1	1	
Brown	1	1	1	10	10	± 1 %
Red	2	2	2	100	100	± 2 %
Orange	3	3	3	1K	1,000	
Yellow	4	4	4	10K	10,000	
Green	5	5	5	100K	100,000	
Blue	6	6	6	1M	1,000,000	
Violet	7	7	7	10M	10,000,000	
Gray	8	8	8		100,000,000	
White	9	9	9		1,000,000,000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

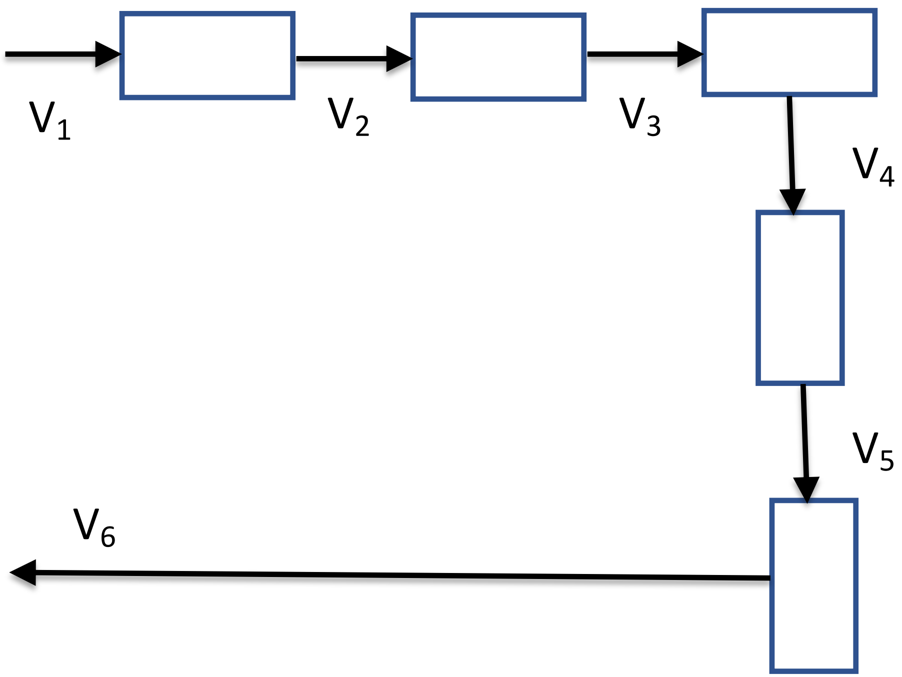
- Resistors: ohms
- Capacitors: picoFards
- Inductors: milliHenries

Kirchhoff

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



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



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