Microwave Final Project
16-QAM Modulation

ECE431 – Microwave Engineering

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Professor Hausman

16-QAM

- A Phase and Amplitude Modulation technique that sends data over the real and complex plane by varying the amplitude and sign on each axis and summing them.
- The total number of states is equal to 2^n bits.
  - The current implementation has 4 bits of data per symbol transmitted, so 16 symbols in total
- This scheme is very bandwidth efficient and power efficient since the constellation points are close to each other and close to the origin.
  - The points being close to each other causes the scheme to be very error prone
- A vector modulator allows for phase shift and amplitude control

Vector Modulator

- A Vector Modulator is a circuit that can create this constellation.
- This presentation details our design process to meet certain specifications:
  - 50 Ohm system
  - Carrier frequency = 5.4 GHz
  - 900 mega symbols per second
  - DSB, meaning a BW of 1.8 GHz
  - Over this bandwidth:
    - 8.5 dB max insertion loss
    - 1.4:1 max VSWR
    - Each star of the constellation has no more than:
      - +/- 3.5 degrees phase error
      - +/- 0.7 dB amplitude variation

Notes on Specifications

- Maximum insertion loss refers to the outermost points of the constellation, meaning the points with the largest amplitude.
- Phase and amplitude error is with respect to a reference ideal constellation
- Bandwidth is the symbol rate, and hence the actual bit rate is 3.6 Gbps

Encoding

- We used **Gray Coding Scheme**
  - Only one bit changes when moving to an adjacent point
  - Why use this? In real-life applications, it's used to minimize errors while transitioning from one state to the next since only one bit is changing without trading off bandwidth or power
  - Helps with error detection
  - It can also simplify the logic used to transition from state to state
- What does the symbol ABCD represent?
  - Bit A (0/1): 0/180 phase shift on Q-axis
  - Bit B (0/1): 0/180 phase shift on I-axis
  - Bit C (0/1): Attenuation/No Attenuation on I-axis
  - Bit D (0/1): Attenuation/No Attenuation on Q-axis

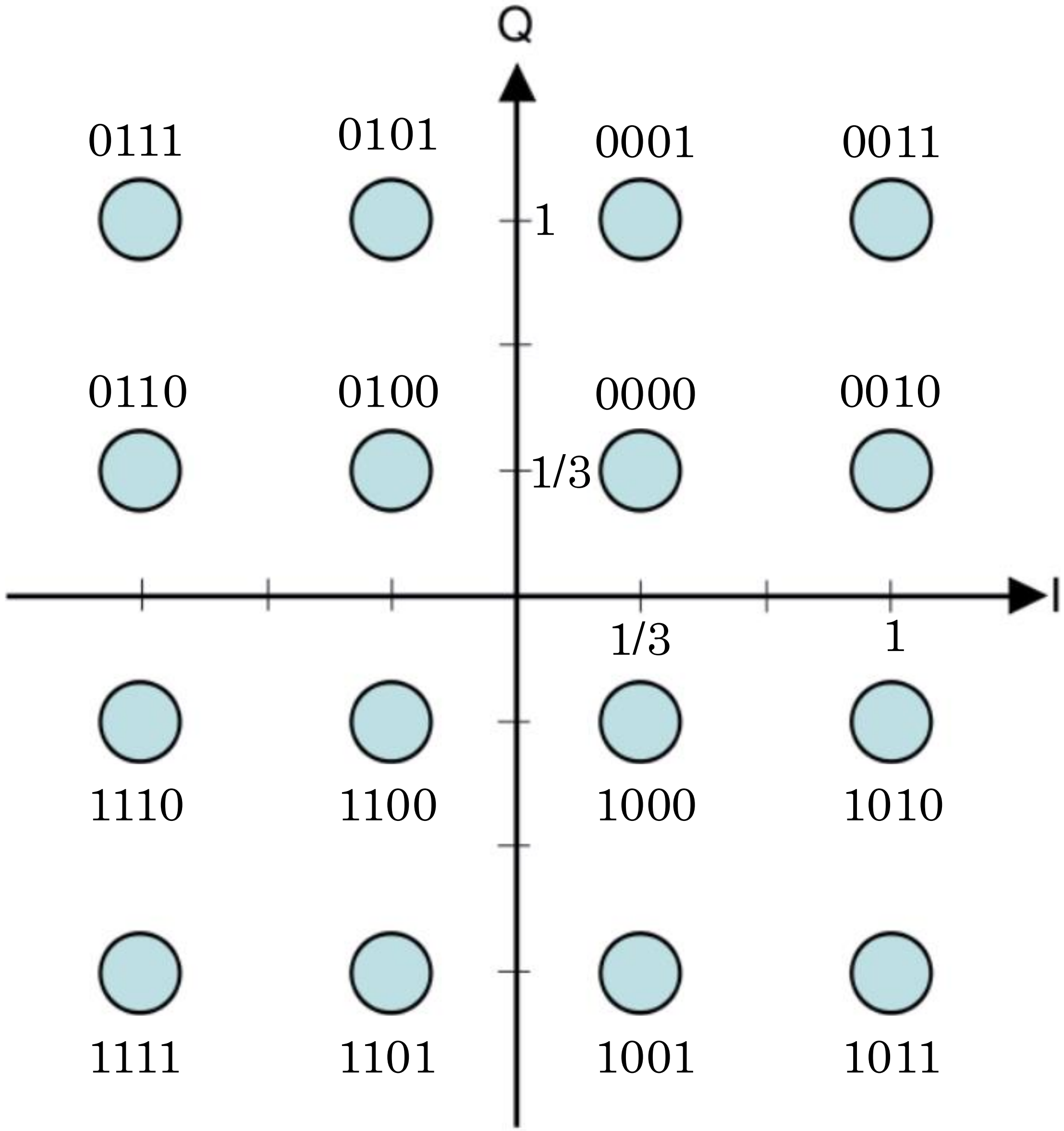
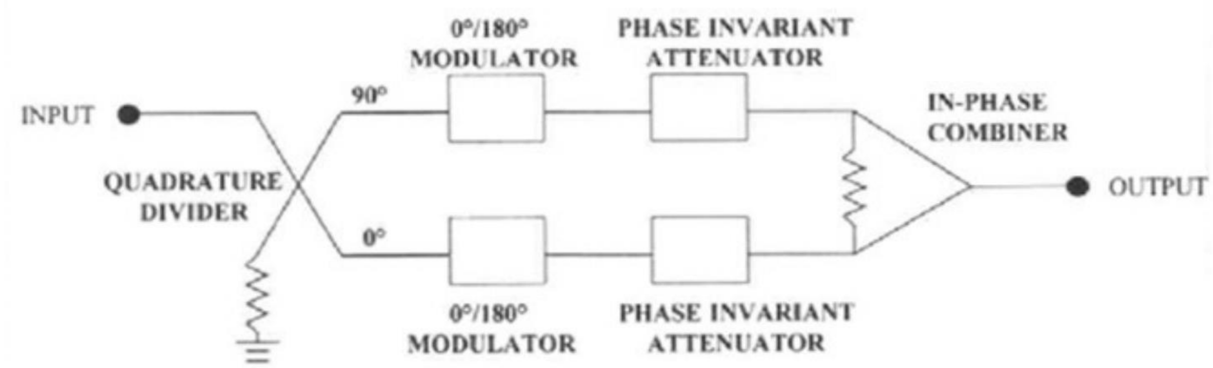
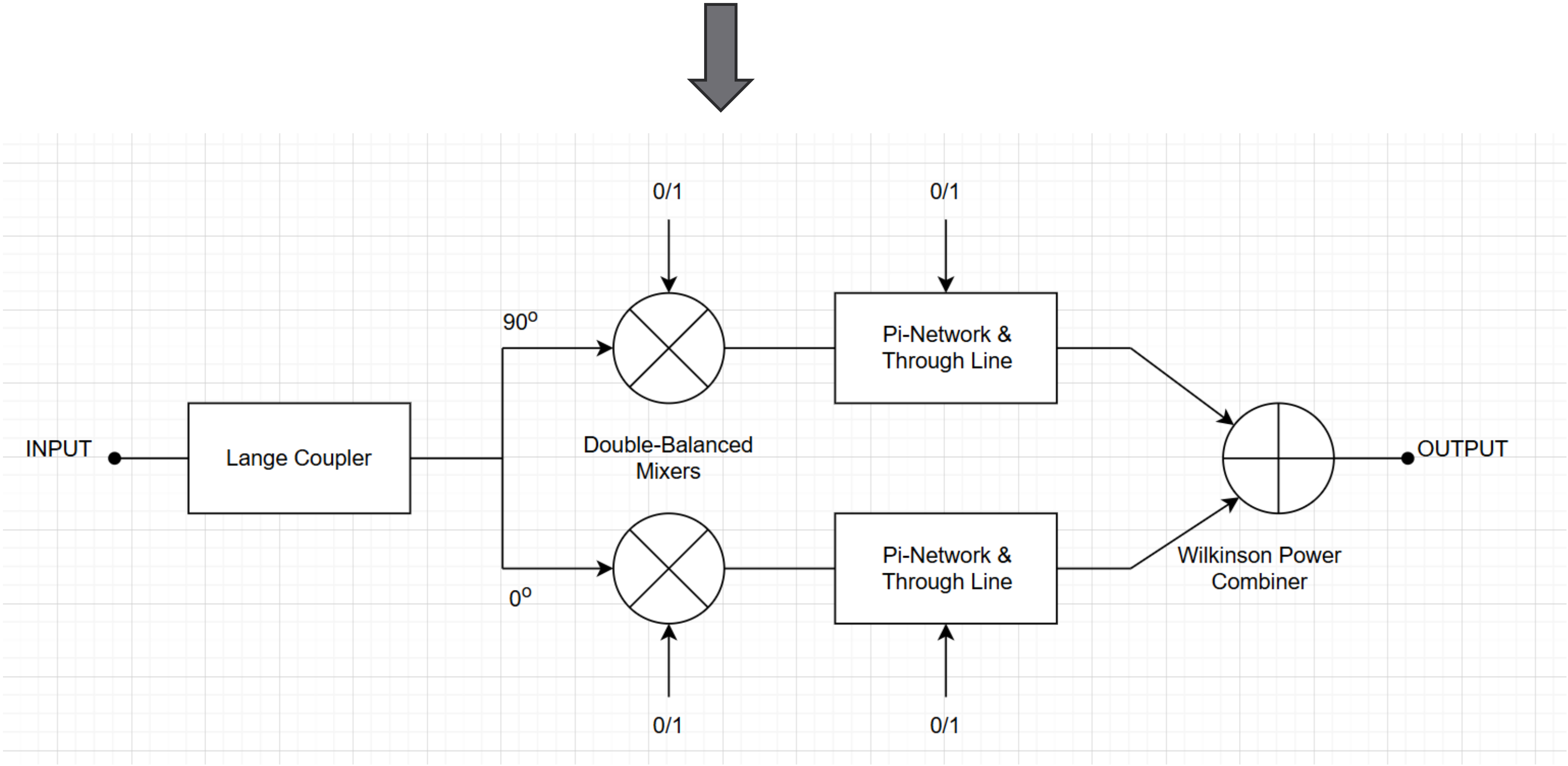


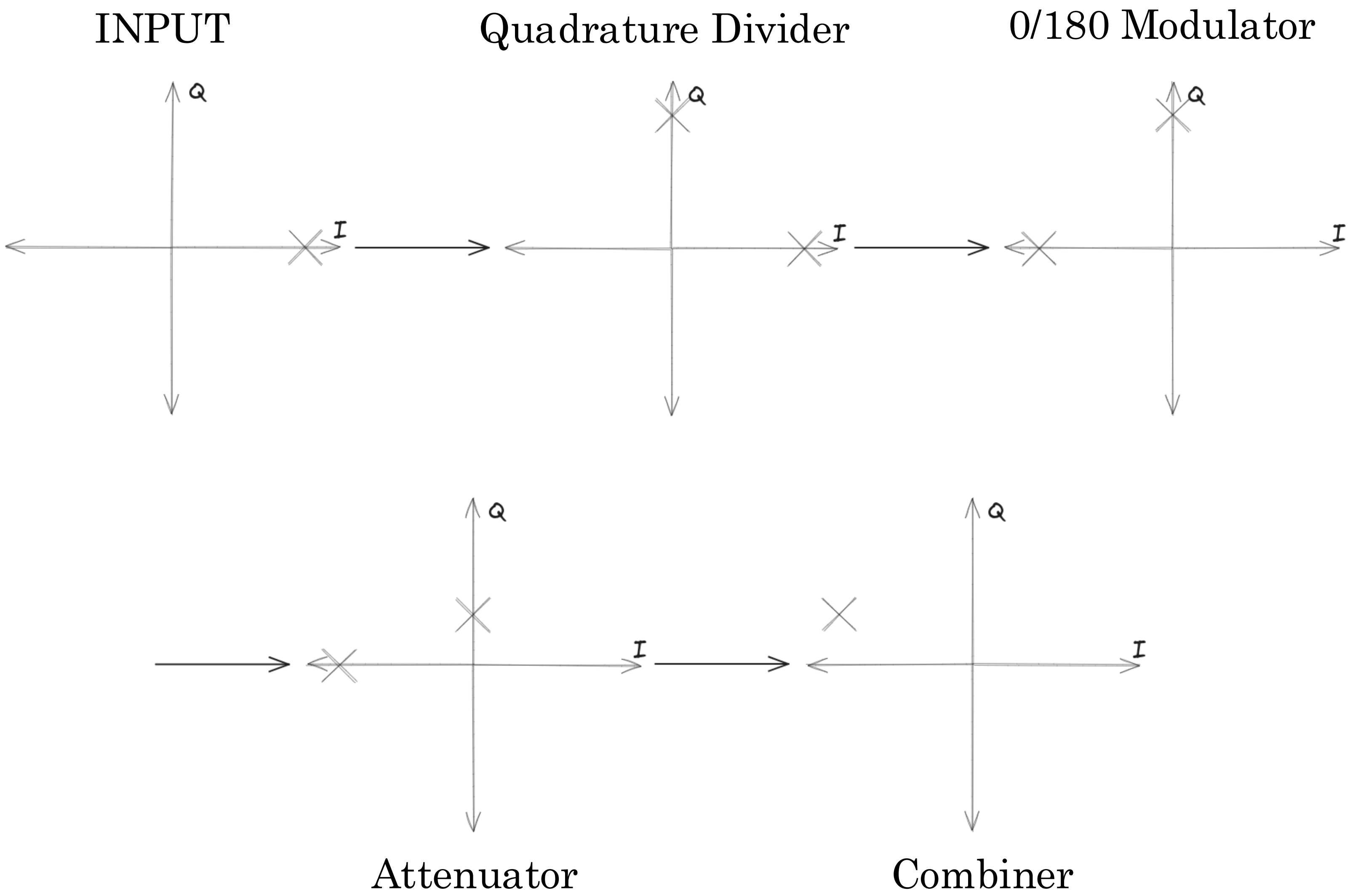
Figure 1: Constellation Coding Scheme.

Block Diagram

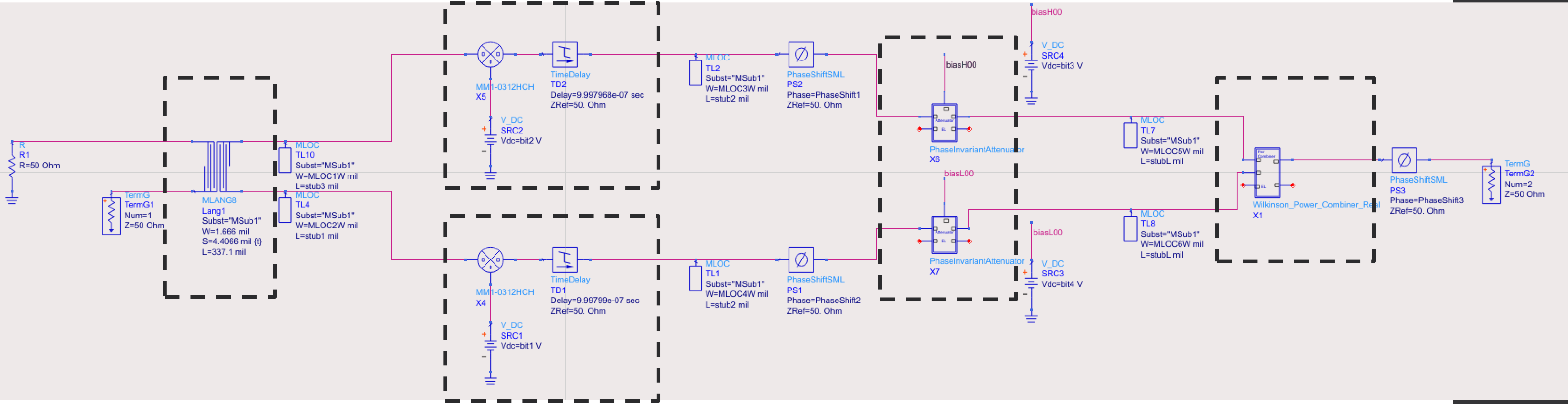




0110 State Example



Overall Schematic



Quadrature Divider

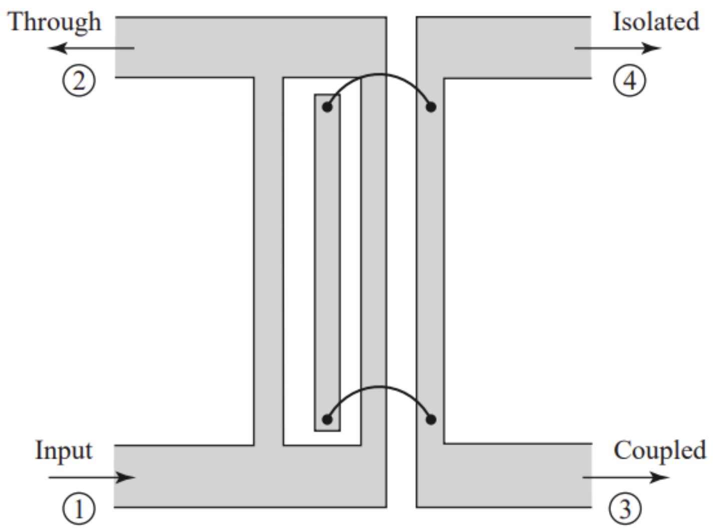
0/180 Modulator

Phase Invariant Attenuator

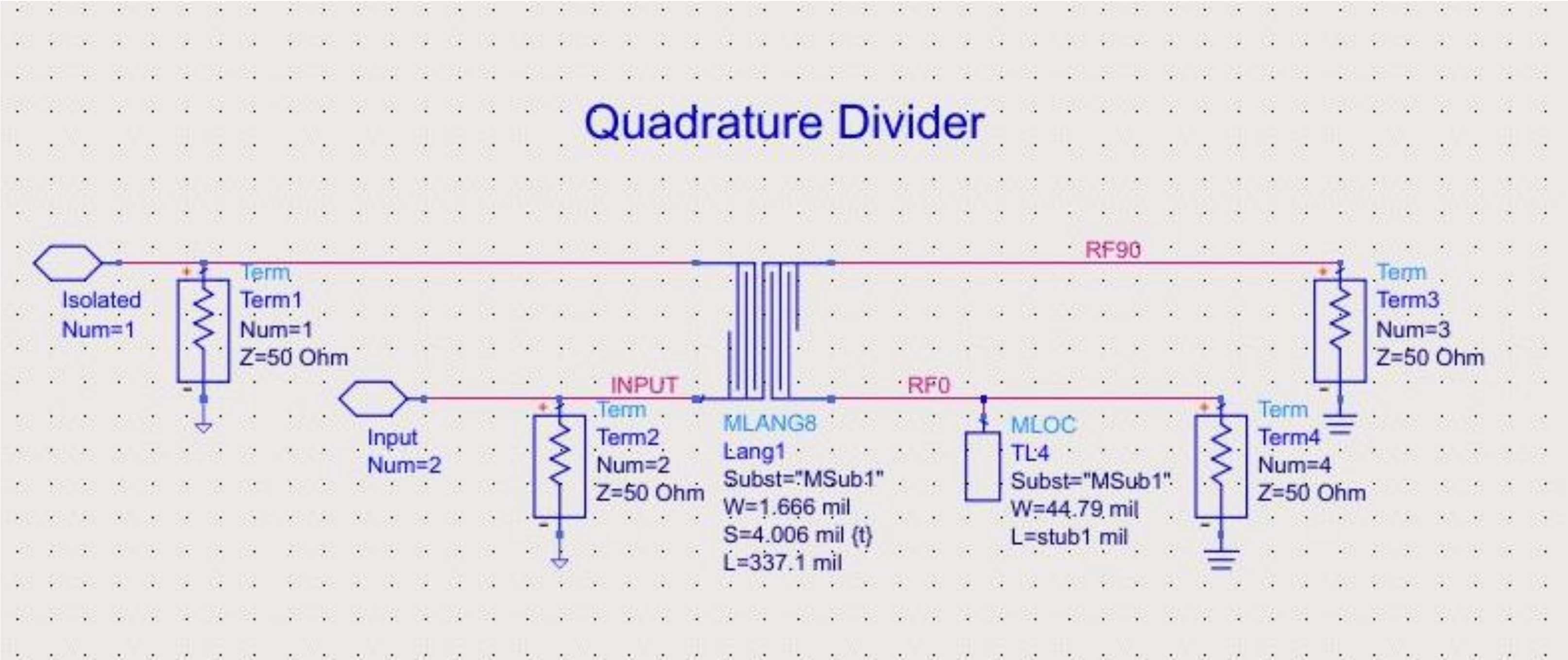
In-Phase Combiner

Quadrature Divider: Theory

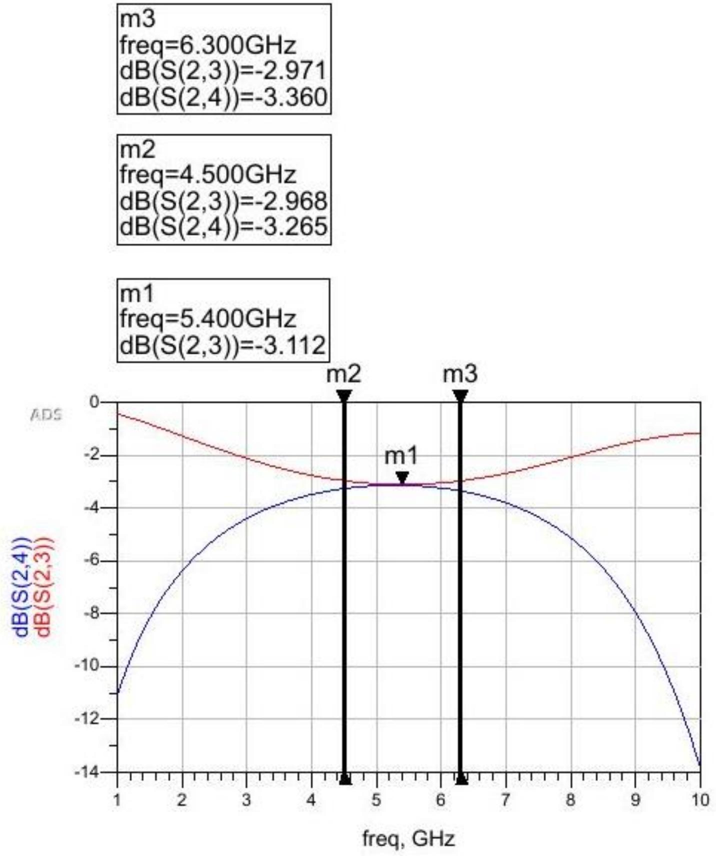
- Need a 90-degree phase shifted version of the RF and a 0 degrees RF
- We decided to use a Lange Coupler to do this
  - Could have used a different 90-degree hybrid, but the values that we want degrade quickly as we move away from center freq.
  - So, we use quadrature divider that works for a higher BW and better achieves the 3 dB coupling since 8 parallel lined are used to provide tight coupling

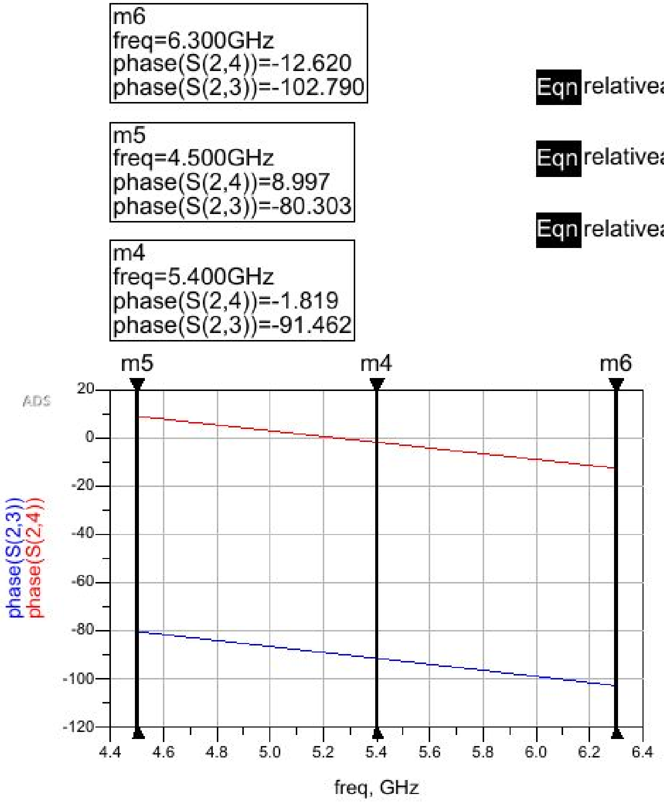


Quadrature Divider: Schematic



Quadrature Divider: S Params





Eqn relativeangle_f0 = 91.462-1.819

Eqn relativeangle_minBW = 80.303 + 8.997

Eqn relativeangle_maxBW = 91.462-1.819

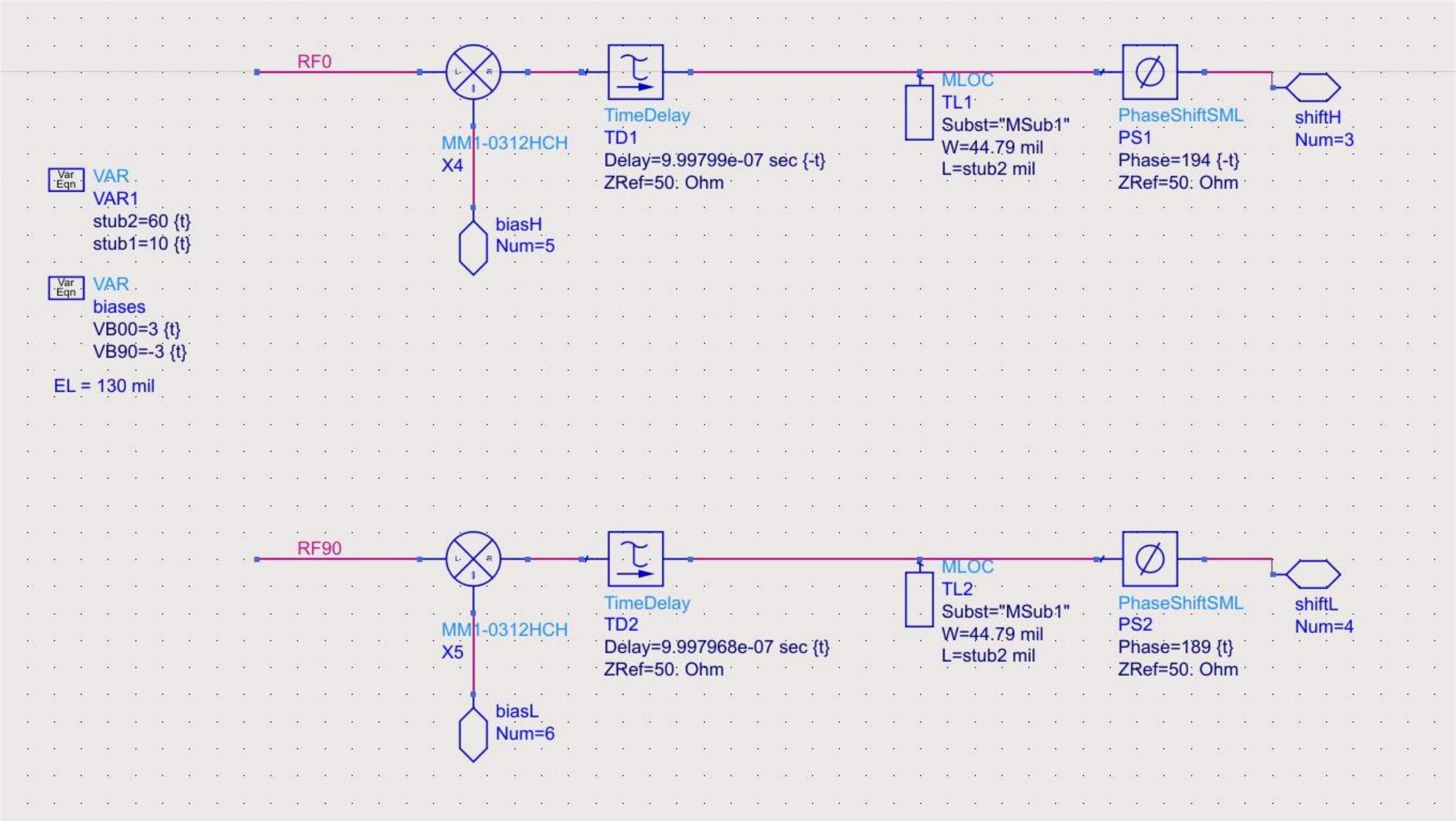
relativeangle_f0	...angle_minBW	...angle_maxBW
89.643	89.300	89.643

phasevar
1.697

0/180 Phase Modulator: Theory

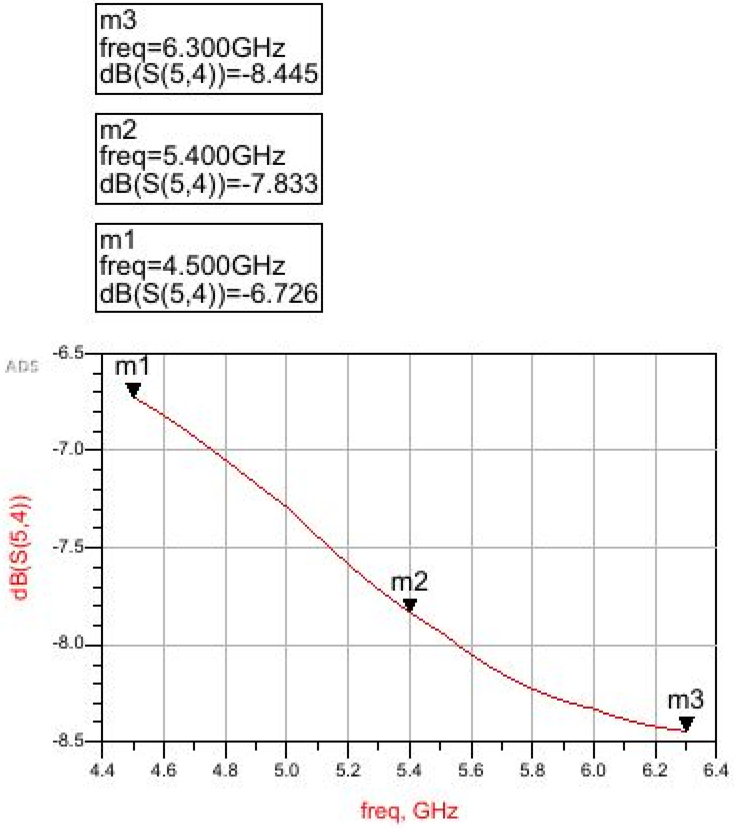
- Using a mixer as a modulator allows for a wide BW and a phase shift of the RF controlled by the LO
- Decided on a Double-Balanced mixer
  - Uses two transformers for good isolation between all 3 ports
  - Rejection of all even harmonics of RF and LO
  - Higher IIP3 than a single-ended mixer
- Mixers can be used as modulators, where it's just viewed as sign changes of the input based on the sign of the LO
  - To do this, RF must go in the LO port, the LO square wave must go into the IF port, and the output must out of the RF port

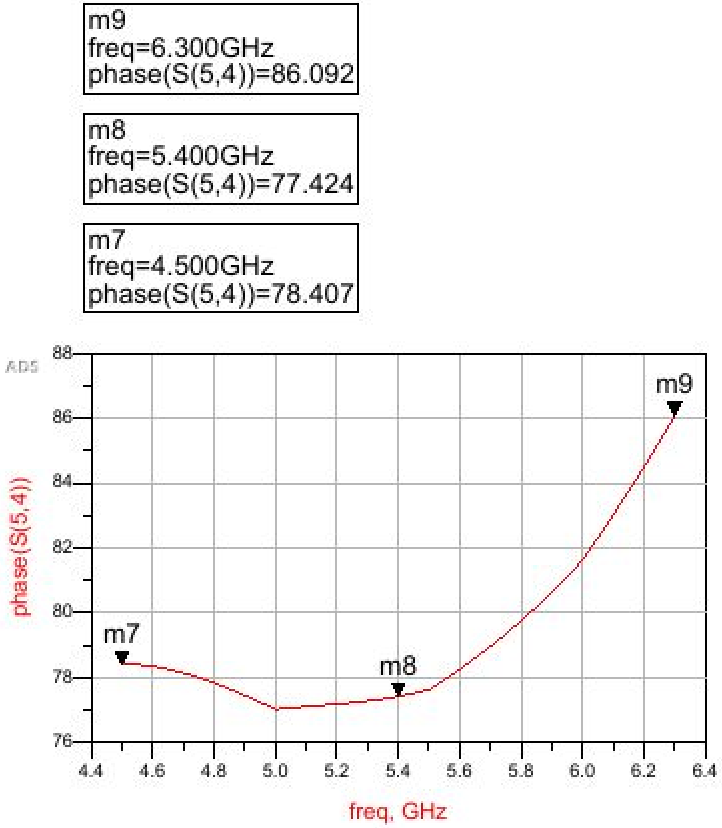
0/180 Phase Modulator: Schematic



0/180 Phase Modulator: S-Params 00xx

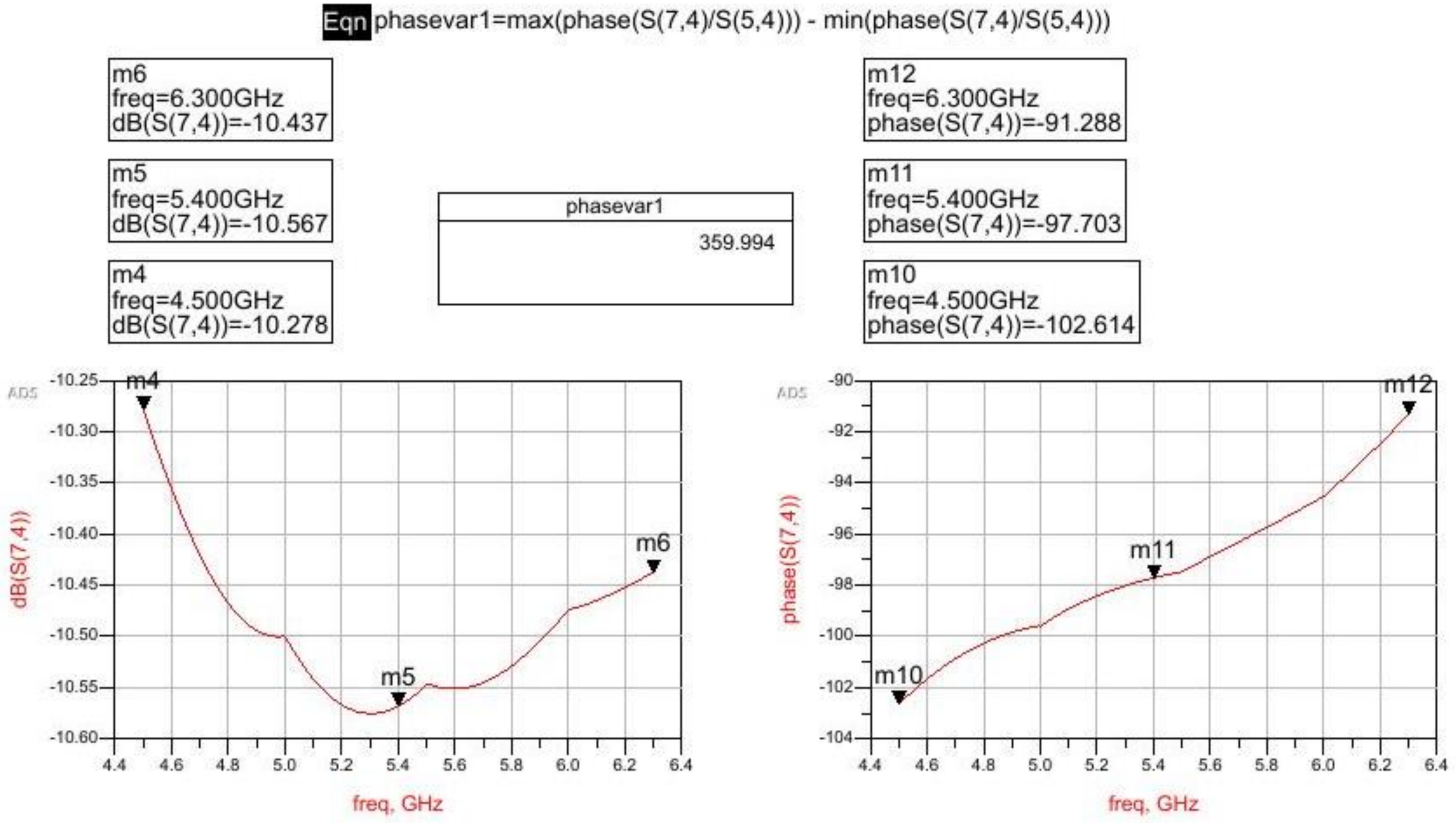
- State: 00xx. This is used as the reference for the following phase and amp variation calcs





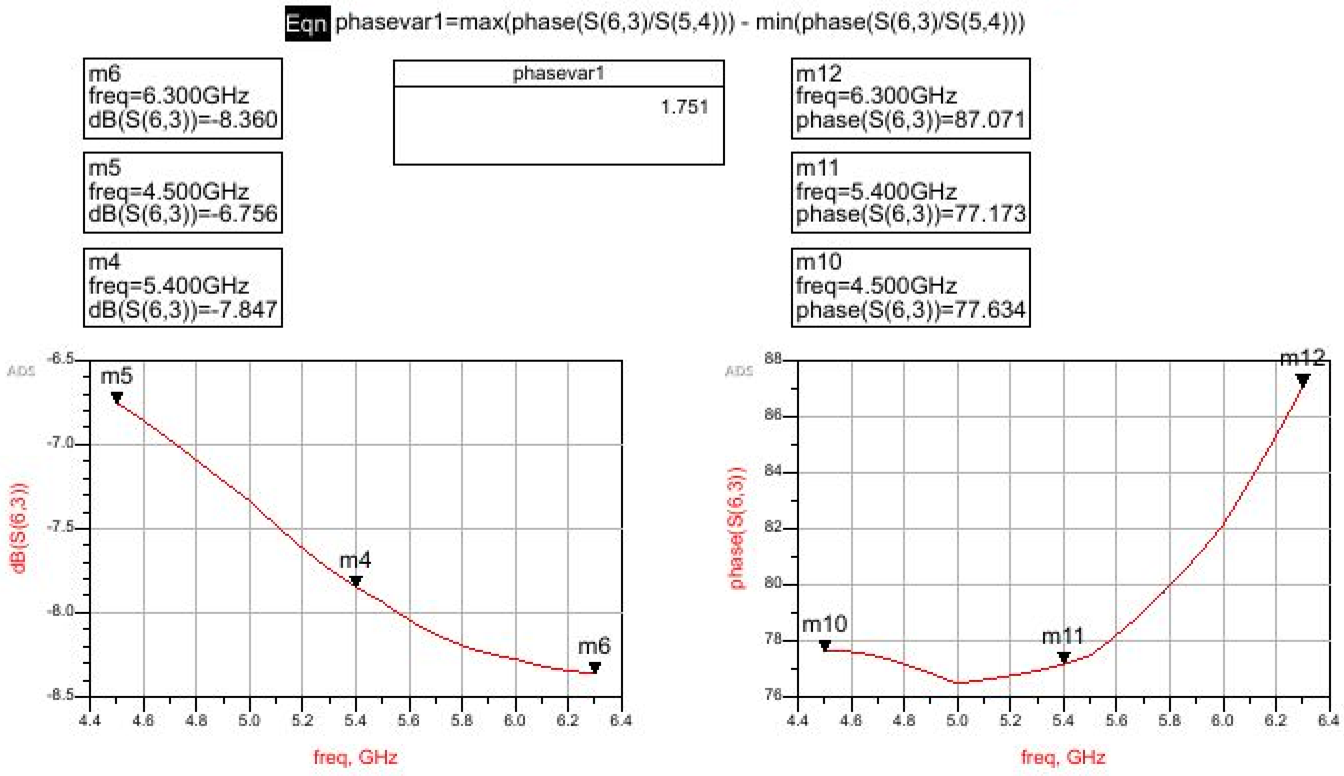
0/180 Phase Modulator: S-Params 01xx

- State: 01xx



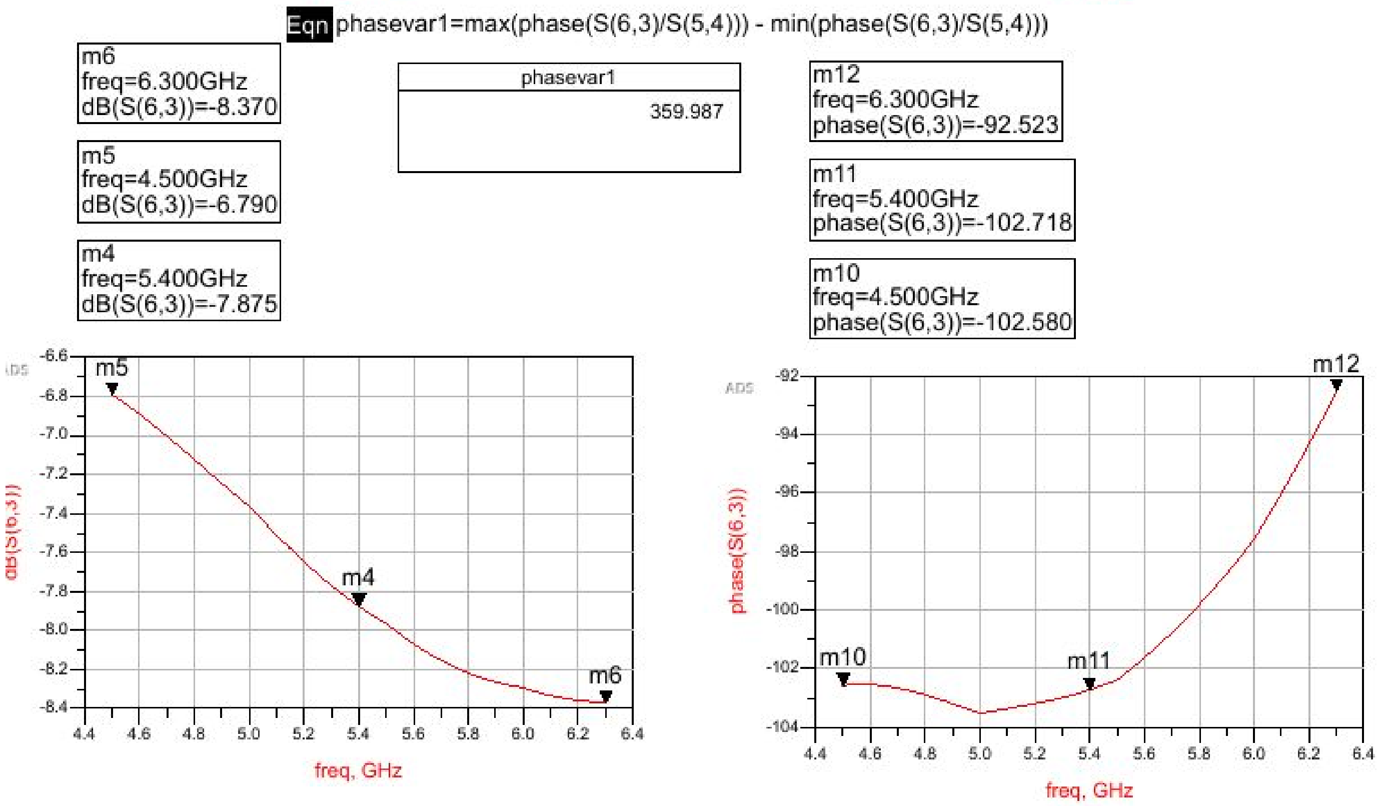
0/180 Phase Modulator: S-Params 10xx

- State: 10xx



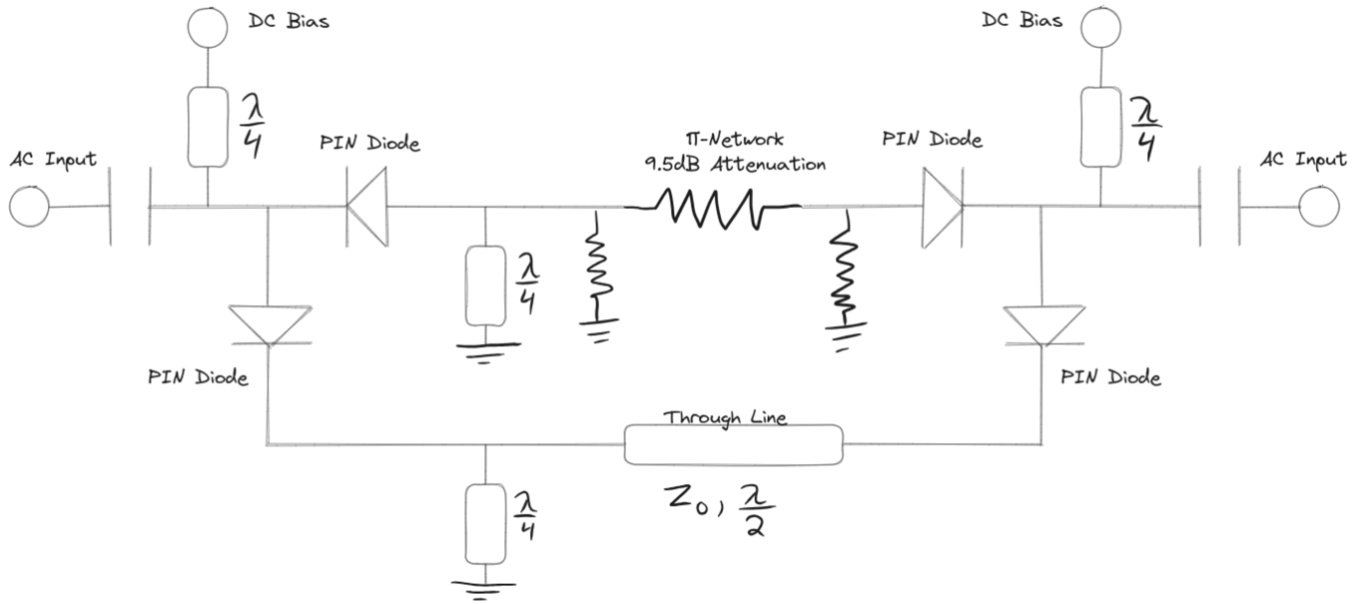
0/180 Phase Modulator: S-Params 11xx

- State: 11xx



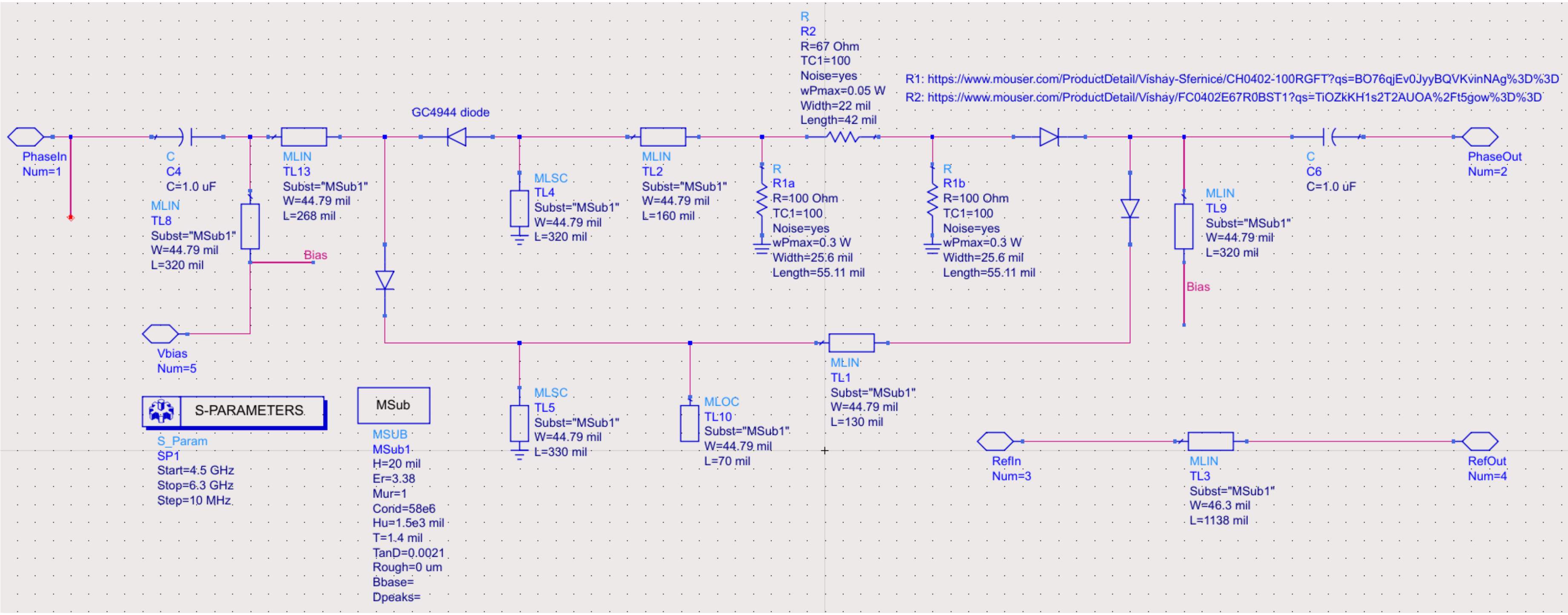
Phase Invariant Attenuator: Theory

- The Phase Invariant Attenuator takes in a bit to determine if the input signal will be attenuated by 0dB or 9.5dB.
- To decide if the signal would be attenuated or not, the circuit was switched using two PIN diodes and had a DC bias (representing the bits) whether the diodes were forward or reverse biased.



Phase Invariant Attenuator: Implementation

- To implement the Phase Invariant Attenuator, some changes were made compared to the ideal schematic.
  - The biggest differences are the additional MLINs after the DC bias and a MLOCs transmission line on the through line to meet specs, which were determined using the tuning tool.
  - At the bottom is a sample circuit to determine the electrical length of this block (using the tuning tool) to remove the phase offset from the circuit to get more accurate simulation results.



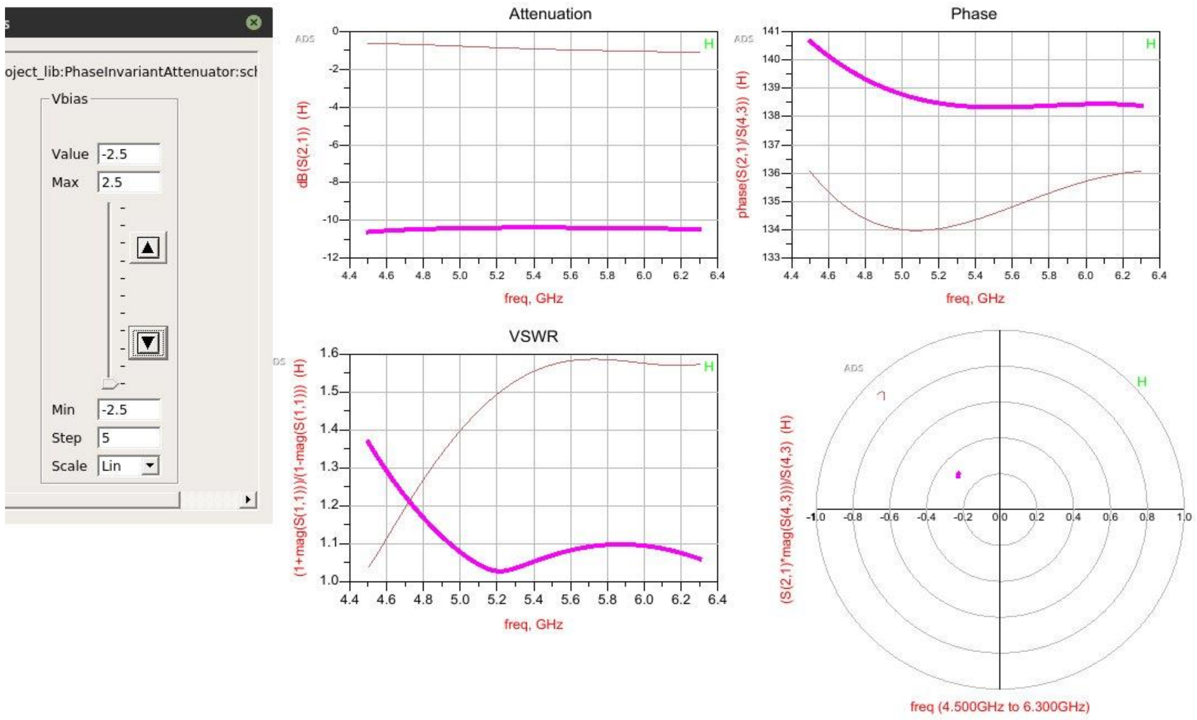
Phase Invariant Attenuator: Simulation Results

Eqn dBvariation=max(dB(S(2,1)))-min(dB(S(2,1)))

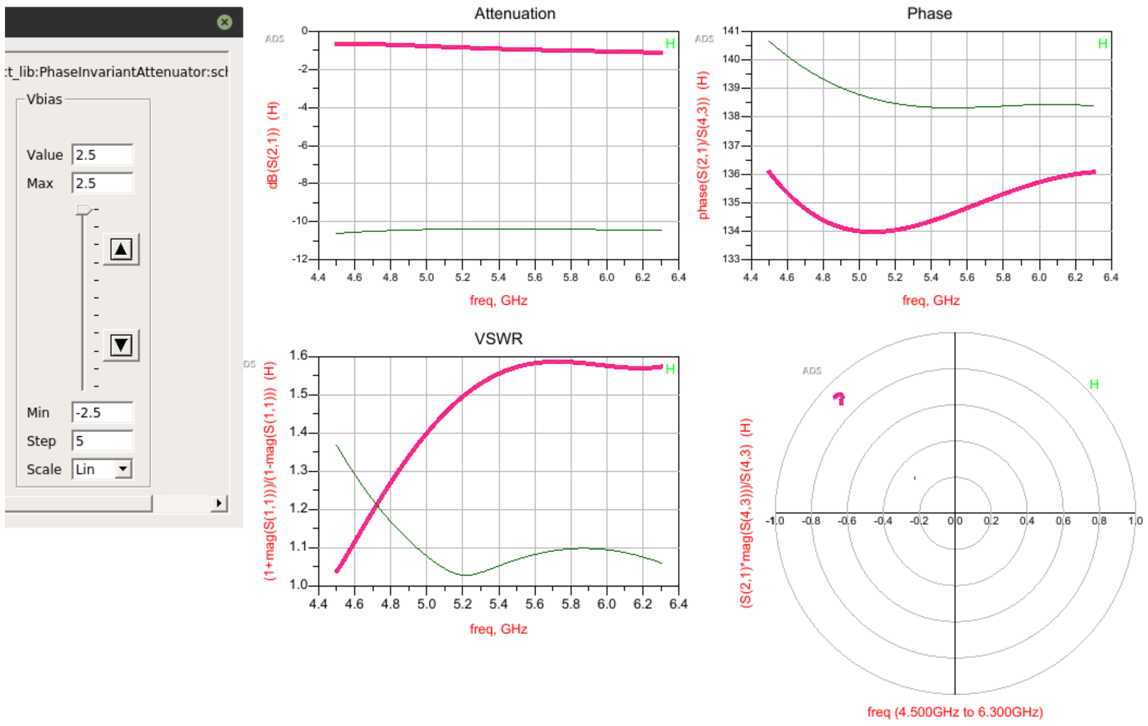
Eqn phasevariation=max(unwrap(phase(S(2,1)/S(4,3))))-min(unwrap(phase(S(2,1)/S(4,3))))

dBvariation	phasevariation
0.233	2.326

dBvariation	phasevariation
0.472	2.092



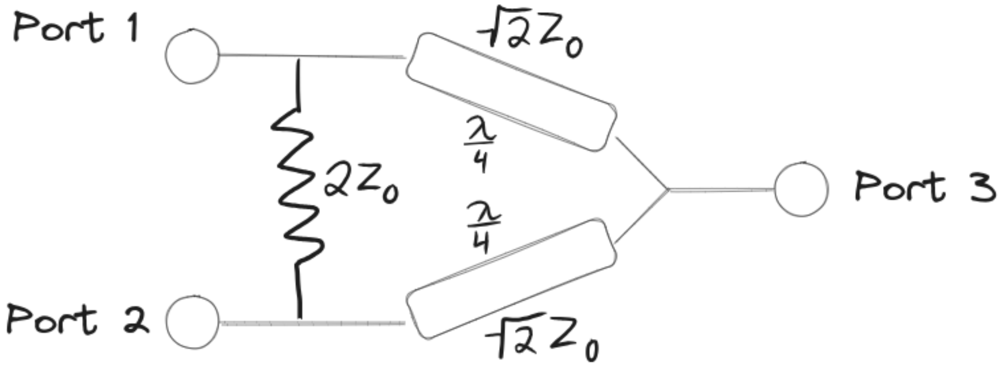
State xx0x/xxx0 (Negative Bias)



State xx1x/xxx1 (Positive Bias)

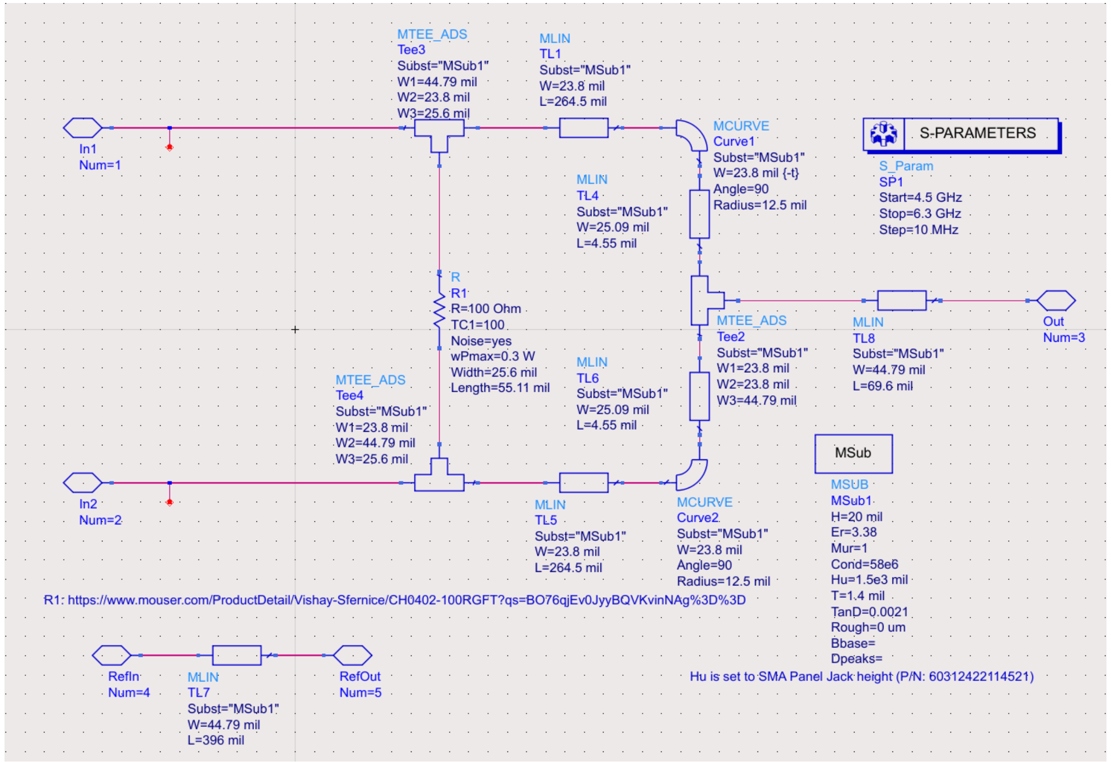
Wilkinson Power Combiner: Theory

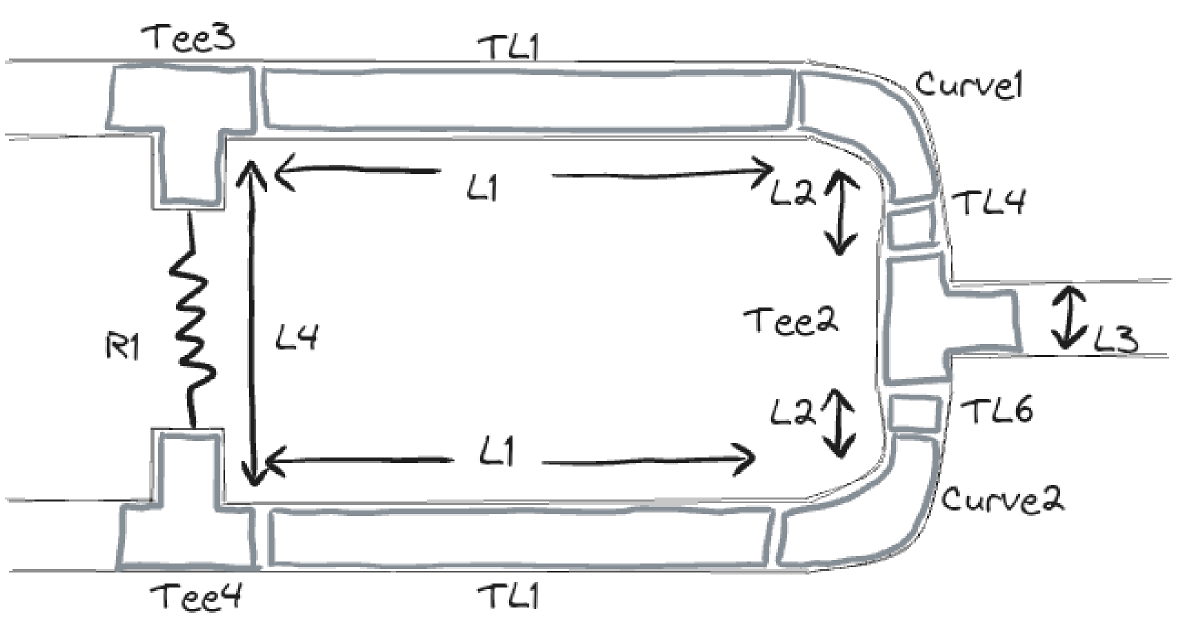
- The main purpose of the Wilkinson Power Combiner is to combine the power of two ports with the benefits of:
  - Minimal attenuation (3dB)
  - High isolation between the two input ports
  - Maintaining phase coherence
  - Allows impedance matching to minimize reflection losses
- This is used to combine the output from the Q-axis and I-axis to generate the final constellations graphs for 16-QAM.



Wilkinson Power Combiner: Implementation

- The biggest difference between the ideal and final schematic was the consideration on the geometry for the Wilkinson Power Combiner.
  - The transmission lines were added to make sure the length and the geometry of the final design lined up. Below is a sample image of how this design would look in real life.





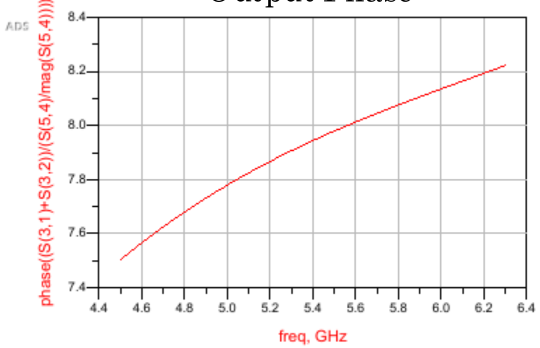
Wilkinson Power Combiner: Simulation Results

phaseVar	dBVar
0.718	0.061

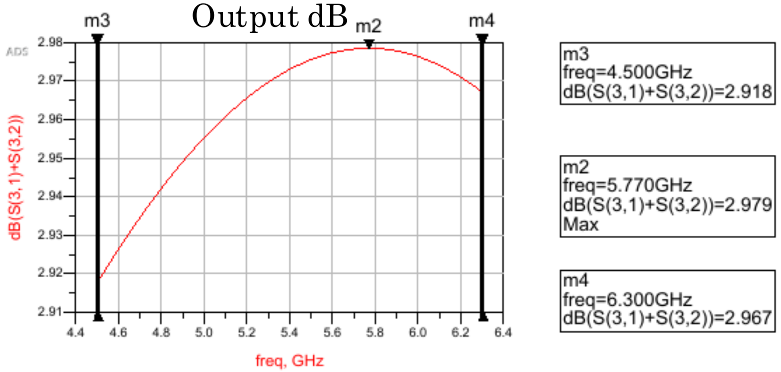
Eqn dBVar = max(dB(S(3,1)+S(3,2)))-min(dB(S(3,1)+S(3,2)))

Eqn phaseVar = max(phase((S(3,1)+S(3,2))/(S(5,4)/mag(S(5,4)))))-min(phase((S(3,1)+S(3,2))/(S(5,4)/mag(S(5,4)))))

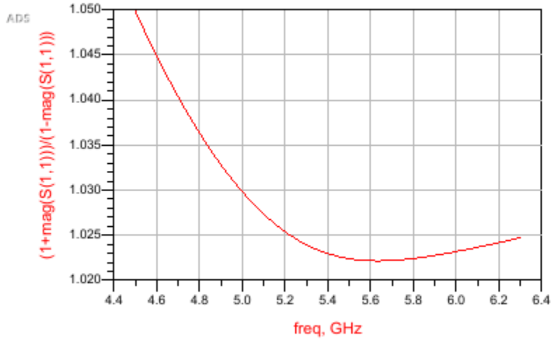
Output Phase

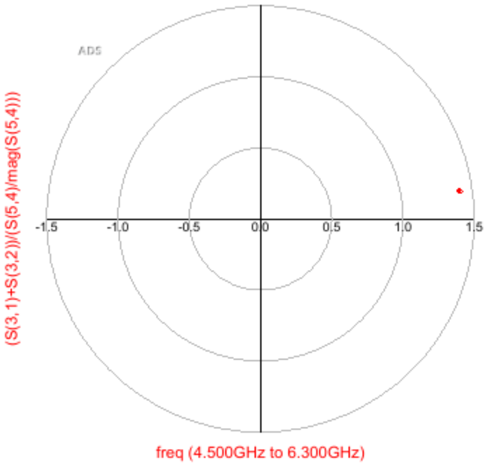


Output dB

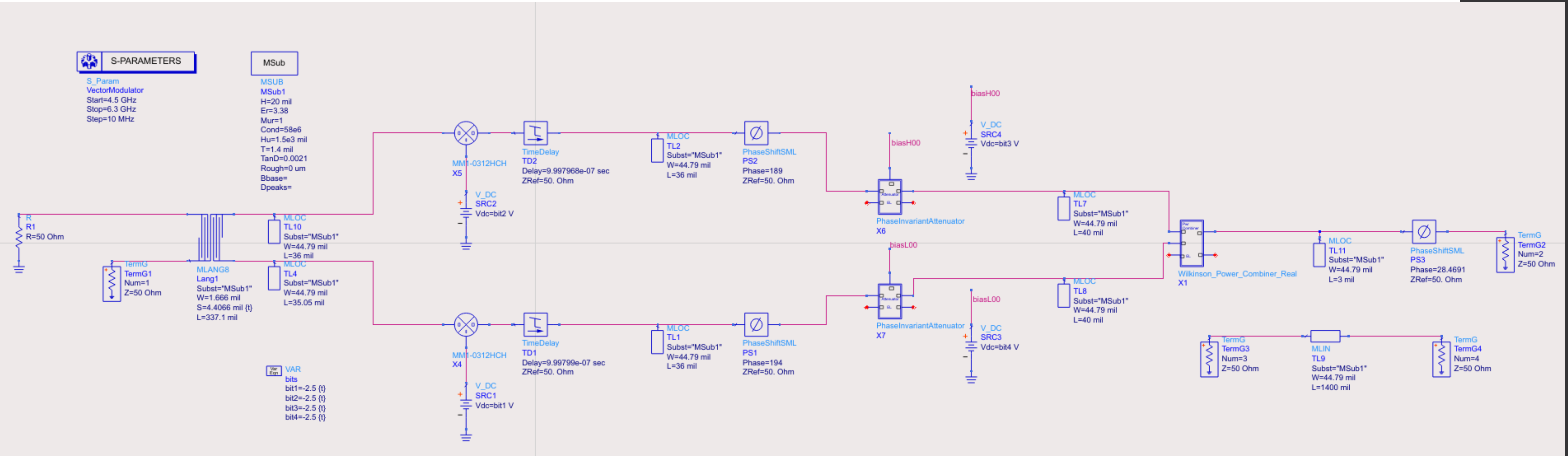


VSWR



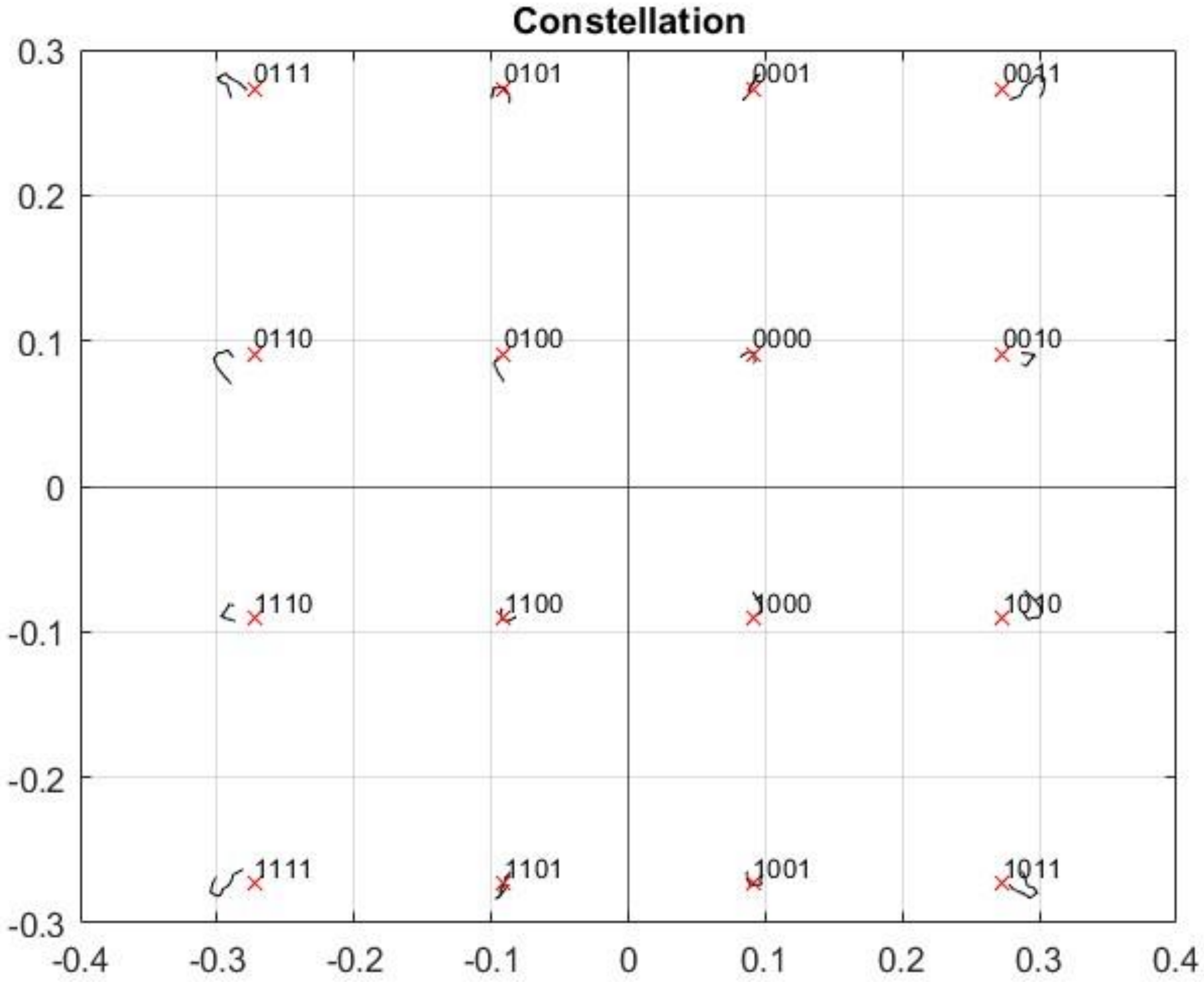


Full Schematic

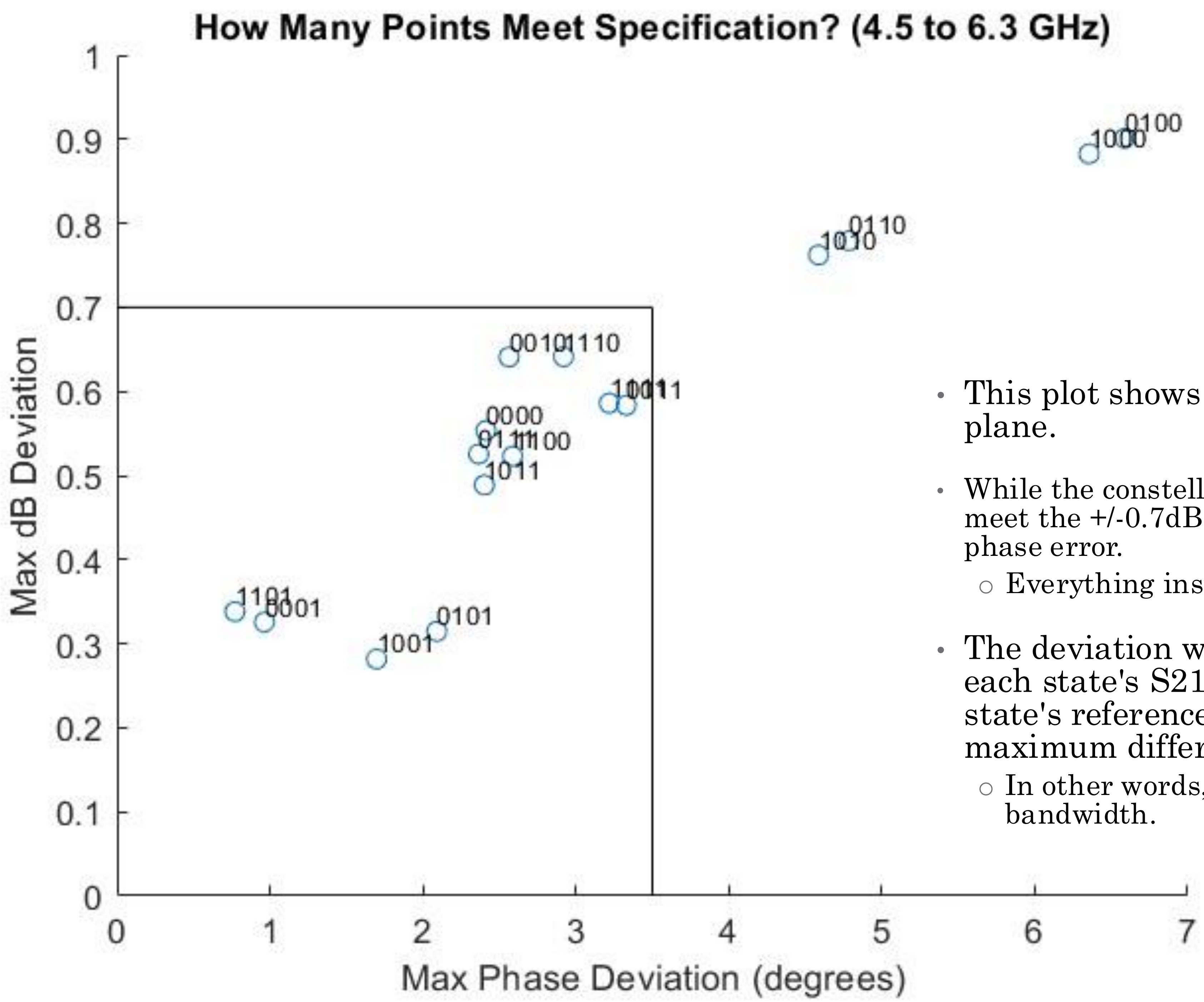


Final Design Specs/Graphs

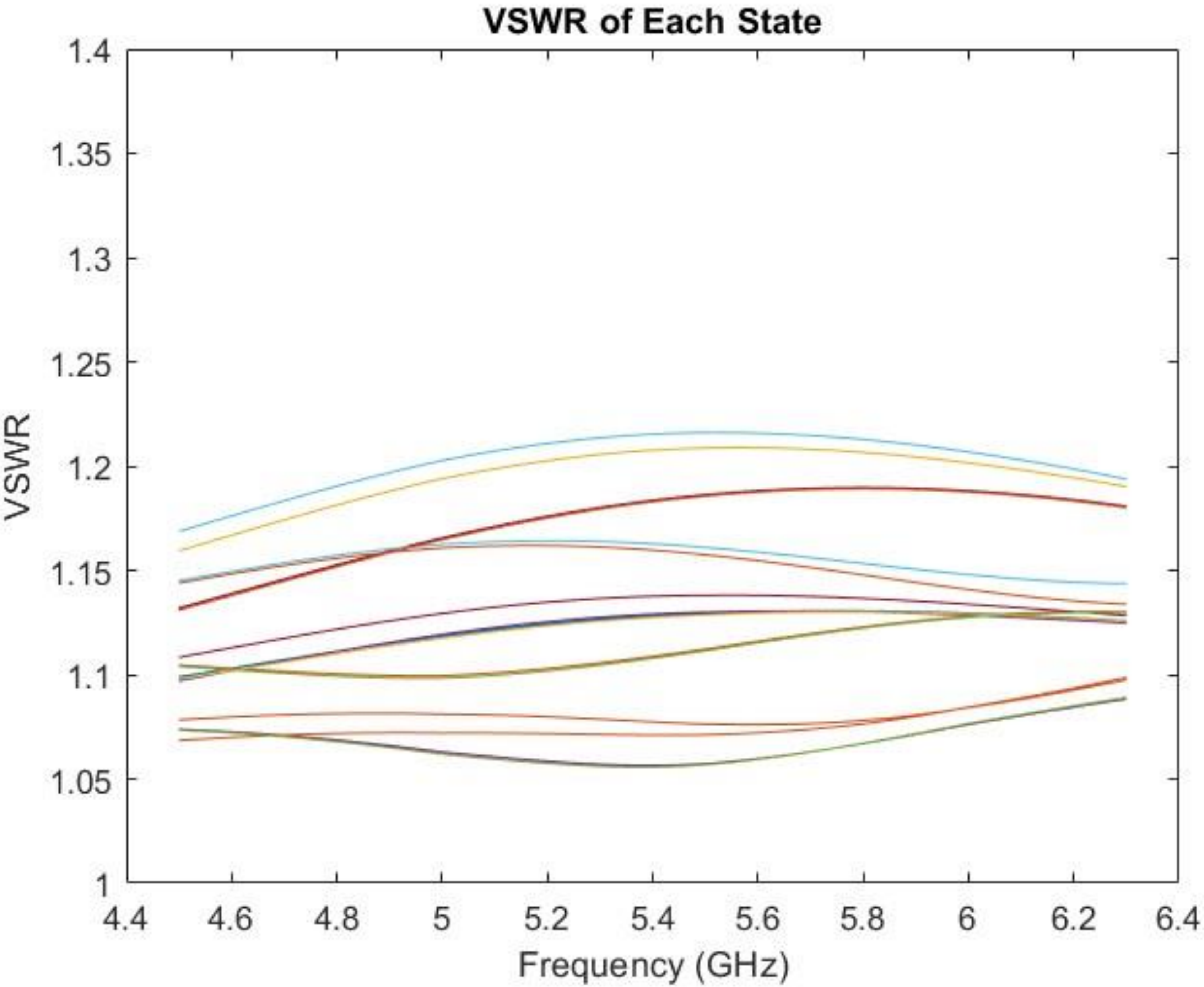
- To process the final data outputs from ADS, the S parameter outputs were exported from ADS into a CSV file which was given to a MatLab script.
- For all 16 states, S11 and S21 were collected, to measure insertion loss, VSWR, and their maximum phase and dB variation compared to a reference constellation.

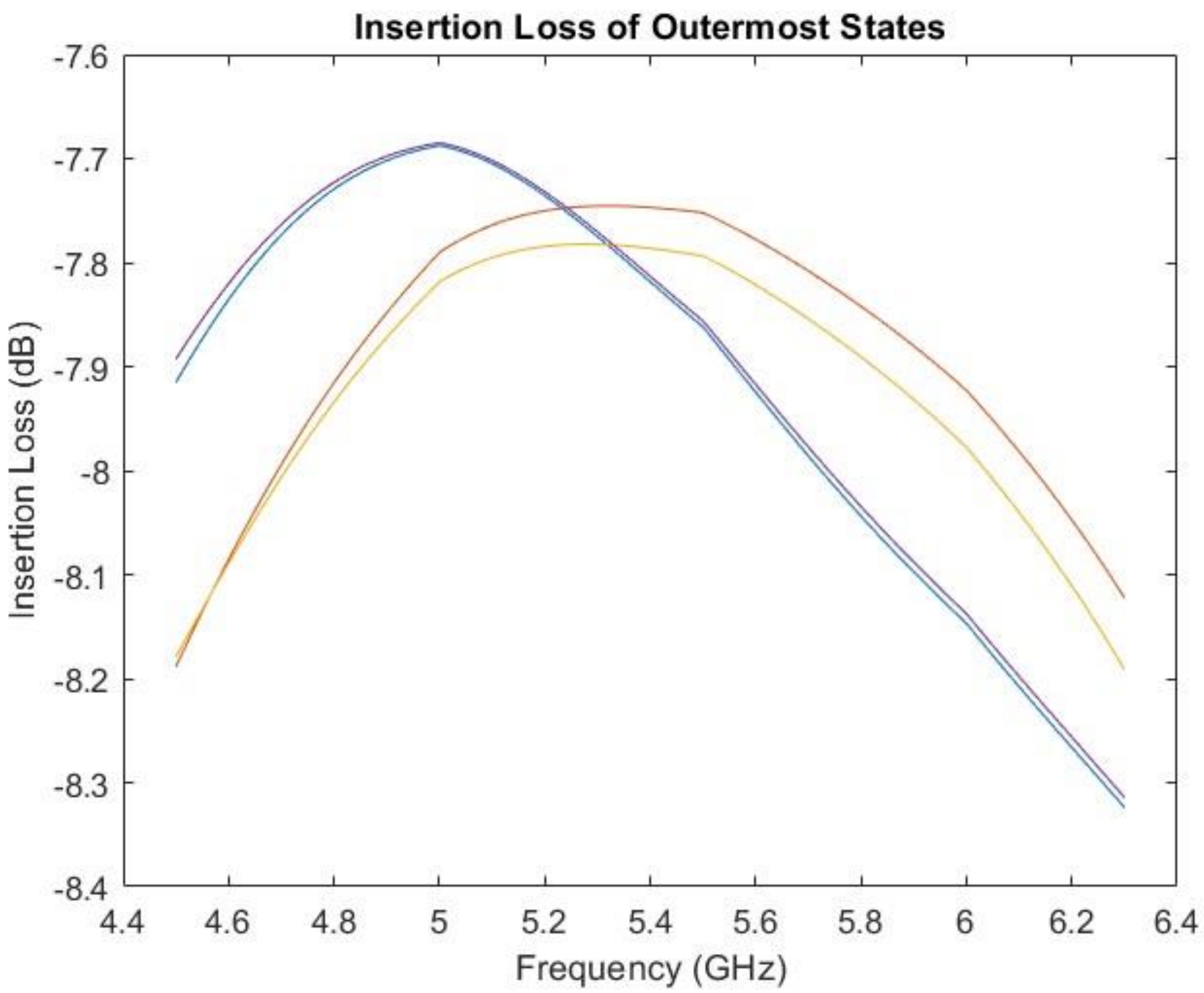


- State 0000 was chosen as a reference point, and a scaled-down **ideal** constellation was generated, shown by the red X's .
- The small black squiggles are each state's respective S21 over the 1.8GHz BW.
- Notice the 180-degree rotational symmetry!



- This plot shows all our points in a dB/phase plane.
- While the constellation looks nice, not all points meet the +/-0.7dB and +/-3.5deg amplitude and phase error.
  - Everything inside the box meets specification
- The deviation was calculated by sweeping each state's S21 with respect to the same state's reference constellation and finding the maximum difference in dB and in phase.
  - In other words, a worst-case scenario over our bandwidth.


VSWR of Each State
VSWR
Frequency (GHz)
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
6
6.2
6.4


Insertion Loss of Outermost States
Insertion Loss (dB)
Frequency (GHz)
-7.6
-7.7
-7.8
-7.9
-8
-8.1
-8.2
-8.3
-8.4
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
6
6.2
6.4

Specifications Met

	dB Variation	Phase Variation	Max VSWR	Max Insertion Loss
Achieved	States 4,6,8,10 failed (0100, 0110, 1000, 1010)	States 4,6,8,10 failed (0100, 0110, 1000, 1010)	1.22	8.32 dB
Specification	+/- 0.7dB	+/- 3.5 degrees	1.4	8.5 dB
Error	4/16 points failed	4/16 points failed	-0.18	-0.14 dB

Appendix: Components

- Substrate Material: Rogers 4003 mil
- 0/180 Modulator
  - Mixer: MM1-0312HCH https://markimicrowave.com/products/surface-mount/mixers/mm1-0312hsm-2/datasheet/
- PIN Diode: GC4944 https://ww1.microchip.com/downloads/aemDocuments/documents/RFDS/ProductDocuments/DataSheets/GC4900.pdf
- Phase Invariant Attenuator
  - Ra: CH0402-100RGFT https://www.vishay.com/docs/53014/ch.pdf
  - Rb: FC0402E67R0BST1 https://www.vishay.com/docs/60093/fcseries.pdf
- Wilkinson Power Combiner
  - R1: https://www.vishay.com/doc?53014