CHAPTER 2
Amplitude Modulation

2.1 Need for Modulation:

A baseband signal is a signal produced from a transducer (microphone, camera, etc.), and is transmitted as it is without a carrier.

Baseband communication is usually restricted to short distances, and limited applications. The problem with baseband signals is that the communication infrastructure becomes occupied by only one user at a time (dedicated channel). Very low efficiency results in dedicated channel operation. Baseband communication is acceptable in such applications as local telephone calls, computer interface signals and video signals in editing suits.

With the advent of wireless communication, it is required to use antennas, where electrical signals cause electrons in the wire to oscillate at the signal frequency, giving rise to electromagnetic radiation at the same frequency. There is an intimate relation between the wavelength and the dimensions of the antenna. Therefore, it is mandatory to raise the frequency level of the signal from baseband frequencies to carrier frequencies. Such a carrier is loaded by the information at the baseband frequencies.

The carrier is a high frequency sinusoidal wave characterized by amplitude, frequency and phase. As to the signal to be transmitted (called modulating signal), we alter one of the features of the carrier (amplitude, frequency or phase). If the amplitude of the carrier is modulated (changed) by the modulating signal, we call this amplitude modulation (AM). If the frequency of the carrier is modulated by the signal, we call this frequency modulation (FM). If the phase of the carrier is modulated by the signal, we call this phase modulation (PM).

The carrier frequency itself is chosen according to the specific application. The antenna length is proportional to the wavelength (λ). By increasing the carrier frequency (f_c), the antenna length falls to reasonable values $\left(\lambda = c/f_c\right)$, where c is the velocity of light.

We note also that the concept of modulation is not restricted to wireless communication. It is extended to wire communication as well. Its main advantage is being able to serve many customers (or subscribers) over the same communication hardware by assigning a carrier frequency to each subscriber (or channel), so that the infrastructure is shared by many users. This is called frequency division multiplexing (FDM).

With so many customers, channels and users, the demand is ever increasing for utilizing all parts of the electromagnetic spectrum. Every trick in the book has been used to maximize the exploitation of the limited spectrum, and to increase the efficiency of utilization of all communication possibilities in a rather crowded and limited scope of electromagnetic spectrum. In all cases, the bandwidth of information - with which the carrier is loaded - must be a small percent of the carrier frequency itself. The choice of the carrier frequency must also take into account the nature of the medium of propagation, such as to minimize losses and attenuation as much as possible. Obviously, the carrier frequencies must fall within the passband window (frequencies within the allowable bandwidth of the medium).

2.2 Communication Spectrum:

The frequency spectrum extends from zero to infinity The region used in telecommunication - called radio frequency (RF) - is divided into portions as shown in Table 2.1. The 20 Hz-20 kHz is the band of frequencies resulting from mechanical vibrations, which the ear is theoretically capable of hearing.

The range 300 Hz – 3.4 kHz is the portion of audio frequencies, as baseband electrical signals transmitted over telephone lines. VLF band (10 kHz – 30 kHz) is used for undersea communication, maritime services and mine detection. Such applications use mostly acoustic waves, since the use of electromagnetic radiation would require unreasonable antenna lengths.

Table 2.1 Frequency bands used in communication

Frequency Band	Classification	Abbreviation
20 Hz - 20 kHz	Audio frequencies	AF
300 Hz - 3.4 kHz	Baseband Telephony	AF
10 kHz - 30 kHz	Very Low frequencies	VLF
30 kHz - 300 kHz	Low frequencies	LF
300 kHz - 3 MHz	Medium frequencies	MF
3 MHz - 30 MHz	High frequencies	HF
30 MHz - 300 MHz	Very High frequencies	VHF
300 MHz - 3 GHz	Ultra High frequencies	UHF
3 GHz - 30 GHz	Super High frequencies	SHF
30 GHz - 300 GHz	Extra High frequencies	EHF

LF is used in industrial, medical and scientific applications.
MF, HF and VHF are used by commercial radio stations. VHF and UHF are used for commercial TV. SHF is used for direct line - of - sight communication microwave links and satellite communication. EHF is used in optical fibers.

2.3 Amplitude Modulation:

We start with an RF carrier wave of the form (Fig. 2.1b)

$$v_c(t) = A_c \cos \omega_c t \,, \qquad (2-1)$$

where A_c is the peak of the instantaneous value $v_c(t)$.

We let a modulating signal $v_m(t)$ (Fig. 1.2a) affect the amplitude of the carrier, such that the carrier has an instantaneous amplitude, $a_c(t)$ given by (Fig. 2.1c):

$$a_c(t) = A_c + v_m(t) \qquad (2-2)$$

Thus, the composite waveform $v_{AM}(t)$ becomes

$$v_{AM}(t) = [A_c + v_m(t)]\cos\omega_c t \qquad (2-3)$$

Usually, $v_m(t)$ is a complex function of time, which represents the useful signal or information. It can be represented by a band of frequency components comprising the signal spectrum or bandwidth. Let us concentrate on one of these sinusoidal components, such that

$$v_m(t) = A_m \cos\omega_m t \,, \qquad (2-4)$$

where ω_m is a modulating signal frequency. From eqns. (2.2) and (2.3),

$$v_{AM}(t) = (A_c + A_m \cos\omega_m t)\cos\omega_c t \qquad (2-5)$$

We define the modulation index (or modulation depth) m_a as:

$$m_a = \frac{A_m}{A_c} \qquad (2-6)$$

Thus, eqn. (2.5) becomes

$$v_{AM}(t) = A_c(1 + m_a \cos\omega_m t)\cos\omega_c t \qquad (2-7)$$

$$= A_c \cos\omega_c t + m_a A_c \cos\omega_m t \cos\omega_c t$$

$$= A_c \cos\omega_c t + \tfrac{1}{2} m_a A_c \cos(\omega_c + \omega_m)t$$

$$+ \tfrac{1}{2} m_a A_c \cos(\omega_c - \omega_m)t \qquad (2-8)$$

We see that three frequency components result, the carrier ω_c, the upper sideband (USB) frequency $(\omega_c + \omega_m)$, and the lower sideband frequency (LSB) $(\omega_c - \omega_m)$.

We see that the representation of an AM signal is a troika: a carrier (ω_c), USB ($\omega_c + \omega_m$) and LSB ($\omega_c - \omega_m$). The range of ω for this troika $\Delta\omega = 2\omega_m$.

Thus, the bandwidth (BW or Δf) is given by

$$BW = \Delta f = 2\omega_m / 2\pi = 2\hat{f}_m, \qquad (2-9)$$

Where $\hat{f}_m$ is the maximum modulating frequency.

All other modulating frequencies fall within the BW range, with two sidebands for each component. Transmission and reception of this type of AM signals is called double sideband (DSB). The power distributed in this troika may be calculated by considering the power as the square of the signal amplitude (voltage or current).

Ex 2.1:
Find the power distribution in AM components, and the maximum power efficiency in DSB AM.

Solution:

The power in the carrier component in eqn. (2-8) is $(A_C/\sqrt{2})^2$. The factor $1/\sqrt{2}$ accounts for the rms value.

The power in either USB or LSB is given by $\left(\dfrac{m_a A_c}{2\sqrt{2}}\right)^2$

The total power in the troika is

$$P_{AM} = \frac{1}{2}A_c^2 + \frac{1}{8}m_a^2\ A_c^2 + \frac{1}{8}m_a^2\ A_c^2$$

Only USB or LSB contains the information needed. The power efficiency η_{AM} is defined as the power of the information in one side band to the troika power.

$$\eta_{AM} = \frac{\frac{1}{8}m_a^2 A_c^2}{\frac{1}{2}A_c^2 + \frac{1}{4}m_a^2 A_c^2} = \frac{1}{2}\left(\frac{m_a^2}{2+m_a^2}\right)$$

The maximum value for m_a is 1 (100%). Thus, the maximum value for η_{AM} is 16.5%. For both sidebands, the maximum value for η_{DSB} (in DSB AM) is 33%.

Sometimes, we get rid of the carrier power. This scheme is called double sideband suppressed carrier (DSBSC). If we get rid of the second sideband, we call this single sideband transmission (SSB). It is more complex to design SSB receivers. It becomes a tradeoff between saving the spectrum and economizing on the complexity of the receiver design. The SSB is not usually used in commercial broadcasting, but is used extensively in large capacity point to point systems, to save as much as possible on the limited electromagnetic spectrum. We call this procedure spectrum conservation.

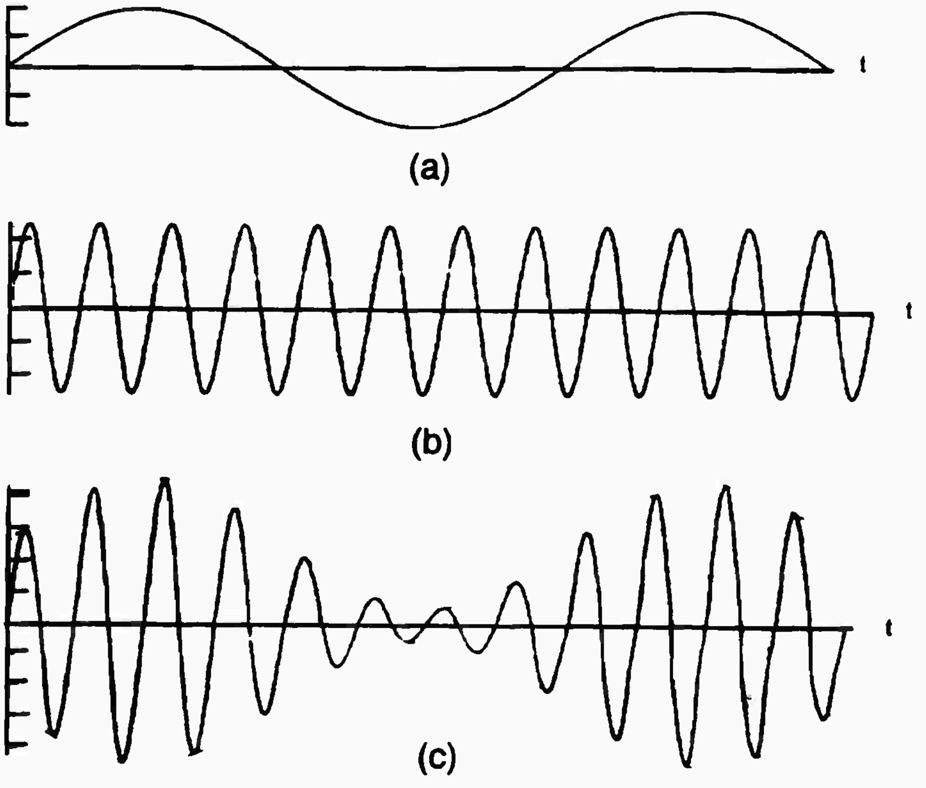


Fig. 2.1 AM signal

a) modulating signal b) carrier c) AM waveform

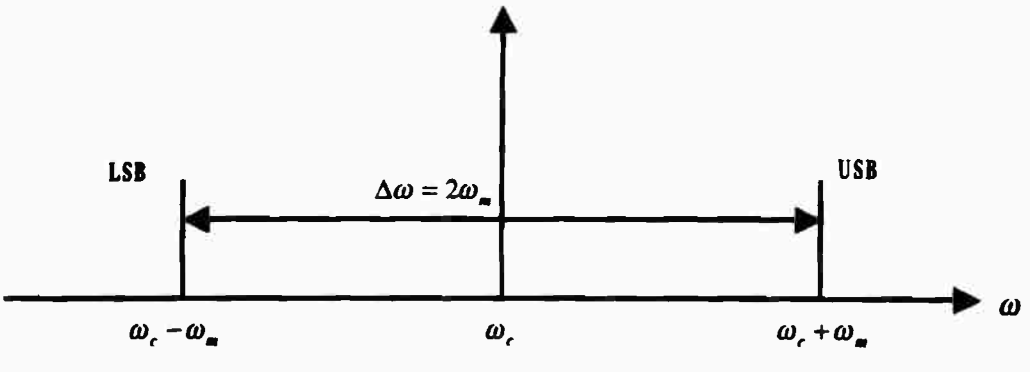


Fig. 2.2 AM spectrum

2.4 AM Modulators and Demodulators:

There are several schemes for AM modulation. One of the early circuits is that of collector modulation (Fig. 2.3a). In this push-pull circuit, the modulating signal - being at a low frequency - is considered as a variation in the bias voltage. The peak collector current varies in push-pull (and class C amplifiers) according to the peak collector voltage. Thus, the peak collector current follows the modulating signal. Such a peak provides the envelope for the RF voltage developed across the tank circuit. For 100 % modulation, the collector tank voltage varies between zero and twice the supply voltage ($2V_{CC}$), (Fig. 2.3b).

A diode can also be used for AM modulation. In the circuit shown (Fig. 2.4) - and with no modulating signal - the RF waveform is rectified by the diode, and hence, only bursts of RF current pass through, corresponding to positive half cycles. Due to the tank circuit, a sine wave is reconstructed. When an audio signal is applied along with the RF, the peak amplitude of each diode current burst depends on the instantaneous value of the bias (peak of RF plus the instantaneous value of the audio signal). The tank circuit reconstructs the modulated waveform.

Note that the output across the tank circuit results from the mixing of the audio and RF, giving rise to the standard AM (carrier plus double sidebands). It is interesting to see that what appears to be the sum of RF and audio amounts at the end to a multiplication of the RF with the AF envelope. This is because of the dependence on the instantaneous value of the bias, in a way similar to collector modulation and the selective function of the tank circuit. We should note that the audio signal - in the end - is filtered out by the tank circuit, which is tuned to the RF.

A balanced modulator is a diode arrangement, which suppresses the RF carrier. A common circuit arrangement is the balanced ring modulator (Fig. 2.5). The audio signal is applied between points X and Z of the ring, and the RF carrier is applied at equal levels between point A and ground, and between point B and ground. When the RF carrier is positive, current flows in resistors R_2 and R_3, and in diodes X_1 and X_3, so that we have two branches $R_2/\ X_1$ and R_3/X_3. Hence, a positive voltage exists at points A and B. Thus, no RF current exists in the output of the transformer T_1. During the negative half cycle, current flows through R_2 and R_3 and in diodes X_2 and X_4, causing a negative voltage at points A and B. Again, no RF carrier is present in transformer T_1. Thus, we call this type of modulation suppressed carrier. R_1 is used to balance the bridge for zero RF carrier at the output.

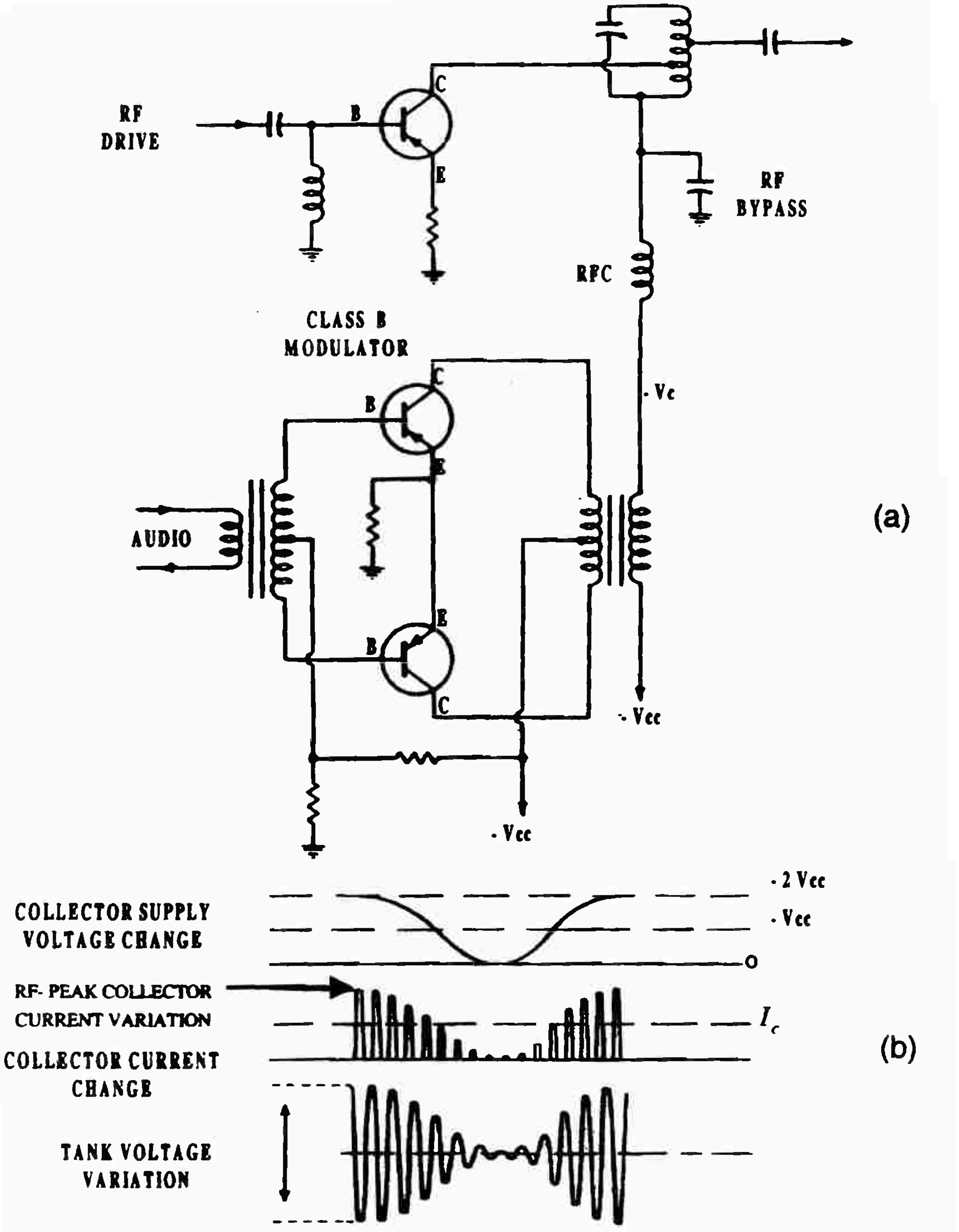
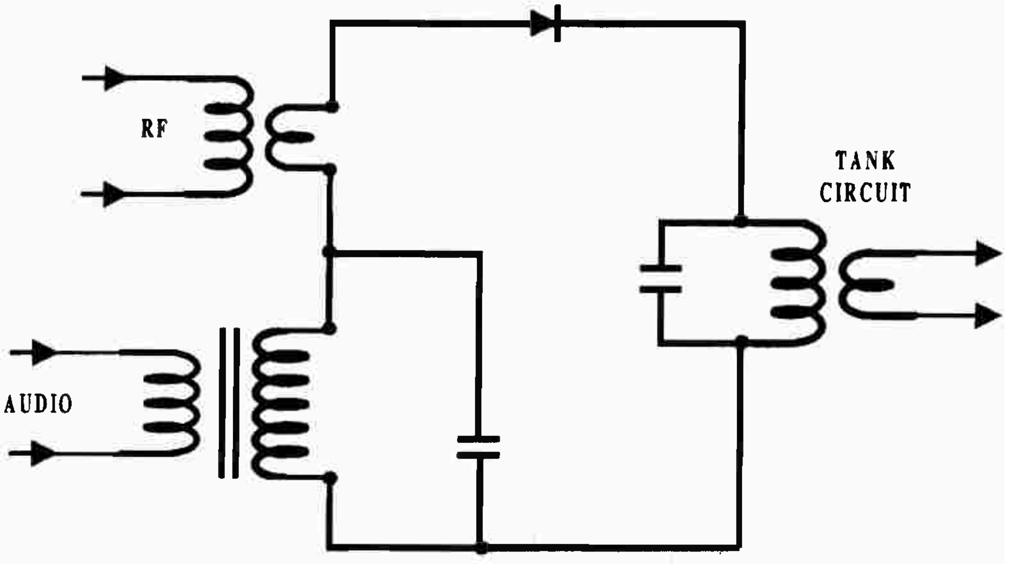
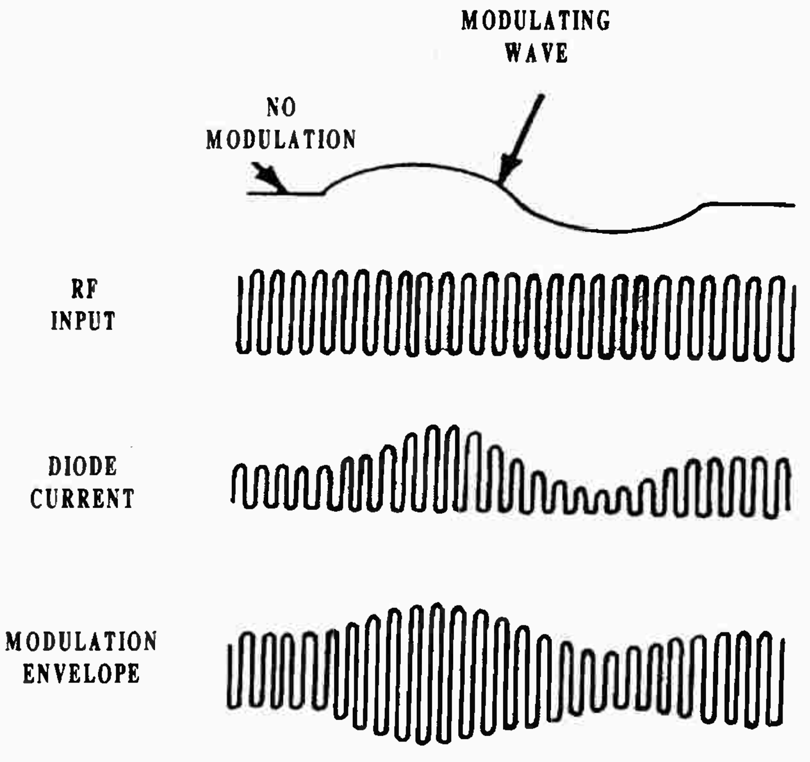


Fig. 2.3 Collector modulator
a) circuit b) waveforms



(a)



(b)

Fig. 2.4 Diode modulator
a) circuit b) waveforms

When an audio signal is applied to the bridge at points X and Z, the bridge becomes unbalanced. A positive audio signal causes diodes X_4 and X_1 to conduct heavier, due to the forward biasing by the audio signal. Conduction in diodes X_2 and X_3 decreases due to the reverse biasing effect of the audio signal. The RF current in R_2 increases and the RF current in R_3 decreases, resulting in an RF current in the primary of T_1 , which is proportional to the amplitude of the audio signal.

We should note that in all AM modulation schemes, the end result is a form of a product of RF and modulating signal. Therefore, a modern method for obtaining the AM wave is to use a product multiplier, which multiplies the audio signal with an RF carrier. Multipliers such as MC 1496 exist in monolithic form, and can be used for a variety of applications, including DSBSC product detector and frequency doublers.

A familiar form of AM detectors is the envelope detector (Fig. 2.6). The diode conducts in the positive half cycles of the modulated wave. The capacitor charges to the peak of the input pulse. During negative half cycles, the capacitor discharges through R. A smoothing filter may be added to smooth out the output. It should be noted that the time constant during the diode conduction must be short enough to allow the capacitor to charge up to the peak RF value within the RF half cycle. Yet, the time constant RC must be long enough so that the capacitor will remain charged to the peak input voltage, without discharging into R. If the time constant RC, however, were made too long, the output circuit would not be able to follow (detect) the variations in the peak due to AM modulation. The output voltage would saturate at the maximum of the peaks.

Thus,

$$\frac{2\pi}{\omega_{m_{max}}} >> RC >> \frac{2\pi}{\omega_c}, \qquad (2-12)$$

where $\omega_{m_{max}}$ is the maximum frequency component in the modulating signal.

Another type of modulation is called nonlinear modulation, and is obtained by inputting the carrier and the modulating signal to a nonlinear amplifier. Suppose that such an amplifier has the following characteristic.

$$\upsilon_o = a_o + a_1\upsilon_i + a_2\upsilon_i^2 \qquad (2-13)$$

The input signal υ_i is given by

$$\upsilon_i = V_c \cos \omega_c t + V_m \cos \omega_m t \qquad (2-14)$$

$$\upsilon_o = a_o + a_1\left(V_c \cos \omega_c t + V_m \cos \omega_m t\right)$$

$$+ a_2\left(V_c \cos \omega_c t + V_m \cos \omega_m t\right)^2$$

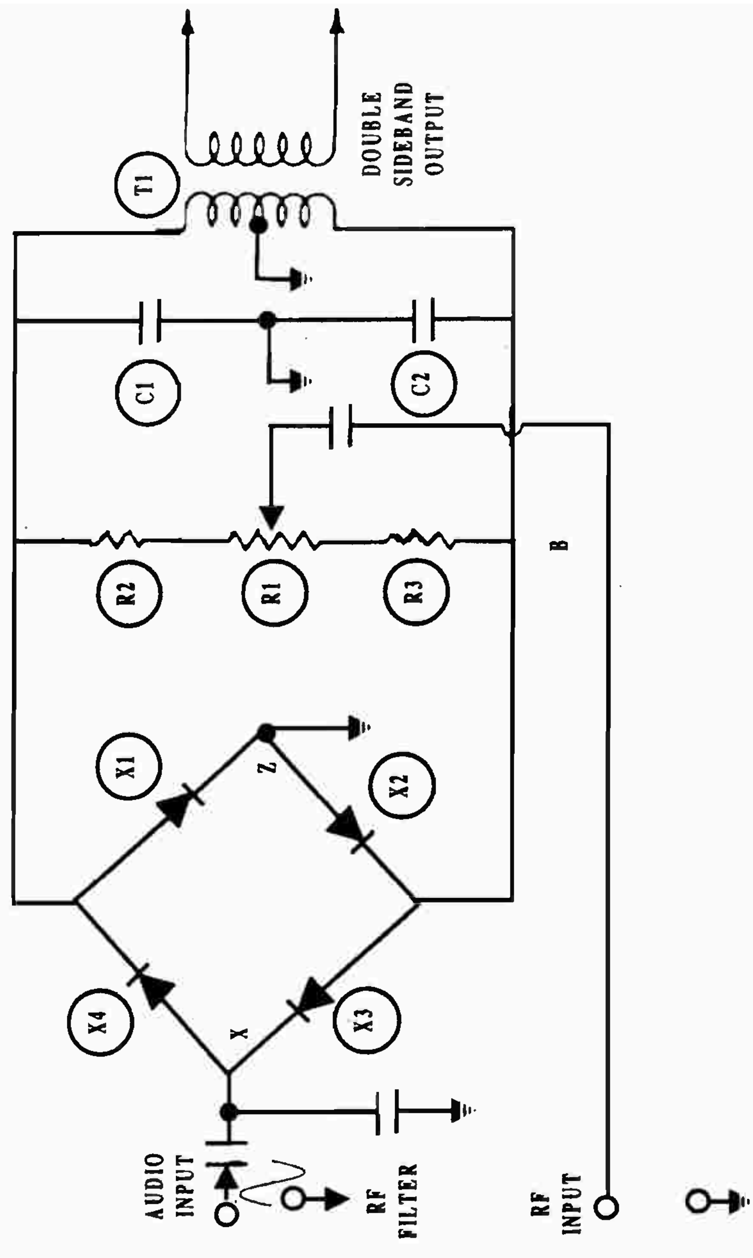


Fig 2.5 Balanced ring modulator

$$= a_o + a_1 V_c \cos \omega_c t + a_1 V_m \cos \omega_m t + a_2 V_c^2 \cos^2 \omega_c t$$
$$+ 2a_2 V_c V_m \cos \omega_c t \cos \omega_m t + a_2 V_m^2 \cos^2 \omega_m t$$
$$= a_o + \frac{a_2}{2}\left(V_c^2 + V_m^2\right) + a_1\left(V_c \cos \omega_c t + V_m \cos \omega_m t\right)$$
$$+ \frac{a_2}{2}\left(V_c^2 \cos 2\omega_c t + V_m^2 \cos 2\omega_m t\right)$$
$$+ a_2 V_c V_m \left[\cos(\omega_c + \omega_m)t + \cos(\omega_c - \omega_m)t\right] \qquad (2-15)$$

If $\omega_c >> \omega_m$, and the signal is passed through a band pass filter - which passes only the sum and difference frequency components - we have

$$\upsilon_o = a_1 V_c \left\{\cos \omega_c t + \frac{a_2 V_m}{a_1}\left[\cos(\omega_c + \omega_m)t + \cos(\omega_c - \omega_m)t\right]\right\} \qquad (2-16)$$

Hence, we have achieved AM. This modulation is called square law modulation, because the sidebands owe their existence to the V_i^2 term in eqn. (2-13).

Square law circuits can also be used for detection. This is called nonlinear detection. Consider an input

$$V_i(t) = V_c\left[1 + m_a \cos \omega_m t\right]\cos \omega_c t \qquad (2-17)$$

Assume that this input is applied to a detector whose characteristic is given by eqn. (2-13), and that the output of the square law circuit is inputted to a LPF amplifier, which rejects all frequencies close to ω_c or its multiples ,i.e., it passes only audio components. Thus, the output $V_O(t)$ is given by.

$$V_o(t) = a_2 V_c^2 m_a\left(\cos \omega_m t + \frac{m_a}{4}\cos 2\omega_m t\right) \qquad (2-18)$$

Thus, the audio signal has been demodulated. However, 25 % distortion has resulted. A LPF must be added to eliminate the harmonic term.

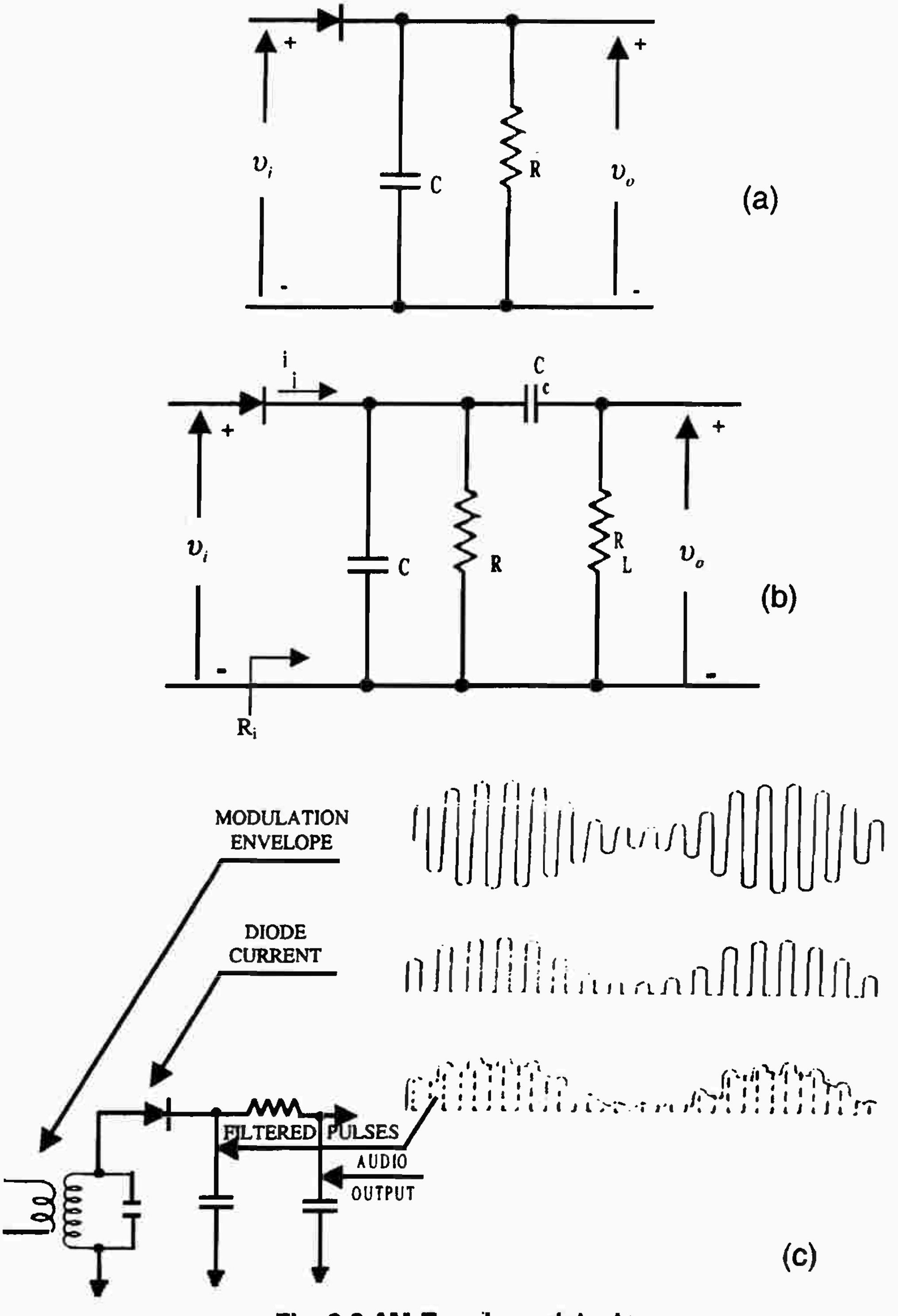


Fig. 2.6 AM Envelope detector
a) ideal circuit b) ideal circuit with a smoothing filter
c) practical circuit with output waveform

Problems:

1- Calculate the modulation depth for an amplitude modulation if the carrier peak is 300 mV, and the modulating signal has a peak of 200 mV. Discuss the case when overmodulation occurs as the modulation depth exceeds 100 %. Sketch the waveforms and the frequency spectrum.

2- The carrier peak is 10V. The output load resistor is 1kΩ. Plot the following quantities as functions of m_a; and sketch the frequency spectrum:

   a) power in the RF carrier.
   b) power in each sideband.
   c) total power.
   d) efficiency of modulation.

3- The carrier of an AM transmitter is 70 W, and when modulated, the power increases to 80 W. Calculate the following, and sketch the frequency spectrum.

   a) depth of modulation.
   b) modulation efficiency.
   c) range of variation in the wave envelope.

4- The power in an AM wave is 3kW, while the RF power is 2.5 kW. A second modulating signal having a modulation depth of 0.3 is applied. Calculate the total power when both signals are applied. Sketch the frequency spectrum.

5- An AM signal having a carrier frequency 200 kHz and an amplitude 10V is modulated by a 10 kHz signal to a depth of 80 %.

   a) sketch the spectrum and the time function.
   b) calculate the bandwidth.
   c) calculate the power in a 100 Ω load.

6- Three signals a,b,c, are to modulate an RF of 1 MHz and voltage 10V. Calculate the modulation depth and power components if the modulating signals are

   a) 100 Hz and amplitude 1 V.
   b) 200 Hz and amplitude 0.5 V.
   c) 300 Hz and amplitude 2 V.

   Sketch the frequency spectrum.

7- Analyze the balanced ring modulator (Fig. 2.5).

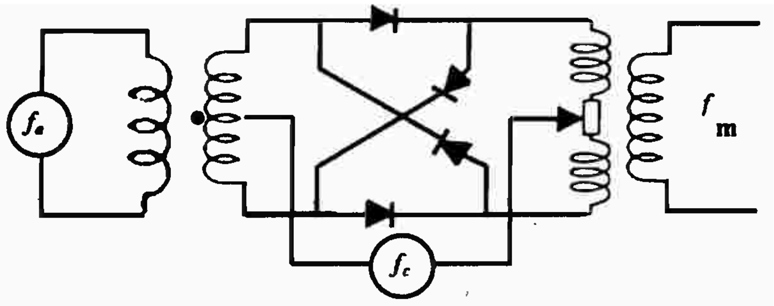
8- Discuss the operation of the `circuits shown a, b. c,.

9- Discuss the operation of the circuits shown d, e.

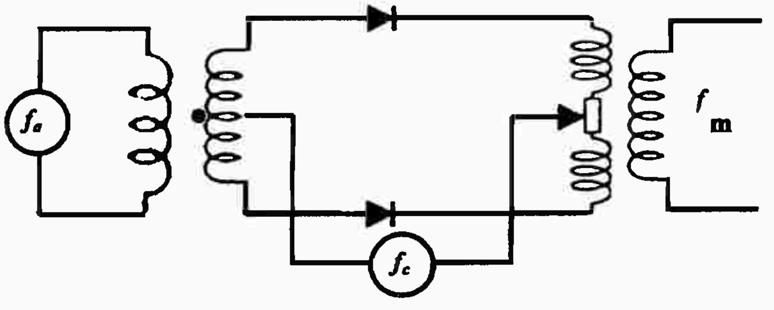
10- Discuss the operation of the circuits shown f, g.

11- Show how a multiplier may be used as a modulator and also as a detector. Estimate the percent distortion.

12- Verify eqn. (2-18)



(a)



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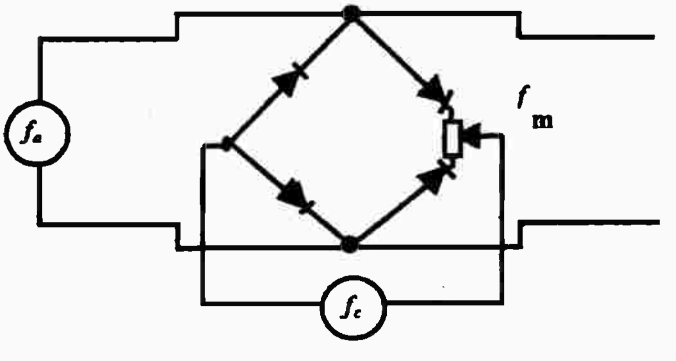
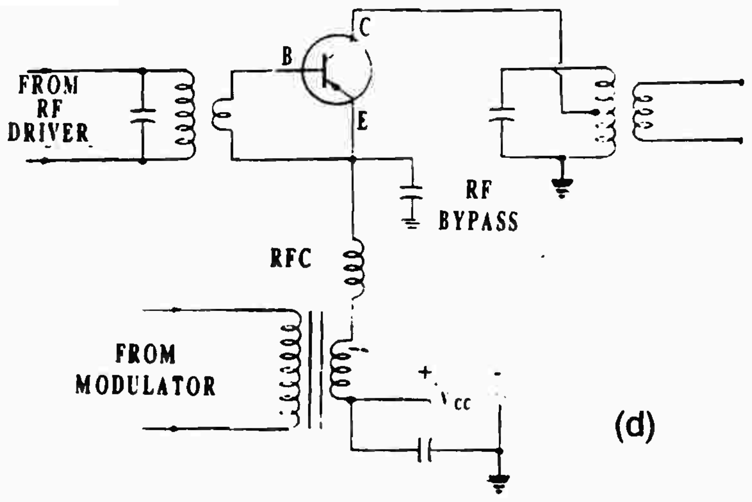


(c)

Prob. 2-8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DRIVER
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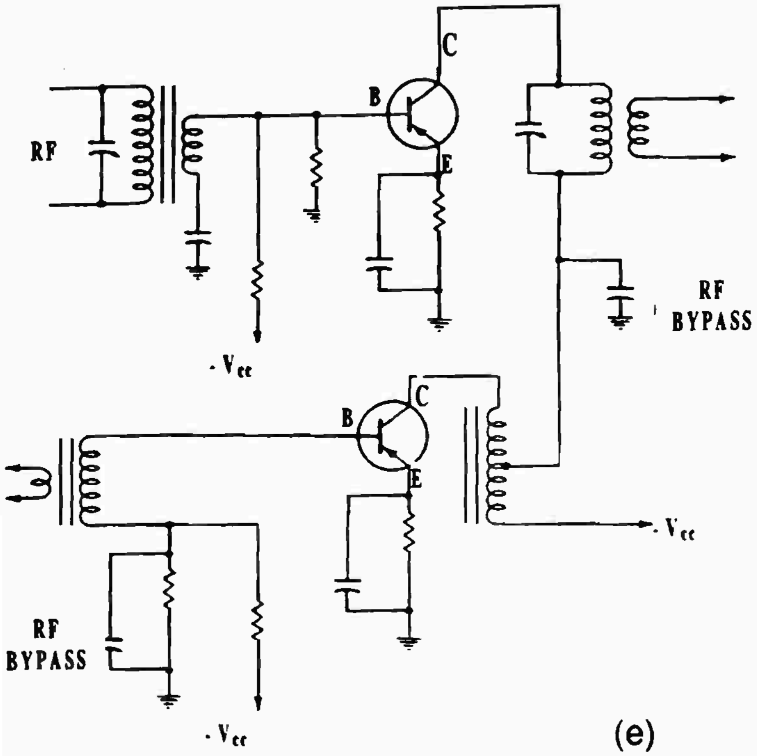
(d)


RF
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RF
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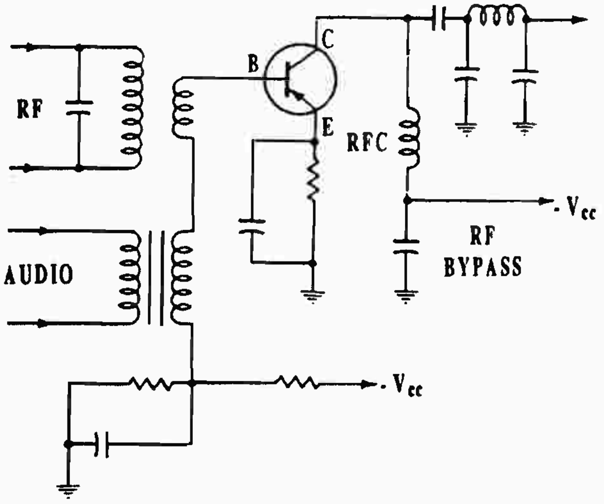
(e)

Prob. 2-9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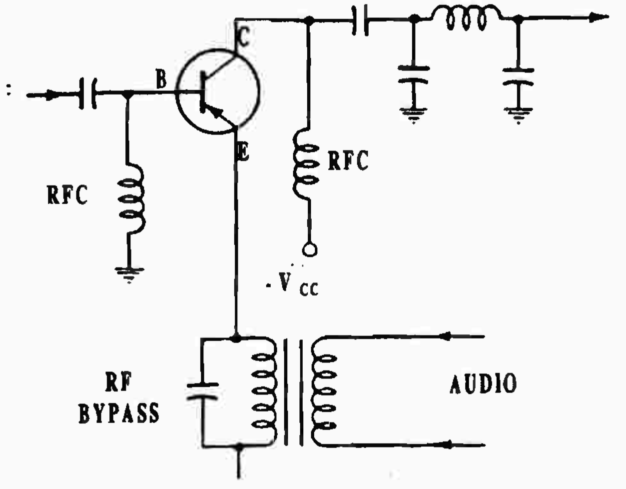
RF
BYPASS
- Vcc

(f)


B
C
E
RFC
RFC
- Vcc
RF
BYPASS
AUDIO
MODULATING
AMPLIFIER

(g)

Prob. 2-10

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