5.3 GENERATION AND DETECTION OF FM AND PM

The operating principles of several methods for the generation and detection of exponential modulation are presented in this section. Other FM and PM systems that involve phase-lock loops will be mentioned in Sect. 7.3. Additional methods and information regarding specific circuit designs can be found in the radio electronics texts cited at the back of the book.

When considering equipment for exponential modulation, you should keep in mind that the instantaneous phase or frequency varies linearly with the message waveform. Devices are thus required that produce or are sensitive to phase or frequency variation in a linear fashion. Such characteristics can be approximated in a variety of ways, but it is sometimes difficult to obtain a suitably linear relationship over a wide operating range.

On the other hand, the constant-amplitude property of exponential modulation is a definite advantage from the hardware viewpoint. For one thing, the designer need not worry about excessive power dissipation or high-voltage breakdown due to extreme envelope peaks. For another, the relative immunity to nonlinear distortion allows the use of nonlinear electronic devices that would hopelessly distort a signal with linear modulation. Consequently, considerable latitude is possible in the design and selection of equipment. As a case in point, the microwave repeater links of long-distance telephone communications employ FM primarily because the wideband linear amplifiers required for amplitude modulation are unavailable at microwave frequencies.

Direct FM and VCOs

Conceptually, direct FM is straightforward and requires nothing more than a **voltage-controlled oscillator** (VCO) whose oscillation frequency has a linear dependence on applied voltage. It's possible to modulate a conventional tuned-circuit oscillator by introducing a **variable-reactance** element as part of the LC parallel resonant circuit. If the equivalent capacitance has a time dependence of the form

$$C(t) = C_0 - Cx(t)$$

and if $Cx(t)$ is "small enough" and "slow enough," then the oscillator produces $x_c(t) = A_c \cos \theta_c(t)$ where

$$\dot{\theta}_c(t) = \frac{1}{\sqrt{LC(t)}} = \frac{1}{\sqrt{LC_0}}\left[1 - \frac{C}{C_0}x(t)\right]^{-1/2}$$

Letting $\omega_c = 1/\sqrt{LC_0}$ and assuming $|(C/C_0)x(t)| \ll 1$, the binomial series expansion gives $\dot{\theta}_c(t) \approx \omega_c[1 + (C/2C_0)x(t)]$, or

$$\theta_c(t) \approx 2\pi f_c t + 2\pi \frac{C}{2C_0} f_c \int^t x(\lambda)\,d\lambda \tag{1}$$

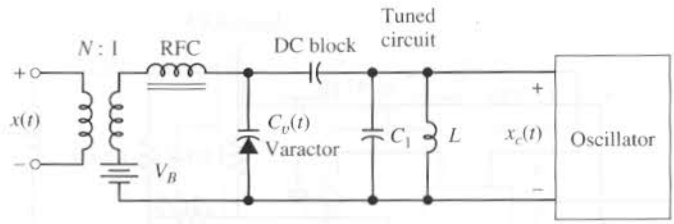

Figure 5.3–1 VCO circuit with varactor diode for variable reactance.

which constitutes frequency modulation with $f_\Delta = (C/2C_0)f_c$. Since $|x(t)| \leq 1$, the approximation is good to within 1 percent when $C/C_0 < 0.013$ so the attainable frequency deviation is limited by

$$f_\Delta = \frac{C}{2C_0} f_c \leq 0.006 f_c \tag{2}$$

This limitation quantifies our meaning of $Cx(t)$ being "small" and seldom imposes a design hardship. Similarly, the usual condition $W \ll f_c$ ensures that $Cx(t)$ is "slow enough."

Figure 5.3–1 shows a tuned-circuit oscillator with a varactor diode biased to get $Cx(t)$. The input transformer, RF choke (RFC), and dc block serve to isolate the low-frequency, high-frequency, and dc voltages. The major disadvantage with this type of circuit is that the carrier frequency tends to drift and must be stabilized by rather elaborate feedback frequency control. For this reason, many older FM transmitters are of the indirect type.

Linear integrated-circuit (IC) voltage-controlled oscillators can generate a direct FM output waveform that is relatively stable and accurate. However, in order to operate, IC VCOs require several additional external components to function. Because of their low output power, they are most suitable for applications such as cordless telephones. Figure 5.3–2 shows the schematic diagram for a direct FM transmitter using the Motorola MC1376, an 8-pin IC FM modulator. The MC1376 operates with carrier frequencies between 1.4 and 14 MHz. The VCO is fairly linear between 2 and 4 volts and can produce a peak frequency deviation of approximately 150 kHz. Higher power outputs can be achieved by utilizing an auxiliary transistor connected to a 12-V power supply.

Phase Modulators and Indirect FM

Although we seldom transmit a PM wave, we're still interested in phase modulators because: (1) the implementation is relatively easy; (2) the carrier can be supplied by a stable frequency source, such as a crystal-controlled oscillator; and (3) integrating the input signal to a phase modulator produces a *frequency*-modulated output.

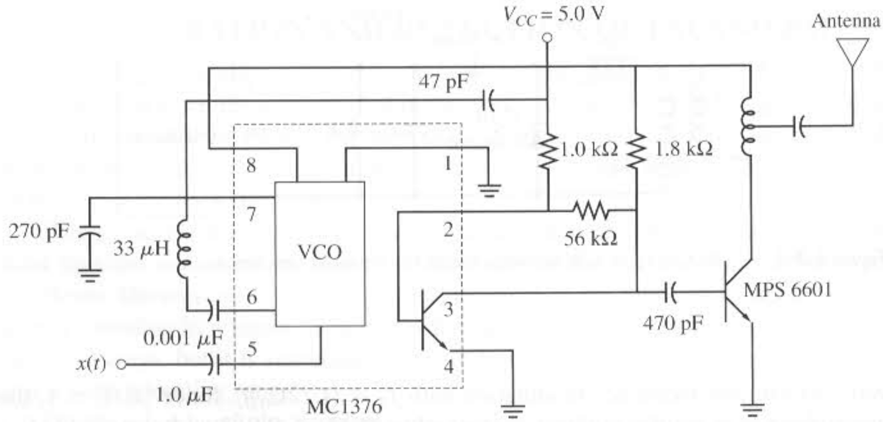

Figure 5.3–2 Schematic diagram of IC VCO direct FM generator utilizing the Motorola MC1376.

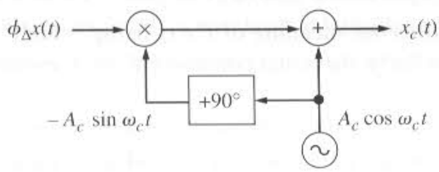

Figure 5.3–3 Narrowband phase modulator.

Figure 5.3–3 depicts a narrowband phase modulator derived from the approximation $x_c(t) \approx A_c \cos \omega_c t - A_c \phi_\Delta x(t) \sin \omega_c t$—see Eqs. (9) and (11), Sect. 5.1. The evident simplicity of this modulator depends upon the approximation condition $|\phi_\Delta x(t)| \ll 1$ radian, and phase deviations greater than 10° result in distorted modulation.

Larger phase shifts can be achieved by the **switching-circuit** modulator in Fig. 5.3–4. The typical waveforms shown in Fig. 5.3–4 help explain the operation. The modulating signal and a sawtooth wave at twice the carrier frequency are applied to a comparator. The comparator's output voltage goes high whenever $x(t)$ exceeds the sawtooth wave, and the flip-flop switches states at each rising edge of a comparator pulse. The flip-flop thus produces a phase-modulated square wave (like the output of a hard limiter), and bandpass filtering yields $x_c(t)$.

Now consider the indirect FM transmitter diagrammed in Fig. 5.3–5. The integrator and phase modulator constitute a *narrowband frequency modulator* that generates an initial NBFM signal with instantaneous frequency

$$f_1(t) = f_{c_1} + \frac{\phi_\Delta}{2\pi T} x(t)$$

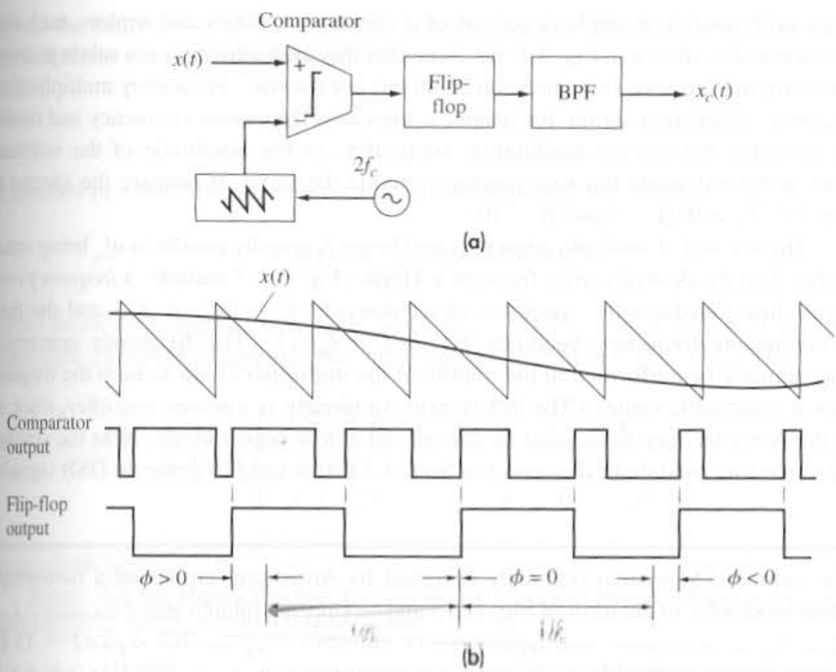

Figure 5.3–4 Switching-circuit phase modulator. (*a*) Schematic diagram (*b*) waveforms.

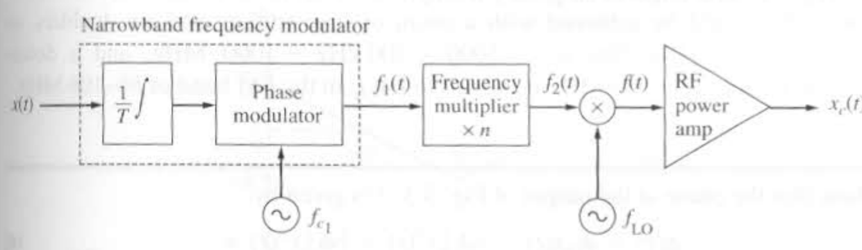

Figure 5.3–5 Indirect FM transmitter.

where T is the integrator's proportionality constant. The initial frequency deviation therefore equals $\phi_\Delta/2\pi T$ and must be increased to the desired value f_Δ by a **frequency multiplier.**

The frequency multiplier produces n-fold multiplication of *instantaneous frequency*, so

$$f_2(t) = nf_1(t) = nf_{c_1} + f_\Delta x(t) \qquad [3]$$

where

$$f_\Delta = n\left(\frac{\phi_\Delta}{2\pi T}\right)$$

Typical frequency multipliers consist of a chain of doublers and triplers, each unit constructed as shown in Fig. 5.2–6*b*. Note that this multiplication is a subtle process, affecting the *range* of frequency variation but not the *rate*. Frequency multiplication of a tone-modulated signal, for instance, increases the carrier frequency and modulation index but not the modulation frequency, so the amplitude of the sideband lines is altered while the line spacing remains the same. (Compare the spectra in Fig. 5.1–7*a* with $\beta = 5$ and $\beta = 10$.)

The amount of multiplication required to get f_Δ usually results in nf_{c_1} being much higher than the desired carrier frequency. Hence, Fig. 5.3–5 includes a *frequency converter* that translates the spectrum intact down to $f_c = |nf_{c_1} \pm f_{\text{LO}}|$ and the final instantaneous frequency becomes $f(t) = f_c + f_\Delta x(t)$. (The frequency conversion may actually be performed in the middle of the multiplier chain to keep the frequencies at reasonable values.) The last system component is a *power amplifier*, since all of the previous operations must be carried out at low power levels. Note the similarity to the ring modulator discussed in Sect. 4.3 that is used to generate DSB signals.

EXAMPLE 5.3–1

The indirect FM system originally designed by Armstrong employed a narrowband phase modulator in the form of Fig. 5.3–3 and produced a minute initial frequency deviation. As an illustration with representative numbers, suppose that $\phi_\Delta/2\pi T \approx 15$ Hz (which ensures negligible modulation distortion) and that $f_{c_1} = 200$ kHz (which falls near the lower limit of practical crystal-oscillator circuits). A broadcast FM output with $f_\Delta = 75$ kHz requires frequency multiplication by the factor $n \approx 75{,}000 \div 15 = 5000$. This could be achieved with a chain of four triplers and six doublers, so $n = 3^4 \times 2^6 = 5184$. But $nf_{c_1} \approx 5000 \times 200\text{ kHz} = 1000$ MHz, and a down-converter with $f_{\text{LO}} \approx 900$ MHz is needed to put f_c in the FM band of 88–108 MHz.

EXERCISE 5.3–1

Show that the phase at the output of Fig. 5.3–3 is given by

$$\phi(t) = \phi_\Delta x(t) - \tfrac{1}{3}\phi_\Delta^3 x^3(t) + \tfrac{1}{5}\phi_\Delta^5 x^5(t) + \cdots \qquad [4]$$

Hence, $\phi(t)$ contains *odd-harmonic distortion* unless ϕ_Δ is quite small.

Triangular-Wave FM★

Triangular-wave FM is a modern and rather novel method for frequency modulation that overcomes the inherent problems of conventional VCOs and indirect FM systems. The method generates virtually distortionless modulation at carrier frequencies up to 30 MHz, and is particularly well suited for instrumentation applications.

We'll define triangular FM by working backwards from $x_c(t) = A_c \cos\theta_c(t)$ with

$$\theta_c(t) = \omega_c t + \phi(t) - \phi(0)$$