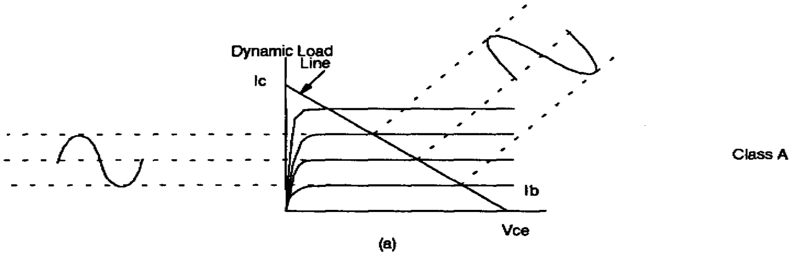
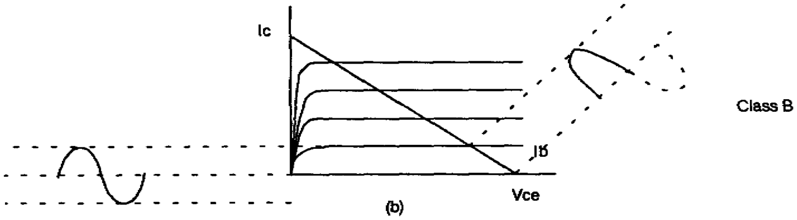
EC597 – Wireless Communications Electronics
SU2000 - DRV
Class Notes – Session 8

Amplifier Modes of Operation – See Chapter 10 of the textbook.

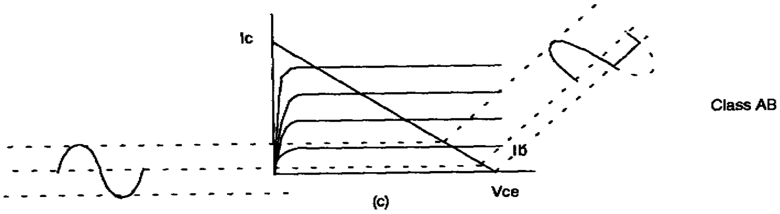
Class A: Purely linear in operation; the device is conducting for 360° of each cycle. Great for exact reproduction of waveshape so it is used greatly for audio applications where fidelity is desired and for RF signals that require undistorted outputs such as AM, SSB, and QAM. But, it suffers from poor efficiency due to the fact that it must be biased on at $V_Q=V_{PEAK}/2$ so that power is dissipated even with no signal input. The best efficiency from Class A operation is when the sinusoidal signal is driven to it's peak value. This gives an efficiency of $\eta=P_{AC}/P_{POWER\ SUPPLY}=25\%$. (I don't know how Rutledge got 35%!) This is the best, it is lower for smaller signal levels.



Class B: This mode is biased just at cutoff condition so that when no signal is present it does not dissipate power. Therefore, the device conducts for 180° of each cycle. Obviously this distorts the wave shape. But when two devices are connected with opposite polarity one conducts for positive signals the other for negative to theoretically produce a distortionless signal. The most common Class B circuit is known as a push-pull circuit. However, practically, the 0.6 V positive bias required by a BJT transistor to turn on makes introduces crossover distortion near the zero crossings. The efficiency of Class B operation is $\eta=78.5\%$. The average or DC current in each transistor keeps the efficiency below 100%.



Class AB: This mode is a compromise between Class A and Class B. A push-pull configuration of the devices is required with each device biased slightly on to avoid crossover distortion. This results in conduction between 180° and 360° depending upon the bias point. The efficiency is somewhat less than Class B operation, but it is significantly better than Class A operation, typically $\eta\approx60$-70%. On the other hand, the Class AB operation is significantly more linear than Class B operation.



Class C: The device is biased significantly in the off state so that the input signal turns on the device for only a small portion of the cycle and conduction occurs for less than 180°. When operated properly, the device is driven nearly to saturation so that short, but large pulses at the input frequency appear in the output. The transistor acts as a switch turning the power supply voltage on and off at the signal frequency. Consequently the output is a highly distorted version of the input. Fourier series analysis shows that there are many harmonics of the input frequency present in the output. (If it operated in a limiting Class C case it becomes Class B and has only odd harmonics.) To isolate the original frequency from the harmonics a filter is used in the output. This mode of operation is also used to generate harmonics of the original frequency usually doublers or triplers are the most common. The percent of on time must be carefully selected to get generate the desired harmonic efficiently. Ideally power is dissipated only when the device is turned on. However, due to energy storage mechanisms in the device, the transition between the on and off states dissipate power and reduce the efficiency. Nevertheless, Class C operation is very efficient, up to 90%, but more typically 80%.

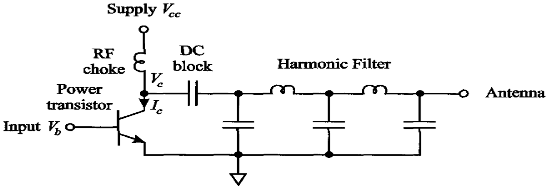


Figure 10.2. Class-C Power Amplifier in the NorCal 40A.

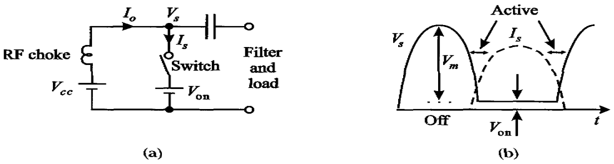
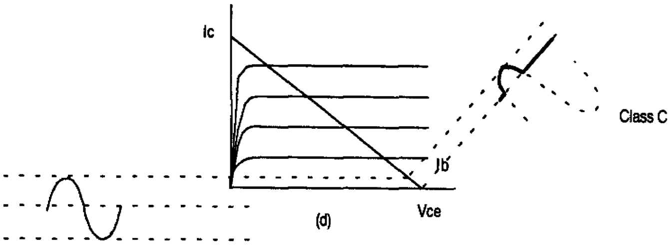


Figure 10.3. Switch model for the Class-C amplifier (a), and switch voltage V_s and current I_s waveforms (b).



Saturating Class C: When the input signal is sufficient to drive the transistor to saturation, a nearly rectangular pulse is produced. However, the amplitude is relatively constant independent of small variations in the input signal. For this reason, This mode is used most often as an RF modulator.

Class D: In an effort to reduce the transition power dissipation of Class C operation, a switching mode of operation with a 50% duty cycle is used in a push-pull configuration. Obviously, filtering is required. The efficiency is improved, but more complicated circuitry is required. A variant of the mode is available using pulse width modulation (PWM) of an audio signal. This mode is sometimes known as Class S mode. The switching frequency is much above the audio band so the filtering is to remove the switching frequency and its harmonics. TI has a Class D, PWM mode audio output chip with extremely low distortion; see http://www-s.ti.com/sc/psheets/slyt005/slyt005.pdf.

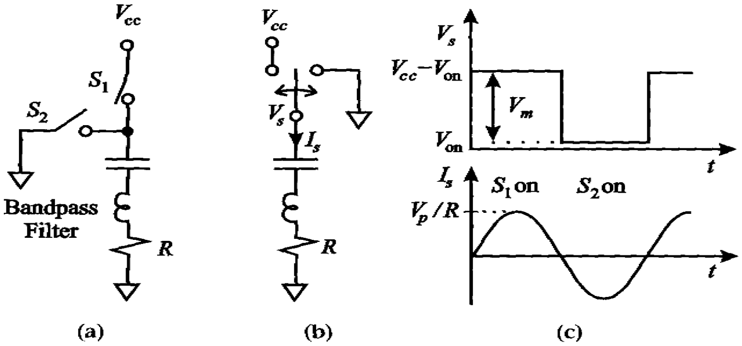
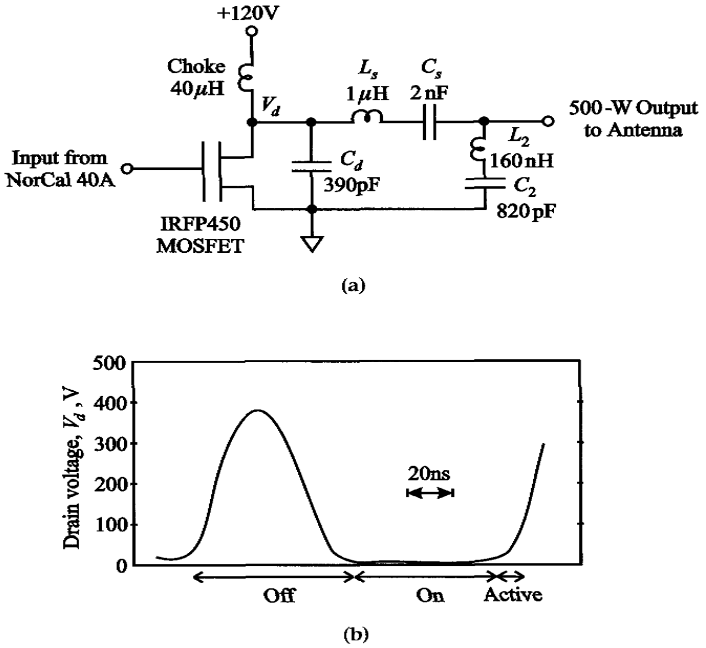


Figure 10.7. Class-D amplifier with a pair of transistor switches (a), and a simplified circuit with a single double-throw switch (b). The switch voltage and current waveforms (c).

Class E: If the output voltage can be made zero during the on portion of the device, then nearly 100% efficiency can be realized. This is achieved by inserting a series resonant circuit (tuned to the input frequency) in cascade with the device and the load. This enables this mode to achieve efficiencies in excess of 90%. A great example is given in the textbook. This example also includes a second harmonic trap in parallel with the load.

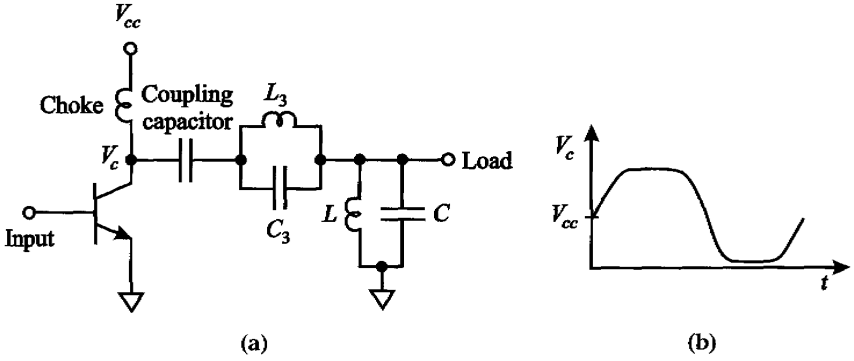


(a)

(b)

Figure 10.10. 500-W Class-E amplifier developed at Caltech. Circuit diagram (a), and drain voltage (b). For more information, see "High-Efficiency Class-E Power Amplifiers," by Eileen Lau, Kai-Wai Chiu, Jeff Qin, John Davis, Kent Potter, and David Rutledge, in *QST* magazine, Part 1, May 1997, pp. 39–42, and Part 2, June 1997, pp. 39–42.

Class F: Similar to the Class D in its approach, but using a parallel resonant circuit (tuned to the third harmonic of the input signal) in cascade with the load. This adds a significant fraction of the third harmonic and tends to flatten the otherwise sinusoidal output voltage of the device (remember Fourier series for a square wave?). Ideally, all odd harmonics should be retained and all even harmonics eliminated from the output. So a series resonant circuit in parallel with the load is often added. Higher harmonics are usually neglected. Theoretically, a λ/4 transmission line would accomplish this function for all harmonics, but not usually used. This action doesn't increase the efficiency significantly over a Class D amplifier, but it keeps the output voltage smaller for the same power output, a critical factor when the peak voltages are a problem.



(a)

(b)

Figure 10.11. Class-F amplifier (a), and collector voltage waveform (b).

Class G: This mode is essentially a Class B amplifier with two power supplies, the higher voltage is not switched on for signals of lower level, improving the efficiency.

Class H: This mode uses a variable power supply; the power supply voltage is controlled by logic circuitry to keep it just large enough to accommodate the level required by the input signal.

Distortion: The measure of distortion is frequently measured as total harmonic distortion (THD). If the distortion of the ith harmonic is defined as the absolute value of the ith harmonic voltage to the fundamental voltage as $D_i = \left|\frac{V_{oi}}{V_{o1}}\right| \times 100\%$, then $THD = \sqrt{D_2^2 + D_3^2 + D_4^2 + \dots}$.

Operational Amplifiers – See sections 13.1-2 of the textbook. Operational amplifiers are essentially low-frequency devices used for predominately for audio applications. They are composed of several simple electronic building blocks.

Current Mirror: Accurately setting several currents to be equal (or related) to each other is accomplished on an IC chip by using current mirrors. The base and collector of the left-hand transistor are connected together making it act as a diode. The current through the LH transistor is controlled by voltage V and resistance R. On a chip Q1 and Q2 are close to each other so have nearly identical properties. Since their bases are connected together the same current will flow in the collector of Q2 as in Q1 (if β>>1). Several transistors can be connected in parallel with Q2; each will have the same collector current.

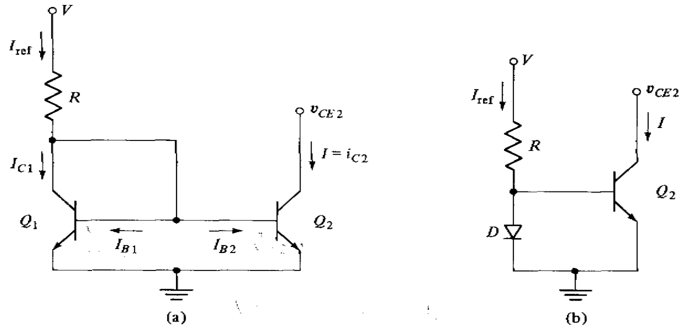


Figure 14-17. (a) A simple current source. (b) A simplified representation of this source.

The main difficulty with the current mirror above is that the resistor R takes a lot of space on the chip. To reduce the space required the Widlar current mirror, shown below, is often used. For V=10 V and IC1=10 µA, this configuration results in R of one tenth the size required by the original current mirror, a significant saving of chip real estate!

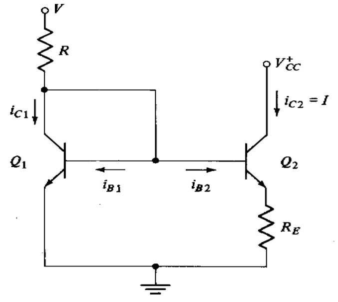
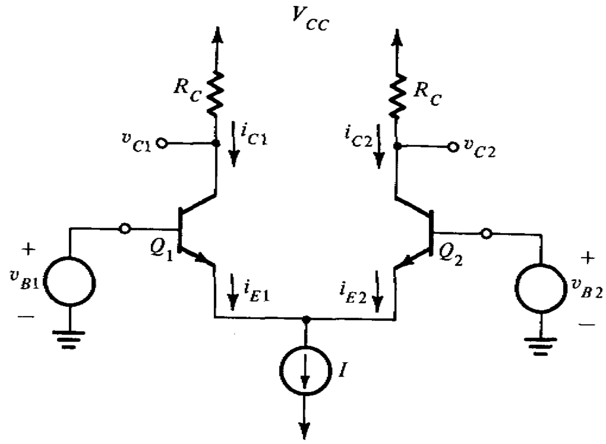


Figure 14-19. A Widlar current source.

A current mirror has an effective resistance across the collector emitter that is of the order of megohms, a useful fact in a differential pair amplifier.

Differential Pair Amplifier – When two identical transistors are connected as shown below they form what is known as a differential pair. The current source connected to the two emitters is usually a current mirror. The symmetry of the circuit enables two modes of analysis—the common mode and the differential mode. In the common mode the same signal is applied to both inputs. Consequently, the currents and the two collector voltages in the LH and RH of the circuit are equal. In the differential mode one input signal is positive and the other negative; the name is derived from this excitation. The currents in the two halves of the circuit still add to equal the current source value, but one is $I_{SOURCE}/2+\Delta I$ while the other is $I_{SOURCE}/2-\Delta I$ which creates a voltage difference between the two collector voltages. This characteristic makes this circuit particularly attractive when the signals on the two inputs have a weak difference signal superimposed upon a large common signal such as noise. In practice the common mode signal is not zero, but the ratio of the common mode output signal to the difference mode signal is known as the common-mode rejection ratio (CMRR). For a good op amp this is often 80 dB or more. For equal positive and negative output swing that dual voltage power supplies are required.



The basic differential-pair configuration.

Darlington Amplifier – A much larger input impedance as well as gain proportional to β^2 is achieved with the Darlington amplifier circuit shown below.

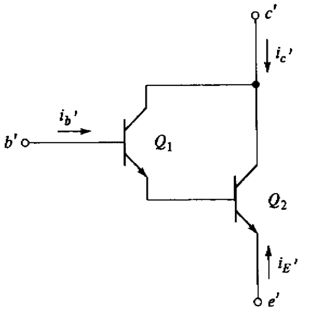


Figure 14-39. A Darlington compound transistor.

Push-pull Output – To keep distortion relatively low, a push-pull output is used. The simple Class B circuitry produces the cross over distortion as shown in the LH figure below. The resulting signal is shown at right.

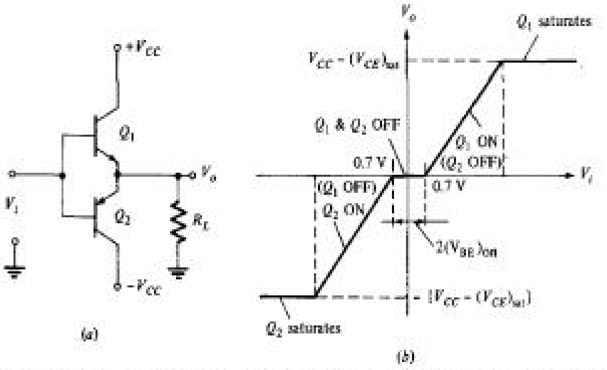


FIGURE 6.14 (a) A complementary output stage. (b) Its transfer characteristic.

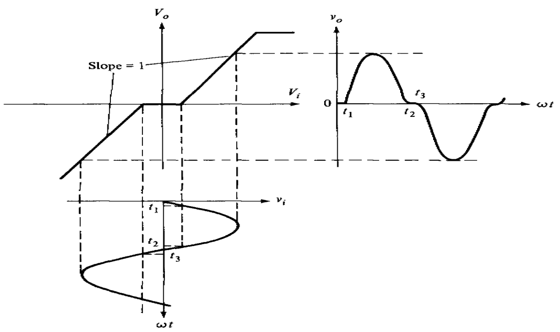


FIGURE 6.15 Input and output waveforms illustrating the dead-zone distortion.

Usually Class AB circuitry is used to minimize this distortion. See the output circuits of the opamp circuit shown below. Note the component building blocks of the complete opamp.

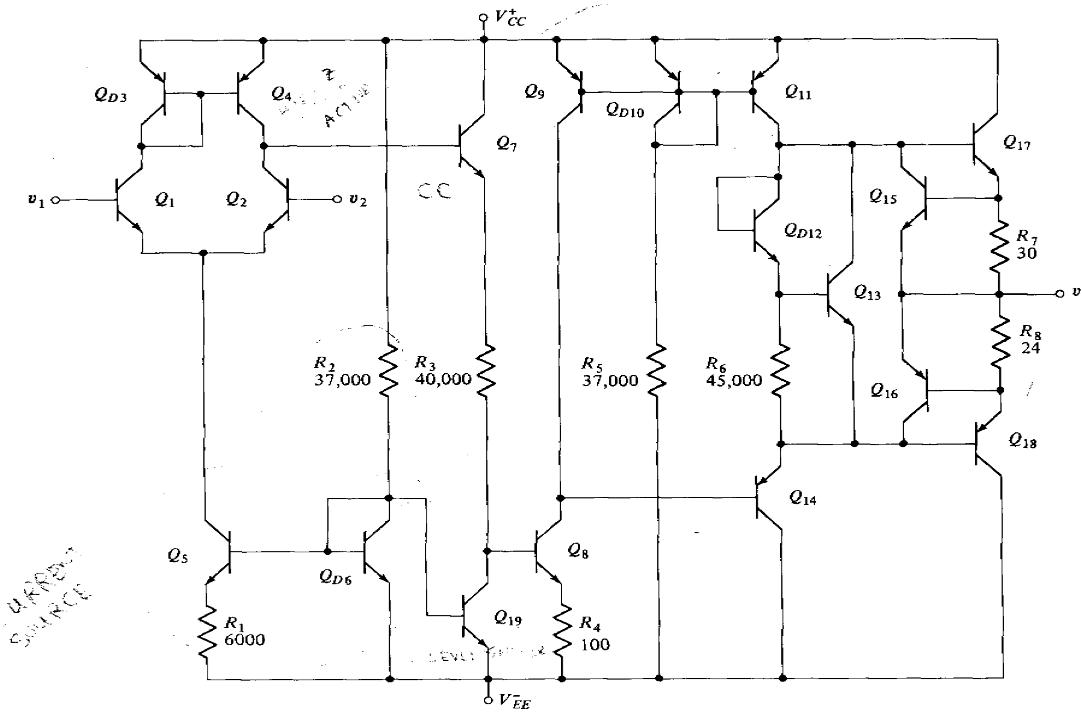


Figure 14-37. A simple complete operational amplifier. Resistance values are given in ohms.

NorCal40 Audio Amplifier – The NorCal40 uses an LM386N audio amplifier which contains a built in opamp. The feedback resistor is the 15 kΩ; the input resistor is the 1.5 kΩ resistor. Since it is in the differential mode the gain is twice this ratio or 20 as given in the spec sheet. By shorting out the 1.35 kΩ resistor between pins 1 & 8 the gain is set at 200. The mono-polar power supply requirement makes this an extremely useful device. The current source shown in the upper RH portion of the amplifier is another current mirror. See for example an LM380 specification where it is given explicitely.

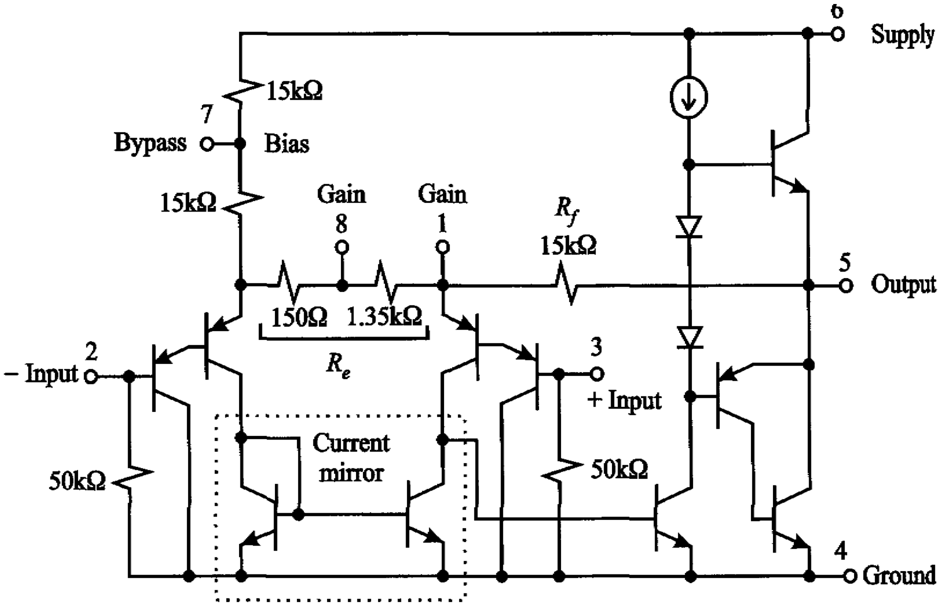


Figure 13.1. Schematic for the LM386N-1 Audio Power Amplifier, from the National Semiconductor data sheet in Appendix D.

Active Resistors – Electronically variable resistors can be realized using JFETs operating in the LH portion of the characteristic curves. In this region, varying V_{gs} produces different V_{ds} vs. I_d curves. The steeper the slope, the less the resistance. When $V_{gs}=V_C$ the resistance is infinite; when $V_{gs}=0$ it is minimum. This forms the basis of automatic gain control in many receivers.

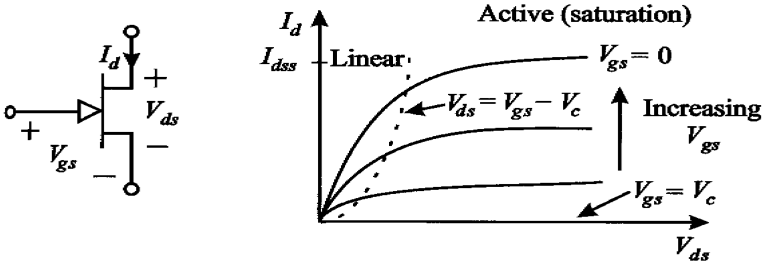


Figure 13.4. Drain current characteristics for a JFET.

Automatic Gain Control – The audio output of the product detector provides a differential mode signal, i.e., one output has a positive wave shape, the other has the negative of this waveshape. The differential signal is amplified and combined by the AGC circuit shown below. The Schottky diodes rectify the bipolar signal and use this to charge capacitor C29 through the resistance of R6. This capacitor voltage makes the JFET gate bias voltage less positive, hence, the resistance increases and the audio signal is less. Small audio voltages charge the capacitor less than large voltages and result in less attentuation. The speed of recovery (return to maximum gain) is determined by the time constant of C29-R6.

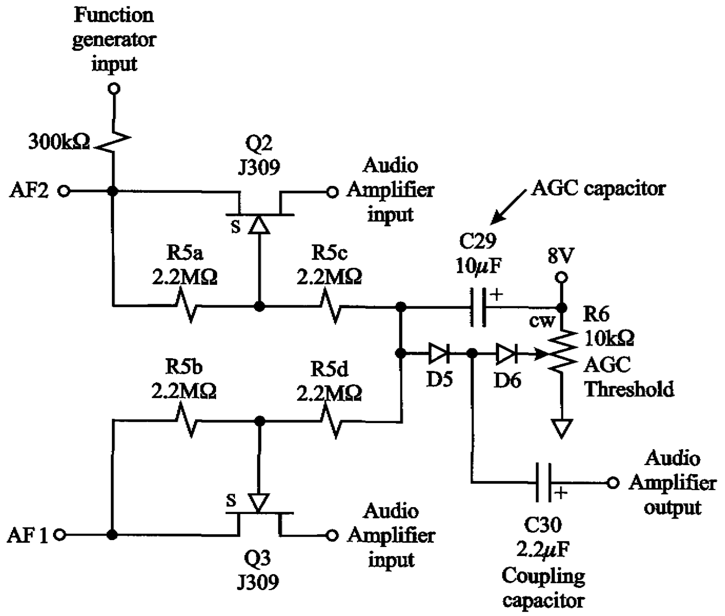


Figure 13.10. Adding the AGC capacitor C29 and the coupling capacitor C30.

Thermal Considerations – The performance of power amplifiers is limited by their thermal performance. The heat generated internally by power dissipation at the junction causes the temperature to rise. The rise in temperature is related to the thermal resistance of the device. Without a heat sink, the heat is convected to ambient air. The thermal resistance of the junction to air, Θ_{JA}, is given in °C of temperature rise of the junction temperature per watt of internal power dissipation. The greater Θ_{JA} the greater the junction temperature rise above ambient. A maximum junction temperature limits the performance of every device. Consequently, a low value of Θ_{JA} will tend to keep the junction temperature low. Of course, the internally generated power will be less if the device efficiency is high. The design of the case affects the thermal resistance.
But, heat sinks can be added to the case to increase the heat flow out of the device, hence, keeping it’s temperature lower for a given power dissipation. A second parameter the thermal resistance of the junction to case is given, Θ_{JC}. This describes the junction temperature in terms of case temperature. Usually, this is a rather low number compared to Θ_{JA} since the mechanism of heat flow within the transistor is by conduction.

The case temperature can be kept low by the addition of a heat sink that enhances the convection of heat to air. Heat sinks have a thermal resistance as well, Θ_{SA}, that describes the resistance from the heat sink to air. When the heat sink is well attached to the device (usually with the aid of heat sink compound) the heat sink is the same temperature as the device. Then the thermal resistances of the heat sink to air and the junction to case are added to give the combined thermal resistance of the device with a heat sink. This results in a much better transmission of heat from the junction and a correspondingly lower temperature. Conversely, more power can be dissipated within the device without exceeding the maximum junction temperature. A power-temperature derating curve describes the power limitation due to temperature increases in the junction temperature. The maximum power dissipation up to roughly room temperature is represented by the horizontal portion of the curve. The slope is proportional to Θ_{JC}; the steeper the slope, the greater the thermal resistance. The horizontal intercept represents the maximum junction temperature allowed.

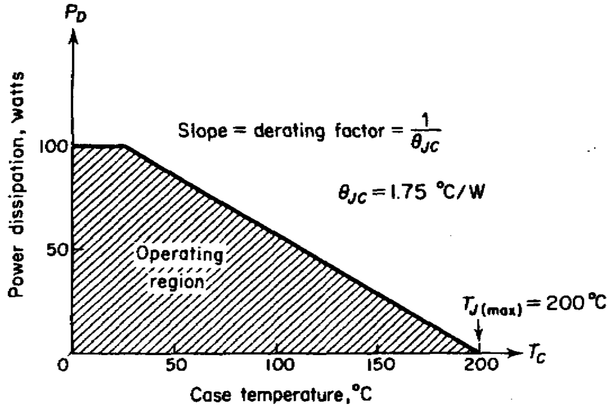
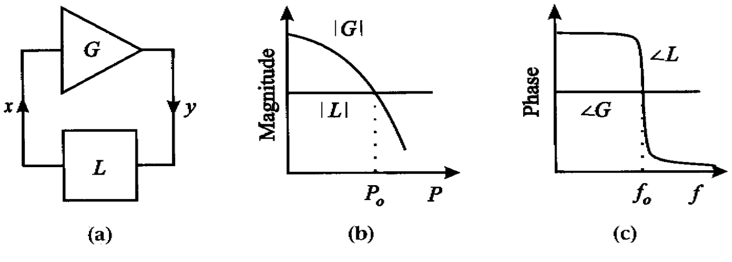


Figure 20.5. Typical power-temperature derating curve for a silicon power transistor.

Oscillators – See Chapter 11 of the textbook. See also Kurokowa, "Some Basics of Broadband, Negative-Resistance Oscillator Circuits," Bell System Technical Journal, vol 48, pp1937-55, July-August 1969.

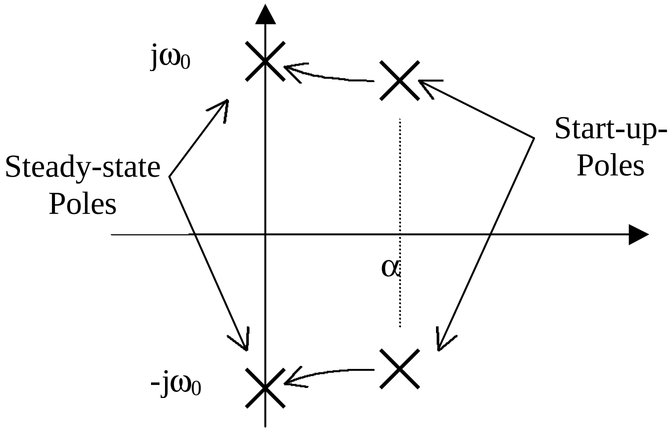
Sustaining Conditions: Self-sustained generation of electrical signals occurs whenever a closed path exists for which the loop gain of the signal is $1\angle 0°$; the magnitude and phase of the returning signal are such that the signal reinforces the original signal. Usually the gain is provided by some electronic device such as a BJT or FET and the phase is adjusted by some external circuit which acts as resonator. These conditions can be stated alternatively in terms of S-parameters as $\Gamma_{IN} = s_{11} + \frac{s_{21}s_{12}\Gamma_L}{1-s_{22}\Gamma_L}$ and $\Gamma_{OUT} = s_{22} + \frac{s_{21}s_{12}\Gamma_S}{1-s_{11}\Gamma_S}$.



(a) (b) (c)

Figure 11.1. Oscillator network consisting of an amplifier with a gain *G*, and a feedback network with a loss *L* (a), satisfying the magnitude (b) and phase (c) criteria.

Startup Conditions: The initiation of oscillations usually is due to thermal noise and is possible only if the loop gain is greater than 1. Thermal noise contains all frequencies so a resonant circuit is needed to select out the frequency of interest for amplification. As the signal grows from extremely small levels of noise, the gain of the oscillator must be reduced until it is unity, otherwise the signal would continue to grow until the device was destroyed. As the signal gets larger, the system must have some non-linearity that limits the signal to a steady-state value. From a systems viewpoint, oscillations begin when there are poles in the RHP; the rate of build-up and the frequency of oscillation are determined by the pole location. As the signal increases the poles move toward the imaginary axis; at steady state condition, the poles lie on the imaginary axis, their location determining the frequency of oscillation.



Alternate View: During start-up, noise signals progress around the loop increasing in power due to circuit amplification; the power gain exceeds the power loss. Those signals that traverse the loop return with the proper phase to reinforce the original signal. Signals at frequencies that satisfy these conditions will grow; the power of the device is supplied to these signals. Signals at other frequencies do not reinforce their original signal and are not amplified. As the preferred frequencies grow, the amplifier tends to saturate due to the signal amplitude. The signal is limited and steady state oscillations are maintained.

Configurations: A multitude of configurations can work as oscillators. For this course the emphasis is upon a variant of the Colpitts configuration, the Clapp oscillator, that uses a capacitive divider and a resonant circuit as feedback of amplified signal to the input of the active device.

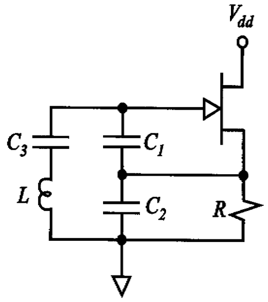


Figure 11.4. Clapp oscillator circuit that is used for the variable-frequency oscillator (VFO) in the NorCal 40A. C_1 and C_2 form the divider network, and R is the load. The gate and source bias networks and the tuning are complicated, and we omit them for now.

Two different circuits are used—a discrete element version with electronic tuning to make a variable frequency oscillator (VFO) and an integrated circuit version using an SA602AN chip and an external crystal. The VFO uses a JFET, lumped element resonator, and a varactor diode for tuning.

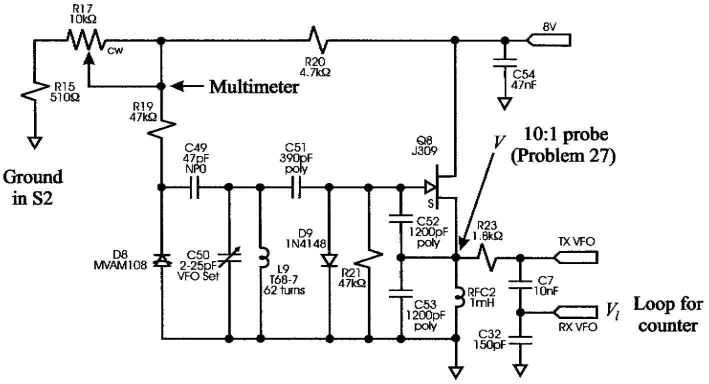


Figure 11.15. The VFO in the NorCal 40A.

The crystal controlled oscillator uses a built-in oscillator within the IC and external elements to establish feedback and control the oscillator frequency.

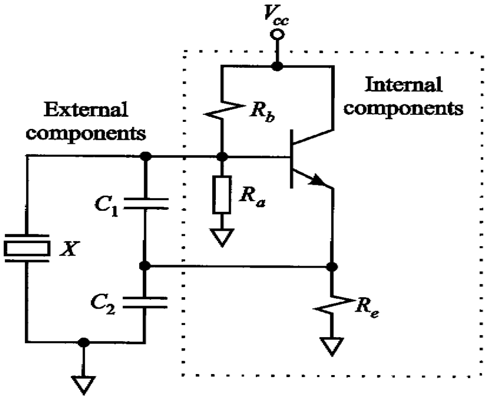


Figure 11.10. Clapp crystal oscillator in the SA602AN integrated circuit that is used for the Transmit Oscillator and the Beat Frequency Oscillator.