CornellEngineering
Electrical and Computer Engineering

ECE 4880: RF Systems

Fall 2016

Lab 4: RF Amplifiers

1 Learning Objectives

The students will learn to:

1) Use the network analyzer (NA) to measure the amplifier as a two-port RF module
2) From the S parameters to estimate the power amplifier stability
3) Use the leveled input and output methods to safely measure a power amplifier
4) Understand the nonlinear effects in amplifiers by 1-dB gain compression from signal source and spectrum analyzer.

2 Background Information

2.1 S parameters by the network analyzer

We will continue our use of the network analyzer for amplifier analysis. Different from the filters in Lab 2, amplifiers are asymmetric, active devices and often have noise and nonlinearity concerns. We will learn a few more techniques of using NA for the analysis. In Fig. 1, we can map the S parameters to the more familiar amplifier characteristics. S_{11} is defined as the voltage reflection in ratio to impinging at the input side and relates to the input impedance match. S_{11} is typically inspected in the Smith Chart to see how far the locus is away from the polar origin where the perfect match to the input cable is achieved. In a similar manner, S_{22} is the voltage reflection in ratio to impinging from the output side. S_{21} is the voltage gain by output voltage in ratio of input voltage, where the gain, nonlinear distortion and phase shift are most critical to the amplifier function. S_{21} is often plot in amplitude and phase in dB as a function of frequency with a constant small input power to understand its linear characteristics, and as a function of power input at a constant frequency to characterize its nonlinear characteristics of 1-dB compression and intermodulation distortion (IMD). S_{12} provides the information of reverse isolation, and its magnitude ratio to S_{21} defines the reverse isolation for unilateral signal propagation. Sample S parameter measurements for linear characteristics are shown in Fig. 2.

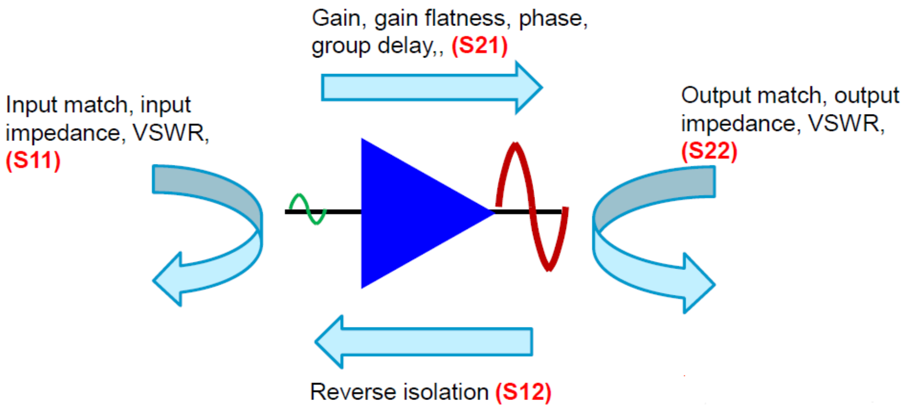


Fig. 1. The S parameters of an amplifier and the associated characteristics.

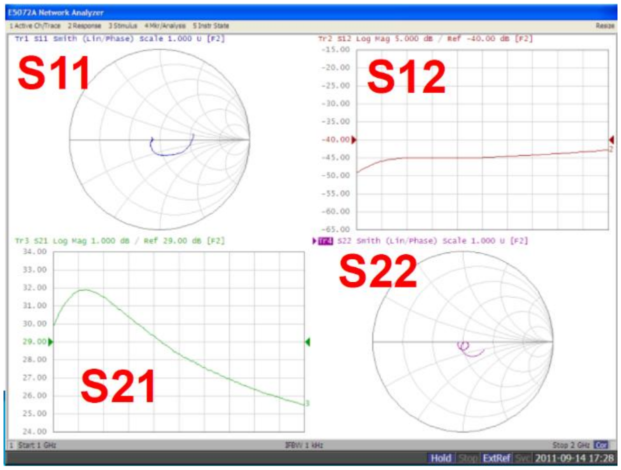


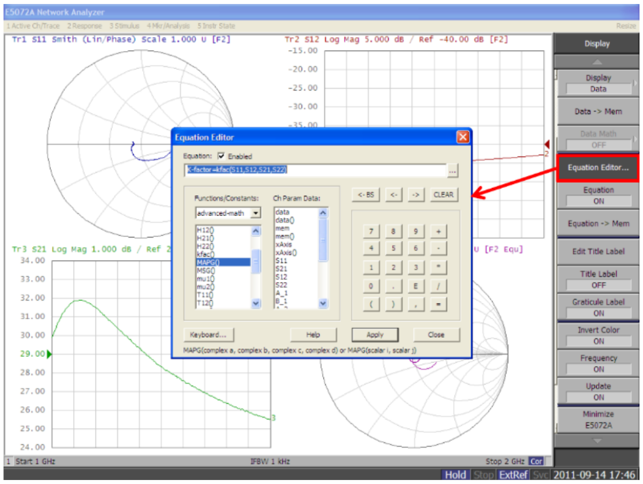
Fig. 2. Typical S parameters of an amplifier. S_{11} and S_{22} relate to the impedance match at the input and output ports, respectively, and are often shown in Smith charts with frequency sweeps. S_{21} is the voltage gain which is large around 29dB here, whereas S_{12} is the reverse isolation which is small around −40dB here, provides about 70dB unilateral isolation.

The stability (in the linear domain) of an amplifier can be estimated from the Δ and K factors defined by:

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \qquad (1)$$

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

The amplifier is unconditionally stable for any load if $\Delta < 1$ and $K > 1$. The criteria derives from whether the feedback signal will be amplified again to go to saturation (similar to speaker feedback). As the Δ and K factors are frequently used for stability monitoring, most NA has built-in functions for display, as shown in Fig. 3.



Equation: ☑ Enabled

K-factor=kfac(S11,S12,S21,S22)

Functions/Constants: advanced-math

MAPG(complex a, complex b, complex c, complex d) or MAPG(scalar i, scalar j)

Fig. 3. (a) The direct calculation of the K factor in Keysight NA.

The NA receiver has very delicate design of almost identical Port 1 and Port 2 for high sensitivity limited by thermal noises as we introduce in Lab 1. The signal source power is natively in the range from -20 dBm to 0 dBm with a resolution of 0.05 dB . This is usually sufficient for measurements of filters, couplers and other bi-lateral components. On the other hand, amplifiers are very asymmetrical in S_{21} (forward gain) and S_{12} (reverse isolation). If Port 1 and Port 2 have the identical setup, one of them may not be accurately measured. NA provides two ways to tackle this asymmetry in inputs and outputs: independent attenuators (the receiver in Port 1 and Port 2 can be in different ranges) and uncoupled powers (the testing signal in Port 1 and Port 2 can be in different power levels), as shown in Fig. 4. Good choices in attenuation and testing transmitter power levels will improve the measurement accuracy, as shown in Fig. 5, where the less noisy S parameters translate into much better K-factor measurements.

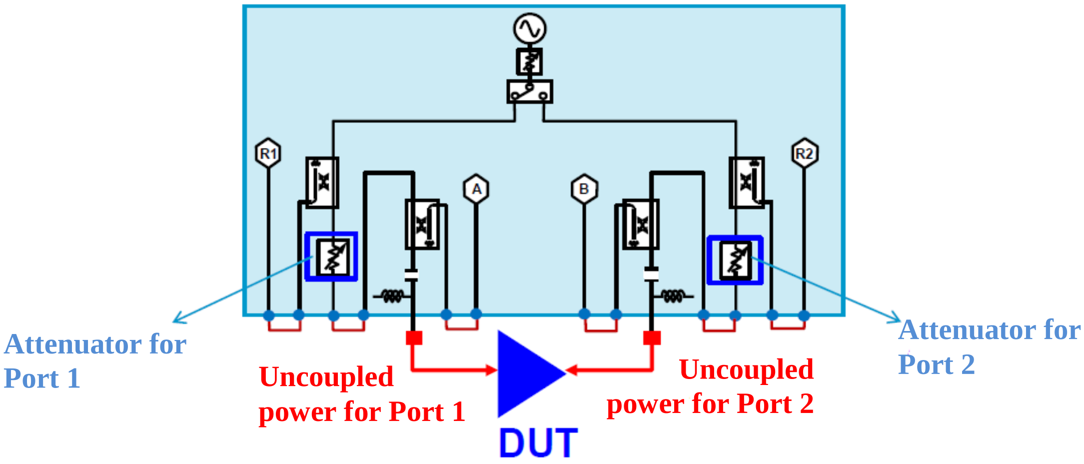


Fig. 4. Different setups in Port 1 and Port 2 transceivers to facilitate amplifier measurements.

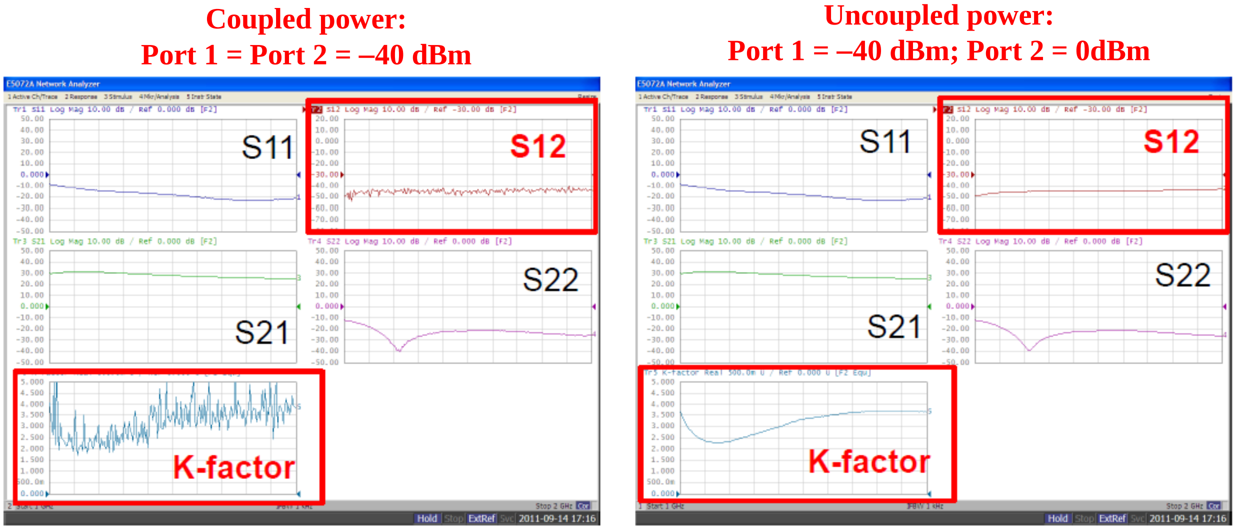


Fig. 5. Different setups in Port 1 and Port 2 transceivers to facilitate amplifier measurements.

The effect of different attenuation in the receiver of Port 1 and Port 2 is shown in Fig. 6, where Port 1 has attenuation factor of *A* and Port 2 has *B*. If we express the S parameters in dB, then Port 1 shifts down *A* dB and Port 2 shifts down *B* dB.

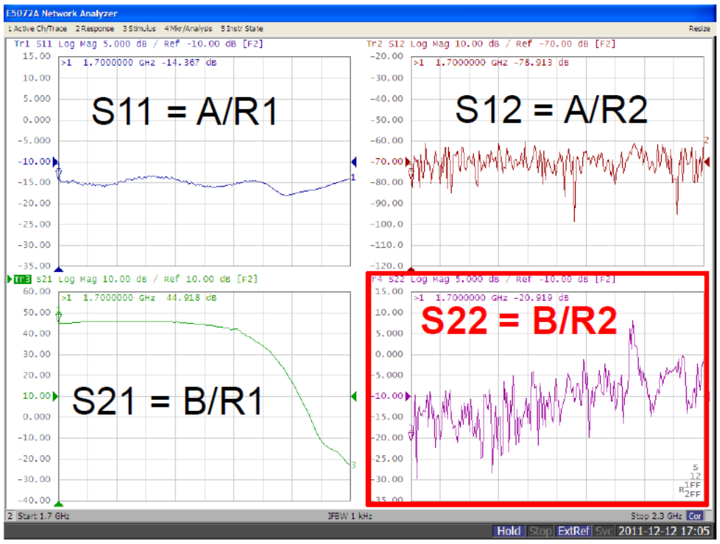


Fig. 6. Independent attenuator setup for Port 1 and Port 2.

2.2 High power and nonlinear considerations.

Linearity in amplifiers implies a constant gain with respect to the input frequency f_{in} and power level P_{in}. It is often important to understand when nonlinear effects in f_{in} and P_{in} will happen so that we can operate in the linear range with confidence. In the old days of radios, compensation for nonlinearity is most critical, as it will lead to signal distortion, intermodulation and spurs, as well as expensive components due to the precision requirements. Surely if the compensation component is not accurate, it can deteriorate instead of help the design. In recent years when the base and intermediate-frequency (IF) bands are implemented digitally, compensation is still critical, but is much cheaper in system cost.

Nonlinearity in P_{in} is easiest to be characterized by the 1-dB compression point P_{1dB}, input interception points (IIP2 or IIP3) and output interception points (OIP2 and OIP3), which are mostly exchangeable for common amplifiers. In this lab, we will mainly use P1dB in different frequencies to characterize the amplifiers.

At a fixed frequency, when we sweep P_{in}, P_{out} will follow P_{in} by a fixed multiplication gain factor or a fixed increase in dB, which we denoted as power gain or voltage gain (in dB), as shown in Fig. 7. We define P_{1dB} at the P_{in} level when the actual gain falls 1dB below the projected constant gain. Notice that this figure is frequency dependent!

As we are pushing the amplifier much harder in nonlinear measurements, we should be MUCH MORE careful in measurement settings to protect the instrument and to achieve accuracy. The uncoupled power and attenuator options in the NA need to be carefully considered for the best and safest measurements. Notice that for amplifiers with very high gain or very high power output level, additional gain boosters or attenuators may be needed to make the nonlinear measurements. When any power level is above 30dBm (1W), heat may need to be considered, as heat generated by the DUT can potentially shift its characteristics.

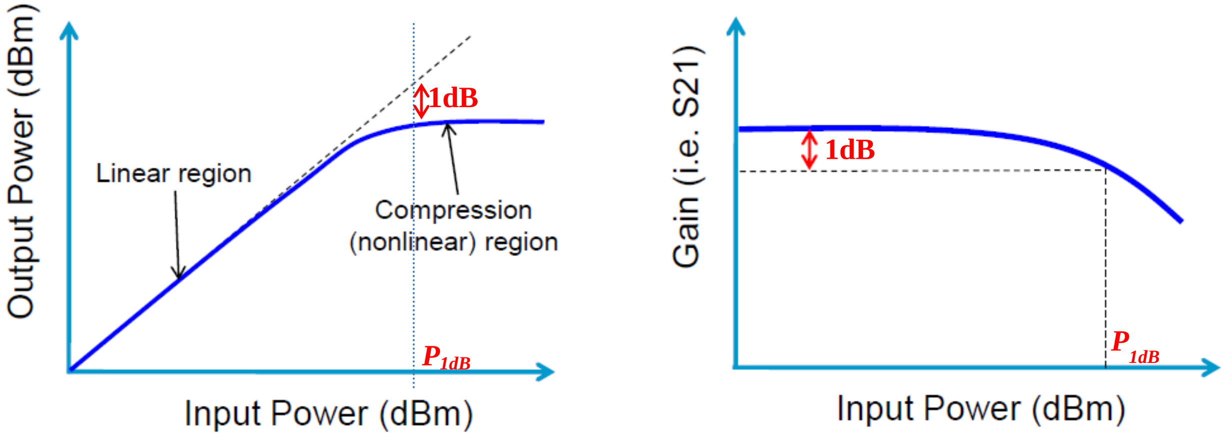


Fig. 7. Gain compression in P_{out} and gain plots. P_{1dB} is defined when the actual gain is 1dB smaller than the projected constant gain.

3 Lab Procedures

As we are performing larger range of power measurements, it would be helpful to bear these numbers in mind:

For the network analyzer, the test signal source has a small range from –20dBm to –5dBm. To give even lower power than -20dBm, an attenuator will be needed. For example, a 24dB attenuator can be added to give –44dBm testing voltage at all sweeping frequencies. To reach RF power higher than –5dBm, we have to switch to RF signal sources (from –100dBm to 10dBm), sacrificing the convenience of the network analyzer. The network analyzer and spectrum analyzer receivers should not see power more than 6 dBm, with the permanent damage at 26 dBm (from the manual, I did not test it!) When you expect a high RF power output especially in the case of amplifier cascade, attenuator before the receiver is needed. For example, if you expect RF_{out} to be at 20 dBm, add a 14 dB attenuator to protect the receiver. You will be given two attenuators with 10 dB and 14 dB attenuation. They have good matching impedance at 50 Ω and can be used individually or in series. Our network analyzer does not have built-in attenuators as in the higher end model of Fig. 4.

3.1 Characterization of single amplifiers

1. Obtain two amplifiers from TA. ZX60-P162LN by Mini-Circuits is typically used as a low-noise amplifier (LNA) and ZX60-2510M-S as a buffer amplifier at the intermediate stage for RF frontend.
   ZX60-P162LN specifications (5.5V dc):
   - Noise figure, 0.5 dB @ 1GHz
   - BW, 0.7 – 1.8 GHz
   - Gain, 22.5 dB @ 1GHz
   - OIP_3, 29.9 dBm @ 1 GHz
   - P_{out} at 1 dB compression, 19.9 dBm @ 1GHz

   ZX60-2510M-S specifications (5V dc):
   - Noise figure, 5.4 dB @ 1.1 GHz
   - BW, 0.5 – 2.5 GHz
   - Gain, 12.77 dB @ 1.1 GHz
   - OIP_3, 28.8 dBm @ 1 GHz

  - P_{out} at 1 dB compression, 15.96 dBm @1.1 GHz

2. Perform the TL de-embedding measurements for the connector you will use for the amplifier connection for the frequency range from 0.4 to 3 GHz.
3. Measure the S parameters of the two amplifiers with three P_{in} (–44dBm, –20dBm and –5dBm) while sweeping the frequency range from 0.4 to 3 GHz. At –44dBm, an attenuator will be needed at Port 1. Also remember the MAXIMUM receiver power should be lower than 6 dBm, so use proper attenuation for P_{in} = –5dBm!
4. To obtain the 1-dB compression point, measure the output power by the RF signal source and the spectrum analyzer. Measure ZX60-P162LN and ZX60-2510M-S at three f_{in} (0.8, 1.1, 1.6) GHz while sweeping P_{in} from –90dBm to 10dBm, with proper 10dBm step resolution. When P_{in} is more than –20dBm, proper attenuation should be used at P_{out} so the expected value is lower than 6 dBm.

3.2 Characterization of amplifier cascades

1. We will measure two different cascades of LNA and other amplifier to understand the consequence, although it seems strange to ever construct an Amplifier-LNA cascade. Please use your CAREFUL discretion in your measurements, as now the gain is much higher.
2. Perform the TL de-embedding measurements for the connector if they are different from the single amplifier setup.
3. Measure the S parameters of the two cascades with P_{in} (–44dBm, –20dBm, –15dBm, –10dBm, –5dBm) while sweeping the frequency range from 0.4 to 3 GHz. As mentioned before, use the attenuators appropriately, either at P_{in} to achieve lower power or at P_{out} to protect the receiver.
4. To obtain the 1-dB compression point, measure the output power by the RF signal source and the spectrum analyzer for the two cascades at three f_{in} (0.8, 1.1, 1.6) GHz while sweeping P_{in} from –90dBm to –5 dBm, with proper 10dBm step resolution. When P_{in} is more than –30dBm, proper attenuation should be used at P_{out} so the expected value is lower than 6 dBm. Notice now the gain of the cascade is expected to be at around 30 dB.

4 Optional Explorations

1. Try different attenuation and uncoupled power to see the influence on the parameter accuracy.
2. Quantify your noise measurements by post processing.

5 Report Guidelines

In addition to the NA measurements, there are significant post processing of data you need to perform in Matlab or Excel. You may need to use the de-embedding routines you developed in Lab 2 if the connection parasitic is of concern.

The main purpose of the lab report is to present findings (and enable people to trace, and repeat if necessary) of your results. Therefore, the ambient information can be as important as the direct results from the instrument. The following content is suggested, but not meant as a template or limitation.

1. Brief description of the lab
2. Brief description of instruments
3. Brief description of the procedures
4. Measurement results in 3.1. Determine if the de-embedding procedure is needed.
5. Obtain the gain as a function of frequency at different P_{in} levels, and then gain as a function of P_{in} at three different frequencies to determine P_{1dB}. Does P_{1dB} depend on frequency?

6. Convert the S parameters into Y parameters, and express the two amplifiers in the π network. Rationalize whether the Y parameters are reasonable for common amplifiers.
7. Notice the main differences in qualitative behavior difference between LNA and PA, especially for noise behavior at low P_{in} and nonlinear behavior at high P_{in}.
8. Convert the S parameters into T or ABCD parameters to be ready for the expected cascade parameters.
9. Compare the S parameters of the cascade from direct measurements and from calculation using the individual amplifier measurements. Plot the S parameters as a function of frequency at three P_{in} levels, overlaying the direct measurements and calculation from individual amplifiers.
10. At low P_{in}, compare the behavior of S_{21} of the two cascades.
11. Compare P_{1dB} of the two cascades from direct cascade measurements and from prediction of individual amplifiers.

For report submission, please name your lab reports as: netid_netid_ECE4880_Lab4 for two students in a lab group. Submit your final report in Word or pdf to kan@ece.cornell.edu. The report should be by each group. Submit your Matlab script or Excel sheet for the de-embedding procedure as a separate file.