Power Flow

Note: This lab manual has been created by modifying the original application note developed by Keysight (http://literature.cdn.keysight.com/litweb/pdf/5992-0333EN.pdf)

Introduction

In this laboratory two important RF components are introduced: the power splitter and the directional coupler. Both of these components are concerned with the accurate division of power flowing from one port and out from two or more other ports. Power directing components have performance measures of insertion loss, coupling, directivity, and isolation which will be examined in this laboratory. While power splitting might seem a simple task, it ends up being far from trivial when realistic network constraints are imposed. This laboratory will examine some of these fundamental limits and their tradeoffs for these two important types of RF components.

A quick overview

For waves travelling along a transmission line, the voltage phasors can be broken down into forward and reverse travelling components, V^+ and V^-. The average real power flow is

$$P_{avg} = \frac{V^+V^{+*}}{2Z_0} - \frac{V^-V^{-*}}{2Z_0}$$

which can be simply interpreted as the real power entering the port, minus the real power leaving the port due to any reflections.

Next, some important properties of the scattering matrix will be examined. For this development, an arbitrary number of ports *N* will be considered, and the forward and reflected voltage amplitudes in each port will be represented by column vectors,

$$[V^+] = \begin{bmatrix} V_1^+ \\ V_2^+ \\ \vdots \end{bmatrix}$$

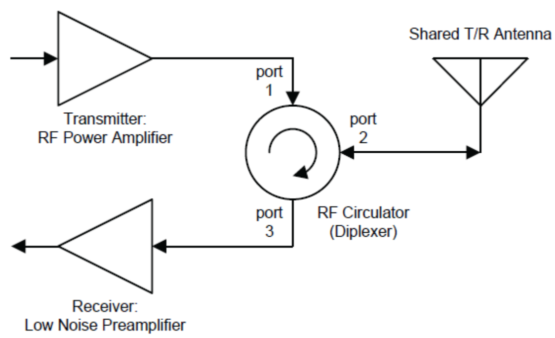
The scattering matrix by definition expresses $[V^-] = [S][V^+]$.

If the network is *reciprocal*, reversing the roles of any pair of ports *i* and *j* will result in the same transfer function, $S_{ij} = S_{ji}$, and the scattering matrix will be symmetric about the main diagonal. If the network is *lossless*, the total incident power must equal the total reflected power, since the network itself cannot absorb any of it. A lossless network must therefore have the sum of the incident power to each of its ports balance the sum of the reflected power from those same ports.

Next, consider the application of the above principles to power splitters. A basic power splitter is a 3-port device whose purpose is to equally divide the input power between the other two output ports. An ideal power splitter should be matched on all ports, lossless, and reciprocal. These requirements mean that the 3 × 3 scattering matrix must simultaneously have a zero diagonal ($S_{11} = S_{22} = S_{33} = 0$, so that all ports are matched), be symmetric (so that power is divided equally), and unitary (so that it's lossless). Sounds simple enough, but it turns out that simultaneously satisfying these three requirements is mathematically impossible for the 3-port case.

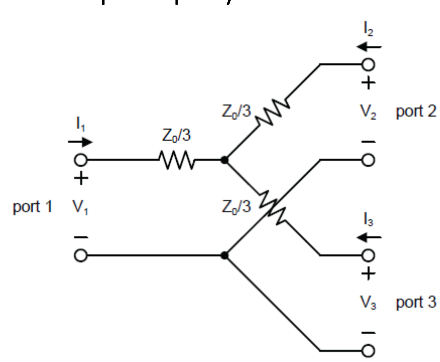
The design of a practical 3-port power splitter therefore requires relaxing one or more of these requirements. What if the requirement for a reciprocal network is relaxed? Relaxing the reciprocal network condition allows the scattering matrix to become non-symmetric, and one possible solution which is both matched and lossless is the circulator whose scattering matrix takes the form of $[S] = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$ (called a *circulator*).

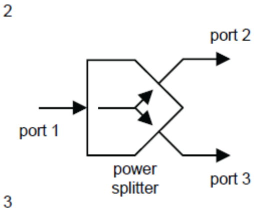
This circulator takes input power from port 1 and directs it to port 2, ($S_{21} = 1$), input power from port 2 and directs it to port 3 ($S_{32} = 1$), and input power from port 3 and directs it to port 1 ($S_{13} = 1$). A circulator does not split the input power, but simply shuffles each input power over to the next adjacent port. The most common application for a circulator is a transmit/receive diplexer which allows both a transmitter and receiver to share the same antenna without the worry of the high power from the transmitter accidentally destroying the delicate input stage of the receiver. A T/R diplexer using a circulator is shown here. Most circulators are constructed using an anisotropic ferrimagnetic material such as YIG (yttrium iron garnet), and they also require a permanent magnet to properly bias the material. Their operational principles lie beyond the present discussion.



If the requirement for a lossless network is relaxed instead, a power splitter can be achieved using a resistive divider. One simple example of this is to add a purely real resistance of $Z_0/3$ in series with each of the three inputs and then connect them all together into a common node as shown below. It can be verified by inspection that if two ports are terminated in matched loads of Z_0, then the input impedance of the third port will also be Z_0, producing proper matching on all three ports. This network is 3-way symmetric, so that input power to any port will be split equally into the other two ports. The cost, however, is that only half of the input power will emerge from the other two ports due to the loss incurred by the resistors. This resistive divider creates a wideband 3 dB split, but it imposes a −3 dB insertion loss. The scattering matrix for this resistive divider is

$$[S] = \frac{1}{2}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$





There are a wide variety of other RF power splitting and combining components; the above short sampling only provides a glimpse of the strategies and tradeoffs that are employed in their design.

A practice measurement of a power splitter

The FieldFox will be used to characterize a practical RF power splitter to determine some typical performance parameters and to also gain some further insight into RF power management techniques.

The first component to be examined will be a Mini-Circuits model ZMSCQ-2-120+ power splitter. This component is designed for an equal (3 dB) split of power over the band of 80 to 120 MHz.

1. Set up the FieldFox to run from its AC power supply. Start up the instrument and load and launch the network analyzer (NA) application. Set the frequency sweep to a range of 80 to 120 MHz, the same as the nominal range of the Mini-Circuits power splitter. For convenience, all of the measurements will be made at a frequency of 100 MHz.
2. Ensure that both ports of the FieldFox have Type-N to SMA adapters installed, and then attach a 24-inch long SMA coaxial cable to each port. The objective is to characterize only the Mini-Circuits power splitter taken by itself, but simply connecting this component directly to the coaxial cables will give measurements which include the phase delays from these cables. The phase delay of the coaxial cables and the adapters can be removed from the measurements by using the port extensions feature of the FieldFox. To accomplish this, the first step is to measure the phase delay for each cable.
3. For port 1, set up the FieldFox to measure the S_{11} parameter from the Measure menu, and display the result as Phase using the Format soft key in the range 0 Hz to 120 MHz. The display should show a yellow trace that decreases linearly with frequency and which has an abrupt jump between −180° and +180° around 80 MHz. Use the Marker function to find the frequency at which the phase is 180° by picking a point in the middle of the vertical jump. This is the frequency at which the round trip phase delay through the cable is 180°, which corresponds to 1/4 wavelength in distance from the FieldFox to the open circuit reflection at the end of the cable. The transit time through this distance will be $\Delta t = 1/4f_{180°}$. For the 180° frequency found for port 1, compute the one-way time delay Δt_1, which should be close to 3.1 ns.
4. Repeat this same process for port 2 by simply selecting the S_{22} parameter from the Measure menu. The value for the 180° frequency should again be close to 80 MHz, and the corresponding Δt_2 should also be close to 3.1 ns.
5. Enter these time delays to correct for the test cables. Press the Meas Setup button and then the Port Extensions soft key. Press the Port Extensions ON soft key, and then enter the one-way time delays for port 1 and port 2. The reason you enter the one-way delays is that S_{11} measurements display the roundtrip delay of the cable, but for port extensions for S_{11} and S_{22} measurements, we enter the one-way delay.
6. As a check, after entering the port extension time delays, the S_{11} and S_{22} parameters should both show a nearly zero phase over the full frequency range. <u>Take a screenshot of the S_{11} and S_{22} parameters after this correction</u>. Connecting the two free ends of the SMA cables with a female to female barrel connector should also show the S_{21} and S_{12} parameters to be nearly zero phase as well. The fact that the barrel connector has a small, finite length will produce a small phase delay of about 2.5° over this frequency range. This gives an indication of the measurement accuracy that results from not having a precise reference plane for the SMA connectors, but this will be adequate for the present measurements. <u>Take a screenshot of the S_{12} and S_{21} parameters with the barrel connector in place</u>.

The FieldFox is now properly set up to take S-parameter measurements using the ends of the test cables as the reference planes. **Keep these specific SMA coaxial cables attached to the FieldFox for the duration of this laboratory and also keep the port extensions turned on and programmed with these proper time delays.** The measurement of a 3-port device such as the power splitter with a 2-port instrument such as the FieldFox will require some cable swapping to permute through all of the possible signal paths. In addition, **the unused ports of the device under test must be properly terminated in a 50 Ω load.** The Mini-Circuits power splitter has port 3 labeled as 'S' for the sum port.

The power splitter is designed for incident power to enter port 3 (port S) and be divided nearly equally between ports 1 and 2. By connecting port 3 (S) on the power splitter to port 2 of the FieldFox and port 1 on the power splitter to port 1 of the FieldFox, four of the nine S-parameters can be measured first. With these connections, the {S_{11}, S_{31}, S_{13}, and S_{33}} parameters of the power splitter are then mapped to the {S_{11}, S_{21}, S_{12}, and S_{22}} parameters of the FieldFox, respectively. Clearly, there is potential for confusion and misconnections, so **it is very important to keep track of how the device is connected, how the ports of the device under test map to the ports of the instrument, and which measurement is being read from the FieldFox.** The goal of the next set of measurements will be to populate the 3 × 3 S-parameter matrix for the power splitter at a frequency of 100 MHz.

7. To better organize this process, first set the marker frequency to 100 MHz so that the readings can be read off directly. For each connection, four of the nine S-parameters can be obtained, and for each of these, the FieldFox will be used to measure the log magnitude in decibels. It is easiest to record each of these values into a matrix in one's laboratory notebook.
8. Begin the measurements with S_{11}, which is the reflection coefficient from port 1 of the power splitter, and which is mapped to S_{11} on the FieldFox. Use the Measure button and soft keys to select the measurement for the active trace, and use the Format soft keys to change to Log Mag. For each measurement record the log magnitude to a tenth of a dB.
9. Measure S_{31} of the power splitter which is mapped to S_{21} of the FieldFox. Next, measure S_{13} of the power splitter which is mapped to S_{12} of the FieldFox. Finally, measure S_{33} of the power splitter which is mapped to S_{22} of the FieldFox.
10. Change the connections so that the 50 Ω terminator is on port 1 of the power splitter and ports 2 and 3 are connected to ports 1 and 2 of the FieldFox, respectively. Verify that this connection now maps {S_{22}, S_{32}, S_{23}, and S_{33}} of the power splitter into {S_{11}, S_{21}, S_{12}, and S_{22}} of the FieldFox. Follow the same procedure to gather log magnitude values for each of these four S-parameters.
11. Lastly, change the connections so that the 50 Ω terminator is on port 3 (S) of the power splitter and ports 1 and 2 of the power splitter are connected to ports 1 and 2 of the FieldFox, respectively. This connection straightforwardly maps ports 1 to 1 and 2 to 2 so that the {S_{11}, S_{21}, S_{12}, and S_{22}} parameters are the same for the power splitter and the FieldFox. Once more, gather log magnitude values for each of these four S-parameters to complete the overall 3 × 3 S-parameter matrix for the power splitter. Include in your report the values you recorded, as well as the resulting S-parameter matrix.

Some of the S-parameters, in particular the S_{11}, S_{22}, and S_{33} values, will have been measured twice, and it may be observed that slightly different values result from the different test cable connections. This is a consequence of only compensating for the test cables through the port extension time delays. The test cables still introduce their own loss and reflections which are not cancelled out by a pure time delay alone. Later on, more precise calibration methods will be introduced to remove these errors. For now, the measurements taken as above will be adequate for the immediate purposes.

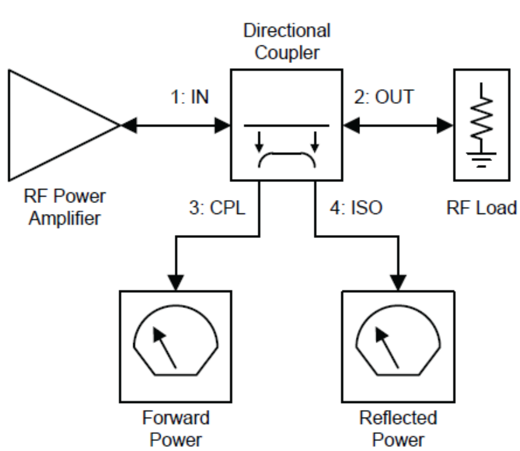
Examine the resulting S-parameter matrix for the power splitter. The power splitter is designed to divide the input power to port 3 (the port labeled 'S' on the part) equally into power flowing out from ports 1 and 2. Does the S-parameter matrix indicate that this is achieved? A perfect power split would produce a 3.01 dB attenuation for the S_{13} and S_{23} parameters. Any attenuation beyond this value would be attributed to loss caused by the power splitter. The specifications for the Mini-Circuits power splitter give an insertion loss of 0.3 dB, maximum. Is this verified by the measurements? Is the output from ports 1 and 2 properly balanced, i.e. equal in magnitude? The isolation of the power splitter is the amount of power passed between ports 1 and 2. The specifications give this as 21 dB, minimum. Is this verified by the measurements? This Mini-Circuits power splitter uses a different strategy than those previously mentioned and instead employs an RF transformer. One terminal of the transformer is connected to an internal 50 Ω load, which does provide an internal loss element.

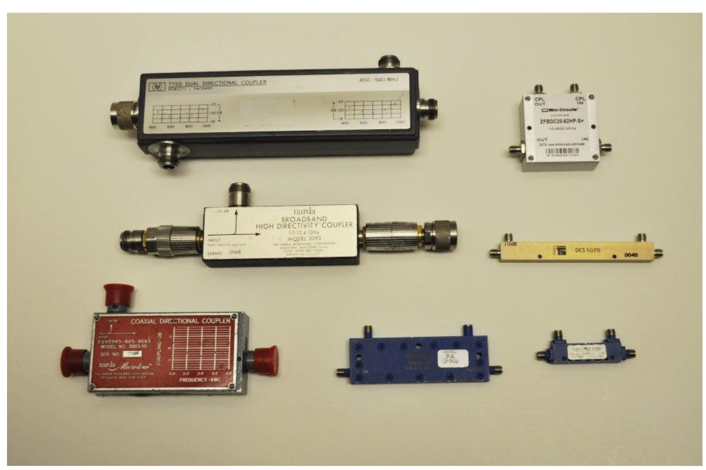
Directional Couplers

The directional coupler plays an important role in many microwave and RF systems. Instead of splitting the power flow into significant portions, that is, halves or thirds, the directional coupler peels off only a small, yet precise, fraction, usually −10 to −20 dB of the incident power, that is, one tenth to one hundredth, which can be used as a measure of how much power was flowing through the main channel. Directional couplers are most often used as monitoring or sampling devices in a transmission line. Their distinguishing property is that they are sensitive to the direction of power flow, and power flowing in different directions is coupled into different output ports, allowing the forward and reflected power to be simultaneously sampled, independently of one another. As noted previously, the directional coupler is an essential component of any network analyzer test set.

The directional coupler is a 4-port device. Like the 3-port power splitter, an ideal directional coupler would be matched at all ports, reciprocal, and lossless. Unlike the 3-port power splitter, the presence of the 4th port adds an additional degree of freedom which allows these three properties to be simultaneously achieved in certain special cases.

Directional couplers are sufficiently well established that their ports have conventional names. Port 1 is named the input port; port 2 is named the output or through port; port 3 is named the coupled or forward coupled or input coupled port; and port 4 is named the isolated or output coupled or reverse coupled port. Directional coupler modules are most frequently packaged as rectangular blocks. The input and output ports are normally placed axially on opposite sides, a visual cue that most of the power will be flowing straight through the coupler from one of these ports to the other. The coupled and isolated ports are normally placed orthogonally to the input-output axis, and the coupled port is most commonly closer to the input port. Even if the directional coupler has no markings at all, there is a good chance of correctly guessing which port is which. The figure below illustrates the use of a directional coupler for monitoring forward and reverse power flow through a transmission line. We also show an assortment of directional coupler modules. All directional couplers are fundamentally 4-port devices. Those that appear to have only 3 ports internally have a matched load connected to port 4, the isolated port.





Directional couplers have several performance measures which come directly from their S-parameter measurements. The insertion loss is the fraction of power that is lost in passing through the main channel of the directional coupler, $L = P_2/P_1$. The coupling is the fraction of input power that is directed over to the coupled port, $C = P_3/P_1$. The directivity is a measure of how much of the output power is directed into the coupled port, $D = P_3/P_2$. And finally, the isolation measures how much of the input power makes its way to the isolated port, $I = P_4/P_1$. Since each of these four performance measures are power ratios, they are normally expressed in decibels.

The FieldFox will now be used to characterize a directional coupler. The Mini-Circuits model ZFBDC20-62HP-S+ directional coupler will be the device under test, and it is specified as a 50 Ω bi-directional coupler, capable of handling up to 25 W over a frequency range of 10 to 600 MHz. It is specified to have an insertion loss of no more than 0.25 dB, a 20 dB coupling, a directivity of at least 25 dB, and an isolation of at least 25 dB.

Using the techniques discussed previously, populate the 4 × 4 S-parameter matrix for this directional coupler at a frequency of 100 MHz. For each of the 16 S-parameters, record the log magnitude to a tenth of a dB. Plan out the measurements and work through them methodically. It is very easy to make errors by misinterpreting a measurement, or misconnecting the device under test. Double check that the port extensions are still turned on and properly calibrated to the lengths of the test cables before starting. Make sure that all of the unused ports are terminated properly in a 50 Ω load.

To fully populate the S-parameter matrix for the directional coupler, at least 6 different connections between the DUT and the FieldFox will be required.

From the measured S-parameters for the directional coupler, analyze the results, and determine the insertion loss, the coupling, the directivity, and the isolation. Do these measured values validate the published specifications for this device?

Grading scheme

This lab is out of 15 marks.

- 6 marks for answering the questions about power splitter measurements
- 6 marks for answering the questions about the directional coupler measurements
- 3 marks for INDIVIDUALLY answering additional questions about this lab found on eClass.

All questions can also be found on eClass, where you will enter your answers. Note that all group members may have similar answers, EXCEPT for the questions indicated that are to be answered INDIVIDUALLY, where each group member is expected to have their own answer.