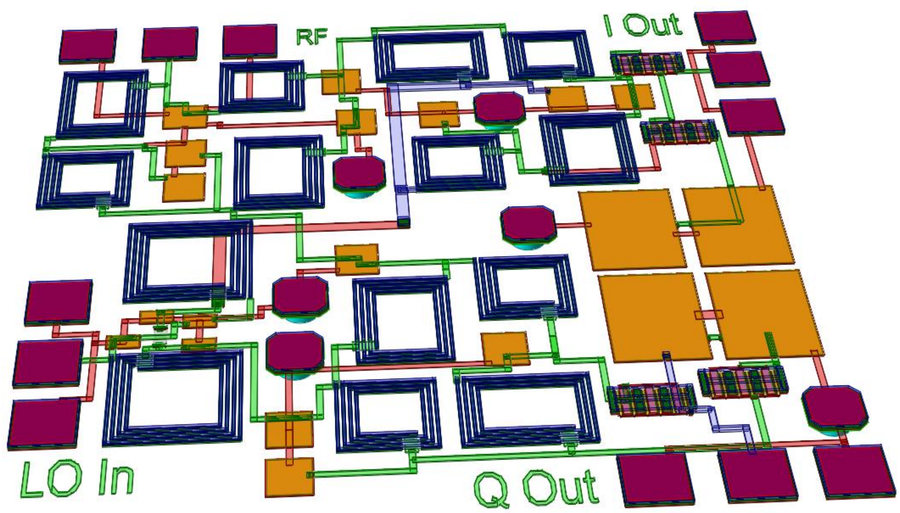
IQ Demodulator

David C. Nelson

14 December 2009



ABSTRACT
The IQ Demodulator is an RF down-converter that converts an RF input into two IF outputs with a 90 degree phase difference. The demodulator has two inputs. The RF input ranges from 2.4 to 2.5 GHz, and a fixed LO of 2.45 GHz is used. The IF outputs range from 1 to 50 MHz. The phase shift in the RF input is implemented using a hybrid coupler. The down-conversion is performed by two single-balanced mixers. The LO input is split between the two mixers using a Wilkinson Divider. Using an RF input power of 10 dBm and an LO input power of 15 dBm, a conversion loss of 10 to 14 dB was achieved at the IF output. The I and Q outputs have a phase difference of between 125 and 133 degrees.

INTRODUCTION
An IQ demodulator splits the received signal into two paths. A phase shift of 90° is applied to one signal path while the other is passed with no phase shift, essentially performing a Hilbert transform on the "Q" path. A down-conversion is performed on each path.

In a receiver, if the received signal were

$$A\cos(\omega_1 t)$$

In order to sample this signal directly the Nyquist theorem must be adhered to because the signal has both positive and negative frequency content. The minimum sampling rate would thus be limited to:

$$f_s \geq 2 f_1$$

However, by summing the I and Q paths of the IQ Demodulator the received signal becomes:

$$A\cos(\omega_2 t) + jA\sin(\omega_2 t) = A\exp(j\omega_2 t)$$

Where $\omega_1 > \omega_2$

This signal has only positive frequency content and sub-sampling can be performed without harmful aliasing.

This IQ demodulator was implemented using a hybrid coupler, a Wilkinson divider, and two single-balanced mixers. A block diagram is shown in Figure 1.

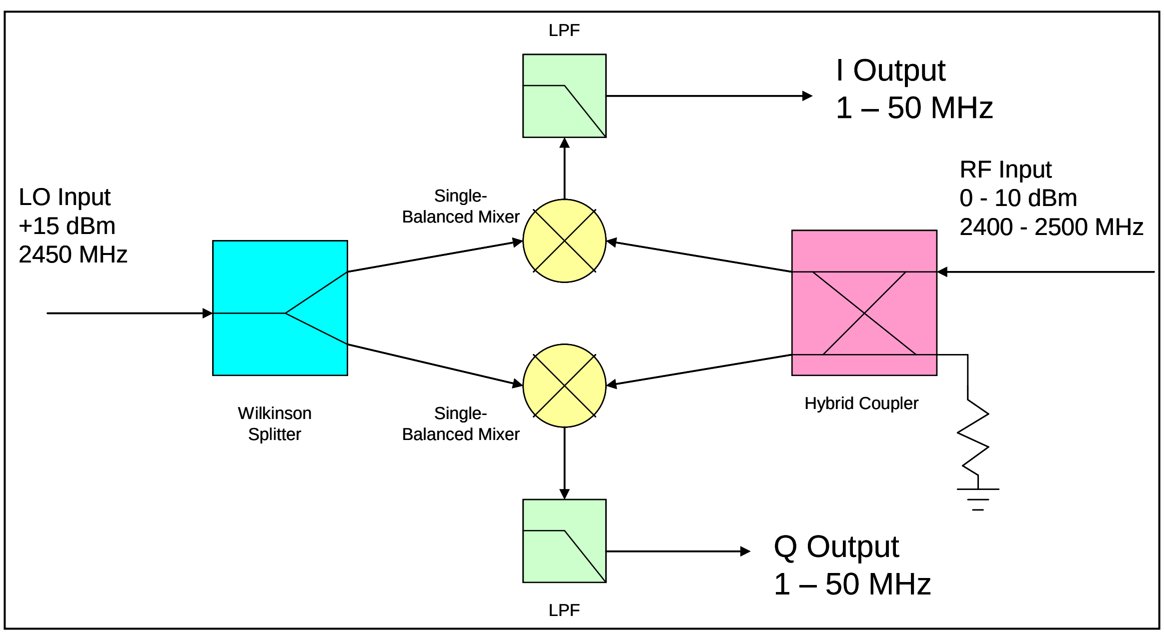


Figure 1: IQ Demodulator Block Diagram

Design Approach

This design was not given a lot of specifications, so the designer derived some self-imposed goals.

Specifications	
RF Frequency	2.4 – 2.5 GHz
LO Frequency	2.3 – 2.6 GHz
LO Power	+7 dBm
IF Frequency	1 – 50 MHz
Goals	
Conversion Loss	About 10 dB
IQ Phase Difference	90 +/- 5 degrees
Input Return Loss	15 dB

The following procedure was used to design the IQ demodulator:

- Design and Simulate Sub-Circuits
  - Hybrid Coupler
  - Wilkinson Divider
  - Single-Balanced-Mixer
- Integrate Sub-Circuits
- Simulate IQ Demodulator
- Iterate as needed

The hybrid coupler designed in Homework 1 was re-tuned and used in the I-Q Demodulator. The coupler was used for two purposes. The first was to split the RF input into the I and Q paths of the demodulator and provide the Q path with a 90 degree phase shift. The coupler was also used as the balun in the single-balanced mixers.

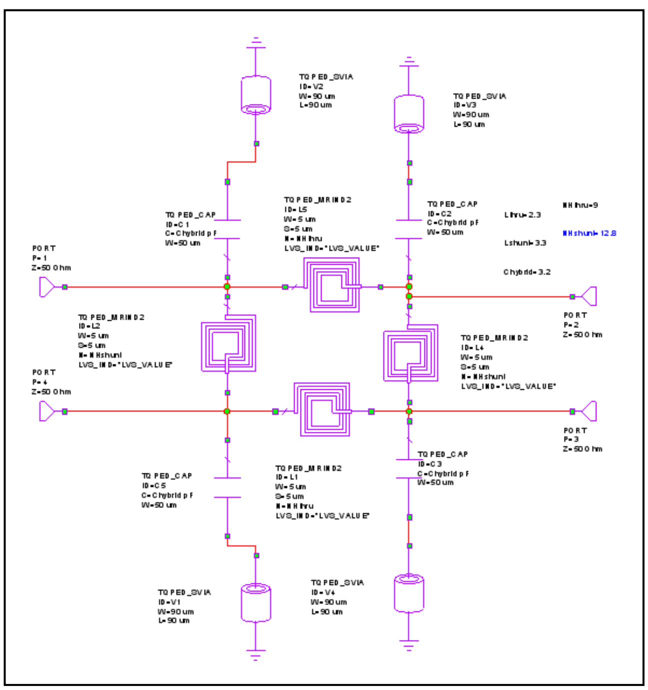


Figure 2: Hybrid Coupler Schematic

It can be seen in Figure 2 that pi networks were used for the quarter-wave lumped-element equivalent circuits. The pi networks were chosen in order to minimize the number of inductors in the design. The coupler was designed for a center frequency of 2.4 GHz.

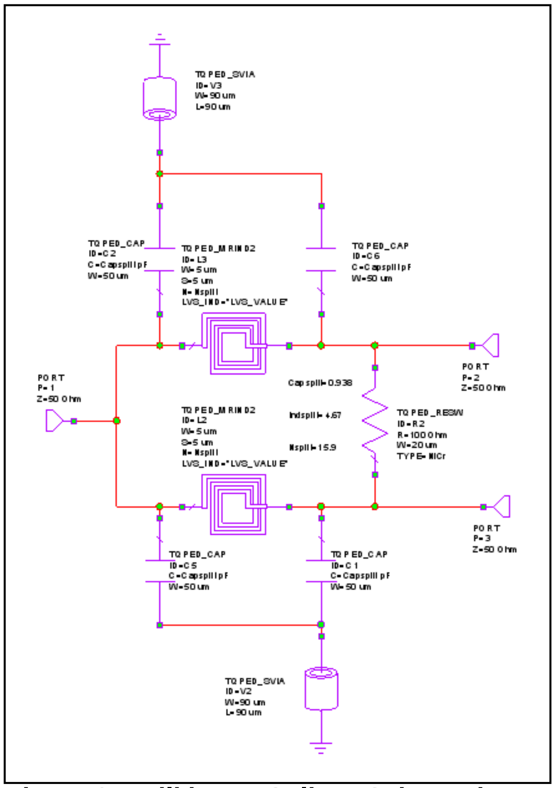


Figure 3: Wilkinson Splitter Schematic

The splitter shown in Figure 3 was designed for a center frequency of 2.4 GHz. Pi networks were used for the quarter wave lumped-element equivalent circuits to minimize the number of inductors in the design.

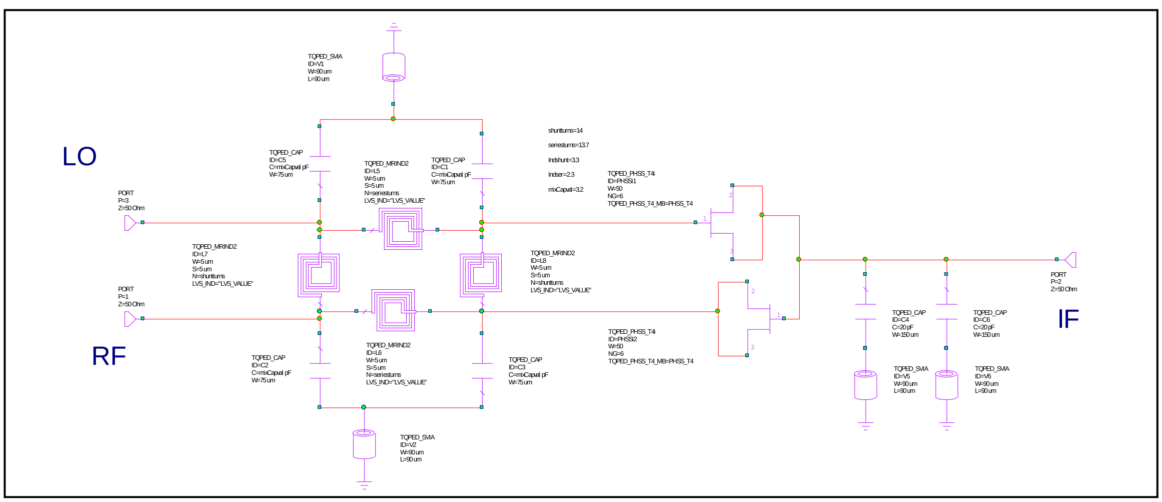


Figure 4: Single-Balanced Mixer

A rat-race coupler would have provided better isolation, but a hybrid coupler was used in the SBM design because it was already being used elsewhere in the modulator. The rat-race coupler would have added another inductor, which probably would not have fit on the 60x60 mil substrate that was used.

The topology used for this mixer is somewhat different than what was suggested in class.

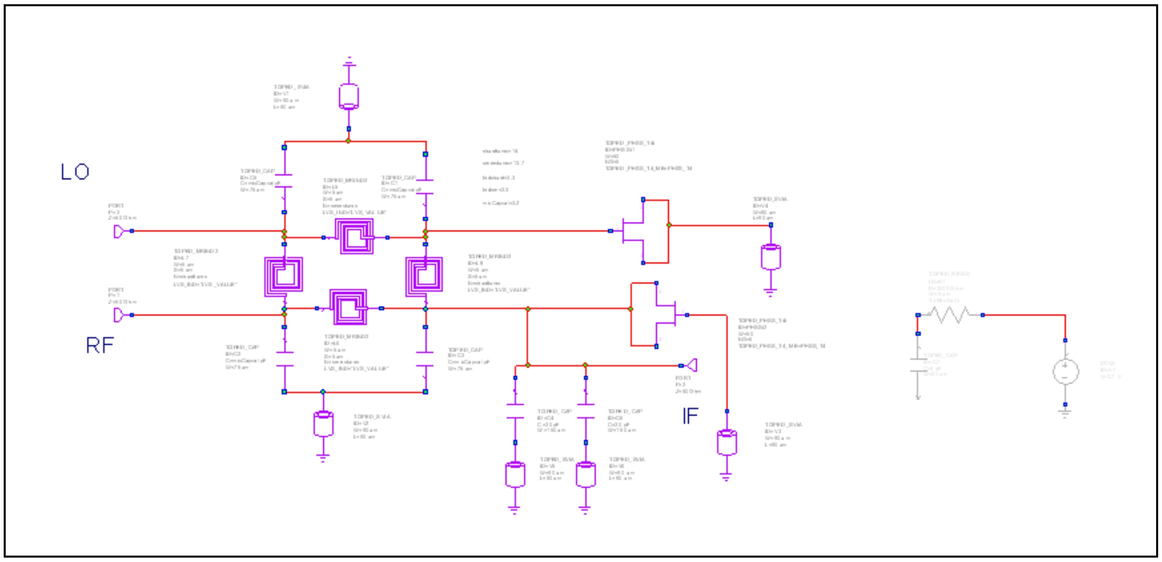


Figure 5: Mixer topology suggested in class

It can be seen in Figure 4 that rather than connecting the diodes to ground the diodes were connected in series between the two output ports of the coupler. This topology was derived from McClaning's design in *Radio Receiver Design* Shown in Figure 6.

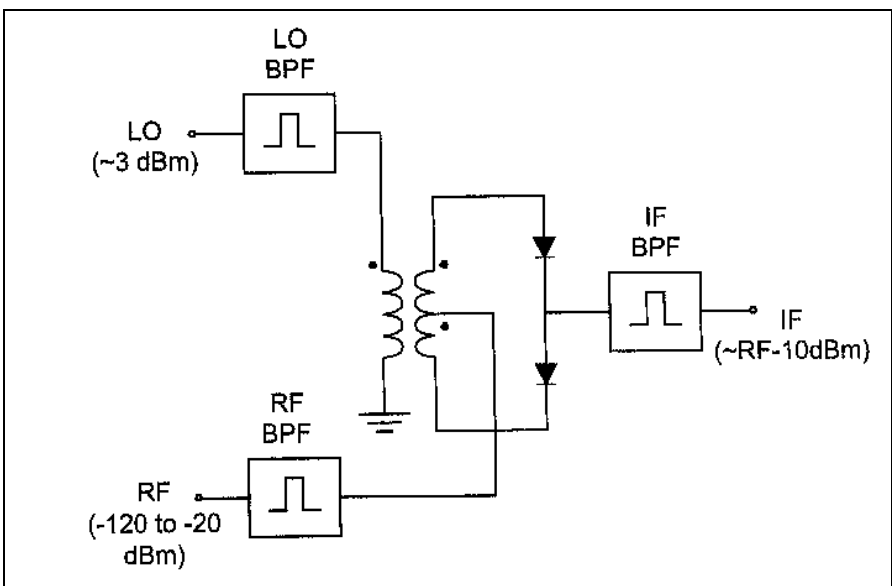


Figure 6: Single-balanced mixer from *Radio Receiver Design*[1]

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[1] McClaning, Kevin and Tom Vito. *Radio Receiver Design*. Noble Publishing Corporation, Atlanta GA. 2000.

Changing the design from the topology shown in Figure 5 to the topology shown in Figure 4 resulted in a 5 dB improvement in conversion loss with the same RF input powers.

Combining the three sub-circuits resulted in the IQ demodulator schematic shown in Figure 7

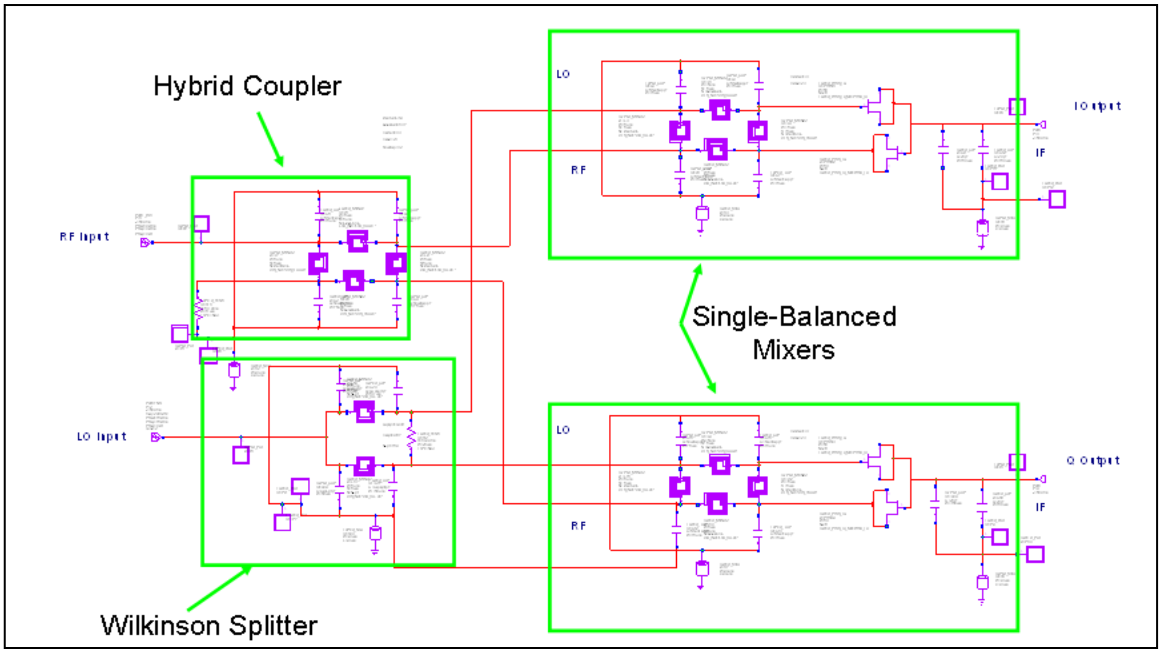

Figure 7: IQ Demodulator Schematic

The demodulator was simulated with the RF frequency swept from2.4 to 2.5 GHz and a fixed LO of 2.45 GHz. The RF Power was set to 10 dBm and the LO power was stepped from 0 to 20 dBm to determine the necessary LO power.

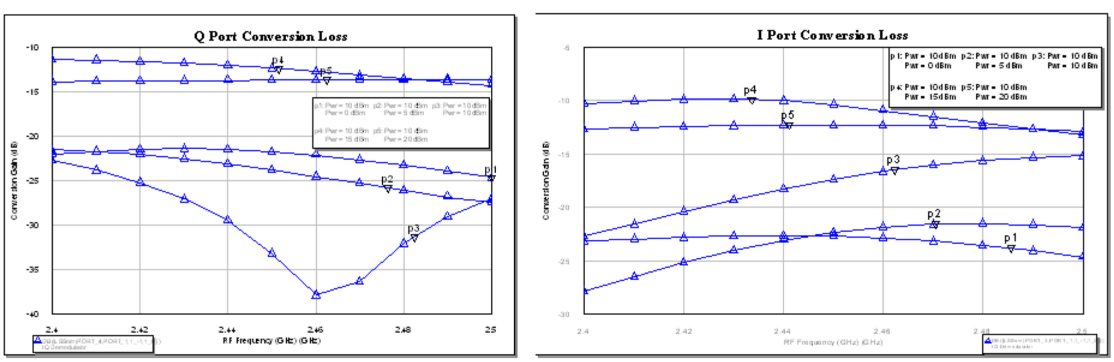

Figure 8: Conversion loss for different LO input powers

Figure 8 shows that with an LO input power of 7 dBm that was specified initially the demodulator would not be able to achieve the goal of 10 dB conversion loss. Using the ideal LO input power of 15 dBm the demodulator can come close to meeting the goal of 10 dB conversion loss.

With a fixed LO power of 15 dBm the RF power was then stepped from 0 to 10 dBm to see what effect that would have on the conversion loss.

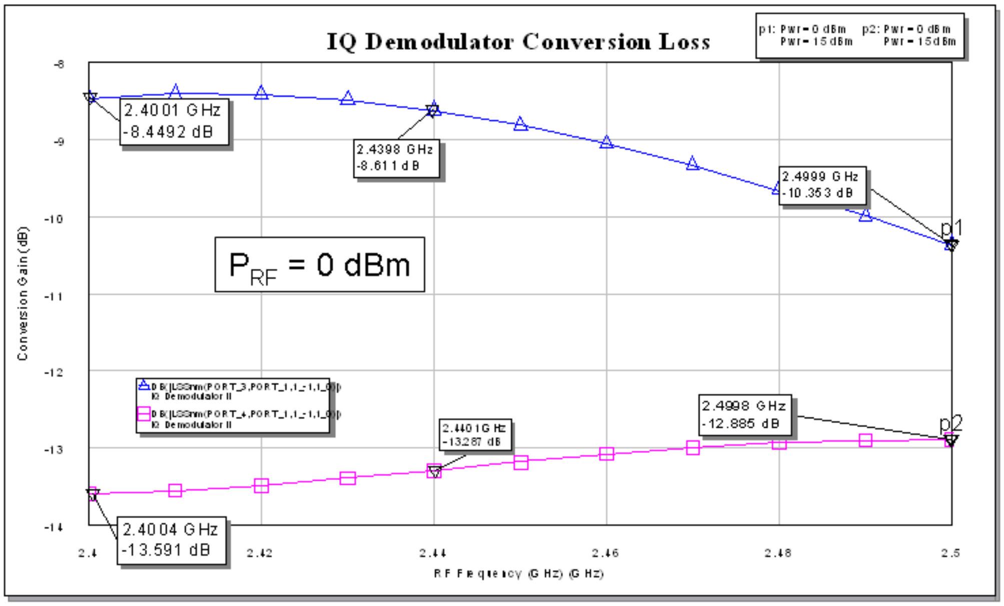

Figure 9: Conversion loss with 0 dBm RF input

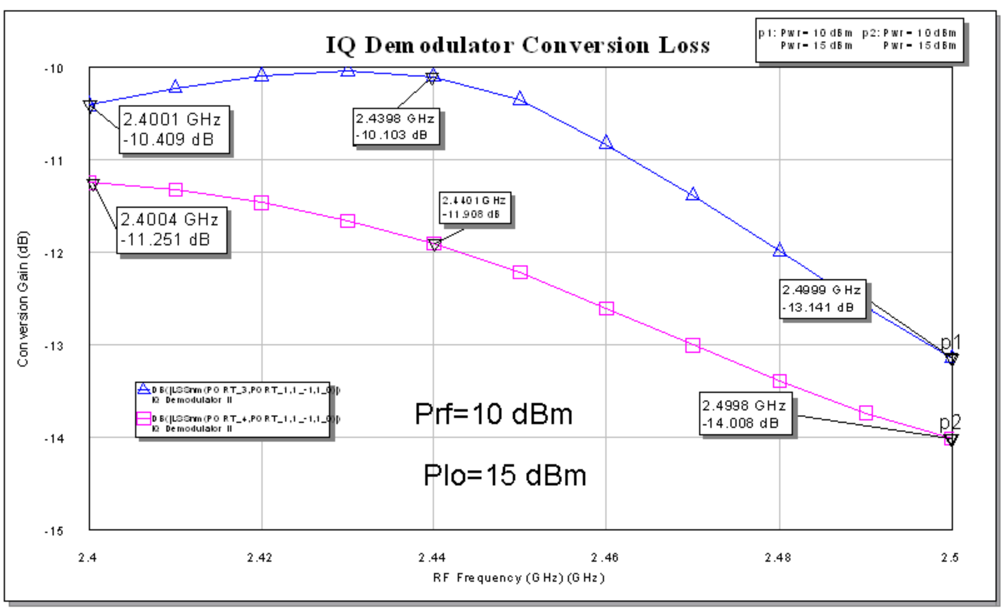

Figure 10: Conversion Loss with 10 dBm RF Input

Figures 9 and 10 show that with a 0 dBm input, there was a five dB difference between the conversion loss on the I port and the conversion loss at the Q port. As the RF power increased the difference in the output powers decreased to about 1 dB.

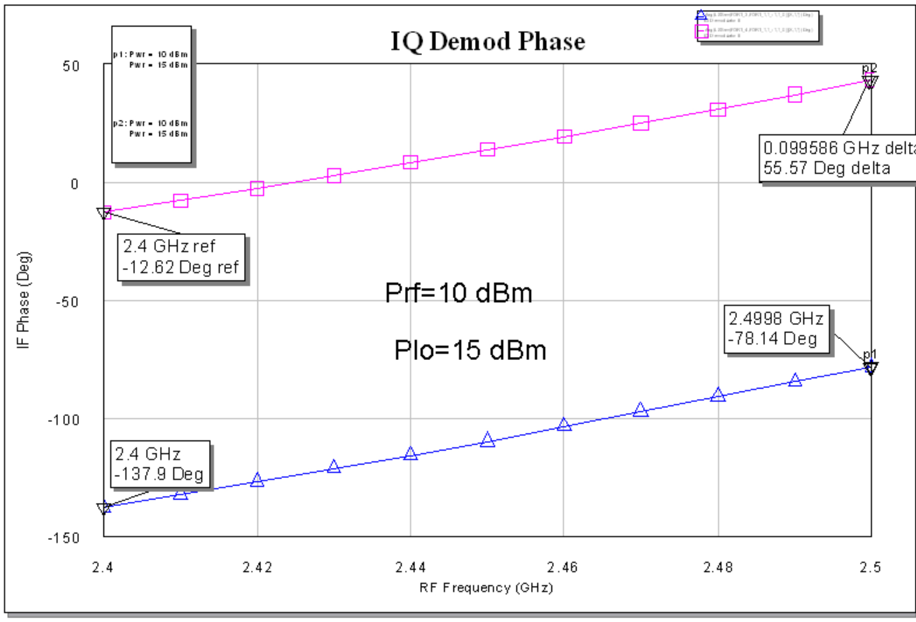

Figure 11: IQ Demodulator Phase

The phase difference between the I and Q ports ranged from 125 degrees to 133 degrees which did not meet the goal of 90 +/- 5 degrees.

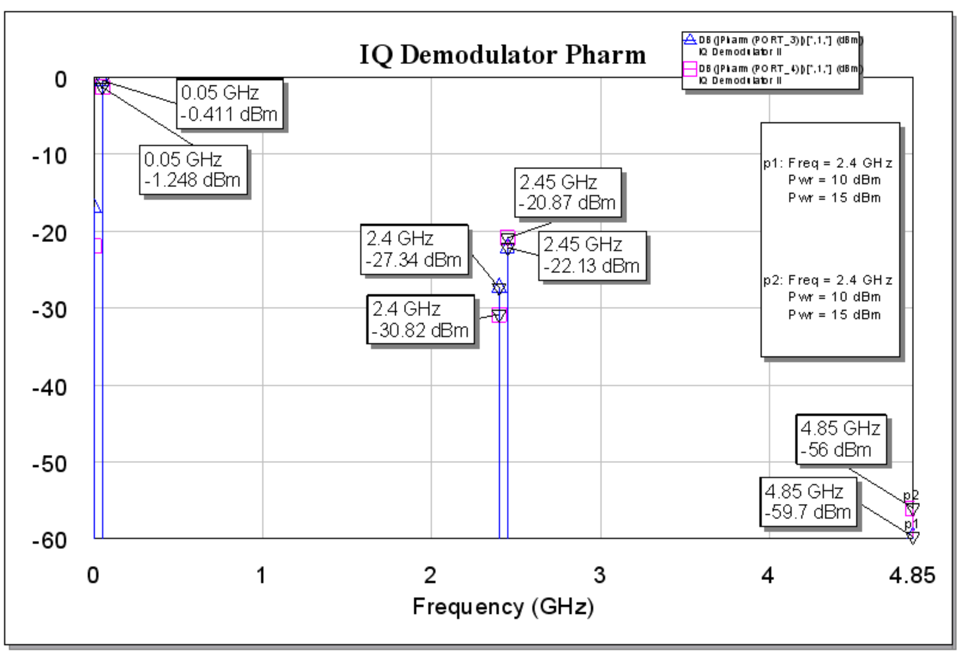

Figure 12: IQ Demodulator Output Spectrum

I Port RF-IF Isolation	**-37.3 dBc**
Q Port RF-IF Isolation	**-40.8 dBc**
I Port LO-IF Isolation	**-37.1 dBc**
Q Port LO-IF Isolation	**-35.9 dBc**
I Port LO + RF Suppression	**-59.3 dBc**
Q Port LO + RF Suppression	**-57.2 dBc**

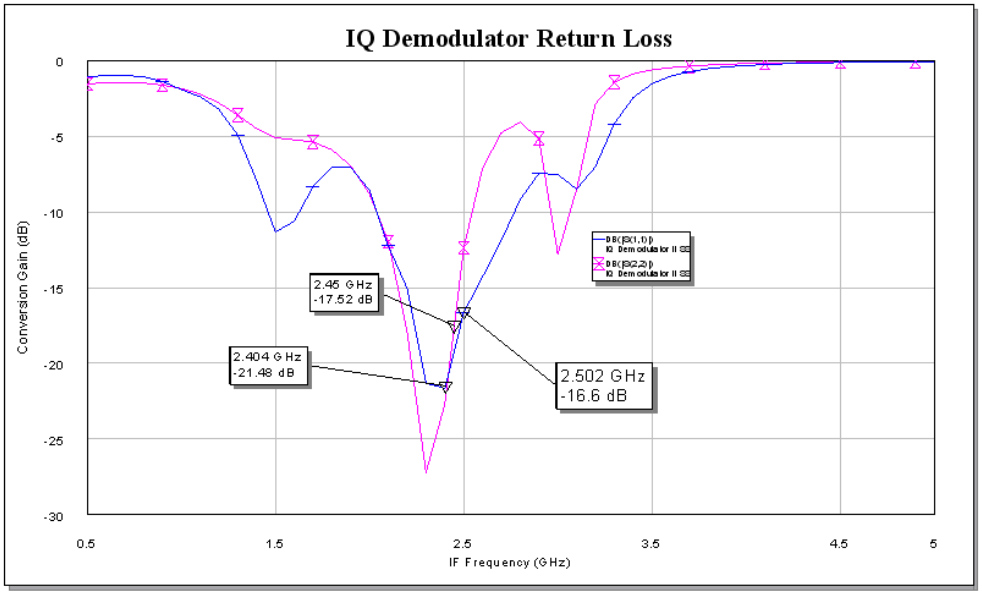

Figure 12: Input Return Loss

The input return loss for both the RF and LO ports meets the 15 dB goal.

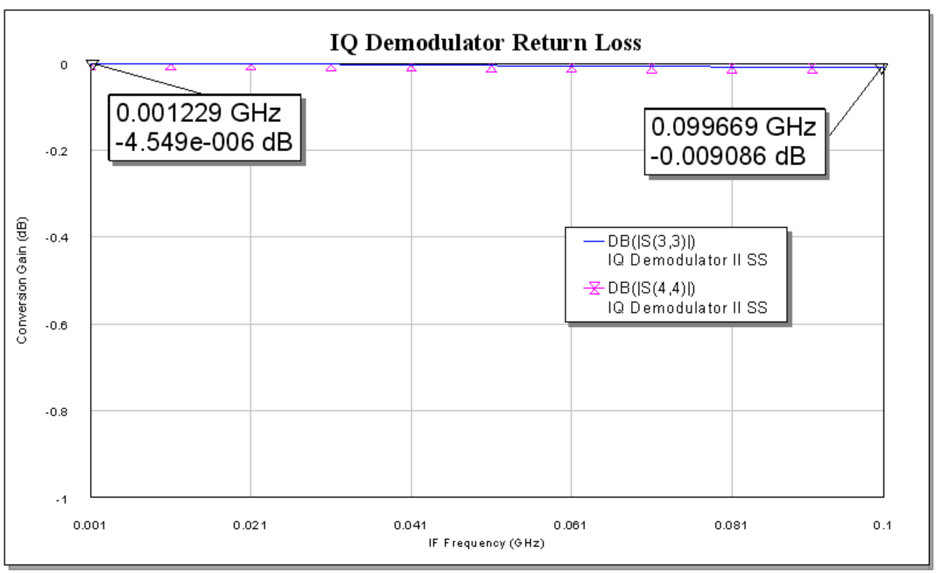

Figure 13: Demodulator Output Return Loss

The demodulator output return loss is very poor (0 dB for all output frequencies). This is due to the large filter caps and diodes at the output of the mixers.

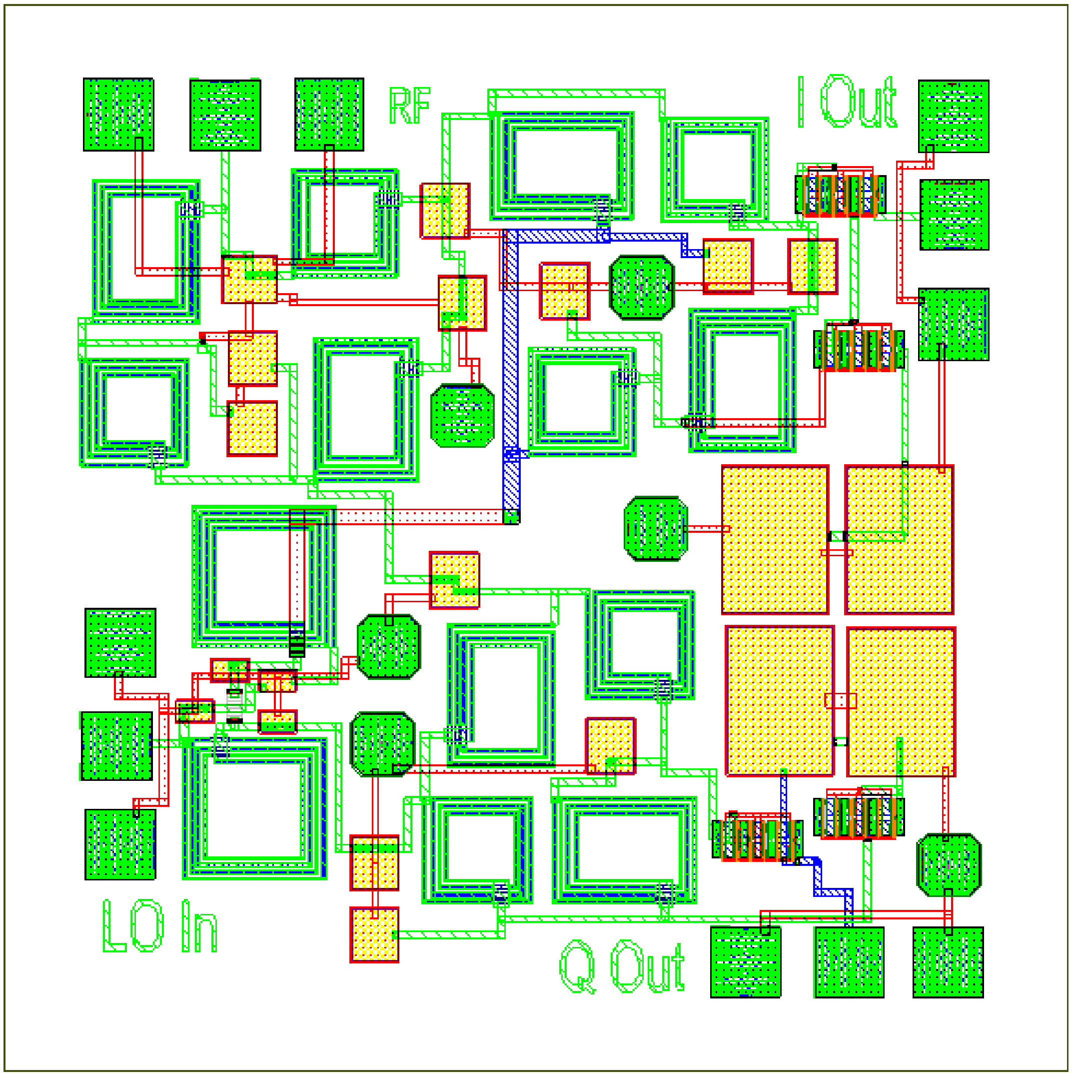

Figure 14: Demodulator Layout

Test Plan

f_{lo} = 2.45 GHz
f_{rf} = 2.4 – 2.5 GHz
P_{lo} = 15 dBm
P_{rf} = 0 -10 dBm

1) Use a network analyzer to measure the return loss at all four ports.
    a. RF and LO: 0.5 – 5 GHz
    b. I and Q: 1 – 100 MHz
2) Sweep the RF from 2.4 to 2.5 GHz and record the conversion loss.
3) Apply a fixed RF at 2.4 GHz. Record the output spectrum. Determine RF-IF and LO-IF isolations.

Conclusion

I was able to achieve a conversion loss of approximately 10 dB. The RF inputs required to achieve this were higher than desired however. The input ports had good return losses but the output match was very poor.

I would have liked to have designed some matching circuits for the output ports, but there was not enough room on the chip. Another improvement that could be added is an LO amplifier, which would allow this demodulator to be used with the VCO being designed. Finally, changing the mixers to include a rat-race coupler instead of the hybrid coupler would improve the performance as well. All of these changes would require a larger substrate.