I&Q Mixers, Image Reject Down-Conversion & Single Sideband (SSB) Up-Conversion

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Introduction

In superheterodyne receivers and transmitters, frequency mixers perform the vital function of frequency translation. In down-converters, the incoming radio frequency (RF) signal is down-converted to an intermediate frequency (IF) to facilitate signal processing. Mixers are generally wideband devices, which convert unwanted image frequencies along with desired content to the same IF frequency, which is undesirable. Frequency mixers are often combined with quadrature hybrids to create image reject mixers (IRM), which we will explain herein.

In up-converter applications, the mixer combines the IF signal with the local oscillator signal (LO) to generate sum and difference frequency signals (LO+/-IF) at the output. Given the wideband nature of mixers, both mixing products will have similar conversion loss. In single side band (SSB) applications, only one of the upconverted signals (LO-IF or LO+IF) is needed, and the other needs to be filtered out to meet system requirements and avoid unwanted effects. When the frequency of the IF signal is low compared to that of the LO signal, a sharp bandpass filter is required, which may be impractical in many cases due to size constraints. Single side band up-converters come to the rescue.

Both IRM and SSB mixers use the same circuit configuration. They differ only with respect to which ports are used for which signals. The key building block for both IRM and SSB mixers is the I&Q mixer. This

90º splitter and a 0º splitter/combine

(hence the “I&Q” argot). One can also build IRM and SSB mixers by adding an external 90º hybrid to a garden variety frequency mixer.

Much of the complexity in optimizing performance for IRMs and SSB mixers comes from the impedance mismatches and parasitics associated with integrating splitters, hybrids and mixers. The higher the frequency, the more complex the integration task. To simplify this task for system designers, Mini-Circuits has developed an ultra-wideband I&Q mixer in die form, SMIQ-653H-D+ covering the 18 to 65 GHz frequency range on the RF and LO ports and DC to 20 GHz on the IF port as a single chip. As both mixers are realized in a single chip, they provide near identical performance (conversion loss and translation phase). Further integrating these mixers with an on-chip LO 90º hybrid and RF 0º splitter/combiner results in a small chip with tiny interconnecting lines and minimal associated parasitics.

This article will explain the fundamentals of how I&Q mixers function in both image reject down-conversion and single sideband up-conversion applications.

Frequency Mixer Fundamentals

Before we get into the details of IRM and SSB mixers, let’s review some mixer basics. Figure 1 shows a simplified schematic of double balanced mixer. This circuit configuration is used in many Mini-Circuits mixers from the SRA-1+, one of the company’s first products, to the more recent MDB-653H-D+ MMIC mixer which operates from 20 to 65 GHz. Every double balanced mixer has three ports: Local Oscillator (L or LO), Radio Frequency (R or RF) and Intermediate frequency (I or IF).

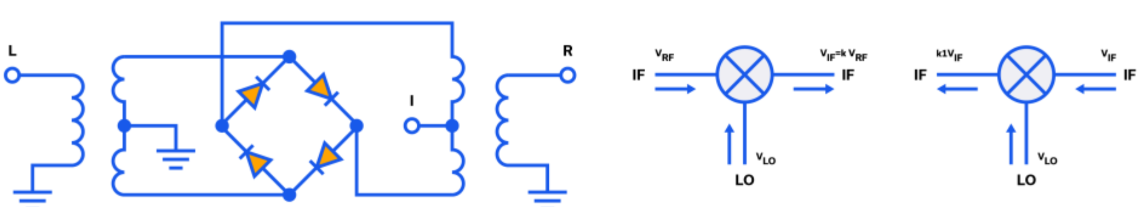

Figure 1: Simplified schematic (left) and symbol for a double balanced mixer used as a down-converter (middle) and an up-converter (right).

The Mixer as a Down-Converter

In today’s world, the frequency spect
unwanted image signal present. Emis

often are at the image frequency for a given band of interest. This content can corrupt the desired IF.

In down-converter applications, the RF port is used as the signal input and the IF port is the output so that:

$f_{IF}=f_{RF2}-f_{LO}$ or $f_{LO}-f_{RF1}$

Where f_{IF}, f_{RF1}/f_{RF2}, and f_{LO} are IF, RF and LO frequencies, respectively. If f_{RF1} is the desired signal, f_{RF2} is the image (or vice versa), as both signal and image are translated into same IF frequency by the mixer.

If V_{RF1} is the amplitude of the RF1 signal, the amplitude of the IF signal $V_{IF}=k * V_{RF1}$, where k is less than one, proportional to the mixer's conversion loss and expressed in logarithmic form (see Figure 1b).

Figure 2 represents LO, RF and IF signals in the frequency domain.

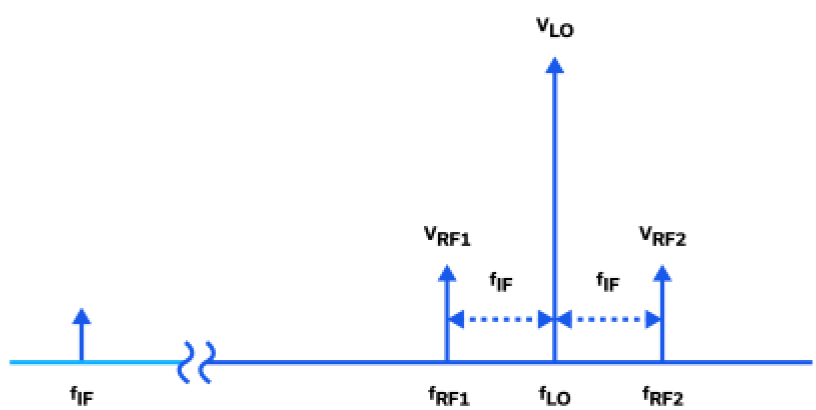

Figure 2: Spectral representation of a mixer output in a down-converter application.

The desired RF signal and its image are each spaced from the LO frequency by a distance equivalent to the IF frequency value as shown in Figure 2. If RF1 is the desired signal, RF2 is the image, and vice versa. Because mixers are inherently wideband and exhibit similar conversion loss for both the desired RF and image signals, both are converted into the same IF frequency

output. Sharp bandpass filters are th

the image signal. Note, however, that

between the RF signal and the image

filters are typically bulky, expensive and have high passband insertion loss, making them impractical for most designs. I&Q mixers provide a practical alternative to address this problem using phase cancellation as we will see.

Mixer as an Up-Converter

In up-converter applications, the IF port of the mixer is used as the signal input, and the RF port as the output. As mentioned previously, the mixer produces RF outputs of both LO + IF and LO − IF frequencies. These are referred to as the upper and lower sidebands, respectively.

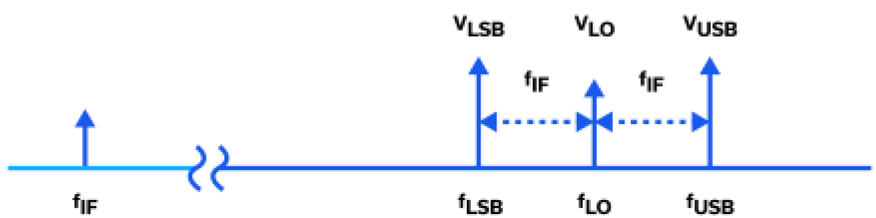

Figure 3: Spectral representation of mixer output in an up-converter application.

$f_{USB} = f_{LO} + f_{IF}$ and $f_{LSB} = f_{LO} - f_{IF}$

Where f_{USB} is the upper sideband signal, f_{LSB} is the lower sideband signal. In this case, let the upper sideband signal be the desired signal. A bandpass filter with sharp selectivity is again required to remove the unwanted signal, this time at the mixer output. The distance of the upper and lower sideband signals from the LO frequency is exactly the IF frequency. The lower the IF frequency, the closer the two mixer outputs are to each other, and the sharper the required filter response. Again, for systems with low IF frequency, using a discrete filter in series with the mixer adds cost, size and insertion loss to the system. If the LO is tunable, the complexity of filtering increases many fold.

SSB mixers overcome these inadequa
cancellation, and I&Q mixers are the

I&Q Mixers

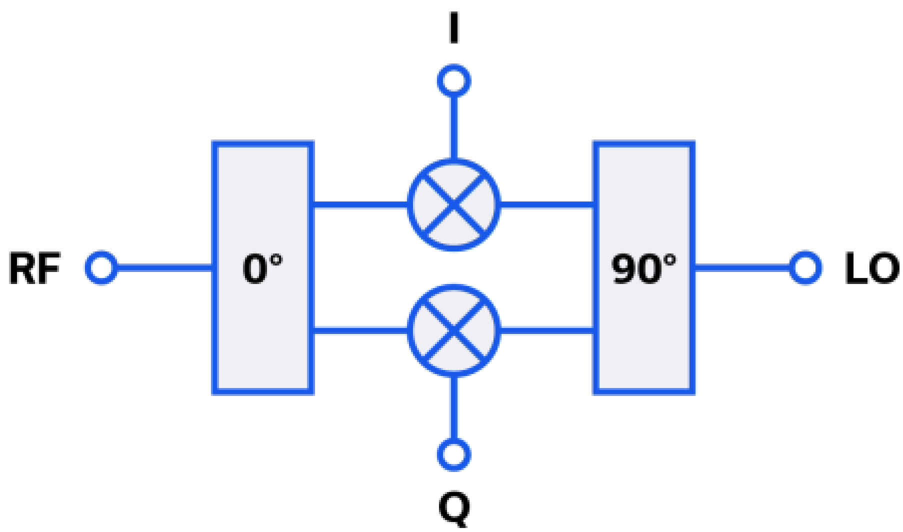

Figure 4: Simplified schematic of an I&Q mixer.

An I&Q mixer is a pair of identical mixers, a 90º hybrid and a 0º splitter connected as shown in Figure 4. Instead of one IF port as in a conventional mixer, the I&Q mixer has two IF ports, one in phase and one in quadrature phase. In theory, the LO and RF ports can be interchanged. However, 90^{0} hybrids typically have greater amplitude unbalance than 0^{0} splitters. Mixers are forgiving of small LO power variations, so connecting the 90^{0} splitter to the LO ports minimizes the effect of its unequal output signals.

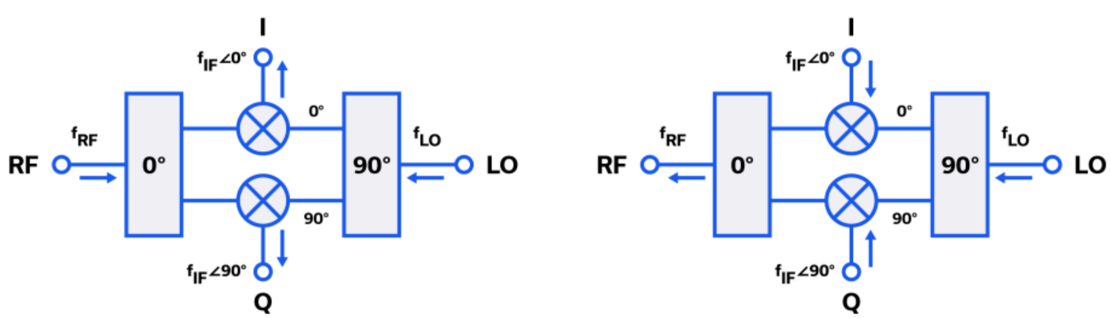

Figure 5: I&Q mixer port configurations and signal flow in down-converter (left) and up-converter (right) applications.

Figure 5 shows I&Q mixer as a down converter (Fig 5a) and as an upconverter (Figure 5b). In the case of down-conversion,
outputs 90˚ out of phase from each c
true. So far so good. Let us see how

Simplified math will be used in what follows to show the benefits of this device in image reject and single sideband applications.

Image Reject Mixers

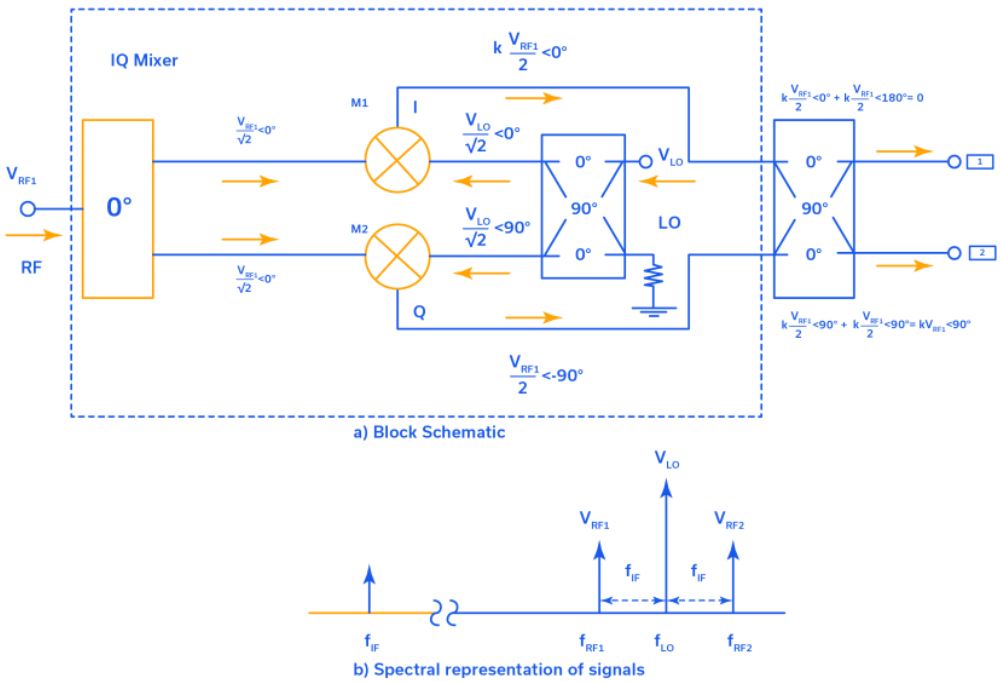

Figure 6: Image reject mixer schematic and spectral representation for desired RF signal. (RF1)

Figure 6 shows an image reject mixer (IRM), which consists of an I&Q mixer and an external 90º hybrid operating at the IF frequency. It also shows the various signal paths through the circuit. Here's a brief play-by-play.

1. The input RF signal, RF1 is split into two, in-phase, equal amplitude signals at the output of the 0º power splitter.
2. LO signal is split in the internal 90º hybrid of the I&Q mixer into two signals of equal amplitude but differing in phase by 90º.
3. Incoming RF signal is converted to an IF signal in mixers on both paths. The two resulting IF signals are equal in ampl
on bottom mixer (M2) has a 90º phas
(M1).

4. These two IF signals at the I&Q mixer output are applied to an external 90º hybrid. At the output of the external 90º hybrid, Port 1 has no signal due to phase cancellation and Port 2 has the full output IF as if it were a single mixer.

But what happens to the image frequency signal, RF2, in the same image reject mixer?

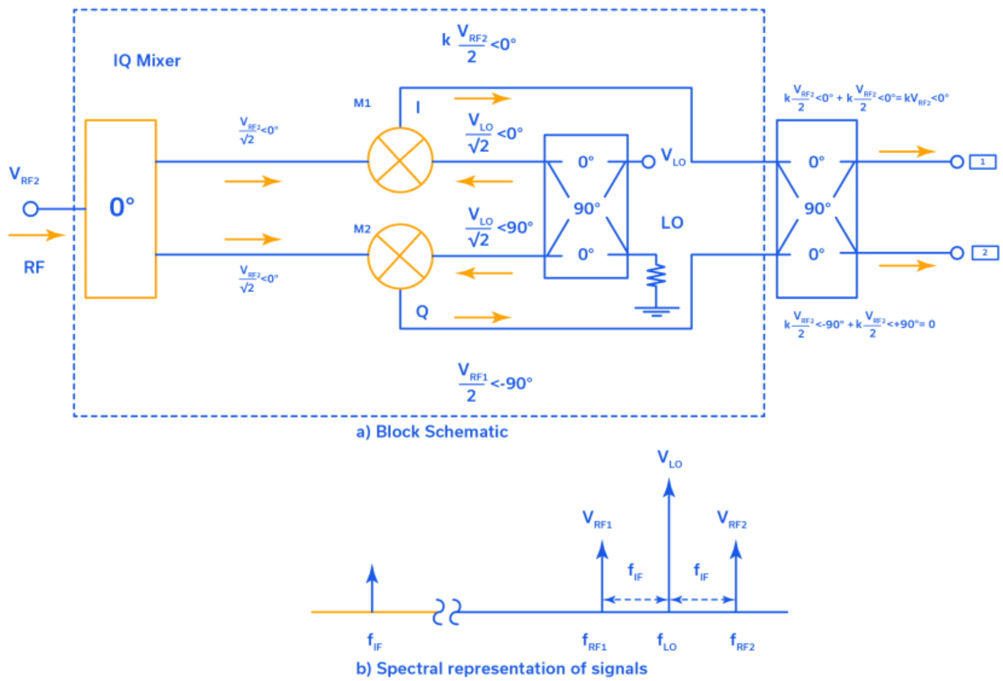

Figure 7: Image reject mixer schematic and spectral representation for unwanted image signal (RF2)

1. The input image signal RF2 is split into two in-phase, equal amplitude signals at the output of the 0º power splitter, just like the desired RF signal, RF1.
2. The LO signal is split into two signals of equal amplitude but differing in phase by 90º in the internal 90º hybrid, again, just as in Figure 6.
3. The incoming Image signal is converted to an IF signal at both mixers, each equal in amplitude but differing in phase by -90º (instead of +90º for RF1).
4. These two IF signals at the I&Q output are applied to an external 90º hybrid. At the output of the external hybrid, Port 2 h
has the full output IF as if it were a si

From Figure 6, we can see that desired IF signal due to RF1 goes to Port 2, and from Figure 7, we can see that undesired IF signal from the image goes to Port 1. This allows the designer to terminate the undesired signal at Port 1 of the external 90º hybrid into 50Ω, and keep the desired IF signal at Port 2.

Effect of Amplitude and Phase Unbalance on Image Rejection

In a practical world, things are never perfect. Mixer conversion loss can be slightly different from one mixer to another, and so can conversion phase. Power splitters (0º and 90º) also have inherent amplitude and phase unbalance. The cascaded effect these imperfections can be stated as Amplitude Unbalance A(dB) and Phase Unbalance (Θº). The effect of A and Θ on image rejection can be computed [1] as follows:

$$Image\ Rejection\ (dB) = -10\log\left(\frac{1+A^2-2A\cos\theta}{1+A^2+2A\cos(\theta)}\right)$$

$$Where\quad A = 10^{-\left(\frac{A(dB)}{20}\right)}$$

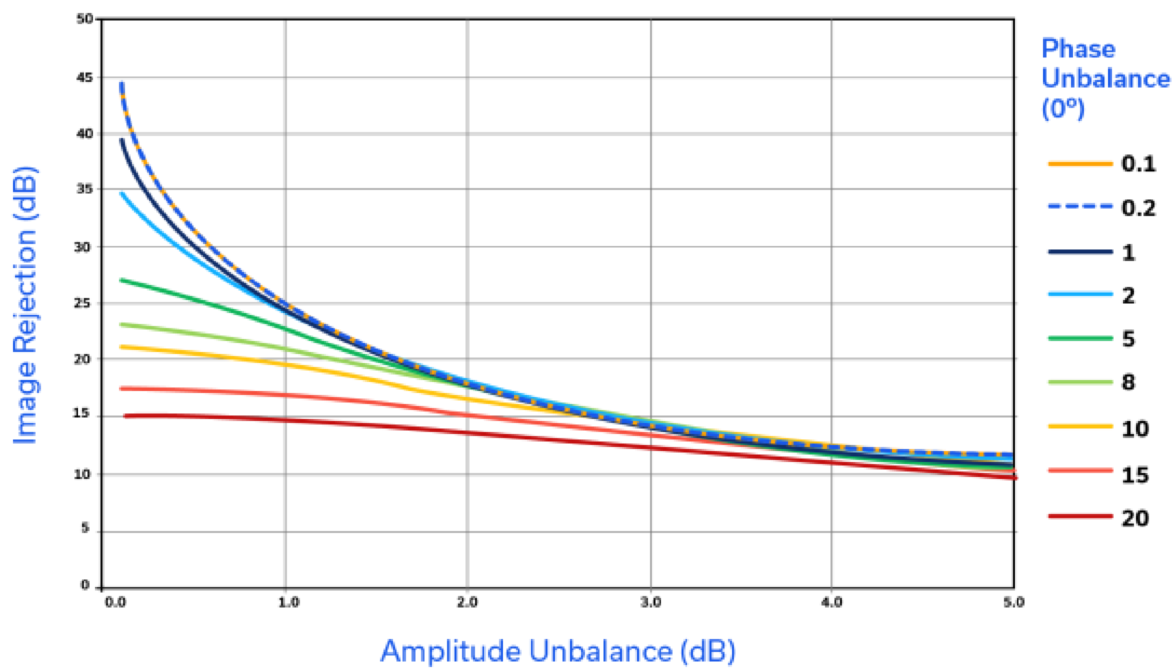

Figure 8: Image rejection vs. amplitude and phase unbalance.

From the graph in Figure 8, we can se[...]
unbalance, which are easily achieved

Figure 9 shows the image rejection measured in SMIQ-65H-D+ at an IF frequency of 200 MHz, which is typically 20 dB over most of the band, and better than 25 dB typically over 40 to 52 GHz.

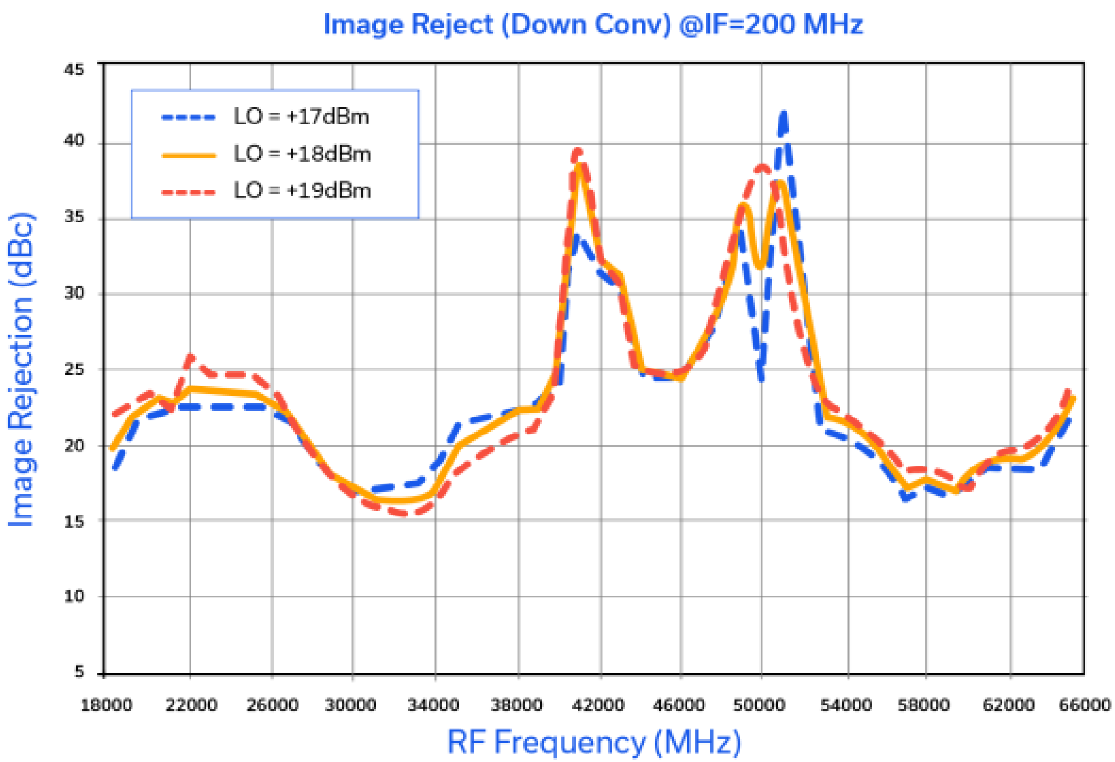

Figure 9: Measured image rejection of SMIQ-653H-D+.

This demonstrates outstanding performance in IRM applications over such a wideband, which is nearly impossible to realize through an assembly of discrete components.

Single Sideband (SSB) Mixers

In single sideband (SSB) mixer applications, I&Q mixers also play a pivotal role. The block diagram of an SSB mixer is same as that of an IRM mixer, except the IF signal is applied to external 90º splitter and the lower sideband (LSB) and upper sideband (USB) signals are extracted from the RF port. SSB mixers have been a mainstay of RF system design for some time[2] but still find extensive use in transmitters.

Lower Sideband (LSB) SSB Mixer

Refer to the block diagram in Figure 1

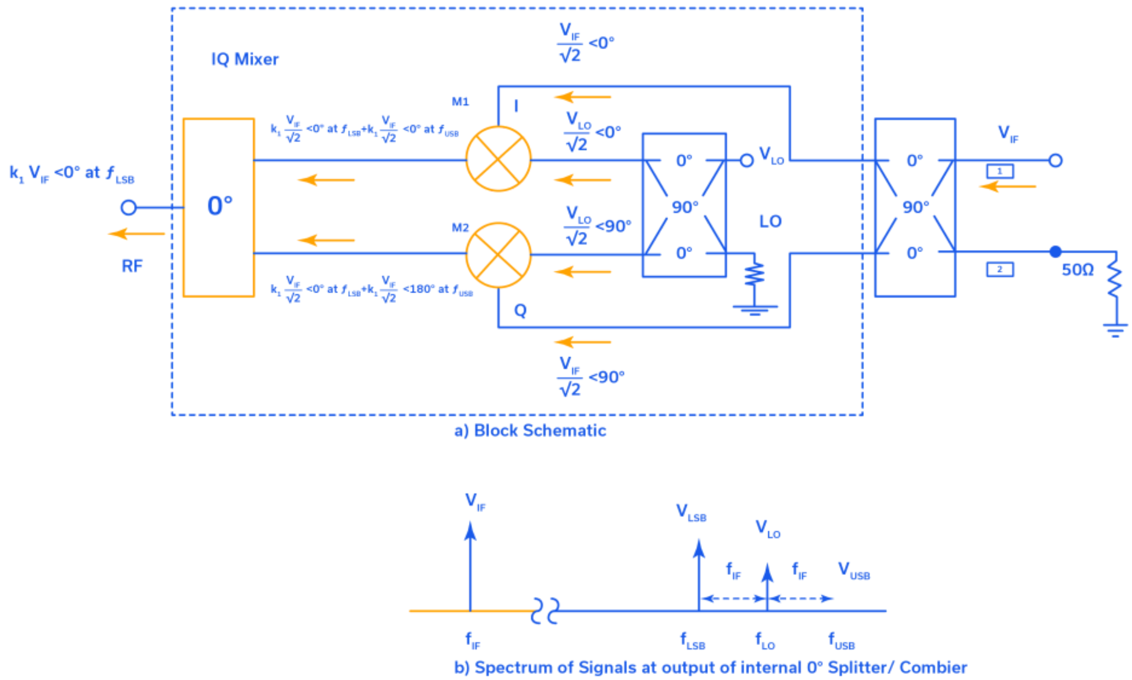

Figure 10: SSB Mixer with LSB output.

1. IF signal is applied to Port 1 of the external 90º hybrid and split into signals of equal-amplitude, offset in phase by 90˚.
2. LO signal is split into two equal-amplitude signals differing in phase by 90º in the internal 90º hybrid of IQ mixer.
3. Incoming IF signal is converted to LSB and USB signals equal in amplitude at mixers M1 and M2. LSB signals are in-phase and USB signals are 90˚ out of phase.
4. Both signals are applied to an internal 0º splitter/combiner. LSB signals add up and appear at the output at full power; USB signals are terminated in the isolation resistor of the internal 0º splitter/combiner.

Upper Sideband (USB) Mixers

Refer to the block diagram in Figure 11:

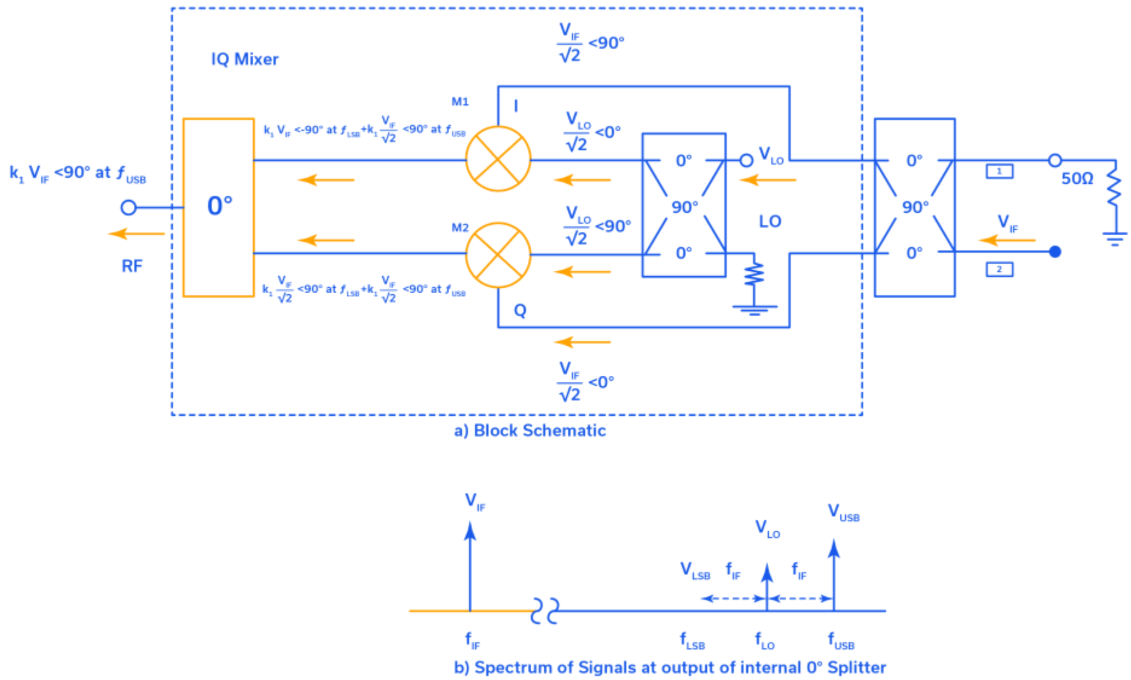

Figure 11: SSB mixer with USB output.

1. IF signal is applied to Port 2 (instead of Port 1 as in LSB operation) of the external 90º hybrid and split into two equal-amplitude signals, one in phase and the other in quadrature phase.
2. LO signal is split into two equal-amplitude signals differing in phase by 90º in the internal 90º hybrid of the IQ mixer.
3. Incoming IF signal is converted to LSB and USB signals of equal amplitude at mixers M1 and M2. LSB signals are out of phase and USB signals are in-phase (relative to each other).
4. These two the signals are applied to an internal 0º splitter/combiner. USB signals add up and appear at the output and LSB signals get terminated in the isolation resistor of the internal 0º splitter/combiner.

In summary, in SSB mixer operation, the application of IF signal at Port 1 results in LSB signal at the output, and the application of IF signal at Port 2 results in USB signal at output. It's as simple as that. Note th
LO-RF isolation of the IQ mixer as sh

Conclusion

I&Q mixers simplify the task of building of IRM and SSB mixers by integrating elements to suppress unwanted mixing products through phase cancellation instead of filtering. Mini-Circuits has offered I&Q mixers for a variety of applications for many years, both as catalog models and custom designs for special requirements. The recently introduced SMIQ-65H-D+ MMIC I&Q mixer, operating from 18 to 65 GHz in Die form measuring 2.67 x 1.9 mm to enable wideband applications and integration into customer chip and wire hybrid assemblies. This article explains the principle of operation of IRM and SSB mixers to enable customer usage of SMIQ mixers in such applications.

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