Insertion Loss = \frac{\text{Incident Power}}{\text{Power Delivered}}

defined between the input and output ports
See Lecture 4 for more details

Return Loss:

“Loss” due to reflection

\text{R.L.} = -20 \log |S_{11}|

\Gamma = S_{11}

\Gamma = 0; \text{R.L.} = -\infty \text{ dB}
\Gamma = 1; \text{R.L.} = 0 \text{ dB}

\text{SWR and Return Loss are related by the following equations:}

\text{SWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} = \frac{1 + |S_{11}|}{1 - |S_{11}|}

This is the definition, and the network analyzer uses this equation and calculates the SWR for the $S_{11}$ or $S_{22}$ measured. After measuring the $S_{11}$ or $S_{22}$ plot, you can go to the SWR option and get a plot of the SWR. Remember that the SWR is always greater than 1. It is equal to 1 if the ports are perfectly matched.

The phase balance between the output ports - we have already discussed that - see the example of the power splitter. It is the phase difference between two output ports of a device.
Ideally, there will be 0 degrees phase difference between the two ports. Ideally, there will be some phase difference.

If you just have the plots, then unless you have some markers on the plots, it will difficult to determine the exact phase difference.

You should put markers at selected frequencies - the critical frequencies, one at the mid-band, and a couple in between the high and low frequencies. The markers will give you the phase or magnitude at each marker. If you don’t have markers, it will be very inaccurate, because you will have to estimate the position from the plots.

So, in the case of a splitter, the phase balance should be 0 degrees - it should be the same phase.

In a hybrid coupler, the phase difference between ports is 90 degrees.

Here, you do the same thing - take the difference between the phases of $S_{21}$ between ports 3 and 4, the difference should be 90 degrees, or 90 degrees ± some variation.

What I hope you do is to see the variation in phase between the nominal value over the band. If the band is 4 to 8 GHz, then say the phase varies by + or - so many degrees over the band.

So again the markers are useful. If you don’t want to use the markers, the other option is to go the table where frequency and phase of $S_{21}$ is listed, at points you have selected before.

In the first lab, when you followed the directions, you didn’t care about so many points, if you printed 401 frequency points, you don’t really need so much data. Keep the number of points
small. See what is the smallest you can get; try 51 points. You can select a different number of points, which gets programmed, and only goes by a certain fixed number of points.

Use the smallest number of points and print a table, or put markers in the plots.

When you do the calibration for each part, pay attention to the incident power and number of points, and do not change those two during the measurement for that part, otherwise you will have to re-calibrate.

All are passive components, except for the amplifier, so you don’t have to worry about overloading the device. With an amplifier, you have to think about the gain of the amplifier, and consider the maximum power input to the analyzer.

There is an option to save the calibration, but that is necessary only if you are going to repeat the experiment later. There are four registers to save the calibration.

So that’s the magnitude and phase balance.

Gain of the device is straight forward.

The $S_{21}$ of the amplifier is the gain. The magnitude of $S_{21}$ is the gain, and there is a phase associated with $S_{21}$, which is the change the signal undergoes while passing through the amplifier.

$S_{21}$ is nothing but a transfer function. Here you must be careful with the input power to the analyzer. The nominal gain of the amplifier is 20 dB, so the output of the amplifier should be less than 20 dBm; to be on the safe side, I have suggested an input of -20 dBm.

Sometimes what happens during amplifier measurements, for some reason - due to some instability within the amplifier, the amplifier goes unstable and starts generating signals. It’s not supposed to generate it’s own signals - it’s supposed to amplify what is going in and give a true replica of what comes in. There may be a phase and magnitude shift, but should be no distortion of the waveform.

It’s not supposed to add noise, but all amplifiers add noise - all components add white noise - if the amplifier becomes unstable, and output power may increase dramatically, and the network analyzer sees the increase and becomes confused. You cannot do any measurements in that condition, so we have to decrease the input and see what is happening.

Keep that in mind, but this amplifier should not have that problem.

Other precautions, are when you apply the dc - there are two terminals - one terminal is ground and the other is positive voltage. Be careful not to short the power to ground, etc.
So here the gain is nothing but the magnitude of the transmission coefficient of the device.

We also talked about the bias T. The bias-T is a device which is used to isolate dc and ac parts of the circuit. You have a high value of inductance and a bypass and blocking capacitor. The inductor acts as a short circuit for dc, so the dc is blocked one way, but not the other way. The AC signal can go through this path.

On the bias T, DC/RF is marked. Where the RF is marked, the RF should be connected, where the DC is marked, the device should go.

What I would suggest before you do the measurements, look at the specifications for the components so you know what to expect.

The isolation between the ports of the device, for example the power splitter.

![Power Splitter Diagram](image)

The power splitter can be used either for splitting a signal into two channels, or for combining signals from two channels into one channel. It can be used as a combiner or splitter.

If it is used as a combiner, you don’t want the signal from port 1 to get to port 2. This is known as isolation between the ports.

How do you measure that? You terminated port S and find the S21 between ports 1 and 2. This has to be a small number. This should be as high a negative number as possible, say -10 or -20 dB.

If the isolation is 10 dB, this means that 1/10 of the power from port 1 will appear at port 2. Say the input is 10 mW. If the isolation between the two ports is 10 dB, 1 mW will be seen at the other port. If the isolation is 20 dB, 1/100 of the power will be seen at the other port. The larger the S21, the more isolation. You can give this either as a positive or negative number. You can say this is 20 decibels above port 1 or 20 decibels below port 2.

Isolation is somewhat like insertion loss, but it is not between input and output. In the definition of insertion loss, we said that one port is an input port and one is an output port. In the definition of isolation, both are on the same side; we are measuring between two input ports.
Insert image of inner construction of a power splitter - micro strip drawn image here - see Lecture5.sdr file

1/4 wavelength transformer; at low frequencies, you have used a BNC - T; so you can split two signals into two parts, or combine two signals together. Why can’t you just use a BNC - T here?

Why can’t we just have transmission lines in parallel as shown below?

The problem is impedance matching. At the junction of the two, the impedance seen is $Z_0/2$. As far as Port 1 is concerned, it sees $Z_0/2$, so there is an impedance mismatch, and a reflection. An ordinary T junction cannot be used at these frequencies. At low frequencies, the lengths of the BNC connectors are so small compared to the wavelengths, that the impedance mismatch is negligible. As frequencies increase, the wavelength keeps dropping, so the component appears longer and longer compared to the wave, so transmission line effects come.

You can’t just divide the signal into two parts. You have to take into account the impedance matching. You want each port to see 50 $\Omega$. You have to convert the $Z_0/2$ into another impedance, so that the input lines match.
So there is the input line, and the other two lines, both at 50Ω, and another line that connects them that has a different characteristic. This divides the signal into two parts, there is no phase difference, no difference in magnitude.

Notice that there is also a resistor, in this case, 100Ω, 2 time Z₀; this provides isolation between the output ports. You won’t see this in the device you use. If you open the outer cover of the box, you’ll see this circuit.

You’ll be measuring S₁₁ at the input port and terminate one of the other two ports. You always convert a multiple port device into a two port device by terminating the other ports. In the case of a network analyzer, we are measuring twice, the other port is terminated into 50 Ω. You always convert an N-port device into a 2 port device by terminating all the other ports and measuring between two remaining ports.
Here is a power divider - a 4 way power divider.

The signal comes in from the right and divides into 4 parts.

The hybrid coupler I was talking about is called a quadrature hybrid coupler, or 90° hybrid. That looks like this - Figure 7.21 - internally.

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**FIGURE 7.15** Photograph of a four-way corporate power divider network using three microstrip Wilkinson power dividers. Note the isolation chip resistors.

Courtesy of M. D. Abouzahr, MIT Lincoln Laboratory, Lexington, Mass.

**FIGURE 7.21** Geometry of a branch-line coupler.
An input port, and two output ports; the signal is divided equally, magnitude wise, between the two output ports; phase wise, the two ports are 90° apart. Port 4 is known as an isolated port. Very little, or almost nothing comes out of Port 4. There is theory to show how the ports destructively add to result in 0 signal at Port 4. That is called an isolated port.

When you use this as a coupler, you terminate Port 4, and find $S_{21}$ between Port 1 and 2 and Port 1 and Port 3; then find the magnitude and phase between Ports 2 & 3. This gives you the magnitude and phase balance. There are hybrids you can see in the lab in the display case.

**Insert hybrid images here**
Coupling between the input and output ports of a device; that’s the same thing as what has been covered. Coupling is nothing but the $S_{21}$ between the input and output ports. Coupling in the case of the directional coupler - the second lab, is illustrated below:

If this is the box of the directional coupler, ports 1, 2, 3 & 4 are shown.

Usually, as in a hybrid coupler, you have the input on port 1, and the signal comes out of port 2, the through port, and the other port, port 3, is known as the coupled port, and the other port is known as the isolated port, and is normally terminated and sealed, and is usually not accessible.

So you input a signal and only a part of the signal gets to port 3. $S_{21}$ between port 1 and port 3 and is referred to as coupling.

A 10 dB coupler means that 1/10 of the incident power is coupled to port 3.
A 20 dB coupler means that 1/100 of the incident power is coupled to port 3.

A small amount of power is sampled. Such directional couplers are used inside the network analyzer to sample the reflected wave from the device under test. Refer to the block diagram of the network analyzer.

Here, coupling is defined as:

$$Coupling = C = 10 \log \frac{P_1}{P_3} = -20 \log \beta dB$$

10 log because this is the power ratio; power at port 1 divided by power at port 3; this is nothing
but the negative of the $S_{21}$ between port 1 and port 3.

You can consider port 1 as the input port and two output ports - port 2 is the through port and port 3 is the coupled port. Coupling is nothing but the $S_{21}$ between port 3 and port 1.

In the pre-lab definitions, if you cannot give a word definition, at least draw a picture - a block diagram and show the power, and give a mathematical definition, and state in a word or two what the diagram represents.

You don’t have to give a word definition as long as you understand the concept and can show analytically what it means, that’s enough. That’s the pre-lab part.

The fourth part, the power splitter, you have to do all the calculations after you get the data.

You better have at least one marker at the center frequency of the band. If 4 to 8 GHz is the frequency band, then the band center is 6 GHz; if 1 to 2 GHz is the band, the band center frequency is 1.5 GHz.

Measure the following at the band center frequency:

1) Insertion loss between ports S & 1, and S & 2  
2) Return losses at port S, 1 & 2  
3) Isolation in dB between ports 2 & 3  
4) Magnitude and phase balance between ports 1 & 2

For the hybrid coupler, do essentially the same thing

For the amplifier,
1) Forward gain, $S_{21}$  
2) Reverse isolation  
   The amplifier should amplify the signal in one direction, from port 1 to port 2, and should not amplify the signal in the other direction, from port 2 to port 1. An ideal amplifier is unilateral. This means there is gain from port 1 to port 2 and no gain from port 2 to port 1; in fact, there is a loss.

$S_{21}$, gives you a magnitude greater than 1, perhaps 20 dB gain, and $S_{12}$ is very small, perhaps -10 or -20 dB. That’s known as reverse isolation.

3) Return losses at input and output ports  
   So you measure $S_{11}$ and $S_{22}$ are measured - with the same setup, you don’t need to change anything, just go to the menu and pick what you want to measure. You can determine the return losses. Suppose $S_{11}$ turns out to be -15 dB as measured on the network analyzer, the return loss will be 15 dB. It is understood when you say that return loss is 15 dB, $S_{11}$ is -15 dB at port 1.
I think I want you to pay attention to the measurements you get - see if the measurements make sense.

Suppose you have connected a short circuit - what should you expect? $S_{11}$ magnitude should be very close to 1. A 1 coefficient corresponds, translates to a 0 dB value - so you should see a 0 dB value. So the reference, which is the red line at the center, so a short circuit should correspond to the reference.

Supposed you put a 50 $\Omega$ termination - a broadband load - so there should be no reflection ideally, $\Gamma$ should be 0, and the log of 0 is negative infinity, and you should get a large negative value, so the display should go down. You usually get -20 or -30 dB reflection coefficient with a matched load.

So, pay attention to that - does the measurement make sense to what I have learned?

I’d like you to try the polar plots, even though you only are required to do the rectangular plots. When you are doing the reflection coefficient measurements, go to the Smith charts. Plot $S_{11}$ and $S_{22}$ with several markers at different frequencies. That way you will learn how to get the information from the Smith chart.

Since the reflection coefficients are less than 1, they can be displayed on Smith chart.

For $S_{21}$, and $S_{12}$, they can be greater than 1, so you can’t use a Smith chart, since the maximum value, the radial distance is 1. You must use a polar chart to plot a quantity greater than 1.

Try to learn different options - we are probably using only 30 or 40 % of the functions of the network analyzer.

**End of lecture**