Electronics of Radio

Notes on David Rutledge's book

John Manferdelli

Basic concepts

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

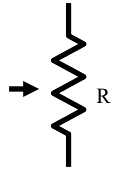
- Gain (G) expressed in decibels: $G = 10\ log_{10}(^{P_{out}}/_{P_{in}})$
- Mixer:
  - $V(t) = \cos(\omega_1 t)\cos(\omega_2 t) = \frac{1}{2}[\cos(\omega_+ t) + \cos(\omega_- t)], \omega_+ = \omega_1 + \omega_2, \omega_- = \omega_1 - \omega_2$
- Modulation

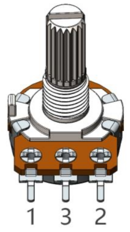
Name	Equation
AM	$V(t) = a(t)\cos(\omega_c t)$
FM	$V(t) = V_c\cos((\omega_c + a(t))t)$
FSK	$V(t) = V_c\cos(\omega_1 t)$, if 1 $V(t) = V_c\cos(\omega_0 t)$, if 0
PSK	$V(t) = +V_p\cos(\omega t)$, if 1 $V(t) = -V_p\cos(\omega t)$, if 0

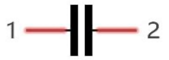
Resistors, capacitors, inductors

- 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: $E = \int_{t_i}^{t_f} IV\,\mathrm{dt} = \int_{t_i}^{t_f} LI\frac{dI}{dt}dt = \frac{1}{2}LI^2$





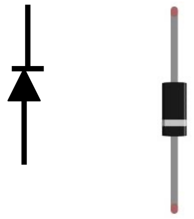


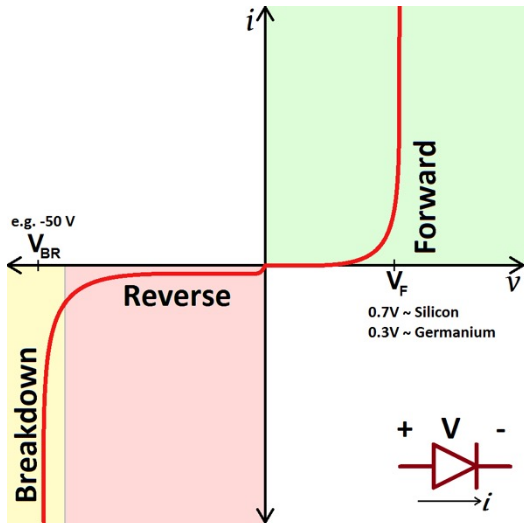



Credit: Make Electronics

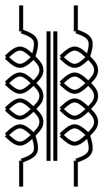
diodes, transformers

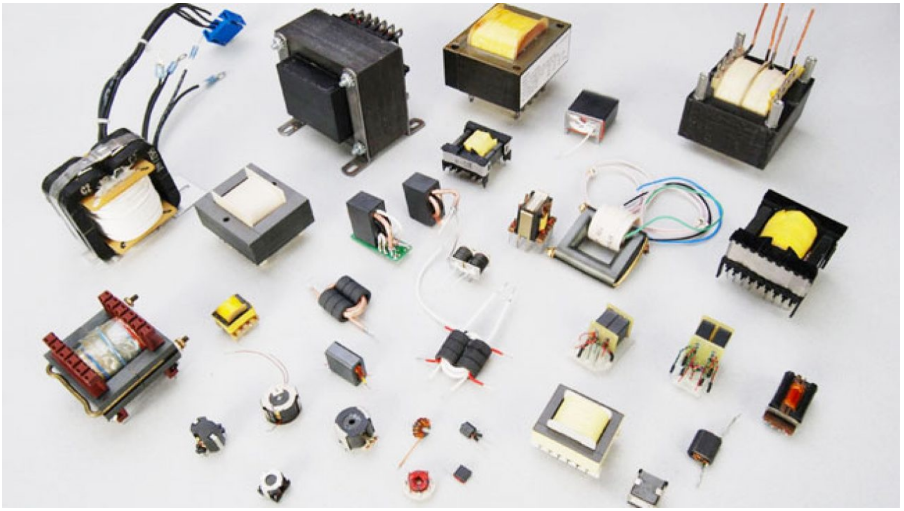
- Diodes
  - Devices that allow current to flow only in one direction
  - Silicon diodes, for example have, essentially infinite resistance if $V_{ac}<0$, that is if the cathode is at a higher potential than the anode and very low resistance if $V_{ac}>.7V$.
  - The cathode is usually labelled with a band
- Transformers
  - AC only: $\frac{N_2}{N_1} = \frac{V_2}{V_1}$





Credit: Make Electronics





Impedance and phasors

- Impedance and phasors

Phasor Power

- Impedance and phasors

Circuit analysis with Kirchhoff and impedance

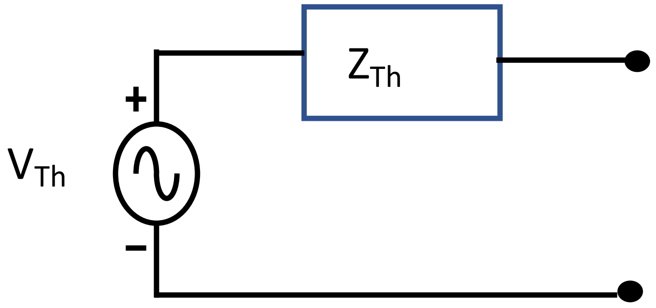
- RC circuits
- Parallel and series

Filters

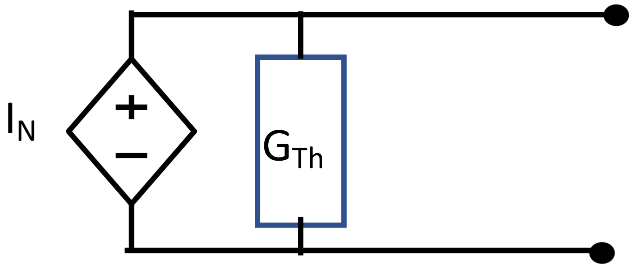
- x

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

- Lookback

Resonance and Q

- Resonance

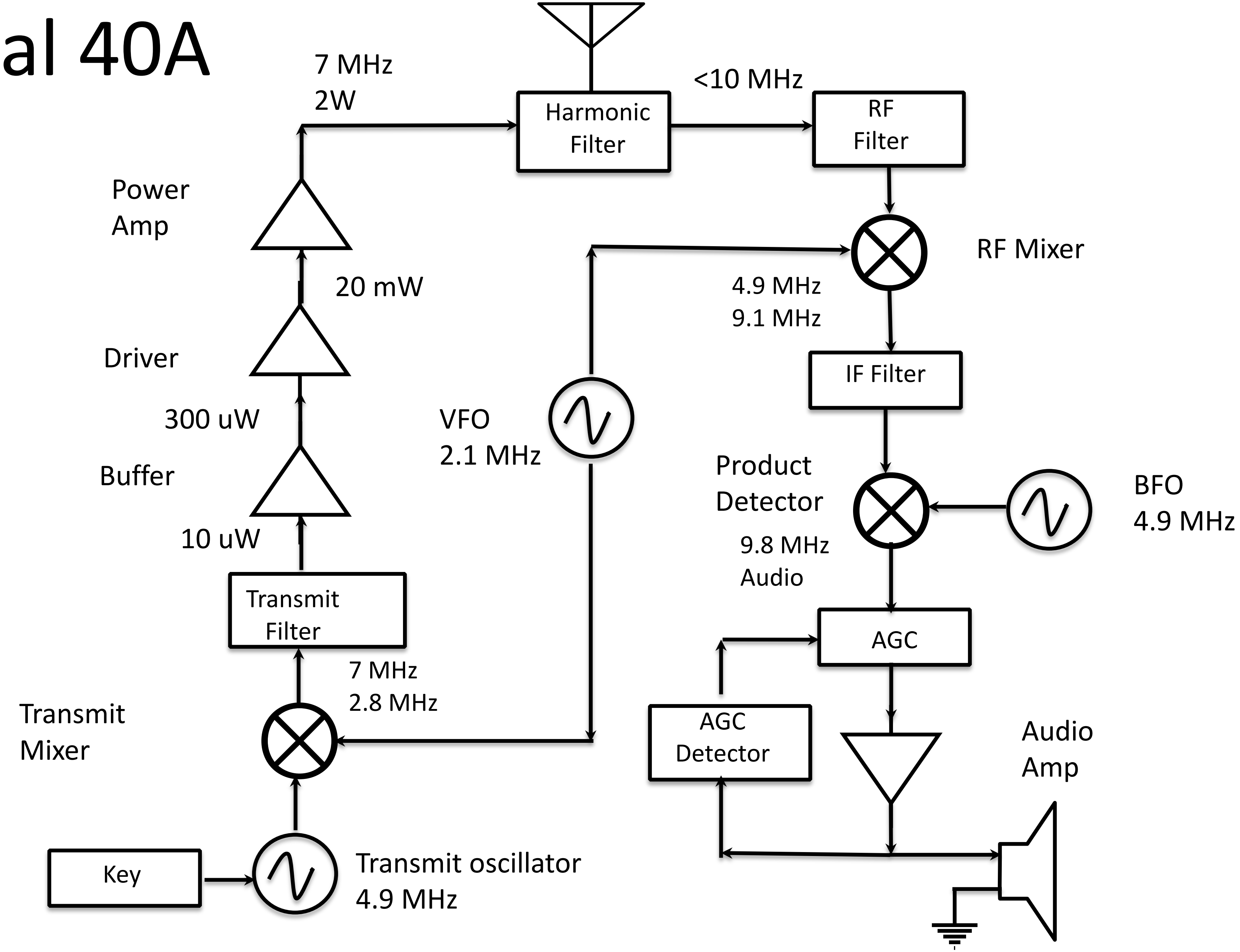
Exercises

1. Voltage dividers
2. RC and RL circuit analysis
3. Resonance
4. Resistors and Thevenin
5. Sources
6. Capacitors
7. Inductors
8. Diods and snubbers

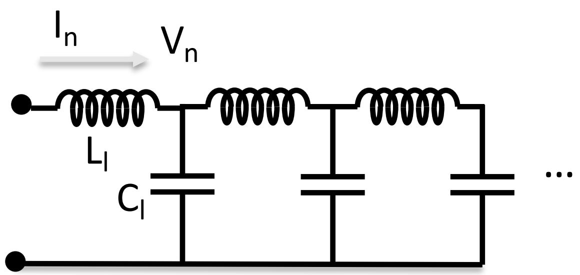
Direct conversion and superhet

- Image frequencies

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 MHz
Buffer
Product Detector
BFO
4.9 MHz
10 uW
9.8 MHz
Audio
Transmit Filter
AGC
7 MHz
2.8 MHz
Transmit Mixer
AGC Detector
Audio Amp
Key
Transmit oscillator
4.9 MHz

Transmission Lines



Power

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

Lookback resistance is $R_s = Z_0$

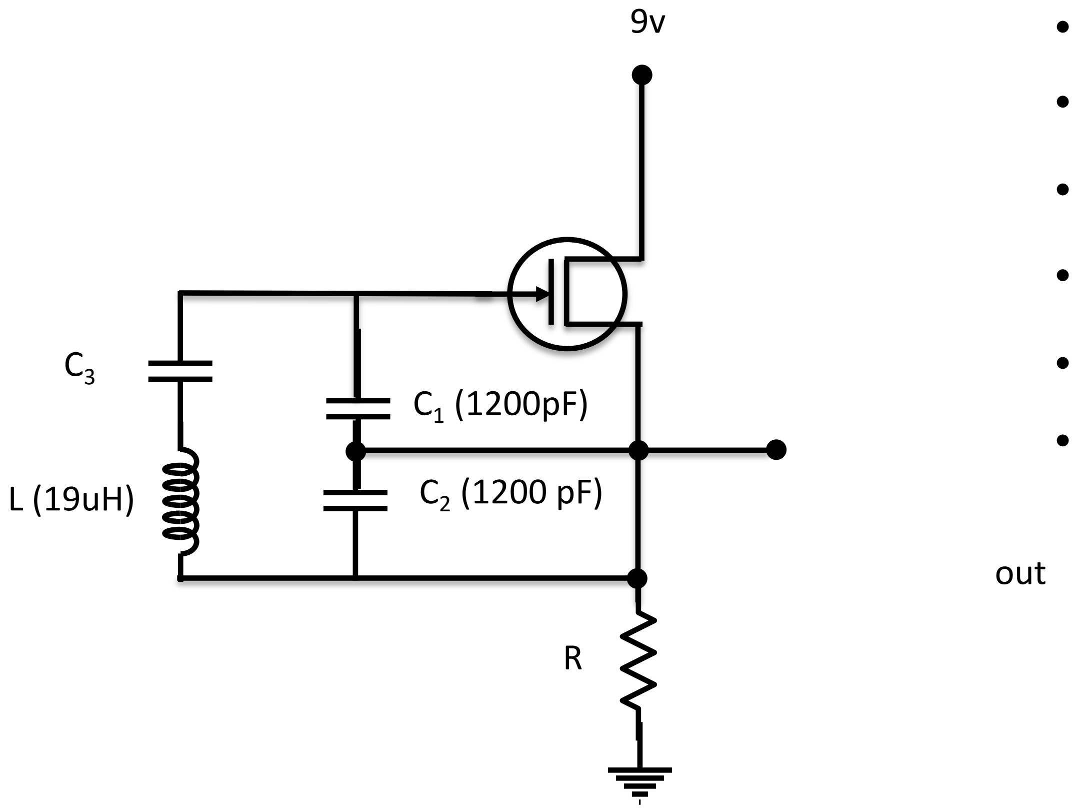
$P_+ = \frac{{V_+}^2}{2Z_0} = \frac{{V_0}^2}{8Z_0}$, This is the total available power

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

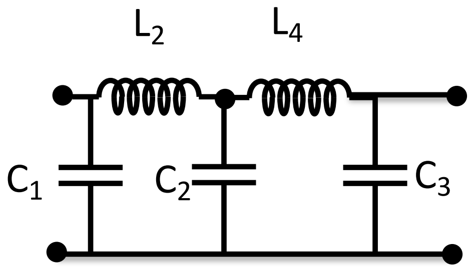
Norcal Clapp oscillator



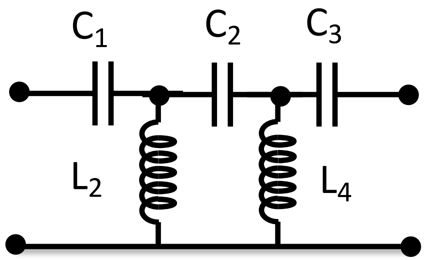
- $i_d = g_m v_{gs}$
- Resonance: $-\frac{1}{j\omega_0 C_2} = j\omega_0 L + \frac{1}{j\omega_0 C_3} + \frac{1}{j\omega_0 C_1}$
- $\omega_0 = \frac{1}{\sqrt{LC}}, C = C_1||C_2||C_3$
- At resonance, $v_{gs} = Ri_d\frac{C_1}{C_2}, L = \frac{C_1}{RC_2}$
- Oscillation continues if $g_m > \frac{C_1}{RC_2}$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

Filters

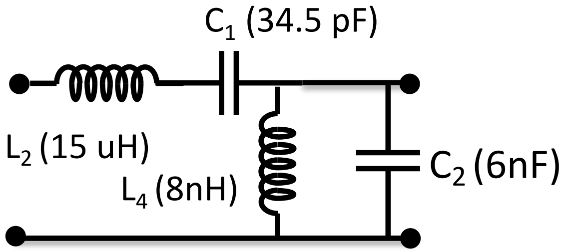
Low pass



High pass



7 MHz bandpass

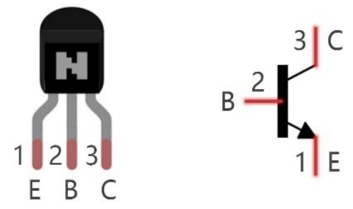


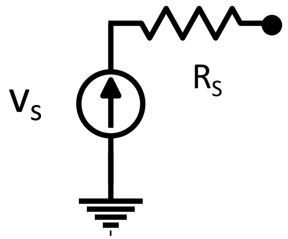
Acoustics

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

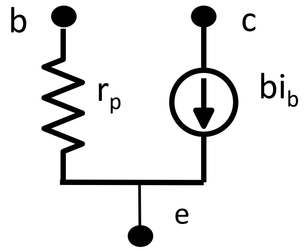
Bipolar Transistors

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





Bipolar source model

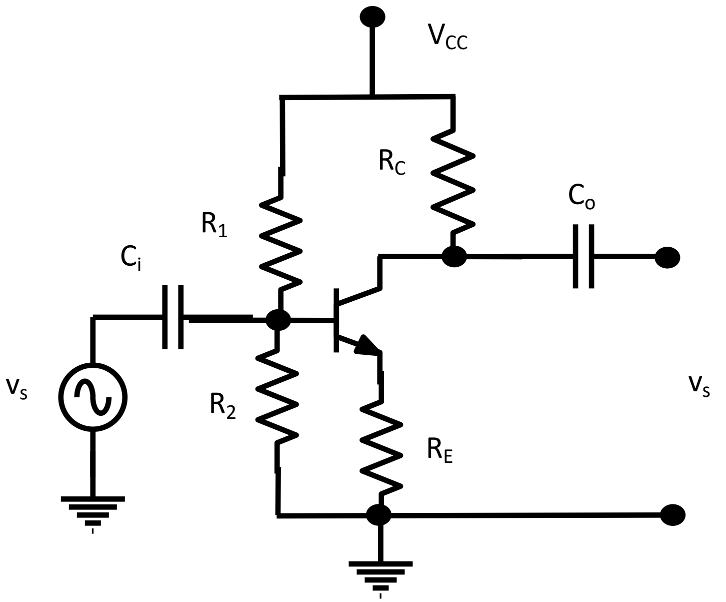


Bipolar equivalent circuit

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



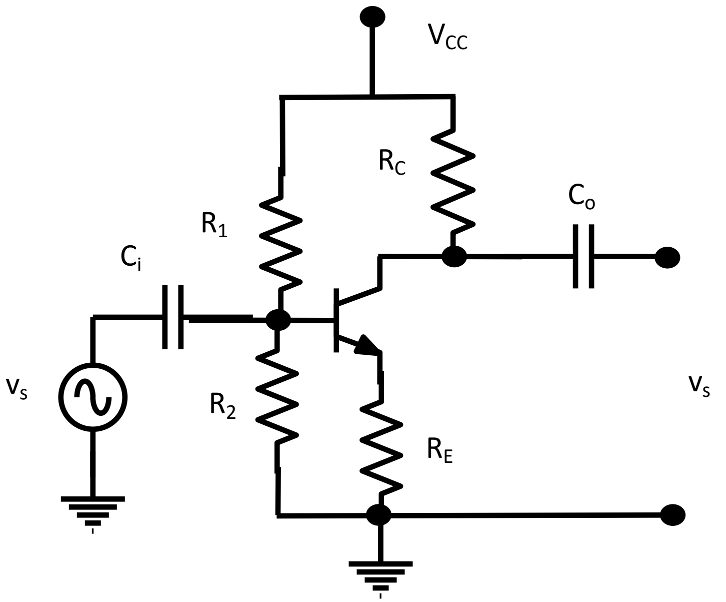
Common emitter amp

- 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



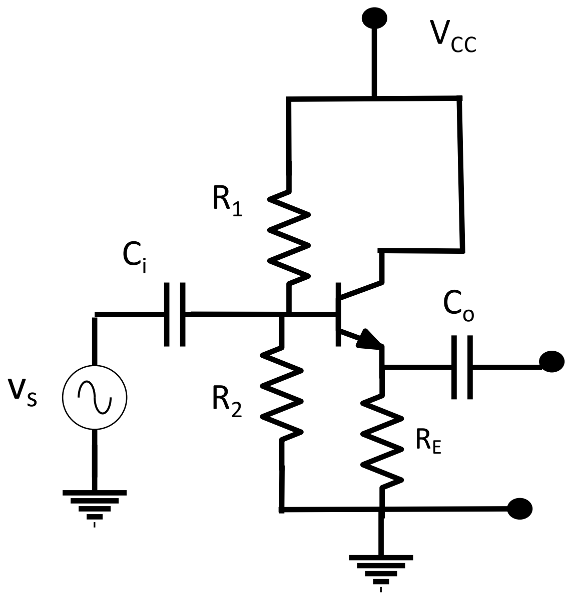
Common emitter amp

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 $V_{be} + i_c R_E$ = 1.8V.
8. We insert a voltage divider consisting of R_1 and R_2, so that R_1= (12-1.8)/270 μA $\sim$ 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



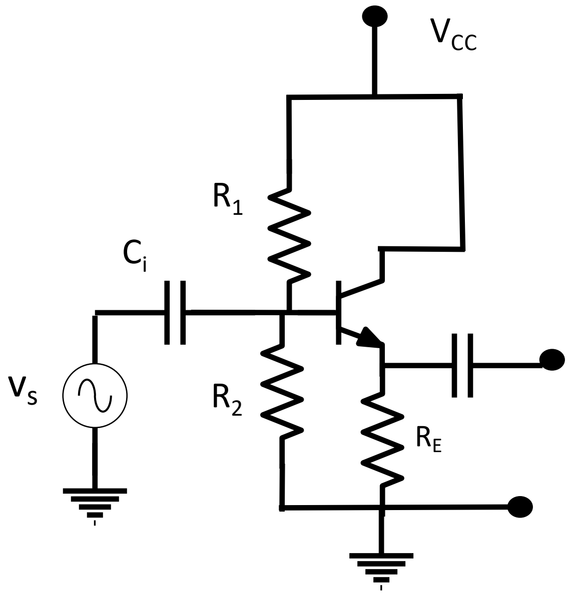
Common collector amp (Emitter Follower)

1. d

Common collector amp

Credit: Ward, Hands on Radio.

BJT common collector amplifier continued

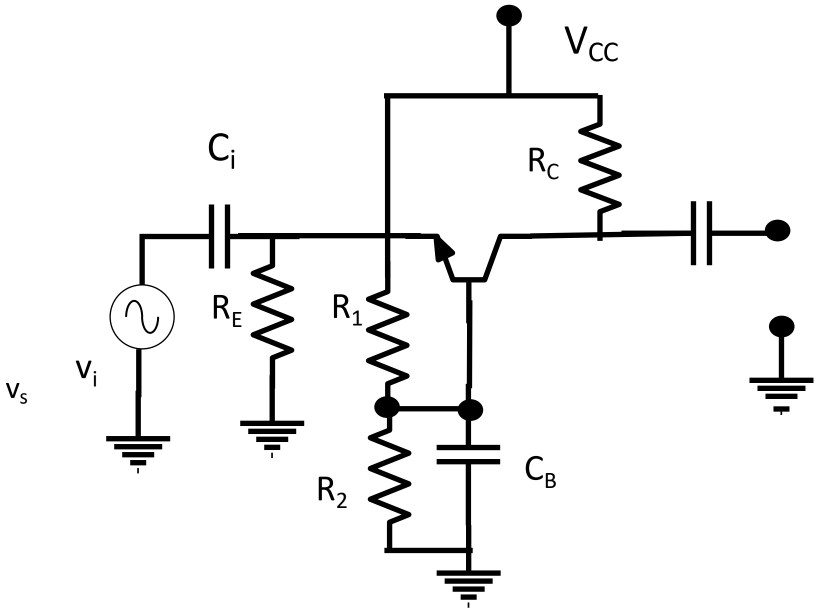


Common collector amp (Emitter Follower)

6. x

Credit: Ward, Hands on Radio.

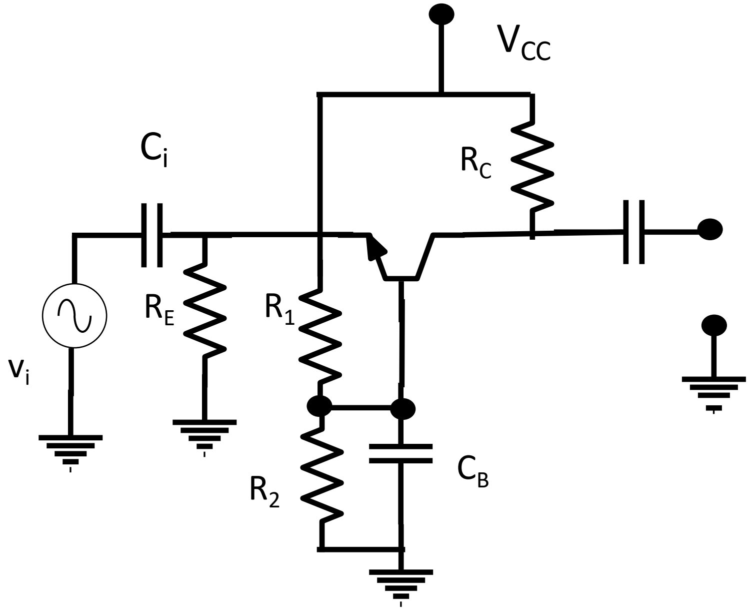
BJT common base amplifier



Common base amp

- x

BJT common base amplifier continued

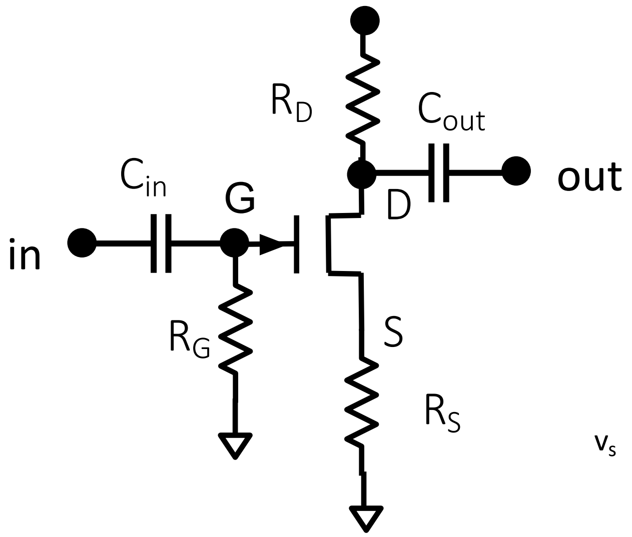


6. x

Common base amp

JFETs

JFET Common Emitter Amplifier



v_s

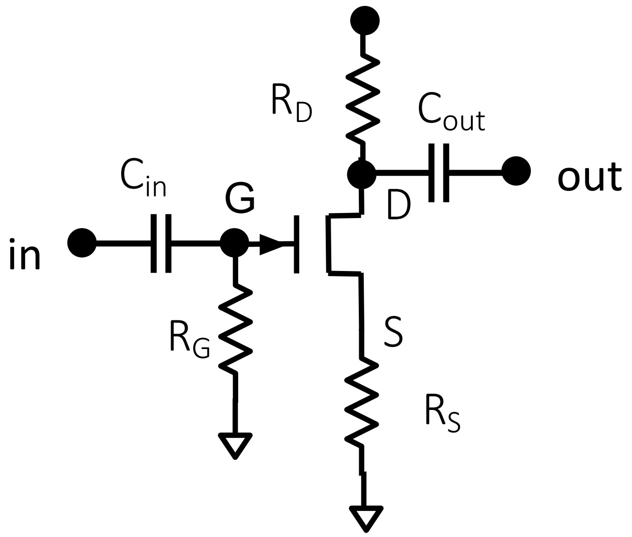
v_s

- x

JFET common emitter amplifier continued

6. x

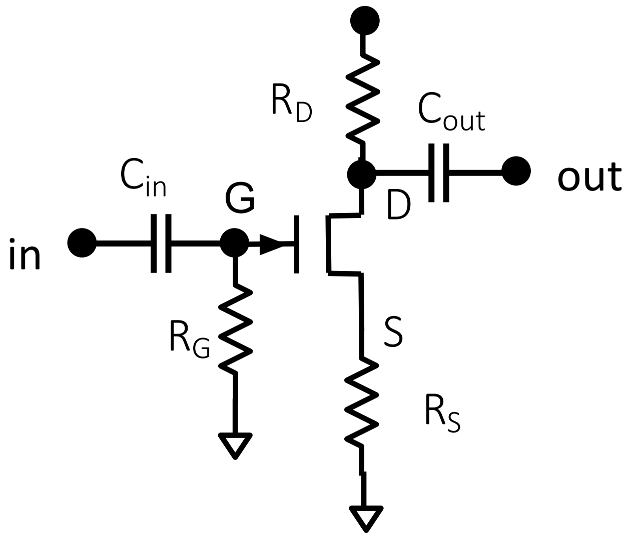
JFET common source amplifier



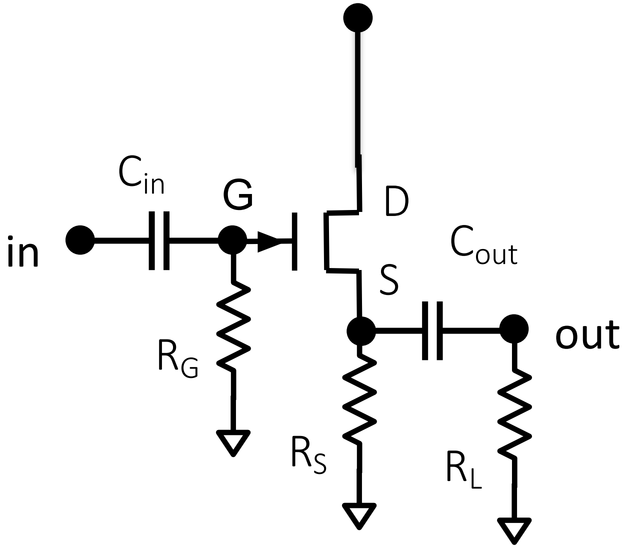
1. d

JFET Common Source Amplifier continued

6. x



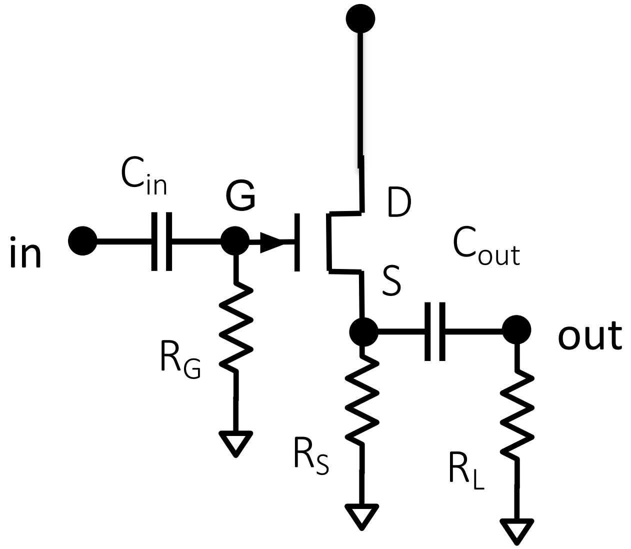
JFET common drain amplifier



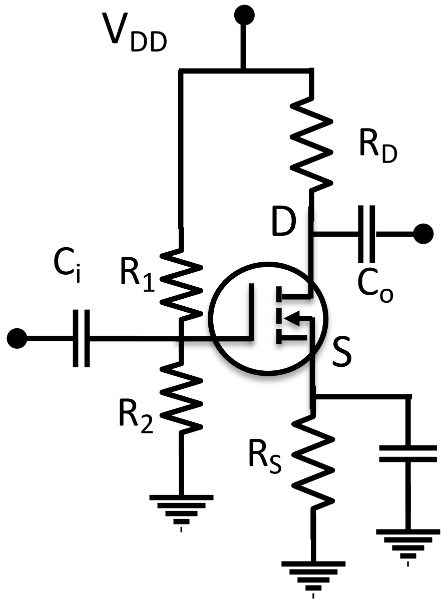
- x

JFET common drain amplifier continued

6. x



CMOS common emitter amplifier

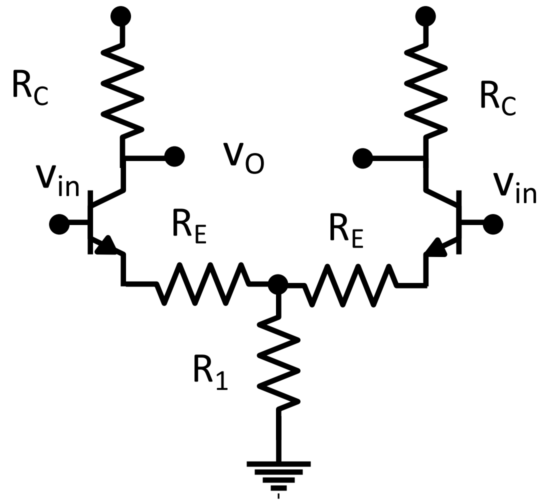


- Pick power
- $V_{DD} = i_D R_D + V_{DS} + i_D R_S$
- $V_{GS} = V_G - i_S R_S$
- $V_G = V_{DD} \frac{R_1}{R_1+R_2}$
- $i_D = k(V_G - V_{TH})^2$
- Bias around $\frac{V_{DD}}{3}$
- Pick gain, $A = \frac{R_D}{R_S+\frac{1}{g_m}}$

Differential Amplifier

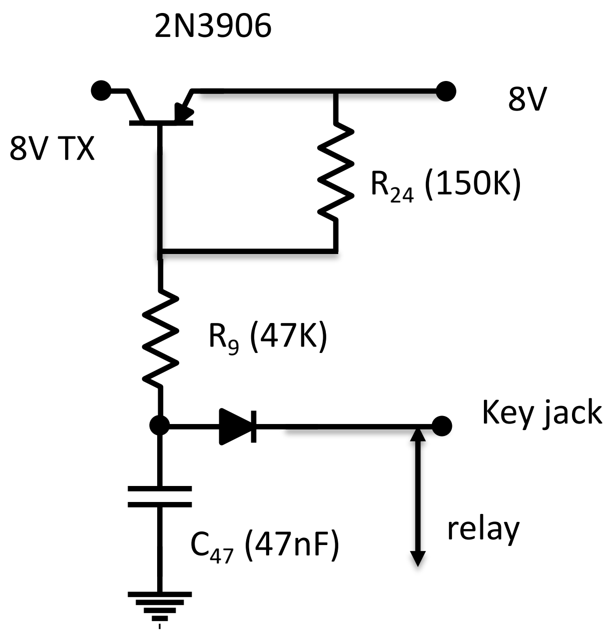
- Two port model
- $\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}$

Differential amplifier



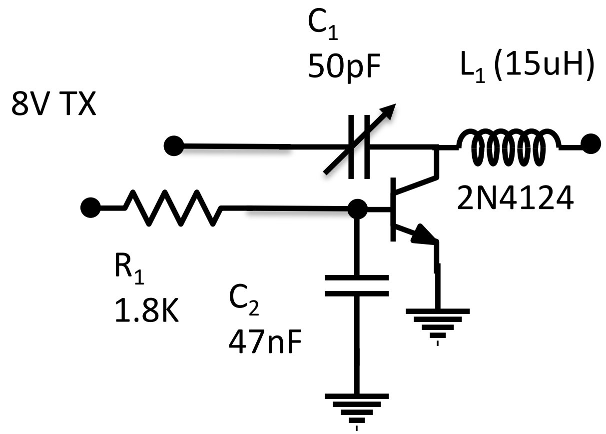
- Pick power ∓ 12
- Choose collecter current ($2mA$) by picking R_1
- Pick gain, $A = \frac{R_C}{2R_E}$

NorCal transmitter switch



- When key is down, transistor conducts

Norcal receiver switch

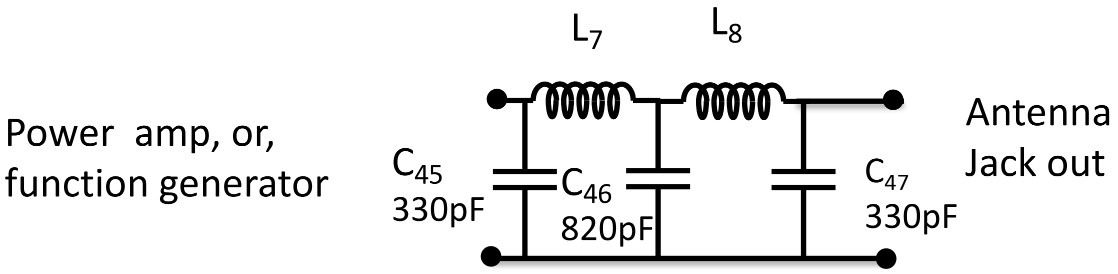


Harmonic filter

If using function generator
use a 1.8K resistor

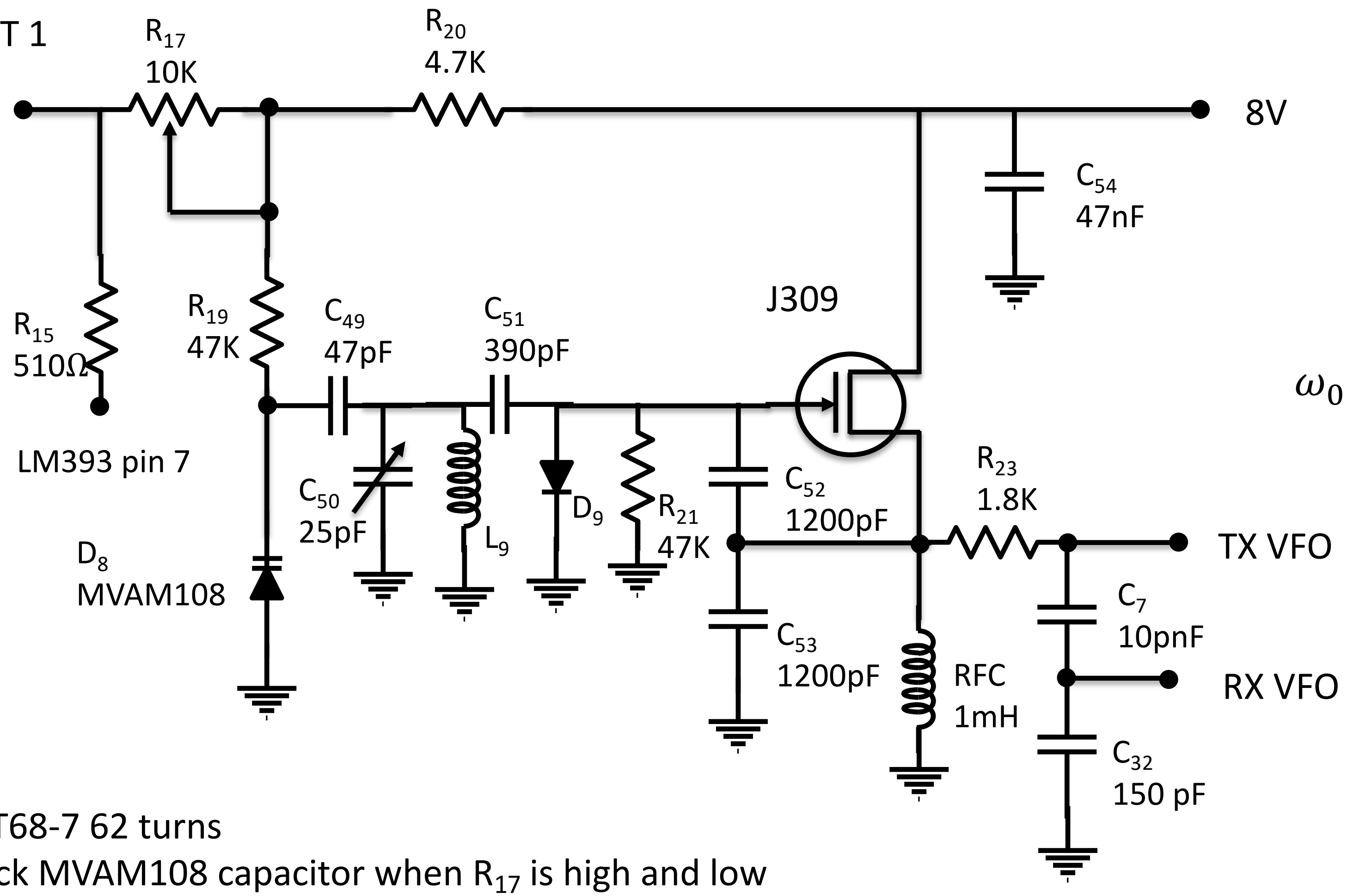
- Receiver mixer or an oscilloscope with 50Ω
- When transistor conducts the receiver filter shor ts

Norcal Harmonic Filter



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

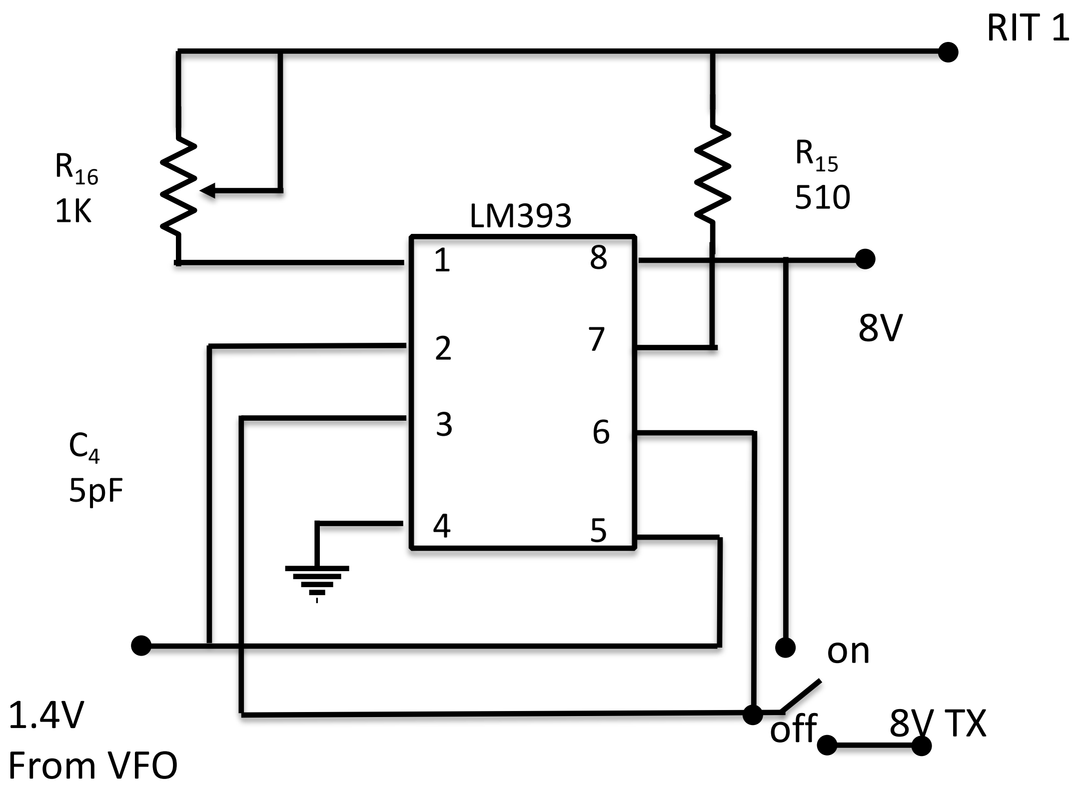
Norcal VCO



$$\omega_0 = \frac{1}{\sqrt{LC}}$$

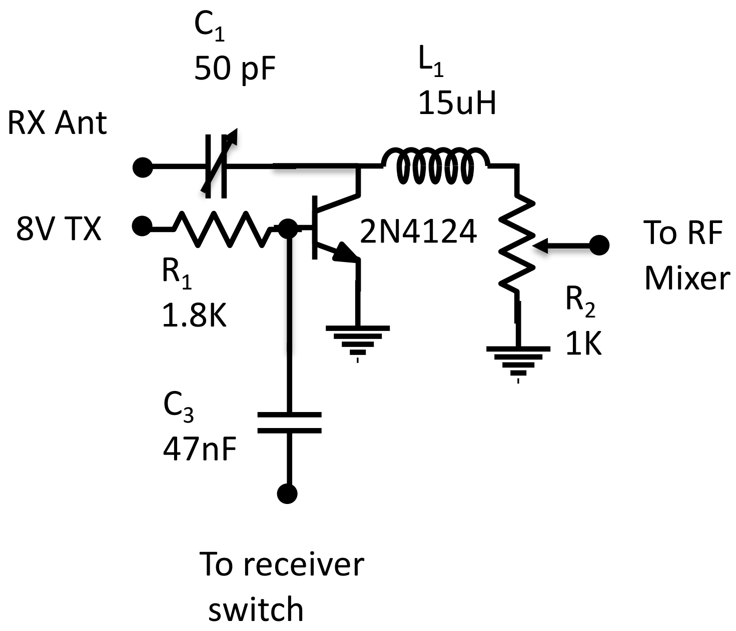
- L9: T68-7 62 turns
- Check MVAM108 capacitor when R_{17} is high and low
- Start resistor (R_{21}) pulls gat to ground at start
- When gain limiting diode (D9) conducts, it pulls gate negative
- Oscillator keeps growing as long as g_m>1/R

Norcal Receiver Incremental Tuning (RIT)

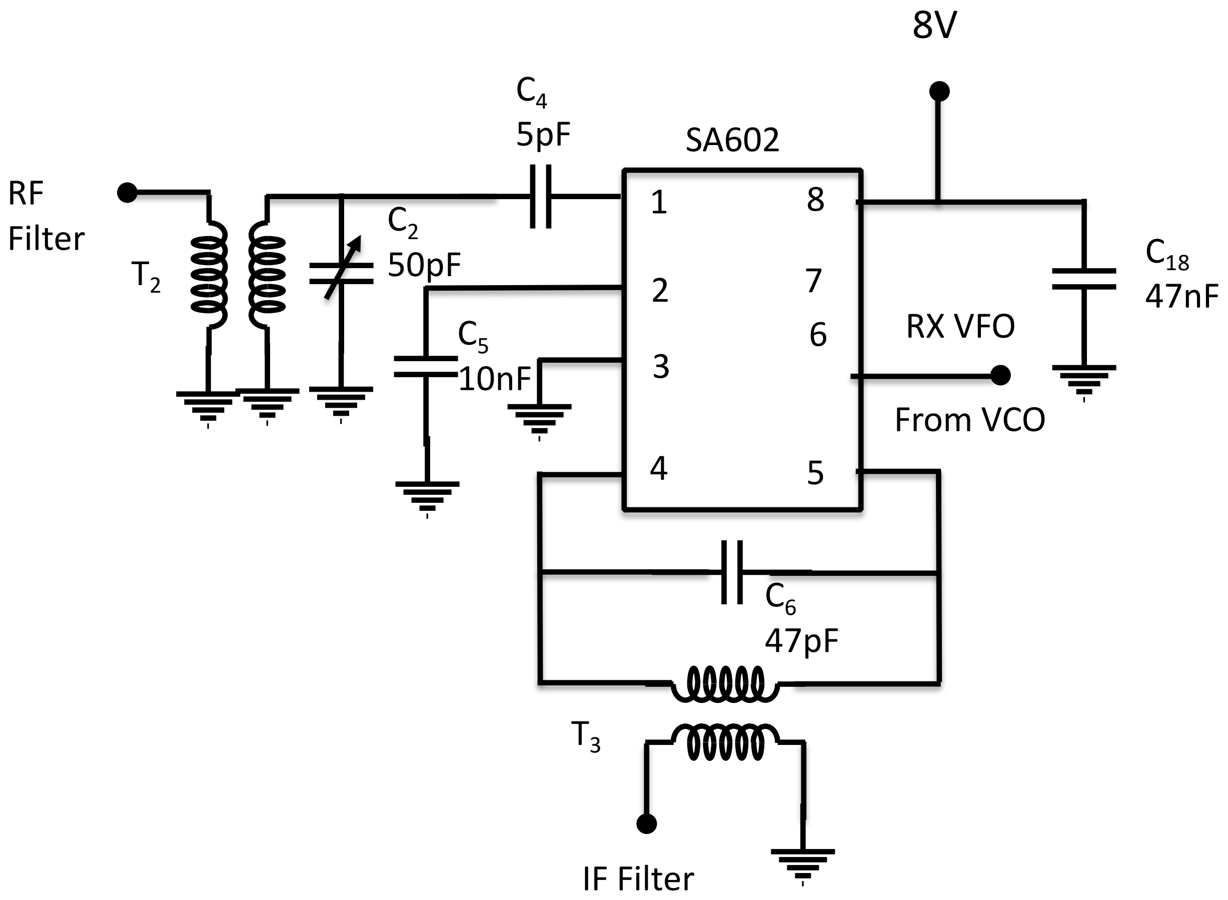


- LM393 is a comparator
- For function generator connect through 1.5K

Norcal RF Filter

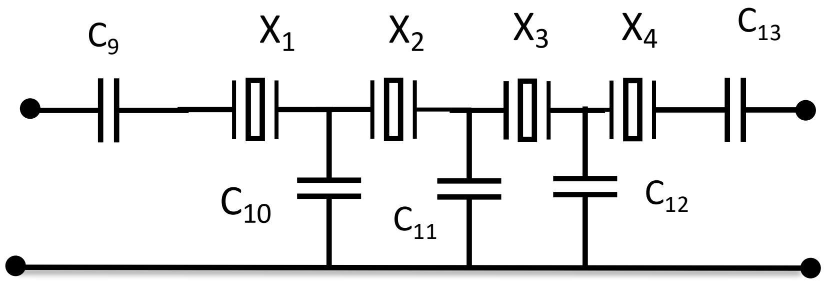


Norcal RF Mixer

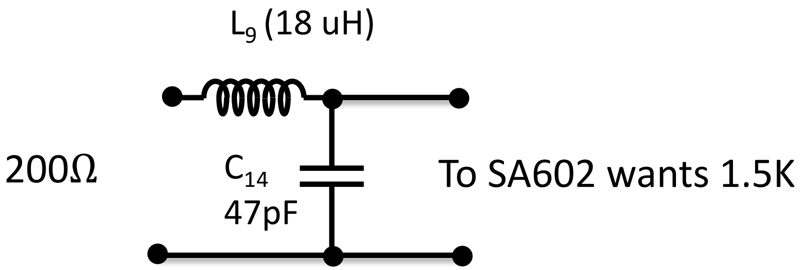


50mVpp if
using function
generator

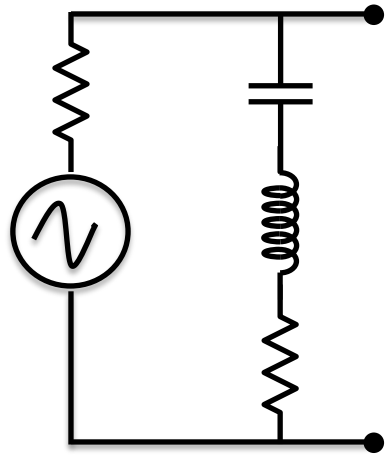
Norcal IF Cohn Filter



- 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

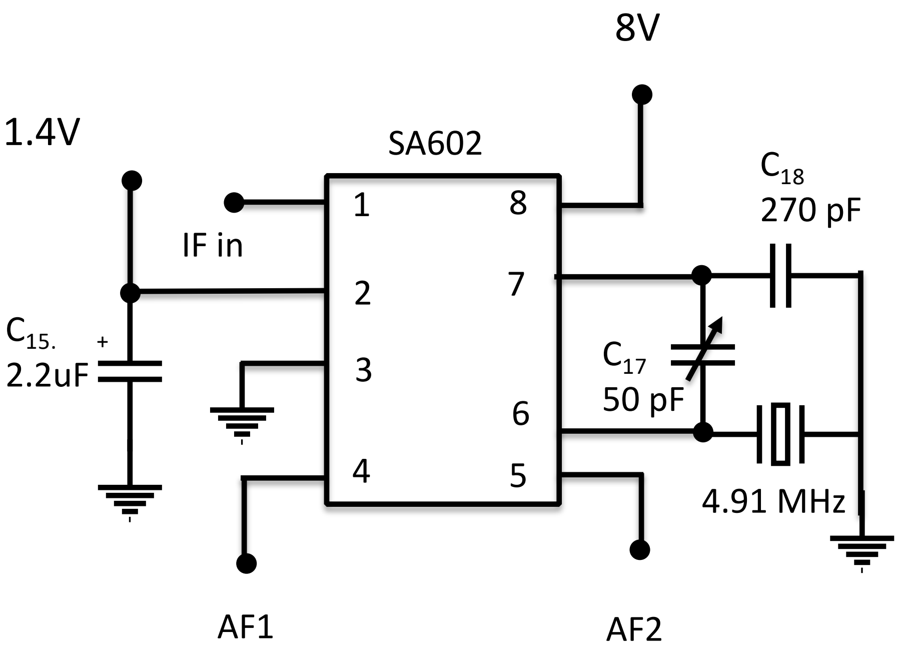


Matching network



Equivalent circuit for crystal and generator

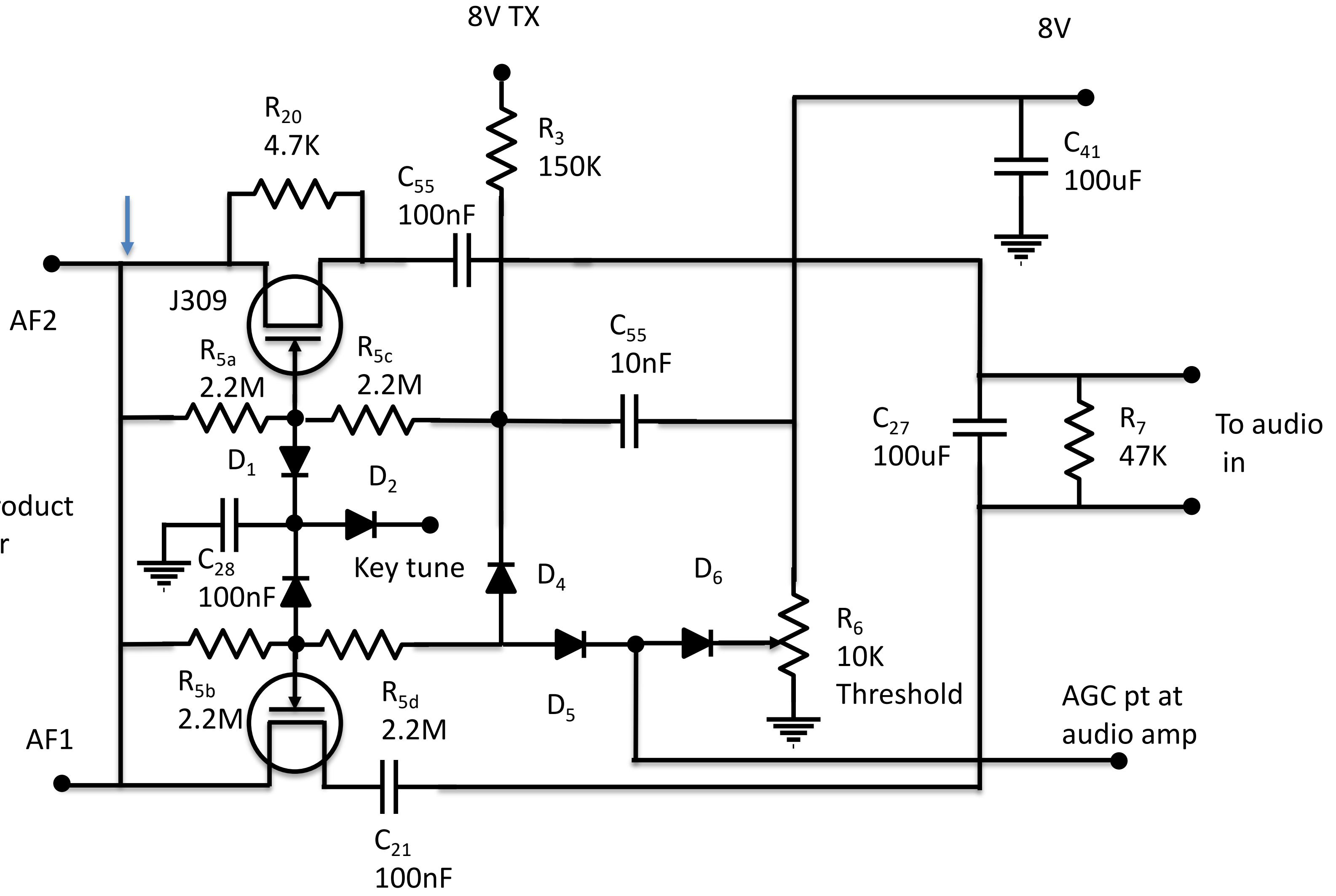
Norcal Product Detector



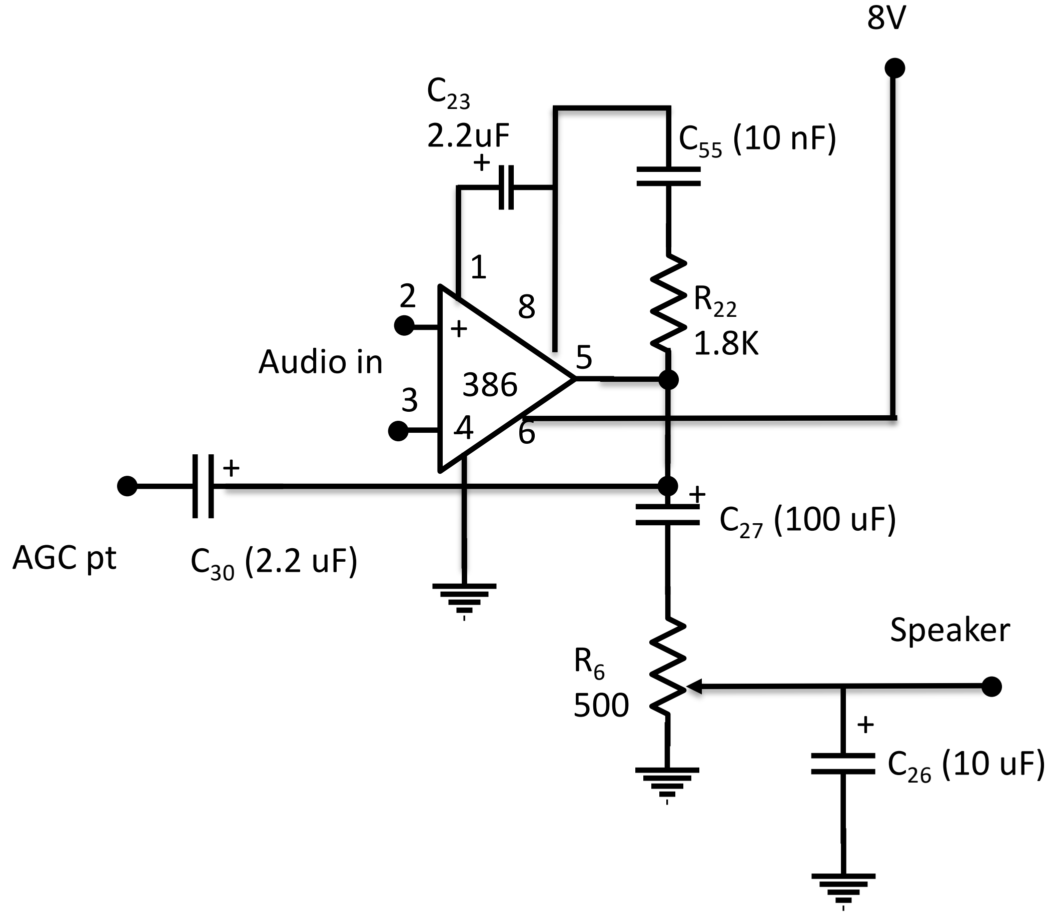
- 620 Hz output through AF1 and AF2

Norcal AGC

Connect to
function generator
through 300K, here



Norcal Audio Amp

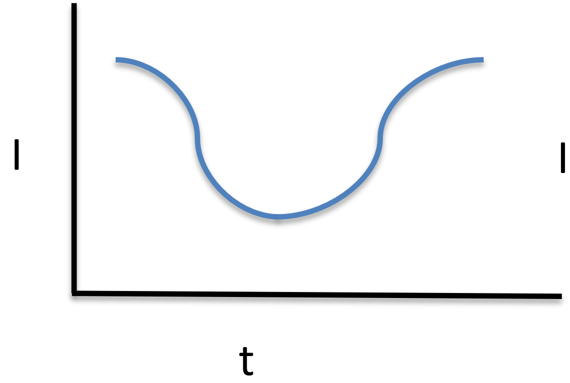


Amplifier classes

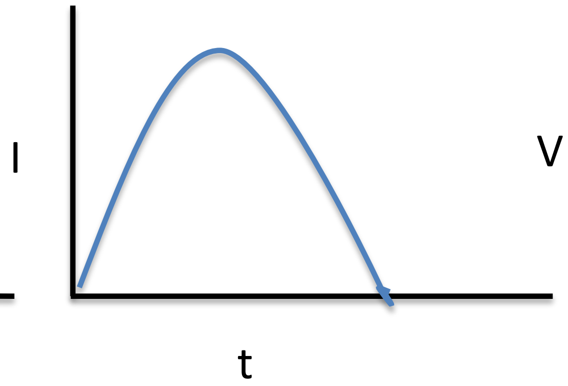
Class	**Efficiency**	**Characteristics**
A	35%	Full bias
B	60%	Low bias
C	75%	Saturating
D	75%	Switch in pass-band
E	90%	Voltage switch
F	80%	Harmonic resonators

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

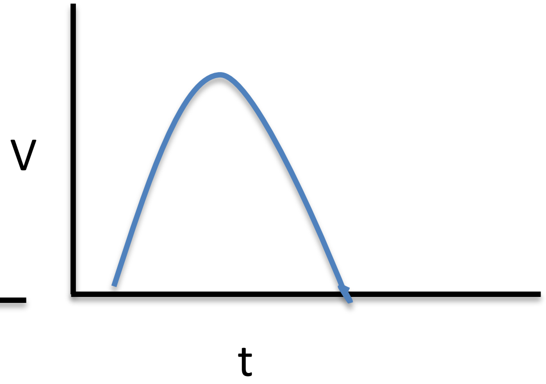
$$P_d = P_a + P_{on}$$



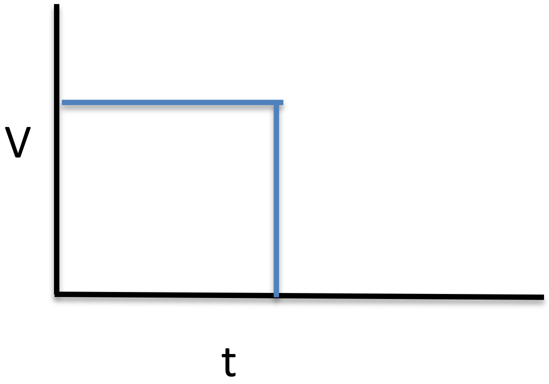
Class A



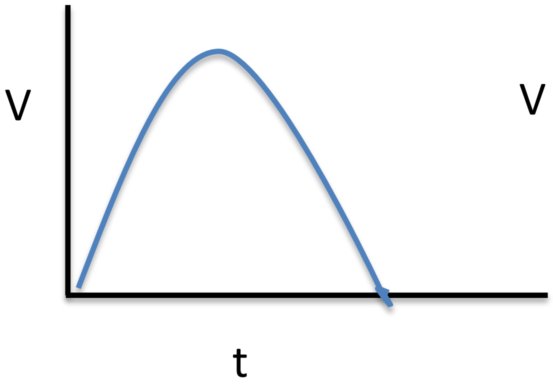
Class B



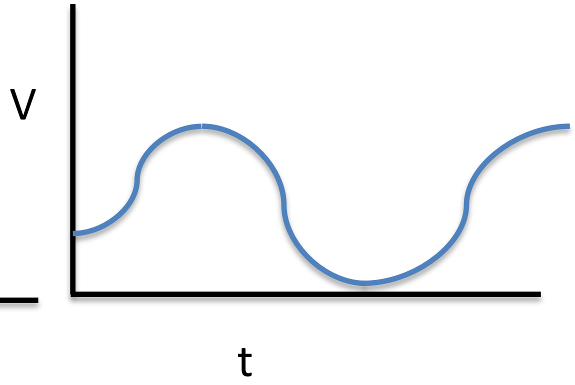
Class C



Class D



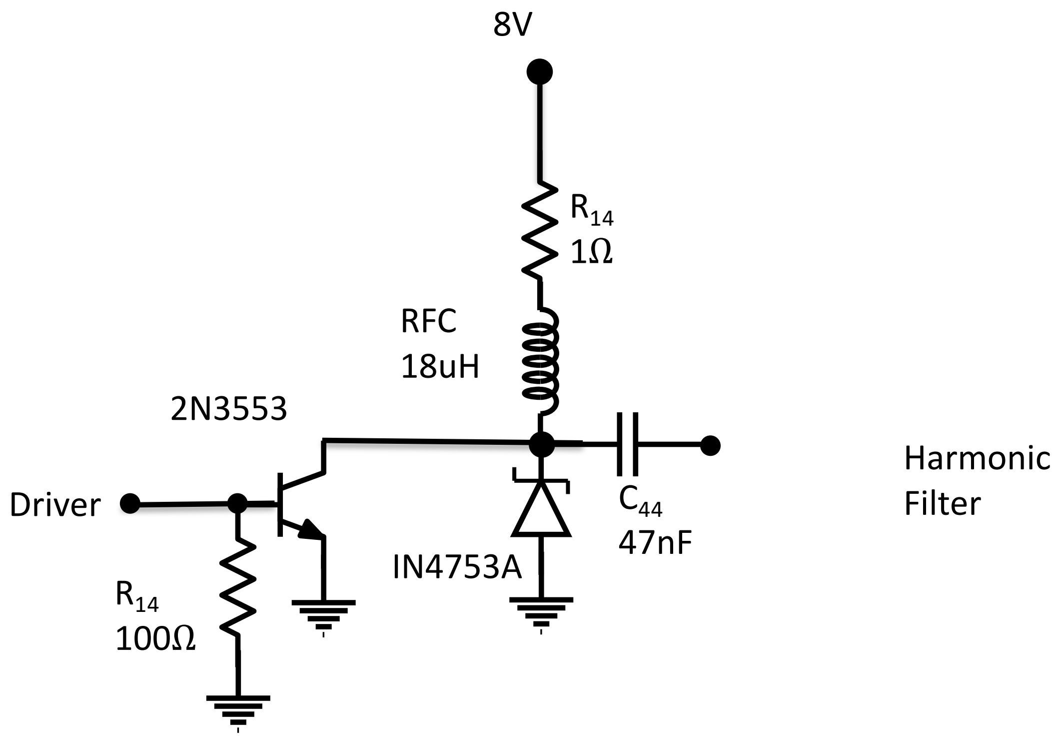
Class E

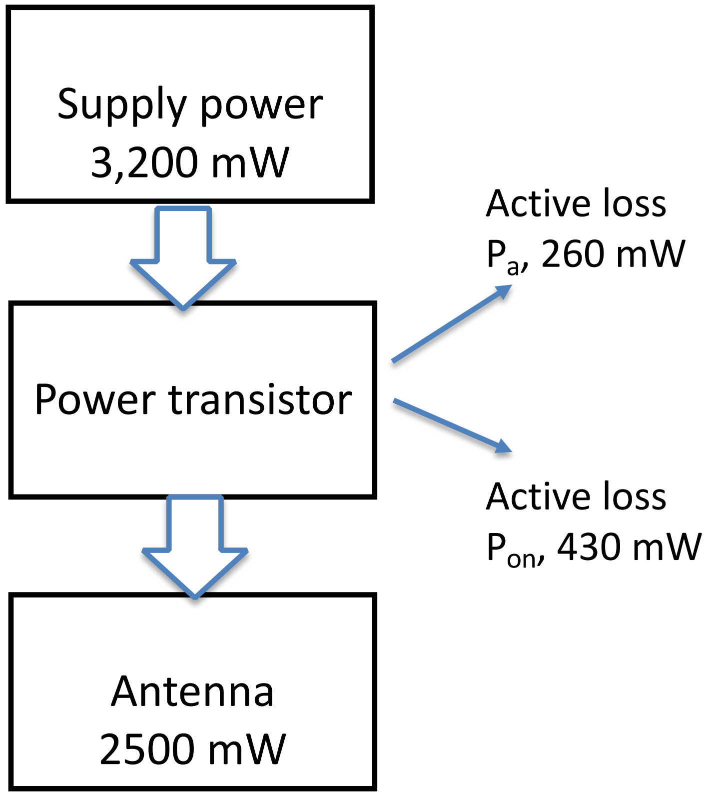


Class F

Norcal Power Amp

Norcal-40 Power amp is class C



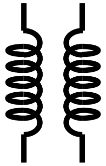


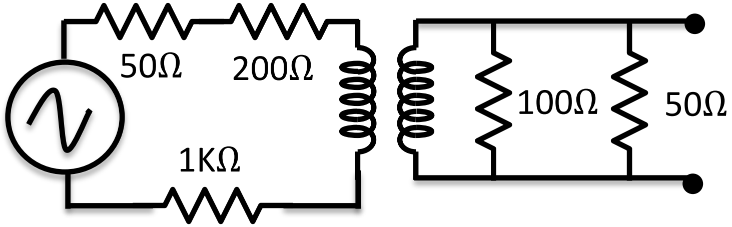
- $R_t = \frac{T - T_0}{P_d}$
- T_0 is ambient temperature, T is heat sink temperature

Norcal matching transformers

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

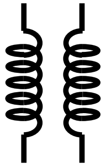
T_1, 14:4

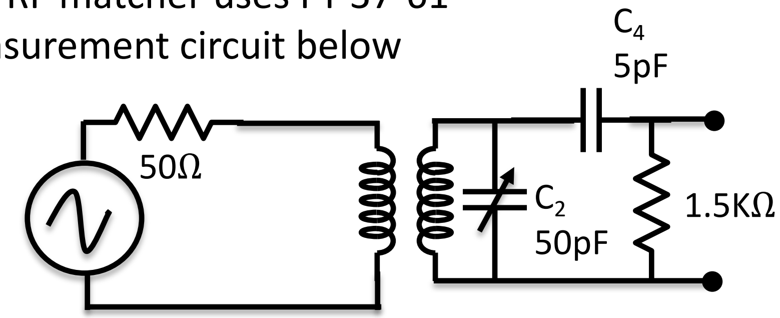




- T_2 is RF matcher uses FT 37-61
- Measurement circuit below

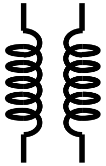
T_2, 1:20

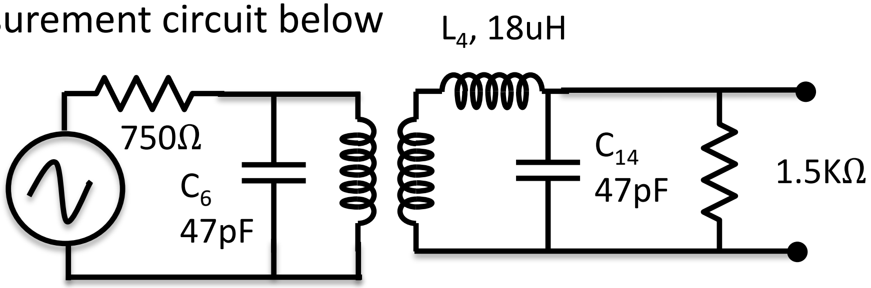




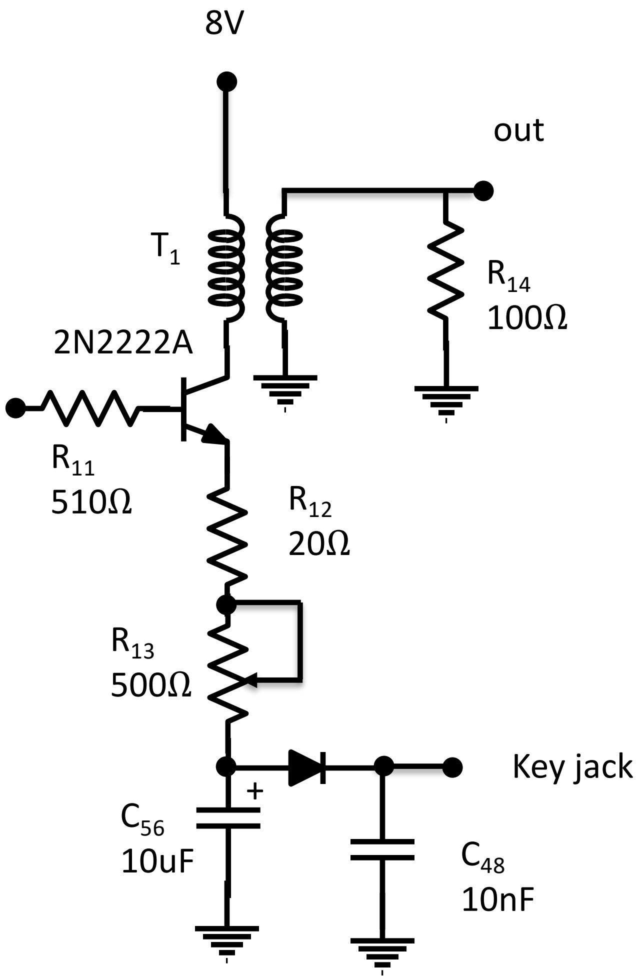
T_3, 23:6

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



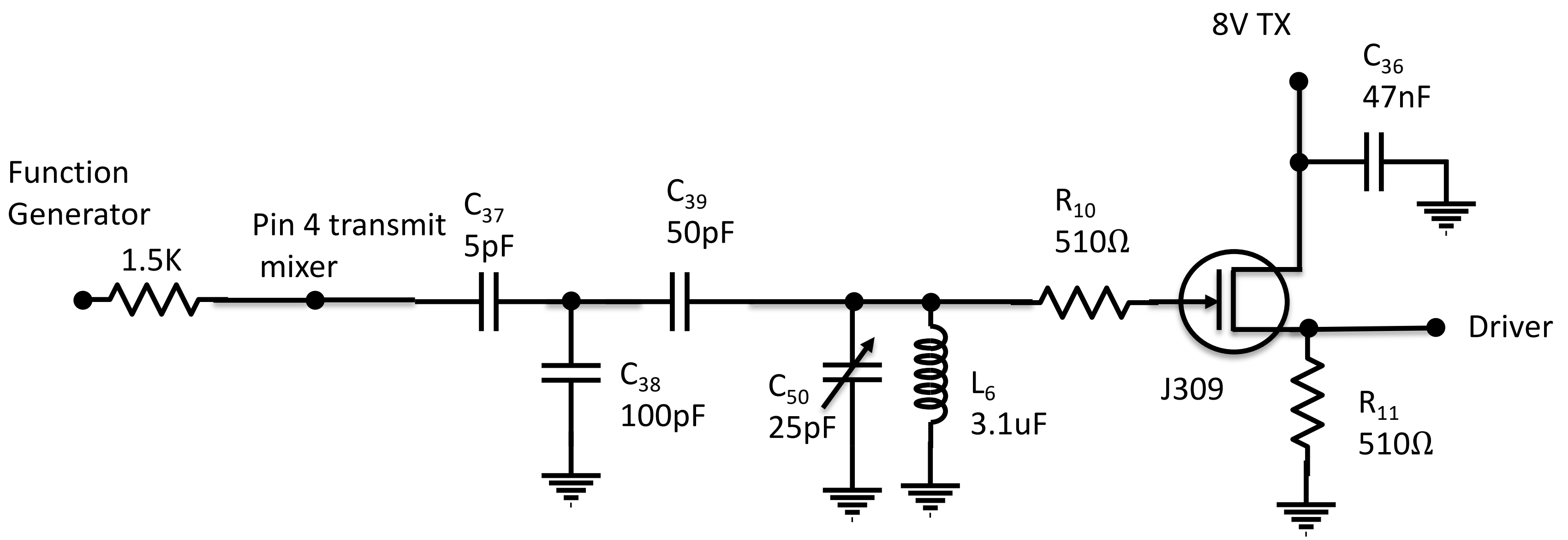


Norcal Driver



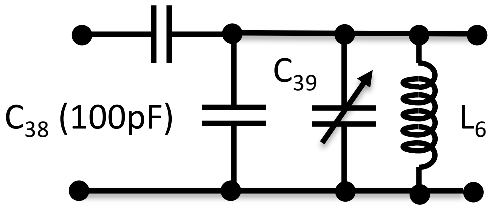
- Use 50Ω scope probe

Norcal Buffer



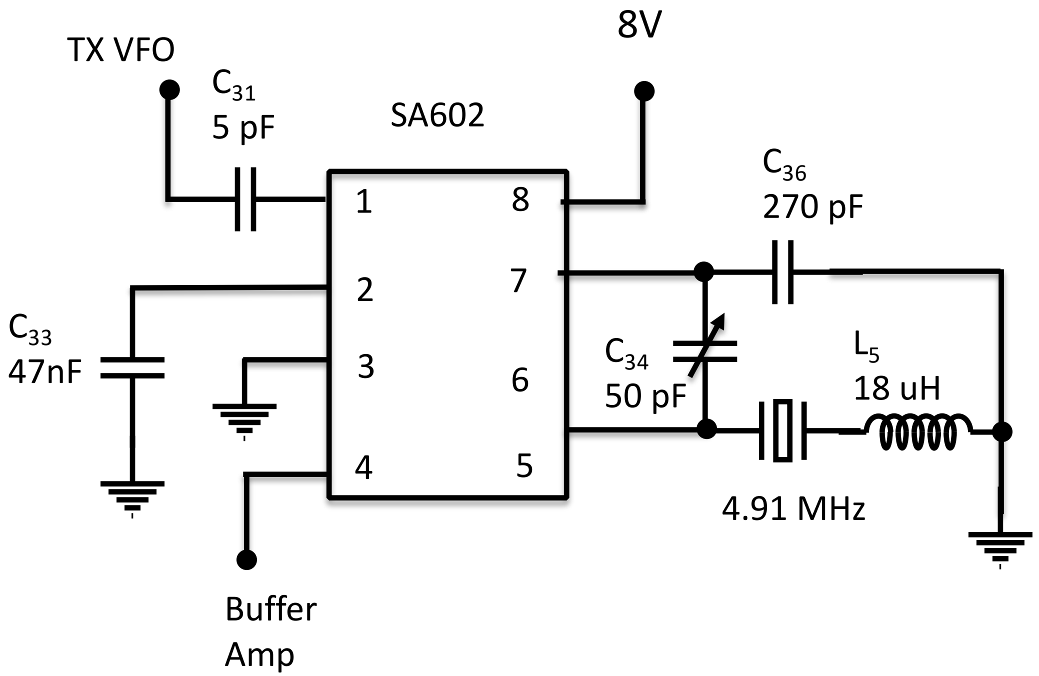
$$G_V = \frac{V}{V_i}$$

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

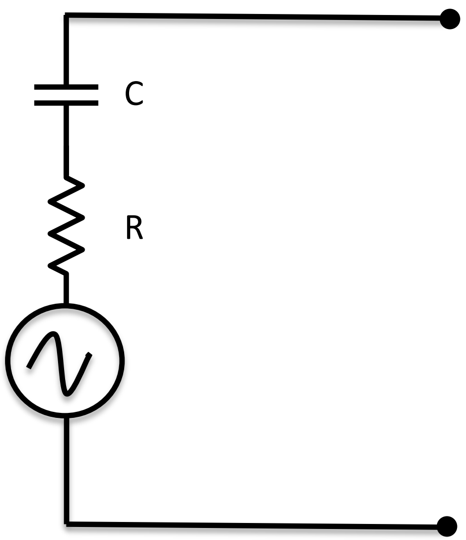
Norcal transmit mixer and oscillator



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

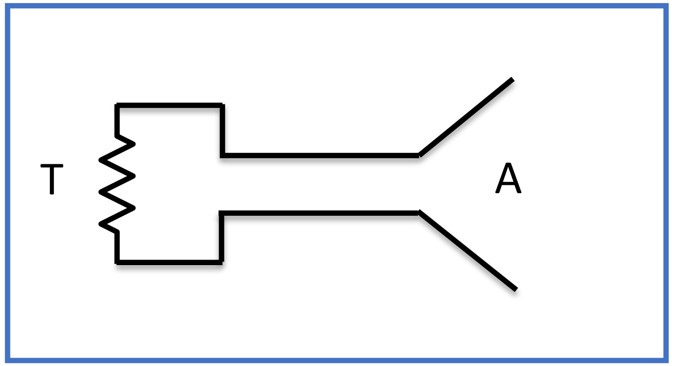


Antennas and propagation

- 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

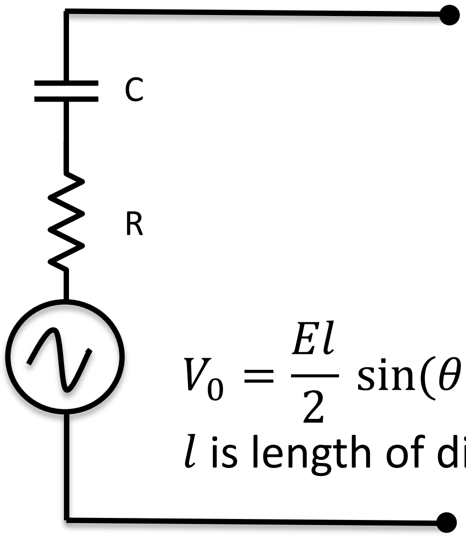
Insulated cavity



- 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

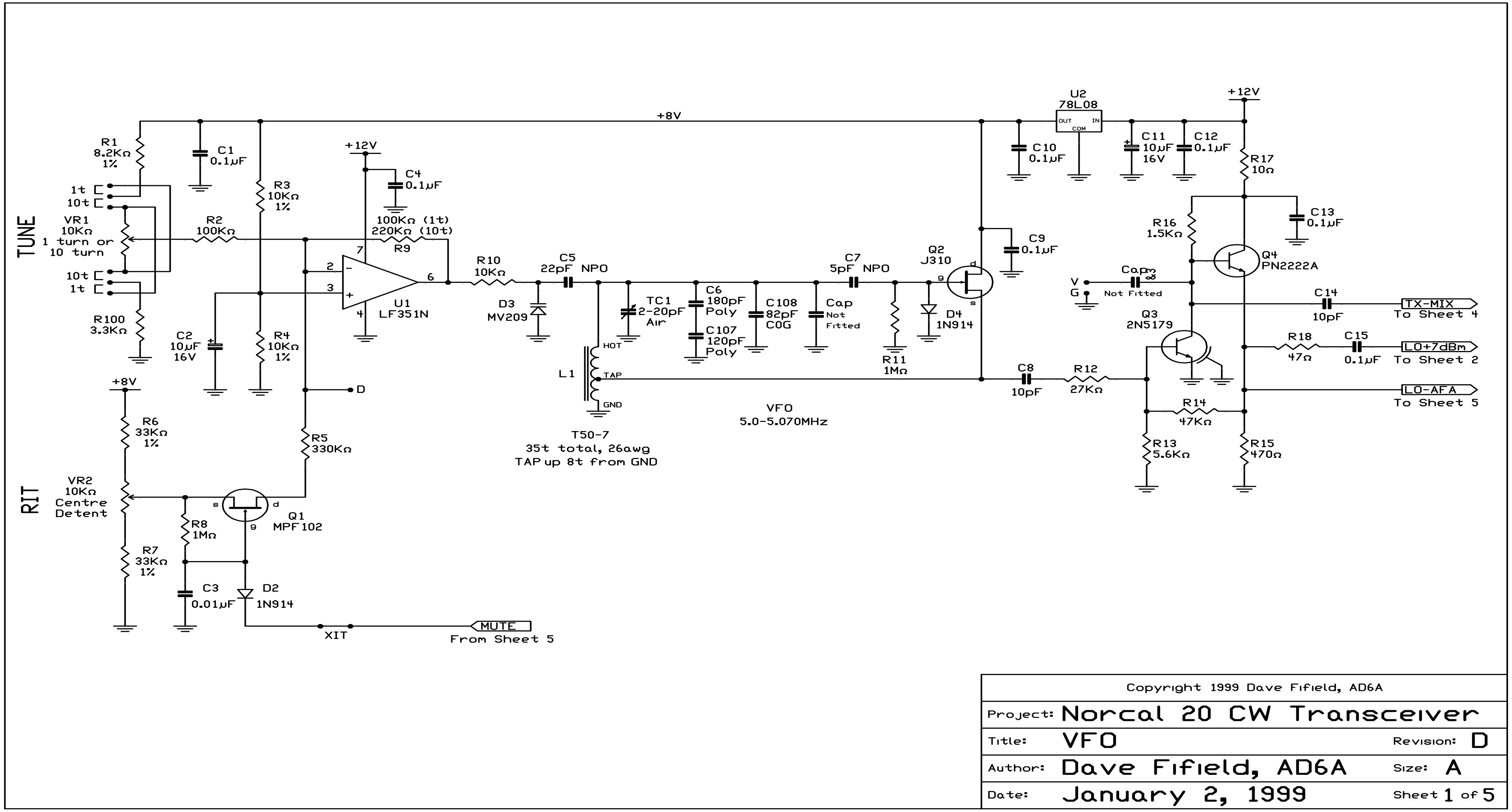
- For dipole (Length: $l = \frac{\lambda}{2}$)
- $\lambda^2 = \int A \, d\Omega = \int \frac{h^2 \eta_0}{4R_r} \, d\Omega$, so
- $R_r = \frac{l^2 \eta_0}{16\lambda^2} \int sin^2(\theta) d\Omega = \eta_0 \frac{\pi}{6} \, (\frac{l}{\lambda})^2$
- $A = \frac{3\lambda^2}{8\pi} \, sin^2(\theta)$ and $G =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

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

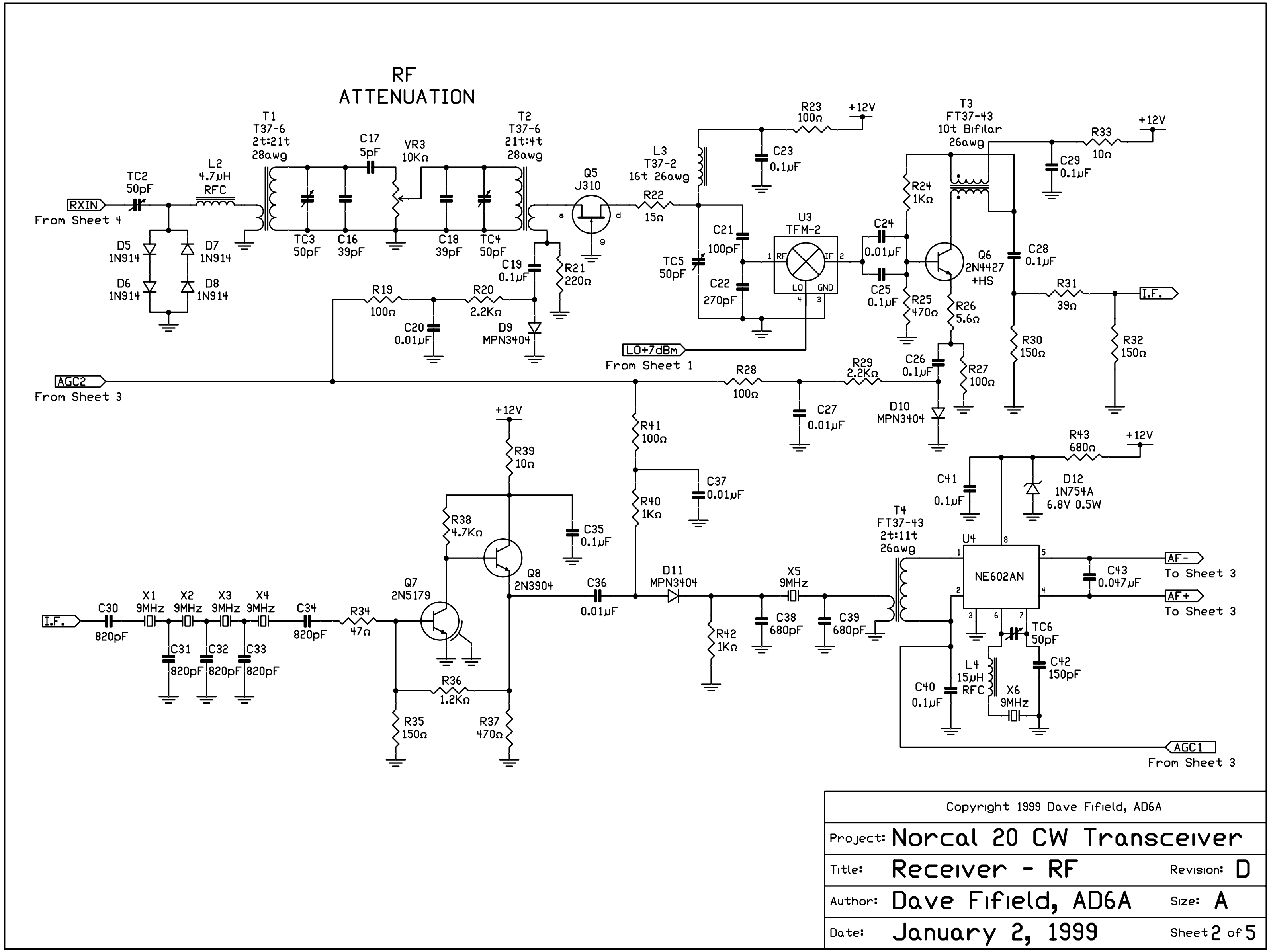
Noise

- $V_{n(rms)} = \sqrt{\frac{1}{\tau}\int_0^{\tau} V(t)^2 \; dt}$
- $P_n = \frac{{V_{n(rms)}}^2}{R}$, 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, $\overline{|V_c|^2} = 8\mathrm{kTR}$

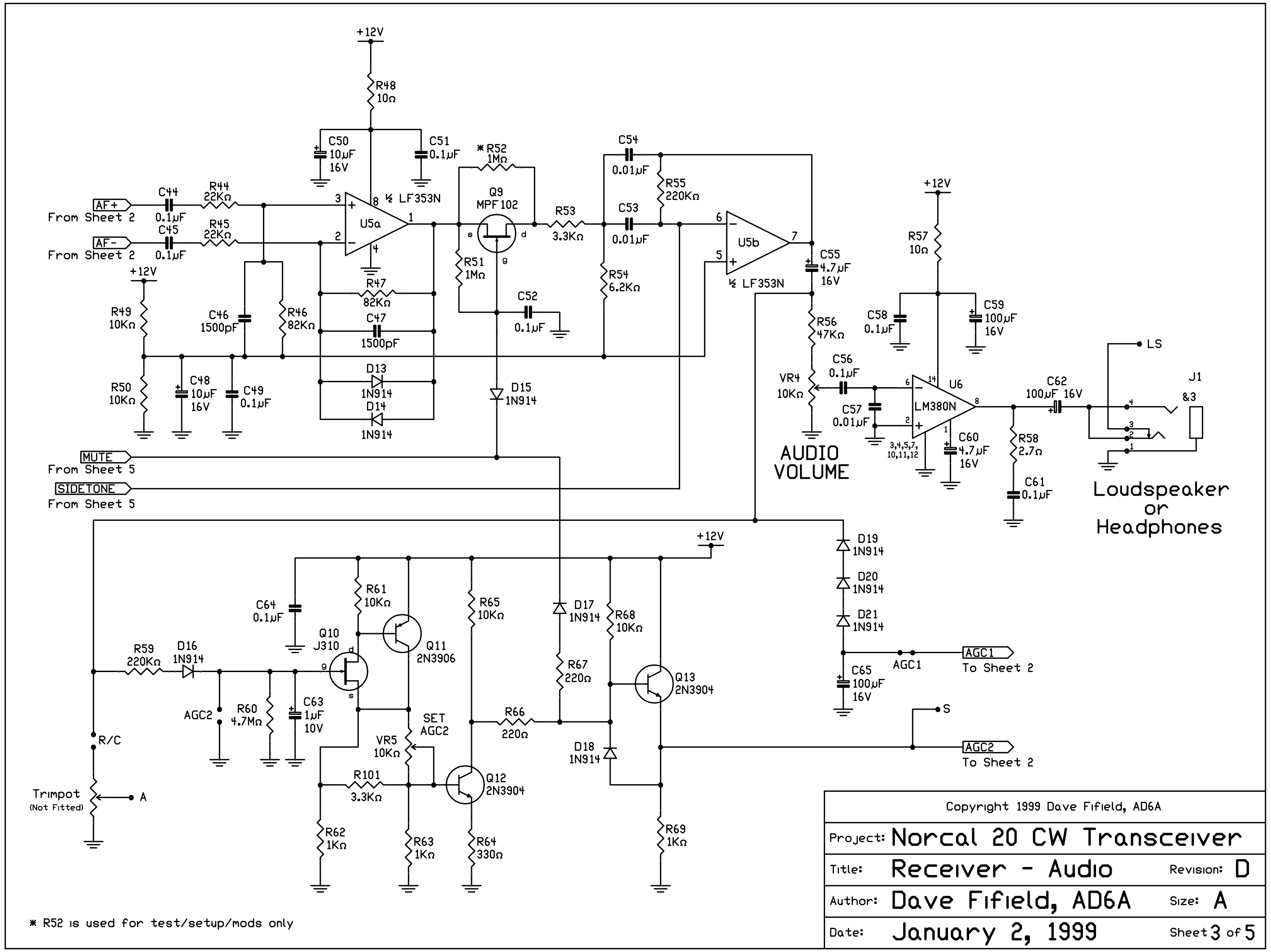
Norcal circuit diagram, 1



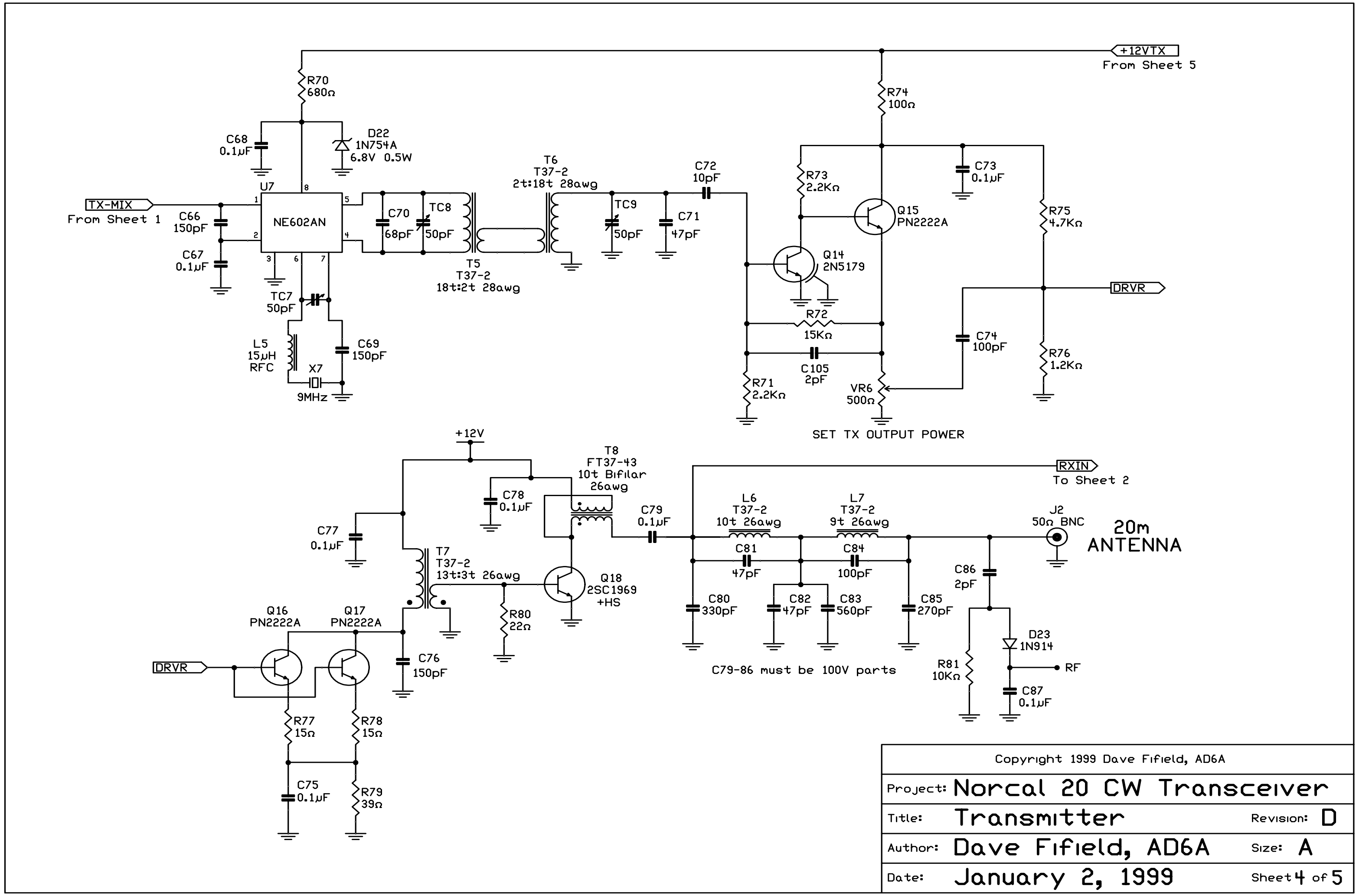
Norcal circuit diagram, 2



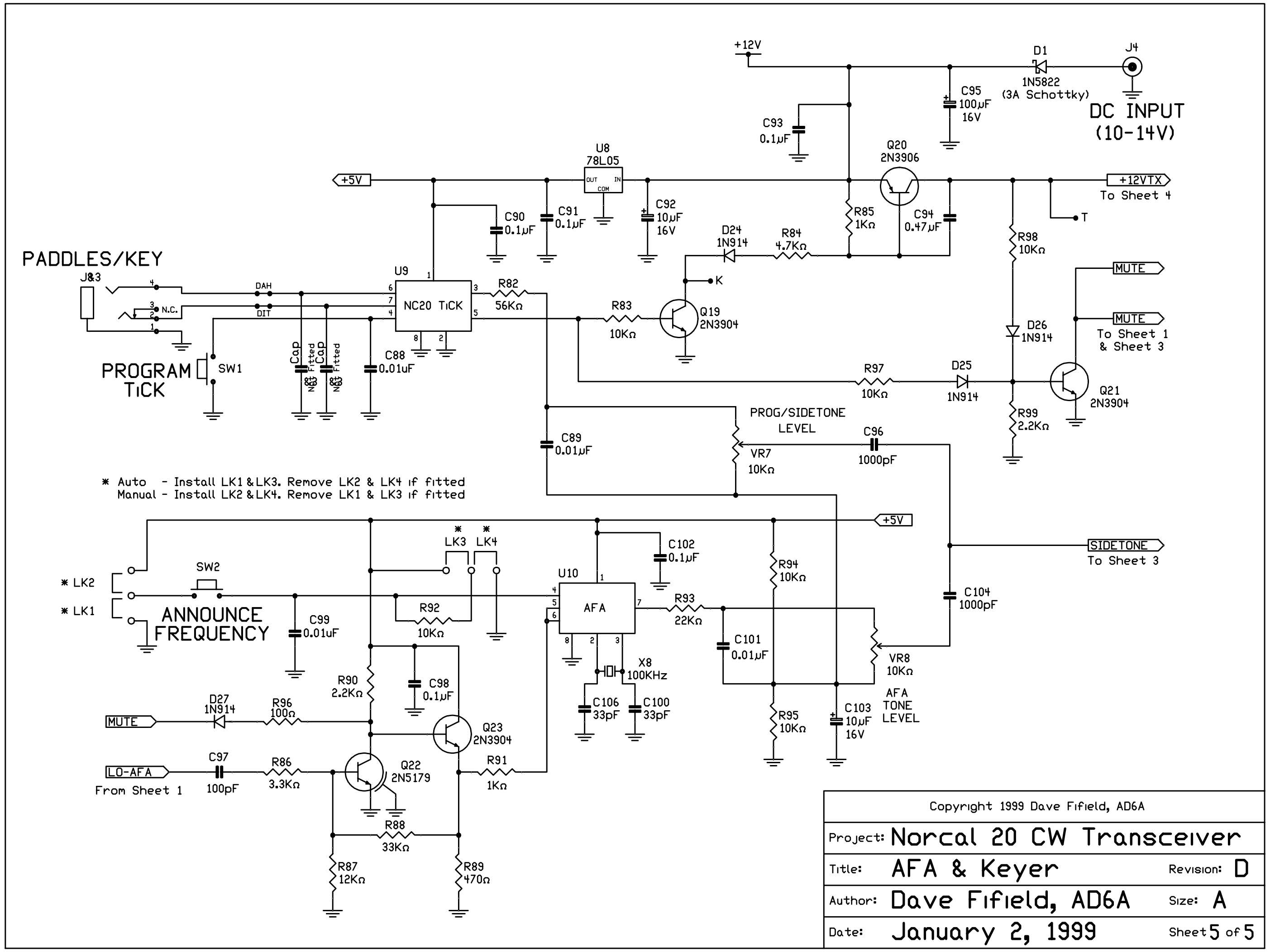
Norcal circuit diagram, 3



Norcal circuit diagram, 4



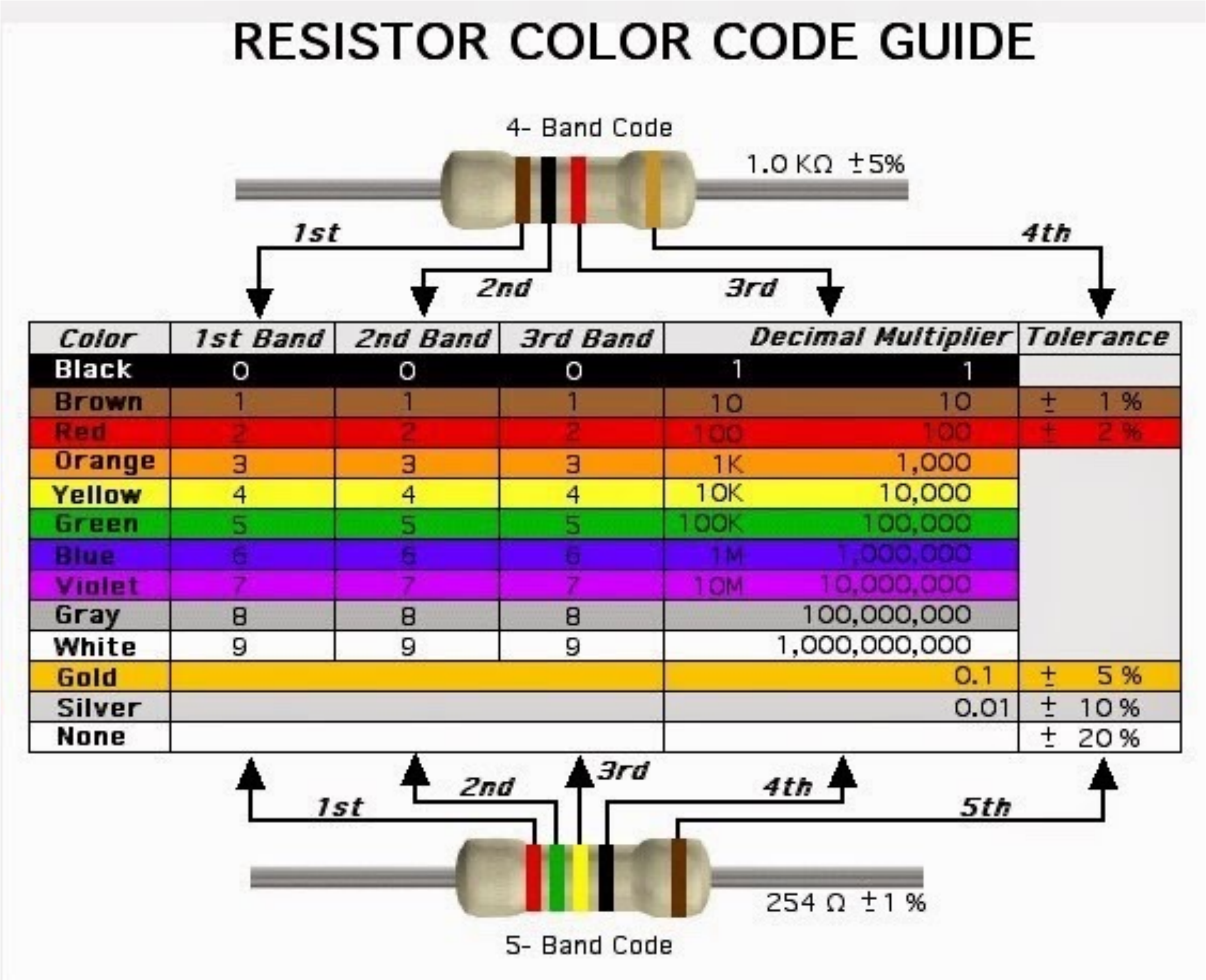
Norcal circuit diagram, 5



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

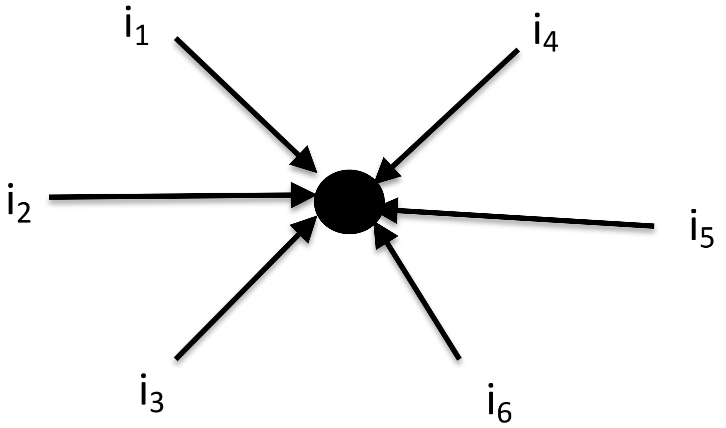


Color	1st Band	2nd Band	3rd Band	Decimal Multiplier	Tolerance
Black	0	0	0	1 1	
Brown	1	1	1	10 10	± 1 %
Red	2	2	2	100 100	± 2 %
Orange	3	3	3	1K 1,000	
Yellow	4	4	4	10K 10,000	
Green	5	5	5	100K 100,000	
Blue	6	6	6	1M 1,000,000	
Violet	7	7	7	10M 10,000,000	
Gray	8	8	8	100,000,000	
White	9	9	9	1,000,000,000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

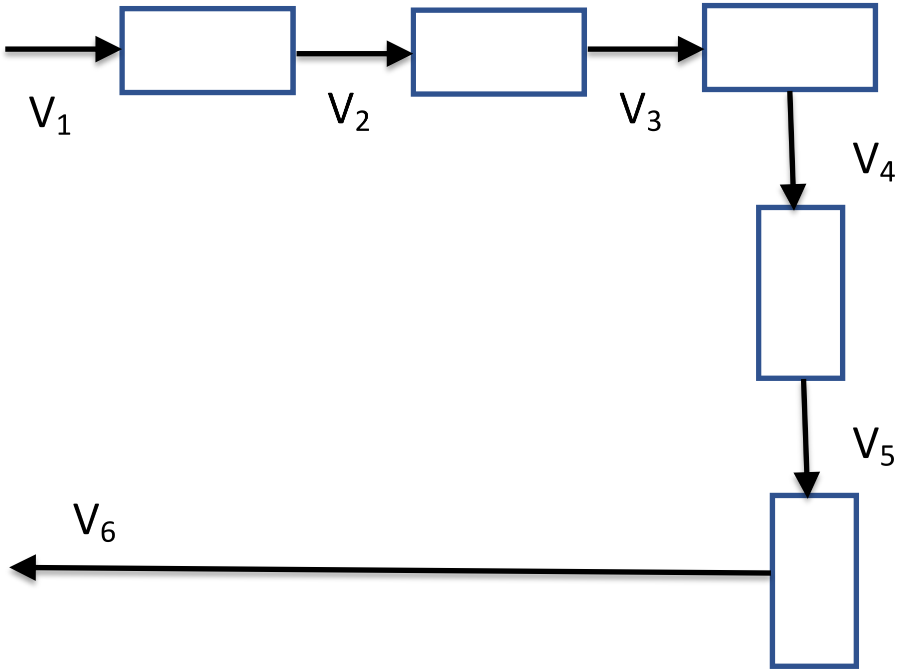
- Resistors: ohms
- Capacitors: picoFards
- Inductors: milliHenries

Kirchhoff

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



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



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