

RF

MICROELECTRONICS



BEHZAD RAZAVI

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circuit, v_{out} can be considered as the product of v_{in2} and a square wave toggling between 0 and 1, the output spectrum is given by

$$V_{out}(f) = V_{in2}(f) * \sum_{n=-\infty}^{+\infty} \frac{\sin(n\pi/2)}{n\pi} \delta\left(f - \frac{n}{T_1}\right) \quad (2.3)$$

$$= \sum_{n=-\infty}^{+\infty} \frac{\sin(n\pi/2)}{n\pi} V_{in2}\left(f - \frac{n}{T_1}\right), \quad (2.4)$$

where $*$ denotes convolution, $\delta(\cdot)$ is the Dirac delta function, and $T_1 = 2\pi/\omega_1$. Thus, the output consists of vertically scaled replicas of $V_{in2}(f)$ shifted by n/T_1 .

A system is called “memoryless” if its output does not depend on the past values of its input. For a memoryless linear system,

$$y(t) = \alpha x(t), \quad (2.5)$$

where α is a function of time if the system is time variant [e.g., Fig. 2.1(c)]. For a memoryless nonlinear system, the input-output relationship can be approximated with a polynomial,

$$y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) + \dots, \quad (2.6)$$

where α_j are in general functions of time if the system is time variant. Fig. 2.2(a) illustrates an example where the input signal is applied to the base of Q_1 while Q_2 and Q_3 are periodically switched by means of a square wave. For ideal bipolar transistors, the circuit can be viewed as in Fig. 2.2(b) and

$$v_{out}(t) = \left(I_{S1} \exp \frac{v_{in}}{V_T}\right) s(t) \cdot R, \quad (2.7)$$

where I_{S1} represents the saturation current of Q_1 , $V_T = kT/q$, and $s(t)$ is a square wave toggling between -1 and $+1$.

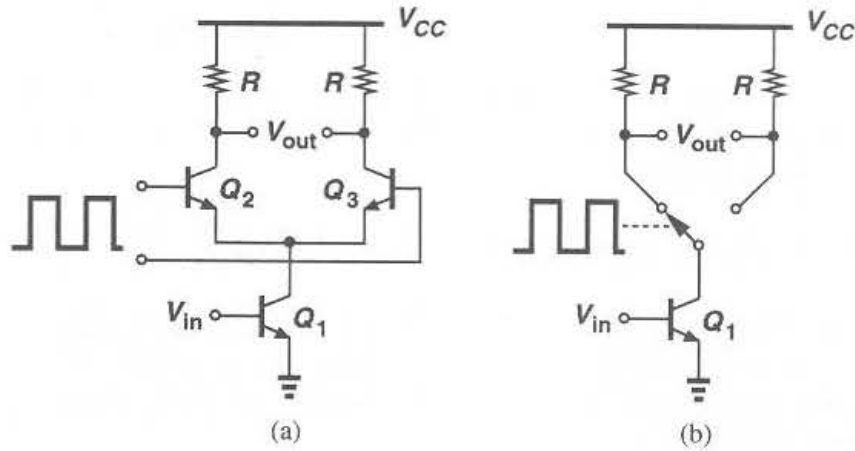


Figure 2.2 (a) Switching differential pair with tail current source driven by a signal, (b) equivalent circuit of (a).

put even after low-pass filtering, then the following stage may be desensitized. Finally, the RF-IF isolation determines what fraction of the signal in the RF path directly appears in the IF, a critical issue with respect to the even-order distortion problem in homodyne receivers (Chapter 5).

The required isolation levels greatly depend on the environment in which the mixer is utilized. If the isolation provided by the mixer is inadequate, the preceding or following circuits may be modified to remedy the problem.

Single-Balanced and Double-Balanced Mixers If a mixer accommodates a differential LO signal but a single-ended RF signal, it is called “single-balanced,” an example being the topology shown in Fig. 6.19(a). If a mixer operates with both differential LO and RF inputs, then it is called “double balanced,” the active version of which assumes the form of a Gilbert cell [Fig. 6.19(b)].

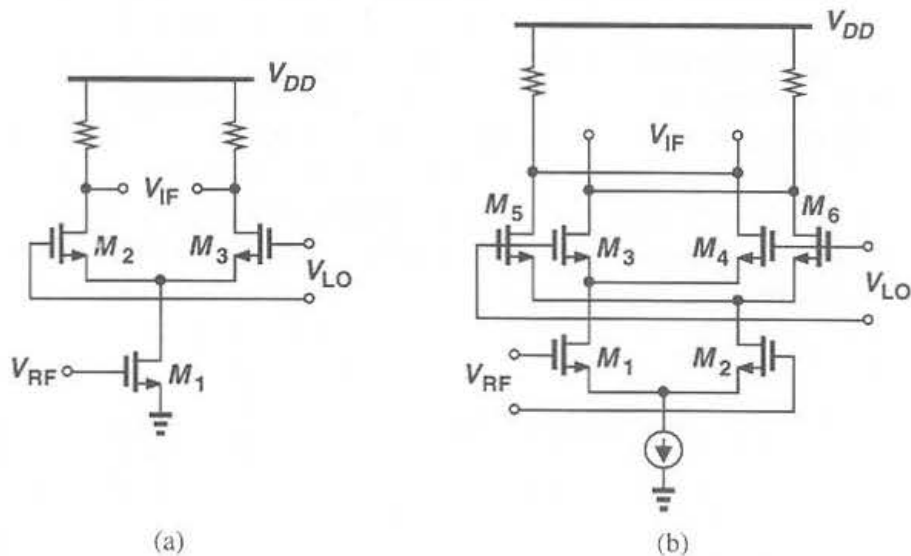


Figure 6.19 (a) Single-balanced mixer, (b) double-balanced mixer.

The single-balanced configuration exhibits less input-referred noise for a given power dissipation than the double-balanced counterpart. However, as explained in Section 6.2.4, the circuit is more susceptible to noise in the LO signal. The double-balanced mixer generates less even-order distortion, thus relaxing the half-IF issue in heterodyne receivers and lowering the beat components in homodyne architectures. Nevertheless, since the RF signal processed by the LNA (and possibly the image-reject filter) is usually single ended, one of the input terminals of the double-balanced mixer is simply connected to a bias voltage. This in turn creates different propagation times—i.e., phase shifts—for the two signal phases amplified by M_1 and M_2 in Fig. 6.19(b), leading to finite even-order distortion.

A drawback of the single-balanced mixer shown in Fig. 6.19(a) is the LO-IF feedthrough. Note that M_2 and M_3 operate as a differential pair, thus amplifying the LO signal. If the IF is not much lower than the LO frequency, then a first-order low-pass filter following the mixer may not adequately suppress the LO feedthrough without attenuating the IF signal. Thus, the large LO content may desensitize the IF amplifier. In the case of the double-balanced mixer of Fig. 6.19(b), on the other hand, the differential pairs M_3 – M_4 and M_5 – M_6 add the amplified LO signal with opposite phases, thereby providing a first-order cancellation. In general, the LO-IF feedthrough must be carefully studied in conjunction with the nonlinearities of the stages following the mixer.

In both mixer topologies of Fig. 6.19, the output can be sensed as either a differential or a single-ended signal. In addition to higher conversion gain, a differential output provides much more immunity to feedthrough of the RF signal to the IF output. To understand this effect, consider the simplified single-balanced mixers shown in Fig. 6.20, where the operation of both circuits can be viewed as multiplication of I_{RF} by a square wave. The difference is that in Fig. 6.20(a), the square wave toggles between 0 and +1, whereas in Fig. 6.20(b), it does between –1 and +1. Thus, the output voltage of both mixers can be expressed as $V_{out}(t) = I_{RF}R[a + bS(t)]$, where $a = b = 0.5$ in Fig. 6.20(a), $a = 0$, $b = 1$ in Fig. 6.20(b), and $S(t)$ is the square wave depicted in Fig. 6.20(b). This equation indicates that the single-ended output contains a component equal to $0.5I_{RF}R$, with no frequency translation. We call this effect “direct feedthrough.”

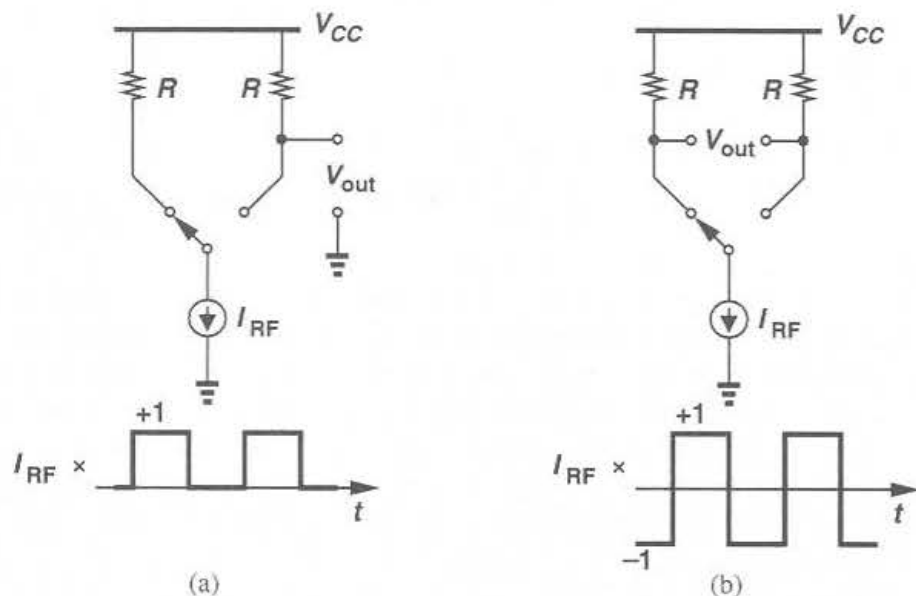


Figure 6.20 Simple mixers with (a) single-ended and (b) differential outputs.

What is the desired output waveform of an RF oscillator? Recall from the analysis of mixers in Chapter 6 that the noise contributed by the switching pair is minimized if the LO waveform exhibits abrupt transitions. Moreover, effects such as direct feedthrough are suppressed if the LO signal has a 50% duty cycle. Thus, the ideal waveform in this case is a square wave. In practice, however, circuit bandwidth limitations, particularly in LC oscillators, result in a waveform close to a sinusoid. Consequently, as shown in Fig. 7.4, the waveform is generated with a large amplitude to approximate a square wave in the vicinity of the zero crossings.

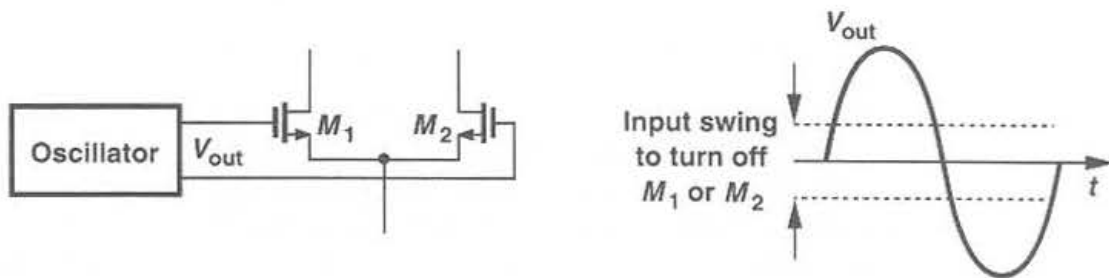


Figure 7.4 Approximation of a square wave with a large sinusoid.

In applications where the outputs of two or more oscillators are mixed to produce new frequencies, the desired waveform may be a low-distortion sinusoid. We return to this issue in Section 7.9.

The need for a 50% duty cycle in most oscillators calls for differential topologies, an important point to remember in the study of various oscillator configurations.

7.2 BASIC LC OSCILLATOR TOPOLOGIES

Most *discrete* RF oscillators incorporate only one active device. This is for two reasons: (1) to minimize the noise, and (2) to lower the cost. While the first reason still holds, the second is of little concern in IC technologies. The basic oscillators described in this section fall in the “one-transistor” category, serving as the first step toward understanding the design principles.

Following the feedback model of Fig. 7.1(a), we postulate that a one-transistor LC oscillator may include an LC tank at the collector of a bipolar transistor, with the feedback signal applied to the base or the emitter (Fig. 7.5). (The same idea applies to FET implementations as well.) Let us assume that, as shown in Fig. 7.6(a), the tank consists of an inductor and a capacitor in parallel. Since at resonance, the impedance of the tank is real, the phase difference between its current and voltage is zero. Thus, to achieve a total phase equal to zero, the feedback signal must return to the *emitter* of the transistor. This is the basic idea in a number of oscillator topologies.