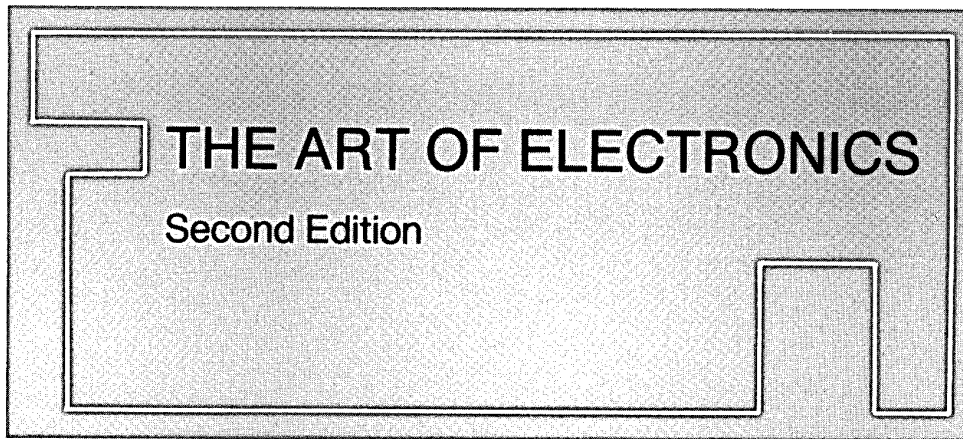


THE **ART** OF ELECTRONICS

PAUL HOROWITZ
WINFIELD HILL

SECOND EDITION



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waveform is always positive, as in normal AM.) Then, either by using sharp crystal filters or by using a method known as "phasing," one of the remaining sidebands can be eliminated. The "single-sideband" (SSB) signal that remains forms a highly efficient mode of voice communication and is widely used by radio amateurs and commercial users for long-range high-frequency telephony channels. When you're not talking, there's nothing being transmitted. To receive SSB, you need a BFO and product detector, as shown in the last block diagram, to reinsert the missing carrier.

□ Modulation spectra

Figure 13.43 shows representative spectra of voice-modulated AM, DSBSC, and SSB. When transmitting SSB, either sideband can be used. Note that SSB consists simply of the audio spectrum translated upward in frequency by f_c . When SSB is being received, the BFO and mixer combine to translate the spectrum down to audiofrequencies again. If the BFO is slightly mistuned, all audiofrequencies will be offset by the amount of mistuning. This dictates good stability for the LO and BFO in a receiver used for single-sideband.

Note that a mixer (modulator) can always be thought of as a frequency translator, especially when combined with suitable filters to eliminate the undesired outputs: When used as a modulator, a low-frequency band of frequencies is shifted up by the carrier frequency, to form a band

centered around f_c . When used as a mixer, a band of frequencies around f_c is shifted down to audiofrequencies ("baseband"), or to a band centered around the IF frequency, by the action of a high-frequency LO.

□ 13.18 Frequency modulation

Instead of modulating the amplitude of a carrier, as in AM, DSBSC, and SSB, it is possible to send information by modulating the frequency or phase of the carrier:

$$\text{signal} = \cos [\omega_c t + k \int f(t) dt]$$

frequency modulation (FM)

$$\text{signal} = \cos [\omega_c t + k f(t)]$$

phase modulation (PM)

FM and PM are closely related and are sometimes referred to as "angle modulation." FM is familiar as the mode used in the 88–108MHz VHF broadcast band, and AM is used in the 0.54–1.6MHz broadcast band. Anyone who has tuned an FM receiver has probably noticed the "quieting" of background noise characteristic of FM reception. It is this property (the steep rise of recovered SNR with increasing SNR of the channel) that makes wideband FM preferable to AM for high-quality transmission.

Some facts about FM: When the frequency deviation $k f(t)/2\pi$ is large compared with the modulating frequency [highest frequency present in $f(t)$], you have "wideband FM" as used in FM broadcasting. The modulation index, m_f , equals

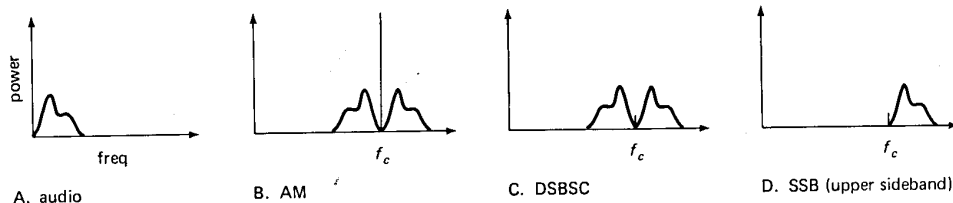


Figure 13.43. Suppressed-carrier spectra.

the ratio of frequency deviation to modulating frequency. Wideband FM is advantageous because under the right conditions the received SNR increases 6dB per doubling of FM deviation. The price you pay is increased channel bandwidth, since a wideband FM signal occupies approximately $2f_{\text{dev}}$ of bandwidth, where f_{dev} is the peak deviation of the carrier. FM broadcasting in the 88–108MHz band uses a peak deviation f_{dev} of 75kHz, i.e., each station uses about 150kHz of the band. This explains why wideband FM is not used in the AM band (0.54–1.6MHz): There would be room for only six stations in any broadcasting area.

FM spectrum

A carrier that is frequency-modulated by a sine wave has a spectrum similar to that shown in Figure 13.44. There are

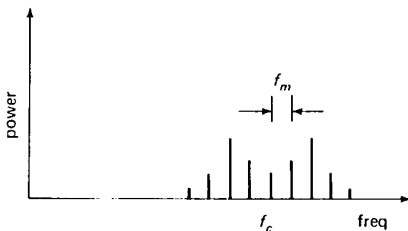


Figure 13.44. Wideband FM spectrum.

numerous sidebands spaced at multiples of the modulating frequency from the carrier, with amplitudes given by Bessel functions. The number of significant sidebands is roughly equal to the modulation index. For narrowband FM (modulation index <1), there is only one component on either side of the carrier. Superficially this looks the same as AM, but when the phase of the sidebands is taken into account, you have a waveform of constant amplitude and varying frequency (FM), rather than a waveform of varying amplitude and constant frequency (AM). With wideband FM

the carrier amplitude may be very small, with correspondingly high efficiency, i.e., most of the transmitted power goes into the information-carrying sidebands.

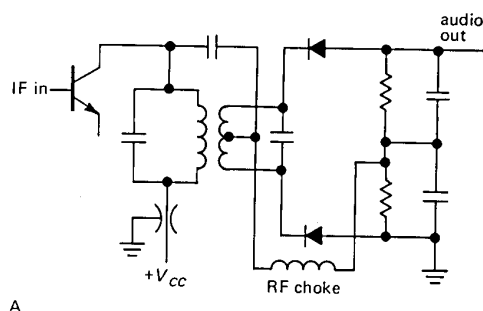
□ Generation and detection

FM is easily produced by varying an element of a tuned circuit oscillator; a varactor (a diode used as a voltage-variable capacitor, Section 5.18) is ideal. Another technique involves integrating the modulating signal, then using the result to do phase modulation. In either case it is often best to modulate at low deviation, then use frequency multiplication to increase the modulation index. This works because the rate of frequency deviation is not changed by frequency multiplication, whereas the deviation is multiplied along with the carrier.

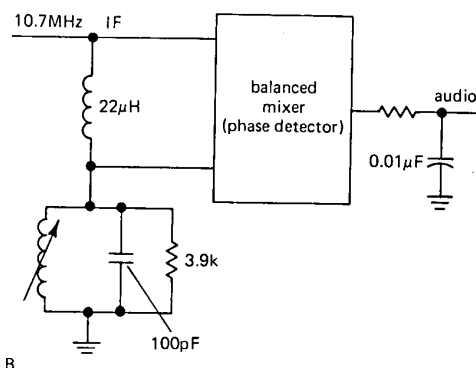
To detect FM, an ordinary superheterodyne receiver is used, with two differences. First, the final stage of IF amplification includes a "limiter," a stage run at constant (saturated) amplitude. Second, the subsequent detector (called a discriminator) has to convert frequency deviation into amplitude. There are several popular methods of detection:

1. A "slope detector," which is nothing more than a parallel LC circuit tuned off to one side of the IF frequency; as a result, it has a rising curve of response versus frequency across the IF bandwidth, thereby converting FM to AM. A standard envelope detector converts the AM to audio. There are improved versions of the slope detector involving a balanced pair of LC circuits tuned symmetrically to either side of the IF center frequency.
2. The Foster-Seely detector, or its variant, the "ratio detector," using a single tuned circuit in a fiendishly clever diode arrangement to give a linear curve of amplitude output versus frequency over the IF bandpass. These discriminators are superior to the simple slope detector (Fig. 13.45)

3. A "phase-locked loop" (PLL). This is a device that varies the frequency of a voltage-controlled oscillator to match an input frequency, as we discussed in Section 9.31. If the input is the IF signal, the control voltage generated by the PLL is linear in frequency, i.e., it is the audio output.



A



B

Figure 13.45. FM discriminators.
A. Foster-Seeley.
B. Balanced quadrature detector.

4. An averaging circuit, in which the IF signal is converted to a train of identical pulses at the same frequency. Averaging this pulse train generates an output proportional to IF frequency, i.e., the audio output plus some dc.

5. A "balanced quadrature detector," which is a combination of a phase detector (see Sections 9.27 and 9.31) and a phase-shifting network. The IF signal is passed through a network that produces a

shift varying linearly with frequency across the IF passband (an LC circuit would do nicely). The resultant signal and the original signal are compared in a phase detector, giving an output that varies with relative phase. That output is the desired audio signal (Fig. 13.45).

It is often pointed out that FM provides essentially noise-free reception if the channel has sufficient SNR, as compared with AM, where the rejection of interference improves only gradually with increasing signal power. This makes sense when you remember that FM signals pass through a stage of amplitude limiting before detection. As a result, the system is relatively insensitive to interfering signals and noise, which appear as amplitude variations added to the transmitted signal.

□ 13.19 Frequency-shift keying

Transmission of digital signals (radioteletype, RTTY) is usually done by shifting a continuous-running carrier in frequency between two closely spaced frequencies according to the 1's and 0's being transmitted; 850Hz of shift is a typical value. The use of frequency-shift keying (FSK), rather than on/off modulation, is extremely effective in the presence of large signal fading from changing propagation conditions. To demodulate FSK, you simply use a differential amplifier looking at the outputs from a pair of filters set at the two detected audio frequencies. You can think of FSK as digital FM. Narrow-shift FSK has been used to circumvent selective fading between the two signal frequencies. However, the shift cannot be reduced below the information bandwidth of the keyed signal itself, roughly the "baud" rate (number of bit cells per second), or about 100Hz for ordinary radioteletype.

□ 13.20 Pulse-modulation schemes

There are several methods whereby analog signals can be transmitted as pulses.

The basic fact that makes digital transmission of analog signals possible is expressed in the Shannon sampling theorem, which states that a band-limited waveform is fully described by sampling its amplitude at a rate equal to twice the highest frequency present. Thus, a method that conveys the amplitude of a waveform, by digital methods or whatever, at instants of time separated by $1/2f_{\max}$ can be used instead of a continuous modulation scheme. Several methods are shown in Figure 13.46.

channel, since the time between samples can be used to transmit the samples of another signal (with an increase of bandwidth, of course). In pulse-width modulation (PWM), the width of fixed-amplitude pulses is proportional to the instantaneous signal amplitude. PWM is easy to decode, using simple averaging. In pulse-position modulation (PPM), pulses of fixed width and amplitude are delayed or advanced relative to a set of fixed times, according to the amplitude of the signal.

□ Pulse-code modulation

Finally, in pulse-code modulation (PCM) the instantaneous amplitude of the signal is converted to a binary number and transmitted as a serial string of bits. In the illustration, a 4-bit offset binary code corresponding to 16 levels of quantization has been used. PCM excels when error-free transmission is required over noisy channels. As long as 1's and 0's can be identified unambiguously, the correct digital code, and hence a replica of the original signal, can be recovered. PCM is particularly useful in repeater application, e.g., transcontinental telephone channels, where the signal must pass through many stations and be amplified along the way. With any of the linear modulation schemes (AM, FM, SSB) noise accumulated in transit cannot be removed, but with PCM the digital code can be correctly regenerated at each station. Thus the signal starts anew at each station.

There are variations of PCM (known as coded PCM) in which techniques other than simple serial binary sequences are used to encode the quantized samples; for instance, a burst of one of 16 tones could be used in the preceding example. PCM is routinely used for telemetry of images from space vehicles, owing to its error-free properties. It is also used for "compact-disc" digital audio, in which each stereo channel is sampled and converted to a

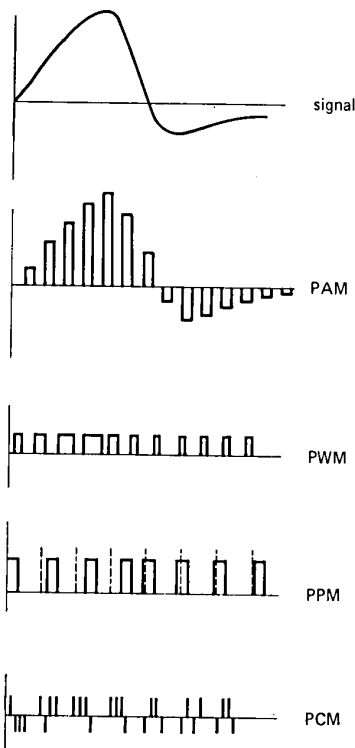


Figure 13.46. Pulse-modulation schemes.

In pulse-amplitude modulation (PAM), a train of pulses of amplitude equal to the signal is transmitted at regular intervals. This scheme is useful for *time multiplexing* of several signals on one information

16-bit number 44,100 times per second. In any PCM application the bit rate must be chosen low enough to ensure a low probability of error in bit recognition. In general, this limits transmission on a given channel to speeds much below what could be used with direct analog modulation techniques.

□ RADIOFREQUENCY CIRCUIT TRICKS

In this chapter we are attempting to highlight some of the motivation and techniques of circuitry operated at radiofrequencies. In such limited space it is not possible to consider circuit design and construction in as much detail as we have generally attempted in the other chapters, nor would that even be desirable in a book intended as a broad introduction to electronics. In keeping with this philosophy, we would like to give some idea of the techniques that are ordinarily used in RF circuits. These are generally aimed at reducing stray inductance and capacitance and coping with circuitry whose dimensions are often comparable with a wavelength. There will be no attempt to weave these together into a coherent methodology; just think of them as a bag of tricks.

□ 13.21 Special construction techniques

RF "chokes" (small inductors, in the range of microhenrys to millihenrys) are used extensively as signal-blocking elements. Power-supply voltages will usually be brought into a shielded enclosure with shielded "feedthrough capacitors" (bypass to ground combined with a mechanical feedthrough terminal), with an RF choke in series. A variation is to use ferrite beads on leads of transistors, FETs, etc. These are used because of the tendency of RF circuits toward "parasitic" oscillations, encouraged by unintentional tuned circuits at UHF formed by the wiring itself. Stringing

a few beads on a base or collector lead here and there adds a lossy series inductance to prevent the oscillation (if you're lucky, that is!).

Inductors play a major role in RF design, and you see plenty of open coils and "slug-tuned" inductors and transformers (such as the little metal IF transformer cans you see everywhere in receiver circuits). Small-value air-variable capacitors are equally popular.

As suggested earlier, RF circuits are constructed in shielded enclosures, often with internal grounded partitions between sections of the circuit to prevent coupling. It is common to build circuits on double-sided PC board, with one side used as a ground-plane. Alternatively, a circuit may be constructed immediately adjacent to a shield or other grounded surface. Grounds can't be wishy-washy at RF; you've got to solder a shield along its whole length, and you have to use a lot of screws to mount a partition or cover.

When building circuits at higher radio frequencies, it is absolutely essential to keep component leads as short as possible. That means snipping off leads right at the resistor or capacitor and soldering them with no visible lead showing (the components get plenty hot, but they seem to survive). At VHF and UHF you often use ceramic capacitor "chips," soldered to PC strips, etc., without leads at all. Watch out when using conventional capacitors, because their internal series inductance can lead to self-resonance effects, sometimes at frequencies as low as a megahertz. The use of wide straps or metal ribbon, rather than ordinary wire, reduces inductance and is a favorite at UHF. At these frequencies you get into stripline and microstrip techniques, where every lead is itself a transmission line, complete with impedance matching. In fact, strips of sheet metal can be used as parts of tuned circuits; here's a specification for an inductor in a 440MHz circuit (ARRL handbook):