915 MHz Power Amplifier

EE172 Final Project

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Introduction:

Radio Frequency Power amplifiers are used in a wide range of applications, and are an integral part of many daily tasks. For my EE172 final project I designed an RF power amplifier for 915MHz. The design specification required that the amplifier have at least 25dB gain, have 2 or 3 stages. I designed my amplifier to exceed the gain specification while providing 31 dB gain and 28 dBm out at 915MHz. To meet these specifications I needed to select devices which will give me both the required gain and the high P1dB. In order for all sections of this amplifier to me conjugate matched I needed to select devices which were unconditionally stable at 915 MHz. This set of selection criteria greatly reduced the number of usable devices for me to select from.

After selecting devices, I chose a bias point, and I calculated what my matching networks needed to be. Once I knew the values for my reflection coefficients, I was able to select a type of matching network, and I used a smith chart to find the values for the components in both of my matching networks.

Biasing:

In this project I designed a class A amplifier. This amplifier class means that my transistors are always going to be in their linear range of operation. Their operation region is determined by the bias point that I set for each device. In order for our transistors to operate in their linear range, I need to select a base and collector, current and voltage which will allow keep the transistor in the middle of its linear operation region. Setting the bias point in the middle of the linear region maximizes my gain by allowing equal signal swing on both sides of the bias point.

The bias point also changes the amplification properties of the device. Different bias points can increase or decrease the noise figure, increase or decrease the gain, and even push the device out of its stable region of operation. I selected my bias points to make my device unconditionally stable at my operation frequency. This was done so that I could perform a simultaneous conjugate match on both ports of my device.

Matching:

Accurate impedance matching is required when working at high frequencies. If two systems are not matched in impedance than some portion of the power will be reflected back to the sender. Conjugate matching provides the most power transfer between two RF systems. A conjugate match is where the input impedance of the receiving system is designed to be the complex conjugate. Other types of impedance matching set the source and load impedance equal to each other, but this transfers less of the incident power than a conjugate match.

Impedance matching active devices requires specific steps to be taken which may not be needed in other situations. If the transistor being matched has a high S12 than the device needs to be matched simultaneously, whereas a device with an S12 near zero can have both ports matched separately. Simultaneous conjugate matching requires solving through the system of equations formed by the two matching networks and the devices S parameters at that frequency. A derivation of these equations is provided in the class text “Microwave Engineering 3rd edition” by David M. Pozar. The system of equations solved for the input and output gammas are

$$\Gamma_S = \frac{B_1 \pm \sqrt{B_1^2 - 4|C_1|^2}}{2C_1} \qquad \Gamma_L = \frac{B_2 \pm \sqrt{B_2^2 - 4|C_2|^2}}{2C_2}$$

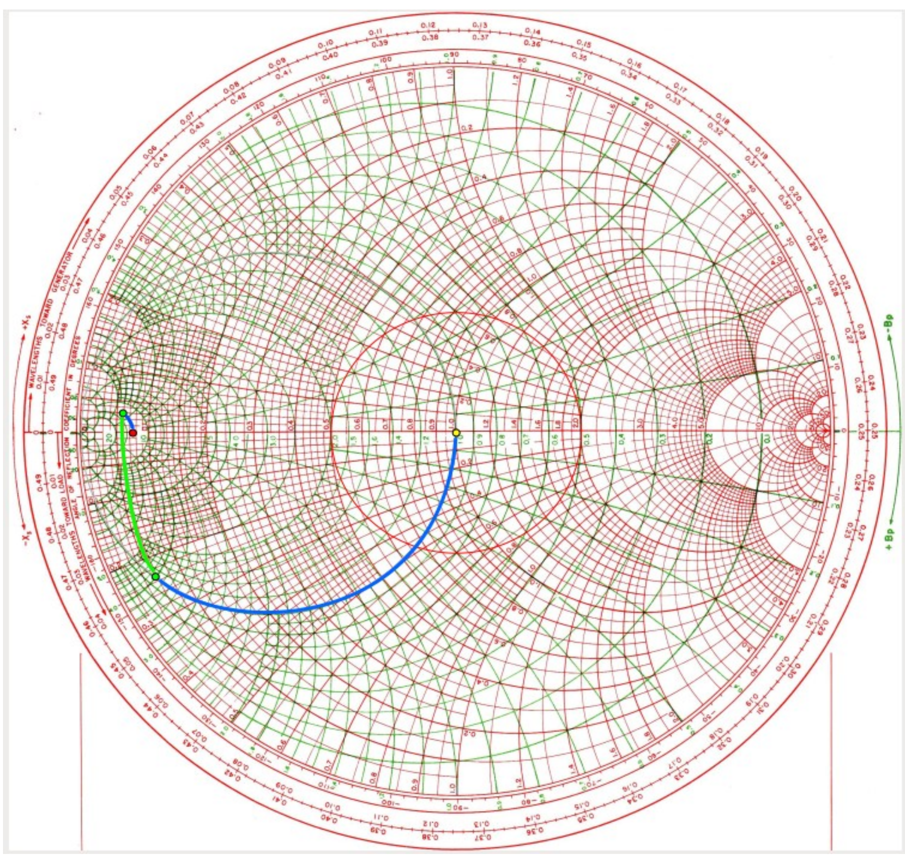
where

$$\begin{gathered} B_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2, \\ B_2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2, \\ C_1 = S_{11} - \Delta S_{22}^*, \\ C_2 = S_{22} - \Delta S_{11}^* \text{ and} \\ \Delta = S_{11} S_{22} - S_{12} S_{21} \end{gathered}$$

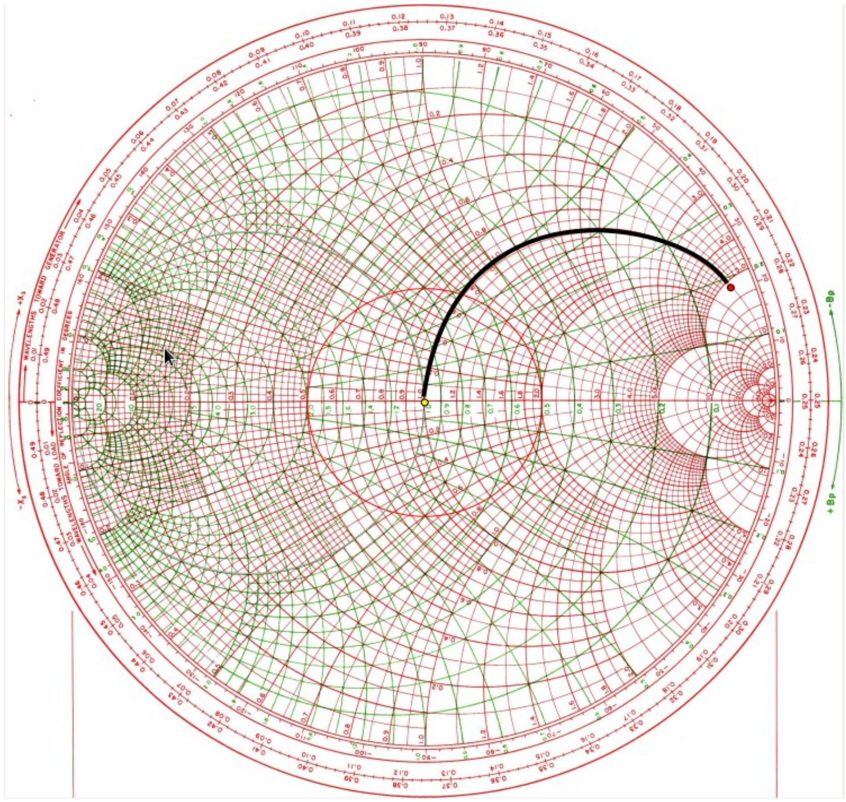
When matching networks with these gammas are attached to the input and output of the amplification device, than both ports are conjugate matched.

One important fact about simultaneous conjugate matching is that the device must be stable unconditionally before it can be conjugate matched at both ports. This is true because the term under each square root needs to be positive for the solution to be valid. $B_2^2 - 4|C_2|^2$ is greater than zero at the same times as the Rollet Stability factor is greater than 1. Both indicate that the device is unconditionally stable.

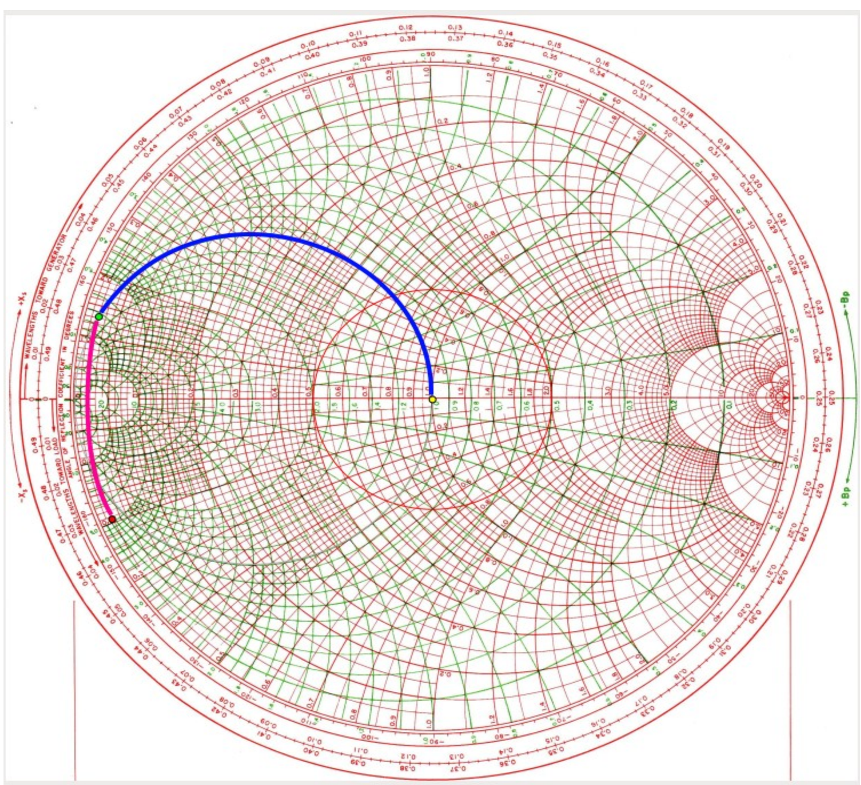
Once I calculated the required reflections for each of the two matching networks, I needed to design matching networks for each one. Using a Smith Chart I chose a type of matching network, and found the needed values for each lump element. Because the goal is to eventually build this amplifier, I needed to be sure that all of my components had realistic values. Because of this constraint, I had to be careful about my selection of matching network types and paths around the Smith Chart. One Smith Chart is included below for each of my 4 matching networks. Each chart shows the path I took for the network. Additionally the schematics below show both stages of my amplifier in Microwave Office's schematic editor. After those are the simulated frequency sweeps of each stage.



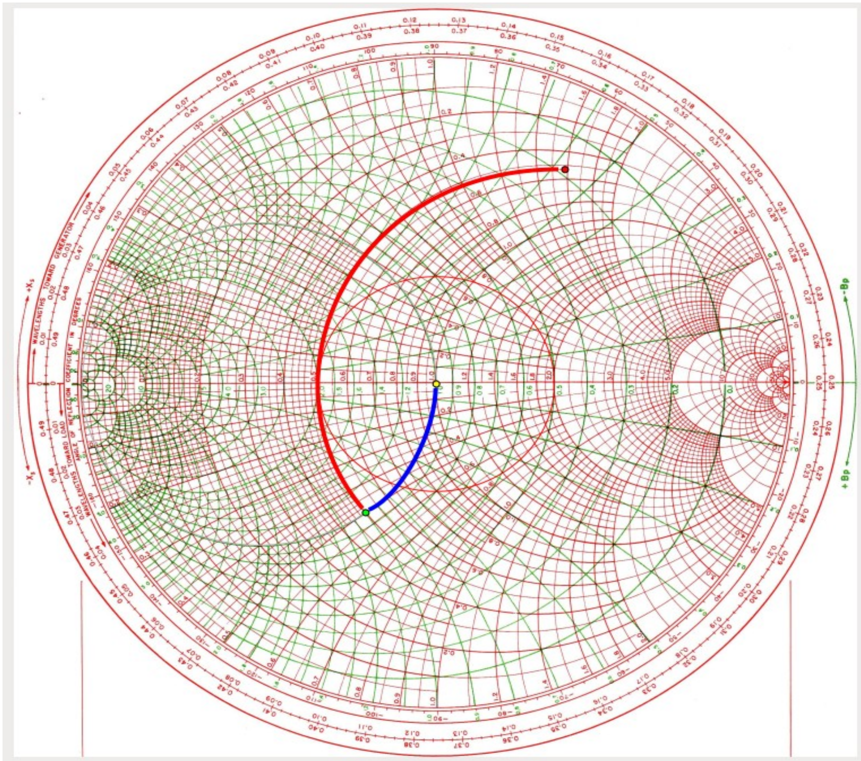
Stage 1 Source Matching



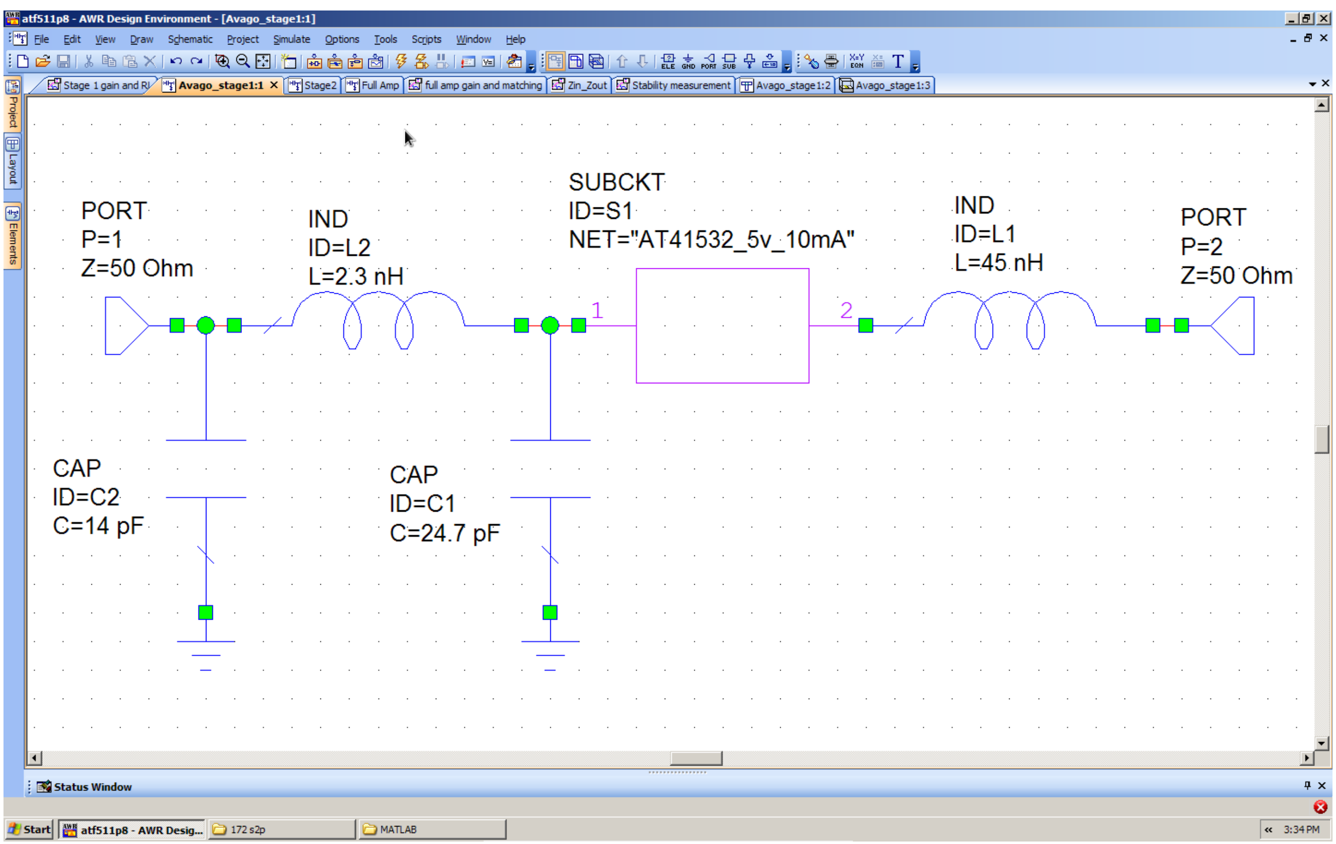
Stage 1 Load Matching



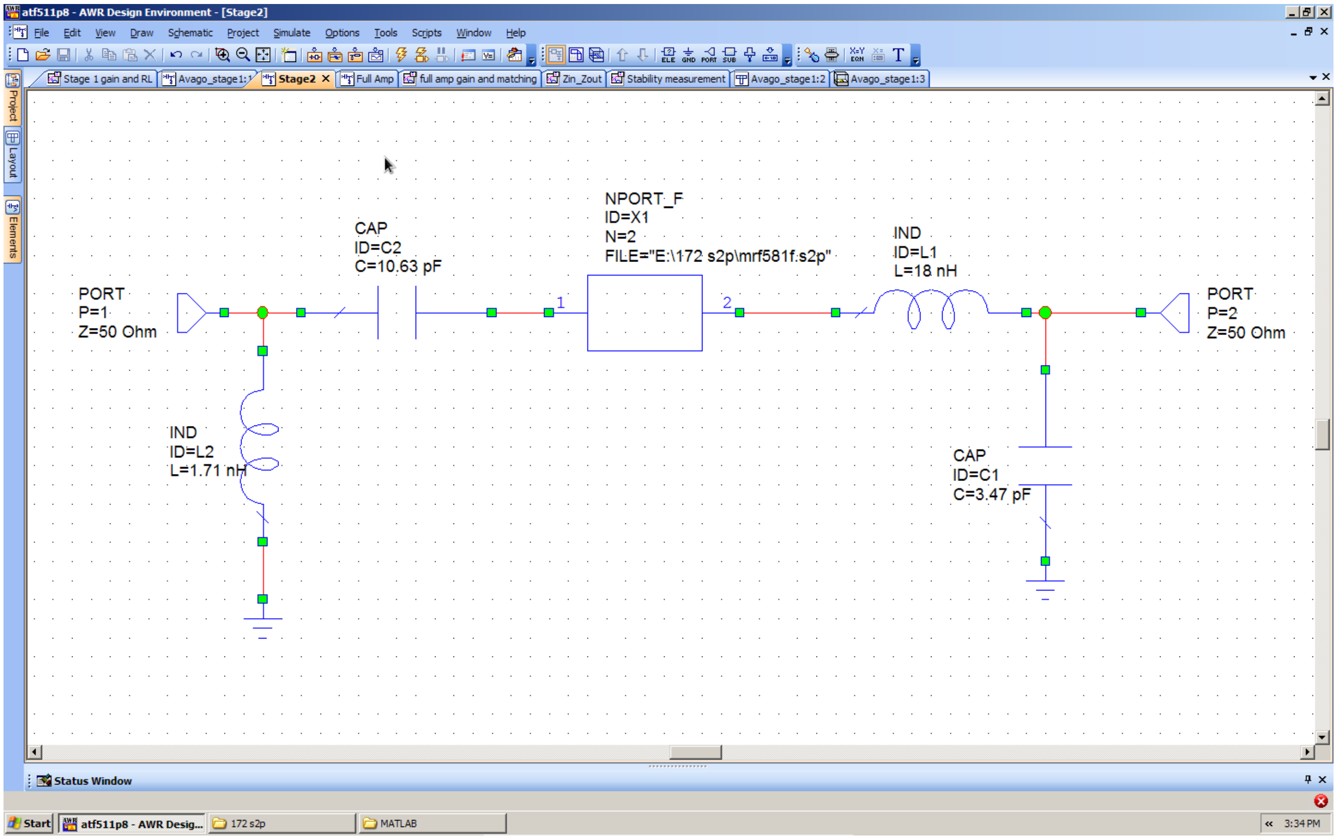
Stage 2 Source Matching



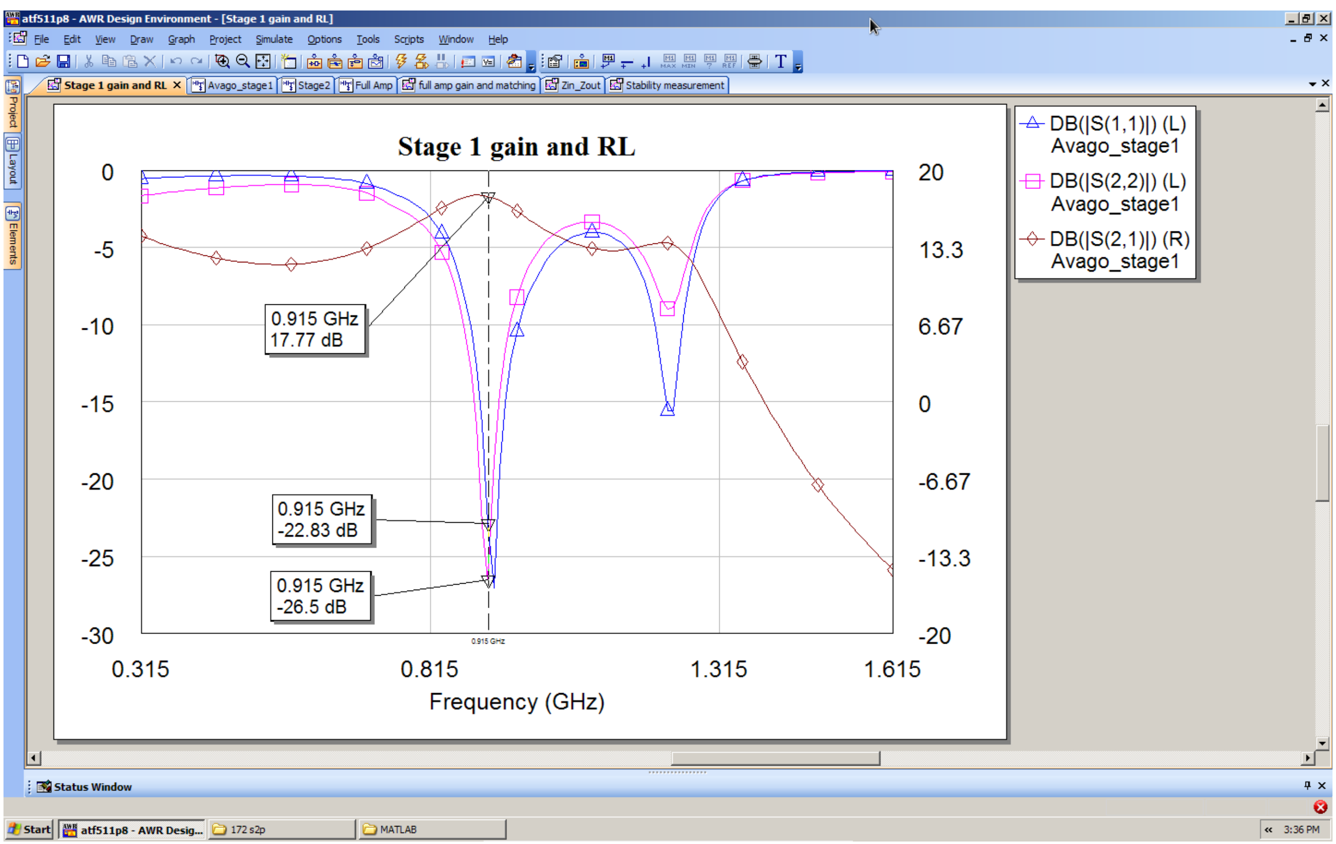
Stage 2 Load Matching



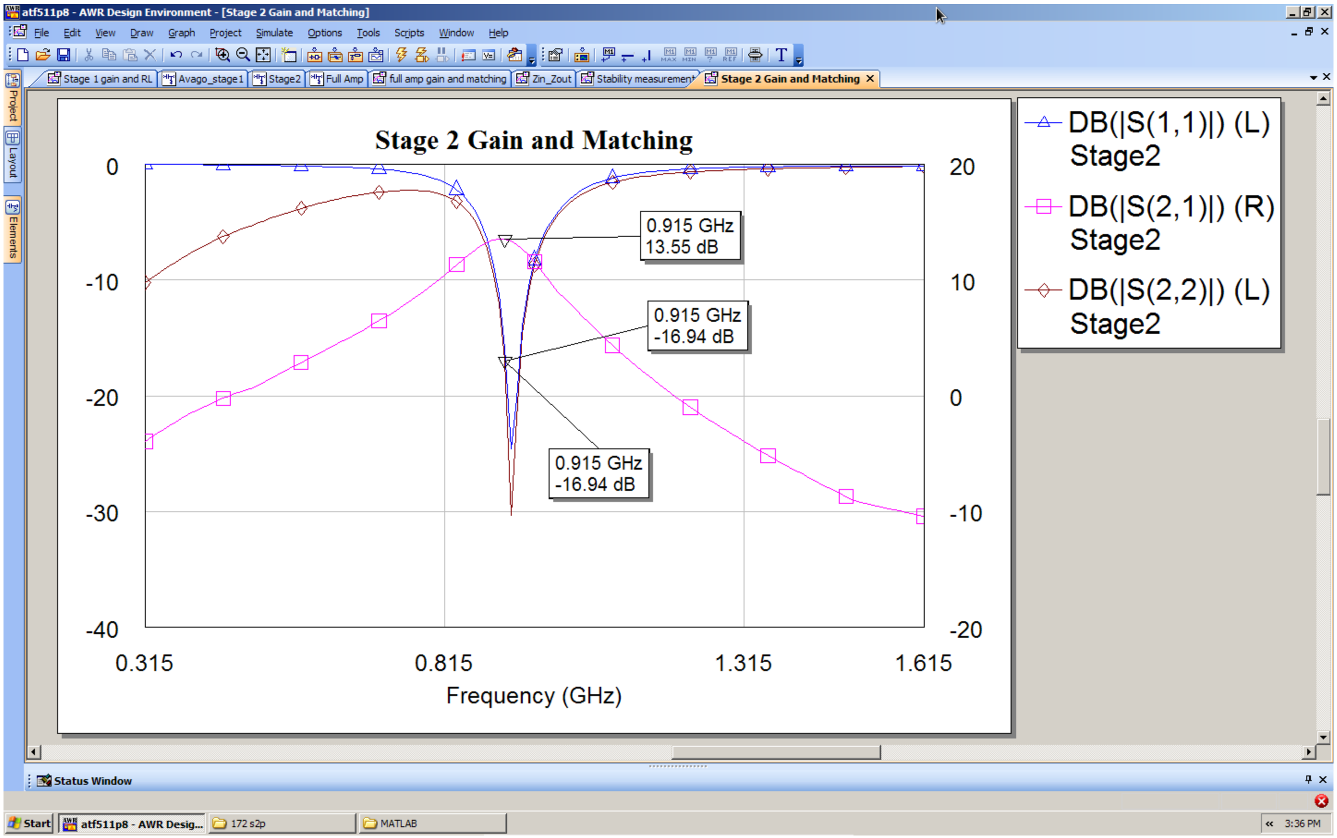
Stage 1 Matching Network:



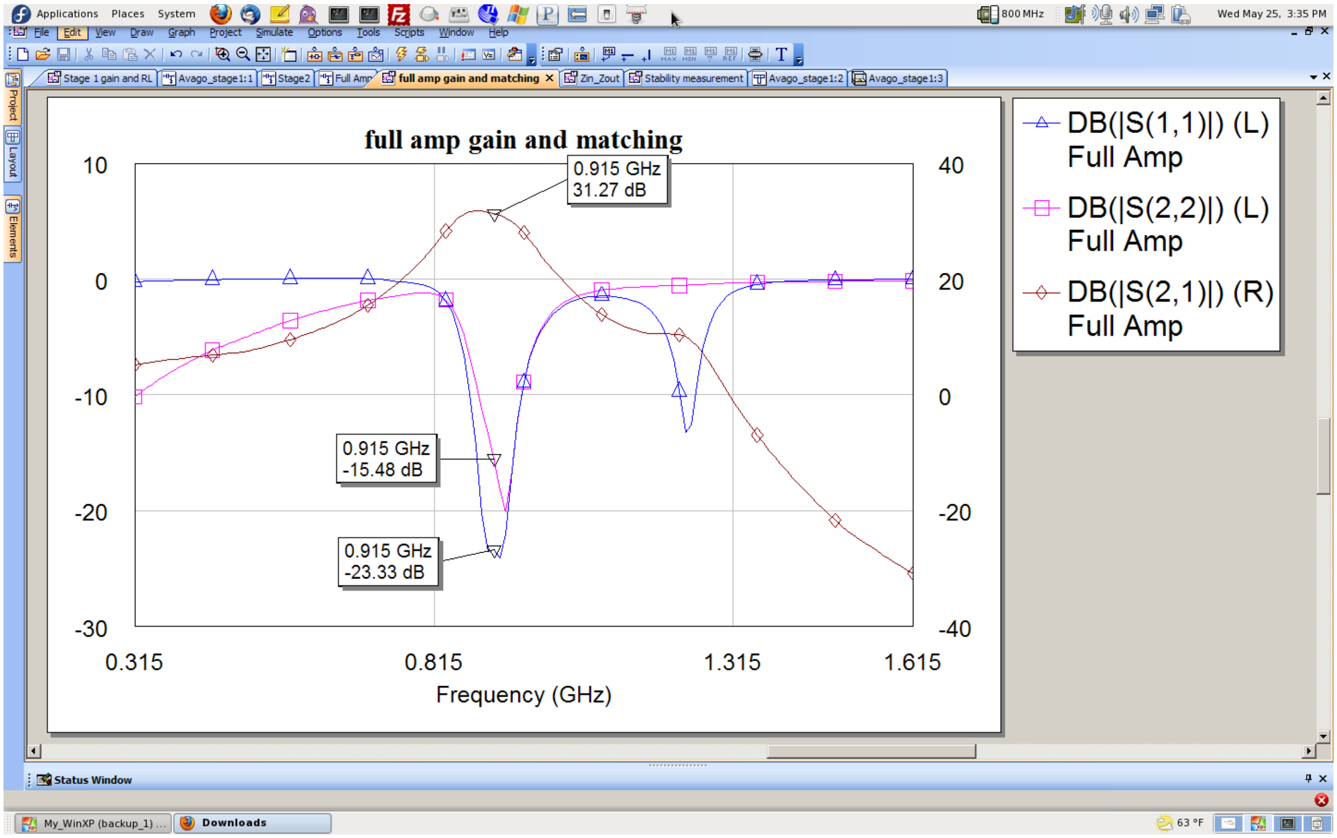
Stage 2 Matching Network:



Stage 1 Return Loss and Gain:



Stage 2 Return Loss and Gain:



Full Amplifier Return Loss and gain:

Stability:

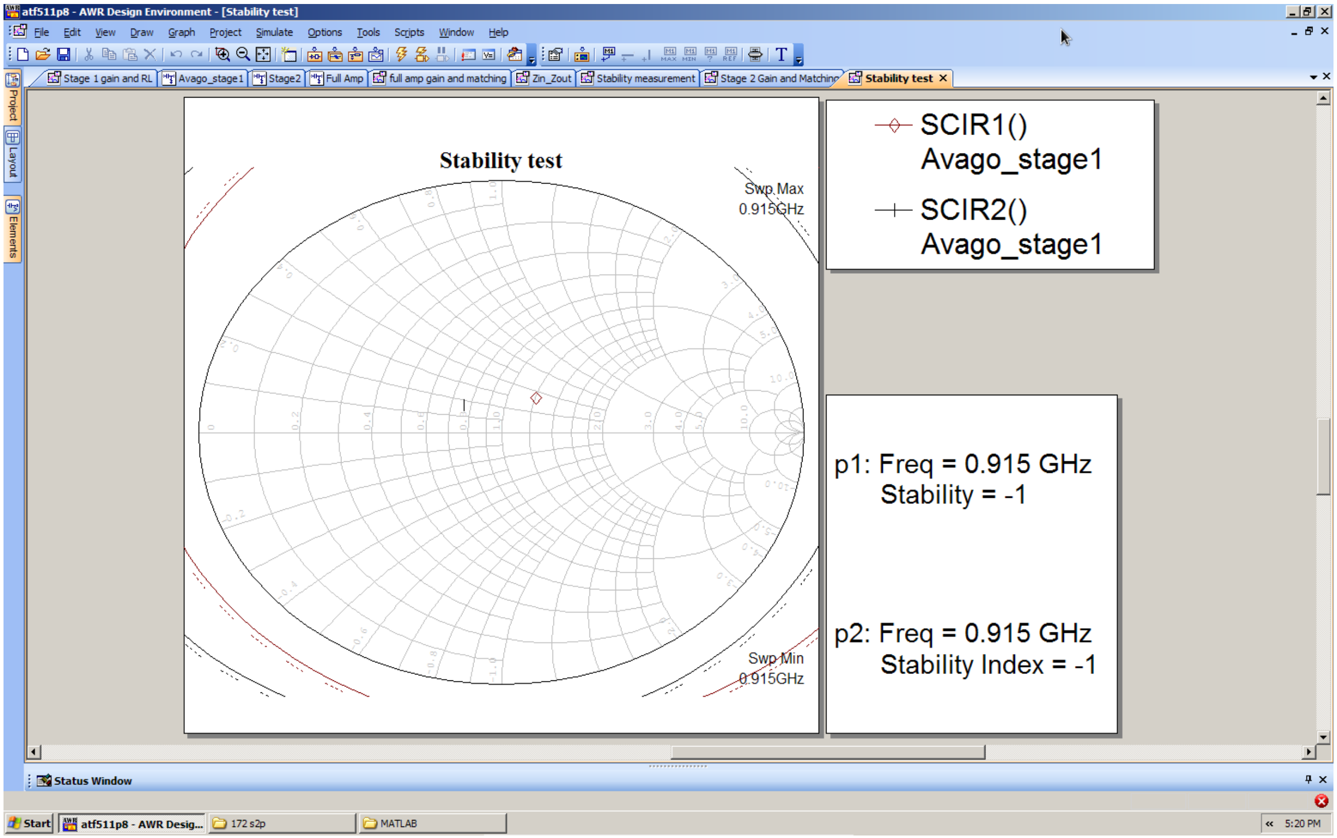
All amplifiers need to be stable, otherwise they are not amplifying the original signal, and are instead generating spurious frequencies. RF amplifiers are not stable when there is positive feedback. All RF transistors have parasitic inside of them which can make the device unstable. Proper matching and good design practices must be used to make the device stable again. A device or system can be either conditionally or unconditionally stable. An unconditionally stable amplifier is one which can have any impedance attached to the input or output, and it will not become unstable. A conditionally stable amplifier will potentially oscillate. Oscillations in a power amplifier can output a large amount of power in an arbitrary range of frequencies. This can damage later stages in a system, break FCC rules, or damage and destroy equipment inducing the transistor which is unstable.

There are several methods in RF amplifier design which can be used to calculate the stability of a particular transistor. For my design process I used the Rollet stability factor to determine if my device was unconditionally stable or not. The equations to calculate this number is

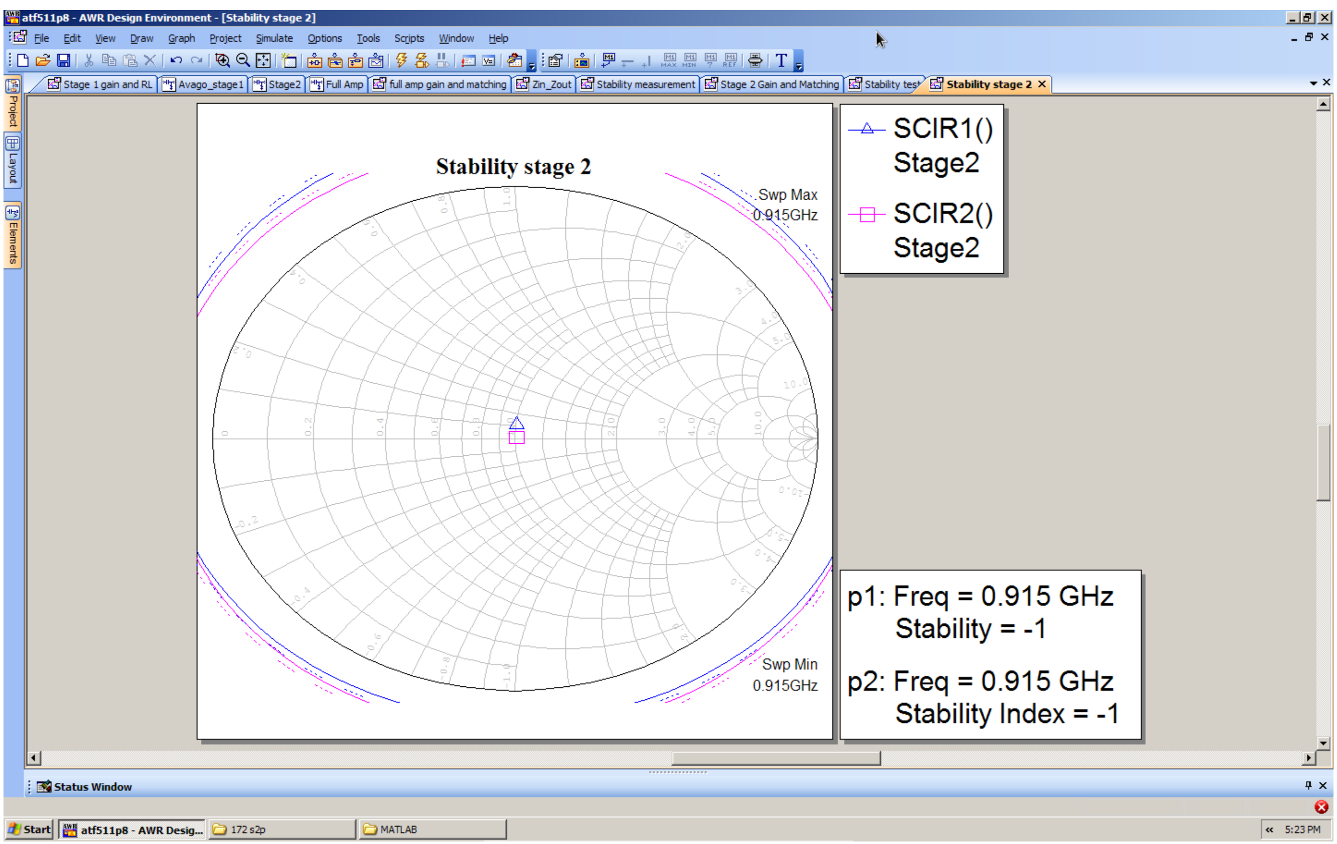
$$K=\frac{1-|S_{11}|^2-|S_{22}|^2+|\Delta|}{2|S_{12}S_{21}|}$$

For a device to be unconditionally stable, the Rollet number needs to be greater than 1 and the determinate of the S matrix needs to be less than 1. Only when both of these happen is the amplifier stable unconditionally. As mentioned previously, a transistor can only be simultaneously conjugate matched at both ports if it is unconditionally stable, therefore I needed to either select devices which were unconditionally stable at 915MHz or I needed to stabilize the devices I chose using resistors. Using resistors to increase stability causes the losses in the circuit to go up, therefore I searched more to find transistors which did not need stabilization resistors.

Microwave Office has the ability to print the stability circles from a circuit. These show the regions of gamma for both the source and load side of the transistor as circles on a smith chart. They also plot the gamma present at each of the two ports. These plots show the use how close they are to the edge of their stable region. The stability circles from both of my stages are below, they demonstrate that the amplifier will remain stable so long as the attached circuit is not generating power (passive).



Stability Plot, Stage 1:



Stability Plot, Stage 2:

Non-Linear Device Properties:

Semiconductor Amplifiers are not ideal devices, the two largest problems for RF amplifier design are that they are not completely linear, and their linear range of operation is finite. All amplifiers generate inter-modulation products. Happens when two different frequencies are amplified by a device which has a non-linear transfer characteristic. The nonlinearity in the device effectively causes each of the frequency components to amplitude modulate the other one. This creates a new set of frequencies in the output signal which were not present in the input. RF power devices are typically characteristic in this regard by a value called the OIP3. This number is typically in dBm and it is the power output where the amplitude of the fundamental frequency and the third harmonic intersect. The device can not generate this power output level. This number is calculated by extrapolating the plots of the first harmonic power and the third harmonic power, then calculating or plotting the intercept point.

Power amplifiers also suffer from finite power output. The power limit for a particular RF transistor is typically specified as the one dB compression point, or P1dB. This is the power output level where the gain of the device has decreased by 1dB. This is caused by the swing of the output signal starting to reach into the non-linear region of the transistor's operation. For the design of my amplifier the P1dB level is the primary limiting factor to the available gain and the available power output. The first stage device of my design has a P1dB of 14.5dBm, a gain of 17.7dB and a OIP3 of 25dBm. My second stage has a P1dB of 31dBm, a gain of 13.55dB, but the OIP3 is not listed. This combination of 1dB compression points and gains produces an amplifier which, according to the following math, has a gain of 31.25dB and a power output of 28.25dBm.

Maximum Input Power: $14.5\,\mathrm{dBm}-17.7\,\mathrm{dB}=-3.2\,\mathrm{dBm}$

Total Gain: $17.7\,\mathrm{dB}+13.55\,\mathrm{dB}=31.25\,\mathrm{dB}$

Total Power Output: $-3\,\mathrm{dBm}+31.25\,\mathrm{dB}=28.25\,\mathrm{dBm}$

Conclusion:

This past semester I successfully designed and simulated a two stage power amplifier for use at 915MHz. My design uses affordable devices and provides a higher gain than previous designs from past semester of EE172 projects. The first stage device is available from DigiKey for $0.68 and my second stage device is available from DigiKey for $2.57. Both stages of the amplifier are unconditionally stable and are conjugate matched. This greatly increases the chance that the amplifier will not oscillate, and allows all of the gain from each stage to be utilized. Improvements which could be made to the design are to use a different bias point for each transistor. Picking a different bias point for my first stage could increase the P1dB which would allow me to reach a full watt with this amplifier. A different bias point for the second stage could increase the gain and P1dB. These bias points were not chosen because they are harder to stabilize and match in this application.

The design of this amplifier is both higher gain and lower cost than the designs from previous years. Additionally the amplifiers does not need any resistors to stabilize either of the stages, which improves efficiency and gain. This design does not use any transmission lines in order to keep the layout a manageable size. All of the component values have been chosen to be realizable so that this design can be built. All of these features make this design both cost effective and relatively easy to realize.