chapter 4

Amplitude Modulator and Demodulator Circuits

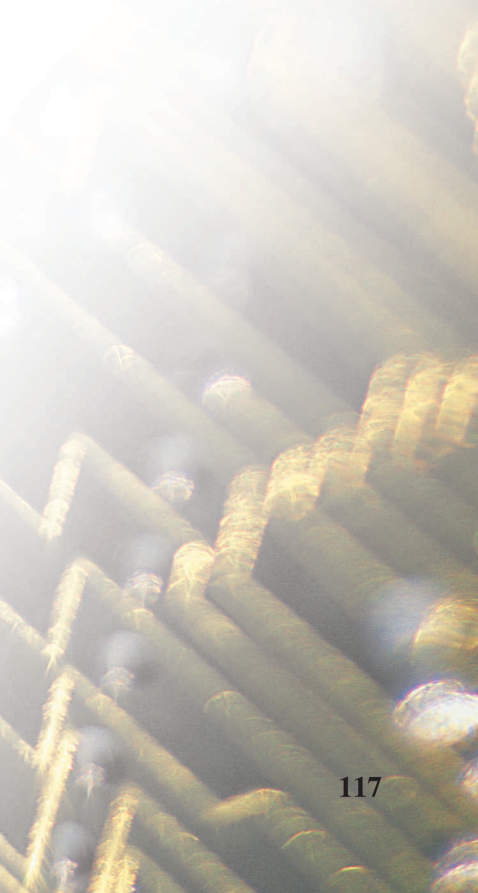
Dozens of modulator circuits have been developed that cause the carrier amplitude to be varied in accordance with the modulating information signal. There are circuits to produce AM, DSB, and SSB at low or high power levels. This chapter examines some of the more common and widely used discrete-component and integrated-circuit (IC) amplitude modulators. Also covered are demodulator circuits for AM, DSB, and SSB.

The circuits in this chapter show individual components, but keep in mind, today most circuits are in integrated circuit form. Furthermore, as you will see in future chapters, modulation and demodulation functions are commonly implemented in software in digital signal processing circuits.

Objectives

After completing this chapter, you will be able to:

- Explain the relationship of the basic equation for an AM signal to the production of amplitude modulation, mixing, and frequency conversion by a diode or other nonlinear frequency component or circuit.
- Describe the operation of diode modulator circuits and diode detector circuits.
- Compare the advantages and disadvantages of low- and high-level modulation.
- Explain how the performance of a basic diode detector is enhanced by using full wave rectifier circuits.
- Define synchronous detection and explain the role of clippers in synchronous detector circuits.
- State the function of balanced modulators and describe the differences between lattice modulators and IC modulator circuits.
- Draw the basic components of both filter-type and phase-shift-type circuits for generation of SSB signals.



4-1 Basic Principles of Amplitude Modulation

Examining the basic equation for an AM signal, introduced in Chap. 3, gives us several clues as to how AM can be generated. The equation is

$$v_{\mathrm{AM}} = V_c \sin 2\pi f_c t + (V_m \sin 2\pi f_m t)(\sin 2\pi f_c t)$$

where the first term is the sine wave carrier and second term is the product of the sine wave carrier and modulating signals. (Remember that v_{AM} is the instantaneous value of the amplitude modulation voltage.) The modulation index m is the ratio of the modulating signal amplitude to the carrier amplitude, or $m = V_m/V_c$, and so $V_m = mV_c$. Then substituting this for V_m in the basic equation yields $v_{\mathrm{AM}} = V_c \sin 2\pi f_c t + (mV_c \sin 2\pi f_m t)(\sin 2\pi f_c t)$. Factoring gives $v_{\mathrm{AM}} = V_c \sin 2\pi f_c t(1 + m \sin 2\pi f_m t)$.

AM in the Time Domain

When we look at the expression for v_{AM}, it is clear that we need a circuit that can multiply the carrier by the modulating signal and then add the carrier. A block diagram of such a circuit is shown in Fig. 4-1. One way to do this is to develop a circuit whose gain (or attenuation) is a function of $1 + m \sin 2\pi f_m t$. If we call that gain A, the expression for the AM signal becomes

$$v_{\mathrm{AM}} = A(v_c)$$

where A is the gain or attenuation factor. Fig. 4-2 shows simple circuits based on this expression. In Fig. 4-2(*a*), A is a gain greater than 1 provided by an amplifier. In Fig. 4-2(*b*), the carrier is attenuated by a voltage divider. The gain in this case is less than 1 and is therefore an attenuation factor. The carrier is multiplied by a fixed fraction A.

Now, if the gain of the amplifier or the attenuation of the voltage divider can be varied in accordance with the modulating signal plus 1, AM will be produced. In Fig. 4-2(*a*) the modulating signal would be used to increase or decrease the gain of the amplifier as the amplitude of the intelligence changed. In Fig. 4-2(*b*), the modulating

Figure 4-1 Block diagram of a circuit to produce AM.

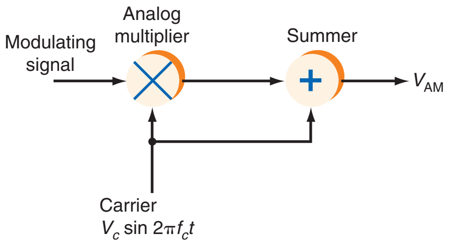


Figure 4-2 Multiplying the carrier by a fixed gain A.

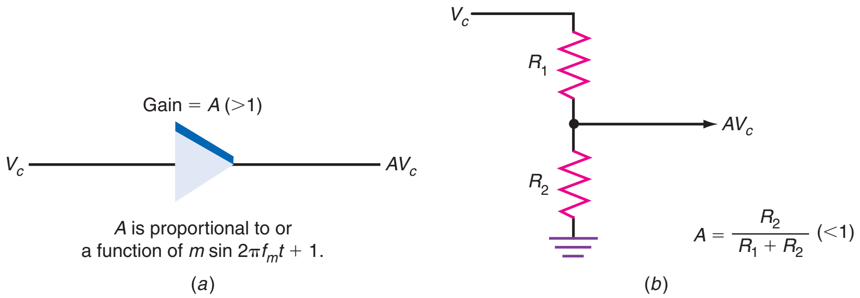
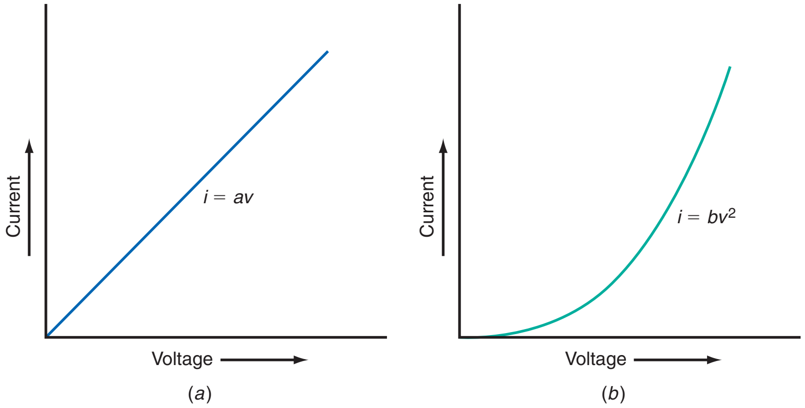


Figure 4-3 Linear and square-law response curves. (*a*) A linear voltage-current relationship. (*b*) A nonlinear or square-law response.



signal could be made to vary one of the resistances in the voltage divider, creating a varying attenuation factor. A variety of popular circuits permit gain or attenuation to be varied dynamically with another signal, producing AM.

AM in the Frequency Domain

Another way to generate the product of the carrier and modulating signal is to apply both signals to a nonlinear component or circuit, ideally one that generates a square-law function. A linear component or circuit is one in which the current is a linear function of the voltage [see Fig. 4-3(*a*)]. A resistor or linearly biased transistor is an example of a linear device. The current in the device increases in direct proportion to increases in voltage. The steepness or slope of the line is determined by the coefficient a in the expression $i = av$.

A nonlinear circuit is one in which the current is not directly proportional to the voltage. A common nonlinear component is a diode that has the nonlinear parabolic response shown in Fig. 4-3(*b*), where increasing the voltage increases the current but not in a straight line. Instead, the current variation is a square-law function. A *square-law function* is one that varies in proportion to the square of the input signals. A diode gives a good approximation of a square-law response. Bipolar and field-effect transistors (FETs) can also be biased to give a square-law response. An FET gives a near-perfect square-law response, whereas diodes and bipolar transistors, which contain higher-order components, only approximate the square-law function.

Square-law function

The current variation in a typical semiconductor diode can be approximated by the equation

$$i = av + bv^2$$

where av is a linear component of the current equal to the applied voltage multiplied by the coefficient a (usually a dc bias) and bv^2 is second-order or square-law component of the current. Diodes and transistors also have higher-order terms, such as cv^3 and dv^4; however, these are smaller and often negligible and so are neglected in an analysis.

To produce AM, the carrier and modulating signals are added and applied to the nonlinear device. A simple way to do this is to connect the carrier and modulating sources in series and apply them to the diode circuit, as in Fig. 4-4. The voltage applied to the diode is then

$$v = v_c + v_m$$

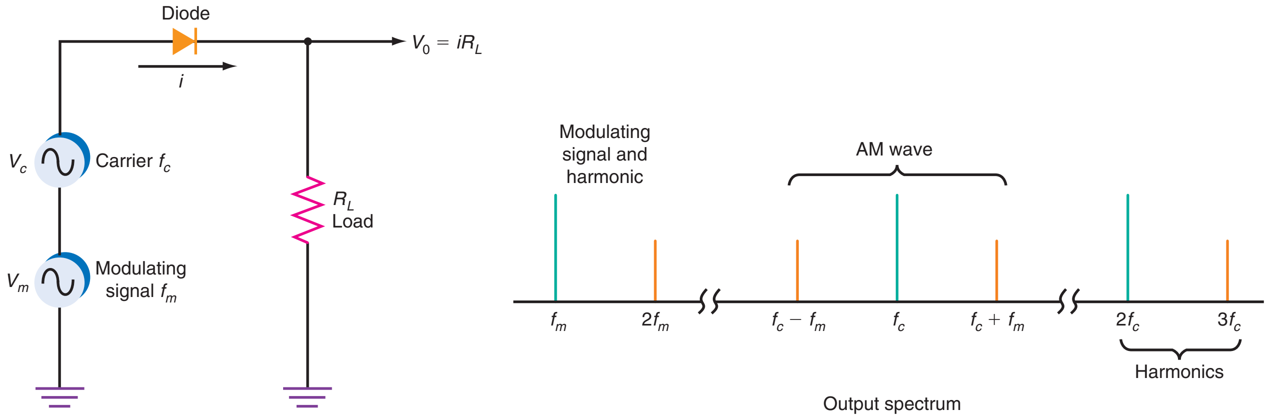
The diode current in the resistor is

$$i = a(v_c + v_m) + b(v_c + v_m)^2$$

Expanding, we get

$$i = a(v_c + v_m) + b(v_c^2 + 2v_cv_m + v_m^2)$$

Figure 4-4 A square-law circuit for producing AM.



Substituting the trigonometric expressions for the carrier and modulating signals, we let $v_c \sin 2\pi f_c t = v_c \sin \omega_c t$, where $\omega = 2\pi f_c$, and $v_m = \sin 2\pi f_m t = v_m \sin \omega_m t$, where $\omega_m = 2\pi f_m$. Then

$$\begin{aligned} i = {} & aV_c \sin \omega_c t + aV_m \sin \omega_m t + bV_c^2 \sin^2 \omega_c t + 2bV_cV_m \sin \omega_c t \sin \omega_m t \\ & + bv_m^2 \sin^2 \omega_m t \end{aligned}$$

Next, substituting the trigonometric identity $\sin^2 A = 0.5(1 - \cos 2A)$ into the preceding expression gives the expression for the current in the load resistor in Fig. 4-4:

$$\begin{aligned} i = {} & av_c \sin \omega_c t + av_m \sin \omega_m t + 0.5bv_c^2(1 - \cos 2\omega_c t) \\ & + 2bv_cv_m \sin \omega_c t \sin \omega_m t + 0.5bv_m^2(1 - \cos \omega_m t) \end{aligned}$$

The first term is the carrier sine wave, which is a key part of the AM wave; the second term is the modulating signal sine wave. Normally, this is not part of the AM wave. It is substantially lower in frequency than the carrier, so it is easily filtered out. The fourth term, the product of the carrier and modulating signal sine waves, defines the AM wave. If we make the trigonometric substitutions explained in Chap. 3, we obtain two additional terms—the sum and difference frequency sine waves, which are, of course, the upper and lower sidebands. The third term $\cos 2\omega_c t$ is a sine wave at two times the frequency of the carrier, i.e., the second harmonic of the carrier. The term $\cos 2\omega_m t$ is the second harmonic of the modulating sine wave. These components are undesirable, but are relatively easy to filter out. Diodes and transistors whose function is not a pure square-law function produce third-, fourth-, and higher-order harmonics, which are sometimes referred to as *intermodulation products* and which are also easy to filter out.

Intermodulation product

Fig. 4-4 shows both the circuit and the output spectrum for a simple diode modulator. The output waveform is shown in Fig. 4-5. This waveform is a normal AM wave to which the modulating signal has been added.

If a parallel resonant circuit is substituted for the resistor in Fig. 4-4, the modulator circuit shown in Fig. 4-6 results. This circuit is resonant at the carrier frequency and has a bandwidth wide enough to pass the sidebands but narrow enough to filter out the modulating signal as well as the second- and higher-order harmonics of the carrier. The result is an AM wave across the tuned circuit.

This analysis applies not only to AM but also to frequency translation devices such as mixers, product detectors, phase detectors, balanced modulators, and other heterodyning circuits. In fact, it applies to any device or circuit that has a square-law function. It explains how sum and difference frequencies are formed and also explains why most mixing and modulation in any nonlinear circuit are accompanied by undesirable components such as harmonics and intermodulation products.

Figure 4-5 AM signal containing not only the carrier and sidebands but also the modulating signal.

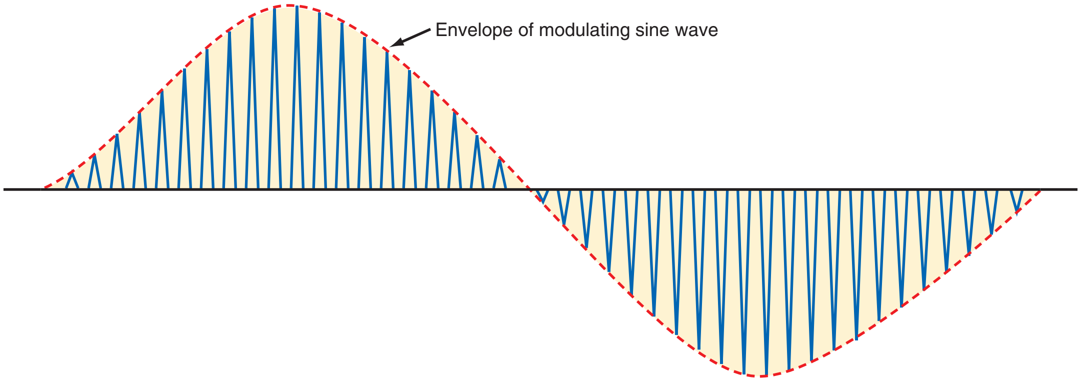
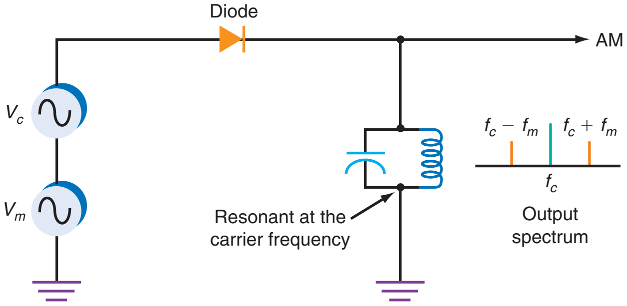


Figure 4-6 The tuned circuit filters out the modulating signal and carrier harmonics, leaving only the carrier and sidebands.



4-2 Amplitude Modulators

Amplitude modulators are generally one of two types: low level or high level. Low-level modulators generate AM with small signals and thus must be amplified considerably if they are to be transmitted. High-level modulators produce AM at high power levels, usually in the final amplifier stage of a transmitter. Although the discrete component circuits discussed in the following sections are still used to a limited extent, keep in mind that today most amplitude modulators and demodulators are in integrated-circuit form.

Low-Level AM

Low-level AM

Diode modulator

Diode Modulator. One of the simplest amplitude modulators is the *diode modulator* described in Sec. 4-1. The practical implementation shown in Fig. 4-7 consists of a resistive mixing network, a diode rectifier, and an *LC* tuned circuit. The carrier (Fig. 4-8*b*) is applied to one input resistor and the modulating signal (Fig. 4-8*a*) to the other. The mixed signals appear across R_3. This network causes the two signals to be linearly mixed, i.e., algebraically added. If both the carrier and the modulating signal are sine waves, the waveform resulting at the junction of the two resistors will be like that shown in Fig. 4-8(*c*), where the carrier wave is riding on the modulating signal. This signal is not AM. Modulation is a multiplication process, not an addition process.

The composite waveform is applied to a diode rectifier. The diode is connected so that it is forward-biased by the positive-going half-cycles of the input wave. During the negative portions of the wave, the diode is cut off and no signal passes. The current through the diode is a series of positive-going pulses whose amplitude varies in proportion to the amplitude of the modulating signal [see Fig. 4-8(*d*)].

Figure 4-7 Amplitude modulation with a diode.

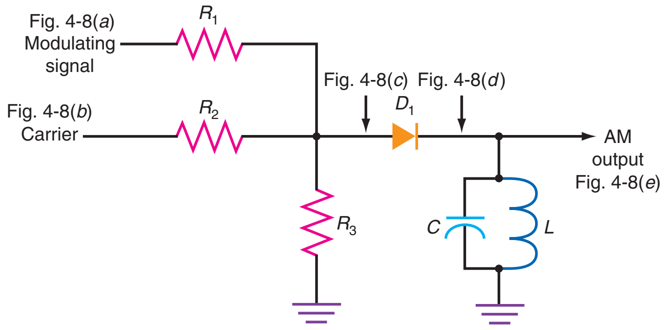
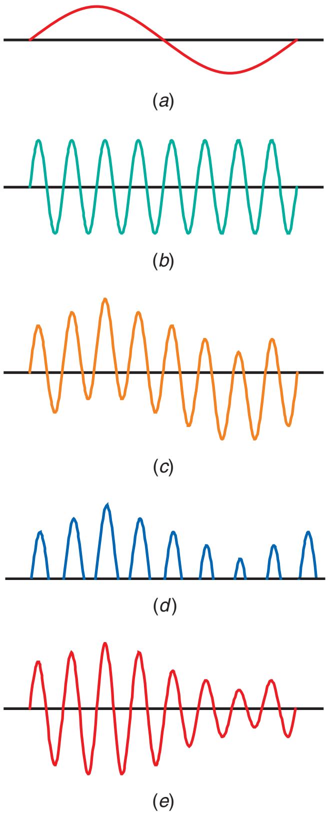


Figure 4-8 Waveforms in the diode modulator. (*a*) Modulating signal. (*b*) Carrier. (*c*) Linearly mixed modulating signal and carrier. (*d*) Positive-going signal after diode D_1. (*e*) Am output signal.


(*a*)

(*b*)

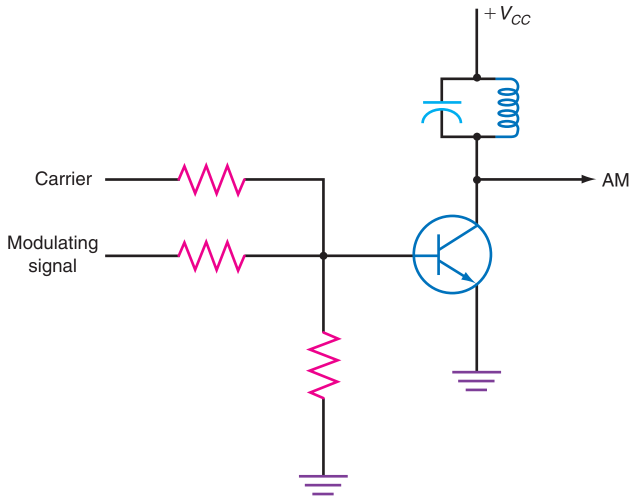
(*c*)

(*d*)

(*e*)

These positive-going pulses are applied to the parallel-tuned circuit made up of *L* and *C*, which are resonant at the carrier frequency. Each time the diode conducts, a pulse of current flows through the tuned circuit. The coil and capacitor repeatedly exchange energy, causing an oscillation, or "ringing," at the resonant frequency. The oscillation of the tuned circuit creates one negative half-cycle for every positive input pulse. High-amplitude positive pulses cause the tuned circuit to produce high-amplitude negative pulses. Low-amplitude positive pulses produce corresponding low-amplitude negative pulses. The resulting waveform across the tuned circuit is an AM signal, as Fig. 4-8(*e*) illustrates. The *Q* of the tuned circuit should be high enough to eliminate the harmonics and produce a clean sine wave and to filter out the modulating signal, and low enough that its bandwidth accommodates the sidebands generated.

Figure 4-9 Simple transistor modulator.



This signal produces high-quality AM, but the amplitudes of the signals are critical to proper operation. Because the nonlinear portion of the diode's characteristic curve occurs only at low voltage levels, signal levels must be low, less than a volt, to produce AM. At higher voltages, the diode current response is nearly linear. The circuit works best with millivolt-level signals.

Transistor modulator

Transistor Modulator. An improved version of the circuit just described is shown in Fig. 4-9. Because it uses a transistor instead of the diode, the circuit has gain. The emitter-base junction is a diode and a nonlinear device. Modulation occurs as described previously, except that the base current controls a larger collector current, and therefore the circuit amplifies. Rectification occurs because of the emitter-base junction. This causes larger half-sine pulses of current in the tuned circuit. The tuned circuit oscillates (rings) to generate the missing half-cycle. The output is a classic AM wave.

Differential amplifier modulator

Differential Amplifier. A *differential amplifier modulator* makes an excellent amplitude modulator. A typical circuit is shown in Fig. 4-10(*a*). Transistors Q_1 and Q_2 form the differential pair, and Q_3 is a constant-current source. Transistor Q_3 supplies a fixed emitter current I_E to Q_1 and Q_2, one-half of which flows in each transistor. The output is developed across the collector resistors R_1 and R_2.

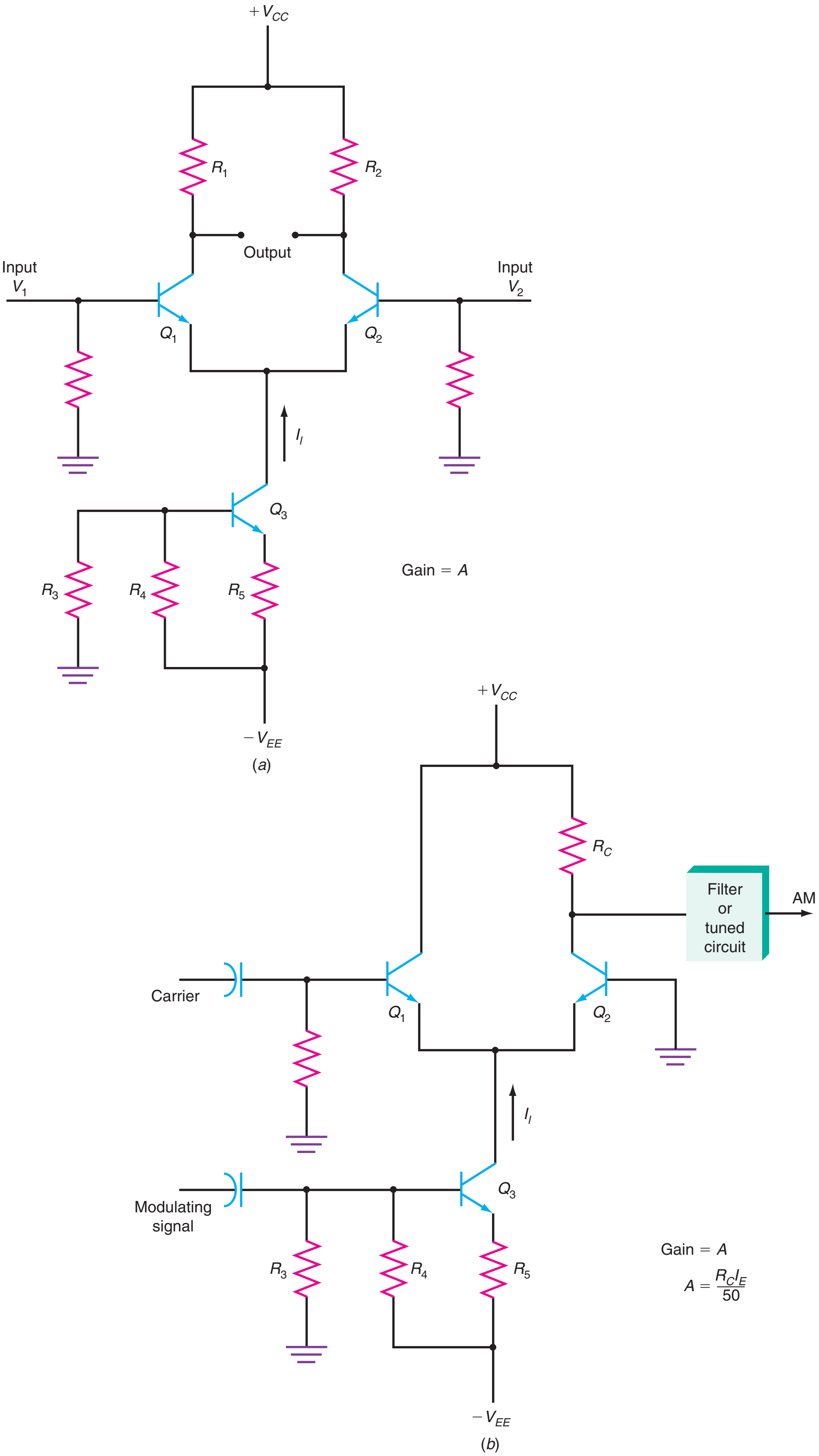
The output is a function of the difference between inputs V_1 and V_2; that is, $V_{out} = A(V_2 - V_1)$, where A is the circuit gain. The amplifier can also be operated with a single input. When this is done, the other input is grounded or set to zero. In Fig. 4-10(*a*), if V_1 is zero, the output is $V_{out} = A(V_2)$. If V_2 is zero, the output is $V_{out} = A(-V_1) = -AV_1$. This means that the circuit inverts V_1.

The output voltage can be taken between the two collectors, producing a *balanced,* or *differential,* output. The output can also be taken from the output of either collector to ground, producing a single-ended output. The two outputs are 180° out of phase with each other. If the balanced output is used, the output voltage across the load is twice the single-ended output voltage.

No special biasing circuits are needed, since the correct value of collector current is supplied directly by the constant-current source Q_3 in Fig. 4-10(*a*). Resistors R_3, R_4, and R_5, along with V_{EE}, bias the constant-current source Q_3. With no inputs applied, the current in Q_1 equals the current in Q_2, which is $I_E/2$. The balanced output at this time is zero. The circuit formed by R_1 and Q_1 and R_2 and Q_2 is a *bridge circuit.* When no inputs are applied, R_1 equals R_2, and Q_1 and Q_2 conduct equally. Therefore, the bridge is balanced and the output between the collectors is zero.

Bridge circuit

Figure 4-10 (*a*) Basic differential amplifier. (*b*) Differential amplifier modulator.



Now, if an input signal V_1 is applied to Q_1, the conduction of Q_1 and Q_2 is affected. Increasing the voltage at the base of Q_1 increases the collector current in Q_1 and decreases the collector current in Q_2 by an equal amount, so that the two currents sum to I_E. Decreasing the input voltage on the base of Q_1 decreases the collector current in Q_1 but increases it in Q_2. The sum of the emitter currents is always equal to the current supplied by Q_3.

The gain of a differential amplifier is a function of the emitter current and the value of the collector resistors. An approximation of the gain is given by the expression $A = R_C I_E/50$. This is the single-ended gain, where the output is taken from one of the collectors with respect to ground. If the output is taken between the collectors, the gain is two times the above value.

Resistor R_C is the collector resistor value in ohms, and I_E is the emitter current in milliamperes. If $R_C = R_1 = R_2 = 4.7\ \text{k}\Omega$ and $I_E = 1.5\ \text{mA}$, the gain will be about $A = 4700(1.5)/50 = 7050/50 = 141$.

GOOD TO KNOW

Differential amplifiers make excellent amplitude modulators because they have a high gain and good linearity and can be 100 percent modulated.

In most differential amplifiers, both R_C and I_E are fixed, providing a constant gain. But as the formula above shows, the gain is directly proportional to the emitter current. Thus if the emitter current can be varied in accordance with the modulating signal, the circuit will produce AM. This is easily done by changing the circuit only slightly, as in Fig. 4-10(*b*). The carrier is applied to the base of Q_1, and the base of Q_2 is grounded. The output, taken from the collector of Q_2, is single-ended. Since the output from Q_1 is not used, its collector resistor can be omitted with no effect on the circuit. The modulating signal is applied to the base of the constant-current source Q_3. As the intelligence signal varies, it varies the emitter current. This changes the gain of the circuit, amplifying the carrier by an amount determined by the modulating signal amplitude. The result is AM in the output.

This circuit, like the basic diode modulator, has the modulating signal in the output in addition to the carrier and sidebands. The modulating signal can be removed by using a simple high-pass filter on the output, since the carrier and sideband frequencies are usually much higher than that of the modulating signal. A bandpass filter centered on the carrier with sufficient bandwidth to pass the sidebands can also be used. A parallel-tuned circuit in the collector of Q_2 replacing R_C can be used.

The differential amplifier makes an excellent amplitude modulator. It has a high gain and good linearity, and it can be modulated 100 percent. And if high-frequency transistors or a high-frequency IC differential amplifier is used, this circuit can be used to produce low-level modulation at frequencies well into the hundreds of megahertz. MOSFETs may be used in place of the bipolar transistors to produce a similar result in ICs.

Amplifying Low-Level AM Signals. In low-level modulator circuits such as those discussed above, the signals are generated at very low voltage and power amplitudes. The voltage is typically less than 1 V, and the power is in milliwatts. In systems using low-level modulation, the AM signal is applied to one or more linear amplifiers, as shown in Fig. 4-11, to increase its power level without distorting the signal. These amplifier circuits—class A, class AB, or class B—raise the level of the signal to the desired power level before the AM signal is fed to the antenna.

High-Level AM

High-level AM

In high-level AM, the modulator varies the voltage and power in the final RF amplifier stage of the transmitter. The result is high efficiency in the RF amplifier and overall high-quality performance.

Collector modulator

Collector Modulator. One example of a high-level modulator circuit is the *collector modulator* shown in Fig. 4-12. The output stage of the transmitter is a high-power class C amplifier. Class C amplifiers conduct for only a portion of the positive half-cycle of their input signal. The collector current pulses cause the tuned circuit to oscillate (ring) at the desired output frequency. The tuned circuit, therefore, reproduces the negative portion of the carrier signal (see Chap. 7 for more details).

Figure 4-11 Low-level modulation systems use linear power amplifiers to increase the AM signal level before transmission.

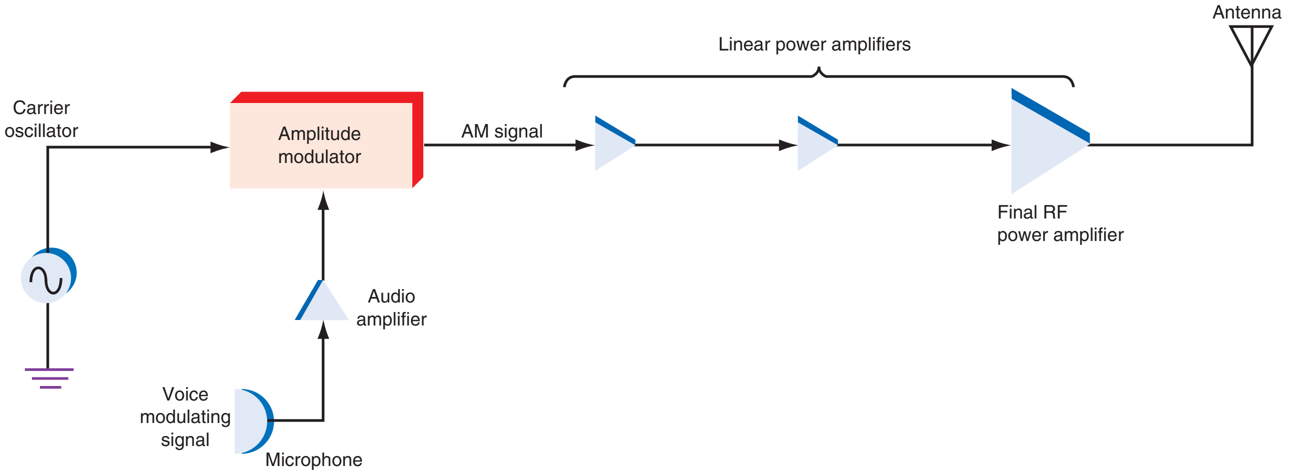
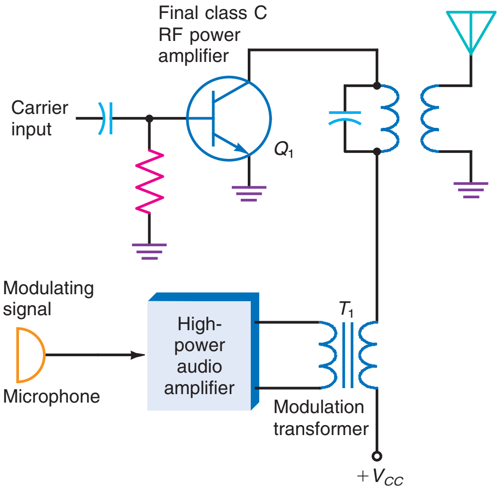


Figure 4-12 A high-level collector modulator.



The modulator is a linear power amplifier that takes the low-level modulating signal and amplifies it to a high-power level. The modulating output signal is coupled through modulation transformer T_1 to the class C amplifier. The secondary winding of the modulation transformer is connected in series with the collector supply voltage V_{CC} of the class C amplifier.

With a zero-modulation input signal, there is zero-modulation voltage across the secondary of T_1, the collector supply voltage is applied directly to the class C amplifier, and the output carrier is a steady sine wave.

When the modulating signal occurs, the ac voltage of the modulating signal across the secondary of the modulation transformer is added to and subtracted from the dc collector supply voltage. This varying supply voltage is then applied to the class C amplifier, causing the amplitude of the current pulses through transistor Q_1 to vary. As a result, the amplitude of the carrier sine wave varies in accordance with the modulated signal. When the modulation signal goes positive, it adds to the collector supply voltage, thereby increasing its value and causing higher current pulses and a higher-amplitude carrier. When the modulating signal goes negative, it subtracts from the collector supply voltage, decreasing it. For that reason, the class C amplifier current pulses are smaller, resulting in a lower-amplitude carrier output.

For 100 percent modulation, the peak of the modulating signal across the secondary of T_1 must be equal to the supply voltage. When the positive peak occurs, the voltage applied to the collector is twice the collector supply voltage. When the modulating signal goes negative, it subtracts from the collector supply voltage. When the negative peak is equal to the supply voltage, the effective voltage applied to the collector of Q_1 is zero, producing zero carrier output. This is illustrated in Fig. 4-13.

In practice, 100 percent modulation cannot be achieved with the high-level collector modulator circuit shown in Fig. 4-12 because of the transistor's nonlinear response to small signals. To overcome this problem, the amplifier driving the final class C amplifier is collector-modulated simultaneously.

High-level modulation produces the best type of AM, but it requires an extremely high-power modulator circuit. In fact, for 100 percent modulation, the power supplied by the modulator must be equal to one-half the total class C amplifier input power. If the class C amplifier has an input power of 1000 W, the modulator must be able to deliver one-half this amount, or 500 W.

Example 4-1

An AM transmitter uses high-level modulation of the final RF power amplifier, which has a dc supply voltage V_{CC} of 48 V with a total current I of 3.5 A. The efficiency is 70 percent.

a. What is the RF input power to the final stage?

DC input power $= P_i = V_{CC}I \qquad P = 48 \times 3.5 = 168$ W

b. How much AF power is required for 100 percent modulation? (*Hint:* For 100 percent modulation, AF modulating power P_m is one-half the input power.)

$$P_m = \frac{P_i}{2} = \frac{168}{2} = 84 \text{ W}$$

c. What is the carrier output power?

$$\% \text{ efficiency} = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100$$

$$P_{\text{out}} = \frac{\% \text{ efficiency} \times P_{\text{in}}}{100} = \frac{70(168)}{100} = 117.6 \text{ W}$$

d. What is the power in one sideband for 67 percent modulation?

P_s = sideband power

$$P_s = \frac{P_c(m^2)}{4}$$

m = modulation percentage (%) = 0.67

$P_c = 168$

$$P_s = \frac{168(0.67)^2}{4} = 18.85 \text{ W}$$

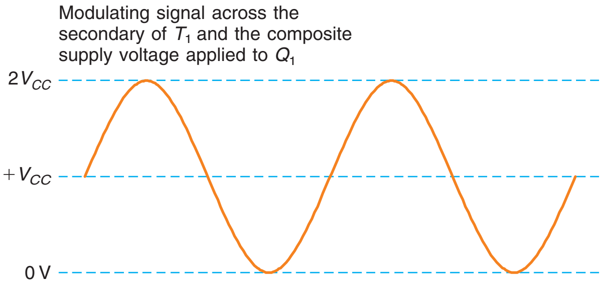
e. What is the maximum and minimum dc supply voltage swing with 100 percent modulation? (See Fig. 4-13.)

Minimum swing = 0

Supply voltage $\nu_{CC} = 48$ V

Maximum swing $2 \times V_{CC} = 2 \times 48 = 96$ V

Figure 4-13 For 100 percent modulation the peak of the modulating signal must be equal to V_{CC}.

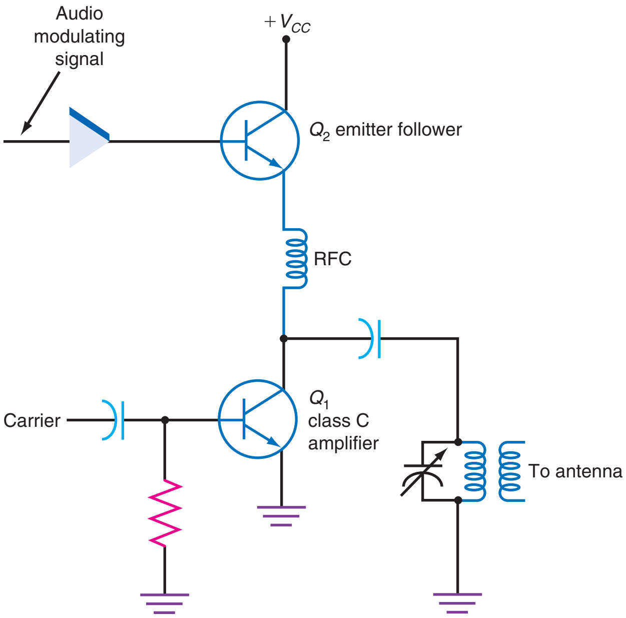


Series modulator

Series Modulator. A major disadvantage of collector modulators is the need for a modulation transformer that connects the audio amplifier to the class C amplifier in the transmitter. The higher the power, the larger and more expensive the transformer. For very high power applications, the transformer is eliminated and the modulation is accomplished at a lower level with one of the many modulator circuits described in previous sections. The resulting AM signal is amplified by a high-power linear amplifier. This arrangement is not preferred because linear RF amplifiers are less efficient than class C amplifiers.

One approach is to use a transistorized version of a collector modulator in which a transistor is used to replace the transformer, as in Fig. 4-14. This series modulator replaces the transformer with an emitter follower. The modulating signal is applied to the emitter follower Q_2, which is an audio power amplifier. Note that the emitter follower appears in series with the collector supply voltage $+V_{CC}$. This causes the amplified audio modulating signal to vary the collector supply voltage to the class C amplifier Q_1, as illustrated in Fig. 4-13. And Q_2 simply varies the supply voltage to Q_1. If the modulating signal goes positive, the supply voltage to Q_1 increases; thus, the carrier amplitude increases in proportion to the modulating signal. If the modulating signal goes negative, the supply voltage to Q_1 decreases, thereby decreasing the carrier amplitude in proportion to the modulating signal. For 100 percent modulation, the emitter follower can reduce the supply voltage to zero on maximum negative peaks.

Figure 4-14 Series modulation. Transistors may also be MOSFETs with appropriate biasing.



Using this high-level modulating scheme eliminates the need for a large, heavy, and expensive transformer, and considerably improves frequency response. However, it is very inefficient. The emitter-follower modulator must dissipate as much power as the class C RF amplifier. For example, assume a collector supply voltage of 24 V and a collector current of 0.5 A. With no modulating signal applied, the percentage of modulation is 0. The emitter follower is biased so that the base and the emitter are at a dc voltage of about one-half the supply voltage, or in this example 12 V. The collector supply voltage on the class C amplifier is 12 V, and the input power is therefore

$$P_{\text{in}} = V_{CC}I_c = 12(0.5) = 6 \text{ W}$$

To produce 100 percent modulation, the collector voltage on Q_1 must double, as must the collector current. This occurs on positive peaks of the audio input, as described above. At this time most of the audio signal appears at the emitter of Q_1; very little of the signal appears between the emitter and collector of Q_2, and so at 100 percent modulation, Q_2 dissipates very little power.

When the audio input is at its negative peak, the voltage at the emitter of Q_2 is reduced to 12 V. This means that the rest of the supply voltage, or another 12 V, appears between the emitter and collector of Q_2. Since Q_2 must also be able to dissipate 6 W, it has to be a very large power transistor. The efficiency drops to less than 50 percent. With a modulation transformer, the efficiency is much greater, in some cases as high as 80 percent.

This arrangement is not practical for very high power AM, but it does make an effective higher-level modulator for power levels below about 100 W.

4-3 Amplitude Demodulators

Demodulator (detector)

Demodulators, or *detectors,* are circuits that accept modulated signals and recover the original modulating information. The demodulator circuit is the key circuit in any radio receiver. In fact, demodulator circuits can be used alone as simple radio receivers.

Diode Detectors

Diode detector

The simplest and most widely used amplitude demodulator is the *diode detector* (see Fig. 4-15). As shown, the AM signal is usually transformer-coupled and applied to a basic half wave rectifier circuit consisting of D_1 and R_1. The diode conducts when the positive half-cycles of the AM signals occur. During the negative half-cycles, the diode is reverse-biased and no current flows through it. As a result, the voltage across R_1 is a series of positive pulses whose amplitude varies with the modulating signal. A capacitor C_1 is connected across resistor R_1, effectively filtering out the carrier and thus recovering the original modulating signal.

One way to look at the operation of a diode detector is to analyze its operation in the time domain. The waveforms in Fig. 4-16 illustrate this. On each positive alternation of the AM signal, the capacitor charges quickly to the peak value of the pulses passed

Figure 4-15 A diode detector AM demodulator.

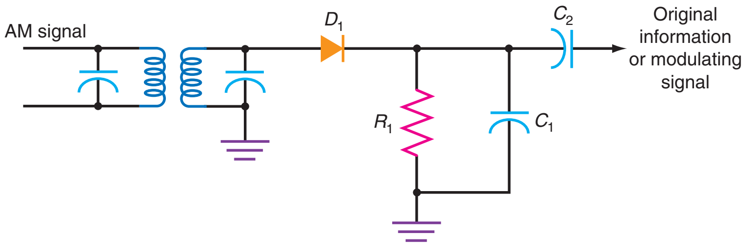
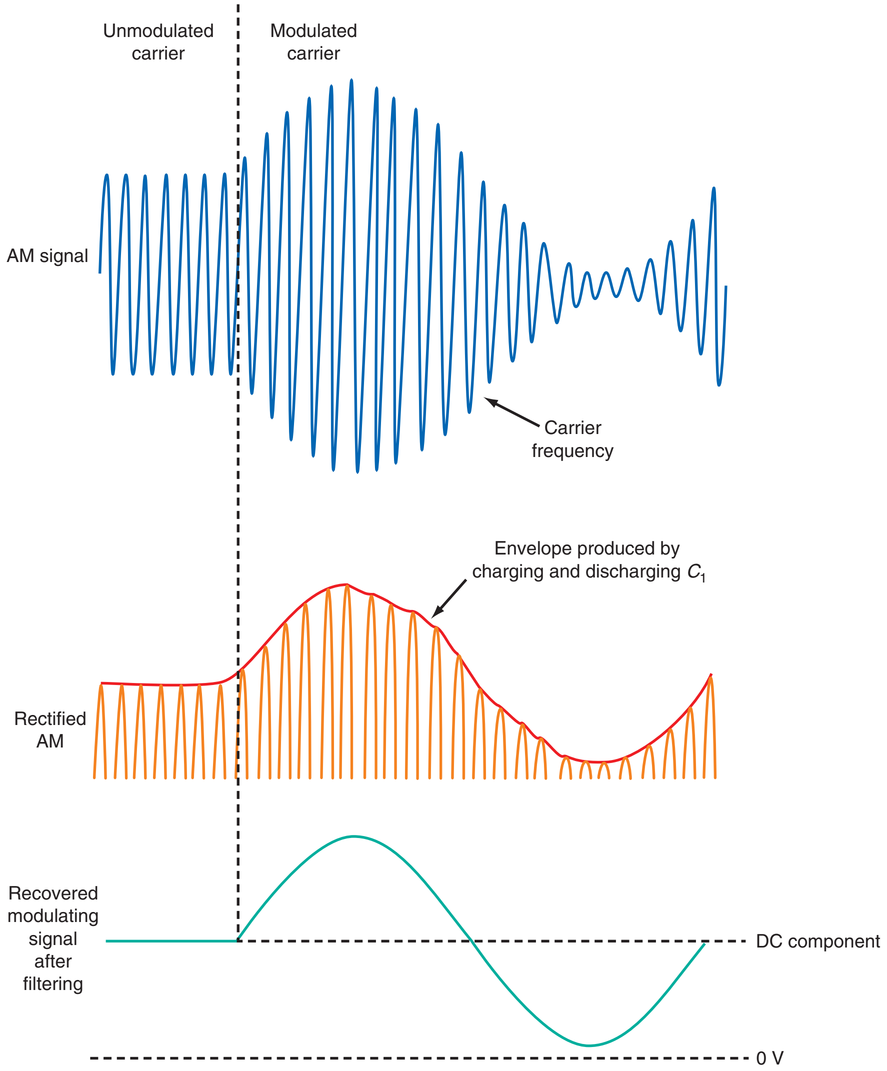


Figure 4-16 Diode detector waveforms.



by the diode. When the pulse voltage drops to zero, the capacitor discharges into resistor R_1. The time constant of C_1 and R_1 is chosen to be long compared to the period of the carrier. As a result, the capacitor discharges only slightly during the time that the diode is not conducting. When the next pulse comes along, the capacitor again charges to its peak value. When the diode cuts off, the capacitor again discharges a small amount into the resistor. The resulting waveform across the capacitor is a close approximation to the original modulating signal.

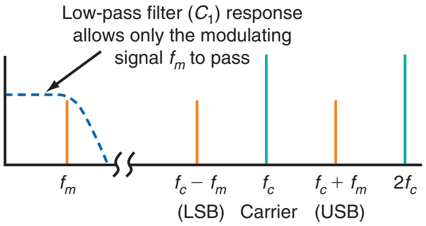
Because the capacitor charges and discharges, the recovered signal has a small amount of ripple on it, causing distortion of the modulating signal. However, because the carrier frequency is usually many times higher than the modulating frequency, these ripple variations are barely noticeable.

Envelope detector

Because the diode detector recovers the envelope of the AM signal, which is the original modulating signal, the circuit is sometimes referred to as an *envelope detector.* Distortion of the original signal can occur if the time constant of the load resistor R_1 and the shunt filter capacitor C_1 is too long or too short. If the time constant is too long, the capacitor discharge will be too slow to follow the faster changes in the modulating signal. This is referred to as *diagonal distortion.* If the time constant is too short, the capacitor will discharge too fast and the carrier will not be sufficiently filtered out. The

Diagonal distortion

Figure 4-17 Output spectrum of a diode detector.



dc component in the output is removed with a series coupling or blocking capacitor, C_2 in Fig. 4-15, which is connected to an amplifier.

Another way to view the operation of the diode detector is in the frequency domain. In this case, the diode is regarded as a nonlinear device to which are applied multiple signals where modulation will take place. The multiple signals are the carrier and sidebands, which make up the input AM signal to be demodulated. The components of the AM signal are the carrier f_c, the upper sideband $f_c + f_m$, and the lower sideband $f_c - f_m$. The diode detector circuit combines these signals, creating the sum and difference signals:

$$\begin{aligned} f_c + (f_c + f_m) &= 2f_c + f_m \\ f_c - (f_c + f_m) &= -f_m \\ f_c + (f_c - f_m) &= 2f_c - f_m \\ f_c - (f_c - f_m) &= f_m \end{aligned}$$

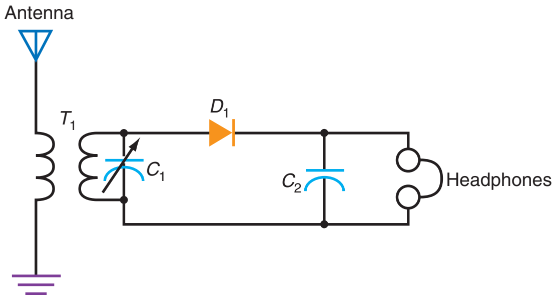
All these components appear in the output. Since the carrier frequency is very much higher than that of the modulating signal, the carrier signal can easily be filtered out with a simple low-pass filter. In a diode detector, this low-pass filter is just capacitor C_1 across load resistor R_1. Removing the carrier leaves only the original modulating signal. The frequency spectrum of a diode detector is illustrated in Fig. 4-17. The low-pass filter, C_1 in Fig. 4-15, removes all but the desired original modulating signal.

Crystal Radio Receivers

Crystal radio receiver

The crystal component of the *crystal radio receivers* that were widely used in the past is simply a diode. In Fig. 4-18 the diode detector circuit of Fig. 4-15 is redrawn, showing an antenna connection and headphones. A long wire antenna picks up the radio signal, which is inductively coupled to the secondary winding of T_1, which forms a series resonant circuit with C_1. Note that the secondary is not a parallel circuit, because the voltage induced into the secondary winding appears as a voltage source in series with the coil and capacitor. The variable capacitor C_1 is used to select a station. At resonance, the voltage across the capacitor is stepped up by a factor equal to the Q of the tuned circuit. This resonant voltage rise is a form of amplification. This higher-voltage signal

Figure 4-18 A crystal radio receiver.



is applied to the diode. The diode detector D_1 and its filter C_2 recover the original modulating information, which causes current flow in the headphones. The headphones serve as the load resistance, and capacitor C_2 removes the carrier. The result is a simple radio receiver; reception is very weak because no active amplification is provided. Typically, a germanium diode is used because its voltage threshold is lower than that of a silicon diode and permits reception of weaker signals. Crystal radio receivers can easily be built to receive standard AM broadcasts.

Synchronous Detection

Synchronous detector

Synchronous detectors use an internal clock signal at the carrier frequency in the receiver to switch the AM signal off and on, producing rectification similar to that in a standard diode detector (see Fig. 4-19.) The AM signal is applied to a series switch that is opened and closed synchronously with the carrier signal. The switch is usually a diode or transistor that is turned on or off by an internally generated clock signal equal in frequency to and in phase with the carrier frequency. The switch in Fig. 4-19 is turned on by the clock signal during the positive half-cycles of the AM signal, which therefore appears across the load resistor. During the negative half-cycles of the AM signal, the clock turns the switch off, so no signal reaches the load or filter capacitor. The capacitor filters out the carrier.

A full wave synchronous detector is shown in Fig. 4-20. The AM signal is applied to both inverting and noninverting amplifiers. The internally generated carrier signal operates two switches A and B. The clock turns A on and B off or turns B on and A off. This arrangement simulates an electronic single-pole, double-throw (SPDT) switch. During positive half-cycles of the AM signal, the A switch feeds the noninverted AM output of positive half-cycles to the load. During the negative half-cycles of the input, the B switch connects the output of the inverter to the load. The negative half-cycles are inverted, becoming positive, and the signal appears across the load. The result is full wave rectification of the signal.

The key to making the synchronous detector work is to ensure that the signal producing the switching action is perfectly in phase with the received AM carrier. An internally generated carrier signal from, say, an oscillator will not work. Even though the frequency

GOOD TO KNOW

Synchronous detectors or coherent detectors have less distortion and a better signal-to-noise ratio than standard diode detectors.

Figure 4-19 Concept of a synchronous detector.

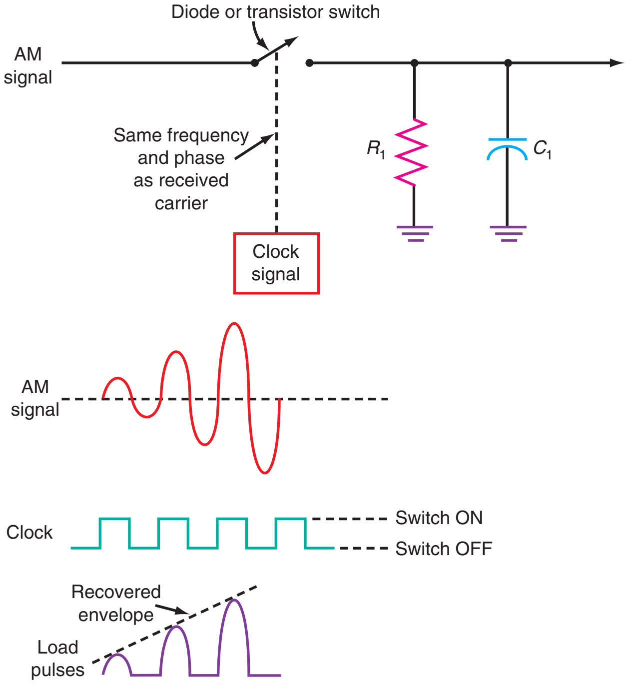
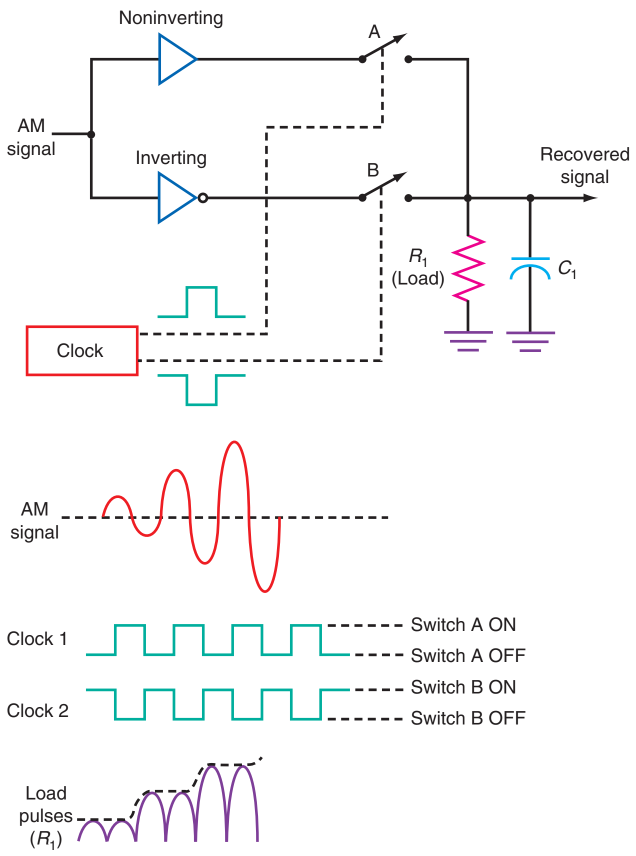


Figure 4-20 A full-wave synchronous detector.



and phase of the switching signal might be close to those of the carrier, they would not be perfectly equal. However, there are a number of techniques, collectively referred to as *carrier recovery circuits,* that can be used to generate a switching signal that has the correct frequency and phase relationship to the carrier.

Carrier recovery circuit

A practical synchronous detector is shown in Fig. 4-21. A center-tapped transformer provides the two equal but inverted signals. The carrier signal is applied to the center tap. Note that one diode is connected oppositely from the way it would be if used in a full wave rectifier. These diodes are used as switches, which are turned off and on by the clock, which is used as the bias voltage. The carrier is usually a square wave derived by clipping and amplifying the AM signal. When the clock is positive, diode D_1 is

Figure 4-21 A practical synchronous detector.

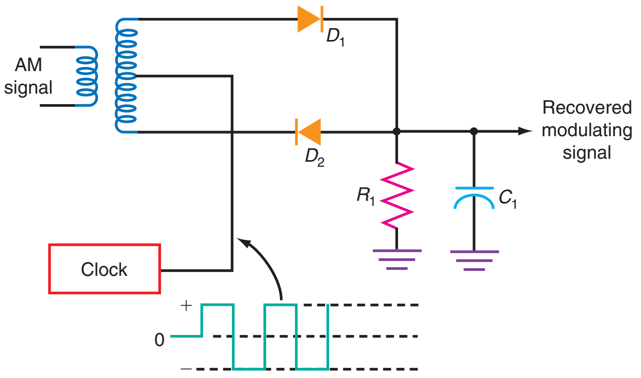
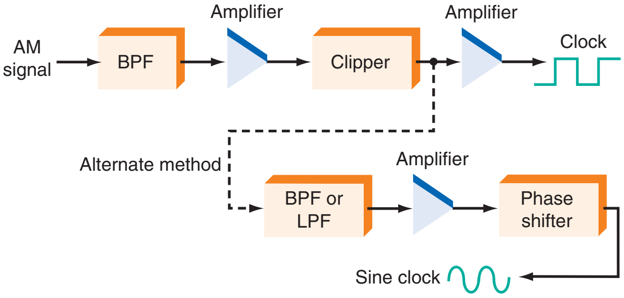


Figure 4-22 A simple carrier recovery circuit.



forward-biased. It acts as a short circuit and connects the AM signal to the load resistor. Positive half-cycles appear across the load.

When the clock goes negative, D_2 is forward-biased. During this time, the negative cycles of the AM signal are occurring, which makes the lower output of the secondary winding positive. With D_2 conducting, the positive half-cycles are passed to the load, and the circuit performs full wave rectification. As before, the capacitor across the load filters out the carrier, leaving the original modulating signal across the load.

GOOD TO KNOW

Demodulator circuits can be used alone as simple radio receivers.

The circuit shown in Fig. 4-22 is one way to supply the carrier to the synchronous detector. The AM signal to be demodulated is applied to a highly selective bandpass filter that picks out the carrier and suppresses the sidebands, thus removing most of the amplitude variations. This signal is amplified and applied to a clipper or limiter that removes any remaining amplitude variations from the signal, leaving only the carrier. The clipper circuit typically converts the sine wave carrier into a square wave that is amplified and thus becomes the clock signal. In some synchronous detectors, the clipped carrier is put through another bandpass filter to get rid of the square wave harmonics and generate a pure sine wave carrier. This signal is then amplified and used as the clock. A small phase shifter may be introduced to correct for any phase differences that occur during the carrier recovery process. The resulting carrier signal is exactly the same frequency and phase as those of the original carrier, as it is indeed derived from it. The output of this circuit is applied to the synchronous detector. Some synchronous detectors use a phase-locked loop to generate the clock, which is locked to the incoming carrier.

Selective fading

Synchronous detectors are also referred to as *coherent detectors,* and were known in the past as homodyne detectors. Their main advantage over standard diode detectors is that they have less distortion and a better signal-to-noise ratio. They are also less prone to *selective fading,* a phenomenon in which distortion is caused by the weakening of a sideband on the carrier during transmission.

4-4 Balanced Modulators

Balanced modulator

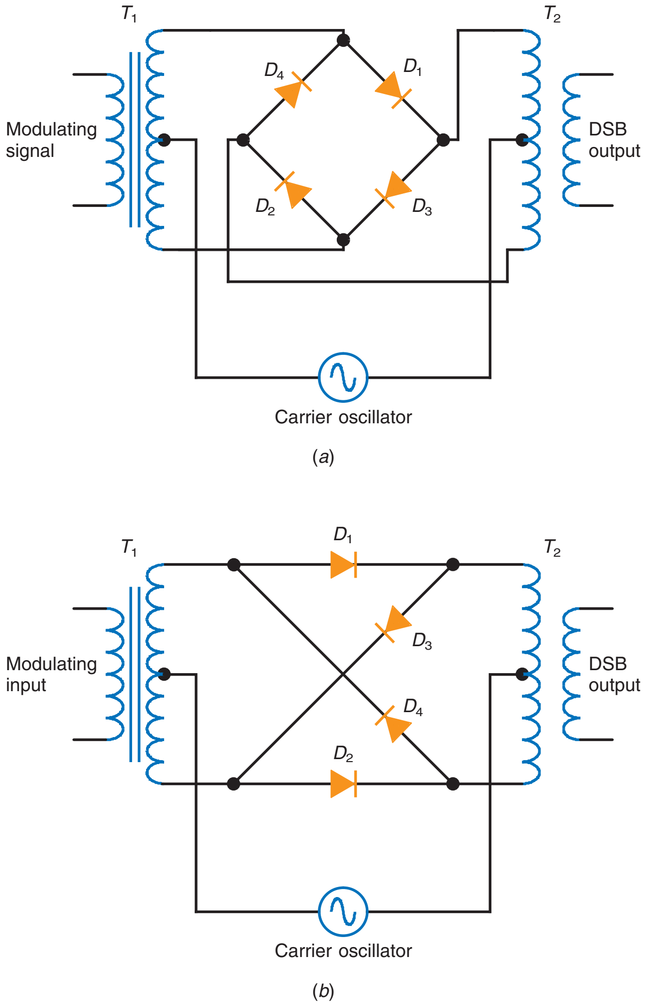
A *balanced modulator* is a circuit that generates a DSB signal, suppressing the carrier and leaving only the sum and difference frequencies at the output. The output of a balanced modulator can be further processed by filters or phase-shifting circuitry to eliminate one of the sidebands, resulting in an SSB signal.

Lattice Modulators

Lattice modulator (diode ring)

One of the most popular and widely used balanced modulators is the diode ring or *lattice modulator* in Fig. 4-23, consisting of an input transformer T_1, an output transformer T_2, and four diodes connected in a bridge circuit. The carrier signal is applied to the center taps of the input and output transformers, and the modulating signal is applied to the input transformer T_1. The output appears across the secondary of the output

Figure 4-23 Lattice-type balanced modulator.



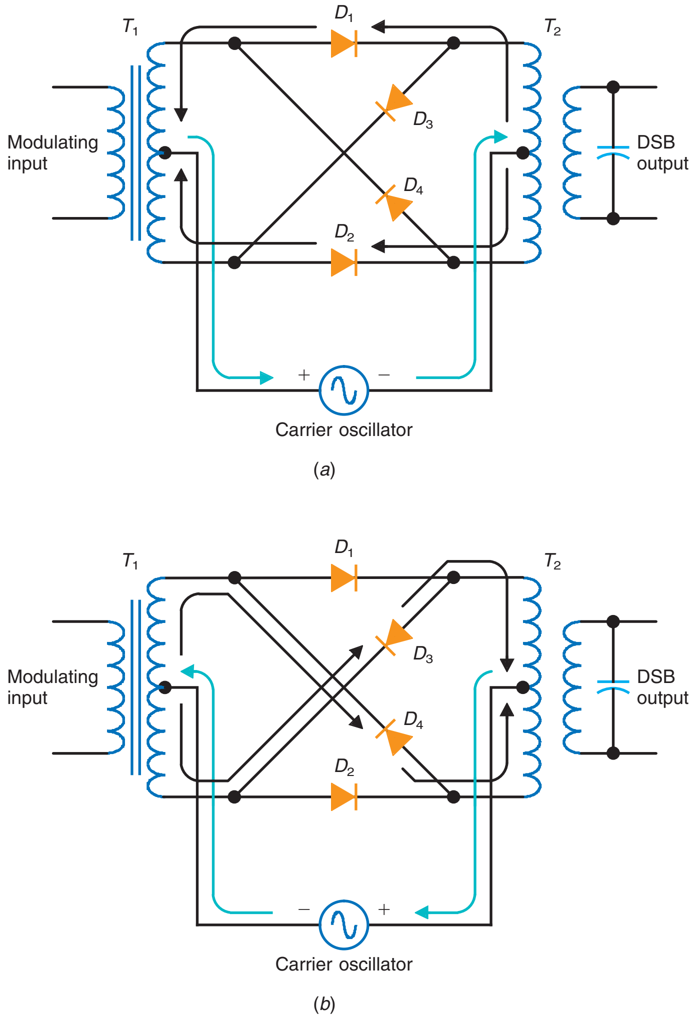
transformer T_2. The connections in Fig. 4-23(*a*) are the same as those in Fig. 4-23(*b*), but the operation of the circuit is perhaps more easily visualized as represented in part (*b*).

The operation of the lattice modulator is relatively simple. The carrier sine wave, which is usually considerably higher in frequency and amplitude than the modulating signal, is used as a source of forward and reverse bias for the diodes. The carrier turns the diodes off and on at a high rate of speed, and the diodes act as switches that connect the modulating signal at the secondary of T_1 to the primary of T_2.

Figs. 4-24 and 4-25 show how lattice modulators operate. Assume that the modulating input is zero. When the polarity of the carrier is positive, as illustrated in Fig. 4-25(*a*), diodes D_1 and D_2 are forward-biased. At this time, D_3 and D_4 are reverse-biased and act as open circuits. As you can see, current divides equally in the upper and lower portions of the primary winding of T_2. The current in the upper part of the winding produces a magnetic field that is equal and opposite to the magnetic field produced by the current in the lower half of the secondary. The magnetic fields thus cancel each other out. No output is induced in the secondary, and the carrier is effectively suppressed.

When the polarity of the carrier reverses, as shown in Fig. 4-25(*b*), diodes D_1 and D_2 are reverse-biased and diodes D_3 and D_4 conduct. Again, the current flows in the secondary winding of T_1 and the primary winding of T_2. The equal and opposite magnetic fields produced in T_2 cancel each other out. The carrier is effectively balanced out, and its output is zero. The degree of carrier suppression depends on the degree of precision with which the transformers are made and the placement of the center tap: the goal is

Figure 4-24 Operation of the lattice modulator.



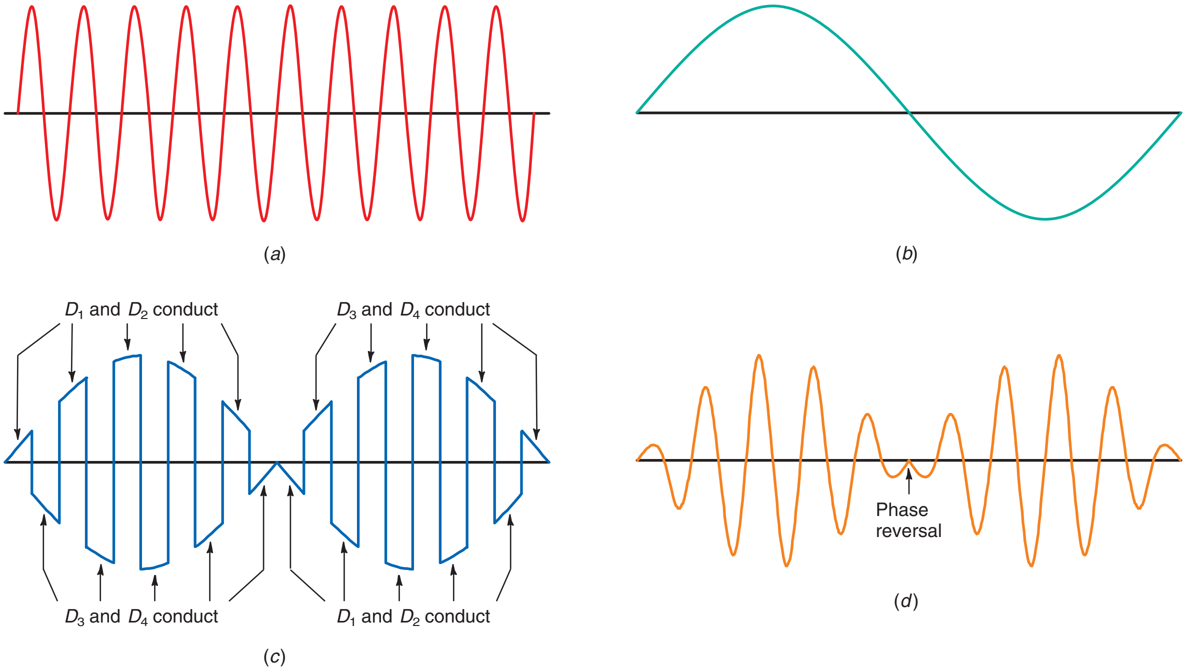
exactly equal upper and lower currents and perfect magnetic field cancellation. The degree of carrier attenuation also depends upon the diodes. The greatest carrier suppression occurs when the diode characteristics are perfectly matched. A carrier suppression of 40 dB is achievable with well-balanced components.

Now assume that a low-frequency sine wave is applied to the primary of T_1 as the modulating signal. The modulating signal appears across the secondary of T_1. The diode switches connect the secondary of T_1 to the primary of T_2 at different times depending upon the carrier polarity. When the carrier polarity is as shown in Fig. 4-25(*a*), diodes D_1 and D_2 conduct and act as closed switches. At this time, D_3 and D_4 are reverse-biased and are effectively not in the circuit. As a result, the modulating signal at the secondary of T_1 is applied to the primary of T_2 through D_1 and D_2.

When the carrier polarity reverses, D_1 and D_2 cut off and D_3 and D_4 conduct. Again, a portion of the modulating signal at the secondary of T_1 is applied to the primary of T_2, but this time the leads have been effectively reversed because of the connections of D_3 and D_4. The result is a 180° phase reversal. With this connection, if the modulating signal is positive, the output will be negative, and vice versa.

In Fig. 4-25, the carrier is operating at a considerably higher frequency than the modulating signal. Therefore, the diodes switch off and on at a high rate of speed, causing portions of the modulating signal to be passed through the diodes at different times. The DSB signal appearing across the primary of T_2 is illustrated in Fig. 4-25(*c*). The steep

Figure 4-25 Waveforms in the lattice-type balanced modulator. (*a*) Carrier. (*b*) Modulating signal. (*c*) DSB signal—primary T_2. (*d*) DSB output.



(*a*) (*b*) (*c*) (*d*)

rise and fall of the waveform are caused by the rapid switching of the diodes. Because of the switching action, the waveform contains harmonics of the carrier. Ordinarily, the secondary of T_2 is a resonant circuit as shown, and therefore the high-frequency harmonic content is filtered out, leaving a DSB signal like that shown in Fig. 4-25(*d*).

There are several important things to notice about this signal. First, the output waveform occurs at the carrier frequency. This is true even though the carrier has been removed. If two sine waves occurring at the sideband frequencies are added algebraically, the result is a sine wave signal at the carrier frequency with the amplitude variation shown in Fig. 4-25(*c*) or (*d*). Observe that the envelope of the output signal is *not* the shape of the modulating signal. Note also the phase reversal of the signal in the very center of the waveform, which is one indication that the signal being observed is a true DSB signal.

Although lattice modulators can be constructed of discrete components, they are usually available in a single module containing the transformers and diodes in a sealed package. The unit can be used as an individual component. The transformers are carefully balanced, and matched hot-carrier diodes are used to provide a wide operating frequency range and superior carrier suppression.

The diode lattice modulator shown in Fig. 4-24 uses one low-frequency iron-core transformer for the modulating signal and an air-core transformer for the RF output. This is an inconvenient arrangement because the low-frequency transformer is large and expensive. More commonly, two RF transformers are used, as shown in Fig. 4-26, where the modulating signal is applied to the center taps of the RF transformers. The operation of this circuit is similar to that of other lattice modulators.

GOOD TO KNOW

In DSB and SSB, the carrier that was suppressed at the DSB and SSB transmitter must be reinserted at the receiver to recover the intelligence.

IC Balanced Modulators

1496/1596 IC balanced modulator

Another widely used balanced modulator circuit uses differential amplifiers. A typical example, the popular *1496/1596 IC balanced modulator,* is seen in Fig. 4-27. This circuit can work at carrier frequencies up to approximately 100 MHz and can achieve a carrier suppression of 50 to 65 dB. The pin numbers shown on the inputs and outputs of the IC are those for a standard 14-pin dual in-line package (DIP) IC. The device is also available in a 10-lead metal can and several types of surface-mount packages.

Figure 4-26 A modified version of the lattice modulator not requiring an iron-core transformer for the low-frequency modulating signal.

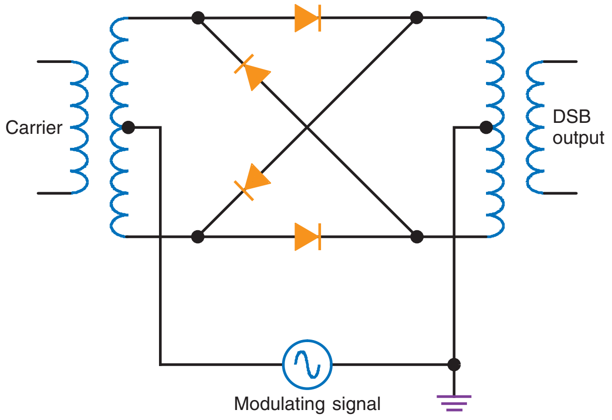
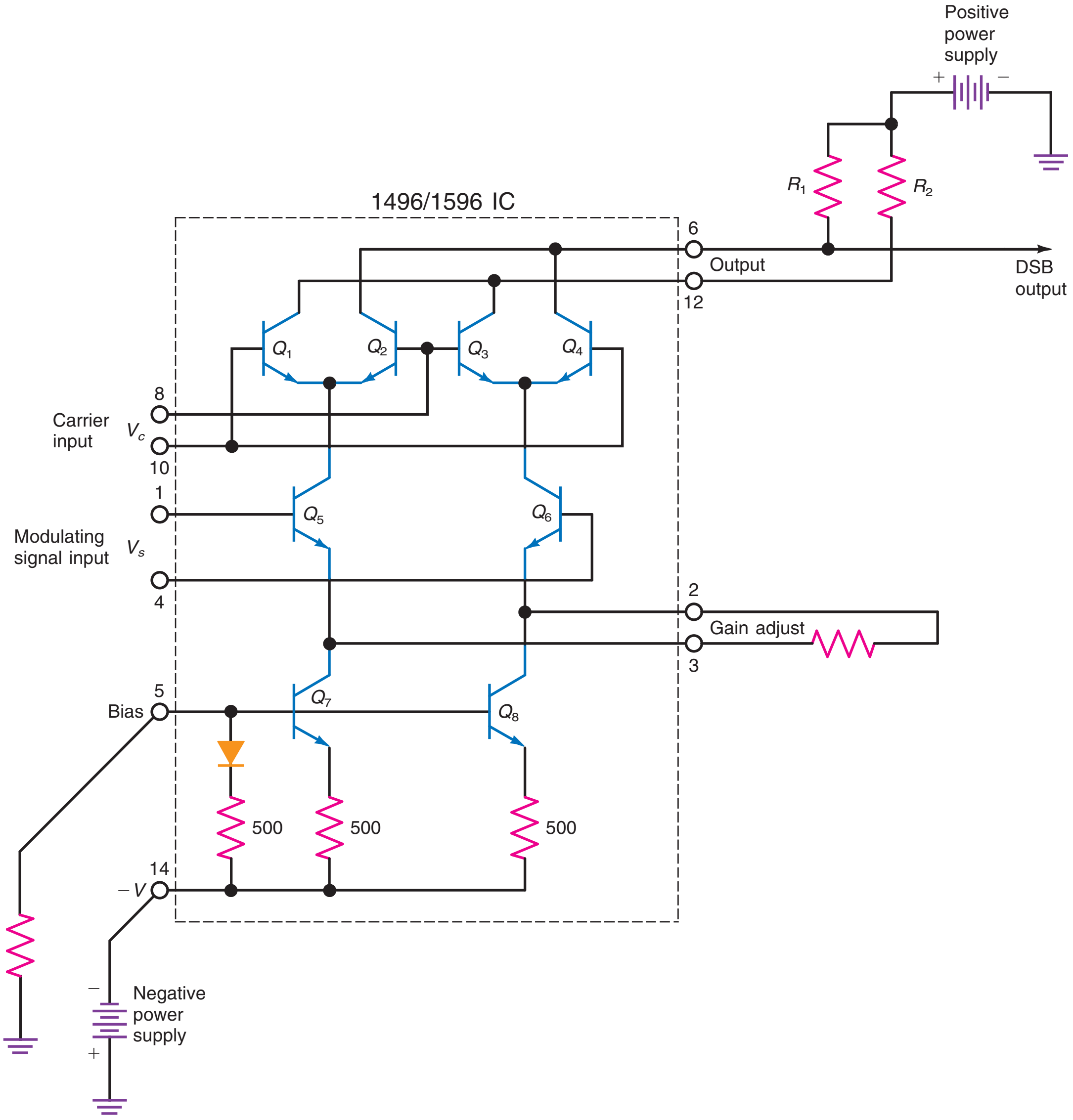


Figure 4-27 Integrated-circuit balanced modulator.



In Fig. 4-27, transistors Q_7 and Q_8 are constant-current sources that are biased with a single external resistor and the negative supply. They supply equal values of current to the two differential amplifiers. One differential amplifier is made up of Q_1, Q_2, and Q_5, and the other of Q_3, Q_4, and Q_6. The modulating signal is applied to the bases of Q_5 and Q_6. These transistors are connected in the current paths to the differential transistors and vary the amplitude of the current in accordance with the modulating signal. The current in Q_5 is 180° out of phase with the current in Q_6. As the current in Q_5 increases, the current through Q_6 decreases, and vice versa.

The differential transistors Q_1 through Q_4, which are controlled by the carrier, operate as switches. When the carrier input is such that the lower input terminal is positive with respect to the upper input terminal, transistors Q_1 and Q_4 conduct and act as closed switches and Q_2 and Q_3 are cut off. When the polarity of the carrier signal reverses, Q_1 and Q_4 are cut off and Q_2 and Q_3 conduct, acting as closed switches. These differential transistors, therefore, serve the same switching purpose as the diodes in the lattice modulator circuit discussed previously. They switch the modulating signal off and on at the carrier rate.

Assume that a high-frequency carrier wave is applied to switching transistors Q_1 and Q_4 and that a low-frequency sine wave is applied to the modulating signal input at Q_5 and Q_6. Assume that the modulating signal is positive-going so that the current through Q_5 increases while the current through Q_6 decreases. When the carrier polarity is positive, Q_1 and Q_4 conduct. As the current through Q_5 increases, the current through Q_1 and R_2 increases proportionately; therefore, the output voltage at the collector of Q_1 goes in a negative direction. As the current through Q_6 decreases, the current through Q_4 and R_1 decreases. Thus, the output voltage at the collector of Q_4 increases. When the carrier polarity reverses, Q_2 and Q_3 conduct. The increasing current of Q_5 is passed through Q_2 and R_1, and therefore the output voltage begins to decrease. The decreasing current through Q_6 is now passed through Q_3 and R_2, causing the output voltage to increase. The result of the carrier switching off and on and the modulating signal varying as indicated produces the classical DSB output signal described before [see Fig. 4-25(*c*)]. The signal at R_1 is the same as the signal at R_2, but the two are 180° out of phase.

Fig. 4-28 shows the 1496 connected to operate as a DSB or AM modulator. The additional components are included in the circuit in Fig. 4-27 to provide for single-ended rather than balanced inputs to the carrier, modulating signal inputs, and a way to fine-tune the carrier balance. The potentiometer on pins 1 and 4 allows tuning for minimum carrier output, compensates for minor imbalances in the internal balanced modulator circuits, and corrects for parts tolerances in the resistors, thus giving maximum carrier suppression. The carrier suppression can be adjusted to at least 50 dB under most conditions and as high as 65 dB at low frequencies.

GOOD TO KNOW

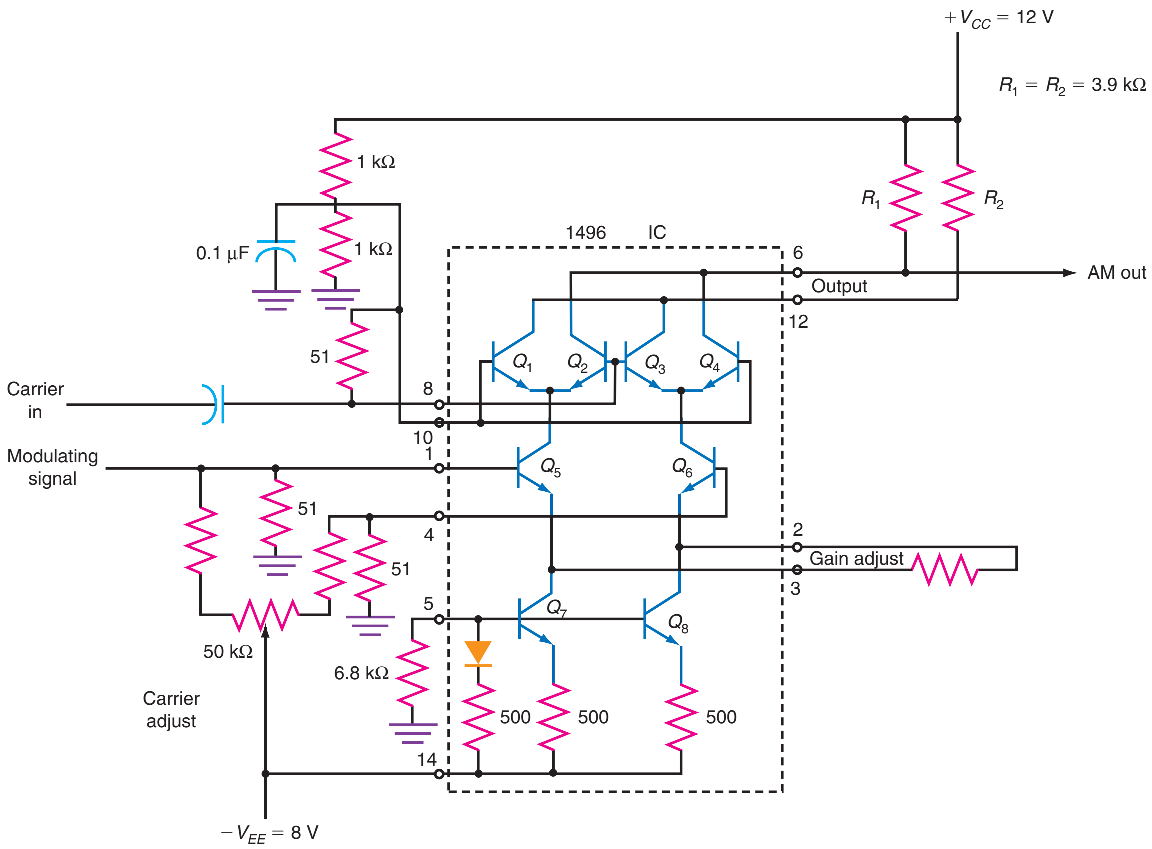
The 1496 IC is one of the most versatile circuits available for communication applications. In addition to being a balanced modulator, it can be reconfigured to perform as an amplitude modulator, a product detector, or a synchronous detector.

Applications for 1496/1596 ICs. The 1496 IC is one of the most versatile circuits available for communication applications. In addition to its use as balanced modulator, it can be reconfigured to perform as an amplitude modulator or as a synchronous detector.

In Fig. 4-28, the 1-kΩ resistors bias the differential amplifiers into the linear region so that they amplify the input carrier. The modulating signal is applied to the series emitter transistors Q_5 and Q_6. An adjustable network using a 50-kΩ potentiometer allows control of the amount of modulating signal that is applied to each internal pair of differential amplifiers. If the potentiometer is set near the center, the carrier balances out and the circuit functions as a balanced modulator. When the potentiometer is fine-tuned to the center position, the carrier is suppressed and the output is DSB AM.

If the potentiometer is offset one way or another, one pair of differential amplifiers receives little or no carrier amplification and the other pair gets all or most of the carrier. The circuit becomes a version of the differential amplifier modulator shown in Fig. 4-10(*b*). This circuit works quite nicely, but has very low input impedances. The carrier and modulating signal input impedances are equal to the input resistor values

Figure 4-28 AM modulator made with 1496 IC.



of 51 Ω. This means that the carrier and modulating signal sources must come from circuits with low output impedances, such as emitter followers or op amps.

Fig. 4-29 shows the 1496 connected as a synchronous detector for AM. The AM signal is applied to the series emitter transistors Q_5 and Q_6, thus varying the emitter currents in the differential amplifiers, which in this case are used as switches to turn the AM signal off and on at the right time. The carrier must be in phase with the AM signal.

In this circuit, the carrier can be derived from the AM signal itself. In fact, connecting the AM signal to both inputs works if the AM signal is high enough in amplitude. When the amplitude is high enough, the AM signal drives the differential amplifier transistors Q_1 through Q_4 into cutoff and saturation, thereby removing any amplitude variations. Since the carrier is derived from the AM signal, it is in perfect phase to provide high-quality demodulation. The carrier variations are filtered from the output by an *RC* low-pass filter, leaving the recovered intelligence signal.

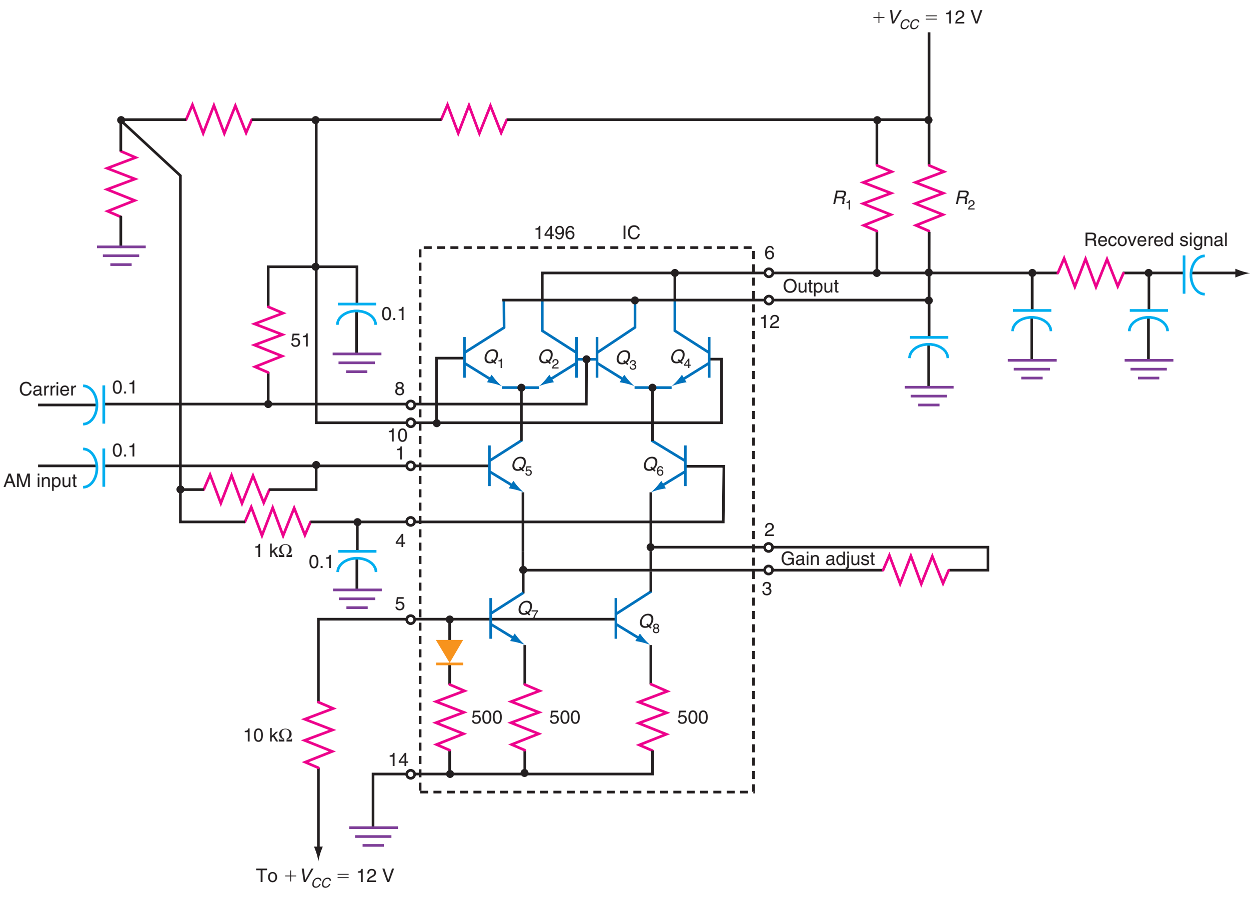
Analog multiplier

Analog Multiplier. Another type of IC that can be used as a balanced modulator is the *analog multiplier.* Analog multipliers are often used to generate DSB signals. The primary difference between an IC balanced modulator and an analog multiplier is that the balanced modulator is a switching circuit. The carrier, which may be a rectangular wave, causes the differential amplifier transistors to turn off and on to switch the modulating signal. The analog multiplier uses differential amplifiers, but they operate in the linear mode. The carrier must be a sine wave, and the analog multiplier produces the true product of two analog inputs.

IC devices

IC Devices. In large-scale integrated circuits in which complete receivers are put on a single silicon chip, the circuits described here are applicable. However, the circuitry is more likely to be implemented with MOSFETs instead of bipolar transistors.

Figure 4-29 Synchronous AM detector using a 1496.



4-5 SSB Circuits

Generating SSB Signals: The Filter Method

SSB circuit

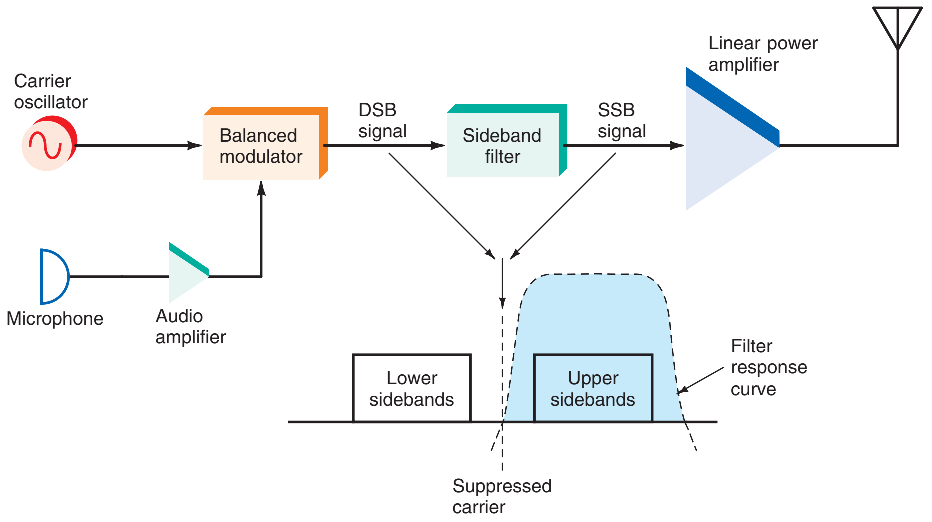
Double-sideband (DSB)

The simplest and most widely used method of generating SSB signals is the filter method. Fig. 4-30 shows a general block diagram of an SSB transmitter using the filter method. The modulating signal, usually voice from a microphone, is applied to the audio amplifier, the output of which is fed to one input of a balanced modulator. A crystal oscillator provides the carrier signal, which is also applied to the balanced modulator. The output of the balanced modulator is a *double-sideband (DSB)* signal. An SSB signal is produced by passing the DSB signal through a highly selective bandpass filter that selects either the upper or lower sideband.

The primary requirement of the filter is, of course, that it pass only the desired sideband. Filters are usually designed with a bandwidth of approximately 2.5 to 3 kHz, making them wide enough to pass only standard voice frequencies. The sides of the filter response curve are extremely steep, providing for excellent selectivity. Filters are fixed-tuned devices; i.e., the frequencies they can pass are not alterable. Therefore, the carrier oscillator frequency must be chosen so that the sidebands fall within the filter bandpass. Many commercially available filters are tuned to the 455-kHz, 3.35-MHz, or 9-MHz frequency ranges, although other frequencies are also used. Digital signal processing (DSP) filters are also used in modern equipment.

With the filter method, it is necessary to select either the upper or the lower sideband. Since the same information is contained in both sidebands, it generally makes no difference which one is selected, provided that the same sideband is used in both transmitter

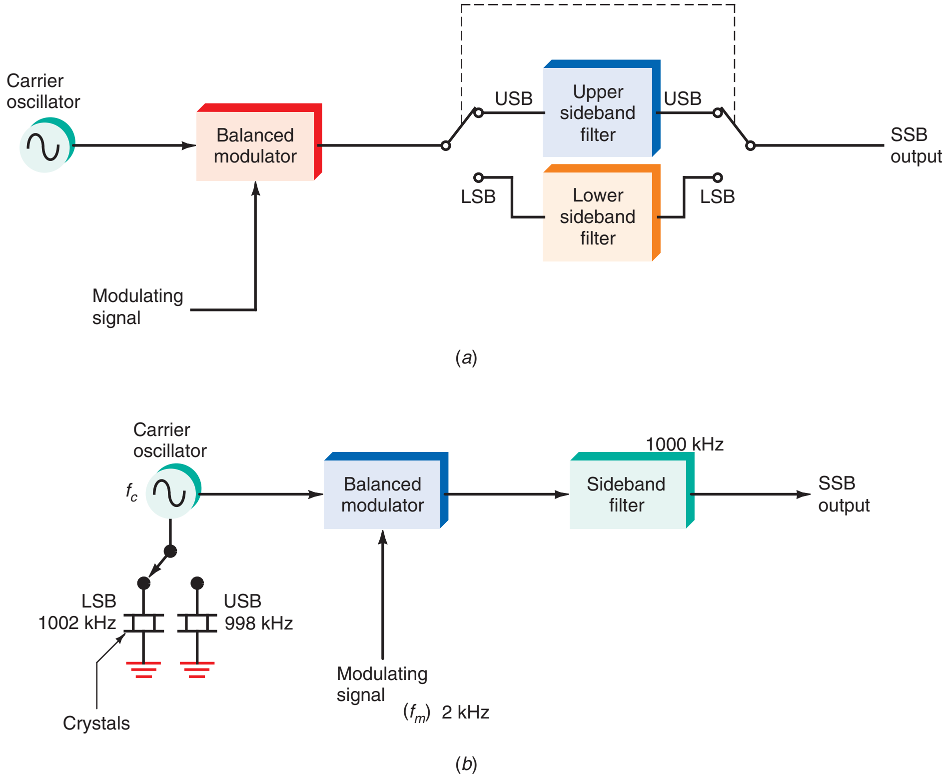
Figure 4-30 An SSB transmitter using the filter method.



and receiver. However, the choice of the upper or lower sideband as a standard varies from service to service, and it is necessary to know which has been used to properly receive an SSB signal.

There are two methods of sideband selection. Many transmitters simply contain two filters, one that will pass the upper sideband and another that will pass the lower sideband, and a switch is used to select the desired sideband [Fig. 4-31(*a*)]. An alternative method is to provide two carrier oscillator frequencies. Two crystals change the carrier

Figure 4-31 Methods of selecting the upper or lower sideband. (*a*) Two filters. (*b*) Two carrier frequencies.



oscillator frequency to force either the upper sideband or the lower sideband to appear in the filter bandpass [see Fig. 4-31(*b*)].

As an example, assume that a bandpass filter is fixed at 1000 kHz and the modulating signal f_m is 2 kHz. The balanced modulator generates the sum and difference frequencies. Therefore, the carrier frequency f_c must be chosen so that the USB or LSB is at 1000 kHz. The balanced modulator outputs are USB $= f_c + f_m$ and LSB $= f_c - f_m$.

To set the USB at 1000 kHz, the carrier must be $f_c + f_m = 1000, f_c + 2 = 1000$, and $f_c = 1000 - 2 = 998$ kHz. To set the LSB at 1000 kHz, the carrier must be $f_c - f_m = 1000, f_c - 2 = 1000$, and $f_c = 1000 + 2 = 1002$ kHz.

Crystal filters, which are low in cost and relatively simple to design, are by far the most commonly used filters in SSB transmitters. Their very high *Q* provides extremely good selectivity. Ceramic filters are used in some designs. Typical center frequencies are 455 kHz and 10.7 MHz. DSP filters are also used in contemporary designs.

GOOD TO KNOW

The main applications for SSB are in amateur radio, citizen's band (CB) radio, and long range marine radio.

Example 4-2

An SSB transmitter using the filter method of Fig. 4-30 operates at a frequency of 4.2 MHz. The voice frequency range is 300 to 3400 Hz.

a. Calculate the upper and lower sideband ranges.

Upper sideband

$$\begin{aligned}\text{Lower limit } f_{\mathrm{LL}} &= f_c + 300 = 4{,}200{,}000 + 300 = 4{,}200{,}300 \text{ Hz}\\ \text{Upper limit } f_{\mathrm{UL}} &= f_c + 3400 = 4{,}200{,}000 + 3400\\ &= 4{,}203{,}400 \text{ Hz}\\ \text{Range, USB} &= 4{,}200{,}300 \text{ to } 4{,}203{,}400 \text{ Hz}\end{aligned}$$

Lower sideband

$$\begin{aligned}\text{Lower limit } f_{\mathrm{LL}} &= f_c - 300 = 4{,}200{,}000 - 300 = 4{,}199{,}700 \text{ Hz}\\ \text{Upper limit } f_{\mathrm{UL}} &= f_c - 3400 = 4{,}200{,}000 - 3400\\ &= 4{,}196{,}600 \text{ Hz}\\ \text{Range, LSB} &= 4{,}196{,}000 \text{ to } 4{,}199{,}700 \text{ Hz}\end{aligned}$$

b. What should be the approximate center frequency of a bandpass filter to select the lower sideband? The equation for the center frequency of the lower sideband f_{LSB} is

$$f_{\mathrm{LSB}} = \sqrt{f_{\mathrm{LL}}\, f_{\mathrm{UL}}} = \sqrt{4{,}196{,}660 \times 4{,}199{,}700} = 4{,}198{,}149.7 \text{ Hz}$$

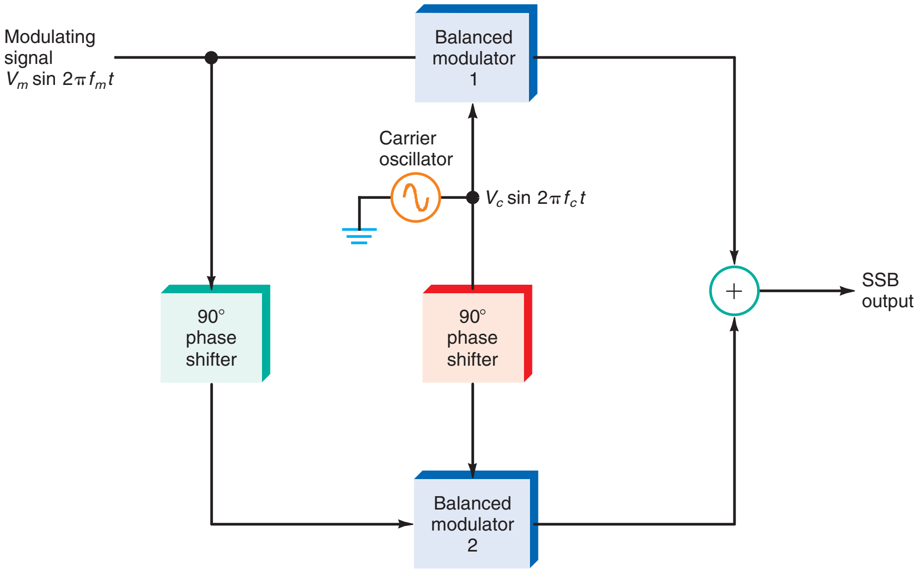
An approximation is

$$f_{\mathrm{LSB}} = \frac{f_{\mathrm{LL}} + f_{\mathrm{UL}}}{2} = \frac{4{,}196{,}600 + 4{,}199{,}700}{2} = 4{,}198{,}150 \text{ Hz}$$

Generating SSB Signals: Phasing

The phasing method of SSB generation uses a phase-shift technique that causes one of the sidebands to be canceled out. A block diagram of a phasing-type SSB generator is shown in Fig. 4-32. It uses two balanced modulators, which effectively eliminate the carrier. The carrier oscillator is applied directly to the upper balanced modulator along with the audio modulating signal. The carrier and modulating signal are then both shifted in phase by 90° and applied to the second, lower, balanced modulator. The phase-shifting

Figure 4-32 An SSB generator using the phasing method.



action causes one sideband to be canceled out when the two balanced modulator outputs are added to produce the output.

The carrier signal is $V_c \sin 2\pi f_c t$. The modulating signal is $V_m \sin 2\pi f_m t$. Balanced modulator 1 produces the product of these two signals: $(V_m \sin 2\pi f_m t)\,(V_c \sin 2\pi f_c t)$. Applying a common trigonometric identity

$$\sin A \sin B = 0.5[\cos(A - B) - \cos(A + B)]$$

we have

$$(V_m \sin 2\pi f_m t)\,(V_c \sin 2\pi f_c t) = 0.5V_mV_c[\cos(2\pi f_c - 2\pi f_m)t - \cos(2\pi f_c + 2\pi f_m)t]$$

Note that these are the sum and difference frequencies or the upper and lower sidebands.

It is important to remember that a cosine wave is simply a sine wave shifted by 90°; that is, it has exactly the same shape as a sine wave, but it occurs 90° earlier in time. A cosine wave *leads* a sine wave by 90°, and a sine wave *lags* a cosine wave by 90°.

The 90° phase shifters in Fig. 4-32 create cosine waves of the carrier and modulating signals that are multiplied in balanced modulator 2 to produce $(V_m \cos 2\pi f_m t) \times (V_c \cos 2\pi f_c t)$. Applying another common trigonometric identity

$$\cos A \cos B = 0.5[\cos(A - B) + \cos(A + B)]$$

we have

$$(V_m \cos 2\pi f_m t)(V_c \cos 2\pi f_c t) = 0.5V_mV_c[\cos(2\pi f_c - 2\pi f_m)t + \cos(2\pi f_c + 2\pi f_m)t]$$

When you add the sine expression given previously to the cosine expression just above, the sum frequencies cancel and the difference frequencies add, producing only the lower sideband $\cos[(2\pi f_c - 2\pi f_m)t]$.

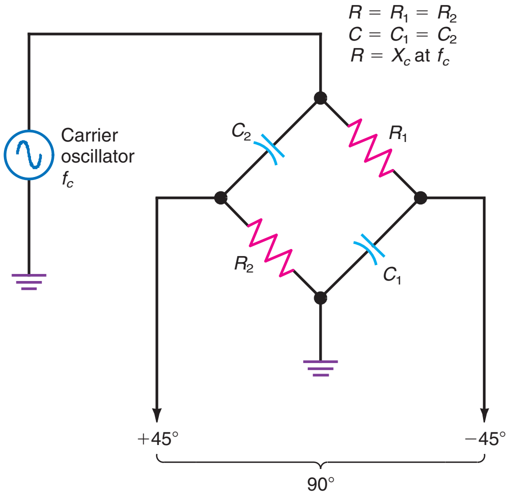
Carrier phase shift

Carrier Phase Shift. A phase shifter is usually an *RC* network that causes the output to either lead or lag the input by 90°. Many different kinds of circuits have been devised for producing this phase shift. A simple *RF* phase shifter consisting of two *RC* sections, each set to produce a phase shift of 45°, is shown in Fig. 4-33. The section made up of R_1 and C_1 produces an output that lags the input by 45°. The section made up of C_2 and R_2 produces a phase shift that leads the input by 45°. The total phase shift between the two outputs is 90°. One output goes to balanced modulator 1, and the other goes to balanced modulator 2.

GOOD TO KNOW

When the filter method is used to produce SSB signals, either the upper or the lower sideband is selected. The choice of upper or lower sideband varies from service to service and must be known to properly receive an SSB signal.

Figure 4-33 A single-frequency 90° phase shifter.



Since a phasing-type SSB generator can be made with IC balanced modulators such as the 1496 and since these can be driven by a square wave carrier frequency signal, a digital phase shifter can be used to provide the two carrier signals that are 90° out of phase. Fig. 4-34 shows two *D*-type flip-flops connected as a simple shift register with feedback from the complement output of the *B* flip-flop to the *D* input of the *A* flip-flop. Also *JK* flip-flops could be used. It is assumed that the flip-flops trigger or change state on the negative-going edge of the clock signal. The clock signal is set to a frequency exactly four times higher than the carrier frequency. With this arrangement, each flip-flop produces a 50 percent duty cycle square wave at the carrier frequency, and the two signals are exactly 90° out of phase with each other. These signals drive the differential amplifier switches in the 1496 balanced modulators, and this phase relationship is maintained regardless of the clock or carrier frequency. TTL flip-flops can be used at frequencies up to about 50 MHz. For higher frequencies, in excess of 100 MHz, emitter

Figure 4-34 A digital phase shifter.

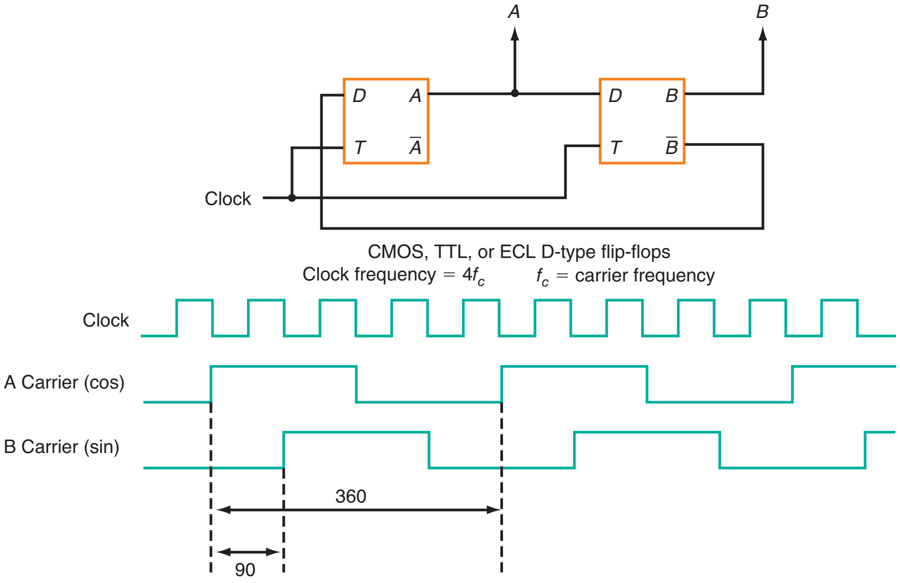
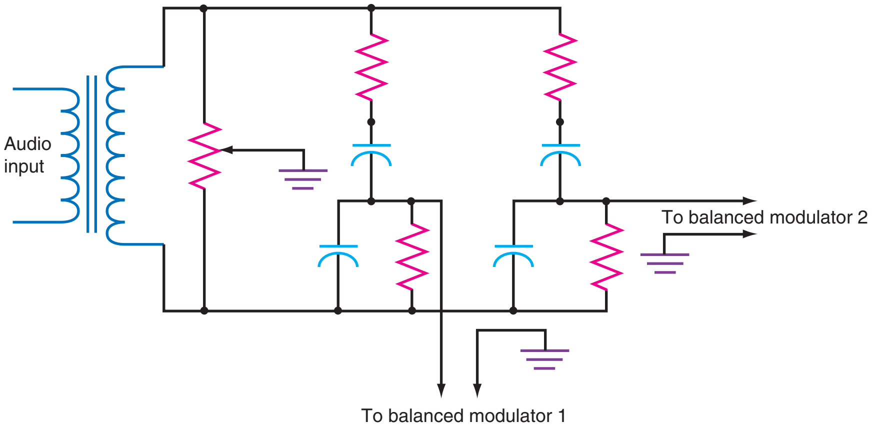


Figure 4-35 A phase shifter that produces a 90° shift over the 300- to 3000-Hz range.



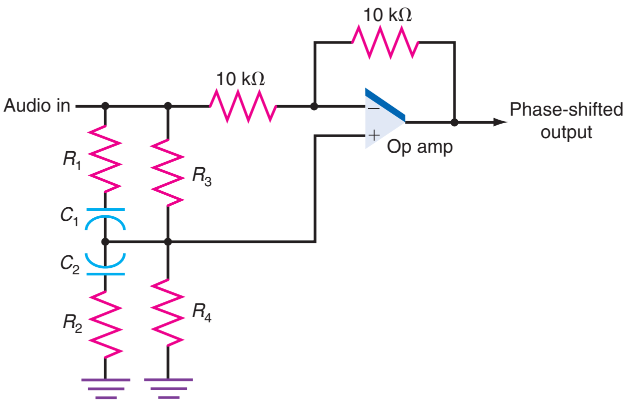
coupled logic (ECL) flip-flops can be used. In CMOS integrated circuits, this technique is useful to frequencies up to 10 GHz.

Audio Phase Shift. The most difficult part of creating a phasing-type SSB generator is to design a circuit that maintains a constant 90° phase shift over a wide range of audio modulating frequencies. (Keep in mind that a phase shift is simply a time shift between sine waves of the same frequency.) An *RC* network produces a specific amount of phase shift at only one frequency because the capacitive reactance varies with frequency. In the carrier phase shifter, this is not a problem, since the carrier is maintained at a constant frequency. However, the modulating signal is usually a band of frequencies, typically in the audio range from 300 to 3000 Hz.

One of the circuits commonly used to produce a 90° phase shift over a wide bandwidth is shown in Fig. 4-35. The phase-shift difference between the output to modulator 1 and the output to modulator 2 is 90° ± 1.5° over the 300- to 3000-Hz range. Resistor and capacitor values must be carefully selected to ensure phase-shift accuracy, since inaccuracies cause incomplete cancellation of the undesired sideband.

A wideband audio phase shifter that uses an op amp in an active filter arrangement is shown in Fig. 4-36. Careful selection of components will ensure that the phase shift of the output will be close to 90° over the audio frequency range of 300 to 3000 Hz. Greater precision of phase shift can be obtained by using multiple stages, with each stage having different component values and therefore a different phase-shift value. The phase shifts in the multiple stages produce a total shift of 90°.

Figure 4-36 An active phase shifter.



The phasing method can be used to select either the upper or the lower sideband. This is done by changing the phase shift of either the audio or the carrier signals to the balanced modulator inputs. For example, applying the direct audio signal to balanced modulator 2 in Fig. 4-32 and the 90° phase-shifted signal to balanced modulator 1 will cause the upper sideband to be selected instead of the lower sideband. The phase relationship of the carrier can also be switched to make this change.

The output of the phasing generator is a low-level SSB signal. The degree of suppression of the carrier depends on the configuration and precision of the balanced modulators, and the precision of the phase shifting determines the degree of suppression of the unwanted sideband. The design of phasing-type SSB generators is critical if complete suppression of the undesired sideband is to be achieved. The SSB output is then applied to linear RF amplifiers, where its power level is increased before being applied to the transmitting antenna.

DSB and SSB Demodulation

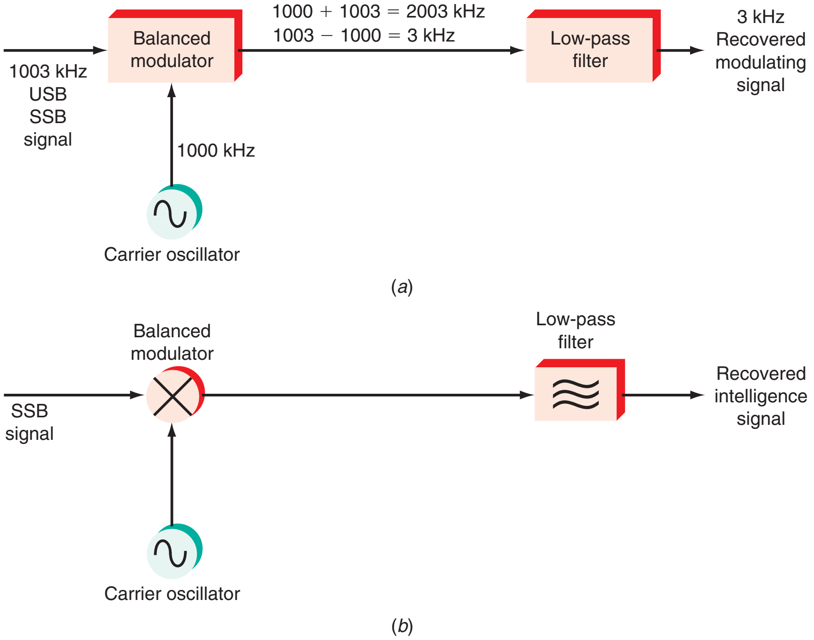
Product detector

To recover the intelligence in a DSB or SSB signal, the carrier that was suppressed at the receiver must be reinserted. Assume, e.g., that a 3-kHz sine wave tone is transmitted by modulating a 1000-kHz carrier. With SSB transmission of the upper sideband, the transmitted signal is 1000 + 3 = 1003 kHz. Now at the receiver, the SSB signal (the 1003-kHz USB) is used to modulate a carrier of 1000 kHz. See Fig. 4-37(*a*). If a balanced modulator is used, the 1000-kHz carrier is suppressed, but the sum and difference signals are generated. The balanced modulator is called a *product detector* because it is used to recover the modulating signal rather than generate a carrier that will transmit it. The sum and difference frequencies produced are

$$\begin{aligned}\text{Sum:}\quad & 1003 + 1000 = 2003\ \text{kHz}\\ \text{Difference:}\quad & 1003 - 1000 = 3\ \text{kHz}\end{aligned}$$

The difference is, of course, the original intelligence or modulating signal. The sum, the 2003-kHz signal, has no importance or meaning. Since the two output frequencies of the balanced modulator are so far apart, the higher undesired frequency is easily filtered out by a low-pass filter that keeps the 3-kHz signal but suppresses everything above it.

Figure 4-37 A balanced modulator used as a product detector to demodulate an SSB signal.



Any balanced modulator can be used as a product detector to demodulate SSB signals. Many special product detector circuits have been developed over the years. Lattice modulators or ICs such as the 1496 both make good product detectors. All that needs to be done is to connect a low-pass filter on the output to get rid of the undesired high-frequency signal while passing the desired difference signal. Fig. 4-37(*b*) shows a widely accepted convention for representing balanced modulator circuits. Note the special symbols used for the balanced modulator and low-pass filter.

CHAPTER REVIEW

Online Activity

4-1 ASK Transmitters and Receivers

Objective: Explore the availability and application of IC ASK transmitters, receivers, and transceivers.

Procedure:

1. Perform an Internet search on the terms *ASK, ASK transmitters, ASK receivers*, and *Ak transceivers*.
2. Identify specific ICs, modules, or other products in this category. Download any available data sheets or other sources of information.
3. Answer the following questions. Repeat step 2 until you are able to answer the questions.

Questions:

1. List at least four manufacturers of ASK ICs in any form.
2. What frequencies of operation do they normally use?
3. What is a common receiver sensitivity level range?
4. What is a typical transmitter output power range?
5. What are the common dc operating voltages for ASK receivers?
6. List three common uses for ASK transceivers.

Questions

1. What mathematical operation does an amplitude modulator perform?
2. What type of response curve must a device that produces amplitude modulation have?
3. Describe the two basic ways in which amplitude modulator circuits generate AM.
4. What type of semiconductor device gives a near-perfect square-law response?
5. Which four signals and frequencies appear at the output of a low-level diode modulator?
6. Which type of diode would make the best (most sensitive) AM demodulator?
7. Why does an analog multiplier make a good AM modulator?
8. What kind of amplifier must be used to boost the power of a low-level AM signal?
9. How does a differential amplifier modulator work?
10. To what stage of a transmitter does the modulator connect in a high-level AM transmitter?
11. What is the simplest and most common technique for demodulating an AM signal?
12. What is the most critical component value in a diode detector circuit? Explain.
13. What is the basic component in a synchronous detector? What operates this component?
14. What signals does a balanced modulator generate? Eliminate?
15. What type of balanced modulator uses transformers and diodes?
16. What is the most commonly used filter in a filter-type SSB generator?
17. What is the most difficult part of producing SSB for voice signals by using the phasing methods?
18. Which type of balanced modulator gives the greatest carrier suppression?
19. What is the name of the circuit used to demodulate an SSB signal?
20. What signal must be present in an SSB demodulator besides the signal to be detected?

Problems

1. A collector modulated transmitter has a supply voltage of 48 V and an average collector current of 600 mA. What is the input power to the transmitter? How much modulating signal power is needed to produce 100 percent modulation? ◆
2. An SSB generator has a 9-MHz carrier and is used to pass voice frequencies in the 300- to 3300-Hz range. The lower sideband is selected. What is the approximate center frequency of the filter needed to pass the lower sideband?
3. A 1496 IC balanced modulator has a carrier-level input of 200 mV. The amount of suppression achieved is 60 dB. How much carrier voltage appears at the output? ◆

◆ *Answers to Selected Problems follow Chap. 22.*

Critical Thinking

1. State the relative advantages and disadvantages of synchronous detectors versus other types of amplitude demodulators.
2. Could a balanced modulator be used as a synchronous detector? Why or why not?
3. An SSB signal is generated by modulating a 5-MHz carrier with a 400-Hz sine tone. At the receiver, the carrier is reinserted during demodulation, but its frequency is 5.00015 MHz rather than exactly 5 MHz. How does this affect the recovered signal? How would a voice signal be affected by a carrier that is not exactly the same as the original?