Termination Insensitive Mixers

By Howard Hausman
President/CEO, MITEQ, Inc.
100 Davids Drive
Hauppauge, NY 11788
hhausman@miteq.com

Abstract

Microwave mixers are non-linear devices that are used to translate one segment of the frequency spectrum to another portion of the frequency spectrum without distorting the signals in the respective segment. Undistorted frequency translation, a key factor in designing most complex microwave systems, has improved over the years with the advent of balanced, double balanced, and triple balanced mixers but is still elusive because they do not adequately address the mixer as a matched building block in the system design. This paper describes a mixer configuration that not only utilizes the most advanced techniques of linear frequency translation but in addition improves the VSWR on all signal ports to enhance the predictability and performance in an actual system environment. A theoretical analysis of this technique is presented along with actual data verifying the expected improvements.

Introduction

The purpose of a mixer in microwave systems is to translate information from one segment of the frequency spectrum to another segment of the frequency spectrum without distorting the information contained in the frequency band of interest. Mathematically this translation can occur whenever two carriers are imposed on a non-linear device. When one carrier is a Continuous Wave (CW) Local Oscillator (LO) and the other carrier contains information, i.e. the Radio Frequency (RF) signal, the information will move to a different portion of the frequency spectrum determined by the sum and difference carrier frequencies of the RF and LO signals. Although this is theoretically very simple, the practical implementation is one of the most complex functions in microwave engineering. Making one signal (LO) large enough to make the non-linear device a high speed switching circuit, limits the problem to keeping the small signal, RF (the signal containing the information, i.e. modulation) in a quasi linear range, i.e. an acceptable amount of distortion. Assuming this is accomplished, the output is still rich with mixing products i.e. harmonic multiples of each signal added and subtracted in an infinite number of combinations, each at a frequency M x RF ± N x LO, where M and N are integers from zero to infinity, and RF and LO are the frequencies of the information signal and the high level local oscillator respectively. The mixing products are interference (spurious) signals that can seriously degrade the system performance.

The component performance, e.g. gain, gain variation, expected spurious degradation (M & N products and cross products), etc. is measured and specified by the mixer manufacturer with perfectly matched wide band resistive source and load impedances. This is not unfair considering the fact that selecting any other interface would make the data unverifiable. In addition, the manufacturer specifies the source and load VSWR at a defined operating signal level because the mixer is a non-linear device and therefore subject to source and load impedances varying with signal level. Mixer performance can be significantly altered by the source and load impedances of the device and seen by the device. This holds true not only for in-band impedances but also out-of-band impedances considering the effects of reflected mixing products (M x RF ± N x LO, where M and N are any integer from zero to infinity) occurring over a very broad frequency spectrum. Since manufacturer's measurements are made with perfectly matched wideband loads considerable performance degradation in terms of spurious interference, gain ripple, non-linear effects, etc. can occur in real systems. These performance degradations are very difficult to calculate, quantify, or compensate. The spurious signal problem is enhanced when a filter is used to drive or receive the mixer signals because a filter reflects out-of-band signals reintroducing them into the non-linear process, possibly increasing the spurious levels derived from M x N mixing products. A suggested solution to this problem is a Termination Insensitive Mixer.

Basic Mixer Function

A Mixer as a Non-Linear Device

A mixer is a device that combines two signals in a non-linear function, see figure 1. Mathematically this results in a translation of frequencies across a predefined spectrum. In its simplest form assume two signals are summed together and passed through a non-linear device that is described by a Taylor series, i.e.

$$F(t) = a_0 + a_1X(t) + a_2X(t)^2 + a_3X(t)^3 + \ldots + a_NX(t)^N$$

The Taylor series contains an infinite number of terms, each term designated by N, where N is an integer between zero and infinity and a respective coefficient a_N.

X(t) are the two signals as a function of time (t) summed together and raised to the power N. In most systems, one signal contains the information (S(t)) and the other signal is a CW local oscillator (LO(t)) used to translate the information spectrum. For simplicity in analysis we assume both signals are CW signals with amplitudes normalized to unity, where:

$S(t) = \cos(2\pi F_{RF}t)$ and $LO(t) = \cos(2\pi F_{LO}t)$

F_{RF} and F_{LO} are the frequencies of the two signals designated as the RF frequency, the signal containing information and the Local oscillator (LO) frequency, the difference between the original frequency of the RF carrier and the final frequency of the carrier designated F_{IF}, the Intermediate Frequency (IF) frequency.

$X(t) = S(t) + LO(t) = \cos(2\pi F_{RF}t) + \cos(2\pi F_{LO}t)$

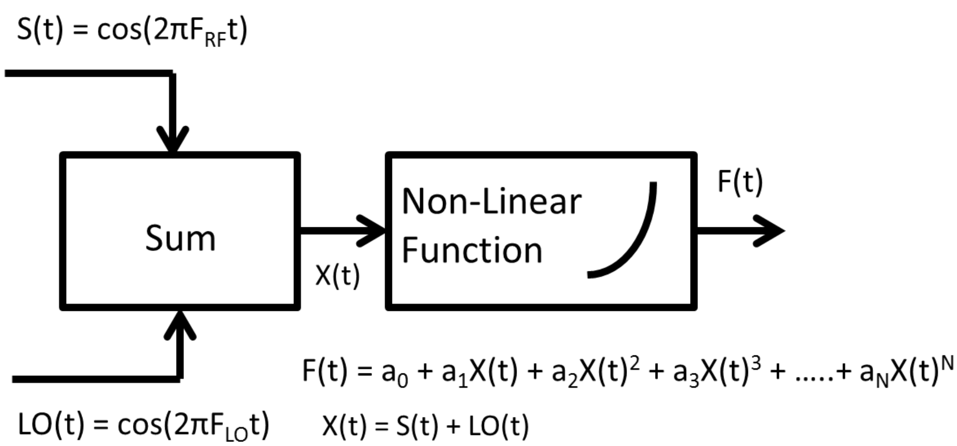

Figure 1: Block Diagram of the basic mixer function

A) The a_0 term is a DC value usually eliminated by AC coupling the signal.

B) The a_1 term is a linear sum of the original signals
$a_1X(t) = a_1 [S(t) + LO(t)] = a_1 [\cos(2\pi F_{RF}t) + \cos(2\pi F_{LO}t)]$

C) The $a_2X(t)^2$ term contains the desired mixing function
$a_2X(t)^2 = a_2 [\cos(2\pi F_{RF}t) + \cos(2\pi F_{LO}t)]^2$
$a_2X(t)^2 = a_2 [\cos(2\pi F_{RF}t)^2 + \cos(2\pi F_{LO}t)^2 + 2[\cos(2\pi F_{RF}t) \cos(2\pi F_{LO}t)]$

$a_2X(t)^2 = a_2 [1/2 + (1/2) \cos(2\pi(2F_{RF})t) + ½ + (1/2)\cos(2\pi(2F_{LO})t) + [\cos(2\pi(F_{RF} - F_{LO})t)]+ [\cos(2\pi(F_{RF} + F_{LO})t)]$

The 1st two terms trigonometrically equate to spectral components twice the frequency of the original signal with added DC terms. In systems less than an octave wide these harmonic terms can be filtered out. AC coupling cancels the DC terms.

The result after filtering are the spectral components [$\cos(2\pi(F_{RF} - F_{LO})t)$] and [$\cos(2\pi(F_{RF} + F_{LO})t)$], the sum and difference frequency of the two input signals.

D) Higher order terms create sum and difference frequencies related to the fundamental components and all of their harmonics, i.e. spectral components at $M F_{RF} +/- N F_{LO}$ where M and N are integers from zero the infinity. The results of these mixing products are spurious signals inside and outside the band of interest that interfere and distort the desired signal.

Single Balanced, Double Balanced, and Triple Balanced Mixers

Interfacing into a mixer, essentially a three port non-linear device, without isolation between ports is problematic even if the ports are matched, which they are not. Various techniques have evolved to handle these issues and make the mixer a predictable and reliable element in microwave system designs.

(1) Single Balanced Mixers

A basic improvement to the single ended mixer is the Single Balanced Mixer. In this configuration the LO and in some configurations the RF, is transformer coupled or hybrid coupled to two single ended mixers, usually diodes or field effect transistors (FET), see Figure 2. The transformer or hybrid sums the RF and LO signals and splits the summed signals to input each of the single ended diodes (or FETs). The resultant output (IF) is a linear translation of the RF frequency spectrum to the sum and difference frequency, $|F_{RF} - F_{LO}|$ and $F_{RF} + F_{LO}$.

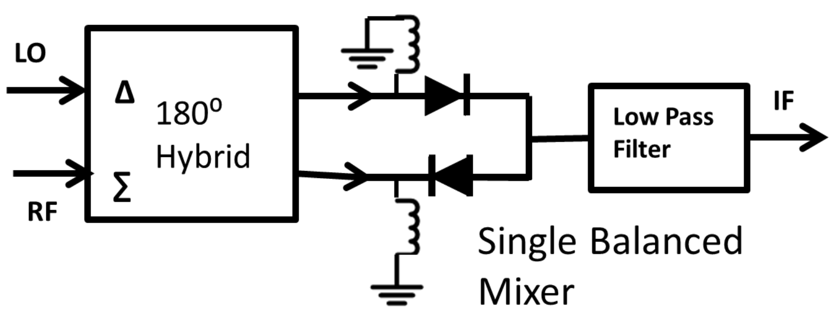

Figure 2: Single Balanced Mixer

The phasing of the hybrid (or transformer) and the diode polarity is such that the even order mixer products of the ($Mx F_{RF}$ +/- $Nx F_{LO}$ where M and N are even integers) are theoretically cancelled and practically suppressed. The hybrid also provides LO to RF isolation and RF to LO isolation equal to the return loss of the mixer diodes. The signal out of the IF port is filtered to attenuate the undesired sum or difference frequency component.

(2) Double Balanced Mixers

Double-Balanced Mixers have a wider bandwidth and improved port to port isolation than single balanced mixers, see figure 3. In the double balance mixer configuration the diodes are switched ON and OFF by a high level Local oscillator (LO). Ideally the LO signal symmetrically switches the diodes with a square wave characteristic. This function tends to eliminate the even order mixing products over a wide frequency range. Figure 4 is a chart of typical mixing products of double balanced mixers when all ports are resistively matched over an extended frequency range. The four diodes in the double balance mixer require a higher LO power to switch them ON and OFF than the two diodes in a single balanced mixer but the 1dB compression point of the mixer is proportionately greater than that of the single balanced mixer. Once the LO power level is sufficient to completely switch the diodes ON and OFF, additional increases in LO power doesn't improve the 1db compression point and the corresponding third order intercept point. Further increases in dynamic range requires modification of the basic four diode quad design and increased LO power. The balanced structure also provides improved isolation between the mixer ports. FETs which have a better square law characteristic than diodes are substituted for the diodes to improve the dynamic range of the mixers. FET mixers have better 1dB compression point performances than diode mixers which translate to a higher third order intercept point and greater dynamic range.

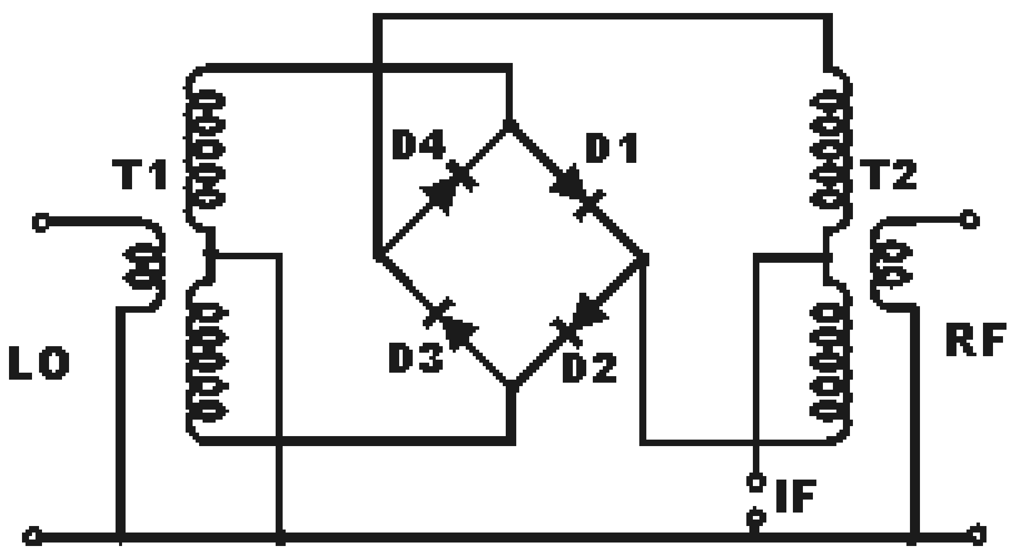

Figure 3, Double Balanced Mixer

RF Components $M x F_{RF}$

7	90	90	90	90	90	85	90	90	90	90
6	90	90	90	90	90	90	90	90	90	90
5	85	80	90	70	90	65	90	65	85	65
4	85	90	85	85	90	85	85	85	90	85
3	70	60	70	50	75	50	75	45	75	45
2	75	70	75	65	70	65	70	65	70	70
1	25	0 Ref	35	10	40	25	45	30	50	40
0		30	35	40	50	40	55	50	55	55
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

LO Components $N x F_{LO}$

Figure 4: Typical spurious levels (-dBc) of Double Balanced Mixer when all ports are matched and the LO level is +7dBm and the RF Level is -10dBm.

(3) Triple Balanced Mixers

Double balanced mixers perform with extremely wide frequency bands at the RF and LO ports but have a limitation in the IF bandwidth. The triple balanced mixer over comes this limitation and allows the IF bandwidth to overlap the LO and RF frequencies. The triple balanced mixer uses two double balanced mixers, sometimes called a double, double balanced mixer, configured as shown in figure 5. This configuration has higher isolation between ports and better spurious performance than double balanced mixers. More LO power is required but the 1dB compression point and the third order intercept point are proportionally higher.

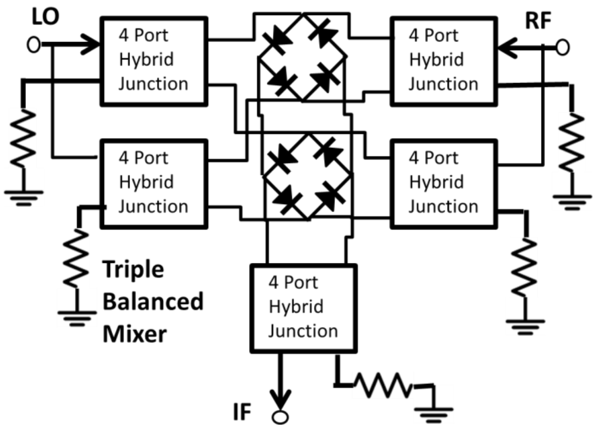

Figure 5: Triple Balanced Mixer

Termination Insensitive Mixer

A Termination Insensitive Mixer (TIM) is actually two mixers configured with quadrature and hybrid couplers to provide cancellation of reflected signals as well as maintain the harmonics rejection, spurious component rejection, and port to port isolation characteristic of the double balanced configuration. The IF port signals (IF1 & IF2) are the sum and difference frequency of the RF and LO signals separated and isolated from each other.

Functional description of a Termination Insensitive Mixer (TIM)

The LO and RF inputs to the Termination Insensitive Mixer (TIM) are quadrature hybrids feeding two identical double balanced mixers. The IF output signal from the double balanced mixers, A and B, are combined in a 180 degree hybrid coupler to separate the sum and difference frequencies, i.e. $F_{IF1} = F_{RF} + F_{LO}$ and $F_{IF2} = |F_{RF} - F_{LO}|$, and see figure 6. The LO drive to the TIM has to be about 3.5dB higher than a standard double balanced mixer to compensate for the 3dB splitting loss plus the insertion loss of the input coupler. Return loss at the RF and LO ports are extremely low because the reflected signals are directed to the isolated port instead of the input port. The isolation of the upper and lower IF frequencies are related to the cancellation characteristics of the sum and delta ports of the hybrid device.

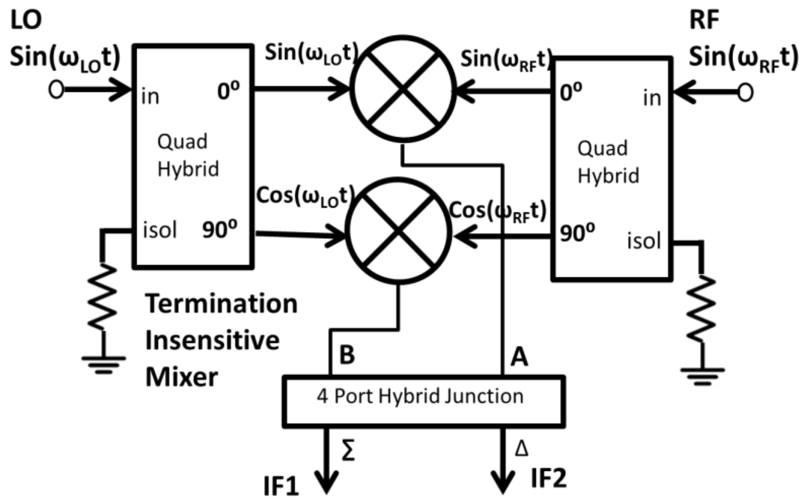

Figure 6, configuration of Termination Insensitive Mixer

The relationship between the input signals and the output IF signals are described by the following trigonometric equations:

$B = Cos(\omega_{LO}t)\ Cos(\omega_{RF}t) = ½\ Cos(\omega_{LO} + \omega_{RF})t + ½\ Cos(\omega_{LO} - \omega_{RF})t$

$A = Sin(\omega_{LO}t)\ Sin(\omega_{RF}t) = ½\ Cos(\omega_{LO} - \omega_{RF})t - ½\ Cos(\omega_{LO} + \omega_{RF})t$

$A\text{-}B = IF1 = Cos(\omega_{LO} + \omega_{RF})t$

$A+B = IF2 = Cos(\omega_{LO} - \omega_{RF})t$

Advantages of the Termination Insensitive Mixer (TIM) Configuration

The TIM advantages over standard double balanced mixers are: (1) Matched RF and LO ports impedances, (2) Improved spurious product rejection, (3) Improved linearity, (4) Improved pass band ripple, and (5) Improved LO to RF Isolation.

1) Impedance matched RF and LO ports.

The input impedance at the RF port of a double balance mixer is usually poorly matched to other system components causing significant system issues with reflected signals. Not only are the reflected signals higher than desired, but they vary as a function of LO power making their predictability difficult. In Termination Insensitive Mixers reflected signals from the double balanced mixers are directed to the isolated port of the hybrid instead of the input port, making the input port (LO or RF) look like a near ideal matched load. The reflected signals from the double balanced mixers are directed to the isolated port of the quadrature coupler is a function of the amplitude and phase match between the mixers. Figure 7 shows the return loss at the quadrature hybrid input port as a function of ampltitude and phase mismatch of the reflected signals from the double balanced mixers. Added to the mismatch loss is the quadrature coupler port to port isolation and the return loss of the input port, where all signals may add coherently, worst case.

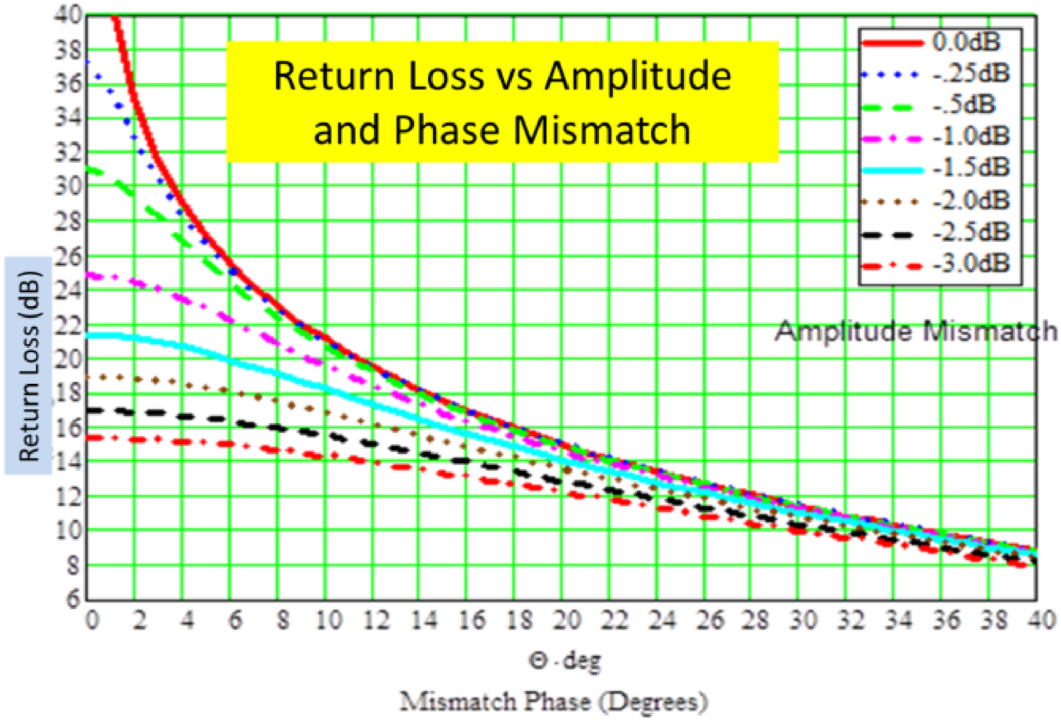

Figure 7: Return loss at the input port of a quadrature hybrid as a function of return signal mismatch at the 0 and 90 degree output ports of the hybrid.

The port to port isolation of the quadrature hybrid is typically 20 dB, and the return loss of the input port is typically 20 dB or less making the total return loss of the TIM mixer typically less than 17dB even with perfectly matched double balanced mixers. The isolation and return loss are degraded when using wide band hybrids.

2) Improved spurious product rejection

Improved spurious product rejection is due to the RF and LO signal reflections are absorbed in the input quadrature couplers and not resinserted into the mixer at an unknown amplitude and phase. These additonal signals affect the balance of the device and cause the predicted mixing product spurious components to be enhanced (M x F_{RF} +/- N x F_{LO} where M and N are integers). Typical quarter wave quadrature couplers are band limited and show less improvement to spurious component rejection derived from higher values of M and N. Spurious rejection is enhanced by using more complex wideband quadrature couplers.

3) Improved linearity

Linearity is improved because the signal is divided into two paths lowering the power level into the double balanced mixers. The respective TIM improvement in third order intermodulation intercept point is 3dB over that of a double balanced mixer. The LO power should be increased 3dB over that used in a standard double balanced mixer to maximize the mixer dynamic range. The improvement in dynamic range, third order intermodulation products, spectral regrowth, and Noise Power Ratio measurments could be as high as 6dB.

4) Improved pass band ripple

Pass band ripple (amplitude and phase variations with respect to frequency) is always a problem when inserting a device with poor VSWR into a chain of system components. The resultant effects on ripple are determined by the source and load impedance mismatch and the distance between the components. When components are close together, i.e. less than a quarter wave length ($\lambda/4$), the effect will be a seen as a loss uncertainty rather than ripple in the pass band. The impedance of the TIM is matched such that this effect is minimized and almost eliminated.

Another issue affecting pass band ripple is the effect of return loss from the IF output port. Reflected IF signals return back into the mixer, convert back to the RF frequency when mixed with the LO, and add and subtract power from the original input RF signal. This effect is minimized in Termination Insensitive Mixers because the reconverted signal coming out of the mixer is directed to the isolated port through the quadrature coupler and never interferes with the original RF signal.

Another typical mixer problem is the $2F_{LO} \pm F_{RF}$ spurious signal that reflects back to the RF port. Many times the RF signal is fed from a narrow band filter which reflects the $2F_{LO} \pm F_{RF}$ signal back into the RF port of the mixer and converts it to the IF frequency. This spurious component is identical in frequency and bandwidth to the orginal frequency and is superimposed with an offset phase anywhere between 0 and 2π. If the LO is frequency swept the interference will add and subtract from the original signal at different phases and add to the expected system gain ripple across the band of interest. TIMs are not subject to this effect because the reflected signal is directed to the isolation port of the quadrature hybrid and not reflected out of the RF input port.

(5) Improved LO to RF Port Isolation

Typical LO to RF rejection is about 20dB which is usually sufficient when using the mixer as a downconverter but when the mixer is used as an up converter the LO is a fixed, RF signal independent spurious, signal that can have a significant effect on system performance. The quadrature coupler at the RF port of the mixer provides an additional nominal 20dB rejection for a total LO to RF isolation greater than 40dB. LO to RF rejection can actually be further improved for narrow band applications by optimizing the input couplers.

Typical TIM performance data

Termination Insensitive Mixer (TIM) performance is dependent on the quality of the quadrature couplers on the LO and RF ports and the matching of the double balanced mixers. Typical performance for wideband TIM mixers (2GHz to 6GHz) and ultra wideband TIM mixers (2GHz to 18GHz) are shown in figures 8 through 13. Performance can be enhanced under narrower band conditions because the couplers can be optimized for the band of interest.

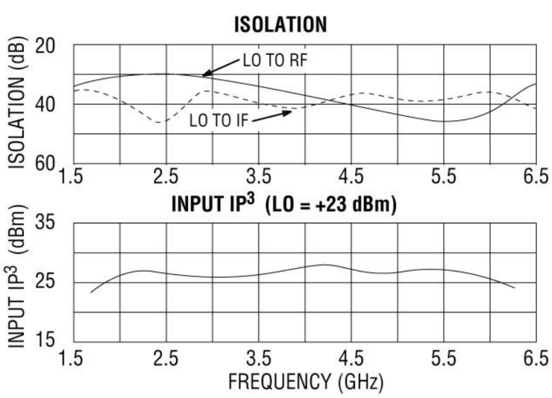

Figure 8: Typical IP3 and port to port isolation data for a wide band TIM that operates from 2GH to 6 GHz.

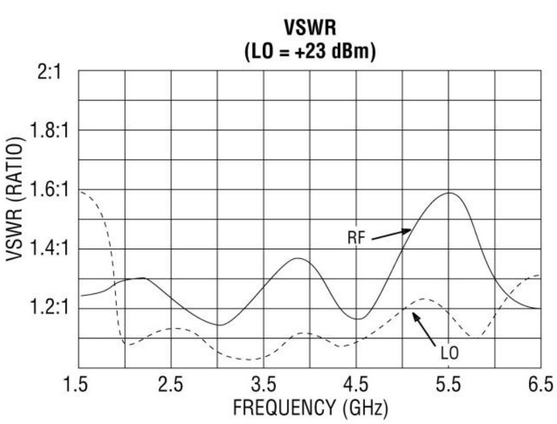

Figure 9: Typical VSWR data for a wide band TIM that operates from 2GH to 6 GHz.

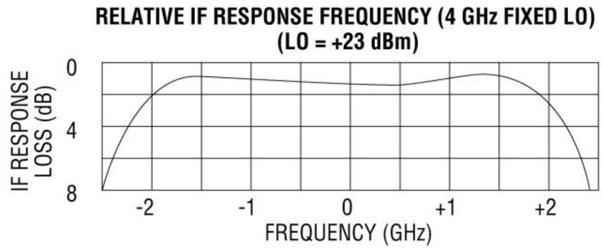

Figure 10: Typical relative IF gain response for a wide band TIM that operates from 2GH to 6 GHz.

Lower frequency quadrature couplers are easier to manufacture than higher frequency couplers, therefore performance tends to degrade at higher frequencies. Typical data of a 2GHz to 18Ghz TIM mixer is shown in figures 11, 12, and 13 .

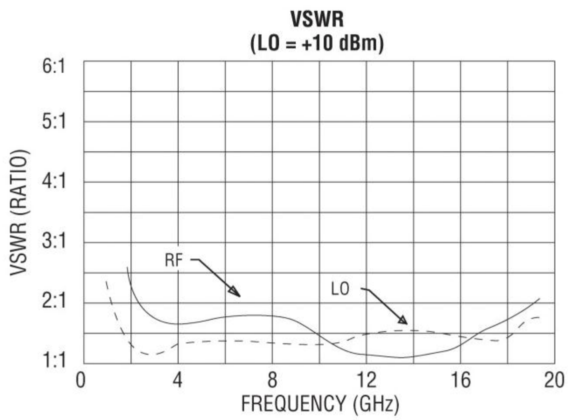

Figure 11: Typical VSWR data for a wide band TIM that operates from 2GH to 18GHz.

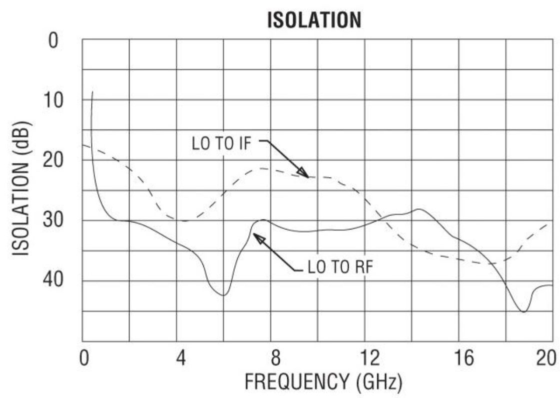

Figure 12: Typical port to port isolation data for a wide band TIM that operates from 2GH to 18GHz.

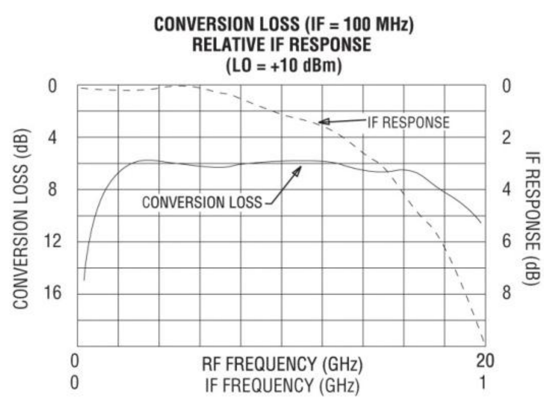

Figure 13: Typical conversion loss and pass band ripple at the RF port and pass band ripple at the IF port for a wide band TIM that operates from 2GH to 18GHz.

Conclusion

Mixers are an essential part of most sophisticated electronic systems. The design of the mixer, which is non-linear device performing a quasi-linear function, is especially challenging and complicated. Techniques for cancelling some of the non-linear effects have incrementally improved time, with Termination Insensitive Mixers being a significant step in the improvement process. The theory is a fundamental extension of techniques used for years in balanced amplifiers and other devices, the difference and difficulty in using them for mixers is the non-linearity of the basic device. Critical and effective implementation of a Termination Insensitive Mixer begins with a superior balaced mixer and wide band couplers that perform beyond the band of interest. The information and data presented shows the advancement of this technology and the possibilities of enhanced performance in the future.

Acknowledgement

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References

1. Henderson, B. “Mixers in Microwave Systems (Part 1), WJ Communications, Inc. Tech-note January/February 1990
2. Henderson, B. “Mixers in Microwave Systems (Part 2), WJ Communications, Inc. Tech-note March/April 1990
3. Butterworth, P. “A Balanced Sub-Harmonic Cold FET Mixer for 40 GHz Communication Systems, 11th GaAs Symposium, Munich 2003
4. Maas, S. “Harmonic balance simulation speeds RF mixer design”, 1999 Wireless Symposium