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**C-Band Up/Down Converter: Final Report**

SUBMITTED BY:

Willie Lee Thompson, II  
wlt@eng.morgan.edu

Morgan State University  
Center of Microwave, Satellite and RF Engineering  
Schaefer 353

## **ABSTRACT**

**A singly balanced 180-degree monolithic microwave integrated circuit (MMIC) is presented in this paper. The mixer exhibits up and down conversion capabilities for RF frequencies ranging from 5150 MHz to 5875 MHz, LO frequencies ranging from 5425 MHz to 5625 MHz and IF frequency of 275 MHz, respectively. Simulations exhibit a conversion loss of < 10 dB for a LO power of 3 dB for both up and down conversion with an LO-to-RF isolation > -22 dB. The MMIC circuit fits on a 60 mils x 60 mils chip with a +5 V power supply and will be implemented in a simplex transceiver for HiperLAN wireless local area network (WLAN).**

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## 1.0 INTRODUCTION

The HiperLAN transceiver will be used to receive and send data within two RF bands. The lower band ranges from 5150 MHz to 5350 MHz, while the upper band ranges from 5725 MHz to 5875 MHz. The mixer is responsible for down converting the RF signal with the two bands to an IF signal in receive mode and up converting the IF signal to a RF signal within the bands in send mode. As a result, the circuit architecture used for the mixer must be able to up and down convert without any modification to the topology.

### 1.1 CIRCUIT ARCHITECTURE

The circuit architecture selected for the mixer is a singly balanced 180-degree mixer, best known as a “rat-race” mixer. The mixer consists of a lumped element 180-degree hybrid, two 80- $\mu\text{m}$  DFETs diodes, a low-pass filter for IF port filtering and two high-pass filters for LO and RF port filtering, respectively. Figure 1.1 illustrates the general topology of a singly balanced 180-degree mixer.

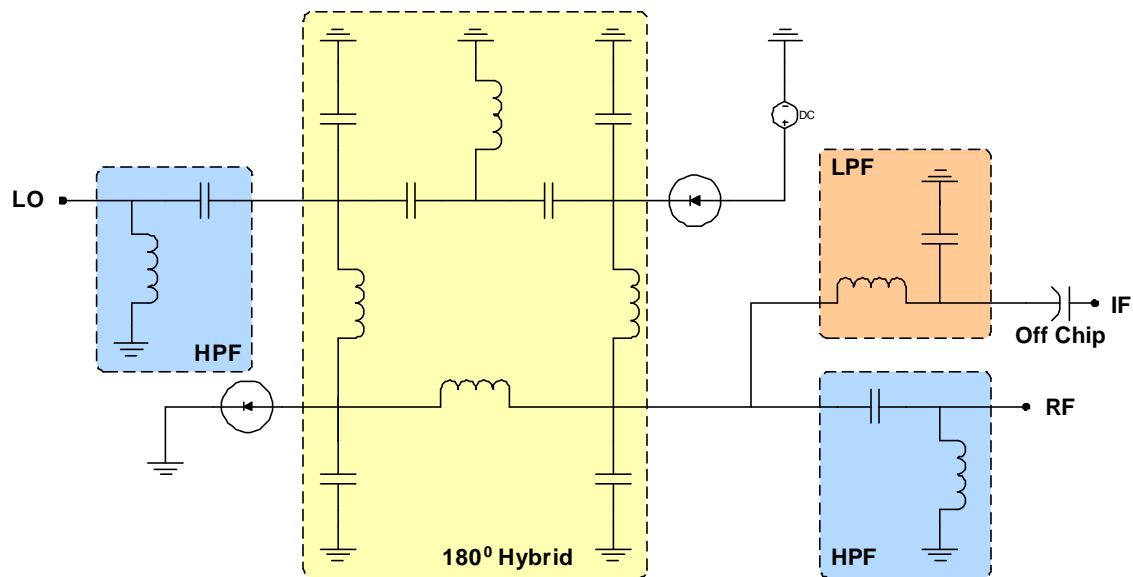


Figure 1.1.1: Singly balanced 180-degree mixer architecture.

This architecture utilizes the nonlinear conductance of the diodes for mixing. Diodes are more stable than field-effect transistors (FETs) and allows for mixing in both directions. The shunt configuration of the diodes allows for easier impedance matching to the 50- $\Omega$  at the hybrid's ports. Proper biasing and sizing of the DFETs can achieve impedance match. We concluded that an 80- $\mu\text{m}$  DFET with 2 gate fingers connected in diode configuration provided the best impedance match.

LO signal is located at the  $\Delta$  port and the RF/IF signals are located at the  $\Sigma$  port of the 180-degree hybrid, respectively. As a result, the hybrid splits the LO power between the two diodes ports with a 180-degree phase shift, while RF/IF powers are split between the diodes ports in phase. Filtering is implemented at the RF/IF port to separate the signals after mixing. In addition, filtering at the ports improves the RF-to-IF isolation and LO-to-IF isolation. LO-to-RF isolation is achieved by the properties of the hybrid, where the  $\Delta$  and  $\Sigma$  ports are mutual isolated from each other.

Biasing of the diodes is used for starved LO operation of the mixer, which allows for smaller LO powers. The DC bias supply is coupled between the diodes via the hybrid and the blocking capacitors at each ports. An off chip blocking capacitor must be used due to low frequency of the IF signal, which requires a high value capacitor that cannot fit onto the chip.

## 1.2 DESIGN PHILOSOPHY

The design philosophy was determined by the specifications for the mixer. The specification of interested were:

- Up and down conversion abilities
- Layout Constraints
- High LO-to-RF isolation
- Low conversion loss

Concerning the above specifications, it was determine that the following architectures were candidates for the mixer: 1) 90-degree mixer, 2) singly balanced 180-degree mixer and 3) doubly balanced mixer.



and RF are connected to the  $\Delta$  and  $\Sigma$  ports, respectively. However, we implemented a novel approach for connecting the diodes. The diodes were connected in a shunt configuration as shown in Figure 1.1. The shunt configuration allows for good impedance matching of the diode independently for each other and easy implementation of DC bias via the hybrid.

### 1.3 TRADE-OFFS

The major trade-off for the design was the layout constraint of the MMIC. The doubly balanced mixer is an excellent general-purpose mixer design. It exhibits wide bandwidth, good spurious response injection and good port isolation. However, the implementation of a balun cannot be achieved. The 180-degree mixer exhibits a narrower bandwidth, which requires the RF/LO frequencies to be within 15% of each other. The bandwidth requirement is met by the frequency specifications for the mixer and the layout of the 180-degree hybrid is easily implemented with lumped elements.

A couple of minor trade-offs were made: 1) the sizing of the diodes for impedance matching, 2) layout design of the hybrid, and 3) inductor values for the RF/LO and IF filters. The input and output impedances of the diodes vary with DC bias and diode size. As a result, special interest was taken to bias and size the diodes to provide proper impedance to the hybrid's ports. Secondly, the hybrid requires the use of four shunt capacitors to ground. A layout design was implemented to share a center via to ground between the shunt capacitors. This configuration prevented the usage of multiple vias, which require significant amount of die area. Lastly, the optimum inductor values were calculated for each filter types. Due to layout constraints, the inductor values were modified with minimum effect on the overall transfer response of the filters. However, changing the inductors values affect the input impedance of the filters and the VSWRs of the ports. The VSWR specifications were still met, but were not ideal.

## 2.0 MODELED PERFORMANCE

### 2.1 SPECIFICATION MATRIX

Table 2.1 summarizes the design specifications and simulated performance of the singly balanced 180-degree mixer. All specifications for the design were met.

Table 2.1: Specification matrix and simulated performance results.

Specification	Goal	Acceptable	Simulated
Frequency Bandwidths	<u>Lower RF Band</u> 5150 – 5350 MHz	<u>Lower RF Band</u> 5150 – 5350 MHz	<u>Lower RF Band</u> 5150 – 5350 MHz
	<u>Upper RF Band</u> 5725 – 5875 MHz	<u>Upper RF Band</u> 5725 – 5875 MHz	<u>Upper RF Band</u> 5725 – 5875 MHz
	<u>LO Band</u> 5425 – 5625 MHz	<u>LO Band</u> 5425 – 5625 MHz	<u>LO Band</u> 5425 – 5625 MHz
	<u>IF Band</u> 275 MHz	<u>IF Band</u> 275 MHz	<u>IF Band</u> 275 MHz
LO-to-RF Isolation	-16 dB	- 10 dB	> -22 dB
Conversion Loss	-7 dB	- 10 dB	9.10 dB*
LO Power	0 dBm	+7 dBm	3 dBm**
VSWR	1.5:1	2.5:1	~1.75:1
Supply Voltage	5 V	0 – 5 V	5 V
Size	60 mils x 60 mils	60 mils x 60 mils	60 mils x 60 mils

\*Conversion loss is an average of up and down conversion simulation results for both RF bands.

\*\*LO power is the LO power that met conversion loss specification for both up and down conversions.

## 2.2 PREDICTED PERFORMANCE

### 2.2.1 180-DEGREE HYBRID PERFORMANCE

The simulated performance of the 180-degree hybrid is illustrated in Figure 2.1. As previously discussed, the LO signal is connected to the  $\Delta$  port ( $S_{1,1}$ ), the RF and IF signals are connected to the  $\Sigma$  port ( $S_{4,4}$ ), and the diodes are connected the port 2 ( $S_{2,2}$ ) and port 3 ( $S_{3,3}$ ), respectively. The powers division of the  $\Delta$  and  $\Sigma$  ports at the diode ports are approximately -3 dB and -4.2 dB, respectively. The phase differences at the diode ports are ~180 degree and ~0 degree across the operating band of the mixer, respectively.

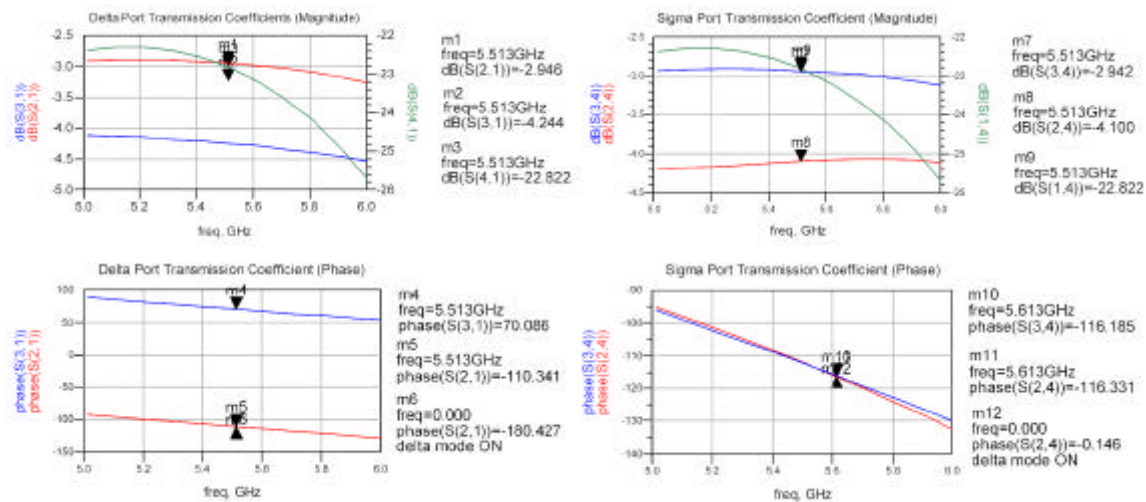


Figure 2.1: Simulated performance of the 180-degree hybrid.

### 2.2.2 FILTERS PERFORMANCE

The simulated performance of the filters is illustrated in Figure 2.2. The LO and RF filters are high-pass filters using series capacitor and shunt inductor configuration. The IF filters is a low-pass filter using series inductor and shunt capacitor configuration. Each filter was design to provide approximately -20 dB of attenuation for the undesired frequencies. As illustrated in Figure 2.2, the LO/RF filters provide approximately -30 dB of attenuation at the IF frequency of 275 MHz, while the IF filter provides at least -20 dB of attenuation across the operating band of the mixer.

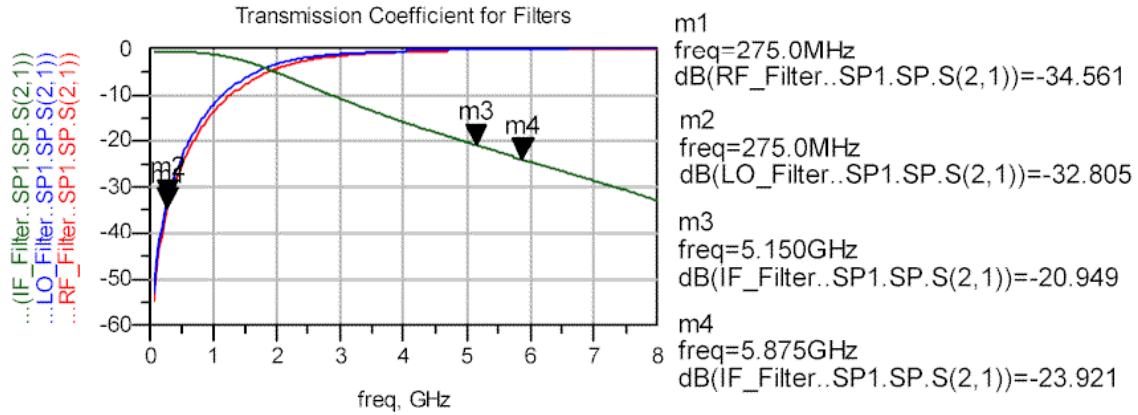


Figure 2.2: Simulated performance of the filters used in the singly balanced 180-degree mixer.

### 2.2.3 Down Converter Performance

The mixer’s performances as a down converter are illustrated in Figure 2.3 and Figure 2.4. In Figure 2.3, the mixer is configured for down converting frequencies in the lower band, while in Figure 2.4, it is configured for down converting frequencies in the upper band. The LO and RF powers were +3 dBm and –20 dBm for both configurations. The conversion losses were –8.22 dB and -8.75, respectively.

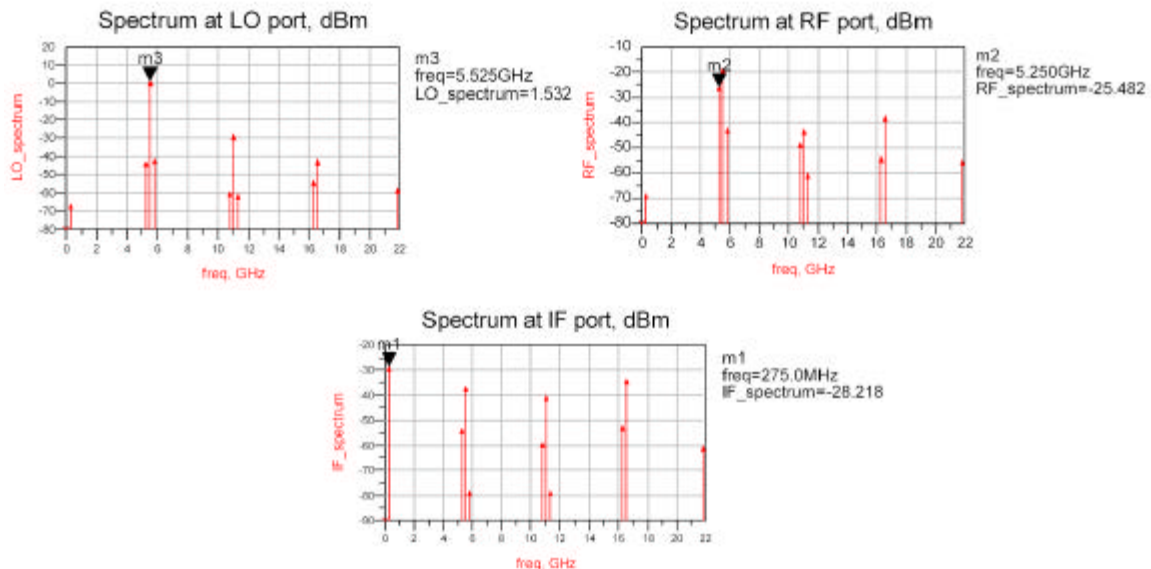


Figure 2.3: Simulated performance of mixer as a down converter for lower band frequencies.

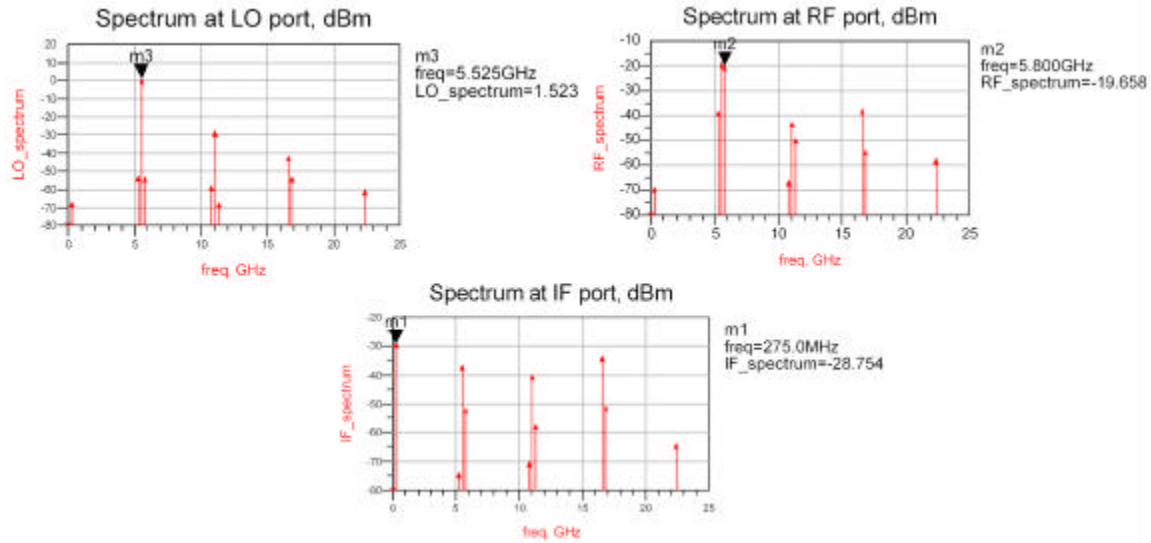


Figure 2.4: Simulated performance of mixer as a down converter for upper band frequencies.

The conversion loss is a function of LO power. To find optimum performance for the mixer, simulations of the conversion loss as a function of LO power were performed. The results of the simulations are plotted in Figure 2.5. The optimum LO powers for the down converter were +3 dBm for the lower band and +5.5 dBm for the upper band. In addition, several other simulations were performed for verification of design and are summarized in Table 2.2.

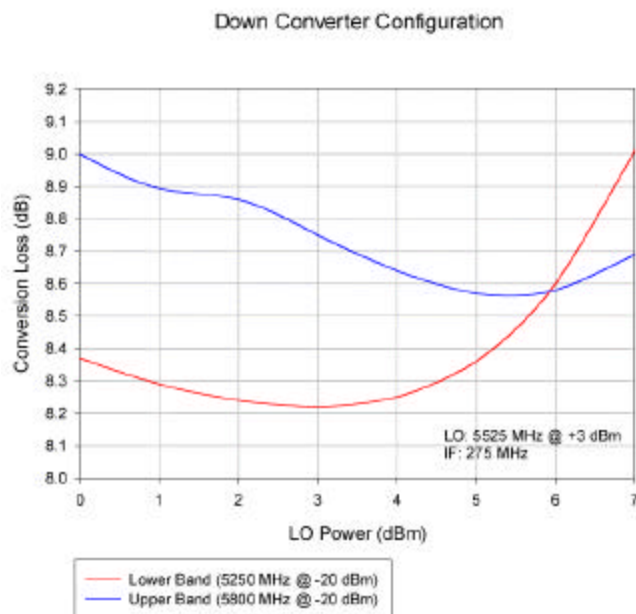


Figure 2.5: Simulation results of conversion loss as a function of LO power.

Table 2.2: Summary of simulated performances for down converter configurations.

RF Frequency	LO Frequency	IF Frequency	Conversion Loss
5250 MHz	5525 MHz	275 MHz	-8.22 dB
5800 MHz	5525 MHz	275 MHz	-8.75 dB
5150 MHz	5425 MHz	275 MHz	-8.21 dB
5875 MHz	5600 MHz	275 MHz	-9.22 dB

\*LO power was +3 dBm and RF power was -20 dBm for all simulations.

### 2.2.4 Up Converter Performance

The simulated performance of the mixer as a up converter is illustrated in Figure 2.6. The up converter produces both lower and upper band RF frequencies for a given LO and IF configuration. The lower band is given by  $f_{\text{LOWER}} = f_{\text{LO}} - f_{\text{IF}}$  and upper band is given by  $f_{\text{UPPER}} = f_{\text{LO}} + f_{\text{IF}}$ . The LO and IF powers for the simulation were +3 dBm and 0 dBm, respectively. Conversion loss as a function of LO power is illustrated in Figure 2.7 and Table 2.3 summarizes the simulated performance of several simulation configurations.

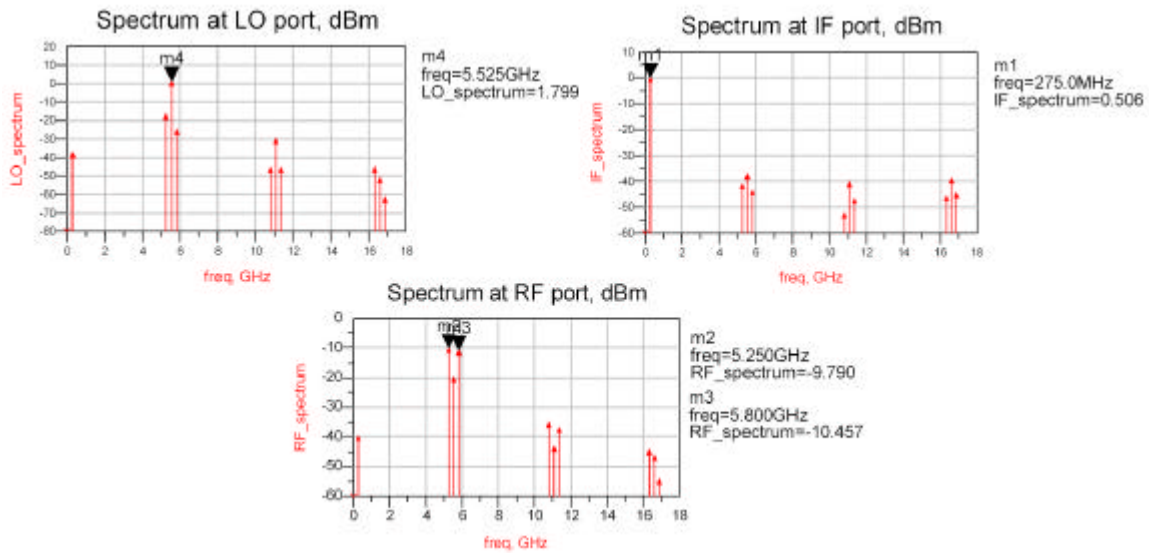


Figure 2.6: Simulated performance of mixer as a up converter.

Up Converter Configuration

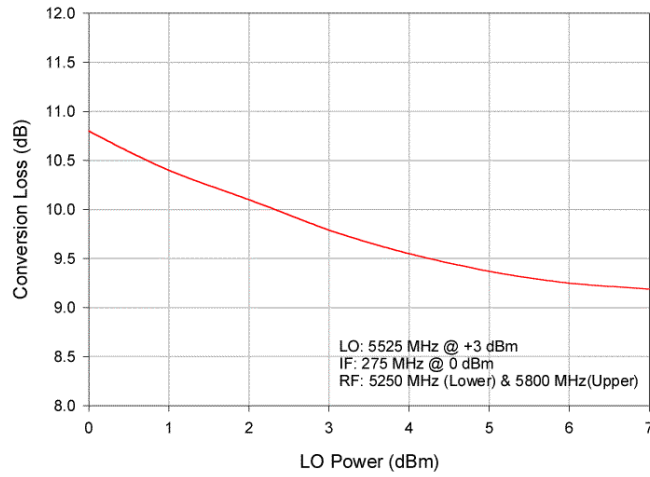


Figure 2.7: Simulation results for conversion loss as a function of LO power.

Table 2.3: Summary of simulated performances for up converter configurations.

LO Freq	IF Freq	Lower Freq	Upper Freq	Conversion Loss
5525 MHz	275 MHz	5250 MHz	5800 MHz	9.79 dB
5425 MHz	275 MHz	5150 MHz	5700 MHz	9.72 dB
5600 MHz	275 MHz	5325 MHz	5875 MHz	9.81 dB

\*LO power was +3 dBm and IF power was 0 dBm for all simulations.

Figure 2.7 demonstrates that the up converter requires more LO power to obtaining the minimum specification of a conversion loss, while the down converter configuration met the specification with a LO power of 0 dBm. In addition, the optimum LO power for the up converter seems to be greater than the allowable LO power of 7 dB.

### 2.2.5 ISOLATION AND VSWR PERFORMANCE

The simulated performance for the LO isolation and VSWRs is illustrated in Figure 2.8. The LO-to-RF isolation is greater than  $-20$  dB across the operating band and LO-to-IF isolation is greater than  $-35$  dB across the operating band. The VSWR specification of 2.5:1 is met for each port.

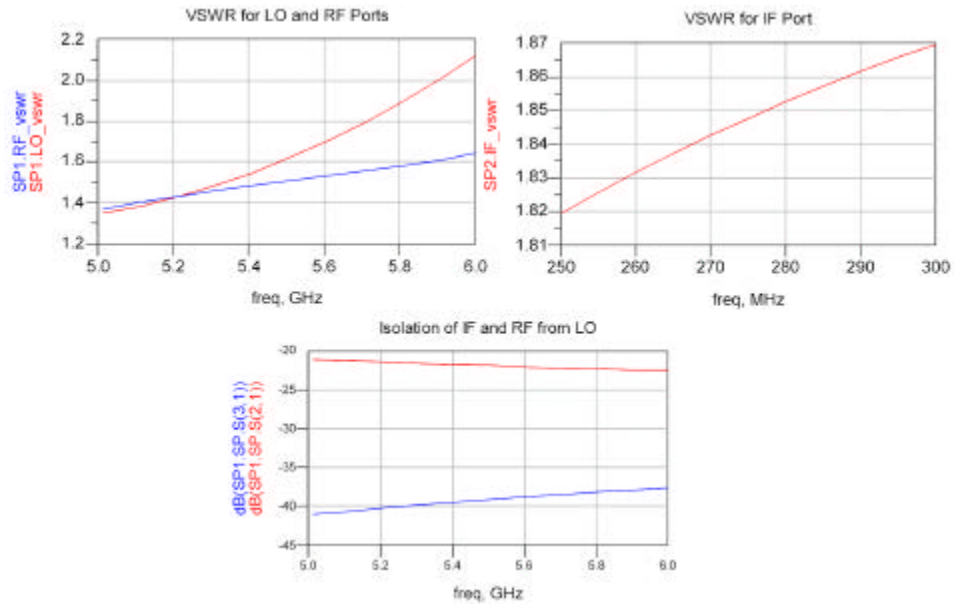


Figure 2.8: Simulated performance for LO isolation and VSWR for each port.

### 3.0 FINAL LAYOUT

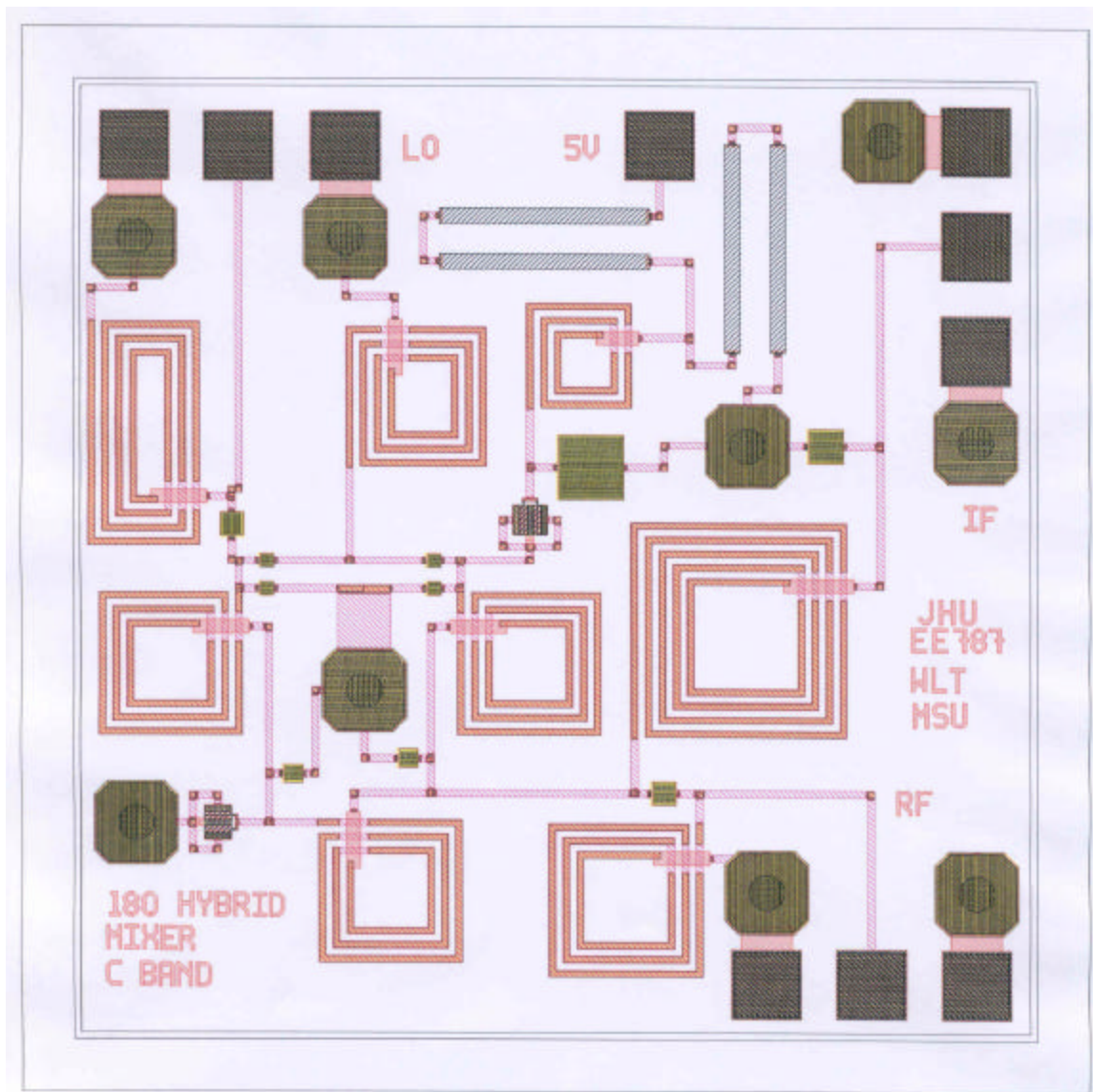


Figure 3.1: Final layout of singly balanced 180-hybrid mixer.

Implanted resistors were used for the voltage divider to provide the proper DC biasing of the DFET diodes. All interconnects, capacitors, inductors and resistors were sized for current capabilities that are twice the maximum circuit current. All inductors, microstrip lines, capacitors and vias were spaced  $\sim 3$  times the line width from each other to minimize signal coupling.

## 4.0 DC ANALYSIS

The DC bias of the diodes is essential for starved LO operation of the mixer. The DFET diodes were bias at a DC voltage of 0.65 V and a DC current of  $\sim 800 \mu\text{A}$ . This bias point provided the best impedance match at the hybrid's ports and the nonlinear conductance that is required for mixing. Figure 4.1 – Figure 4.3 show the DC analysis results for a simplified schematic architecture of the singly balanced 180-degree mixer. The DC current and voltage is coupled between the diodes via the hybrid and the blocking capacitors at each port. A DC voltage of 1.3 V is supplied by a voltage divider and a +5V power supply. The 1.3 V will be approximately dropped evenly across both diodes resulting in biasing voltages of 0.65 V for each diode and DC current of  $\sim 800 \mu\text{A}$ .

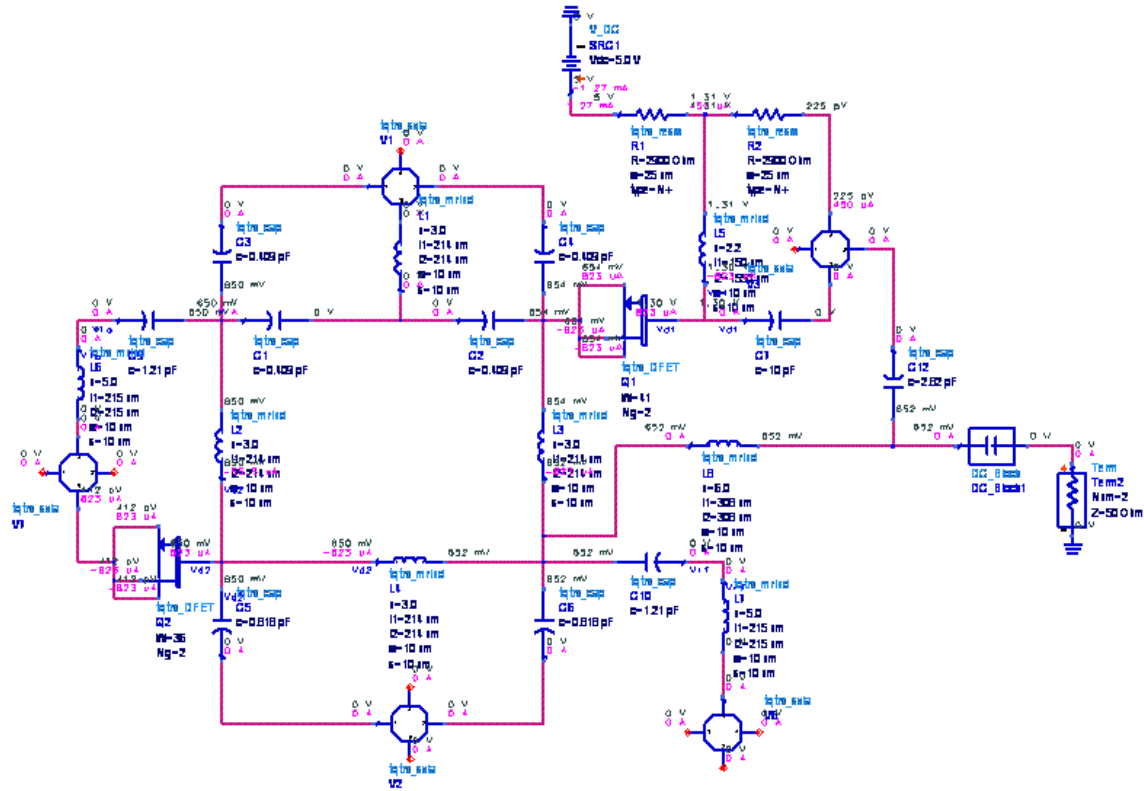


Figure 4.1: DC analysis results for a simplified schematic diagram of the singled balanced 180-degree mixer.

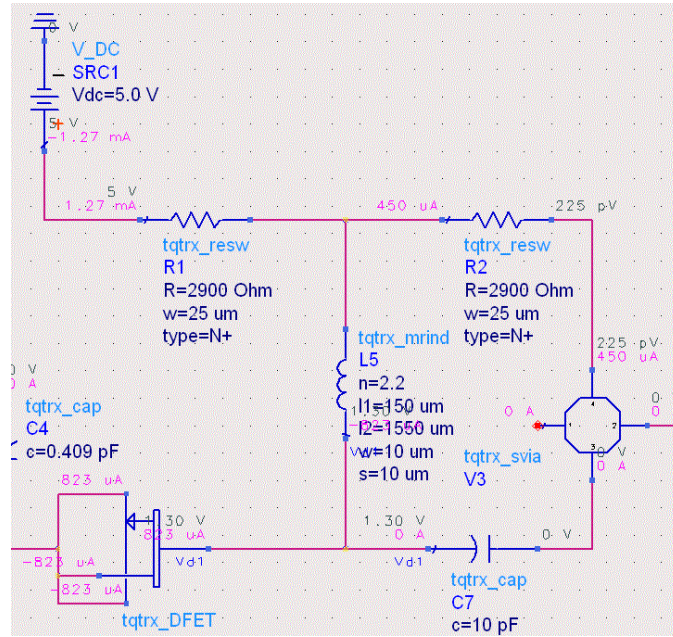


Figure 4.2: DC analysis results for voltage divider and DFET diode @ port 3.

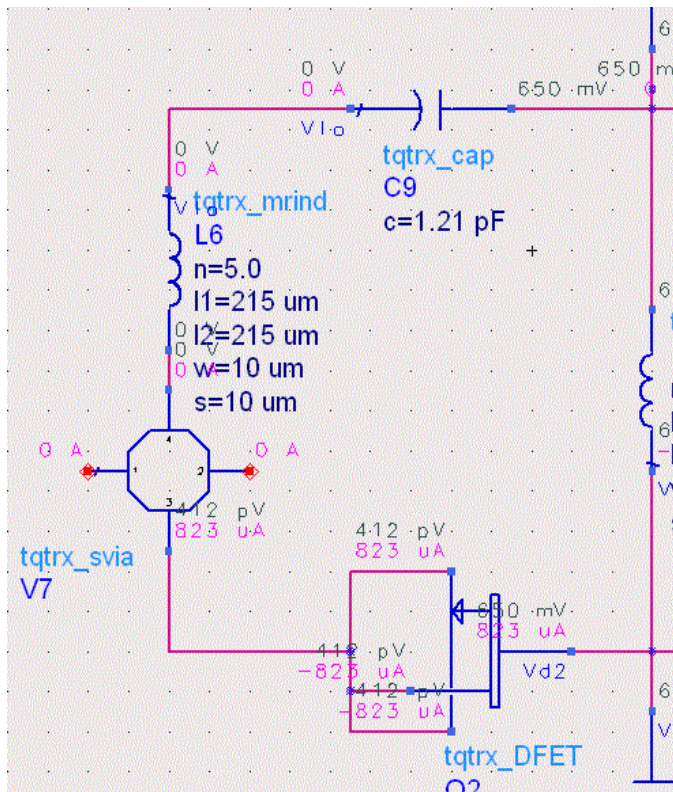


Figure 4.3: DC analysis results for DFET diode @ port 2.

## 5.0 TEST PLAN

### 5.1 SPECTRUM TEST CONFIGURATION

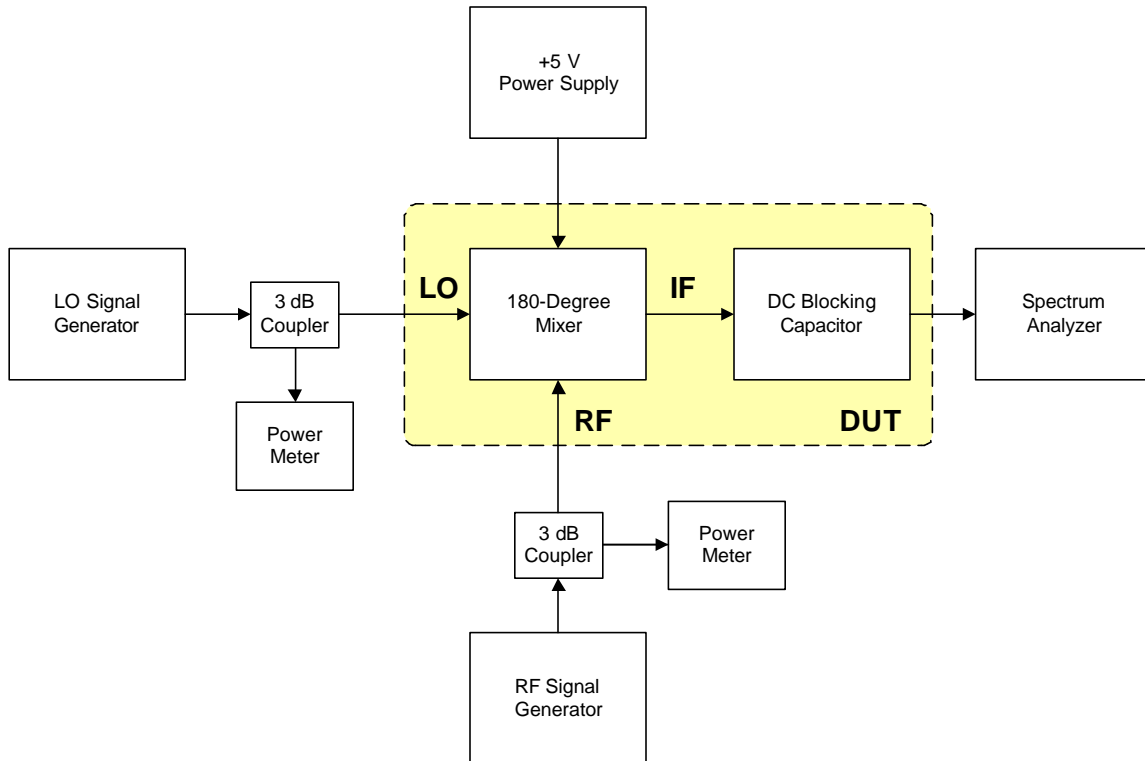


Figure 5.1: Test configuration for spectrum measurement in the down converter configuration.

To properly analyze the mixing capabilities of a mixer requires the measurement of the mixer's output spectrum. The spectrum contains all the frequency components and their power levels within the output signal. Figure 5.1 illustrates the test configuration for measuring the spectrum of the down converter configuration. The LO and RF signals are inserted into the mixer using signal generators and the output spectrum is measured by a spectrum analyzer. The 3 dB couplers and power meters are used to measure the LO and RF power levels, respectively.

To measure the output spectrum for the up converter configuration, the spectrum analyzer would be connected to the RF port of the mixer and the signal generator with the coupler and power meter would be connected to the IF port of the mixer. The LO branch would remain the same.

## 5.2 ISOLATION AND VSWR TEST CONFIGURATION

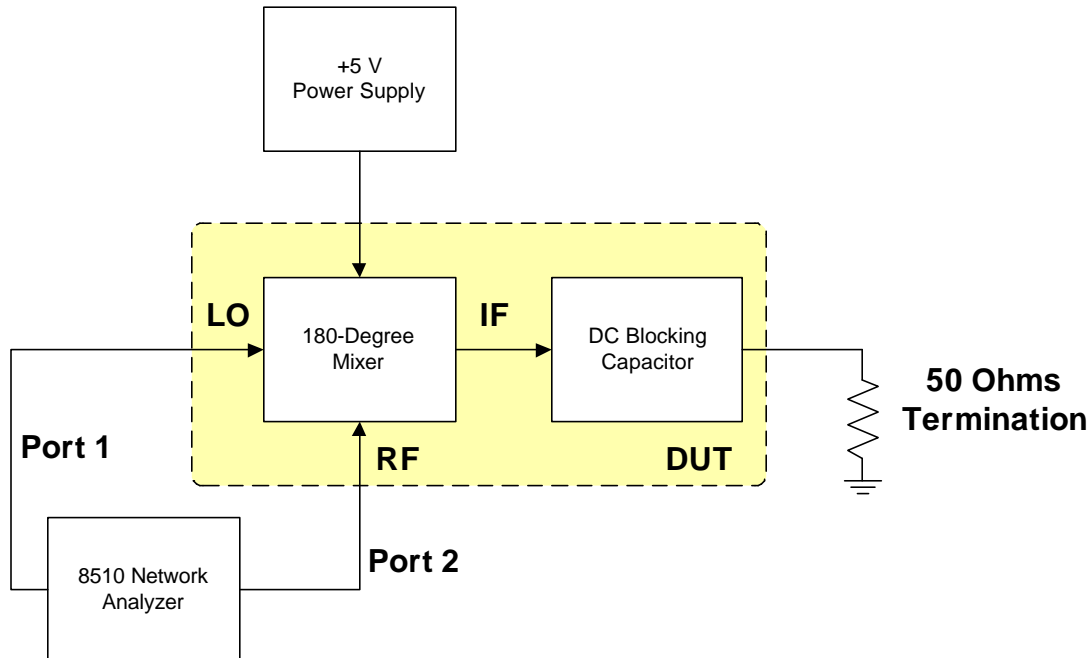


Figure 5.2: Test configuration for measurement of LO isolation and VSWRs

The LO isolation and VSWRs can be measured by using a network analyzer. The network analyzer will measure the LO isolation and VSWRs as a function of frequency. The LO-to-RF isolation can be obtained by measuring the forward transmission coefficient ( $S_{21}$ ) and the VSWRs at each port can be obtained by measuring the input and output reflection coefficients ( $S_{11}$  and  $S_{22}$ ) as illustrated in Figure 5.2. The 8510 network analyzer is a two-port measurement instrument and requires the proper termination of the IF port of the mixer for the down converter configuration. VSWR is calculated using the following equation:

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (5.1)$$

where  $\Gamma$  is the reflection coefficient at that port.

The LO-to-IF isolation and VSWRs for the up converter configuration can be measured by connecting the network analyzer to the IF port and terminating the RF port.

## 6.0 CONCLUSION

A complete MMIC design for a C-Band singly balanced 180-degree mixer was presented with a conversion loss of  $< 10$  dB @ LO power of +3 dBm for both up and down conversion configurations. All other specifications for the mixer were met as demonstrated in Section 2 of this report. The novel shunt diode architecture was used to improve the impedance matching of the diodes at the hybrid's ports, which allowed for better conversion loss.

The conversion loss was a strong function of LO power. It was demonstrated that a LO power of +3 dBm was optimum for both up and down converting to meet the conversion loss specification. The up converter configuration required more LO power than the down converter configuration.

An improvement to this design could be better matching of the filters to  $50 \Omega$ , which may decrease the conversion loss even further for both configurations. Also using better filter architectures (i.e. 3 section Butterworth filter) could improve the LO isolation and conversion loss, but requires more die area.

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