

S-Band (ISM) Down Converter – Double Balanced Star Mixer Implementation

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Abstract: The following paper presents the design of a lumped element implementation of the double balanced star mixer. In its current configuration the device is to operate as a S-band (2.4 GHz) down-converter supporting IF frequencies from 100 - 400 MHz. The double balanced star mixer provides for wide RF and IF bandwidths, desirable third order intercept (IP3) and 1 dB compression characteristics, low conversion losses, and exceptional port to port isolation. The lumped element realization of the double balanced star mixer is much more compact than that of comparable mixers and employs a self biased diode scheme which further reduces the size of the chip by eliminating the need for external DC paths, inductive chokes, and blocking capacitors.

This design is predicated upon a similar design, “*Miniature MMIC star double balanced mixer using dual balun,*” presented in volume 33 of IEEE - March 1997.

Introduction: Down conversion is the process where radio frequency (RF) signals are mixed with a local oscillator (LO) to yield an intermediate (IF) frequency. The process of down conversion yields a desired intermediate (IF) frequency as well as undesirable higher order inter-modulation products. The principle advantage of implementing a double balance mixer (DBM) design hinges upon its ability to suppress unwanted inter-modulation (IM) products. Suppression of these IM products reduces RF/IF conversion losses. A DBM operates with two of its three ports balanced and a single port unbalanced. The third – unbalanced port is almost always more easily implemented at a lower frequency and usually serves as the IF port. For this reason, the double balanced mixer usually provides improved inter-modulation suppression in a down conversion mode, as opposed to up conversion, where an RF or LO signal is injected into the unbalanced port. When operating in a down conversion mode, the double balanced mixer provides for a RF/IF conversion loss that is approximately 3 dB lower than that achieved by conventional balanced mixer designs.

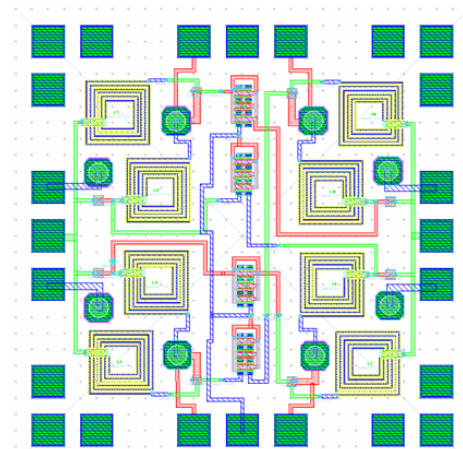


Figure: Double Balanced Star Mixer

Design Approach: The goal of this project is to design and fabricate a compact mixer design that operates in the ISM band (2.4 GHz). IF frequency has not been stipulated, but it has been assumed that the device should function in the 100-400 MHz range. To insure that the device can be successfully tested, LO power shall be limited to 13 dBm. While performance is significantly improved for higher LO drive levels (14 – 16 dBm), available test equipment may not be able

to support signal levels of this magnitude. Port to port isolation, third order intercept (IP3), and 1 dB compression have not been stipulated. Figure 1 summarizes available DBM specifications:

Specification			Simulation Results	
Specification	Conditions	Specification Requirement	Lumped Element	Triquint Elements
Isolation	RF / LO RF / IF LO / IF	20 dB	> 20 dB	> 20 dB
Conversion Gain	RF/IF	< 10dB	NA	- 5.76 dB
VSWR	RF,LO	2.5:1 (2.3-2.5 GHz)	2:1	2:1
DC	NA	NA	NA	NA
Frequency Range	ISM (2.4 GHz)	RF: 2.3-2.5 GHz LO: 2.0 – 2.3 GHz IF: 100 – 400 MHz	RF: 1.8 – 3.0 GHz LO: 1.7 - 2.9 GHz IF: 100 – 400 MHz	RF: 1.8 – 3.0 GHz LO: 1.7 - 2.9 GHz IF: 100 – 400 MHz

Figure 1: Specification vs. Simulated Results for 13 dBm LO

A double balanced mixer (DBM) design offers several advantages that a conventional balanced mixer design does not. Due to its ability suppress inter-modulation products, a DBM may provide <10 dB of conversion loss over a much wider bandwidth than traditional mixer designs. This attribute also makes the DBM design desirable for many low power applications. If bandwidth is sacrificed, available Local Oscillator (LO) power may be reduced while maintaining <10 dB conversion loss. Total LO power shall be limited to 19 mW (13 dBm). While this LO drive level is considerably lower than what is considered optimum for the design, it allows the device to safely function within design limits while maintaining an acceptable level of performance. In addition to fulfilling the specified requirements, the DBM design should also provide for exceptional RF / LO isolation, a high third order intercept (IP3), and a high 1 dB compression point.

A depletion mode PHEMT (P-High Electron Mobility Transistor) has been identified as the most suitable active component to function as a diode in the DBM design. When drain and source are connected, the PHEMT functions in essentially the same manner as a traditional PN diode. Other diodes (DL and DEML) from the Triquint library have been avoided due to concerns about the fidelity of their associated electrical models. In its current configuration, the DBM does not require a DC bias source to function. Biasing of the PHEMT's is provided entirely by injected RF and LO signals. The absence of a DC feed and its associated ground paths significantly reduces the overall chip size and yields a moderate reduction in chip complexity.

Due to a lack of chip area, IF filtering has not been included in the DBM design. To successfully attenuate higher order inter-modulation products, an inductor with a value of at least 20 nH would have to be fabricated in conjunction with a large shunt capacitor. Attempts to design low pass filtering consisting of only a small shunt capacitance (<15 pF) were not successful in lowering the amplitude of the IM products. If the device is to be integrated into a working system additional IF filtering will need to be included external to the chip.

Detailed Design: The basic component in a double balanced star mixer design is a dual balun, or Bal-unced to un-Balanced, transition. The dual balun consists of two out-of-phase power splitters comprised of a parallel combination of high pass and low pass filters. The dual baluns, or impedance transformers, divide power evenly between mixing diodes with an effective phase shift of 180 degrees.

In order to determine the proper lumped element values needed to construct the balun, the Triquint PHSS model has been simulated and its input impedance characterized. The model characterizes the input impedance of the diode without an applied DC bias.

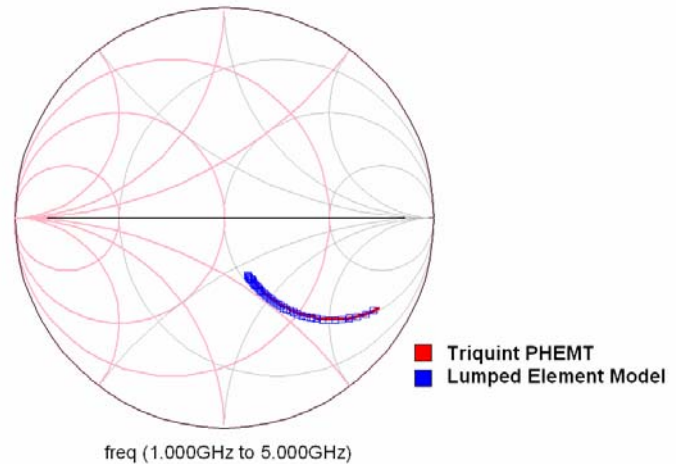


Figure 2: Diode (PHEMT) Input Impedance

The series impedance of the PHEMT diode is approximately 3 ohms with a series capacitance of approximately 1.0 pF. Figure two displays diode input impedance when terminated into a 50 ohm load. The PHEMT may be successfully modeled as a lumped element RC circuit with device values of 53 ohms and 1.0 pF.

Lumped element values are determined based upon the desired balun impedance necessary to match diode input impedance to that of the biasing circuit (180 deg. splitter). Due to the fact that there are two parallel splitters feeding a single 50 ohms port, the desired impedance at the input of a single splitter is 100 ohms. (100 || 100 = 50 Ohms) The line impedance of the balun (impedance transformer) equates to the geometric mean of the diode and splitter input impedances. The relations used for determining balun impedance and associated lumped element values are listed below:

$$Z_t = (Z_0 \times Z_d)^{1/2} \quad (1)$$

$$L = Z_t / (2\pi f) \quad (2)$$

$$C = 1 / (Z_t \times 2\pi f) \quad (3)$$

The calculated value of the impedance of the balun is 72.8 ohms (geometric mean of 53 and 100 ohms). Associated inductor and capacitor values are 4.8 nH and 0.9 pF respectively.

Modeled performance of the circuit employing ideal lumped element values displayed input and output return losses consistent with wide band performance, but did not show an acceptable match at 2.4 GHz for the calculated element values. Additional tuning of the circuit model in ADS yielded modified inductor and capacitor values of 5 nH and 0.3 pF. These circuit values provide for an optimum impedance match at the frequency of interest.

Figure 3 displays device input impedance normalized to 50 ohms for lumped element and Triquint S-parameter models. Input and output matches are reciprocal.

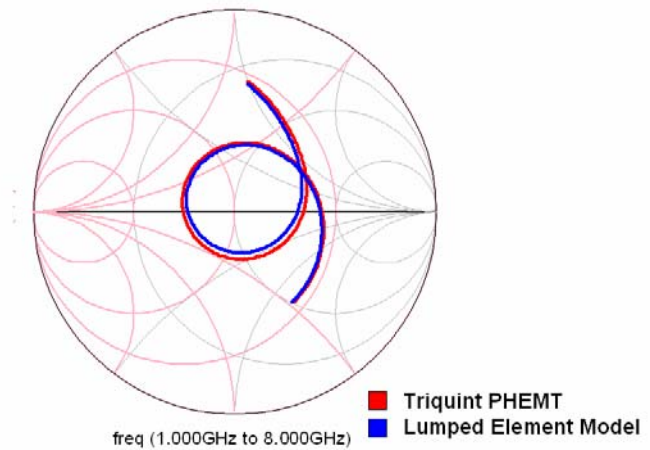


Figure 3: DBM input impedance (normalized 50 ohm)

When modeling the dual balun circuit, great care should be taken in isolating adjacent diodes from one another. A diode is a non-symmetric device with impedance characteristics that differ depending upon bias and the direction of current through the device. The s-parameter model does not include the effects of forward and reverse bias and will not function properly unless the anode and cathode of adjacent diodes are isolated from each other at their junction. If the model is to function properly, diodes should be terminated into 50 ohms at their junction; effectively isolating the 180 and 0 degree legs of the power splitter.

Balun circuits combine to form the basis for a transition from two unbalanced 50 ohm micro-strip ports to a matched and balanced diode input. RF and LO signals are injected via these balanced ports and the IF signal is directly coupled from the junctions at the center of the diode pairs. The summing of the IF signals from the two diode junctions is accomplished using a simple T junction.

Simulations:

Diode Modeling

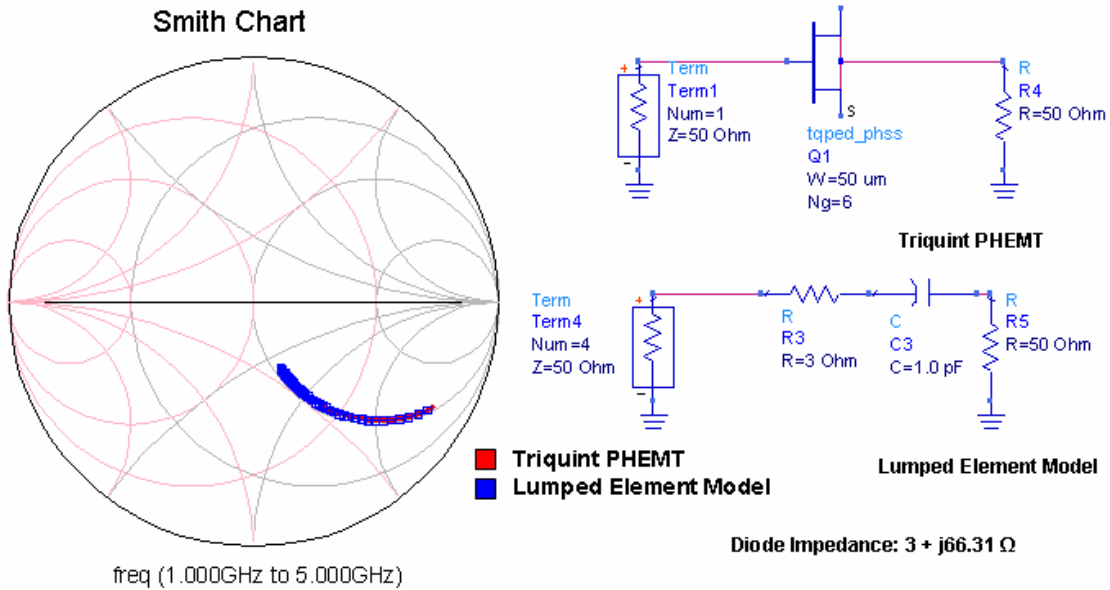
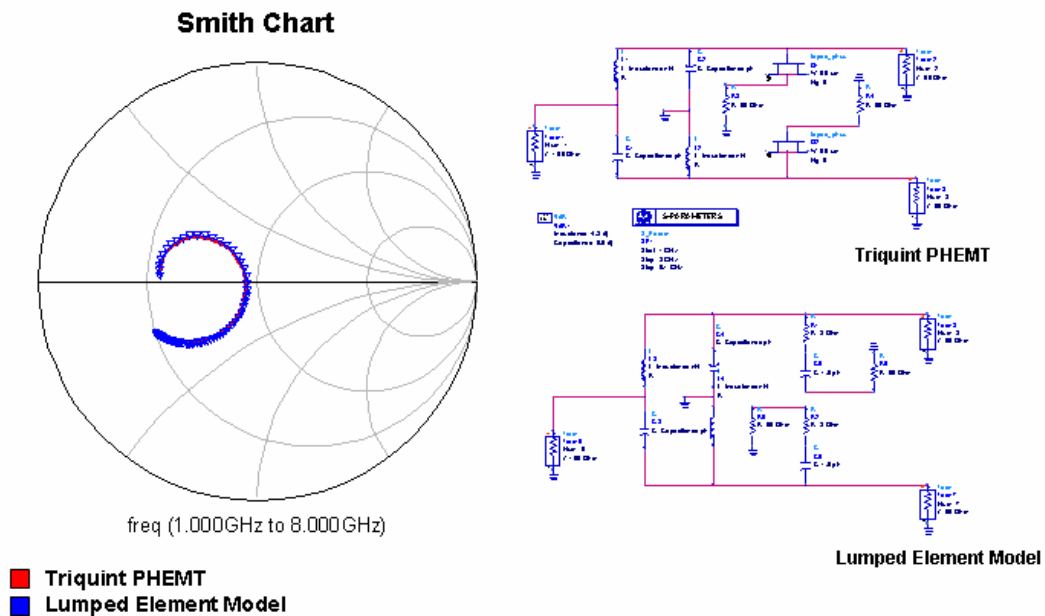
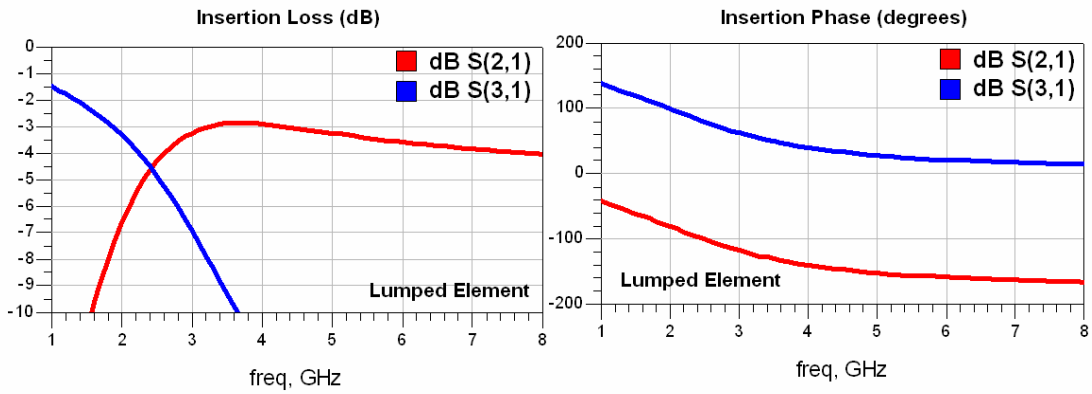
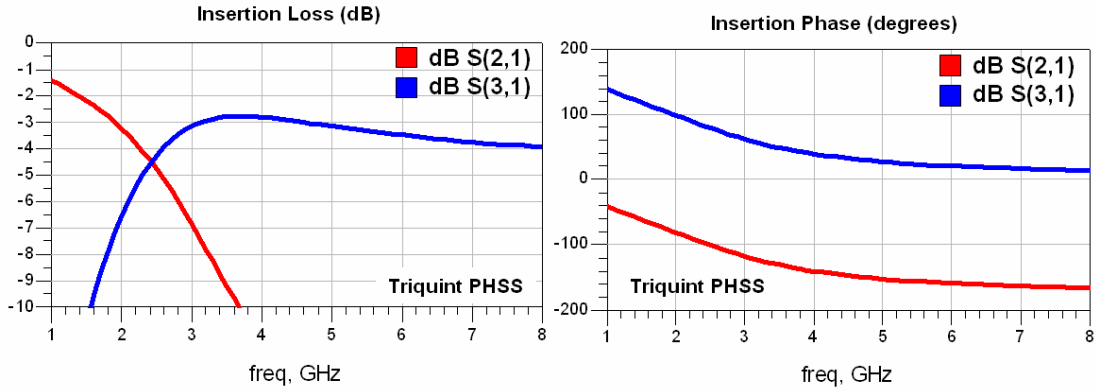


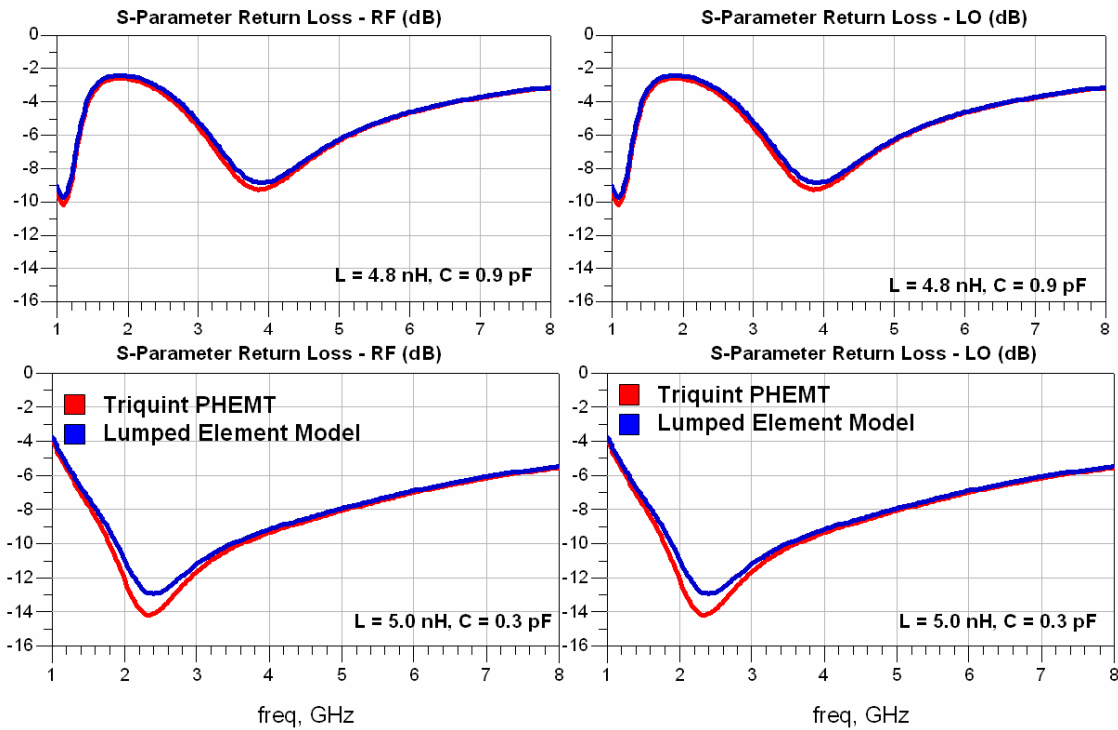
Figure 1: Diode (PHEMT) Input Impedance

180° Power Splitter





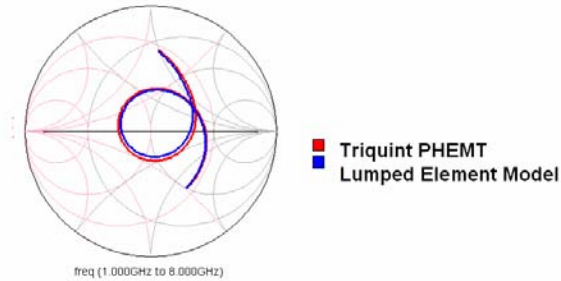
DBM Simulation and Tuning



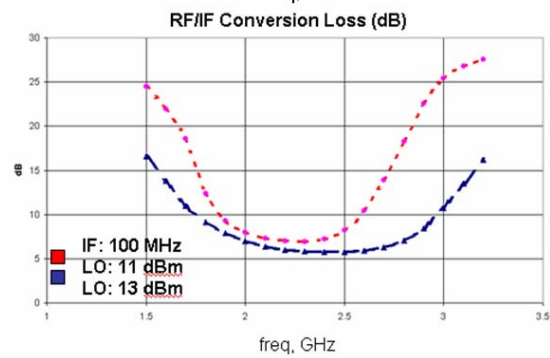
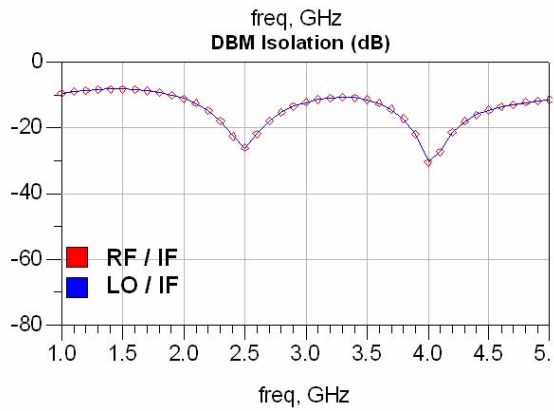
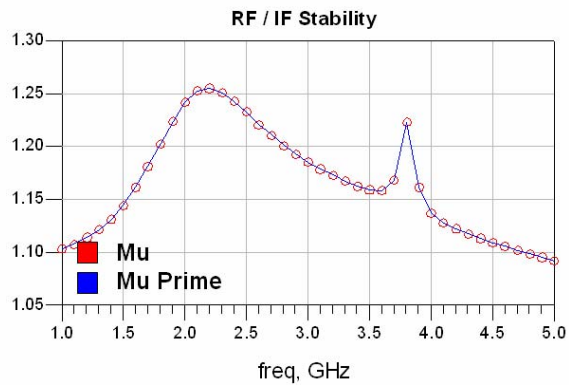
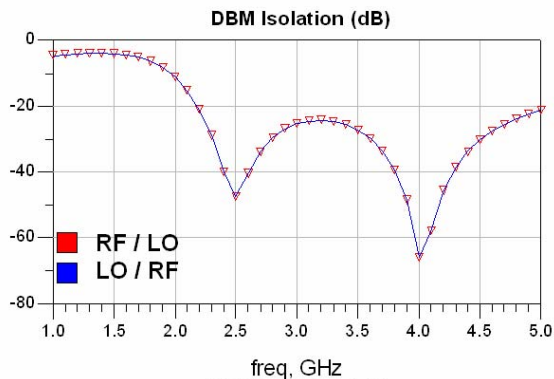
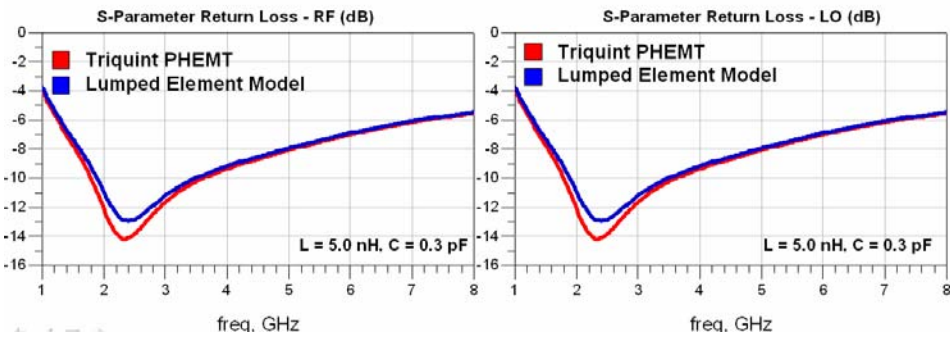
Performance:

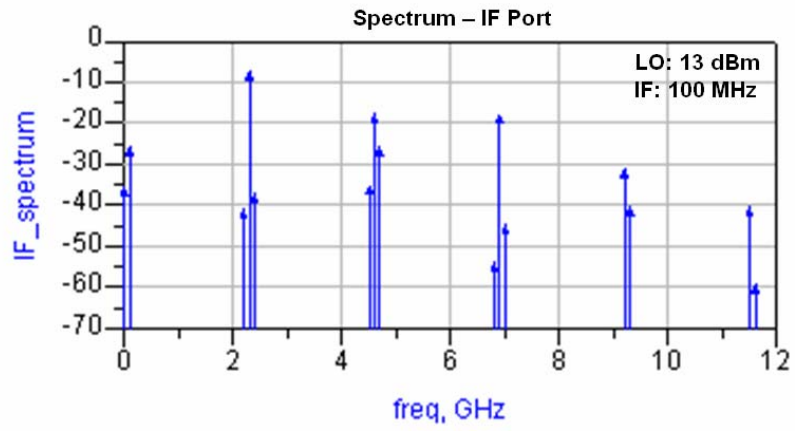
S-Parameters

Smith Chart – RF/LO Input Impedance

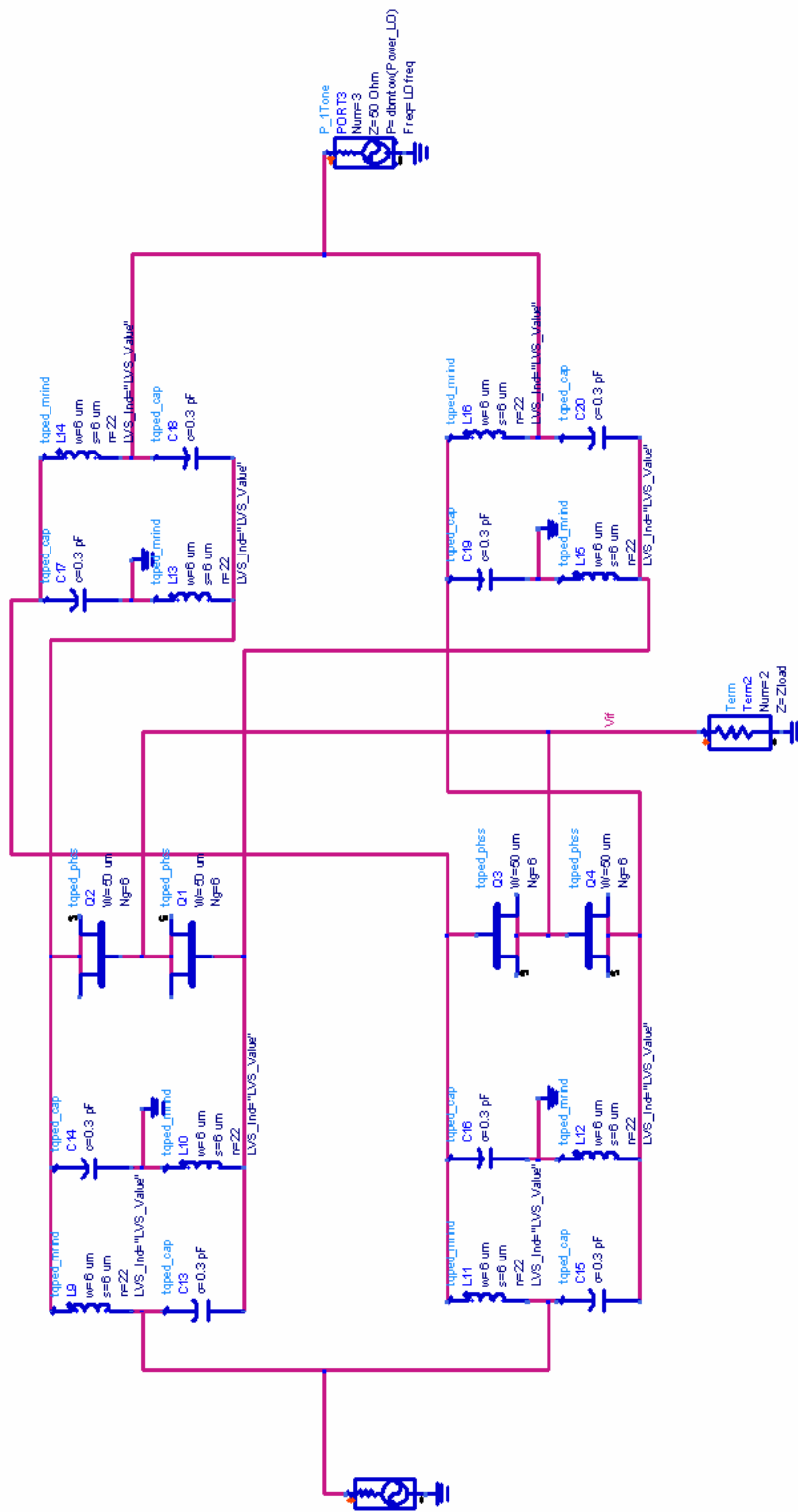


DBM input impedance (normalized 50 ohm)





Schematic:



Layout:

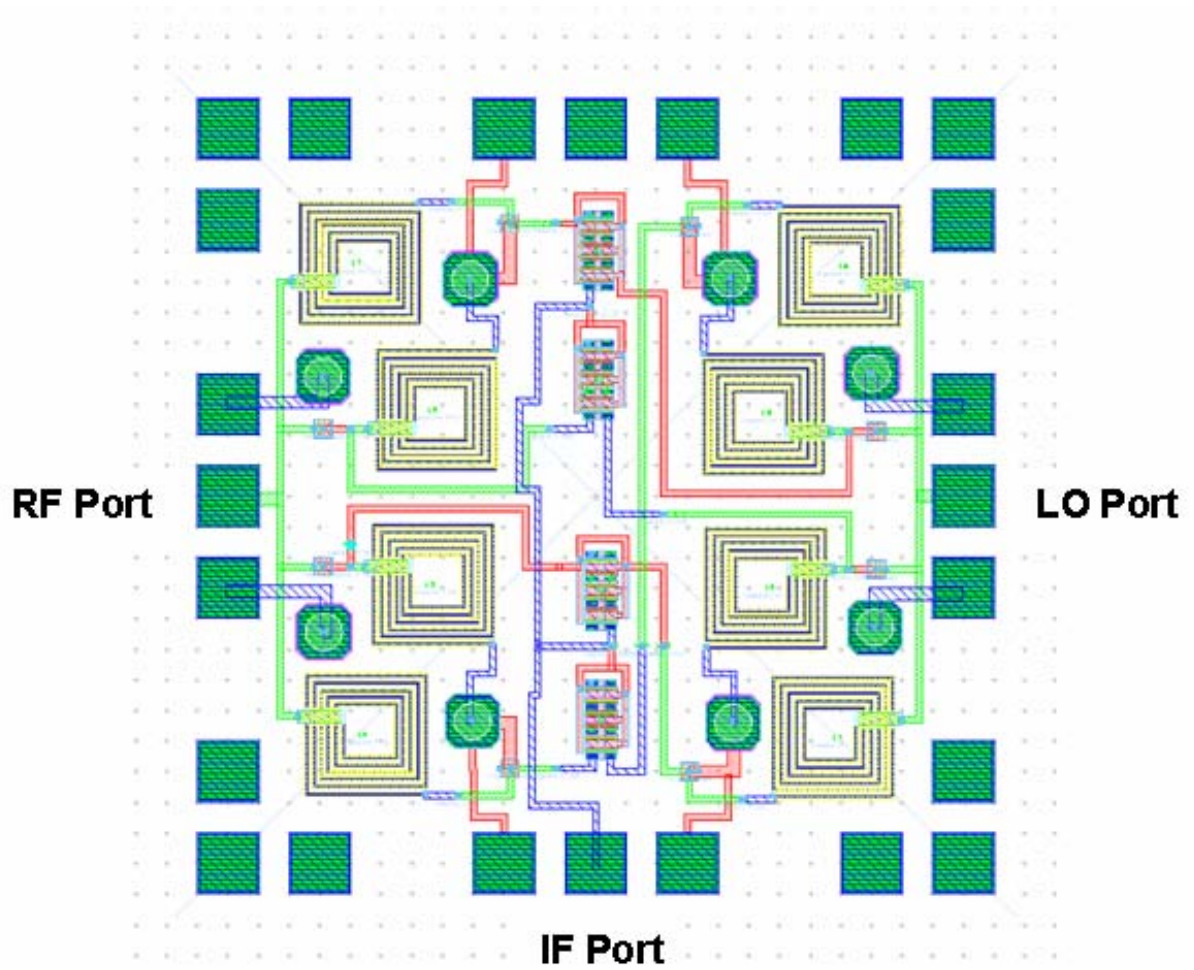


Figure: Double Balanced Star Mixer

Test Plan: Testing of the DBM design is greatly simplified by the fact that mixing is accomplished without the need for DC bias. DC blocking and storage capacitors will not be necessary. Testing of the DBM is a two stage operation consisting of both linear and non-linear tests.

Linear testing consists of a series of two port S-parameter tests to verify input match and isolation in the frequency band of interest. The following procedure shall be followed when performing s-parameter tests.

- Calibrate / Verify calibration of coplanar waveguide (CPW) probes
Frequency band: 1-4 GHz
- Terminate IF port into 50 Ohms. Measure input return loss (S11 and S22) at RF and LO ports. (Return Loss < -10 dB at 2.4 GHz)
- With IF port still terminated into 50 Ohms. Measure isolation between RF and LO ports (S21, S12). Response should be reciprocal. (Isolation ~ 20 dB at 2.4 GHz)
- Terminate RF port into 50 Ohms. Measure LO/IF isolation (S21). (Isolation ~ 20 dB at 2.4 GHz)
- Terminate LO port into 50 Ohms. Measure RF/IF isolation (S21). (Isolation ~ 20 dB at 2.4 GHz)

Non-linear testing primarily focuses upon characterizing the conversion loss characteristics of the mixer. Third order intercept and 1 dB compression may also be studied, but have been excluded from this procedure. Hardware required to complete non-linear testing will include: two (2) signal generators (S-band capable / 13 dBm capability, a spectrum analyzer, and associated connectors / hardware.

Frequency / Signal Levels:

- LO Signal Level: 13 dBm
- RF Signal Level: - 20 dBm
- RF Frequency: 2.4 GHz (ISM-Band)
- LO Frequency: 2.3 GHz
- IF Frequency 100 MHz

The following procedure shall be followed when performing non-linear test:

- Verify RF and LO frequency and signal levels using spectrum analyzer
- Record test cable loss
- Connect RF and LO ports to appropriate signal generator(s)

- Connect IF port to spectrum analyzer.
- Calculate RF/IF conversion loss accounting for test cable losses.
(Conversion loss ~ 7 dB)

Conclusions: Simulation results appear to validate the performance of the current DBM design. Data suggests that the star mixer design will meet or exceed all specified design requirements. Additional simulations to determine expected third order intercept and 1 dB compression points may be useful, but are not required to satisfy current design requirements.

In conclusion, the implementation of a double balanced star mixer (DBM) design architecture may prove to be highly advantageous when used as part of a mobile wireless system. The small size, low power consumption, and pragmatic design of the mixer provides for a wide-band device that may be easily manufactured at low cost. While the current design has been pursued as part of an academic exercise, a device of similar design could prove to be very useful in an industrial setting.

References:

Chiou, K.C., Juang, Y, and Lin, H.: 'Miniature MMIC star double balanced mixer using lumped dual balun', *IEEE Microwave. Electronic Letters.*, 1997, pp 503 - 504