Low-Power Low-Voltage CMOS RF Mixers

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1) Introduction:

RF mixer is an essential part of wireless communication systems. Modern wireless communication systems demand stringent dynamic range requirements. The dynamic range of a receiver is often limited by the first downconversion mixer. This forces many compromises between figures of merit such as conversion gain, linearity, dynamic, range, noise figure and port to port isolation of the mixer. Integrated mixers become more desirable than discrete ones for higher system integration with cost and space savings. In order to optimize the overall system performance, there exist a need to examine the merits and shortcomings of each mixer feasible for integrated solutions. [1]

A few years ago the world of wireless communications and its applications started to grow rapidly. The driving force for this is the introduction of digital coding and digital signal processing in wireless communications. This digital revolution is driven by the development of high performance, low cost, CMOS technologies which allow for the integration of an enormous amount of digital functions on a single die. This allows on its turn for the use of sophisticated modulation schemes, comples demodulation algorithms and high quality error detection and correction systems, resulting in high performance, lossless digital communication channels. Low cost and low power consumption are the driving forces and they make the analog front-ends the bottleneck in future RF design. Both low cost and low power are closely linked to the trend towards full integration. An ever further level of integration renders significant space, cost and power reductions. Many different techniques to obtain a higher degree of integration for receivers, transmitters and synthesizers have been presented over the past years.[2]

Parallel to the trend to further integration, there is the trend to the integration of RF circuitry in CMOS technologies. The mainstream use for CMOS technologies is the integration of digital circuitry. The use of these CMOS technologies for high performance analog circuits yields however, if possible, many benefits. The technology is cheap, if used without any special adaptations toward analog design. Plain CMOS has the extra advantage that the performance gap between devices in BiCMOS and NMOS devices in deep sub-micron CMOS, and even NMOS devices in the same BiCMOS process, is becoming smaller and smaller due to the much higher investments in the development of CMOS than bipoar. The ft's of the NMOS devices are nowadays even higher than the ft's of the NPN devices.

Although some research has been performed in the past on the design of RF in CMOS technologies, it is only since a few years that real attention has been given to its possibilities. Today several research groups at universities and in industry are researching this topic. As bipolar devices are inherently better than CMOS devices, RF CMOS is by some seen as a possibility for only low performance systems, with reduced specification, or that the CMOS process need adaptations, like substrate etching under inductors. Other feel however that the benefits of RF CMOS can be much bigger and that it will be possible to use plain deep sub-micron CMOS for the full integration of transceivers for high performance applications, like GSM, DECT and DCS 1800.

2) General Considerations:

Mixers perform frequency translation by multiplying two signals (and possibly their harmonics). Downconversion mixers employed in the receive path have two distinctly different inputs, called the RF port and the LO port. The RF port senses the signal to be downconverted and the LO port senses the periodic waveform generated by the local oscillator. The performance parameters of typical down conversion mixers are the *noise figure*, the *conversion gain*, the *input impedance*, the 3*rd order intercept point* and the *port-to-port isolation*. These parameters are used to differentiate between the different types of architecture as will be seen in the next sections.

The noise figure is important in mixers as it is a measure of the performance of the mixer, like how much noise is added in the system.The input impedance in heterodyne architectures should be well matched to increase the conversion gain. The 3rd order intercept point is critical as it is a measure for the linearity of the mixer. The port to port isolation is also a critical issue, in fact, the LO-RF feedthrough results in LO leakage to the LNA and eventually the antenna, whereas the RF-LO feedthrough allows strong interferers in the RF path to interact with the local oscillator driving the mixer. The LO-IF feedthrough is important because if substantial LO signal exists at the IF output 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.[6]

3) Different state of the art architectures:

The *heterodyne* or *IF receiver* is the best known and most frequently used receiver topology. In the IF receiver the wanted signal is down-converted to a relatively high intermediate frequency. A high quality passive bandpass filter is used to prevent a mirror signal to be folded upon the wanted signal on the IF frequency. Very high performances can be achieved with the IF receiver topology, especially when several IF stages are used. The main problem of the IF receiver is the poor degree of integration that can be achieved as every stage requires going off-chip and requires the use of a discrete bandpass filter. This is both costly (the cost of the discrete filters and the high pin-count for the receiver chip) and power consuming(often the discrete filters have to be driven by a 50 ohm signal source). Moreover, in CMOS RF circuit design input/output is already becoming a serious problem above the GHz frequency range. [2]

The *homodyne* or *zero-IF receiver* has been introduced as an alternative for the IF receiver that can achieve a much higher degree of integration. The zero-IF receiver uses a direct, quadrature, down-conversion of the wanted signal to the baseband. The wanted signal has itself as mirror signal and sufficient mirror signal suppression can therefore be achieved, even with a limited quadrature accuracy. Theoretically, there is thus no discrete high frequency bandpass filter required in the zero-IF receiver, allowing in this way the realization of a fully integrated receiver, especially if the down-conversion is performed in a single stage (e.g. direct from 900 MHz to the baseband). The problem of the zero-IF receiver is its poor performance compared to IF-receivers. The zero-IF receiver is intrinsically very sensitive to parasitic baseband signals like DC-offset voltages and crosstalk products caused by RF and LO self-mixing. These drawbacks have kept the zero-IF receiver from being used on large scale in new wireless applications. The use of the zero-IF receiver has therefore been limited to rather low performance applications like pagers.[2]

3.1) Conventional Mixers:

3.1.1)Gilbert Mixer Basics

Gilbert mixer was proposed in the 1960 s [1] and is still the backbone of most of the mixers we have today. Figure 1 shows the main elements of the Gilbert mixer, including a RF stage and a LO stage. The RF stage consists of a bipolar differential pair, Q5 and Q6, and a current source.

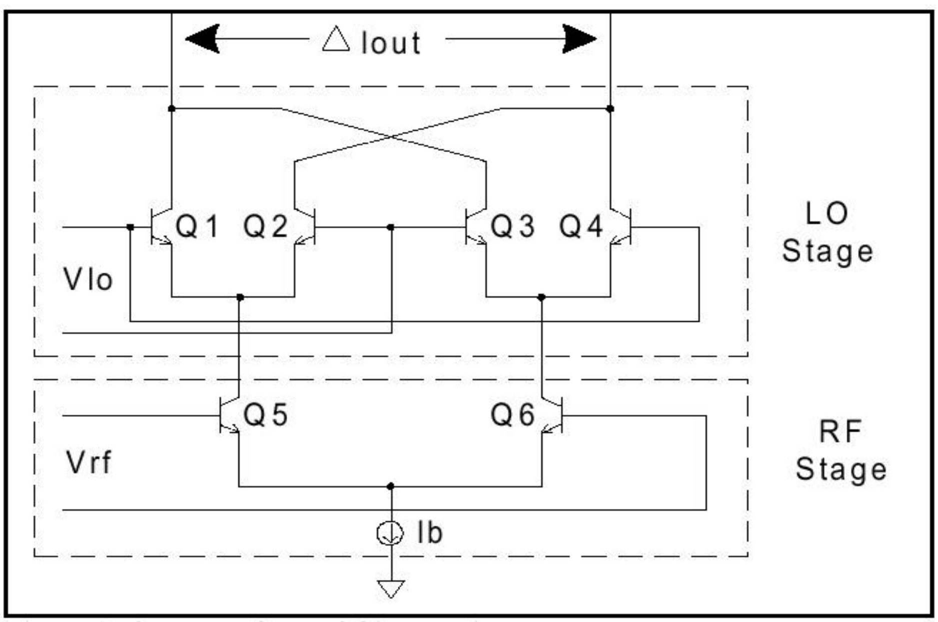

Fig1:Standard form of Gilbert mixer

For the LO stage, including Q1, Q2, Q3 and Q4, if LO voltage, VLO, is sufficiently large, it will operate as a current steering circuit by steering the current from one side to the other side of the differential pairs. It is very common to apply a large LO signal to modulate the RF signal in mixers. But the original multiplier principle of the Gilbert mixer targeted at sinusoidal signal for both RF and LO inputs. Thus, small signal is assumed for LO for the explanation of the principle of the Gilbert mixer.

For the mixers used nowadays, the LO signal is chosen large enough so that the LO stage transistors alternately commutate all of the tail current from one side to the other at the LO frequency. It is equivalent to use a square wave at the LO frequency to modulate the RF signal. Although the square wave introduces a lot of odd harmonics, the undesirable harmonics will be filtered out with the IF filter.[3]

A. single-Balanced Design:

The single-balanced mixer shown in Fig.1 is the simplest approach that can be implemented in most semiconductor processes. The single balanced mixer offers a desired single-ended RF input for ease of application. Though simple in design, it has moderate gain and low noise figure. However, the design has low 1dB compression point, low port-to-port isolation, low input ip3 and high input impedance. [1]

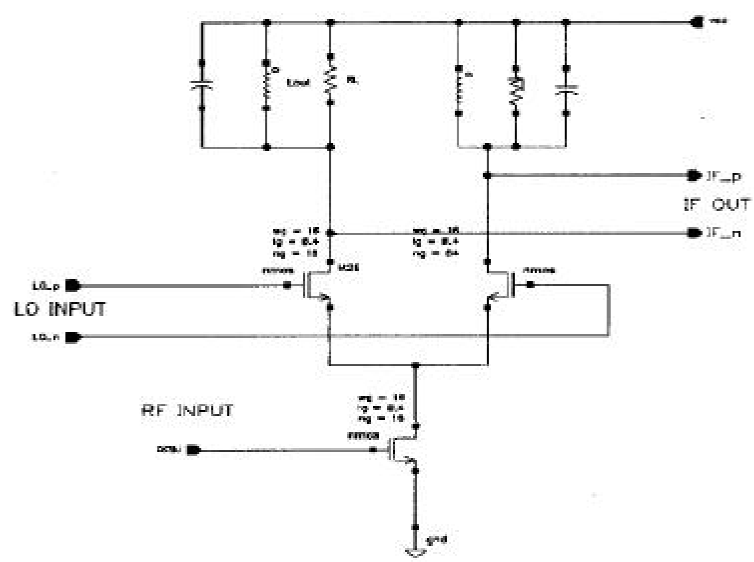

Fig2 :Single balanced mixer

B. Double-Balanced Design:

The double-balanced or Gilbert cell mixer in Fig.3 is most desirable for high port to port isolation and spurious output rejection applications. It can provide high gain and very low noise figure. The linearity is reasonably good. Typically, the RF filter preceding the mixer is single-ended so a balun transformer is needed to convert the single ended input to a differential signal for the mixer. Transformer having lowinsertion loss is very difficult to implement in integrated circuits. This forces the use of an externel transformer which occupies more board space and cost. The additional space and cost may not be justified for consumer products.[1]

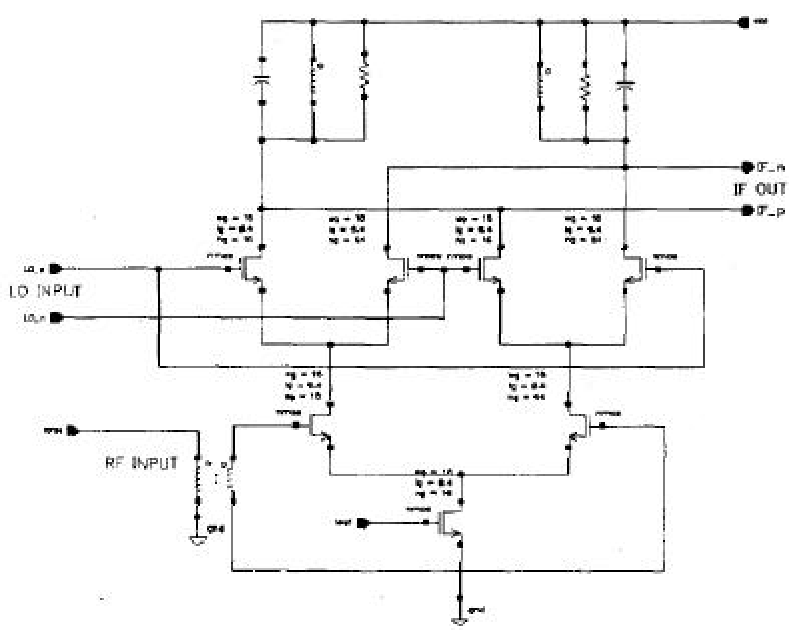

Fig3: Differential input Gilbert Cell

3.1.2) Bulk driven mixer(single transistor mixer):

Usually the MOSFET is used as a 4 terminal device (drain, source, gate and bulk) where the signal is input through the gate, while the bulk is used to isolate the MOSFET from other devices on the same substrate. To properly implement a bulk driven mixer a twin-well technology is required as shown in Fig.4. The n-channel MOSFET in Fig.4 is a 5 terminal device, where both the gate and the bulk can be used for signal input while isolation is provided by the deep n-well.

Using a twin-well technology provides 2 reverse biased p-n junctions worth of isolation between the MOSFET and the substrate, which is important at high frequencies.
The topology of the proposed bulk driven mixer core is illustrated in Fig.5. In the circuit, the switching action is provided via the gate, while the transconductance is obtained through the bulk. LO+ and LO- are two antiphase signals from the local oscillator that are used to switch M!-4 ON and OFF. When switched ON, M1-4 are held in the saturation region by a sufficiently large VDS. This ensures that reasonable gain can be obtained. The mixer core is used as a common source pair in any one phase of the local oscillator. As long as the RF input is differential, the circuit will work differentially.[4]

In the positive phase of the local oscillator, LO+ is sufficiently larger than the threshold voltage of M1 and M4 to switch them ON (in the saturation region). At the same time, LO- is less than the threshold voltage of M2 and M3 to switch them OFF (in cut-off). The RF input can now pass to the IF output via the back gate transconductance (g_{mbs}) of M1 and M4. In the negative phase of the local oscillator, M2 and M3 are ON, while M1 and M4 are OFF. The RF input is now inverted when it appears at the IF output. Thus the RF input is commutated by the action of the local oscillator on the gates of M1-4, and hence converted to the desired IF frequency.

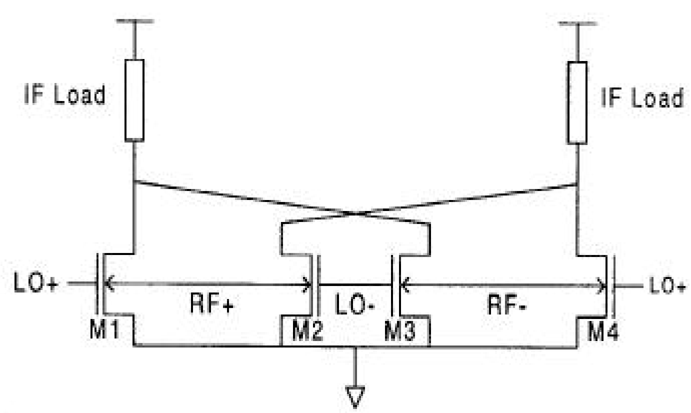

Fig.4:N-channel MOSFET in a p substrate twin-well technology, with bulk-channel
With bulk-channel parasitic p-well resistance.

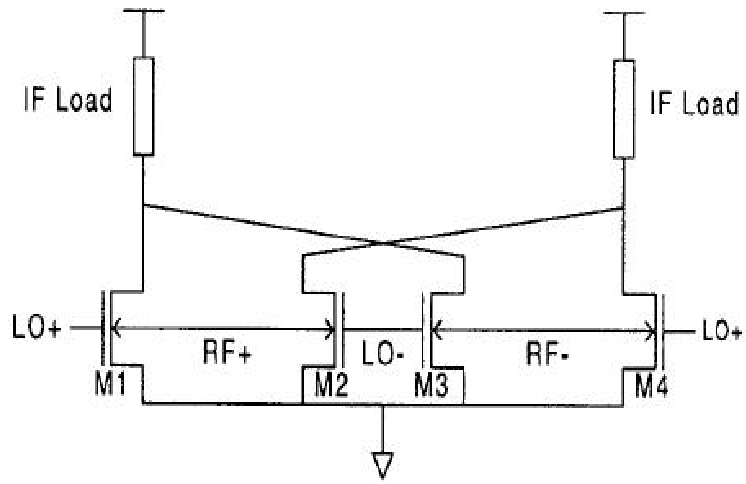

Fig.5: The bulk driven mixer core

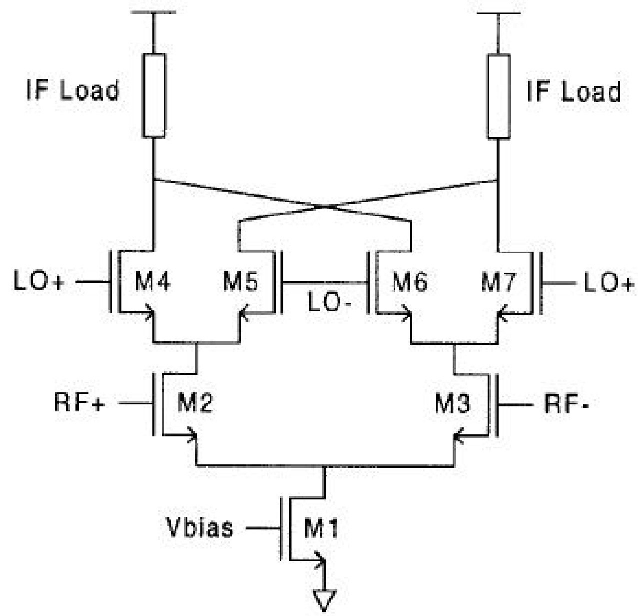

Fig6: Standard Gilbert Architecture

Due to the exploitation of both the gate and the body transconductance, the bulk driven mixer core requires a low supply voltage and consumes less power. The circuit can work with a supply voltage as low as 1V and consumes 1.6mW. However, this reduction in power consumption is not achieved at the expense of linearity of the mixer. The mixer exhibits a reasonably good linearity as shown by the IIP3 in table1. However, the most attractive feature of the bulk driven mixer core, is its low power consumption of 1.6mw. [4]

3.2) The Best Mixer Presented to date:

Some designers deviate from the conventional mixers design to new ideas. The following circuit is a new proposed mixer.

Narrowband Source-Coupled Pair[5]:

The first stage in a balanced Gilbert Mixer is the source-coupledpair (SCP) transconductance stage, shown in Fig. 7a. Here v1 and v2 represent a small RF signal. When a single ended input voltage is fed (e.g., v1=Asinwot, and v2=0), the high impedance of the current source forces the output currents to be balanced. If the input voltage is perfectly balanced (i.e.,v1=-v2=(A/2)sinwot)
the output current is also balanced. In the latter case the current source is unnecessary and can be omitted in favor of higher linearity. The drawback of this omission is that the mixer will not reject imbalance in the RF differential inputs.
Instead of a current source, a tank circuit can be used, as shown in Fig.7b. The inductor provides a low resistance path for the dc bias current of N1 and N2 to sink to ground, therby avoiding the dc voltage drop across the current source. At the resonance frequency, the tank circuit exhibits high impedance to ground, mimicking an ac current source. The functionality of the transconductor is dependent on the design of the tank circuit.

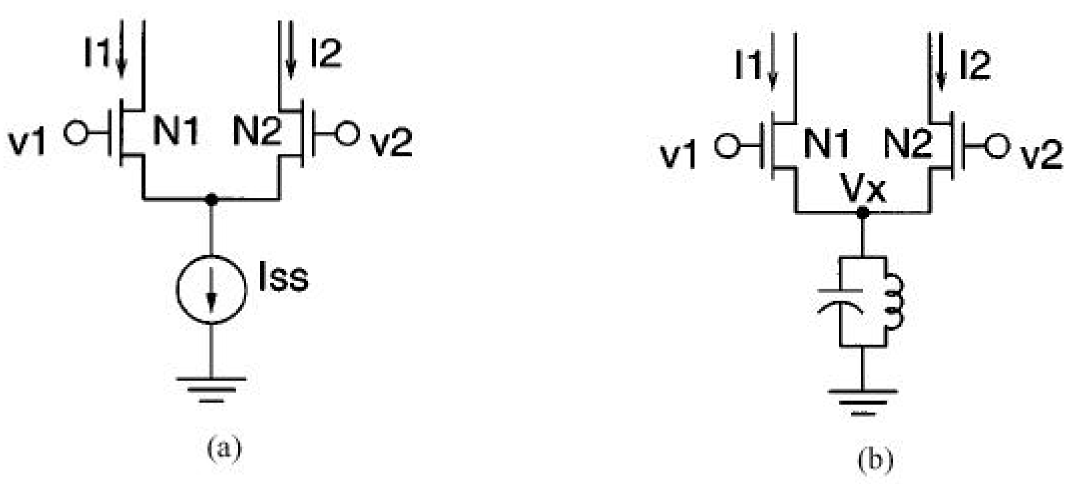

Fig.7:Source coupled pair(a)Conventional approach (b)Narrowband approach

The mixer circuit schematic is illustrated in Fig.8

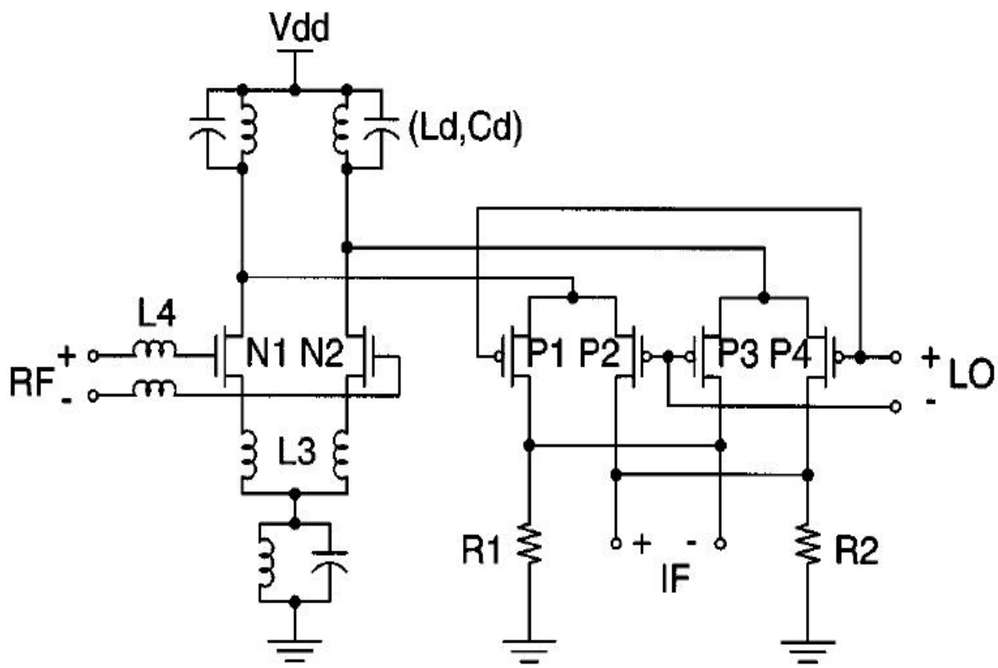

Fig.8: LC-folded cascode mixer

3.3) Comparison between the different architectures performance:

Table 1:

Mixer Type	Gain(dB)	NF(dB)	Input IP3(dBm)
Gilbert-Single	7.3	10.7	-2.7
Gilbert-Differential	7.2	9.15	-2.5
Bulk Driven	2.09	19.8	16.65
Source-Coupled pair	-1.5	12.0	11.0

3.3) Future work:

The main issue regarding the design of CMOS mixers suitable for RF receivers, is innovating a simple structure in terms of both the number of stacked transistors and the number of transistors in the signal path, at the same time maintaining a good port to port isolation. So, future works in the field of RF mixers may be focused on novel circuit architectures to solve this issue.

4) Conclusion:

Wireless communication systems are expanding in many directions. On the hardware frontier, there is a persistent demand for light, inexpensive, low-power, hand-held terminals. This incited rapid evolution of highly integrated radio frequency (RF) receivers within CMOS technologies. Contemporaneous with this evolution is the reduction in supply voltage standards for integrated circuits. This trend dictates that the RF front-end of a wireless system will have to operate under low voltage supplies (i.e., less than or equal 1V). Under reduced supply voltage, many of the circuits commonly used in RF receivers, such as cascode amplifiers and Gilbert mixers will not meet the stringent dynamic range requirements of the receiver. This circuit requires at least two transistors stacked between the supply rails, making them unsuitable for low-voltage operation.

References:

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