Silicon Bipolar Active Mixers

Double balanced mixers are useful for frequency translation because the RF and LO frequencies are inherently suppressed at the IF port. This paper describes a silicon Gilbert cell (emitter-coupled-transistor pair) providing gain of up to 15 dB and operation to 6 GHz.

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Double balanced mixers, commonly used for frequency translation in receivers and transmitters [1,2], ideally operate by multiplying an RF (or modulating) signal

$$RF = A_{rf} \cos(w_{rf} * t) \qquad (1)$$

by ± 1 at an LO rate. This leads to an output IF waveform of

$$IF = \qquad (2)$$

$$A_{rf} \Sigma \frac{2}{n\pi} [\cos(n\omega_{lo} - \omega_{rf})t + \cos(n\omega_{lo} + \omega_{rf})t]$$

Where:

A_{rf}=	**amplitude of signal which is multiplied**
ω_{rf}, ω_{lo}=	**angular frequencies of RF and LO signals**

Specifically, this implies the following characteristics:

1) The output contains a downconverted signal at wif = wlo-wrf. The ± 1 multiplication is responsible for a 3.9 dB loss, but additional

circuit elements may be present which may either add loss or provide gain to compensate for it.

2) Input RF and LO frequencies are suppressed at the IF output.
3) Unless filtered, signals originating in the image band of $\omega'_{rf} = \omega_{lo} + \omega_{if}$ = also will be translated to the IF output band.

This paper discusses the operation and modeling of a Gilbert cell based active bipolar mixer and the associated silicon bipolar MMIC process by which it is produced. RF measurements on two representative mixers fabricated with this technology are discussed. Finally, more complex circuits using active bipolar mixers to achieve greater dynamic range or image rejection are presented.

Process Overview

The foundation of any monolithic microwave bipolar technology must begin with devices having high f_T and f_{MAX} and minimal parasitic capacitances resulting from interconnections and isolations. Figure 1 shows a profile of our process, called Avantek's Isolated Self-Aligned Transistor (ISOSATTM) process, that was used for the active mixers described here.

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Microwave transistors with 0.7 micron emitters on a 4.0 micron pitch are fabricated with a nitride self aligned method. The fully ion implanted structure creates shallow arsenic emitters and basewidths of less than 0.1 micron. This leads to transistors with f_T's of 10 GHz and f_{MAX}'s of 20 GHz.

Parasitic capacitances are also minimized with this process technology. A trench isolation technique reduces collector to substrate capacitances while maintaining tight geometries. Capacitances are further reduced by placing thin film resistors and interconnecting metal on a thick field oxide. Finally, the second level metal application is placed on a thick but low dielectric constant layer of polyimide.

Parasitic capacitances are . . . minimized with . . . process technology

Table 1 shows a partial listing of modeling parameters for a typical bipolar transistor made with this process. The device has 4 emitter fingers each of 20 microns'length and is normally operated at currents of 4 to 6 mA. Normally the voltage breakdown from collector to open circuited emitter, BVceo, is in excess of 12 volts when the epitaxial layer thickness is 1.5 microns. The Table I also contains values of the various parasitic capacitances associated with this integrated circuit process.

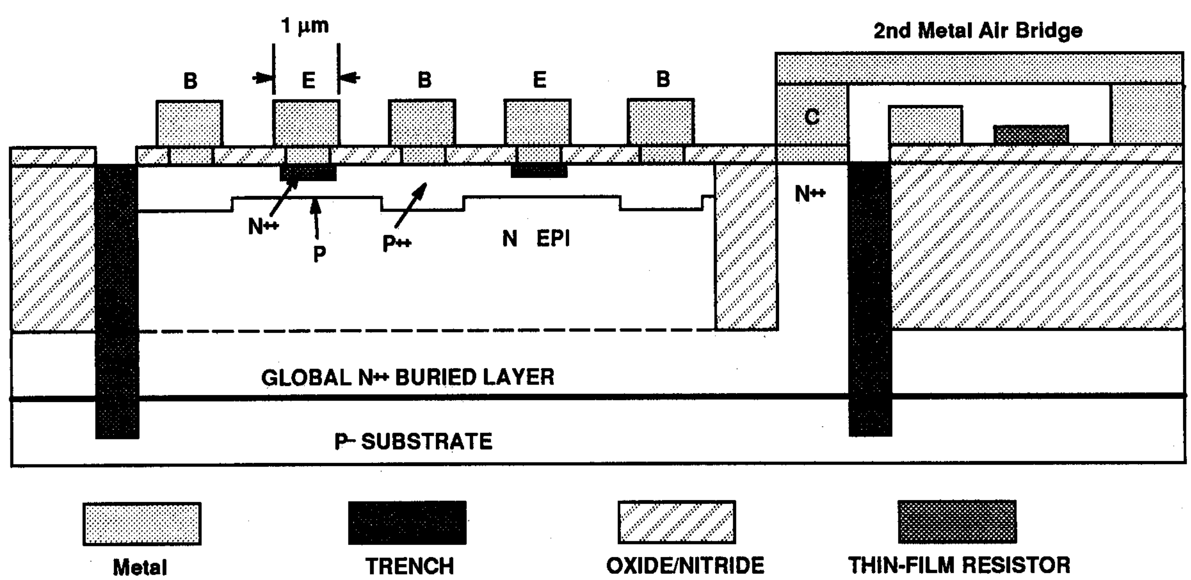

Figure 1. Cross section of the isolated self aligned transistor process.

Parameter	Definition	Value
BF	ideal max. forward beta	100
TF	ideal forward transit time	12 ps
RE	emitter ohmic resistance	1.04 Ω
RB	0-bias (max) base resist.	30 Ω
RC	collector ohmic resistance	29 Ω
CJE	b-e 0-bias p-n capacitance	0.23 pF
CJC	b-c 0-bias p-n capacitance	0.10 pF
CJS	isolation 0-bias p-n cap	0.14 pF
Parasitic Elements:		
CM1	Metal-to-substrate cap.	0.017 fF/μm^2
CR	Resistor-to-substrate cap.	0.017 fF/μm^2
CMX	Metal 1-to-Metal 2 cross-over capacitance (4 μm line width)	0.28 fF
CT	Trench column-to-substrate or column-to-column cap. per μm of trench perimeter	0.035 fF/μm

Table I. SPICE modeling parameters for the bipolar transistor and IC parasitic elements.

Circuit Design and Operation

Mixers for two different power levels of operation were designed using similar circuitry. Both were fabricated and tested, and are designated the IAM-81 (5v, 12mA) and the IAM-82 (10v, 50mA). A simplified schematic of the IAM-81 is shown in Figure 2. The similar higher power IAM-82 mixer includes an additional emitter follower.

The RF signal enters an amplifier formed by the emitter coupled transistor pair (QR1,2), the load resistors (RL), and an emitter resistor (RE). Their amplification is responsible for the overall conversion gain of the mixer. These elements determine the gain, bandwidth, and input power handling capability of the mixer and their critical values are summarized in Table 2 for the two mixers.

A Gilbert cell active mixer is based on an emitter coupled pair amplifier. Operation of this amplifier is best understood by dividing the RF input signal into its common mode and differential mode components.

A Gilbert cell active mixer is based on an emitter coupled pair amplifier

The RF signal enters one side of the pair, while the opposite of that pair is AC grounded through a capacitor. From symmetry, the common mode com-

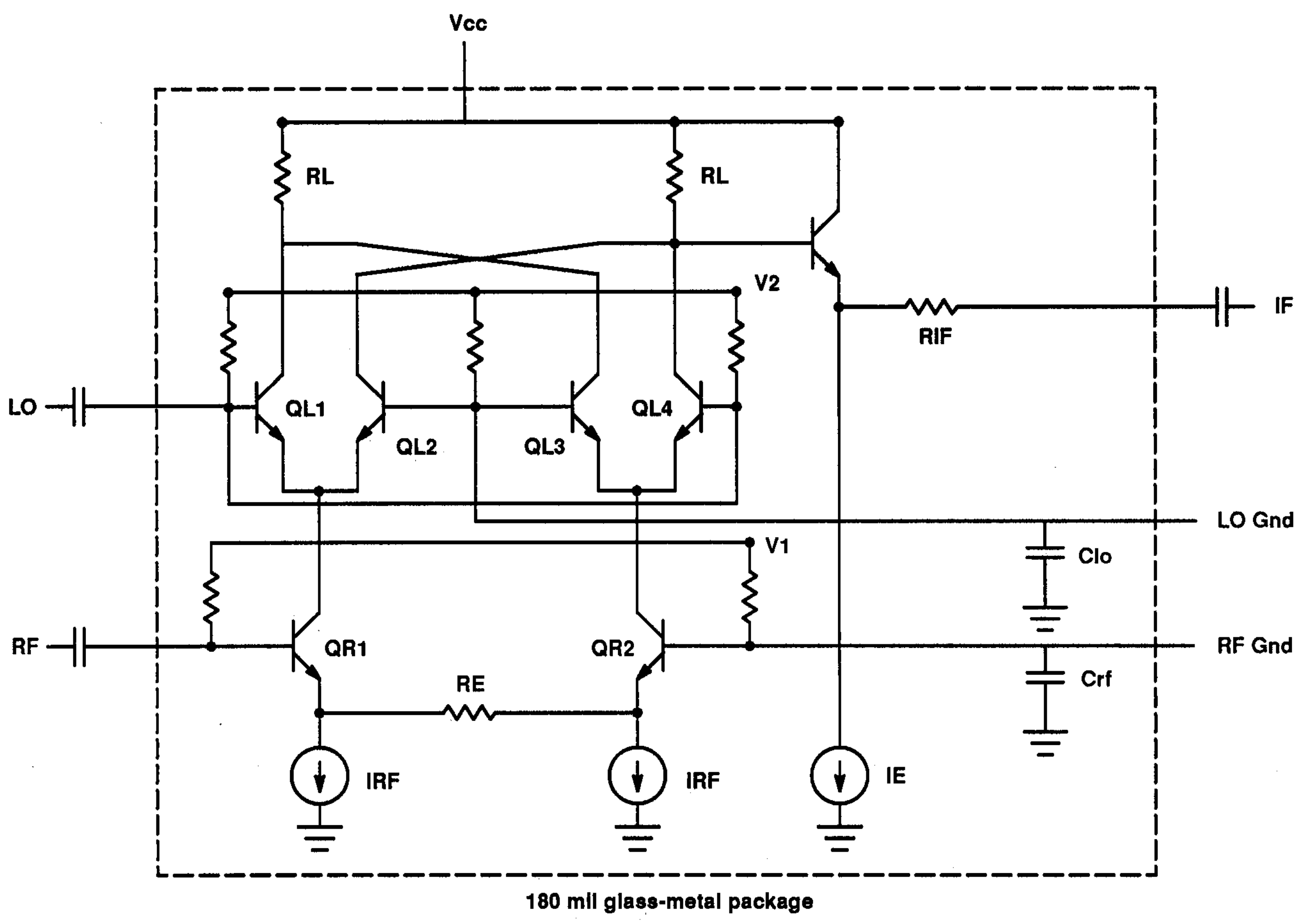

Figure 2. Simplified schematic of the active bipolar mixer.

Element	IAM01	IAM02
VCC	5 V	10 V
RL	400 Ω	700 Ω
RE	20 Ω	40 Ω
IRF (each branch)	1.8 mA	4.3 mA

Table 2. Amplifier elements of the active mixer circuits.

ponent has no first order effect on the output voltage. The differential mode component shifts the current between the two branches, and for small signal operation, acts as a standard common emitter amplifier.

For the Gilbert cell mixer, four cross coupled devices are added to the basic amplifier. As with the RF input to the basic emitter coupled pair, the LO is injected in single ended fashion into the added quad, with the opposite side of the quad AC grounded through a capacitor. Positive LO voltages cause the outer set of devices to be on, resulting in a multiplication of the RF signal by +1 at the LO rate, while negative voltages cause the inner pair to be on, multiplying the RF signal by -1 at the LO rate[3]. A noteworthy feature is the very low power required to alter the states of these four devices (typically -5 to 0 dBm) and produce the necessary multiplication of the RF signal by ±1 at the LO rate.

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Wideband impedance matching is set by 50 ohm resistors in shunt with the high input impedances of the RF and LO devices and by a 25 ohm resistor in series with the low output impedance of the emitter follower. These techniques produce load insensitive impedance matching for the active mixer.

Mounting is done in standard 0.180 inch square glass-metal packages, with internal capacitors provided to enable single ended operation of the RF and LO ports (refer to Figure 1).

No user supplied baluns are necessary

Typical printed circuit board layouts would require 50 ohm lines with blocking capacitors for the three ports and dc power and ground connections. No user supplied baluns are necessary (as are required with some GaAs based active mixers) [4].

Active Mixer Modeling

The ability to model MMICs accurately is essential to their cost effective development. Although active mixers inherently are highly nonlinear circuits, silicon bipolar based MMICs can be modeled adequately as lumped or semi- distributed devices using SPICE based programs [5].

. . . active mixers, inherently . . . nonlinear circuits, . . . can be modeled adequately . . . using SPICE

Although SPICE has been used extensively to analyze the conversion gain and distortion properties of active mixers, little has been reported on its use in analyzing noise figure. A novel method to analyze the noise performance of an active mixer has been developed and will be illustrated by the calculation of the single side band (SSB) noise figure. Due to the mixer's internal frequency conversions, this requries a lengthy calculation, illustrated as follows:

1) Noise sources are identified. These consist of thermal and shot noise sources as shown in Figure 3 with appropriate noise spectral density $<I_{NOISE}>^2$. Transistors are modeled with base resistances separated as shown. Frequency bands where noise could affect the output are assumed to be the IF, LO+IF and LO-IF bands.

2) Conversion factors are calculated from each noise source and in each frequency band to the IF output. These involve separate transient analyses for each source with a small signal at the noise source (for example, 1 mA) and the LO operating to provide possible frequency conversions. Use of a Fourier analysis on the output gives the IF signal and hence the conversion factor.

3) Noise factor contributions are calculated. These are:

$$\frac{P_{out}\ from\ <I_{noise}>}{P_{out}\ from\ R_s\ in\ RF\ band} = g^2 <I^2_{noise}> \frac{R_s}{4kT} \tag{3}$$

where g is the normalized current gain (which is equal to the current gain of the noise source in the specified band to the output in the IF band, divided by the current gain from the mixer input to the mixer output),

$<I_{noise}>$ is the noise current of individual mixer noise sources,

Rs is the source resistance (usually 50 ohms),
k is Boltzman's constant, and
T is the temperature in degrees Kelvin.
4) Noise figure is computed by common summing of noise factors.

The calculated SSB noise figure of 16.1 dB was in good agreement with measured values of 15.5 to 16 dB

The results of a noise figure calculation on the IAM-81 mixer are summarized in Table 3. Listed there are elements, defined in Figure 1, whose noise sources contribute appreciably to the output noise factor. The calculated SSB noise figure of 16.1 dB was in good agreement with measured values of 15.5 to 16 dB (with RF = 500 MHz and IF = 100 MHz).

Device measurements

Figures 4a and 4b show the conversion gains of the IAM-81 and IAM-82 mixers as functions of RF and IF frequencies respectively. The significantly greater gain of the IAM-82 results from the combination of higher device currents (gm's) and load resistors. Some high frequency gain peaking also can be noticed in the IAM-82 mixer, resulting in a steeper frequency roll-off at the high end.

The measured VSWRs for the two mixers ranged from better than 1.5:1 to 2:1 over a 6 GHz RF, LO bandwidth. Very little load sensitivity was observed, with only minor VSWR changes with changes in opposing port impedances or power levels.

Noise Factor Contribution (%)

Source	(LO+IF)+ (LO-IF) bands	IF band	Total contribution
Rb(QR1)	7.7	--	7.7
Rb(QR2)	7.7	--	7.7
RE	5.3	--	5.3
RL2	3.0	--	3.0
Ic(QL1)	3.7	5.0	8.7
Ic(QL2)	3.8	5.1	8.9
Ic(QL3)	3.9	4.9	8.7
Ic(QL4)	3.7	5.2	8.9
Ic(QR1)	3.7	--	3.7
Ic(QR2)	3.4	--	3.4
Rsource	4.9	--	4.9

Table 3. Significant noise sources for the active mixer (IAM01).

Device isolation between ports are summarized in Table 4 with other relevant data for the two mixers. The fact that conversion gain rather than

Very little load sensitivity was observed,

loss prevails contributes significantly to achieving a reduction in RF leakages relative to IF carrier signals. Similarly, small LO power levels required give the mixer a significant advantage in keeping LO power level at opposing ports minimized. The various leakages result primarily from the common mode signal and can be reduced by an additional 15 to 20 dB if differential signals were applied to the RF and LO ports.

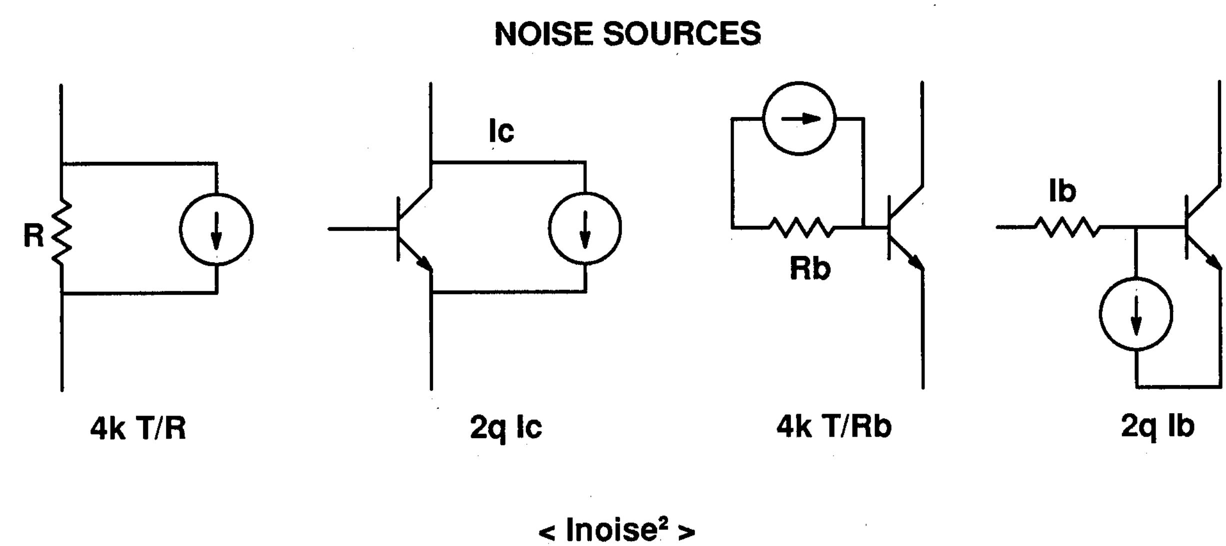

Figure 3. Noise sources for the active bipolar mixer.

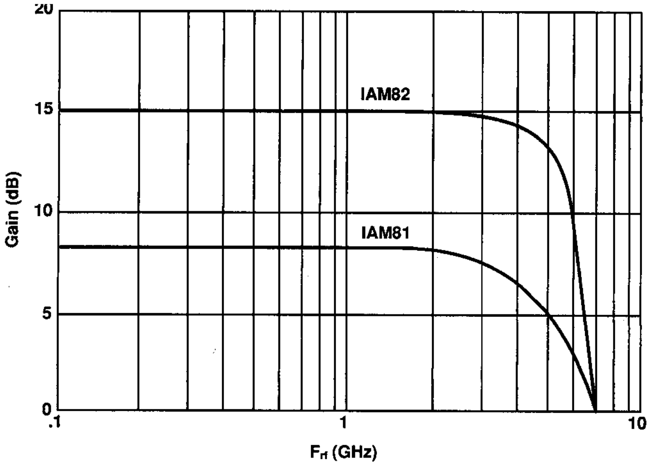

Figure 4a. Conversion gain versus RF frequency; swept RF and LO, IF = 70 MHz. Conversion gain is defined as the ratio of output power at the desired output frequency to the RF input power level, with the LO input at a stated value (- 5dBm for the IAM81, 0 dBm for the IAM82 – which are the LO input levels for which the devices are designed).

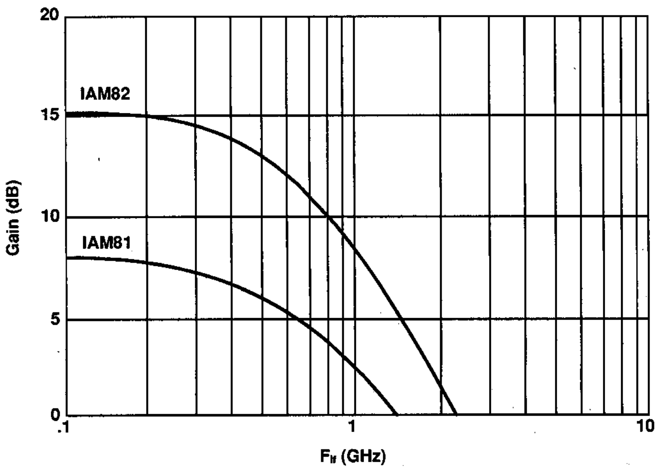

Figure 4b. Conversion Gain versus IF frequency, swept LO, RF = 2GHz.

Various other mixer measurements relating to power, noise figure and dynamic range are summarized in Table 5. Due to the relatively high noise figure and the limited maximum acceptable input power levels these active mixers exhibit a reduced dynamic range in comparison to diode based mixer units. Techniques to improve this limitation, as well as IC-based image rejection techniques will be discussed in the following section.

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Parameter	IAM01	IAM02
R-I isolation	-17 dB	-15 dB
L-I isolation	-20 dB	-20 dB
L-R isolation	-30 dB	-30 dB
RF feedthrough at IF	-25 dBc	-30 dBc
LO Power level	-5 dBm	0 dBm

Table 4. Device isolation between ports.

Parameter	IAM01	IAM02
DC Power	5 V, 12 mA	10 V, 50 mA
LO Power	-5 dBm	0 dBm
Conversion Gain	8 dB	15 dB
SSB Noise Figure	15.5 dB	16 dB
3rd Order Output Intercept Point	+3 dBm	+18 dBm

Table 5. Mixer measurements.

Advanced Active Mixer ICs

The Gilbert cell based active mixer can be used in more complex ICs that provide lower noise operation or provide for image rejection. Noise figure can be reduced by means of an initial low noise amplifier (LNA) stage and filtering to reduce the noise bandwidth as shown in Figure 5. The IC includes an LNA which can be capacitively coupled to an active mixer. This circuit has the following properties:

The Gilbert cell based active mixer can . . . provide lower noise operation or provide for image rejection.

1) The noise figure of the circuit is set predominantly by the LNA. The LNA frequently will also set the RF bandwidth of the mixer.
2) Passive preselect filtering can be done at the amplifier/mixer coupling, and associated losses will introduce negligible noise increases.
3) The active mixer portion must accommodate higher input powers but no longer needs to provide conversion gain. This leads to requirements for higher mixer current levels and greater LO drive powers. Collector resistors (RL, Figure 1) can now be smaller, emitter follower sections can be eliminated, and IF bandwidths will be increased.

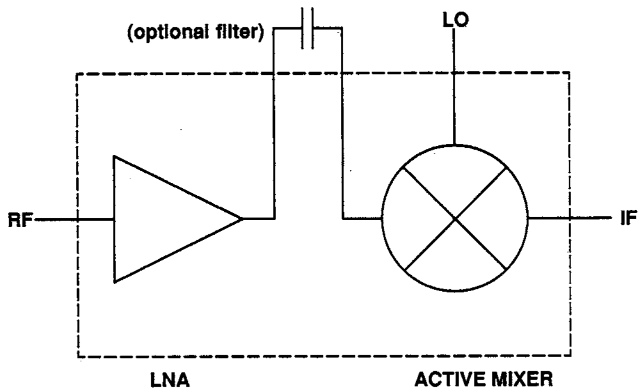

Figure 5. A low noise active mixer IC.

The active mixer IC is also suitable for use in an image rejection mixer system. The general configuration is shown in Figure 6, where an LO signal drives two active mixers with a 90° phase difference. After quadrature combination of the outputs, separate down conversions are applied for the LO-IF and LO + IF input RF frequencies.

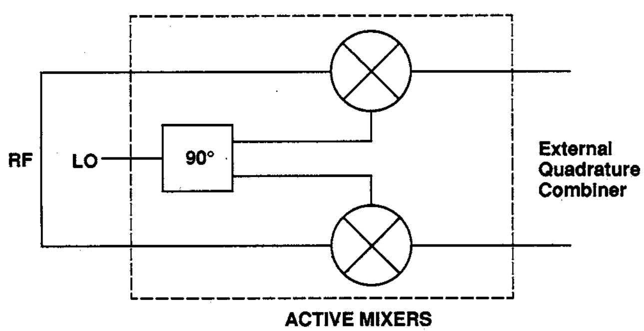

Figure 6. Circuit for an IC image rejecting mixer.

Image rejection depends on symmetrical amplitude and phase transmission through the two mixers and accurate 90° phase differences of the LO drives. The symmetry requirement is well addressed by processing both mixers with the same artwork on a single IC chip. The 90° phase differences can be incorporated in bipolar ICs through the use of digital divider circuits such as master-slave D flip-flops or as direct outputs from sections on a VCO oscillator.

Summary

Silicon bipolar active mixer ICs can provide frequency translation to several GHz. The IC circuit accommodates conversion gain and exceptionally small LO power requirements. Load insensitive performance is achieved and wideband on chip impedance matching is practical. Small package sizes typical of ICs apply, and external power requirements are moderate. Due to higher noise figure and lower input power handling capability, the dynamic range is sacrificed.

More complex ICs using active mixers can provide for lower noise or for image rejection systems. Finally, these ICs can be expected to be practical as basic macrocells in future complex single-receiver-on-a-chip system front ends.

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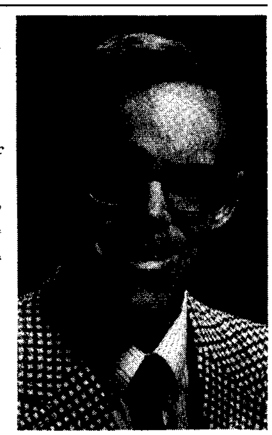

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