CMOS MIXERS

PASSIVE AND ACTIVE

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November 15, 2002

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Abstract

This Paper presetns some techniques for CMOS Mixers with emphasis on downconversion-mixers. These mixers can be either Passive or Active.

Advantages and disadvantages of these techniques will be discussed.

1. Introduction

An important driving force in RF ICs development is the pursuing of single-chip integrated RF CMOS transceivers. Compared with GaAs, Bipolar and BiCMOS, CMOS is the most affordable technology. Therefore, full integration of RF transceivers in CMOS technology means the possibility of integrating a whole system such as a cellular phone in a single chip. This can greatly reduce system design cost, system volume, as well as power consumption, all of which are highly desirable in today's portable systems.

Downconversion mixer is one of the important building blocks for RF transceivers in wireless communications. Modern wireless communication standards such as GSM, CDMA, DECT,GPS demands high performance RF front ends, which are very often constrained by the achievable power gain, noise figure and linearity of the low noise amplifier and downconversion mixers.

Particularly, many design challenges exist when these RF blocks and a whole transceiver are to be implemented in CMOS process.

2. Downconverters System Considerations

In a receiver, all building blocks pass through a huge development process before they provide enough modularity and adjustability to be used in a multimode receiver. Not only the bandwidths and radio transmission frequencies but also the modulation schemes, noise and intermodulation characteristics differ a lot between the cellular standards. Usually the downconversion does not limit the flexibility of the direct conversion receiver for multimode applications.

Generally, the only factors affecting that are the frequency handling capabilities of active devices and ac coupling either at the input or output.The specific modulation as well as the multiple access method is very important to take into account in the proper direct downconverter design. The amplitude variations in the modulation as well as the time varying envelope in the TDMA reception can cause a widespread envelope beat around dc as a consequence of the second-order nonlinearity. Usually the mixer dominates the linearity performance of the receiver.

The envelope distortion is maybe the most essential individual unwanted phenomena in the direct conversion receivers. Therefore, not only every single building block but also the interface between the blocks must be considered properly in the design. The interface between the low noise amplifier and mixer must be ac coupled. Thus, the possible second-order distortion due to the low noise amplifier is rejected to pass to the mixer input and leak through the whole mixing path. In addition, the RF front-end should provide quite high gain in DCR. That is required to suppress the flicker noise of active baseband filters, which is typically quite high.

Primarily, the mixers' function in a DCR is to perform direct demodulation from RF down to baseband. Nevertheless, it is practical to implement to the mixer also other functionality in so far as these can be fulfilled without trading off the quality of the downconversion itself. Functionality can be increased by proper interface design to neighboring blocks. High integration level reduces the need of interstage buffering between the blocks. The interface between the mixer and the baseband can be realized without buffering. If the voltage gain of both low noise amplifier and mixer can be adjusted the linearity and noise specifications of several different cellular standards can be fulfilled easier. Block diagram of direct conversion receiver is shown in figure 1.

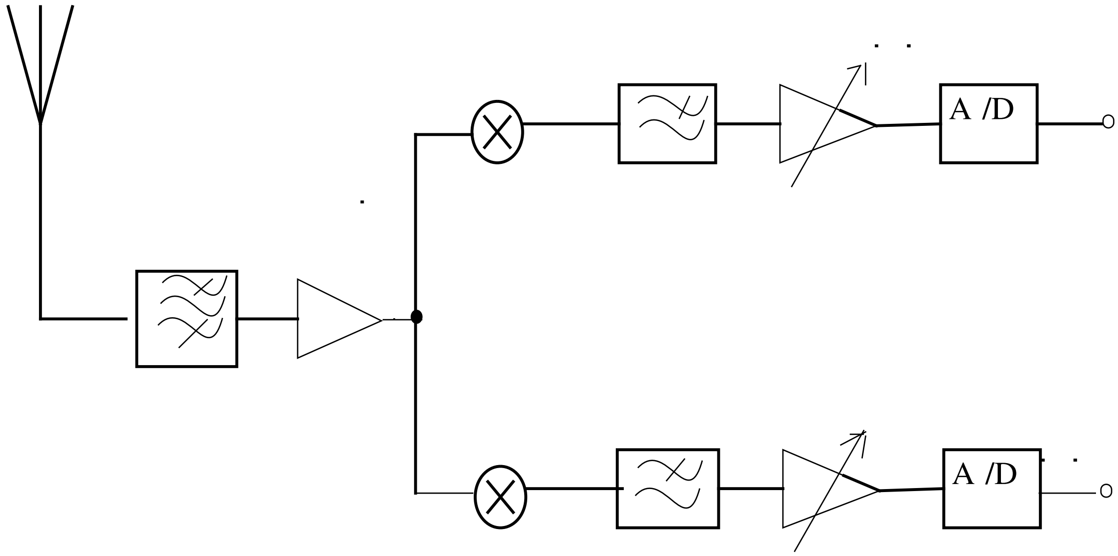

Figure 1. Block diagram of direct conversion receiver

3. The Gilbert Cell

Most popular CMOS mixer topologies are based on the traditional cross-coupled differential modulator stage introduced by Gilbert which is shown in Figure 2.This mixer operates on a switched current principle and cannot be operated with a single 1.2 V supply voltage due to the stack of three saturated transistor. Recently, another approach has been developed to lower the voltage supply of FR mixer-circuit design by replacing the current source transistors and active loads with LC tank circuit. This new approach can reduce the operating voltage, but chip LC tank circuits are very difficult to fabricate due to low Q-value of the spiral inductor.

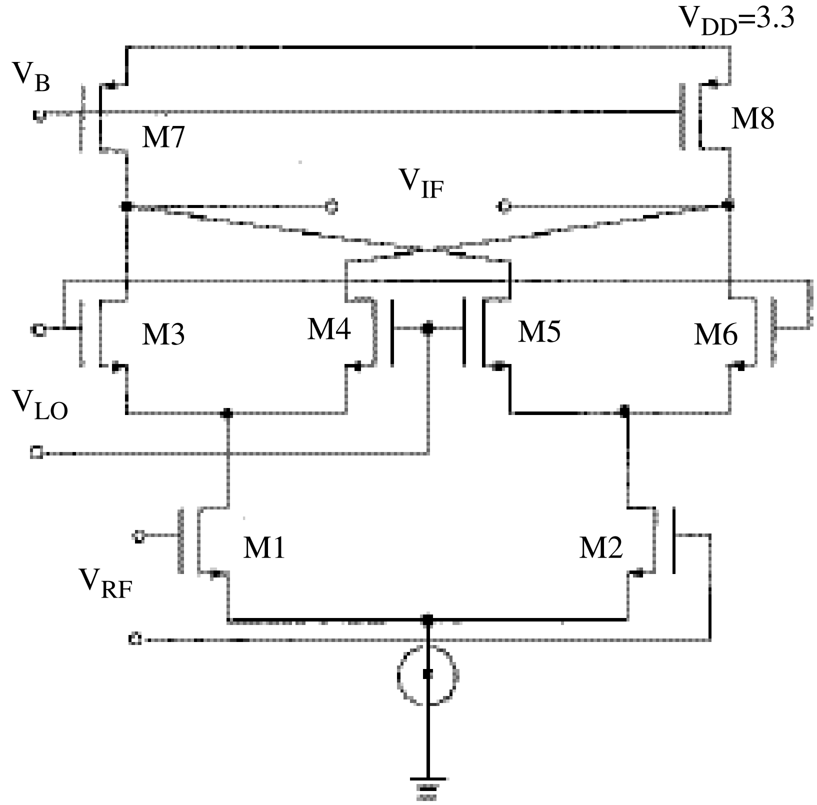

Figure 2. The Gilbert Cell

Transistors M1-2 form the input transconductors, which convert input RF voltage signal. Transistor M3-6 are commutating switches, which are turned on and off by the LO signal, accordingly, current signals from the transconductors are delivered to different branches. The net effect of the switching activities is that the RF current signals are multiplied with the LO signals. Transistors M7-8 serve as active loads. The differential IF output signal is acquisited from these two loads. Since the Gilbert mixer is fully differential, any common mode high frequency signals from the LO and RF ports will be substracted at the output. The mixer is expected to have very good RF-to-IF and LO-to-IF isolation performance. In addition, any second order harmonics at the two IF output ports are canceled by the differential output. Note that such quality greatly depends on the switching behavior and transistors working region. As is well-known, the drain-source current is generally the square of the gate-source voltage for long-channel MOS transistors. The transconductors M1-2 used here hence present nonlinearity when converting input RF voltage signal to current signal. The nonlinearity causes intermodulation. When two signals with close frequencies pass a nonlinear device, the output contain series of high order harmonics and intermodulation products. Among them, 2nd and 3rd intermodulation products are of our concern, since they can mix with the LO signal and generate sideproducts which are in the IF frequency band, resulting in signal distortion. Various methods such as source degeneration or translinear loop are used to improve the linearity of the transconductors.

4. Passive Mixers

In the following section, we will show some passive mixers. Then we will discuss the characteristics of these mixers, followed by their advantages and disadvantages.

4.1 Switching Mixer

In terms of implementation in CMOS the switching mixer has the advantage that the CMOS transistor is a fairly close approximation to an ideal switch. Thus, the topology of a balanced switching mixer can be as simple as shown in figure 3.

The transistors M1-M4 operate as switches concerning either the input or the inverse of the input to the output terminal. In practice, the switching voltages at the transistor gates are not ideal square waves but it can be shown that even rather long rise and fall times of the switching waveforms do not several reduce the conversion gain. For a double-balanced mixer like the mixer shown in figure 3 the conversion gains are multiplied by a factor of 2, so the ideal square switching waveform results in a conversion gain of 0.636. Obviously, with a swtching mixer the conversion gain is less than unity since there is no gain element involved.

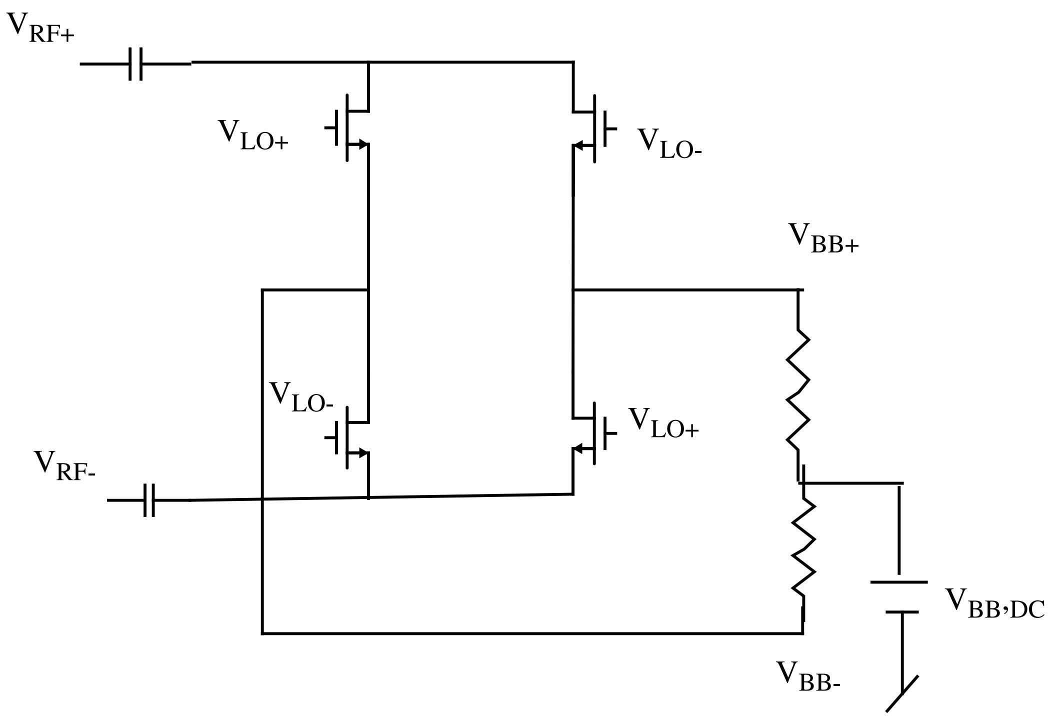

Figure 3. Switching mixer

A distinct advantage of the switching mixer over the Gilbert mixer in CMOS implementations is that the bias current in the transistors is zero, leading to a low flicker noise. Also, the periodic switching of the transistors leads to a reduction of the flicker noise. Another advantage is the inherent linearity of the switching mixer due to the good linearity of MOS device operated in the linear region. With the Gilbert mixer in CMOS the linearity relies on the exact cancellation of the quadratic terms in the device characteristics. For the switching mixer shown in the figure 3 the main source of error is non-symmetry in the circuit or in the driving voltages.

The mixer has been tested with a local oscillator frequency of 2.1The amplitude of the local oscillator was 0.5V. Simulates show that a performance improvement can be obtained by using a larger amplitude. Reasonable agreement is found for gain and noise figure whereas the linearity measurements show considerable deviations from the simulated results. It should also be noted that the 1/f noise does not present a problem for the mixer even though it converts the signal directly to baseband. The noise figure has been measured for the frequency band DC - 100KHz. For the second order intercept point the simulated result is grossly over-optimistic.

4.2 Probe Buffer Mixer

The mixer consists of the four transistors, M1 through M4, which is shown in figure 4. These four transistors are together into two pairs of two transistors each. Transistor M1 and M4 work together and are controlled by the local oscillator signal, while transistor M2 and M3 form a unit controlled by the inverse of the LO signal. Each pair serves the function of connecting the IF port to the RF port of the mixer.The difference between the two pairs is the polarity with which they connect the IF port to the RF port. When M1 and M4 are on, the IF port is connected with a positive polarity to the RF port. But when M2 and M3 are on, the IF port is connected with a negative polarity to the RF port.

A probe buffer, included only for testing purpose, follows the mixer and presents a high impedance load to the mixer while interfacing to off-chip test equipment. A passive network precedes the mixer and can be separated into two parts for convenient analysis: an L-match and an RF tank. The L-match is formed by inductors L1 and L2 with part of the tank capacitance, C3, while the RF tank is formed by inductors L3 and L4 with the remainder of C3. L1 through L4 are implemented with bondwires, and C3 is a metal-to-metal capacitor that incorporates lateral flux as well as vertical flux. The purpose of L-match is to boost the signal voltage across the mixer's RF port via an impedance transformation, while the RF tank is used to filter brad-band noise at the RF port of the mixer. This filtering is important because multiple frequencies at the mixer's RF port are converted to the IF at the mixer's IF port.

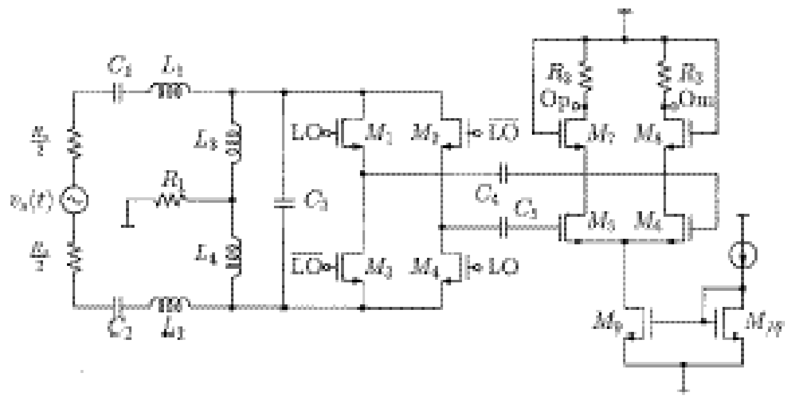

Figure 4. Probe buffer mixer

5. Active Mixers

In this section we will show some active mixers. Then we will discuss about their advantages and disadvantages in comparison to passive mixers.

5.1 Mixer with extra capacitor on VGN

The linearity of an RF mixer is in most cases rather limited. As mentioned before, the Gilbert topology is the most common used in CMOS technology. A double balanced structure which cancels out the quadratic term of the MOS transistor can be used. These mixers have not only a limited linearity which highly depends on matching, even more important is their limited frequency range. The input transistors of these mixers can only be biased with a relatively small V_{GS}-V_T in order to keep them in saturation at all times. The result is large transistors which limits the maximal achievable input bandwidth to about 100 MHz.

A better solution is to use the transistors in the linear region, preferably with a large V_{GS}-V_t. In this way a small R_{on} can be realized with a small transistor, allowing a high input bandwidth. This property has been used to realize high frequency GaAs commutating mixers. The transistors are being used as pass transistors and the linearity of these mixers does therefore not depend on the voltage to current conversion characteristic of the transistors. The linearity is mainly determined by the speed limitation of the pass transistor and by the generation of spurious signals during switching. The output signal after commutation is however still a high frequency signal and it can therefore not be further processed in CMOS. However, receivers only require a downconversion mixer and this means that the output bandwidth may be limited. A solution based on subsampling with a switched capacitor structure has been used. An IP3 of 27 dBm has been reported.

A CMOS mixer with very high linearity can be realized by using the linear voltage to current characteristic of the MOS transistor in its triode region. The use of a double balanced structure cancels out the common-mode dc biasing signals and the nonlinear dependence of g_{DS} on V_{DS}. The remaining problem is still the future processing of the high frequency output current. There are however two very important capacitor added on the virtual ground nodes (VGN) of this topology, the capacitors C_v in figure 5. Indeed, the output stage, the opamp and the feedback resistors, which convert the output current of the mixing transistors back into a voltage, must, in a downconversion mixer, only be able to produce low-frequency output signals. However, in order to let the input structure operate correctly for all frequencies, there may not be a signal on the virtual ground nodes of the mixer at any time. This is normally done with the feedback structure over the opamp which creates the virtual ground at its input. The transistors in the input structure would operate as pass-transistor for high-frequency signals when the frequency capability of the opamp would not be high enough. Therefore the capacitors C_v have been added. They make sure that all high-frequency currents injected to the VGN are filtered out and not converted into voltages. The opamp still generates the virtual ground for low-frequencies. By using this structure, it becomes possible to split the design of the input structure and the opamp. The input structure can now be optimized for operation at very high frequencies (more than 1 GHz), while the opamp can be designed for low-frequency operation (a few MHz).

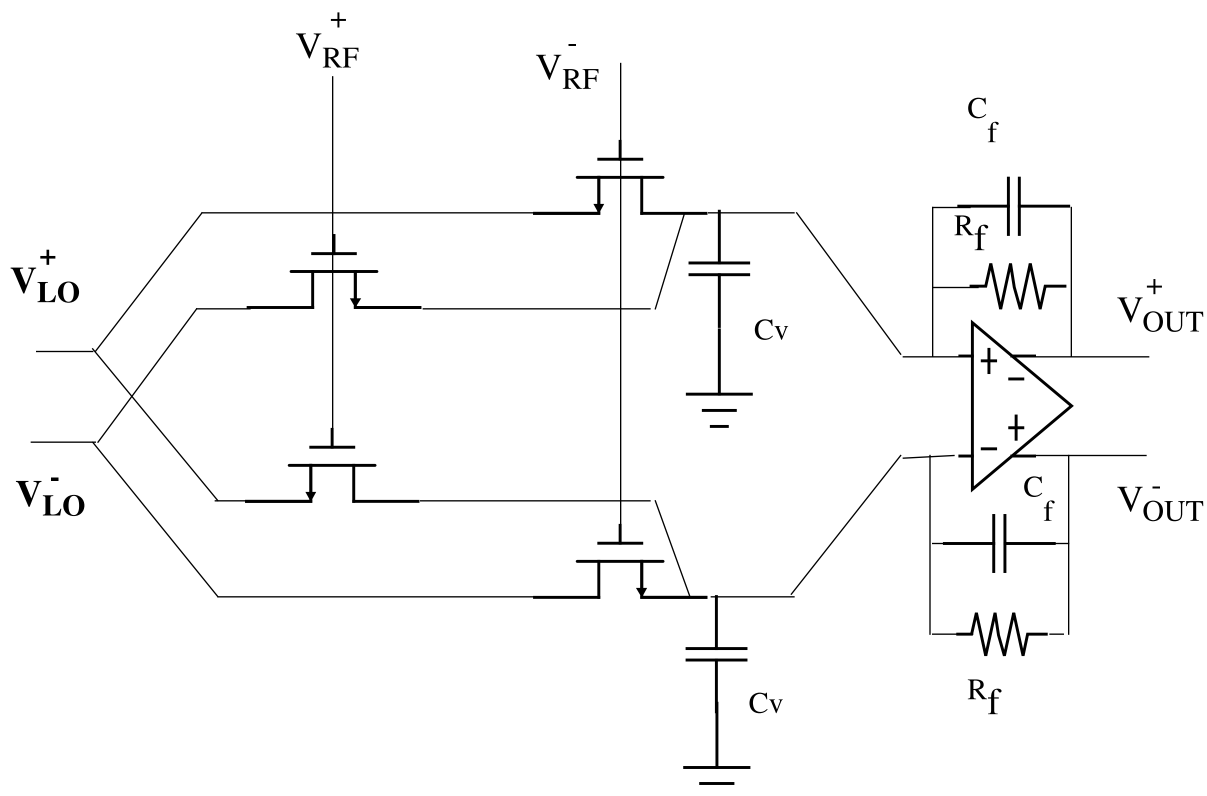

Figure 5. Mixer with the extra capacitor on VGN

5.2 Gilbert-type heterodyne Mixer

We have used a Gilbert-type heterodyne mixer circuit for downconverting input signal. The single-ended output from the IR filter drives the mixer-stage. The bondwire inductance L_{bond2} resonates with capacitor C_{ESD} (pad-capacitance + pin-capacitance + ESD-diode capacitance + $M_{5\text{-}6}$ source capacitance). This ensures that there is good common-mode rejection of substrate noise during operation. Typically, high supply current (in the range of a few mA) flowing in the mixer load resistors R_L, will cause a head-room problem, This becomes even more important if a tail-current source is used for setting the mixer quiescent current and for achieving a good common-mode rejection. Also, at IF frequencies, on-chip inductors cannot be used as load elements (instead of R_L) to increase the voltage head-room. In this mixer, there is DC-grounding of the sources of transistors M5 and M6 via the bondwire inductance L_{bond2}. As a result, the inductor L_{bond2} provides both the benefit of a larger head-room for the mixer transistors, as well as good common-mode rejection of the substrate noise.

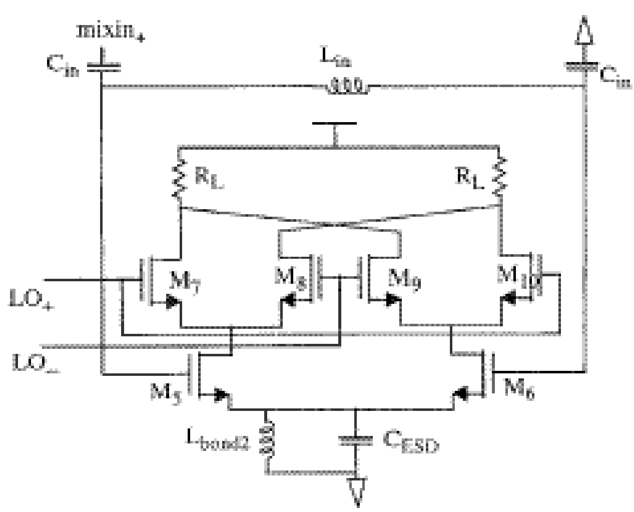

Figure 6. Gilbert-type mixer circuit schematic

The mixer input pair M5-M6 is differentially matched to 50 ohms using an on-chip LC-type (L_{in}-C_{in}) match. Down conversion occurs due to switching action of the quad-transistors M7-10. The switches are driven by an external oscillator through a differential LO buffer. It is essential that there is hard-switching action in the quad in order to reduce the mixer input referred noise and obtain the maximum conversion gain for a fixed power consumption. The LO buffer circuit (not shown here) is a simple 2-stage cascade of resistively loaded differential pairs. At a system level, in order not to degrade the linearity of the overall system, the mixer has been designed with a high over-drive voltage (Vgs-Vt) for the input transistors yields a high IIP3 for the mixer stage. There is an external bypass-capacitor at the mixer input which filters bias-circuit noise from coupling into the mixer input and also improves overall stability of the receiver.

6. Conclusion

The most important parameters in designing a mixer are linearity and noise figure (NF). Linearity can be shown by IIP3 (input intercept point). As we can see in table 1, passive mixers are more linear with higher IIP3 in comparison to active mixers. On the other hand, NF is better in active filters. Active mixers have conversion gain Supply voltage, current voltage and power diss. in passive mixers are less than active mixers. There is a comparison between different characteristics of both active and passive filters in table 1.

Table 1. Characteristics of passive and active mixers

Mixer Type	Switching	Probe Buffer	Extra Cap	Gilbert Type
Technology	CMOS 0.25	CMOS 0.35	CMOS 1.2	CMOS 0.5
LO Frequency	2.1 GHz	1.4 GHz	< 1.5 GHz	1.1 GHz
IF Frequency	0	170 MHz	< 780 KHz	160 MHz
Supply Voltage	1.8 V	1.5 V	5 V	2.7 V
Supply Current	0	0	1.3 mA	4 mA
Power Diss.	0	0	6.5 mW	10.8 mW
Conv. Gain	-7.1 dB	-3.6 dB	18 dB	0.6 dB
NF	6.8 dB	10 dB	32 dB	11 dB
IIP2	20 dB	----	----	----
IIP3	7 dBm	10 dBm	45.2 dBm	0
1 dB Comp.	23 dB	-5 dB	----	----

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