RF and Microwave Wireless Systems. Kai Chang
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CHAPTER SIX

Transmitter and Oscillator Systems

6.1 TRANSMITTER PARAMETERS

A transmitter is an important subsystem in a wireless system. In any active wireless system, a signal will be generated and transmitted through an antenna. The signal's generating system is called a transmitter. The specifications for a transmitter depend on the applications. For long-distance transmission, high power and low noise are important. For space or battery operating systems, high efficiency is essential. For communication systems, low noise and good stability are required. A transmitter can be combined with a receiver to form a transceiver. In this case, a duplexer is used to separate the transmitting and receiving signals. The duplexer could be a switch, a circulator, or a diplexer, as described in Chapter 4.

A transmitter generally consists of an oscillator, a modulator, an upconverter, filters, and power amplifiers. A simple transmitter could have only an oscillator, and a complicated one would include a phase-locked oscillator or synthesizer and the above components. Figure 6.1 shows a typical transmitter block diagram. The information will modulate the oscillator through AM, FM, phase modulation (PM), or digital modulation. The output signal could be upconverted to a higher frequency. The power amplifiers are used to increase the output power before it is transmitted by an antenna. To have a low phase noise, the oscillator or local oscillator can be phase locked to a low-frequency crystal oscillator. The oscillator could also be replaced by a frequency synthesizer that derives its frequencies from an accurate high-stability crystal oscillator source. The following transmitter characteristics are of interest:

1. *Power output and operating frequency*: the output RF power level generated by a transmitter at a certain frequency or frequency range.

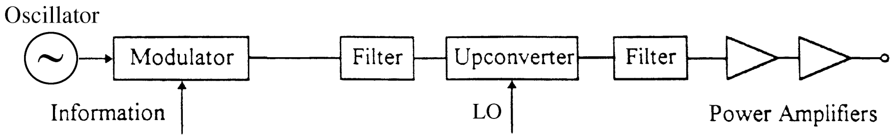

FIGURE 6.1 Transmitter system.

2. *Efficiency*: the DC-to-RF conversion efficiency of the transmitter.
3. *Power output variation*: the output power level variation over the frequency range of operation.
4. *Frequency tuning range*: the frequency tuning range due to mechanical or electronic tuning.
5. *Stability*: the ability of an oscillator/transmitter to return to the original operating point after experiencing a slight thermal, electrical, or mechanical disturbance.
6. *Circuit quality (Q) factor*: the loaded and unloaded Q-factor of the oscillator's resonant circuit.
7. *Noise*: the AM, FM, and phase noise. Amplitude-modulated noise is the unwanted amplitude variation of the output signal, frequency-modulated noise is the unwanted frequency variations, and phase noise is the unwanted phase variations.
8. *Spurious signals*: output signals at frequencies other than the desired carrier.
9. *Frequency variations*: frequency jumping, pulling, and pushing. Frequency jumping is a discontinuous change in oscillator frequency due to nonlinearities in the device impedance. Frequency pulling is the change in oscillator frequency versus a specified load mismatch over 360° of phase variation. Frequency pushing is the change in oscillator frequency versus DC bias point variation.
10. *Post-tuning drift*: frequency and power drift of a steady-state oscillator due to heating of a solid-state device.

Some of these characteristics can be found in an example given in Table 6.1.

6.2 TRANSMITTER NOISE

Since the oscillator is a nonlinear device, the noise voltages and currents generated in an oscillator are modulating the signal produced by the oscillator. Figure 6.2 shows the ideal signal and the signal modulated by the noise. The noise can be classified as an AM noise, FM noise, and phase noise.

Amplitude-modulated noise causes the amplitude variations of the output signal. Frequency-modulated or phase noise is indicated in Fig. 6.2*b* by the spreading of the

TABLE 6.1 Typical Commercial Voltage-Controlled Oscillator (VCO) Specifications

Frequency (f_0)	35 GHz
Power (P_0)	250 mW
Bias pushing range (typical)	50 MHz/V
Varactor tuning range	±250 MHz
Frequency drift over temperature	−2 MHz/°C
Power drop over temperature	−0.03 dB/°C
Q_{ext}	800–1000
Harmonics level	−200 dBc minimum
Modulation bandwidth	DC − 50 MHz
Modulation sensitivity (MHz/V)	25–50
FM noise at 100-kHz offset	−90 dBc/kHz or −120 dBc/Hz
AM noise at 100-kHz offset	−155 dBc/kHz or −185 dBc/Hz

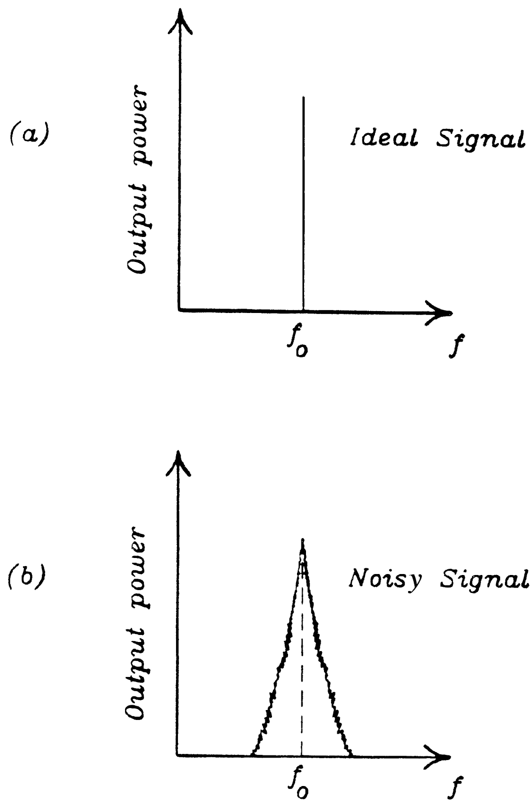

FIGURE 6.2 Ideal signal and noisy signal.

frequency spectrum. A ratio of single-sideband noise power normalized in 1-Hz bandwidth to the carrier power is defined as

$$\mathscr{L}(f_m) = \frac{\text{noise power in 1-Hz bandwidth at } f_m \text{ offset from carrier}}{\text{carrier signal power}}$$

$$= \frac{N}{C} \tag{6.1}$$

As shown in Fig. 6.3, $\mathscr{L}(f_m)$ is the difference of power between the carrier at f_0 and the noise at $f_0 + f_m$. The power is plotted in the decibel scale, and the unit of $\mathscr{L}(f_m)$ is in decibels below the carrier power (dBc) per hertz. The FM noise is normally given as the number of decibels below carrier amplitude at a frequency f_m that is offset from the carrier. Figure 6.4 shows a typical phase noise measurement from a Watkins–Johnson dielectric resonator oscillator (DRO) [1]. The phase noise is 70 dBc/Hz at 1 kHz offset from the carrier and 120 dBc/Hz at 100 KHz offset from the carrier. Here dBc/Hz means decibels below carrier over a bandwidth of 1 Hz.

It should be mentioned that the bulk of oscillator noise close to the carrier is the phase or FM noise. The noise represents the phase jitter or the short-term stability of the oscillator. The oscillator power is not concentrated at a single frequency but is rather distributed around it. The spectral distributions on the opposite sides of the carrier are known as noise sidebands. To minimize the FM noise, one can use a high-

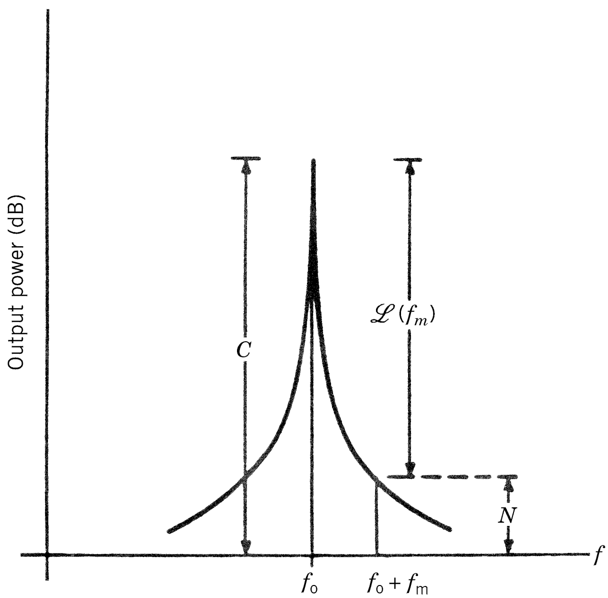

FIGURE 6.3 Oscillator output power spectrum. This spectrum can be seen from the screen of a spectrum analyzer.

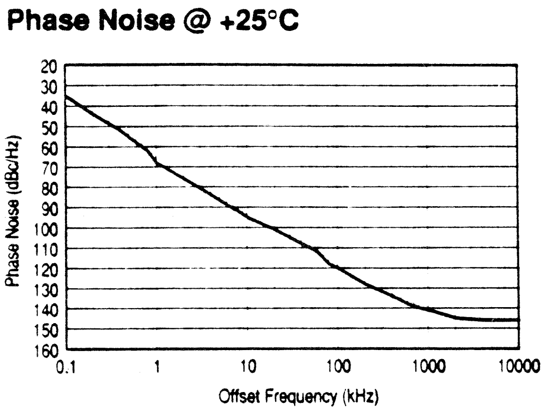

FIGURE 6.4 Phase noise measurement for a WJ VC1001 DRO [1]. (Courtesy of Watkins-Johnson.)

Q resonant circuit, a low-noise active device, a phase-locked loop, or avoid the operation in a region of saturation.

Many methods can be used to measure the FM or phase noise [2–4]. These methods include the spectrum analyzer method, the two-oscillator method, the single-oscillator method, the delay-line discriminator method, and the cavity discriminator method.

6.3 FREQUENCY STABILITY AND SPURIOUS SIGNALS

Slight electrical, thermal, or mechanical disturbances can cause an oscillator to change operating frequency. The disturbance may cause the oscillation to cease since it could change the device impedance such that the oscillating conditions described in Chapter 4 are no longer satisfied.

Stability is a measure that describes an oscillator's ability to return to its steady-state operating point. The temperature stability can be specified in three different ways. For example, at 10 GHz, an oscillator or a transmitter has the following temperature stability specifications: ± 10 KHz/°C, or ± 800 KHz over -30°C to $+50^\circ$C, or ± 1 ppm/°C, where ppm stands for parts per million. At 10 GHz, ± 1 ppm/°C is equivalent to ± 10 KHz/°C. This can be seen from the following:

$$\begin{aligned} \pm 1 \text{ ppm}/^\circ\text{C} \times 10 \text{ GHz} &= \pm 1 \times 10^{-6} \times 10 \times 10^{9} \text{ Hz}/^\circ\text{C} \\ &= \pm 10 \text{ KHz}/^\circ\text{C} \end{aligned}$$

A typical wireless communication system requires a stability range from 0.5 to 5 ppm/°C and a phase noise range from -80 to -120 dBc/Hz.

Frequency variations could be due to other problems such as frequency jumping, pulling, and pushing, as described in Section 6.1. Post-tuning drift can also change the desired operating frequency.

The transmitter with good stability and low noise is important for wireless communication applications. To improve the stability, one can use (1) high-Q circuits to build the oscillators (examples are waveguide cavities, dielectric resonators, or superconducting resonators/cavities); (2) temperature compensation circuits; or (3) phase-locked oscillators or frequency synthesizers, which will be discussed later in this chapter.

For an oscillator, spurious signals are the undesired signals at frequencies other than the desired oscillation signal. These include the harmonics and bias oscillations. The harmonic signals have frequencies that are integer multiples of the oscillating frequency. If the oscillating frequency is f_0, the second harmonic is $2f_0$, and the third harmonic is $3f_0$, and so on. As shown in Fig. 6.5, the power levels of harmonics are generally well below the fundamental frequency power. A specification for harmonic power is given by the number of decibels below carrier. For example, second-harmonic output is −30 dBc and third-harmonic output is −60 dBc. For a complicated transmitter with upconverters and power amplifiers, many other spurious signals could exist at the output due to the nonlinearity of these components. The nonlinearity will cause two signals to generate many mixing and intermodulation products.

6.4 FREQUENCY TUNING, OUTPUT POWER, AND EFFICIENCY

The oscillating frequency is determined by the resonant frequency of the overall oscillator circuit. At resonance, the total reactance (or susceptance) equals zero. Consider a simplified circuit shown in Fig. 6.6, where Z_D is the active device impedance and Z_C is the external circuit impedance. The oscillating (or resonant) frequency is the frequency such that

$$\mathrm{Im}(Z_D) + \mathrm{Im}(Z_C) = 0 \tag{6.2}$$

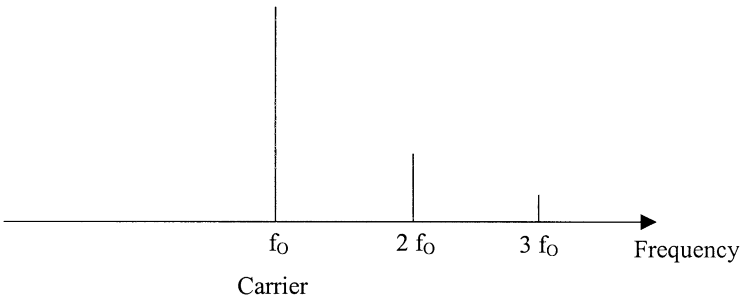

FIGURE 6.5 Oscillating frequency and its harmonics.

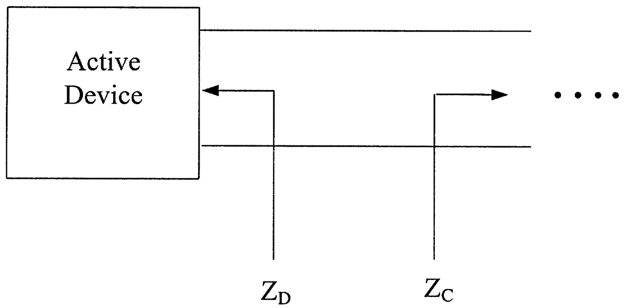

FIGURE 6.6 Simplified oscillator circuit.

where Im stands for the imaginary part. The circuit impedance is a function of frequency only, and the device impedance is a function of frequency (f), bias current (I_0), generated RF current (I_{RF}), and temperature (T). Therefore, at the resonant frequency, we have

$$\mathrm{Im}[Z_D(f, I_0, I_{\mathrm{RF}}, T)] + \mathrm{Im}[Z_C(f)] = 0 \tag{6.3}$$

Electronic frequency tuning can be accomplished by bias tuning or varactor tuning. The bias tuning will change I_0 and thus change Z_D, resulting in a new oscillating frequency. The varactor tuning (as shown in Fig. 6.7 as an example) will change $C(V)$ and thus change Z_C, resulting in a new oscillating frequency. The frequency tuning is useful for frequency modulation in radar or communication systems. For example, a 10-GHz voltage-controlled oscillator (VCO) could have a modulation sensitivity of 25 MHz/V and a tuning range of $\pm$100 MHz by varying the bias voltage to a varactor.

For most systems, a constant output power is desirable. Power output could vary due to temperature, bias, frequency tuning, and environment. A specification for power variation can be written as 30 dBm $\pm$ 0.5 dB, as an example.

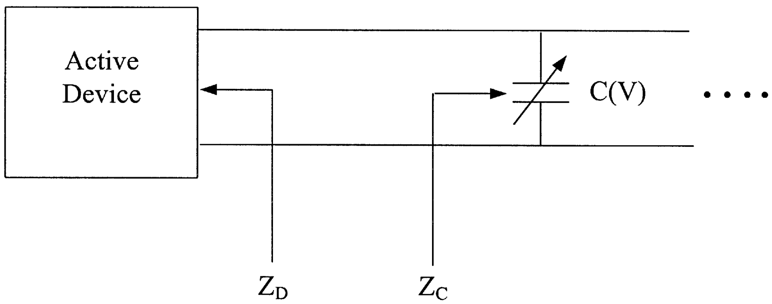

FIGURE 6.7 Varactor-tuned oscillator.

A high-efficiency transmitter is required for space or battery operating systems. The DC-to-RF conversion efficiency is given by

$$\eta = \frac{P_{RF}}{P_{DC}} \times 100\% \tag{6.4}$$

where P_{RF} is the generated RF power and P_{DC} is the DC bias power. In general, solid-state transistors or FETs can generate power ranging from milliwatts to a few watts with an efficiency ranging from 10 to 50%. Solid-state Gunn diodes can produce similar output power at a much lower efficiency of 1–3%. IMPATT diodes can produce several watts at 5–20% efficiency at high microwave or millimeter-wave frequencies.

For higher power, vacuum tubes such as traveling-wave tubes, Klystrons, or magnetrons can be used with efficiency ranging from 10 to 60%. Power-combining techniques can also be used to combine the power output from many low-power sources through chip-level, circuit-level, or spatial power combining [5].

In many cases, a high-power transmitter consists of a low-power oscillator followed by several stages of amplifiers. The first stage is called the driver amplifier, and the last stage is called the power amplifier. The power amplifier is normally one of the most expensive components in the system.

Example 6.1 A 35-GHz Gunn oscillator has a frequency variation of ±160 MHz over −40°C to +40°C temperature range. The oscillator can be tuned from 34.5 to 35.5 GHz with a varactor bias voltage varied from 0.5 to 4.5 V. What are the frequency stability in ppm/per degree Celsius and the frequency modulation sensitivity in megahertz per volts?

Solution

$$\begin{aligned} \text{Frequency stability} &= \pm 160\ \text{MHz}/80^\circ\text{C} = \pm 2\ \text{MHz}/^\circ\text{C} \\ &= A\ (\text{in ppm}/^\circ\text{C}) \times 10^{-6} \times 35 \times 10^{9}\ \text{Hz} \\ A &= \pm 57\ \text{ppm}/^\circ\text{C} \end{aligned}$$

$$\begin{aligned} \text{Modulation sensitivity} &= \frac{f_2 - f_1}{V_2 - V_1} = \frac{33.5 - 34.5\ \text{GHz}}{4.5 - 0.5\ \text{V}} \\ &= 0.25\ \text{GHz/V} = 250\ \text{MHz/V} \end{aligned}$$

■

6.5 INTERMODULATION

The intermodulation distortion and the third-order intercept point discussed in Chapter 5 for a receiver or mixer also apply to a power amplifier or upconverter in a transmitter. Figure 6.8 shows the curves for the fundamental and two-tone third-order intermodulation signals.

Conventional high-power RF/microwave amplifiers were once used to handle only a single carrier communication channel. In this case, they could operate within the nonlinear region of the dynamic range without the risk of intermodulation products generation, thus avoiding channel interference. Currently, many of the contemporary communication systems operate in a multicarrier environment that allows an enhancement in bandwidth efficiency. They are very attractive whenever there is a large demand to accommodate many users within a limited spectrum but are required to operate with minimized adjacent out-of-band spectral emissions (spectral containment). These unwanted frequency components are primarily the result of intermodulation distortion (IMD) products produced by the multiple carriers propagating through nonlinear solid-state devices.

Consider two signals f_1 and f_2 which are the input signals to a power amplifier, as shown in Fig. 6.9. The two signals will be amplified and the output power can be determined from the fundamental signal curve given in Fig. 6.8. The two-tone third-

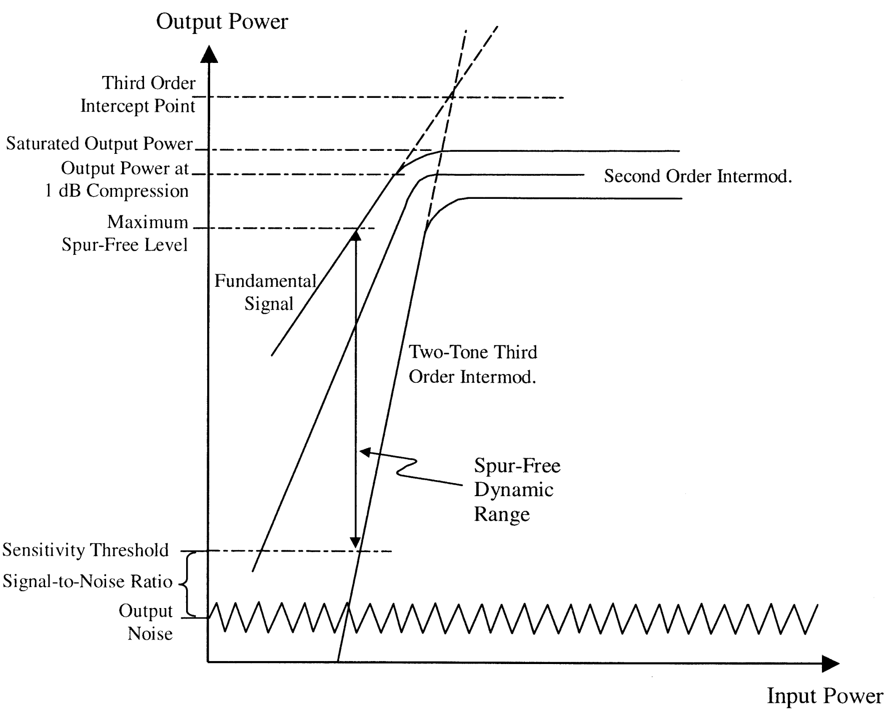

FIGURE 6.8 Nonlinear characteristics for a power amplifier.

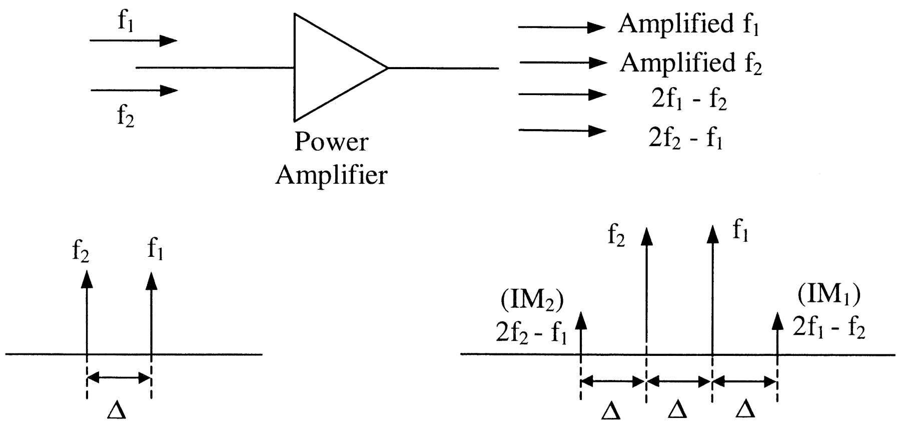

FIGURE 6.9 Power amplifier and its IM3 products.

order intermodulation products ($2f_1 - f_2$ and $2f_2 - f_1$) are also generated and appear in the output port. The power levels of these IM products can be found from the two-tone third-order intermodulation (IM3) curve given in Fig. 6.8. The IM3 power levels are normally well below the fundamental signals at f_1 and f_2. If the frequency difference Δ is very small, the IM3 products are difficult to be filtered out, and it is important to keep their levels as low as possible. Other third-order distortion frequencies $3f_1$, $3f_2$, $2f_1 + f_2$, $2f_2 + f_1$, as well as the second-order distortion frequencies $2f_1$, $2f_2$, $f_1 + f_2$, $f_1 - f_2$, are of little concern because they are not closely adjacent in frequency and they can be easily filtered out without any disturbance to the original signals f_1 and f_2. In most wireless communications, one would like to have IM3 reduced to a level of less than −60 dBc (i.e., 60 dB or a million times below the fundamental signals).

One way to reduce the IM3 levels is to use the feedforward amplifier concept. The amplifier configuration consists of a signal cancellation loop and a distortion error cancellation loop, as shown in Fig. 6.10 [6]. The signal cancellation loop is composed of five elements: an equal-split power divider, a main power amplifier, a main-signal sampler, a phase/amplitude controller, and a power combiner. This loop samples part of the distorted signal out from the main amplifier and combines it with a previously adjusted, distortion-free sample of the main signal; consequently, the main signal is canceled and the IM products prevail. The error cancellation loop is composed of three elements: a phase/amplitude controller, a linear error amplifier, and an error coupler acting as a power combiner. This loop takes the IM products from the signal cancellation loop, adjusts their phase, increases their amplitude, and combines them with the signals from the main power amplifier in the error coupler. As a result, the third-order tones are greatly reduced to a level of less than −60 dBc. Experimental results are shown in Figs. 6.11 and 6.12.

Figure 6.11 shows the output of the main amplifier without the linearizer, where $f_1 = 2.165$ GHz and $f_2 = 2.155$ GHz. At these frequencies, $\mathrm{IM}_1 = 2f_1 - f_2 =$

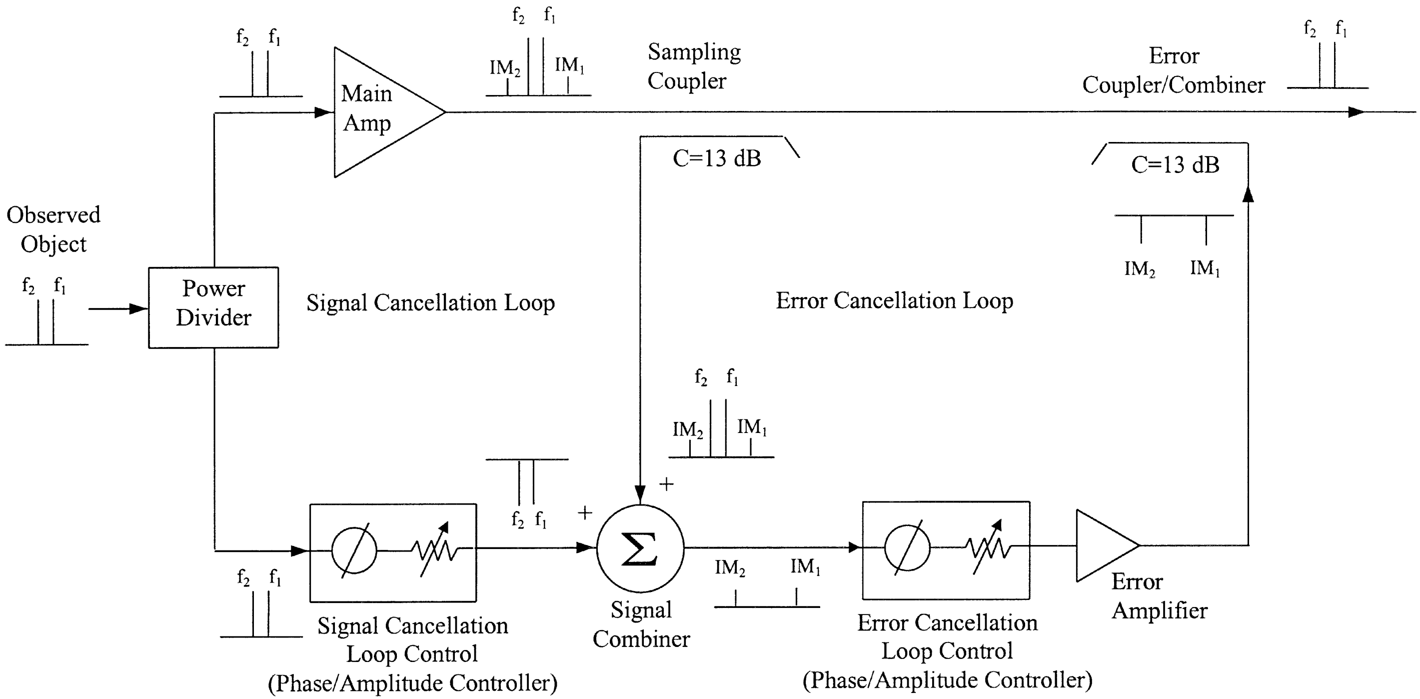

FIGURE 6.10 Feedforward amplifier system block diagram [6].

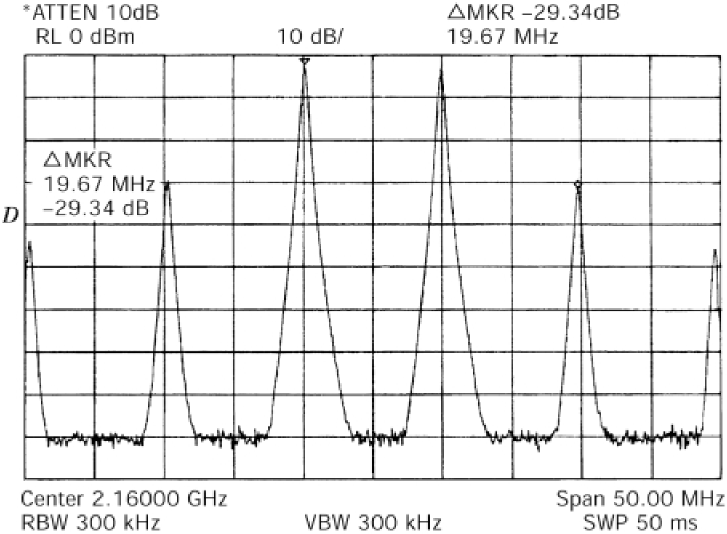

FIGURE 6.11 Nonlinearized two-tone test and intermodulation distortion [6].

2.175 GHz and $IM_2 = 2f_2 - f_1 = 2.145$ GHz, and the intermodulation distortion is approximately -30 dBc. Figure 6.12 shows the linearized two-tone test using the feedforward amplifier to achieve an additional 30 dB distortion reduction, giving a total IM suppression of -61 dBc

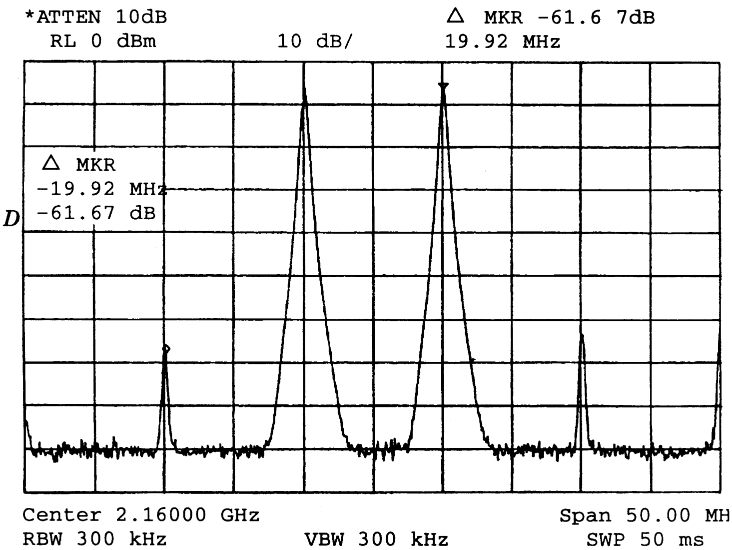

FIGURE 6.12 Linearized two-tone test and intermodulation distortion [6].

6.6 CRYSTAL REFERENCE OSCILLATORS

Crystal oscillators have low phase noise due to their stable output signal. The low-frequency crystal oscillators can be used as reference sources for a phase-locked loop. The crystal oscillator consists of a piezoelectric crystal, usually quartz, with both faces plated with electrodes. If a voltage is applied between the electrodes, mechanical forces will be exerted on the bound charges within the crystal, and an electromechanical system is formed that will vibrate at a resonant frequency. The resonant frequency and the Q factor depend on the crystal's dimensions and surface orientation. The Q's of several thousand to several hundred thousand and frequencies ranging from a few kilohertz to tens of megahertz are available. The extremely high Q values and the excellent stability of quartz with time and temperature give crystal oscillators the exceptional frequency stability.

The equivalent circuit of a crystal can be represented by Fig. 6.13. The inductor L, capacitor C, and resistor R represent the crystal. The capacitor C' represents the electrostatic capacitance between electrodes with the crystal as a dielectric. As an example, for a 90-kHz crystal, $L = 137$ H, $C = 0.0235$ pF, $C' = 3.5$ pF, with a Q of 5500. If we neglect R, the impedance of the crystal is a reactance shown in Fig. 6.14 given by

$$jX = -\frac{j}{\omega C'}\frac{\omega^2 - \omega_s^2}{\omega^2 - \omega_p^2} \tag{6.5}$$

where

$$\omega_s^2 = \frac{1}{LC} \quad \text{and} \quad \omega_p^2 = \frac{1}{L}\left(\frac{1}{C} + \frac{1}{C'}\right)$$

Since $C' \gg C$, $\omega_p^2 \approx 1/LC = \omega_s^2$. The circuit will oscillate at a frequency that lies between ω_s and ω_p. The oscillating frequency is essentially determined by the crystal and not by the rest of the circuit. The oscillating frequency is very stable

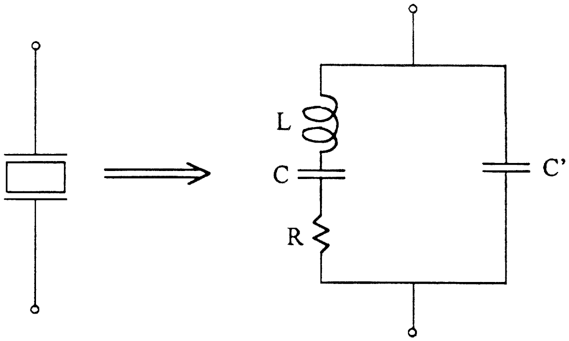

FIGURE 6.13 Piezoelectric crystal symbol and its equivalent circuit.

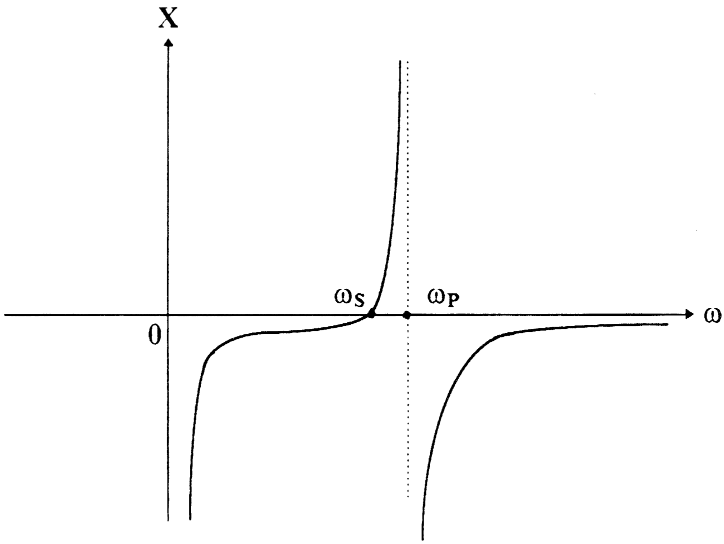

FIGURE 6.14 Impedance of a crystal as a function of frequency.

because $\omega_p \approx \omega_s$, where ω_s and ω_p are the series and parallel resonant frequencies. The crystal can be integrated into the transistor's oscillator circuit to form a crystal oscillator. Figure 6.15 shows two examples of these crystal oscillators [7]. In the next section, we will use the crystal oscillators to build high-frequency phase-locked oscillators (PLOs).

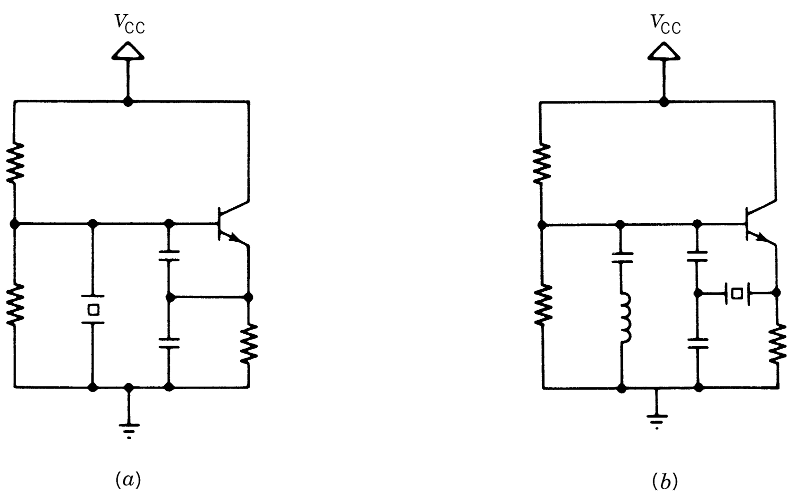

FIGURE 6.15 Colpitts crystal oscillators: (*a*) in parallel resonant configuration; (*b*) in series resonant configuration [7].

6.7 PHASE-LOCKED OSCILLATORS

A phase-locked oscillator is a very stable source with low phase noise and stable output frequency. A high-frequency oscillator can be phase locked to a low-frequency, stable crystal oscillator or crystal-controlled oscillator to achieve good phase noise and frequency stability. A simplified phase-locked loop (PLL) block diagram is given in Fig. 6.16. It consists of a very stable low-frequency oscillator that acts as the reference source, a phase detector, a low-pass filter, a VCO, and a frequency divider. The phase detector produces a DC control voltage at the output of the low-pass filter, with the magnitude and polarity determined by the phase (frequency) difference between the crystal oscillator and VCO output. The control voltage is used to vary the VCO frequency. The process will continue until the VCO frequency (or phase) is aligned with the multiple of the crystal oscillator frequency. The frequency divider is used to divide the output frequency of VCO by N to match the frequency of the reference oscillator. Because of the tracking, the output of the PLL has phase noise characteristics similar to that of the reference oscillator.

Figure 6.17 shows an example of an analog phase detector configuration that is similar to a balanced mixer. It consists of a 90° hybrid coupler and two mixer (detector) diodes, followed by a low-pass filter. If two signals of the nominally same frequency f_R but with different phases θ_1 and θ_2 are applied at the input of the coupler, the voltages across the mixer diodes are

$$\begin{aligned} v_1(t) &= \cos(\omega_R t + \theta_1) + \cos(\omega_R t + \theta_2 - 90^\circ) \\ &= \cos(\omega_R t + \theta_1) + \sin(\omega_R t + \theta_2) \end{aligned} \tag{6.6a}$$

$$\begin{aligned} v_2(t) &= \cos(\omega_R t + \theta_2) + \cos(\omega_R t + \theta_1 - 90^\circ) \\ &= \cos(\omega_R t + \theta_2) + \sin(\omega_R t + \theta_1) \end{aligned} \tag{6.6b}$$

Assuming that the diodes are operating in the square-law region, the output currents are given by

$$\begin{aligned} i_1(t) &= Av_1^2(t) \\ &= A[\cos^2(\omega_R t + \theta_1) + 2\cos(\omega_R t + \theta_1)\sin(\omega_R t + \theta_2) + \sin^2(\omega_R t + \theta_2)] \end{aligned} \tag{6.7a}$$

$$\begin{aligned} i_2(t) &= -Av_2^2(t) \\ &= -A[\cos^2(\omega_R t + \theta_2) + 2\cos(\omega_R t + \theta_2)\sin(\omega_R t + \theta_1) + \sin^2(\omega_R t + \theta_1)] \end{aligned} \tag{6.7b}$$

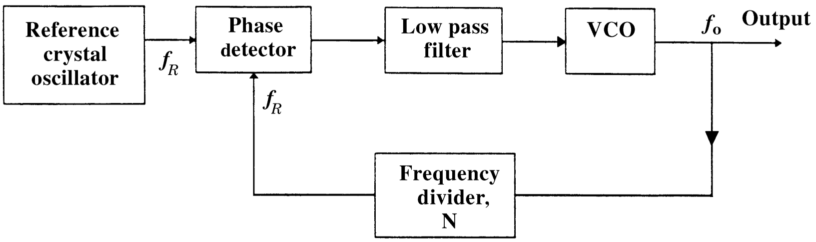

FIGURE 6.16 Simplified PLL block diagram.

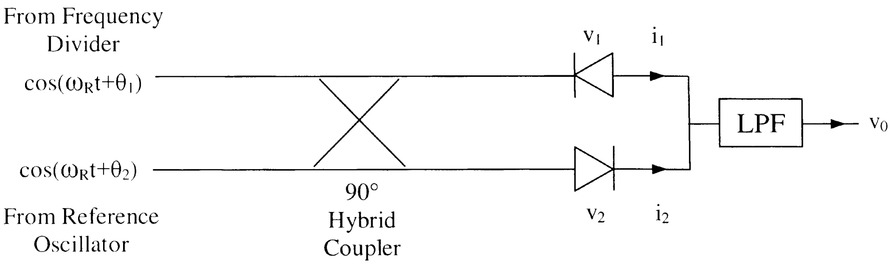

FIGURE 6.17 Analog phase detector.

where A is a constant. The negative sign on i_2 is due to the reversed diode polarity. The two currents will be combined and filtered through a low-pass filter. Now, the following trigonometry identities are used for Eqs. (6.7):

$$\cos^2 \alpha = \tfrac{1}{2}(1 + \cos 2\alpha) \qquad \sin^2 \alpha = \tfrac{1}{2}(1 - \cos 2\alpha)$$

and

$$2 \sin \alpha \cos \beta = \sin(\alpha + \beta) + \sin(\alpha - \beta)$$

Since the low-pass filter rejects all high-frequency components [i.e., $\cos 2\alpha$ and $\sin(\alpha + \beta)$ terms], only the DC current appears at the output

$$i_0(t) = i_1(t) + i_2(t) = A_1 \sin(\theta_2 - \theta_1) \tag{6.8}$$

where A_0 and A_1 are constants. Therefore, the output voltage of a phase detector is determined by the phase difference of its two input signals. For a small phase difference, we have

$$i_0(t) \approx A_1(\theta_2 - \theta_1) \tag{6.9}$$

The two input frequencies to the phase detector should be very close in order to be tracked (locked) to each other. The range of the input frequency for which the loop can acquire locking is called the capture range. The settling time is the time required for the loop to lock to a new frequency. Phase-locked loops can generate signals for FM, QPSK modulation, local oscillators for mixers, and frequency synthesizers. They are widely used in wireless communication systems.

Example 6.2 A 57-GHz phase-locked source has the block diagram shown in Fig. 6.18. Determine the reference signal frequency (f_R). The reference source is a crystal-controlled microwave oscillator. If the reference source has a frequency stability of ± 1 ppm/°C, what is the output frequency variation?

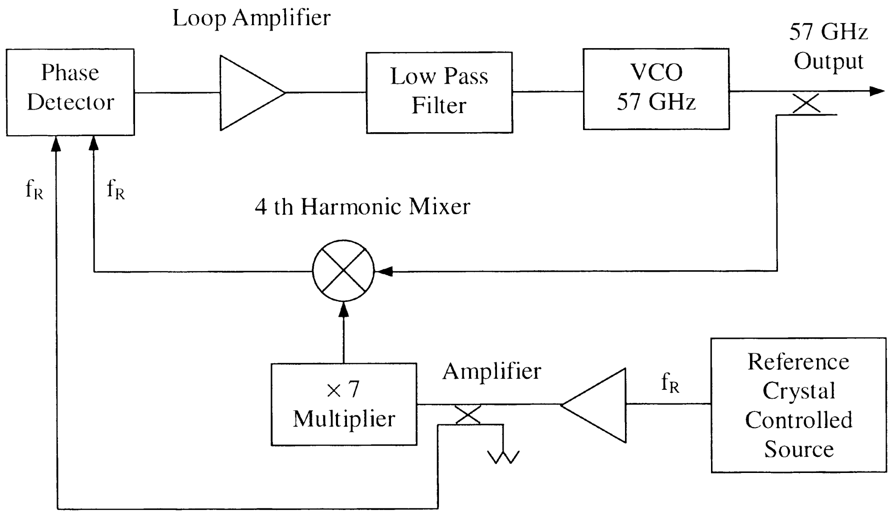

FIGURE 6.18 A 57-GHz phase-locked source. (From reference 8, with permission from IEEE.)

Solution In a harmonic mixer, the RF signal is mixed with the multiple frequency of the LO to generate an IF signal. The IF is given by

$$f_{\rm IF} = f_{\rm RF} - Nf_{\rm LO}$$

or

$$f_{\rm IF} = Nf_{\rm LO} - f_{\rm RF} \tag{6.10}$$

From Fig. 6.18, the reference frequency is given by

$$57\ \text{GHz} - 4 \times 7 \times f_R = f_R$$

Therefore, $f_R = 1.96551724$ GHz. The output frequency variation is

$$\begin{aligned}\Delta f &= \pm f_0 \times 1\ \text{ppm/°C} = \pm 57 \times 10^9 \times 1 \times 10^{-6}\ \text{Hz/°C}\\ &= \pm 57\ \text{kHz/°C}\end{aligned}$$

■

6.8 FREQUENCY SYNTHESIZERS

A frequency synthesizer is a subsystem that derives a large number of discrete frequencies from an accurate, highly stable crystal oscillator. Each of the derived frequencies has the frequency stability and accuracy of the reference crystal source.

In many applications, the frequency synthesizer must cover a wide frequency range. A frequency synthesizer avoids the need for using many independent crystal-controlled oscillators in a wide-band multiple-channel system. Modern frequency synthesizers can be implemented using integrated circuit chips. They are controlled by digital circuits or computers. Frequency synthesizers are commonly used in transmitters, modulators, and LOs in many wireless communication systems such as radios, satellite receivers, cellular telephones, and data transmission equipment.

Frequency synthesizers can be realized using a PLL and a programmable frequency divider, as shown in Fig. 6.19. The signals applied to the phase detector are the reference signal from the crystal oscillator and f_0/N from the output of the frequency divider. A large number of frequencies can be obtained by varying N, the division ratio. As an example, if $f_R = 1$ MHz, we will have the output frequency (f_0) equal to 3 MHz, 4 MHz, ..., 20 MHz if $N = 3, 4, \ldots, 20$. The resolution or increment in frequency is equal to the reference frequency f_R. To improve the resolution, the reference frequency can also be divided before it is connected to the phase detector. This scheme is shown in Fig. 6.20. A fixed frequency divider with division ratio of N_2 is introduced between the crystal oscillator and the phase detector. Zero output from the phase detector requires the following condition:

$$\frac{f_0}{N_1} = \frac{f_R}{N_2} \tag{6.11}$$

Therefore

$$f_0 = \frac{N_1}{N_2} f_R = N_1 \frac{f_R}{N_2} \tag{6.12}$$

The increment in frequency or resolution is equal to f_R/N_2. As an example,

$$f_R = 1 \text{ MHz} \qquad N_2 = 100 \qquad \text{Resolution} = 10 \text{ kHz}$$

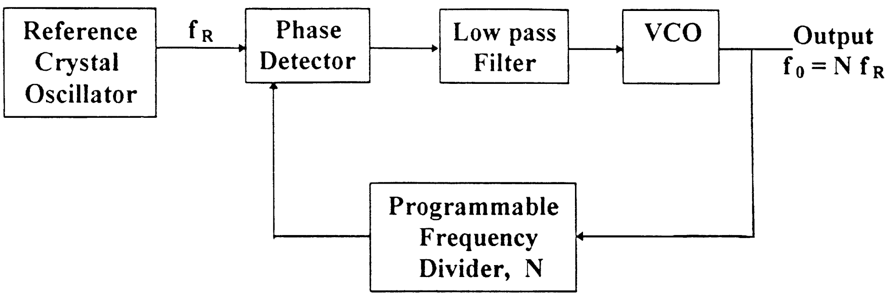

FIGURE 6.19 Frequency synthesizer using a PLL and a programmable frequency divider.

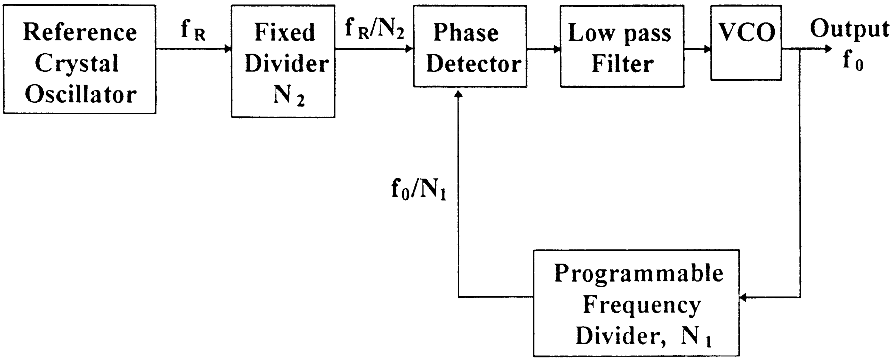

FIGURE 6.20 Frequency synthesizer with improved resolution.

If

$$N_1 = 3, \qquad f_0 = 30 \text{ kHz}$$
$$N_1 = 4 \qquad f_0 = 40 \text{ kHz}$$
$$\vdots \qquad\qquad \vdots$$

To obtain small frequency resolution and rapid frequency change, multiple-loop frequency synthesizers can be used; however, the system is more complicated. The following example shows a multiple-loop frequency synthesizer.

Example 6.3 In the multiple-loop frequency synthesizer shown in Fig. 6.21 [9], $f_R = 1$ MHz, $N_1 = 10$ and $N_2 = 100$. Determine the range of output frequencies of the synthesizer if N_A is varied from 200 to 300 and N_B from 350 to 400.

Solution

$$\frac{f_R N_A}{N_1 N_2} = f_0 - f_R \frac{N_B}{N_1}$$
$$f_0 = \frac{f_R}{N_1}\left(N_B + \frac{N_A}{N_2}\right)$$
$$f_R = 1 \text{ MHz} \qquad N_1 = 10 \qquad N_2 = 100$$

When $N_A = 200$, $N_B = 350$, we have $f_0 = f_{0(\min)}$:

$$f_{0(\min)} = \frac{1 \times 10^6}{10}\left(350 + \frac{200}{100}\right) = 35.2 \text{ MHz}$$

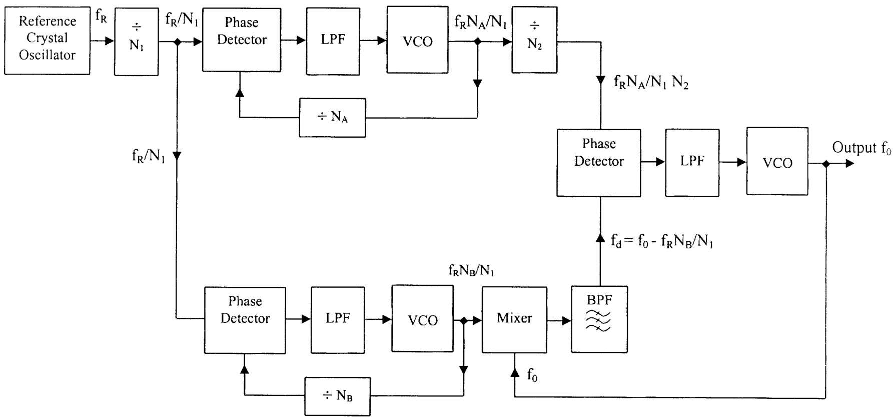

FIGURE 6.21 Multiple-loop frequency synthesizer [9].

When $N_A = 300$, $N_B = 400$, we have $f_0 = f_{0(\max)}$:

$$f_{0(\max)} = \frac{1 \times 10^6}{10}\left(400 + \frac{300}{100}\right) = 40.3 \text{ MHz}$$

The output range is from 35.2 to 40.3 MHz. ■

PROBLEMS

6.1 A power amplifier has two input signals of +10 dBm at frequencies of 1.8 and 1.810 GHz (Fig. P6.1). The IM3 power levels are −50 dBm. The amplifier has a gain of 10 dB and an input 1-dB compression point of +25 dBm. What are the frequencies for the IM3 products f_{IM1} and f_{IM2}? What are the power levels for f_{IM1} and f_{IM2} if the input power levels for f_1 and f_2 signals are increased to +20 dBm?

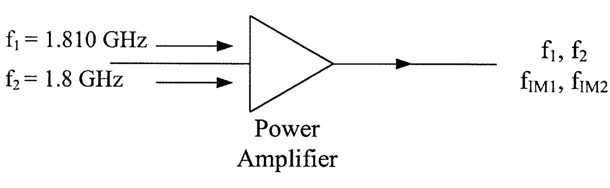

FIGURE P6.1

6.2 A power amplifier has two input signals at frequencies of 1 and 1.010 GHz. The output spectrums are shown in Fig. P6.2. What are the frequencies for the IM3 products f_{IM1} and f_{IM2}? If the output power levels for f_1 and f_2 signals are increased to 30 dBm, what are the power levels for f_{IM1} and f_{IM2} signals? Use $f_1 = 1.010$ GHz and $f_2 = 1$ GHz.

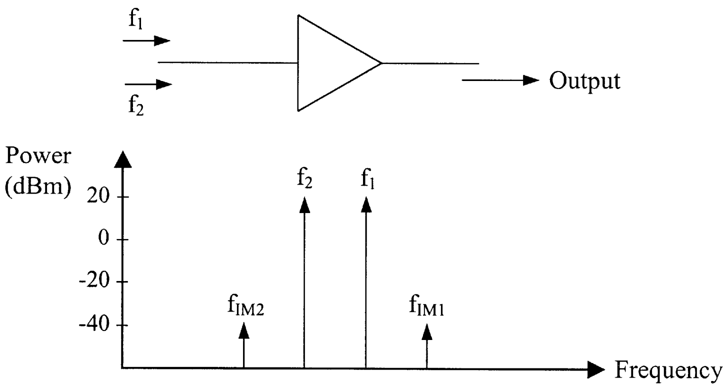

FIGURE P6.2

6.3 A 10-GHz PLO is shown in Fig. P6.3.

(a) Determine the reference frequency of the crystal-controlled source.

(b) If the reference source has a frequency stability of ±0.1 ppm/°C, what is the output frequency variation of the PLO over the temperature range from −40 to +40°C?

(c) What is the reference frequency variation over the same temperature range?

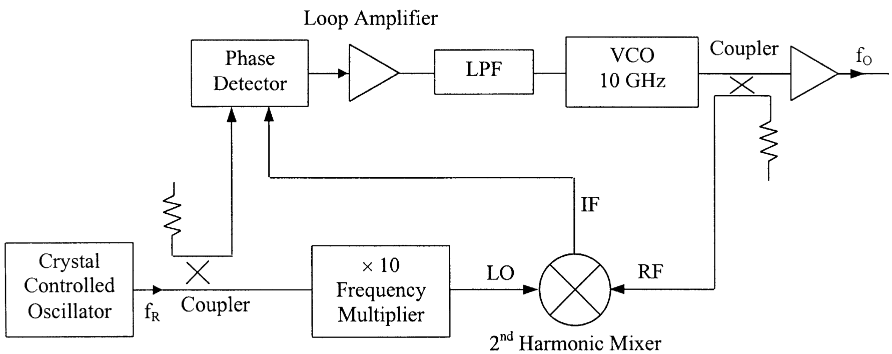

FIGURE P6.3

6.4 Calculate the reference signal frequency in gigahertz for the phase-locked system shown in Fig. P6.4.

6.5 Determine the output frequencies of the frequency synthesizer shown in Fig. P6.5 for $N_1 = 10$ and $N_1 = 20$. Note that $f_R = 1$ GHz and $N_2 = 100$.

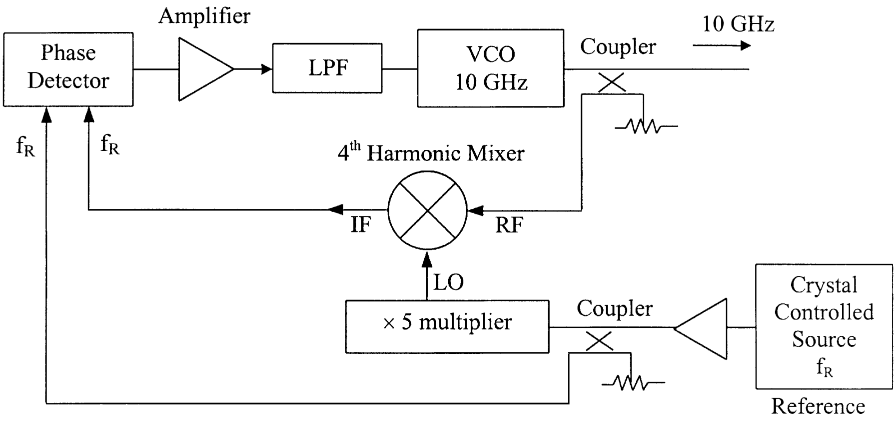

FIGURE P6.4

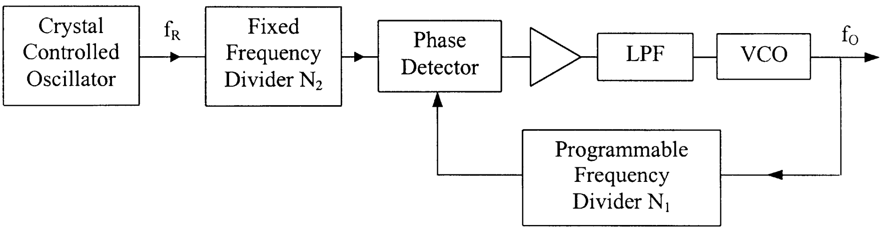

FIGURE P6.5

6.6 In the synthesizer shown in Fig. P6.6, $N_1 = 10$, $N_2 = 10$, and $f_R = 10$ MHz.

(a) What is the frequency resolution?

(b) If $N_3 = 1000$, what is the output frequency f_0? If $N_3 = 1001$, what is the output frequency f_0?

(c) If the frequency stability of the crystal reference oscillator is ± 1 ppm/°C, what is the frequency variation for the output signal over the temperature range from -30 to $+50$°C when $N_3 = 1000$?

6.7 A frequency synthesizer shown in Fig. P6.7 provides 401 output frequencies equally spaced by 10 kHz. The output frequencies are from 144 to 148 MHz.

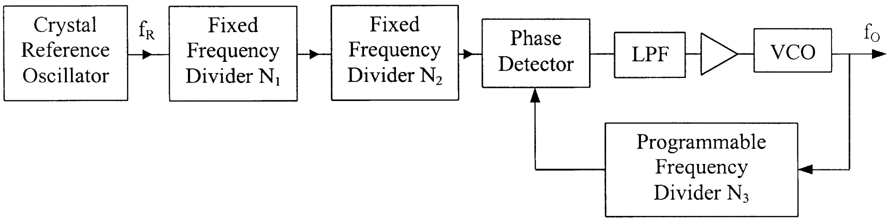

FIGURE P6.6

The reference frequency is 10 KHz, and the local oscillator frequency is 100 MHz. Calculate the minimum and maximum values for N.

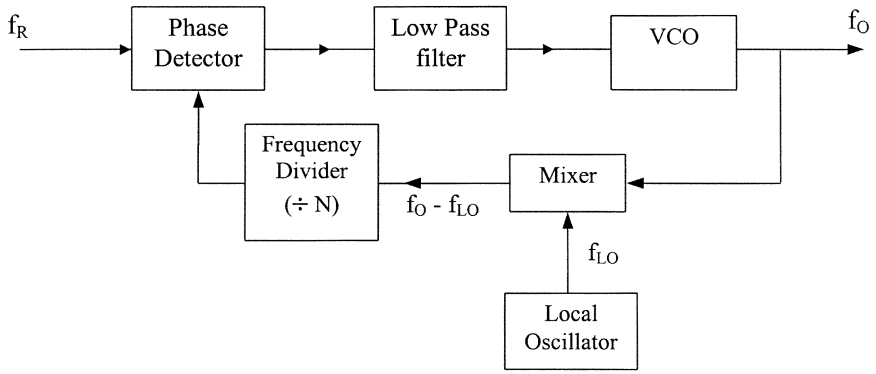

FIGURE P6.7

6.8 In Problem 6.7, if $N = 4600$, what is the output frequency?

6.9 In the synthesizer shown in Fig. P6.9, if $N_3 = 1000$ and $f_R = 1$ MHz, what is the output frequency for $N_1 = 100$ and $N_2 = 200$?

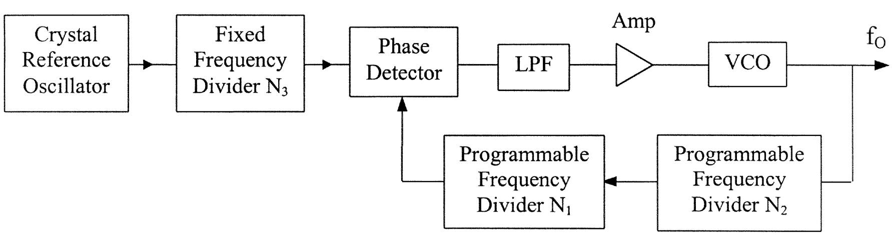

FIGURE P6.9

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