Exploring the Effects of DC Biasing and Varying Local Oscillator Levels on Mixer Linearity Performance with a Novel RF Mixer Design

by

Dale Reitsma
B. Eng, University of Victoria, 1995

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of the Requirements for the Degree of

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University of Victoria

Supervisory Committee

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Abstract

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The mixer/detector is a fundamental component in the communications field in both the receiver and transmitter signal chains. It has been used since the earliest days of radio acting as a demodulator in a cat's-whisker radio and shifting frequencies up and down the electromagnetic spectrum in the superheterodyne receiver. In recent years it has been a significant component in an I/Q modulator and an upconverter/downconverter for today's SDR platforms. A novel RF mixer design is presented in order to test the idea of using DC biasing of the quad ring diodes in a double balanced mixer to improve the linearity performance of the mixer with a lower local oscillator level. The 1 dB compression point and the third order intercept point are measured on a standard double balanced mixer as well as the modified design to determine if any effect is present. There may be applications in mobile handset front end design as well as improved linearity performance in infrastructure that requires low power consumption parameters.

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List of Acronyms and Abbreviations

BOM	Bill of Materials
CL	Conversion Loss
dB	Decibels – ratio of powers in logarithmic scale
dBm	Decibels referenced to 1 milliwatt
GHz	Gigahertz
IF	Intermediate Frequency
LMR	Land Mobile Radio
LNA	Low Noise Amplifier
LO	Local Oscillator
MHz	Megahertz
RF	Radio Frequency
SCADA	Supervisory Control And Data Acquisition
SDR	Software Defined Radio
TOIP	Third Order Intercept Point

Acknowledgements

There are several individuals that I would like to acknowledge that helped move me through this Master's program. First is my wonderful wife Maxine who supported me in pursuing this goal of obtaining my Master's degree and provided the encouragement and support that was necessary to get to this point. Second, my two amazing and beautiful children, Liam and Lara, who understood when I had to work on various assignments, projects, and studying and cheered me on to get it done.

Third, my manager, Robert Small, and colleagues at Daniels Electronics who supported my activities and allowed me to work full time and be actively involved in this part time academic life and in addition, the new management team at Codan Radio Communications that let me continue to chase this goal during our transition from a small family run business to being a new and exciting part of a multinational corporation.

Finally, a big thanks to Dr. Jens Bornemann for taking me on as a mature student and to the incredible faculty of ECE-UVic for their guidance and instruction in this amazing field of Radio, Microwave, and Communications Engineering.

Dedication

To Maxine – for believing in me

To Liam and Lara – for inspiring me

To my parents – for guiding me

To RAH, IA, and SF – for showing me the possibilities

Chapter 1 Introduction

1.1 Introduction

The mixer/detector is a fundamental component in the communications field in both the receiver and transmitter signal chains. It has been used since the earliest days of radio in multiple ways from acting as a amplitude demodulator in a simple cat's-whisker radio (a direct conversion receiver) and as a frequency downconverter/upconverter in the superheterodyne receiver. In recent years it has played a fundamental role in the transmitter chain as a significant component in an I/Q modulator and an upconverter for today's SDR platforms. In my previous projects in the design of Land Mobile Radio (LMR) receivers, the type of mixers, the circuitry around the mixers and the power levels of the signals feeding into and out of the mixer had a significant impact on the performance requirements of the receiver.

Previously in my career, I have designed, modified and extensively tested LMR receivers and receiver front ends from 30 MHz to 1 GHz. The front end of a receiver typically consists of a band pass filter (BPF), a low noise amplifier (LNA), and a mixer stage to downconvert or upconvert the designed signal to the Intermediate Frequency (IF) for further processing by the receiver. Some of the key performance parameters when working on these front ends have been receive sensitivity, intermodulation performance, and power consumption. The type and style of mixer used in the receiver can have an impact on each of these parameters - often directly in competition with each other.

During my work on these previous projects at Daniels Electronics, I worked with multiple types of mixers - both commercially manufactured as well as discretely designed mixers. Each mixer was chosen or designed to achieve the targeted specifications for a specific receiver design. For instance, to achieve improved intermodulation performance in a receiver front end requires both an LNA and mixer that have higher linearity performance. To reduce power consumption in the receiver, a low power LNA was designed along with a mixer that required a low LO level to drive it. The sensitivity and noise figure is affected by the conversion loss or gain of a mixer. During the design process an improvement in one specification could degrade the levels in another specification. The interplay between these specifications was at times very frustrating.

While working on a modification to a front end that required good intermodulation performance but also required a reduction in power consumption I wonder whether a change to the mixer circuitry would help. This front end had a passive double balanced mixer and I wondered if I could prime the passive mixer diodes with a bias voltage. I would then use a lower power local oscillator and might still reach the required linearity requirements while having a lower power consumption specification. I was never able to work on the idea but decided to design a mixer and test this hypothesis as my project to meet my UVic MEng ELEC 598 requirements.

Chapter 2 Mixers

The ideal mixer is essentially a three port device that creates a new signal based in the characteristics of the two input signals. This output could be a representation of the frequency or amplitude differences in the two signals with the output being a DC or AC representation of those static or dynamic differences. The mixer can also directly modulate a signal or shift it's frequency either up or down (upconvert or downconvert). Traditionally, the mixer has been used in receivers to downconvert or upconvert a signal to an intermediate frequency for further processing. The ports are called the RF (Radio Frequency) port, the LO (Local Oscillator) port, and IF (Intermediate Frequency) port in receiver applications. See Figure 2.1 below for traditional schematic symbol for the mixer.

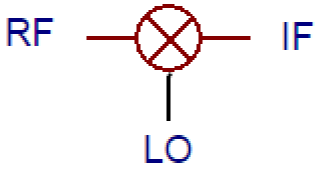


Figure 2.1: Ideal Mixer

The ideal mixer has been put into practice by using the nonlinear behaviour of electronic devices such as diodes and transistors. The simplest mixer traditionally has been a single diode where all three ports were connected across the single diode using frequency appropriate filtering and matching networks to create the required outputs. The nonlinear behaviour of the diode has a multiplying affect on the RF and LO. The IF output of the mixer is the sum (f1 + f2) and difference (f1 – f2) frequencies between the LO and RF. The wanted IF image is selected with the appropriate filter as shown in

Figure 2.2. The product to sum trigonometry identity demonstrates how new frequencies are created:

$$\sin u * \sin v = 0.5 [\cos (u-v) - \cos(u+v)]$$

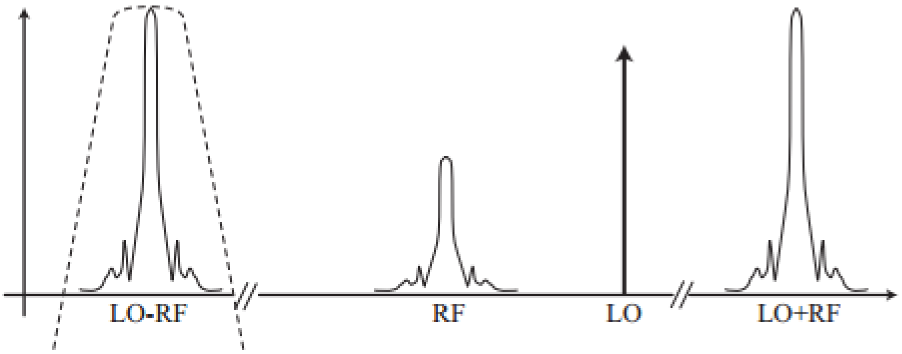


Figure 2.2: IF Sum and Difference Images [1]

Although a single diode can behave like the ideal mixer, far more complicated mixer circuits have been designed to reach the behaviour of the ideal mixer and to compensate for the inherent issues that arise when creating a “real” mixer. Passive and active mixer devices have been crafted from combinations of diodes, transistors and transformers to allow for improved performance and capabilities. Figure 2.3 shows a passive triple balanced mixer which has improved intermodulation performance and image rejection compared to simpler mixer designs.

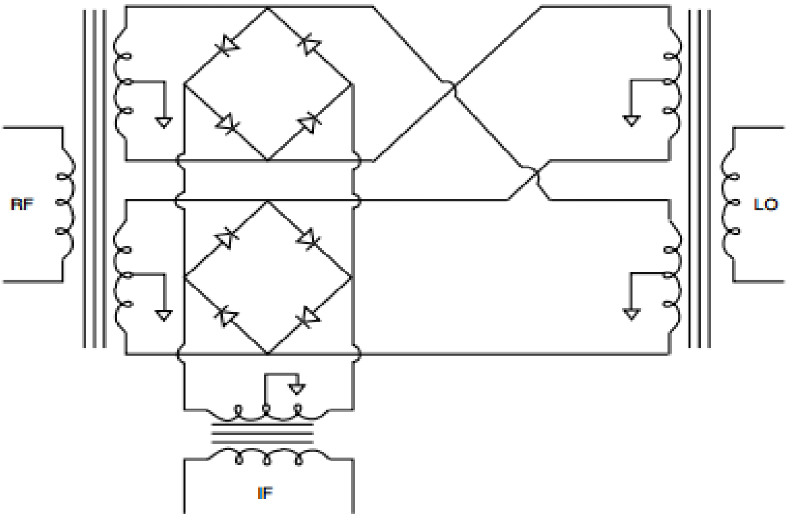


Figure 2.3: Passive Triple Balanced Mixer [2]

The most common passive diode mixer that I've used in my designs is the double balanced mixer with a diode ring (see Figure 2.4). It's available from multiple manufacturers in a variety of packages or can be designed using discrete components.

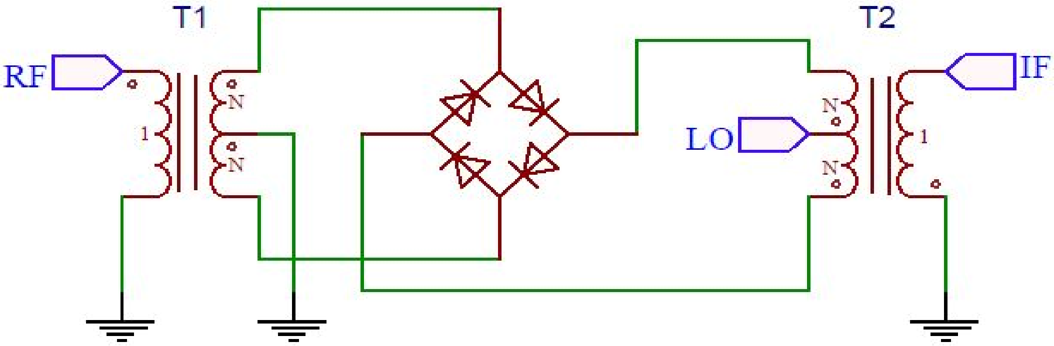


Figure 2.4: Passive Double Balanced Mixer with Diode Ring

Chapter 3 Performance Measurements

The performance of a mixer can be categorized by the measurement of several important parameters. A few of these characteristics are:

- Conversion Loss or Gain
- Linearity
- Isolation
- Noise Figure
- Frequency Range

For this project, my focus was on the linearity of the mixer and how it might be affected by DC biasing and not on the actual performance characteristics of the mixer itself. Therefore the measurements that I focused on were conversion loss and two specific linearity measurements – 1 dB compression point and third order intercept point.

3.1 Conversion Loss

Conversion loss or gain in a receiver mixer is a measurement of the change in power levels between the input RF signal and the output IF signal. In a passive mixer the conversion parameter is always a loss and that loss parameter is usually greater than 6 dB.

Measuring conversion loss is relatively easy. It's a simple measurement of the delta power level between the input RF level and IF output level. E.g. if the measured RF level is -30 dBm and the IF level is -38.5 dBm, the conversion loss would be 8.5 dB. See Figure 3.1 for illustration. The measurement must be taken in the linear range of the mixer so that any compression does not affect the measurement.

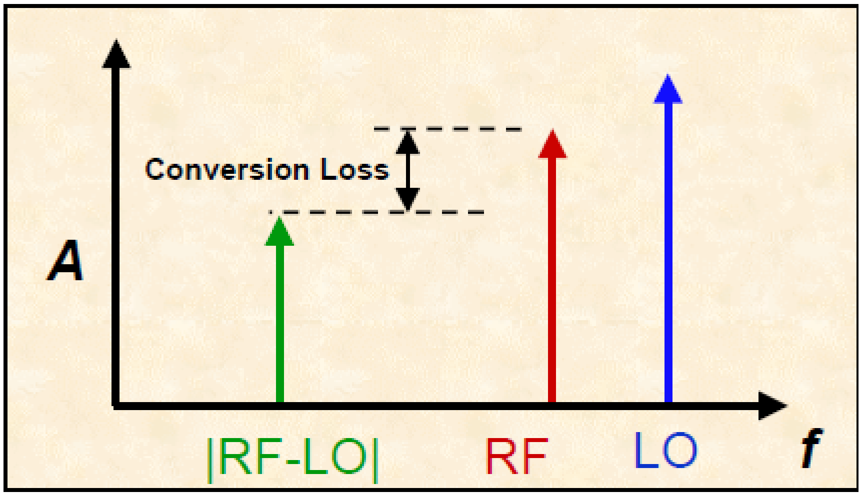


Figure 3.1: Conversion Loss (RF to IF) [3]

3.2 Linearity Measurements

Many devices in communications require linear behaviour to properly calculate and predict the performance of a system under a variety of conditions and multiple parameters have been created to characterize the linearity of devices. System components such as power amplifiers, low noise amplifiers, and mixers all need to be characterized to determine their behaviour when exposed to both multiple signals and high signal levels. Some of these parameters are:

- Spurious Free Dynamic Range (SFDR)
- Intercept Points IPn
- 1 dB Compression Point

The two measurements I used to characterize the linearity in the mixer are the 1 dB compression point and the IP3 or Third Order Intercept Point (TOIP). These measurements are relatively easy to measure in a mixer.

3.2.1 One dB Compression Point

The 1 dB compression point is a figure of merit that indicates the linearity and dynamic range of a mixer. In the ideal mixer, the input RF power would be split into the two ideal IF outputs with each IF image 3 dB (half power point) below the input RF level. However in a real mixer the transfer function between the RF input and IF output starts to become nonlinear (as well as having inherent losses) and the output stops tracking the input. The point where the output is 1dB below the ideal response is the 1 dB compression point as shown if Figure 3.2.

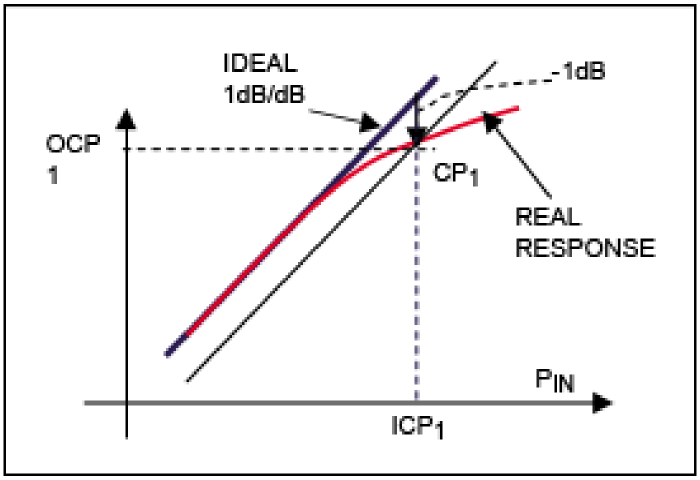


Figure 3.2: One dB Compression Point [4]

Measuring the conversion loss is the first step in measuring the 1 dB compression point. Once the conversion loss is measured, the RF input level is slowly increased and the conversion loss constantly remeasured. When the conversion loss has increased by 1 dB, the 1 dB compression point has been determined. It can be expressed in terms of the RF input level or the IF output level.

3.2.2 Third Order Intercept Point

The IP3 or the third order intercept point (TOIP) is not something that can be directly measured or actually attained by the device that is being characterized. It is an extrapolated parameter from the measurement of other specifications. The IP3 is a specific IPn (nth order intercept point) measurement. IPn measurements plot the levels of the IF output of the nth intermodulation products and extrapolates the signal levels with the fundamental IF output and nth order product. An IP2 measurement would monitor the levels of the fundamental IF output and the 2nd harmonic level (2 * IF frequency). An IP3 measurement would monitor the levels of the 3rd harmonic (3 * IF frequency). These levels would be plotted with the IF fundamental level and the 2nd and 3rd harmonic levels and extrapolated until the IP2 and IP3 intercept point were determined (Fig. 3.3). A 2nd order product increases 2 dB for every 1 dB increase in the fundamental signal and the 3rd order product increases 3 dB. [4]

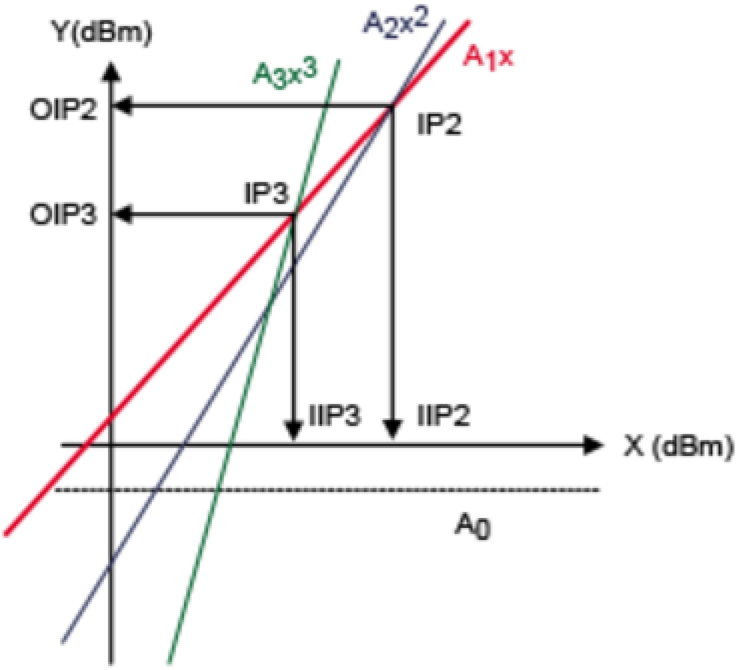


Figure 3.3: IP2 and IP3 Extrapolations [5]

The IP3 measurement does not need to monitor only the 3rd harmonic of the fundamental IF frequency. Any third order product can be monitored and extrapolated to determine the third order intercept. Using the two tone intermodulation test, third order products can be generated in the range of the IF fundamental frequencies. The second harmonic of one of the fundamental tones minus the fundamental frequency of the other tone produce two third order products on either side of the two tones separated from the two tones by the frequency difference between the two tones. (Figure 3.4)

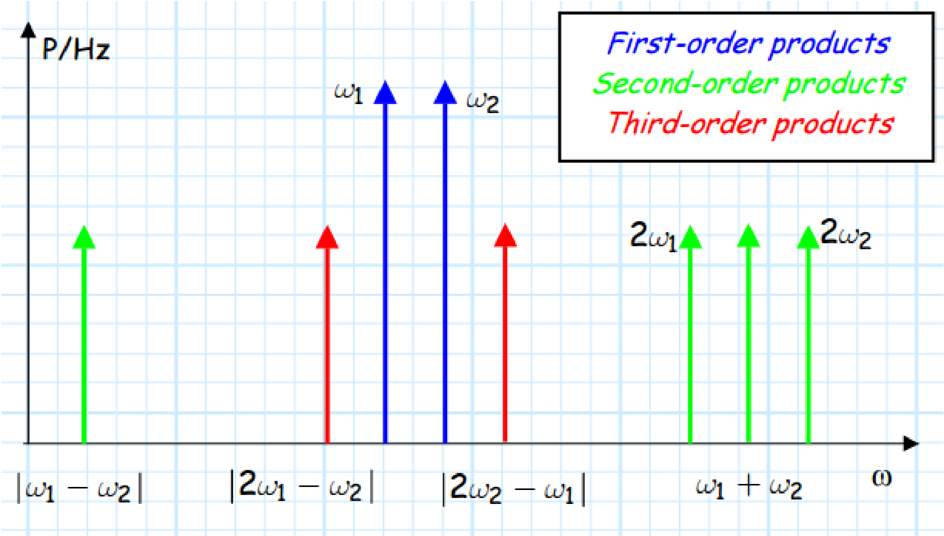
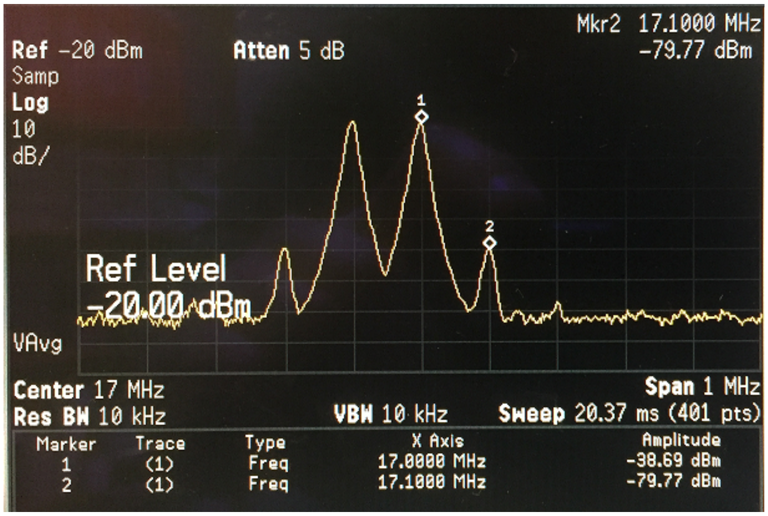


Figure 3.4: Two Tone Intermodulation Products [6]

To measure the IP3 using the two tone test is a simple matter of monitoring the fundamental frequency tones and the 3rd order products. Since the 3rd order products increase 3 dB every 1 dB that the fundamental tone increases, the IP3 can be calculated by adding half of the difference between the power levels to the fundamental level. See Figure 3.5 to see example measurement on Agilent Spectrum Analyzer.

$$IP3 = F1\ dB + 0.5\ (F1\ dB - (2*F2 - F1)\ dB)$$



Mkr2 17.1000 MHz
-79.77 dBm

Ref -20 dBm
Atten 5 dB
Samp
Log
10
dB/

Ref Level
-20.00 dBm

VAvg

Center 17 MHz
Res BW 10 kHz
VBW 10 kHz
Span 1 MHz
Sweep 20.37 ms (401 pts)

Marker	Trace	Type	X Axis	Amplitude
1	(1)	Freq	17.0000 MHz	-38.69 dBm
2	(1)	Freq	17.1000 MHz	-79.77 dBm

Figure 3.5: Two Tone IM Output - Spectrum Analyzer

Chapter 4 Mixer Design

The hypothesis that I wanted to test in this project was to determine if the diodes in a mixer that used a lower local oscillator level could be primed by using a DC voltage to have similar linearity performance as a mixer with a higher local oscillator level. It would require a new mixer design to incorporate a method to DC bias the diodes to test this hypothesis . A baseline mixer would also be designed and tested to compare any performance changes from the DC biasing.

4.1 Baseline Mixer Schematic and Build

To test this hypothesis I decided to build a doubly balanced mixer and then modify it to enable a controlled DC bias voltage across the diodes. I would then control the bias voltage/current to see if any performance changes were seen.

In my past projects as an RF Engineer, I've designed, modified and extensively tested land mobile radio receiver front ends from 30 MHz to 1 GHz. The front end of a receiver typically consists of a band pass filter (BPF), a low noise amplifier (LNA), and a mixer stage to downconvert or upconvert the designed signal to the Intermediate Frequency (IF) for further processing by the receiver. During those past projects I've worked with both commercially manufactured as well as discretely designed mixers. Since I intended to modify the mixer to enable the DC biasing, a discrete mixer would need to be designed.

As previously shown, a double balanced mixer is a three port device (RF, LO, and IF) that consists of two transformers and four diodes in a ring or star configuration.(Figure 4.1)

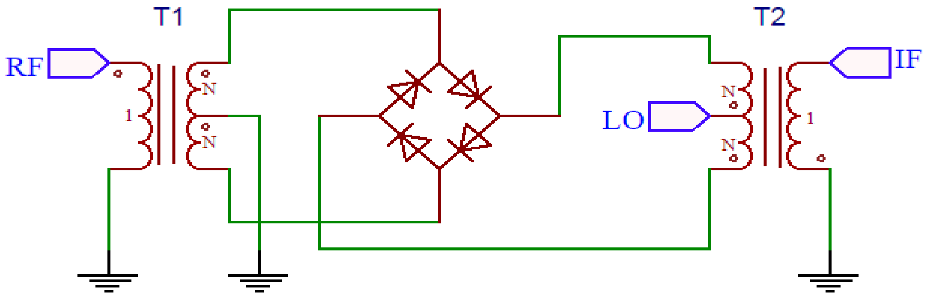


Figure 4.1: Schematic - Double Balanced Mixer

To build the initial mixer, the appropriate components would need to be sourced and then mounted on an appropriately designed printed circuit board. As well, the frequency range that the mixer would operate would need to be chosen. Since the design was about linearity and not frequency range, I choose the IF to be between 5 to 20 MHz. The LO and RF range would be from 50 to 100 MHz. After some research and investigation I decided on the following components for the bill of materials (BOM) for the initial baseline mixer. See Table 4.1.

Manufacturer	Part #	Description	Quantity
ON Semiconductor	MMBD701LT1G	DIODE, SCHOTTKY, Vr 70V MAX, SOT23	4
TOKO	#458DB-1614=P3	TRANSFORMER, SM, BALUN	2
Daniels Electronics	4390-10006801	Test Proto PCB	2
Daniels Electronics	7910-WS7NJ021	CABLE, SMB, 21CM	3

Table 4.1: BOM – Baseline Mixer

To minimize efforts on the design I decided to mount the mixer circuit to two test prototype boards that my colleagues and I had designed previously. Although the use of a prototype test board would likely not provide the best performance for the mixer, it would make it easier to allow the modifications required to test a design based on a DC bias. Pictures of both sides of the test prototype board are shown in Figure 4.2 and figure 4.3.

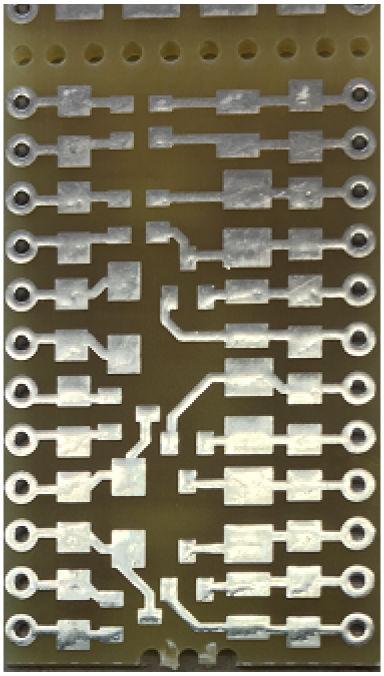


Figure 4.2: Side One Test Prototype Board

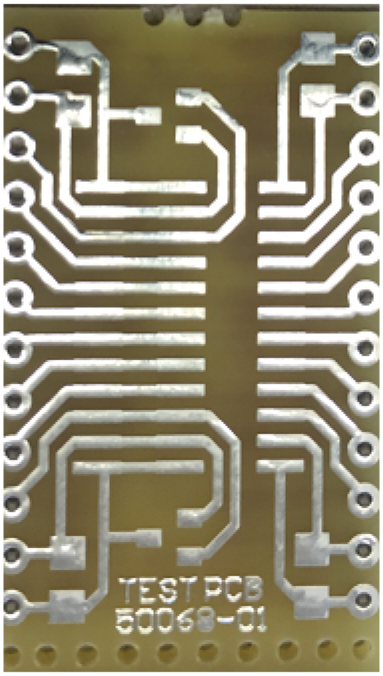


Figure 4.3: Side Two Test Prototype Board

These boards were designed to accommodate a variety of component footprints to easily and quickly develop a test circuit to test and develop ideas when using surface mount components. Figure 4.4 shows the transformers mounted on side two of a test PCB and Figure 4.5 shows the diodes mounted on side one of the other test PCB in a ring configuration.

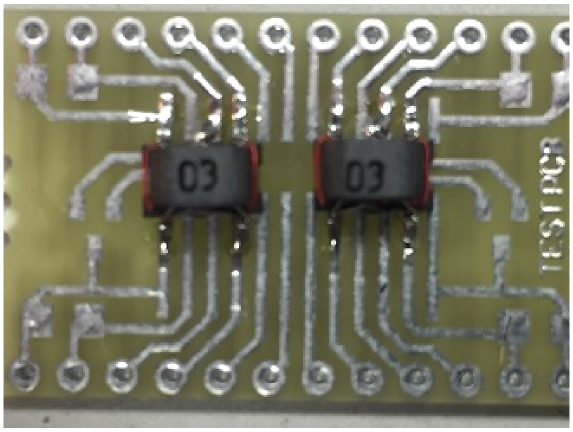


Figure 4.4: Balun Transformers mounted on Test board

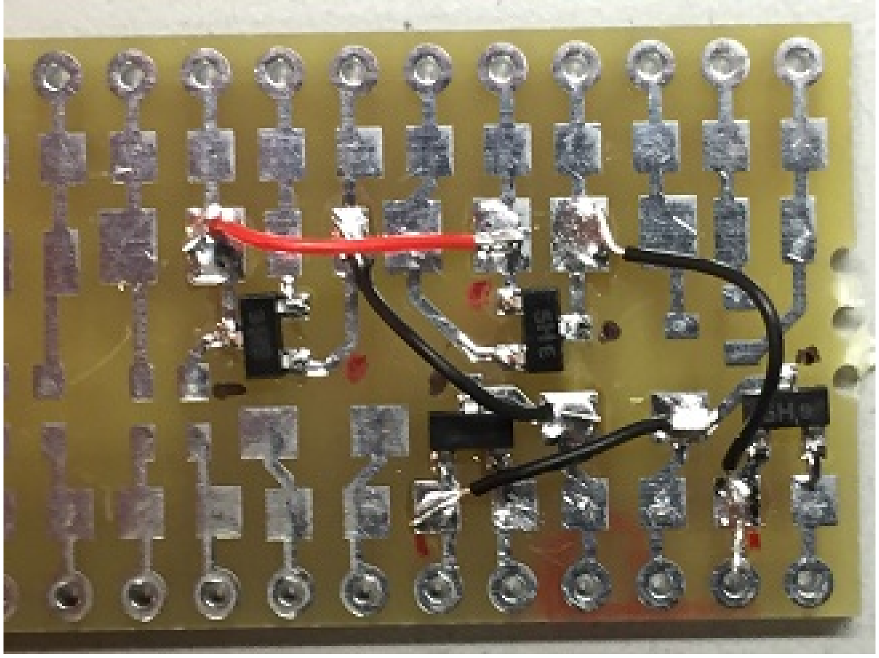


Figure 4.5: Four Diodes mounted in ring configuration

The two boards were initially tested to confirm all solder joints were good and that the diodes were properly oriented. Coaxial cables were soldered to the transformer board and the ring diode board was connected to the transformer board. Figure 4.6 shows the completed double balanced mixer. The design is NOT intended for high frequency operation but merely to test the idea of improving the mixer linearity by biasing the diode ring. The expected frequency operation is 50-100 MHz for the LO and RF inputs and 5-20 MHz for the IF frequencies.

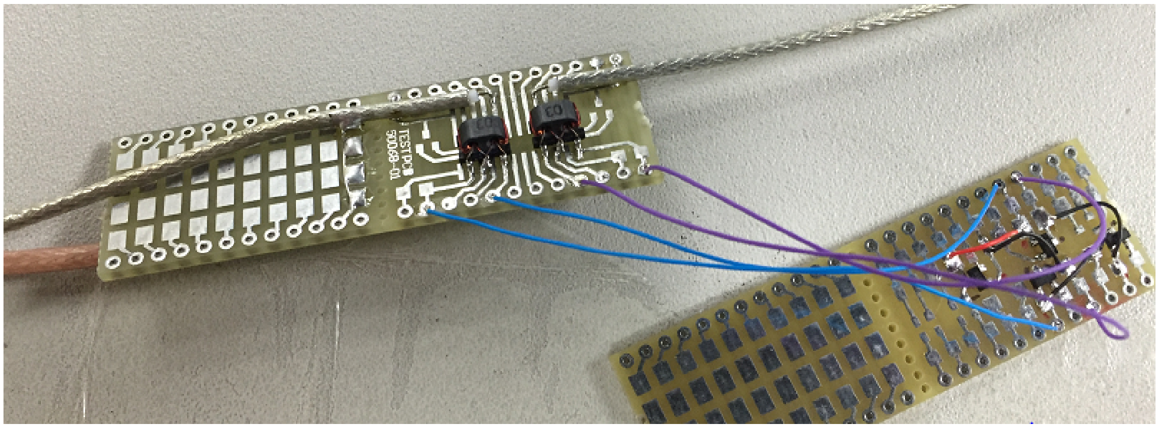


Figure 4.6: Completed Double Balanced Mixer Test boards

4.2 Modified Mixer Schematic and Build

Once the initial mixer was designed and built, a second mixer design was required to test the DC biasing hypothesis. The basis of the idea is to have all diodes biased very close to the conduction/forward voltage so that a reduced LO level would be able to still allow the on/off switching of the ring diodes. Looking at the internal structure of the DB mixer however reveals that there is no way to apply a consistent bias voltage across all the diodes – see Figure 4.7

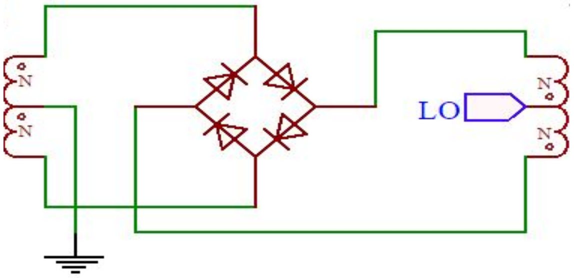


Figure 4.7: Double Balanced Mixer Internal Ring Diodes and DC Path

A bias voltage could be applied via an RF choke at this design's LO input. This bias voltage would allow the top left & bottom right diodes to be forward biased; however it would also reverse bias the top right and bottom left diodes of the ring(Figure 4.8). An alternate method was needed to allow all four diodes to be forwarded biased at the same time.

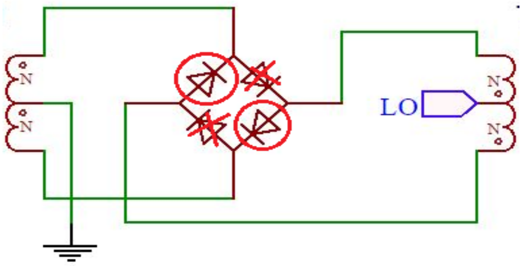


Figure 4.8: Double Balanced Mixer - Only Left Diodes Conducting

After some investigation I came up with the circuit shown in Figure 4.9. This design allowed the diode ring to be DC isolated from the RF and LO/IF transformers except for the AC/DC ground point. It also allows the diode D3 and D1 to be DC isolated so that the DC bias would not be shorted directly to ground. Large value resistors, R1 and R2, and the C1 cap, which shorts AC across R1, prevents any excessive loss in the mixer it.

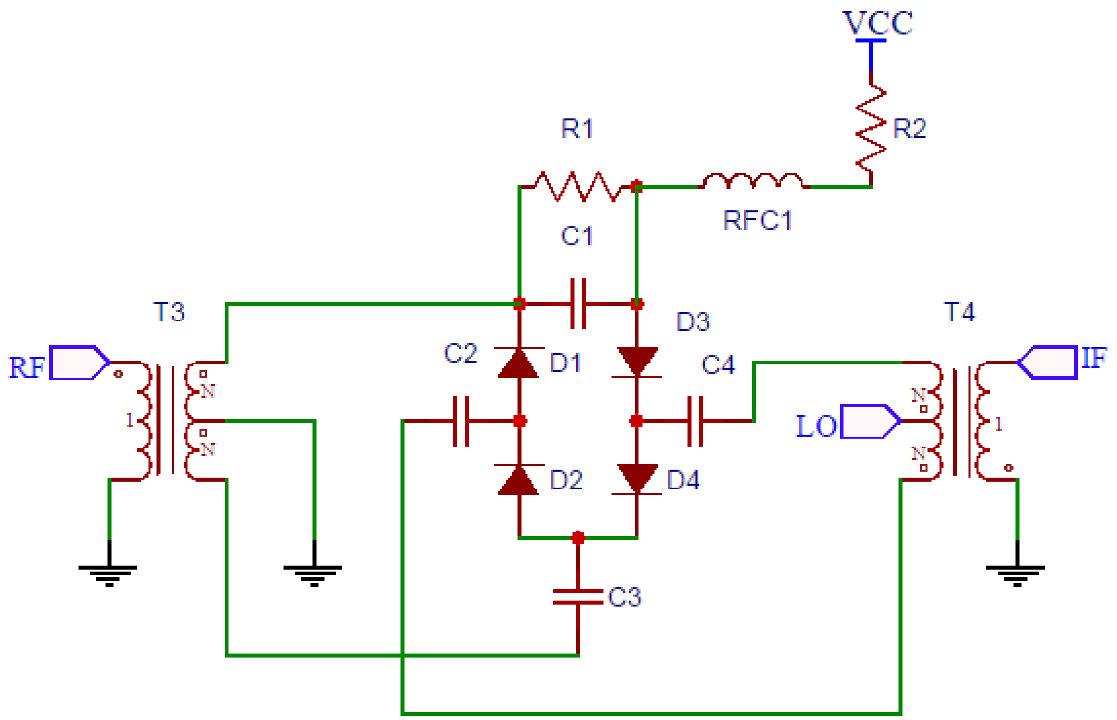


Figure 4.9: Schematic - Modified Double Balanced Mixer with biasing

Observing the AC equivalent circuit (see Figure 4.10) for this circuit, it is seen that it is equivalent to the first double balanced mixer that I designed. Looking at the DC equivalent circuit (Figure 4.11), R1 and R2 are a voltage divider until the diodes start to conduct. Diodes D1 to D4 will have 1/4 of the divided voltage across each device. Once the diodes start to conduct, the diodes will clamp the voltage at ~ 1.6 V (4 x 0.4V – Forward voltage of the ON Semi MMBD701LT1G Schottky diodes), and any further increases in the bias voltage will increase the current through the diodes.

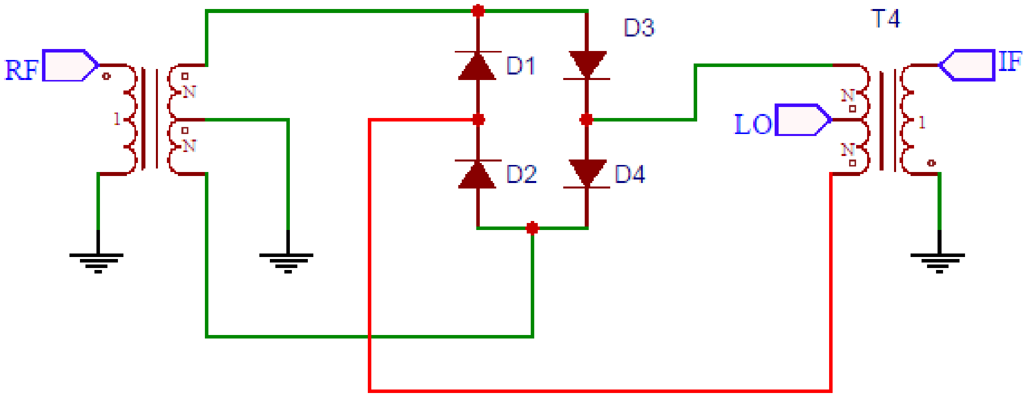


Figure 4.10: AC Equivalent Circuit

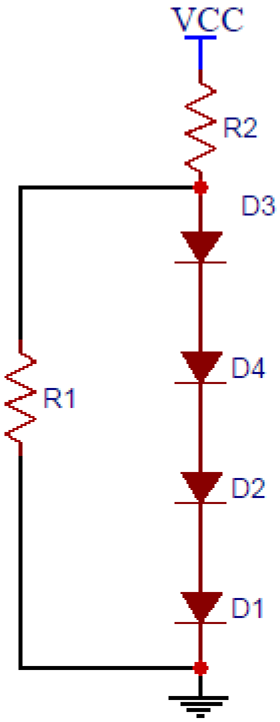


Figure 4.11: DC Equivalent Circuit

Chapter 5 Test Measurements

After completing and verifying the design of the mixers, baseline measurements were performed on the unbiased standard double balanced mixer design to ascertain the basic performance and linearity measurements. Since my supposition is that varying DC biases might have a similar affect to varying LO levels, all tests were done against varying LO levels.

5.1 Baseline Mixer Measurements

The preliminary test was to measure conversion loss against LO level. As seen in Table 5.1, the lowest conversion loss was 8.2 dB at an LO level of +7 dBm. This is relatively poor mixer conversion loss performance. A commercial passive mixer at these frequencies such as the Mini-Circuits TUF-2SM+ has a conversion loss of 6.1 dB. [7] This mixer design was not optimized for best conversion loss as seen in the design pictures (Figure 4.6).

LO Level (dBm)	RF Level (dBm)	IF level (dBm)	Conversion Loss (dB)
-5	-20	-39.6	19.6
-3	-20	-33.5	13.5
-1	-20	-31.2	11.2
1	-20	-29.9	9.9
3	-20	-29	9
5	-20	-28.4	8.4
7	-20	-28.2	8.2
9	-20	-28.3	8.3
11	-20	-28.6	8.6
13	-20	-29.1	9.1

Table 5.1: Conversion Loss vs LO - Baseline Mixer

The next two tests would measure the linearity of the double balanced mixer in two different manners. The first was to ascertain the 1 dB compression point as the LO level was adjusted (Table 5.2) and the second test was to measure the third order intercept point (Table 5.3). Both measurements are used as figures of merits when measuring mixer performance. In Table 5.2, the conversion loss for an RF input of -20 dBm is shown and then the corresponding 1 dB compression point is highlighted.

LO (dBm)	**+13 dBm**					
RF (dBm)	-20	-10	3	5	5.5	6
IF (dBm)	-29.1	-19.1	-6.2	-4.8	-4.5	-4.3
CL (dB)	9.1	9.1	9.2	9.8	10	10.3
LO (dBm)	**+10 dBm**					
RF (dBm)	-20	-10	0	3	4	5
IF (dBm)	-28.5	-18.6	-8.8	-6	-5.4	-5
CL (dB)	8.5	8.6	8.8	9	9.4	10
LO (dBm)	**+7 dBm**					
RF (dBm)	-20	-10	0	2	3	4
IF (dBm)	-28.2	-18.2	-8.6	-6.7	-6.1	-5.6
CL (dB)	8.2	8.2	8.6	8.7	9.1	9.6
LO (dBm)	**+4 dBm**					
RF (dBm)	-20	-10	0	1	1.5	2
IF (dBm)	-28.7	-18.8	-9.4	-8.4	-8.1	-7.9
CL (dB)	8.7	8.8	9.4	9.4	9.6	9.9
LO (dBm)	**+1 dBm**					
RF (dBm)	-20	-10	0	1	1.5	2
IF (dBm)	-28.7	-18.8	-9.4	-8.4	-8.2	-7.9
CL (dB)	8.7	8.8	9.4	9.4	9.7	9.9
LO (dBm)	**-5 dBm**					
RF (dBm)	-20	-10	0	2	3	4
IF (dBm)	-39.7	-28.2	-17.1	-16.3	-16.2	-16
CL (dB)	19.7	18.2	17.1	18.3	19.2	20

Table 5.2: 1 dB Compression vs LO level

LO (dBm)	RF1 = RF2 (dBm)	IF (dBm)	IF IM Prod (dBm)	TOIP (dBm)	CL (dB)
13	-17.8	-27.9	-94	5.15	10.1
10	-17.8	-27.2	-90	4.2	9.4
7	-17.8	-26.8	-89.7	4.65	9
4	-17.8	-27.2	-90.2	4.3	9.4
1	-17.8	-28.2	-84.8	0.1	10.4
-2	-17.8	-30.6	-75.5	-8.15	12.8
-5	-17.8	-36.4	-72.1	-18.55	18.6

Table 5.3: Third Order Intercept Point vs Local Oscillator Level

5.2 DC Biased Mixer Design - No Biasing

After testing the baseline mixer, the first step in testing the modified mixer was with no biasing to compare performance against the baseline mixer. The results are shown in Table 5.4 to 5.6.

LO Level (dBm)	Vbias (V)	RF Level (dBm)	IF level (dBm)	Conversion Loss (dB)
13	0	-30	-40.2	10.2
10	0	-30	-39.7	9.7
7	0	-30	-39.2	9.2
1	0	-30	-41.3	11.3
-2	0	-30	-42.8	12.8
-5	0	-30	-46.5	16.5

Table 5.4: Conversion Loss vs LO - No bias

LO (dBm)	RF1 = RF2 (dBm)	IF (dBm)	IF IM Prod (dBm)	TOIP (dBm)	CL (dB)
7	-15	-24.8	-83.8	4.7	9.8
-5	-15	-32.95	-64.8	-17.025	17.95

Table 5.5: TOIP vs LO - No Bias

LO (dBm)	**+10 dBm**	
RF (dBm)	-30	6.5
IF (dBm)	-39.7	-4.3
CL (dB)	9.7	10.8
LO (dBm)	**+7 dBm**	
RF (dBm)	-20	4.5
IF (dBm)	-29.7	-6.2
CL (dB)	9.7	10.7
LO (dBm)	**+1 dBm**	
RF (dBm)	-20	-1.5
IF (dBm)	-31.3	-13.7
CL (dB)	11.3	12.2
LO (dBm)	**-2 dBm**	
RF (dBm)	-30	-5
IF (dBm)	-42.8	-18.9
CL (dB)	12.8	13.9
LO (dBm)	**-5 dBm**	
RF (dBm)	-30	-2
IF (dBm)	-46.5	-19.6
CL (dB)	16.5	17.6

Table 5.6: 1 dB Compression Point vs LO - No bias

5.3 DC biased Mixer

After verifying basic performance of the biased mixer design with no biasing, the conversion loss and linearity test were performed at different bias levels with different LO levels. Table 5.7 shows the diode currents for some various DC bias voltages. At an initial voltage of 1.6 V, the voltage drop across the four diodes is 0.8 V and no current flows through the diode ring. As the voltage rises, the voltage across the diodes starts to clamp around 1.6 V which is forward voltage for the four diodes in series. At a bias voltage of 4 V, the diodes are fully conducting and the power dissipated across the diode ring is 1.1 mW (+0.4 dBm).

Bias Voltage (V)	Voltage across 4 diodes (V)	Diode Current (mA)	Power (mW)
1.6	0.8	0	0.00
2.4	1.185	0.024	0.03
3.2	1.47	0.249	0.37
3.6	1.57	0.453	0.71
4	1.67	0.66	1.10

Table 5.7: Bias Voltage and Currents

Table 5.8 shows the conversion loss values for various LO levels and DC bias values. Measurements were conducted with four LO levels: +13 dBm, +7 dBm, +1 dBm, and -5dBm. The RF input level was -30 dBm during all measurements. The bias voltage was then varied from 0 V to 4 V. The conversion loss was measured at each voltage step. The table highlights the initial conversion loss measurement at 0V and the best conversion loss with the bias voltage enabled.

Vbias (V)	0.0	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0
LO @ +13 dBm											
RF (dBm)	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0
IF(dBm)	-40.2	-40.1	-40.1	-40.0	-40.0	-39.9	-39.9	-39.8	-39.7	-39.6	-39.5
CL(dBm)	10.2	10.1	10.1	10.0	10.0	9.9	9.9	9.8	9.7	9.6	9.5
LO @ +7 dBm											
RF (dBm)	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0
IF(dBm)	-39.2	-39.1	-38.9	-38.8	-38.7	-38.6	-38.5	-38.5	-38.5	-38.5	-38.9
CL(dBm)	9.2	9.1	8.9	8.8	8.7	8.6	8.5	8.5	8.5	8.5	8.9
LO @ +1 dBm											
RF (dBm)	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0
IF(dBm)	-41.3	-40.8	-40.5	-40.1	-39.7	-39.4	-39.0	-38.8	-38.7	-38.7	-41.3
CL(dBm)	11.3	10.8	10.5	10.1	9.7	9.4	9.0	8.8	8.7	8.7	11.3
LO @ -5 dBm											
RF (dBm)	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0	-30.0		-30.0
IF(dBm)	-50.4	-46.0	-43.7	-42.1	-41.0	-40.1	-39.5	-39.3	-40.3		-51.0
CL(dBm)	20.4	16.0	13.7	12.1	11.0	10.1	9.5	9.3	10.3		21.0

Table 5.8: Conversion Loss vs LO vs DC Bias Voltage

The 1 dB compression point measurements vs LO and DC bias voltage levels is depicted in Table 5.9. The 1 dB compression point is the value of RF input where the IF output no longer tracks the RF input and the conversion loss is 1 dB larger. Measurements were conducted with four LO levels: +10 dBm, +7 dBm, +1 dBm, -2 dBm and -5dBm. The initial RF input level was in the mixers linear region during the initial no bias (0 V) measurements. The RF level was then increased until the conversion loss increased by 1 dB. The bias voltage was then varied from 0 V to 4 V. The conversion loss was measured at each voltage step. The highlighted sections identify the best conversion loss for that voltage. The variation in the conversion indicates whether the 1 dB improved or deteriorated.

Vbias (V)	0	0	0.8	1.6	2.4	3.6
LO	+10 dBm					
RF (dBm)	-30	6.5	6.5	6.5	6.5	6.5
IF (dBm)	-39.7	-4.3	-4.5	-4.9	-5.4	-6.2
CL (dB)	9.7	10.8	11	11.4	11.9	12.7
LO	+7 dBm					
RF (dBm)	-20	4.5	4.5	4.5	4.5	4.5
IF (dBm)	-29.7	-6.2	-6.2	-6.4	-6.9	-8.3
CL (dB)	9.7	10.7	10.7	10.9	11.4	12.8
LO	+1 dBm					
RF (dBm)	-20	-1.5	-1.5	-1.5	-1.5	-1.5
IF (dBm)	-31.3	-13.7	-13	-12.4	-12.6	-14.6
CL (dB)	11.3	12.2	11.5	10.9	11.1	13.1
LO	-2 dBm					
RF (dBm)	-30	-5	-5	-5	-5	-5
IF (dBm)	-42.8	-18.9	-17.3	-16.3	-16	-18.8
CL (dB)	12.8	13.9	12.3	11.3	11	13.8
LO	-5 dBm					
RF (dBm)	-30	-2	-2	-2	-2	-2
IF (dBm)	-46.5	-19.6	-18.1	-17.3	-17.1	-18.5
CL (dB)	16.5	17.6	16.1	15.3	15.1	16.5

Table 5.9: 1 dB Compression vs LO vs DC Bias Voltage

Table 5.10 shows the measurements of the TOIP for a +7 dBm LO and two bias points, 0V and 2.4 V. The highlighted sections indicate the TOIP values used to calculate the average TOIP. The last values were not used since the increasing RF level was affecting the conversion loss values indicating the RF level was entering into the compression zone.

LO	+7 dBm	Vbias = 0V				
RF (dBm)	-15	-12.5	-10	-7.5	-5	
IF (dBm)	-24.8	-22.4	-19.9	-17.4	-15	
IM prod (dBm)	-83.8	-77.45	-70.5	-63.4	-54.5	
CL (dB)	9.8	9.9	9.9	9.9	10	Avg TOIP
TOIP (Calc) (dBm)	4.7	5.125	5.4	5.6	4.75	5.2
LO	+7 dBm	Bias = 2.4V				
RF (dBm)	-15	-12.5	-10	-7.5	-5	
IF (dBm)	-24.2	-21.7	-19.3	-17	-14.8	
IM prod (dBm)	-76.7	-69.7	-62.9	-55.2	-45	
CL (dB)	9.2	9.2	9.3	9.5	9.8	Avg TOIP
TOIP (Calc) (dBm)	2.05	2.3	2.5	2.1	0.3	2.2

Table 5.10: Third Order Intercept Point @ + 7 dBm vs 0 V and 2.4 V

The third order intercept points for a -5 dBm LO and two bias points, 0V and 1.6V are detailed in Table 5.11. The TOIP values used to calculate the average TOIP are highlighted in the last row for each section. The last values were again not used since the increasing RF level was entering the nonlinear range of the the mixer.

LO	**-5 dBm**	**Bias = 0V**				
RF (dBm)	-20.0	-17.5	-15.0	-12.5	-10.0	
IF (dBm)	-38.7	-35.8	-33.0	-30.2	-27.4	
IM prod (dBm)	-79.8	-73.4	-64.8	-56.0	-52.8	
CL (dB)	18.7	18.3	18.0	17.7	17.4	**Avg TOIP**
TOIP (Calc) (dBm)	-18.2	-17.0	-17.0	-17.3	-14.7	-17.4
LO	**-5 dBm**	**Bias = 1.6V**				
RF (dBm)	-20.0	-17.5	-15.0	-12.5	-10.0	
IF (dBm)	-31.6	-28.9	-26.6	-24.3	-22.4	
IM prod (dBm)	-80.9	-76.5	-67.4	-58.0	-49.1	
CL (dB)	11.6	11.4	11.6	11.8	12.4	**Avg TOIP**
TOIP (Calc) (dBm)	-7.0	-5.1	-6.1	-7.5	-9.1	-6.4

Table 5.11: Third Order Intercept Point @ - 5 dBm vs 0 V and 1.6 V

Chapter 6 Results and Analysis

The measurements were analyzed after they were acquired to determine if different biasing levels had an effect on the linearity of the mixer comparable to the effect of different LO levels.

6.1 Conversion Loss – LO level vs Bias Voltage

Figure 6.1 graphically indicates the change in conversion loss as the LO level is modified. The conversion loss is lowest at + 7dbm.

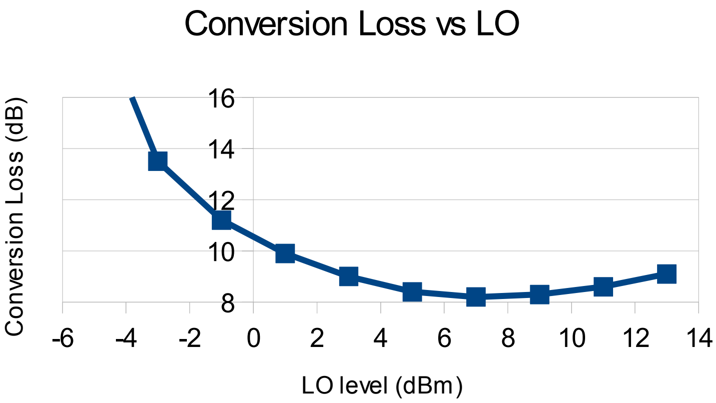


Figure 6.1: Conversion Loss vs LO

Figure 6.2 plots the conversion loss changes for each LO level as the DC biasing is adjusted. Viewing the plots there was a measurable improvement in conversion loss from the biasing for every LO level although the best conversion loss for each LO happened at different bias values.

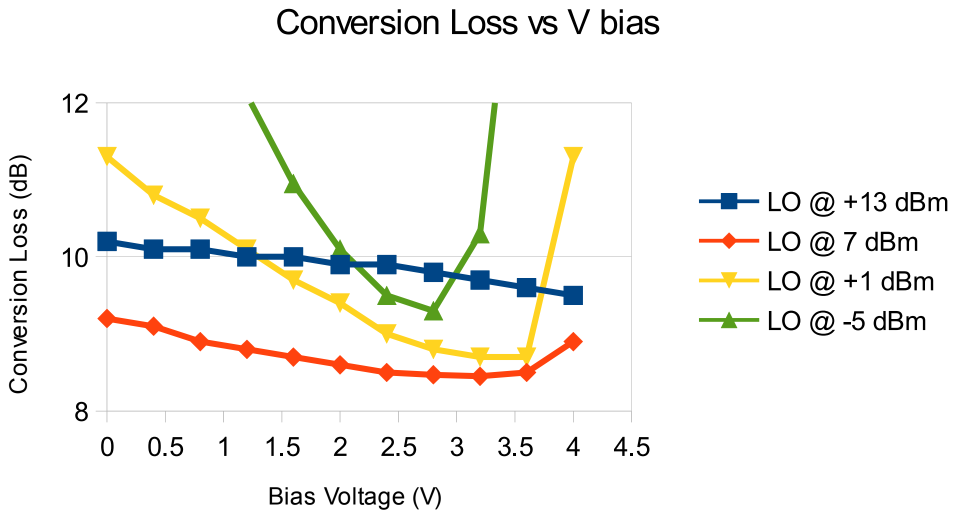


Figure 6.2: Conversion Loss vs Bias vs LO

6.2 1 dB Compression Point – LO level vs Bias Voltage

Figure 6.3 shows that as the LO increases the 1 dB compression point increases as well (higher linearity). The graph flattens on left due to the RF level approaching the LO level. This higher RF level actually allows the mixer to be more linear as well.

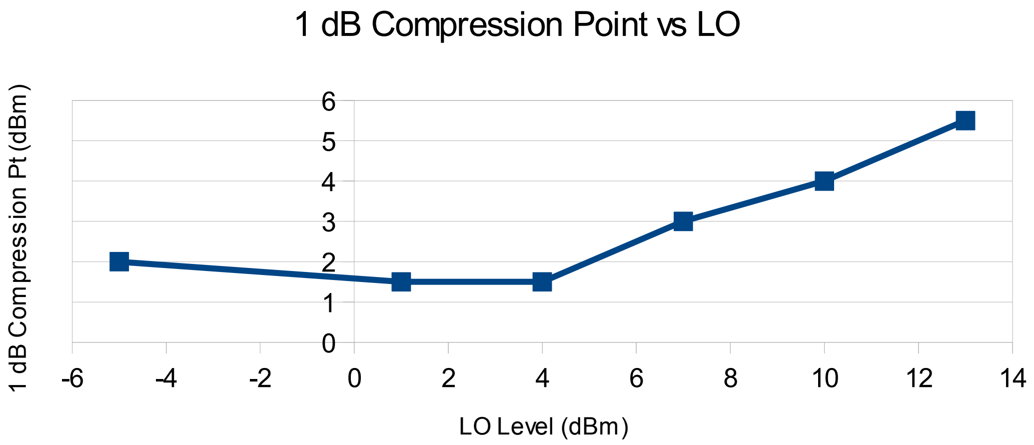


Figure 6.3: 1 dB Compression Point vs LO Level

Figure 6.4 shows the change in the 1 dB conversion loss delta between all LO levels. LO levels above +1 dBm effectively make the 1 dB compression point lower (reduces linearity) whereas with lower LO levels the biasing improves the linearity of the mixer.

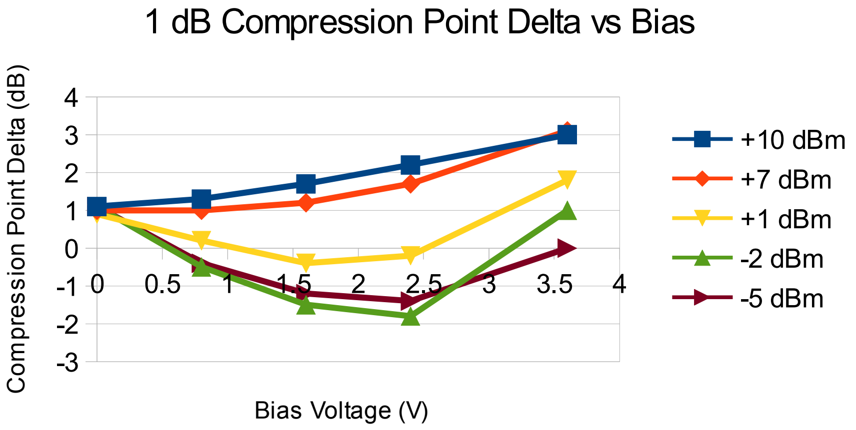


Figure 6.4: Compression Point Delta vs Bias

6.3 Third Order Intercept Point – LO level vs Bias Voltage

Figure 6.5 graphically shows that the conversion loss goes down and the TOIP increases as the LO level increases but eventually flattens around a 4 dBm LO level.

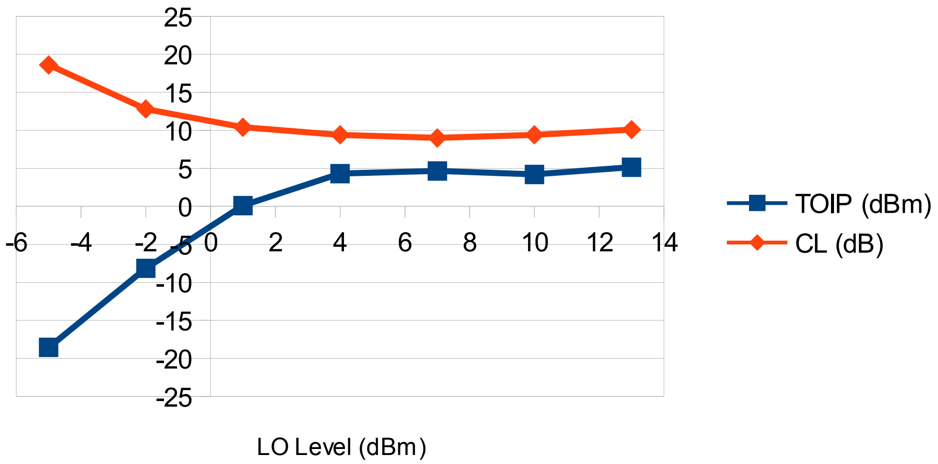


Figure 6.5: Third Order IP and Conversion Loss vs LO

Figure 6.6 shows that below an LO level of 3 dBm, the DC biasing improves the linearity performance of the mixer. Above that point, biasing makes the mixer less linear.

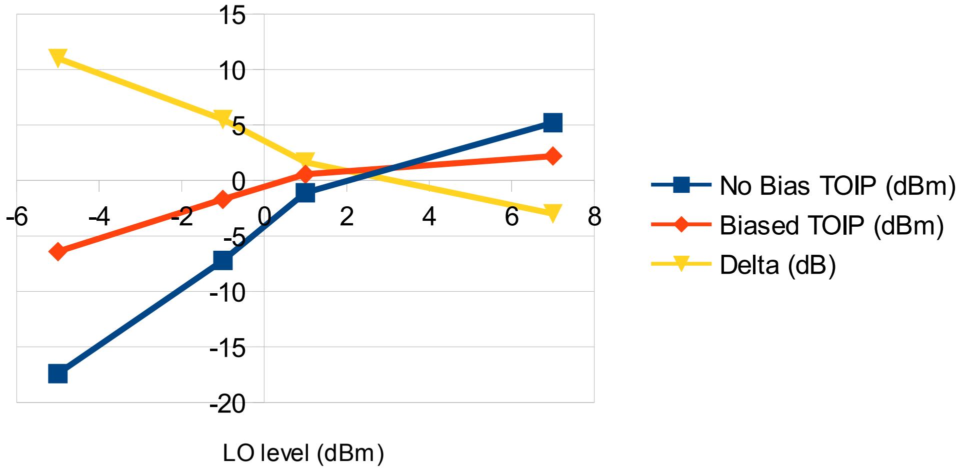


Figure 6.6: Third Order IP Biasing Effects

Chapter 7 Conclusions

After reviewing the measurements and analysis data, a conclusion can be drawn that biasing the diodes in a mixer can have a positive effect on the performance of a mixer. The conversion loss, the 1 dB compression point and the third order intercept point were all affected by the biasing when looking at various LO levels. The conversion loss was improved for all LO levels with a minimum of 0.7 dB of improvement to a maximum of 11.1 dB when the mixer was driven by an LO of -5 dBm. The 1 dB compression point was improved with biasing for LO levels ≤ 1 dBm with a likely knee occurring at ~ +3 dBm. The TOIP was also improved with biasing for LO levels ≤ 1 dBm with a crossover point occurring at ~ 3 dBm. Therefore biasing the diodes in a mixer could help improve mixer performance when LO drive levels are limited due to a design or implementation specification.

Chapter 8 Summary

8.1 Summary of Work done

This project looked at whether DC biasing of the diodes in an RF mixer could improve or maintain the linearity of a mixer with lower LO levels. A double balanced mixer with a quad ring diode configuration was designed, built, and then characterized across three mixer parameters: Conversion Loss, 1 dB Compression Point, and Third Order Intercept Point.

A new mixer was then designed that enabled DC biasing across all 4 diodes at the same time with the same current and forward voltage. The mixer was then built and its basic performance was verified. It was then characterized across the same three parameters (Conversion Loss, 1 dB Compression Point, and Third Order Intercept Point) but at various DC biasing points and LO levels.

An analysis of the measurements was completed and a conclusion was drawn that DC biasing does have a positive affect on the three parameters measured and could be used as alternative method of improving mixer performance when LO power levels are limited due to other design or implementation parameters.

8.2 Future Work

The design and implementation of the test mixer in this project was focused primarily on creating a test device to determine whether my hypothesis of biasing diodes while having lower LO power levels improved linearity. From the results and analysis detailed here there appears to be some merit to this idea.

The next steps are to design a mixer and PCB specifically to meet specific target parameters for a mixer and then to retest the diode biasing against this mixer design across larger frequency bandwidth. Other mixer topologies could also be investigated as well as other bias circuit topologies. The bias circuit component value can be investigated to determine if there is an optimal solution for various frequencies, LO levels and topologies. As well, since a DC bias circuit is much easier to control than RF or microwave amplifier levels, the bias circuit could be used to normalize and compensate for mixer performance across frequencies, temperatures, or performance environments (high intermodulation environments). This would be applicable across both receiver and transmitter signal chains. Since the DC biasing may allow for lower LO levels which typically means lower power consumption requirements, there are applications as well in low power communications equipment such as mobile phones, remote SCADA/monitoring devices, and other similar types of devices.

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