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# A 5.0 GHz Bipolar Active Mixer

## Application Note S010

## Introduction

This applications note contrasts the features and performance of an active bipolar Gilbert cell based mixer with conventional passive diode mixers. The note starts with a review of mixer fundamentals, and continues with a brief description of several kinds of diode based mixers. The circuitry used in the Gilbert cell mixer is then developed. Finally, typical performance for an active mixer is given, with the IAM-81028 used as an example.

## Mixer Review

Refer to Figure 1.

A fundamental property of mixers is frequency conversion; this property is put to use in virtually all receivers. For typical operation, an information bearing Radio Frequency (RF) signal operating at a frequency $f_{RF}$ is injected into one port of the mixer, and a Local Oscillator (LO) signal at a frequency Of $f_{LO}$ is injected into a second port. The resulting output Intermediate Frequency (IF) signal is downconverted to a frequency of $f_{RF} - f_{LO}$. Equivalently, a modulating signal operating at a frequency $f_{mod}$ can be injected into the mixer and combined with the LO signal to create an upconverted RF output signal at a frequency of $f_{mod} - f_{LO}$.

Refer to Figure 2.

Frequency conversion results from a multiplication of the RF waveform, $\cos(f_{RF} * t)$, and the LO waveform, $\cos(f_{LO} * t)$. From trigonometry, we have:

$$\cos(f_{RF} * t) \bullet \cos(f_{LO} * t) =$$
$$1/2 \cos((f_{RF} - f_{LO}) * t) \pm$$
$$1/2 \cos((f_{RF} \pm f_{LO}) * t)$$

In this ideal multiplication the output of the mixer only contains signals at the frequencies $f_{RF} - f_{LO}$ and $f_{RF} + f_{LO}$; i.e. the original RF and LO signals are completely suppressed at the IF port. Further, the amplitude of the IF signals is that of the original RF and LO inputs.

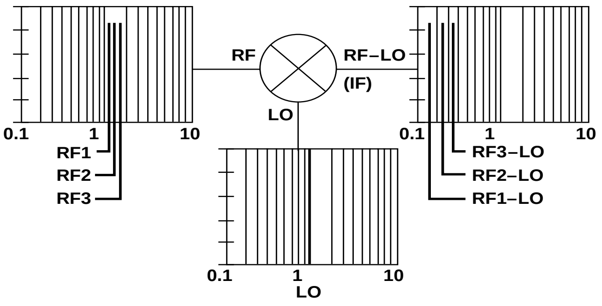


**Figure 1. Recelver/Mixer Fundamentals.**

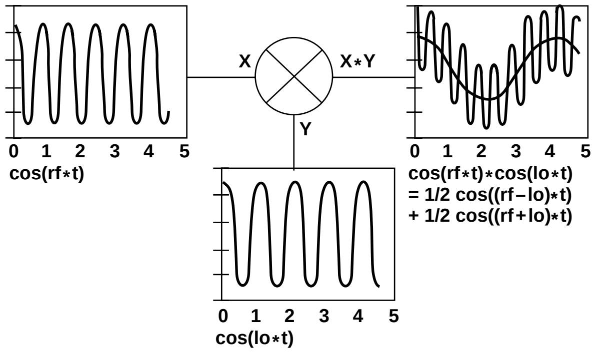


**Figure 2. Multiplier/Mixer Fundamentals.**

## Passive Mixers

Refer to Figure 3.
Common double balanced diode mixers consist of a quad of Schottky barrier diodes and a pair of baluns (balanced to unbalanced transformers). Proper operation depends on a **moderately strong** LO signal (+7 to +23 dBm) controlling the conductivity of the diodes. A square wave LO signal will alternately cause opposite sides of the quad to conduct. Assuming ideal components, the input (RF) signal is consequently multiplied by ±1 at the LO rate.

The **hybrid** construction of these mixers forces them to be of moderate physical size. If the mixer has dimensions comparable to a wavelength at the frequency it is to operate, the summation of internal reflections of different phases will result in ripple in the gain (or loss) versus frequency transfer characteristics.

Assuming 1:1 transformers and ideal diodes, double balanced diode mixers will have input impedances equal to their load impedances. In practical conditions, these impedances are very dependent on the actual operating state of the diode and can be significantly influenced by the loads presented to the ports of the mixer. This **load sensitivity** can cause further reflections and additional re-mixing of various signals.

Refer to Figure 4.
An ideal multiplication of an RF signal by ±1 at the LO rate is shown to scale in both the time and the frequency domains. For a normalized input RF signal of magnitude 1, it can be shown [Grey and Meyer, Analog Integrated Circuits, 2nd Edition, Wiley, 1984] that multiplying by ±1 at the LO rate results in a spectral component at the LO frequency of amplitude $4/\pi$ . The desired IF component in the output spectrum will thus have a magnitude of $2/\pi$, which is 3.9 dB below the level of the input RF signal. Although some higher order frequency terms will also be present in the output spectrum, the double balanced nature of the mixer does suppress the RF and LO signals at the output.

Actual (non-ideal) double balanced diode mixers typically exhibit 6 to 8 dB conversion loss and 20 to 40 dB suppression of the RF and LO signals.

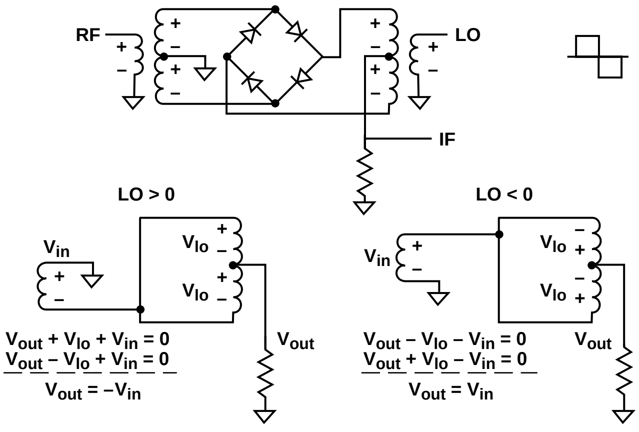


**Figure 3. Double Balanced Diode Mixer.**

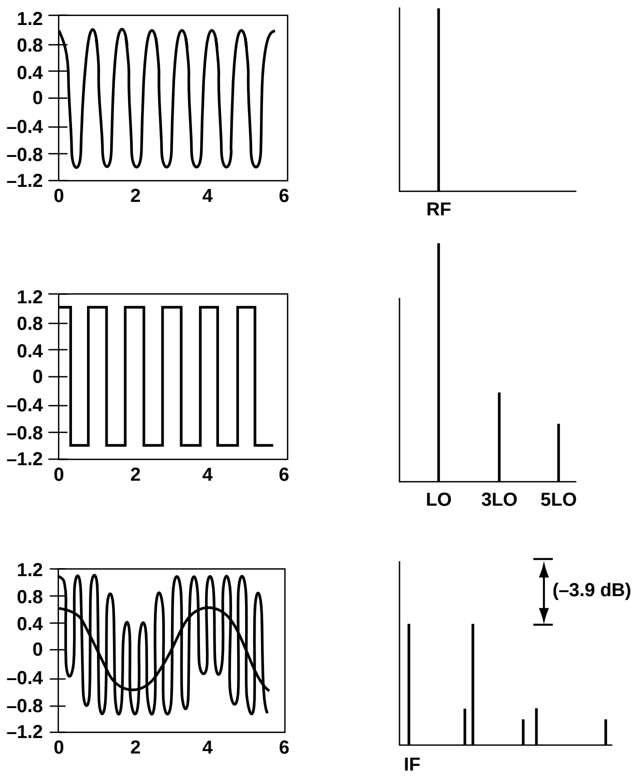


**Figure 4. Double Balanced Mixer Waveforms.**

Refer to Figure 5.
Mixer configurations that suppress either the RF signal or the LO signal, but not both, are said to be single balanced. These topologies usually have the advantage of using fewer components than do double balanced circuits. For the single balanced diode mixer shown, the mixer alternates between a state in which both diodes conduct, and a state in which neither diode conducts. Consequently this mixer multiplies the input RF by ±1,0 at the LO rate. Like the full double balanced diode mixer, this mixer is hybrid in nature and requires moderate LO power to control diode conduction.

Refer to Figure 6.
Ideal multiplication by ±1,0 at the LO rate results in an IF (RF – LO) component 9.9 dB below the input RF level. This follows from the fact that the voltage available when multiplying by ±1,0 is half of that available when multiplying by ±1, hence the IF signal level will be 6 dB lower. Although the LO is fully suppressed, a signal at the RF frequency with the amplitude of the input RF signal will appear in the output spectrum.

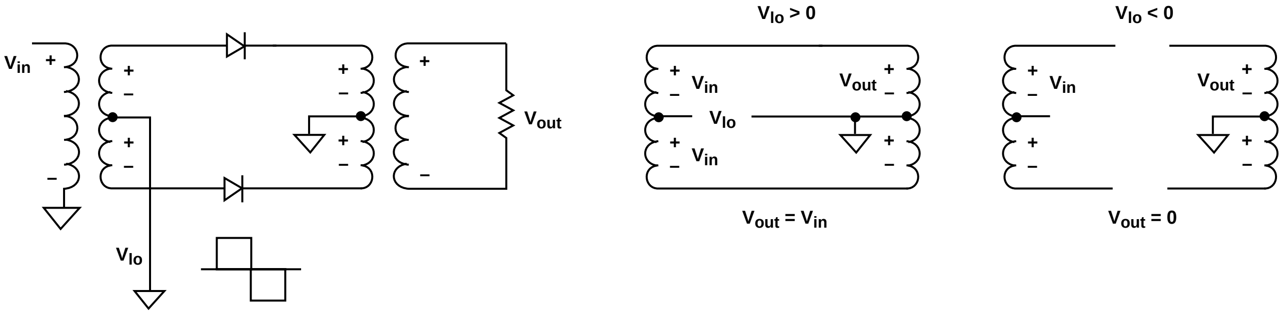


**Figure 5. Single Balanced Diode Mixer.**

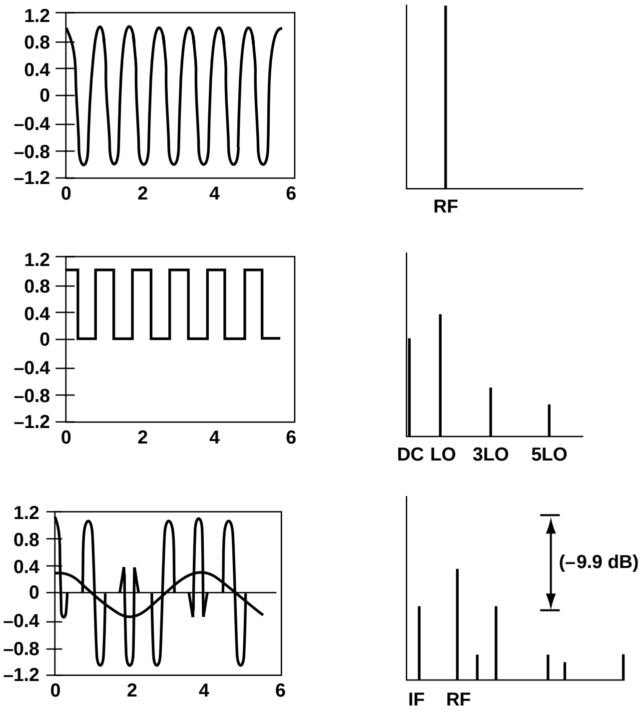


**Figure 6. Single Balanced MIxer Waveforms.**

Refer to Figure 7.

A second single balanced mixer configuration is shown. In this mixer, the LO causes first one diode to conduct, then the other. The resulting output waveform alternates between $V_{LO} \pm V_{in}$ and $V_{LO} - V_{in}$. Thus the output contains the input RF signal multiplied by ±1 as in the double balanced case (i.e. the IF component is 3.9 dB below the input RF level), but also contains the full LO signal that was applied to the mixer. Given the relatively high power requirement placed on the LO in order to switch conduction in the diodes, the LO component in the output spectrum can be very much larger than the desired IF component.

## Active Gilbert Cell Mixer

Refer to Figure 8.

The 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. The RF signal enters one side of the pair while the opposite side is AC grounded through a capacitor. From symmetry, the common mode component has no first order effect on the output voltage. The differential mode component shifts the current between the two branches, and for small signal acts as a standard common emitter amplifier.

The transistors are biased by on-chip current sources in series with their emitters and from on-chip voltage sources through resistors to their bases. The resistors in parallel with the high impedance transistor bases set the input impedance (VSWR) of the device and provide for very wideband load insensitive matching.

Two disadvantages that exist for this configuration are the potential loading of the output voltage and the large DC voltage drop required through the emitter resistors (RE).

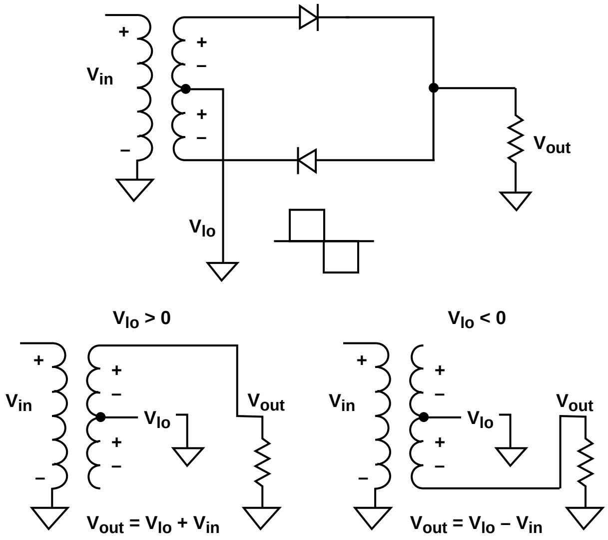


**Figure 7. Two Dlode Mlxer.**

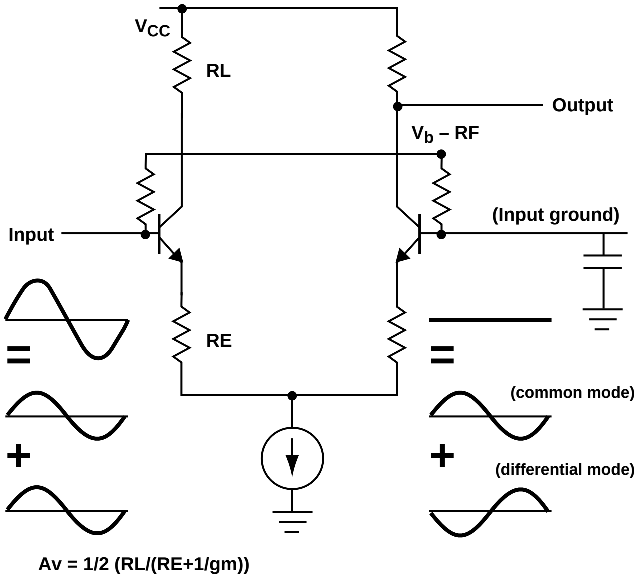


**Figure 8. Emitter Coupled Pair Amplifier.**

Refer to Figure 9.
These disadvantages are overcome by using the illustrated circuit. An emitter follower is used to reduce loading effects at the output port, while a series resistance sets the output impedance. The voltage drop across the emitter resistors is eliminated by eliminating the emitter resistors: by symmetry of common mode and differential mode signals, the two emitter resistors and the single current source of the initial design are replaced by two current sources of amplitude 1/2 and a single emitter to emitter resistance of magnitude 2RE.

Refer to Figure 10.
Four cross-coupled devices are now added to the basic amplifier to multiply the RF signal by ±1 at the LO rate and to achieve the desired double balanced mixer characteristics. The combination of these devices with the emitter coupled pair completes the basic Gilbert cell.

Like the RF input, the LO is injected in single ended fashion with the opposite side 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.

Refer to Figure 11.
To complete the circuit voltage and current sources must be added. Resistor ratioed current sources are used. This chart shows the evolution from a simple current mirror to an $h_{FE}$ insensitive supply with voltage sources for device bases of the LO quad and the RF input transistors.

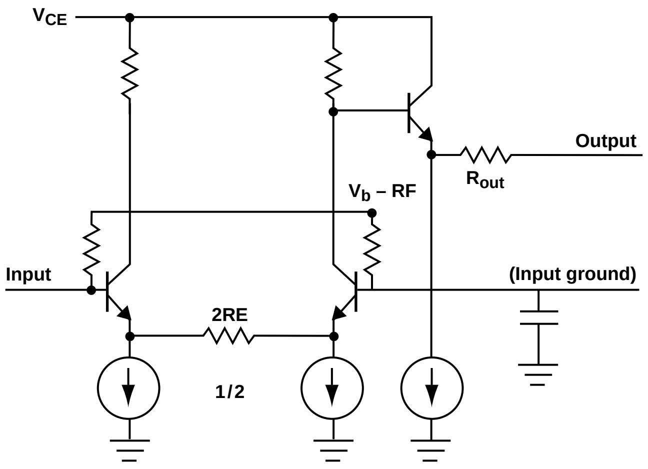


**Figure 9. Modified Emitter Coupled Amplifier.**

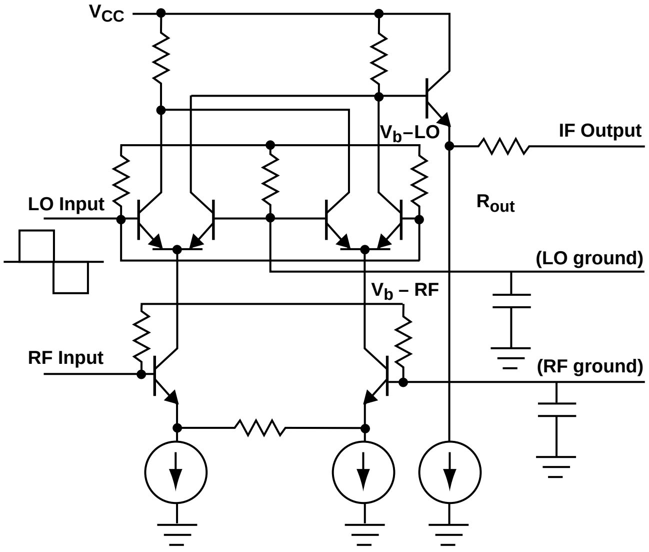


**Figure 10. Bipolar Active MIxer.**

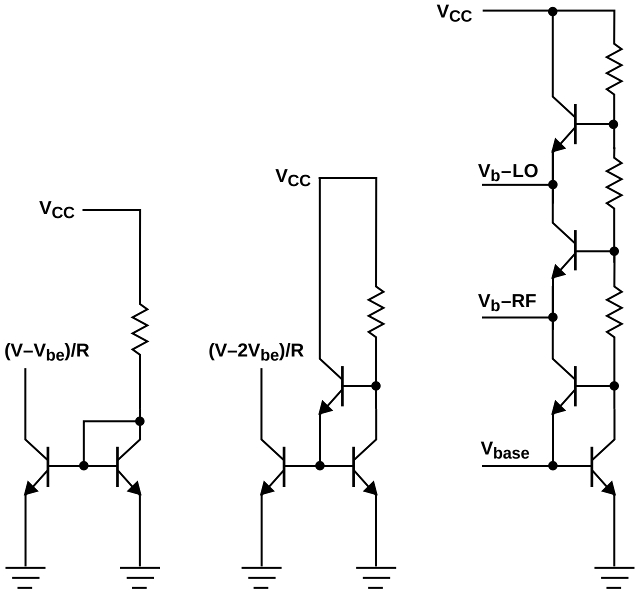


**Figure 11. Internal Bias Supply.**

## Active Mixer Performance

Refer to Figure 12.

A major feature of the Gilbert Cell active mixer is that it has conversion gain, i.e. the output IF signal this mixer produces is larger in magnitude than the input RF signal it receives. This gain arises from the presence of the emitter coupled amplifier in the basic Gilbert Cell, and is in marked contrast to the 6 to 8 dB of conversion loss seen with passive mixers.

The conversion gain performance shown is for the IAM-81028, and is plotted in two ways. To create the first plot, both RF and LO signals are simultaneously swept to give gain versus RF at a fixed IF frequency. For the second plot, the LO signal is fixed and the RF signal is swept to give gain versus IF frequency.

The low end of the mixer’s frequency response is determined by the value of the capacitors used to AC ground the RF and the LO. These capacitors must present a low impedance path to ground at the desired frequencies of operation. Off chip capacitors incorporated in the IAM-81028 provide sufficient grounding for performance down to 50 MHz; connections are provided to allow for the use of an external capacitor to extend this frequency limit still lower.

Refer to Figure 13.

As mentioned above, wideband matching is accomplished by separate resistive circuit elements. This technique results in an excellent match at all ports, and has the additional advantage of making the Gilbert Cell based circuit very insensitive to mismatches or to power levels at adjacent ports. RF, LO, and IF port VSWR’s are plotted here versus frequency.

Refer to Figure 14.

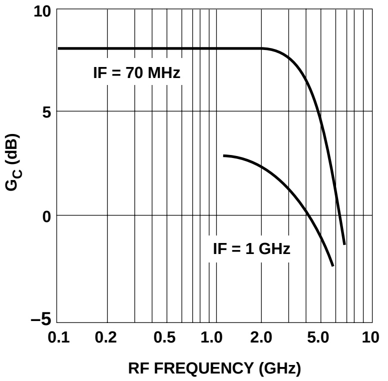
The most important signal leakages in a double balanced mixer are those from the RF port to the IF port and from the LO port to the RF or IF ports. The chart shows signals from the RF port to the IF port. We have:

Conversion Gain =
IF power – RF input power

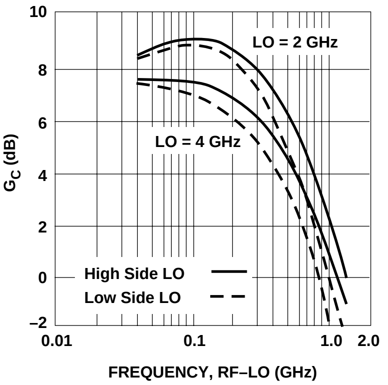
R – I Isolation =
|RF input – RF leakage at IF port|

RF Suppression =
|IF power – RF leakage at IF port|

Typical diode based mixers tend to specify better RF to IF isolation, but actually have comparable system performance. This can be seen as follows. To achieve the same IF signal level as an IAM-81028, a diode mixer with 6 dB conversion loss would have to be followed by an IF amplifier with 14 dB of gain. This amplifier would increase the magnitude of both the desired IF signal and the undesired RF and LO leakage signals; such an amplifier could easily have 7 dB of gain left at the RF frequency. The magnitude of the unwanted RF leakage signal at

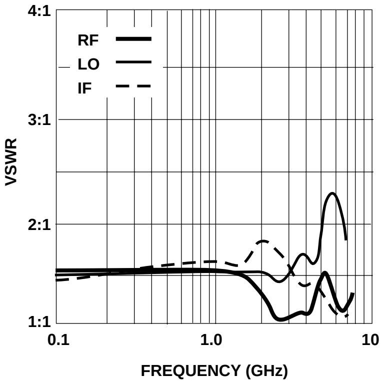


**Typical RF to IF Conversion Gain vs. RF Frequency, $T_A$ = 25°C (Low Side LO).**



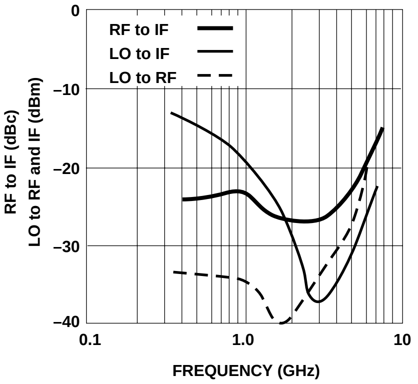
**RF to IF Conversion Gain vs. IF Frequency.**

**Figure12. Conversion Gain.**



**RF, LO and IF Port VSWR vs. Frequency.**

**Figure 13. Load Insensitive VSWR.**



**RF Feedthrough Relative to IF Carrier, dBm LO to RF and IF Leakage vs. Frequency.**

**Figure 14. Isolations.**

the output of the IF amplifier will increase from the level found at the output of the mixer by the gain of the IF amplifier at the RF frequency. Thus, for a cascade of a mixer plus an IF amplifier,

RF Suppression =
|IF power – RF leakage at IF
– gain of IF amp @ RF frequency|.

The combination of a diode mixer specifying an R – I isolation of -30 dBc followed by an IF amplifier with 7 dB gain at RF would have an effective system R – I isolation (output of chain to input to chain) of only -23 dBc. The -25 dBc isolation of the IAM-81028 compares favorably to this number.

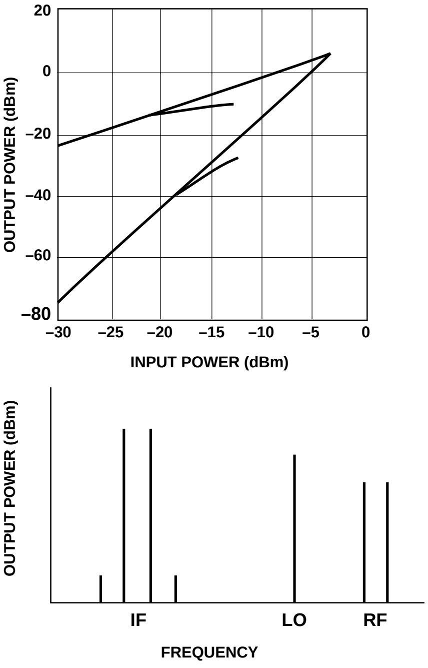
Diode mixers may specify better LO – RF or LO – IF isolations, but their significantly higher LO power levels (+7 to +23 dBm) often result in higher absolute power levels at opposing ports, and consequent poorer actual system performance.

The lower level LO power requirement of the active mixer also gives it a significant “headstart” in keeping single tone intermodulation products (spurs) minimized.

These sometimes confusing details of how the specifications are made reduce to a simple fact: Gilbert cell mixers and diode based mixers yield essentially equivalent system level spectral purity.

Refer to Figure 15.
A pair of input signals will produce both a pair of output signals (IF: RF1 – LO, RF2 – LO), and a pair of adjacent third order intermodulation products (IM3: 2 ∗ RF1 – RF2 – LO, 2 ∗ RF2 – RF1 – LO). Strengths of these signals are plotted versus the RF input power of each signal, and extrapolated lines determine the third order intercept point (IP3). This point can be defined by comparing the distortion products to either the RF input power level (input IP3), or to the output IF power level (output IP3).

Since IP3 is a measure of distortion, it is more a function of the periphery (electrical “size”) of the devices used to make the circuit than it is of the topology. In general relatively small devices are used in active mixers to minimize power consumption, since these devices require bias current. It is often possible to improve the IP3 of an active mixer by several dB by increasing the bias level (always staying within the recommended bias range of the manufacturer to insure reliability, of course).

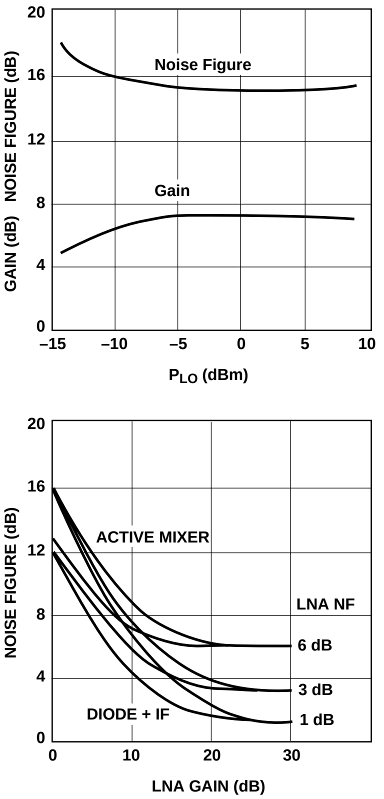


IAM-81018 at 5 V, 12 mA, –5 dBm LO

**Figure 15. Third Order Intercept Point.**

Refer to Figure 16.
The two parameters effected most by variations in LO power level are Noise Figure and Conversion Gain. Although an LO power level of -5 dBm gives optimal gain results, only slight degradations occur when the LO power decreases to -10 dBm. Decreasing the LO drive improves mixer distortion when the device is used at lower frequencies (especially below 1 GHz). A decrease of approximately 10 dB in applied LO power can yield 5 dB or more improvement in spurs. The maximum LO power level that the IAM-81028 can withstand without risk of damaging junctions is +14 dBm.

The relatively high noise contributions from the shot noise originat-



CASCADE NOISE FIGURE

IAM-81018 at 5 V, 12 mA

**Figure 16. Noise Figure.**

ing in the LO quad at the IF, RF and image frequencies, and from the noise originating in the RF and image bands of both devices of the emitter coupled pair prevent the Gilbert cell based mixer from being a “low noise” type of device. The resulting single sideband noise figure is on the order of 15 dB; fair comparisons with diode based mixers would require the latter to include noise effects from an IF amplifier required to produce equal conversion gain.

The lower graph shows the effect of adding a low noise preamplifier to an active bipolar mixer, and compares this to the noise performance of a conventional diode mixer/IF amplifier combination. This plot assumes that the image frequency is filtered prior to the mixer. The results show that the addition of a 20 dB gain low noise preamplifier results in very similar system noise figures for the two mixers.

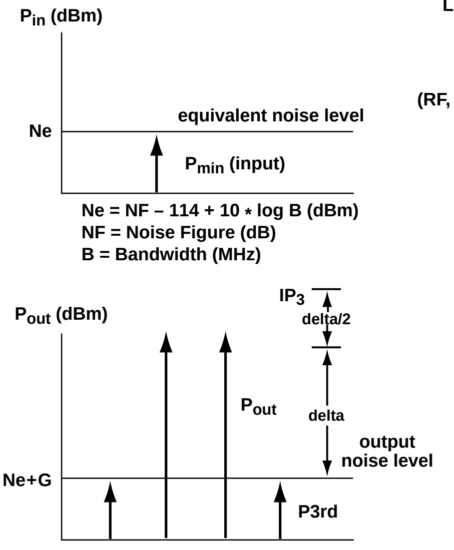
Refer to Figure 17.
A drawback to using an LNA with the active mixer to obtain lower system noise figure is the accompanying reduction in system dynamic range. Dynamic range is a measure of the acceptable maximum to minimum input signal range over which a system or component will operate. It can be calculated from:

Dynamic Range =
Maximum acceptable output power [dBm] – Gain [dB]
– Minimum acceptable input power [dBm]

Several specific definitions exist; the accompanying chart shows a common conservative definition.

If the end use for the mixer is in a system requiring both very low noise figure and wide dynamic range, the Gilbert cell based mixer is probably not the appropriate component. We have shown above how to compensate for the noise figure of the active mixer in systems where dynamic range is not critical. Many systems have down or up conversions for which the noise figure of the mixer is not critical (e.g. the second downconversion of a typical receiver), and for these kinds of applications the active mixer possesses all the advantages discussed above.

Refer to Figure 18.
The monolithic active mixer is packaged in a very small 180 mil square package. Although the mixer topology is full differential, capacitors are used internal to the package to AC ground the RF and LO ports and create a single-ended structure. If RF or LO frequencies below 50 MHz are required, additional AC grounding capacitors should be attached external to the package to the leads labeled “optional RF ground” and/or “optional LO ground”. (Note: the low frequency response of the output IF signal is limited only by the value of the output blocking capacitor.)



Ne = NF – 114 + 10 * log B (dBm)
NF = Noise Figure (dB)
B = Bandwidth (MHz)

$IP_3$ = 3rd Order Intercept Point (dBm)
$P_{out}$ = Pmax(input) + G (dB)
P3rd = Output Noise Level = Ne + G

Dynamic Range = Pmax(input) – Pmin(input)
= 2/3 ($IP_3$ – G – Ne)

**Figure 17. Dynamic Range.**

A typical circuit block diagram for use of the mixer is shown. External circuit elements consist of 50 Ω lines and blocking capacitors at the three mixer ports. Blocking capacitors are needed at all three ports to prevent the DC components of externally applied signals from shifting the bias levels achieved by on-chip circuitry. Unlike some GaAs based active mixers, no user supplied baluns are necessary. A DC power supply and a DC ground are also needed.

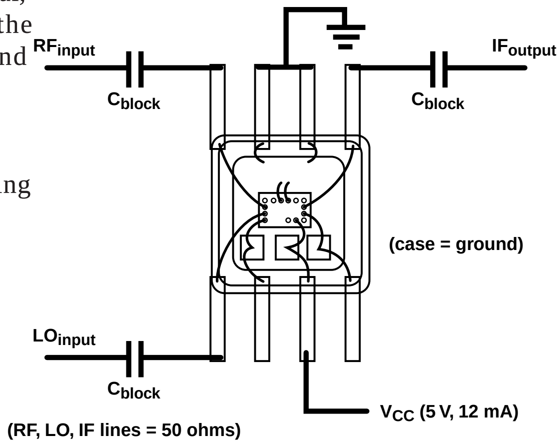


**Figure 18. Circuit Implementation.**

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