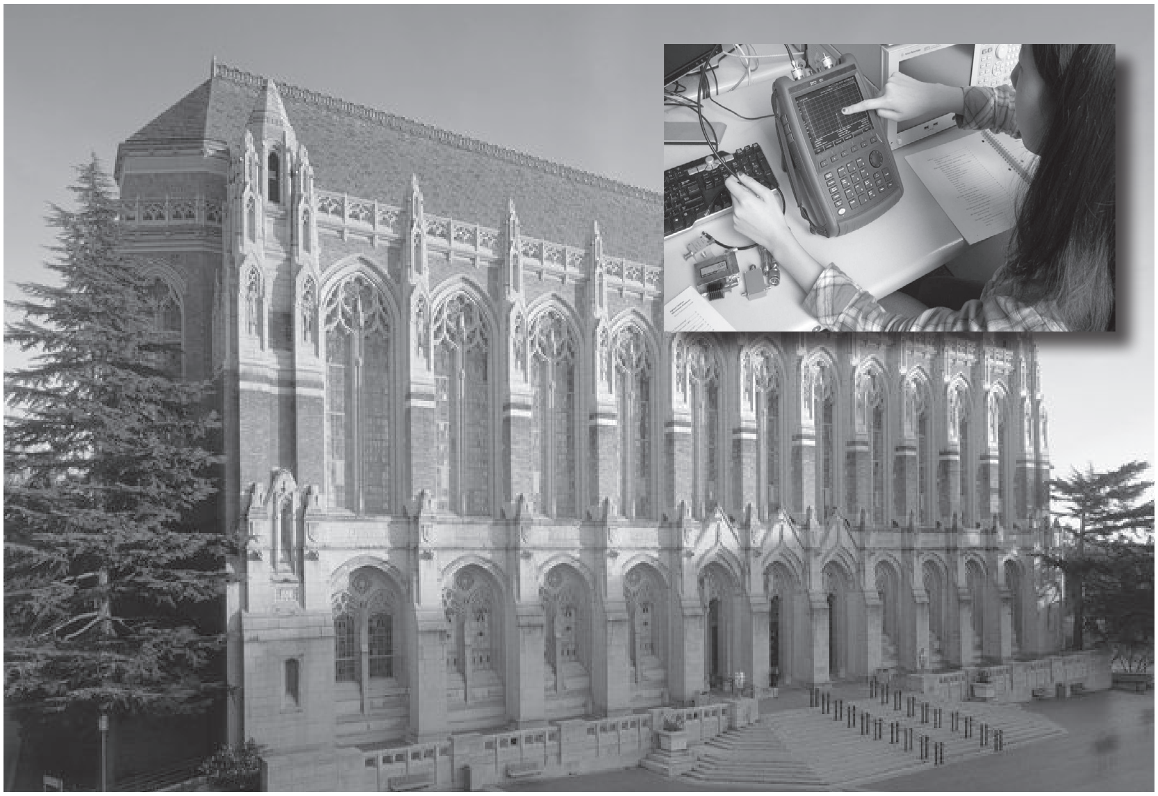
Keysight Technologies
Power Flow and Directional Couplers

University Engineering Lab Series - Lab 6

Application Note



Introduction

The previous laboratory introduced two important RF components: the power splitter and the directional coupler. Both of these components are concerned with the accurate division of power flowing into one port and then 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. Microwave network theory places some fundamental restrictions on these based upon if the network is reciprocal, lossless, and matched at its ports. 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

First, a quick refresher on notation, phasors, and power flow. The instantaneous voltage and current at an electrical port can be expressed as the real part of a phasor and the complex sinusoid $e^{j\omega t}$,

$$v(t) = \operatorname{Re}\left\{Ve^{j\omega t}\right\} \quad , \quad i(t) = \operatorname{Re}\left\{Ie^{j\omega t}\right\}.$$

Here, V and I are the complex amplitudes or phasors. The phasors can also be broken down into magnitudes and phase angles,

$$\begin{gathered} v(t) = |V|\cos\left(\omega t + \psi\right) \quad , \quad i(t) = |I|\cos\left(\omega t + \phi\right) \\ V = |V|\angle\psi \quad , \quad I = |I|\angle\phi \end{gathered}.$$

The instantaneous power passing through the port is simply $p(t) = v(t)i(t)$. The product of the two cosines produces a constant (DC) term and a time varying term at twice the frequency,

$$\cos(\omega t + \psi)\cos(\omega t + \phi) = \frac{1}{2}\cos(2\omega t + \psi + \phi) + \frac{1}{2}\cos(\psi - \phi).$$

The time averaged power flow is obtained by integrating the instantaneous power over one cycle, which retains the DC term while the $2\omega t$ term averages to zero,

$$P_{\text{avg}} = \frac{1}{T}\int_0^T p(t)\,dt = \frac{1}{T}\int_0^T |V|\cdot|I|\cos\left(\omega t + \psi\right)\cos\left(\omega t + \phi\right)dt = \frac{1}{2}|V|\cdot|I|\cos\left(\psi - \phi\right) = \operatorname{Re}\left\{\frac{1}{2}VI^*\right\}.$$

The average, real power flow is the real part of the complex power, $P_{\text{avg}} = \operatorname{Re}\{P_c\} = \operatorname{Re}\{½VI^*\}$.

For waves travelling along a transmission line, the phasors can be broken down into forward and reverse travelling components,

$$V(z) = V^+e^{-j\beta z} + V^-e^{+j\beta z} \quad , \quad I(z) = \frac{V^+}{Z_0}e^{-j\beta z} - \frac{V^-}{Z_0}e^{+j\beta z}.$$

The complex power for the transmission line is

$$P_c = \frac{1}{2}VI^* = \frac{V^+V^{+*}}{2Z_0} - \frac{V^+V^{-*}}{2Z_0}e^{-j2\beta z} + \frac{V^-V^{+*}}{2Z_0}e^{+j2\beta z} - \frac{V^-V^{-*}}{2Z_0}.$$

The middle two terms are together purely imaginary so the average real power flow is

$$P_{\text{avg}} = \operatorname{Re}\left\{P_c\right\} = \frac{V^+V^{+*}}{2Z_0} - \frac{V^-V^{-*}}{2Z_0},$$

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 will be represented by column vectors,

$$\left[V^+\right]=\begin{bmatrix}V_1^+\\V_2^+\\V_3^+\\\vdots\end{bmatrix}\ ,\ \left[V^-\right]=\begin{bmatrix}V_1^-\\V_2^-\\V_3^-\\\vdots\end{bmatrix}\ .$$

The scattering matrix by definition then expresses $\left[V^-\right]=\left[S\right]\cdot\left[V^+\right]$.

If the network is *matched* on all ports, then the scattering matrix will have a zero diagonal, $S_{ii} = 0$, or

$$\left[S\right]=\begin{bmatrix}0 & S_{12} & S_{13} & \cdots\\S_{21} & 0 & S_{23} & \cdots\\S_{31} & S_{32} & 0 & \cdots\\\vdots & \vdots & \vdots & \ddots\end{bmatrix}\ .$$

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,

$$\left[S\right]=\begin{bmatrix}S_{11} & S_{12} & S_{13} & \cdots\\S_{12} & S_{22} & S_{23} & \cdots\\S_{13} & S_{23} & S_{33} & \cdots\\\vdots & \vdots & \vdots & \ddots\end{bmatrix}\ .$$

A network will be reciprocal if it does not contain any anisotropic media or any active devices.

If the network is *lossless*, the total incident power must equal the total reflected power, since the network itself cannot absorb any of it. The total incident averaged real power is, less a factor of $1/2Z_0$,

$$\left[V^+\right]^T\left[V^+\right]^*=V_1^+V_1^{+*}+V_2^+V_2^{+*}+V_3^+V_3^{+*}+\cdots\ ,$$

and similarly for the reflected. 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,

$$\left[V^+\right]^T\left[V^+\right]^*=\left[V^-\right]^T\left[V^-\right]^*.$$

Using the definition of the scattering matrix gives

$$\left[V^{+}\right]^{T}\left[V^{+}\right]^{*}=\left[V^{+}\right]^{T}[S]^{T}[S]^{*}\left[V^{+}\right]^{*},$$

which requires

$$[S]^{T}[S]^{*}=[I],$$

where $[I]$ is the identity matrix. A matrix satisfying the above property is said to be unitary. The inverse of a unitary matrix is its complex conjugate transpose, $[S]^{T*} = [S]^{-1}$. This condition can also be expressed by the set of relations,

$$\sum_{k=1}^{N} S_{ki} S_{kj}^{*} = \delta_{ij} ,$$

where δ_{ij} is the Kronecker delta function and N is the number of ports in the network. A lossless network must therefore have a unitary scattering matrix.

Next, consider the application of the above principles to power splitters. A 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 so that it can be fabricated with purely metals and dielectrics, reducing its cost and increasing its ability to handle RF power. These requirements mean that the 3 × 3 scattering matrix must simultaneously have a zero diagonal, be symmetric, and unitary. Simple enough; but it turns out that simultaneously satisfying these three requirements is mathematically impossible for the 3-port case. As an exercise, write out these relationships explicitly and prove that this is so.

The design of a practical 3-port power splitter therefore requires relaxing one or more of these requirements. What if the requirement for matching was limited to only two ports? This would allow for a non-zero S_{33} while keeping $S_{11} = S_{22} = 0$, for instance. However, the requirements that the scattering matrix also be symmetric and unitary then require that the scattering matrix have the form of

$$[S]=\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{. (useless)}$$

In this case the scattering matrix degenerates into two ports which are coupled by a lossless line, and a third port which is completely mismatched but also completely decoupled from the other two ports. This is not a useful device because it provides no means to transfer power between port 3 and the other two ports.

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

$$[S]=\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \text{. (circulator)}$$

Aside from possible phase delays, 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 below in figure 1. 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 though.

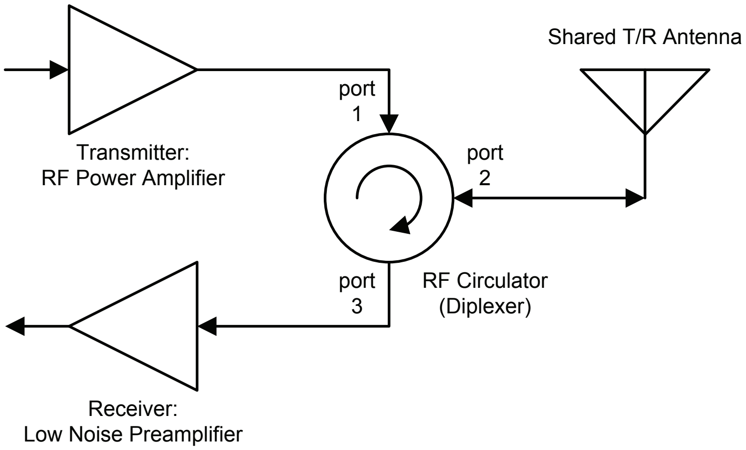


Figure 1. A T/R diplexer using an RF circulator

If the requirement for a lossless network is relaxed, 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 in figure 2. 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

$$[S] = \frac{1}{2}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}. \text{ (resistive divider)}$$

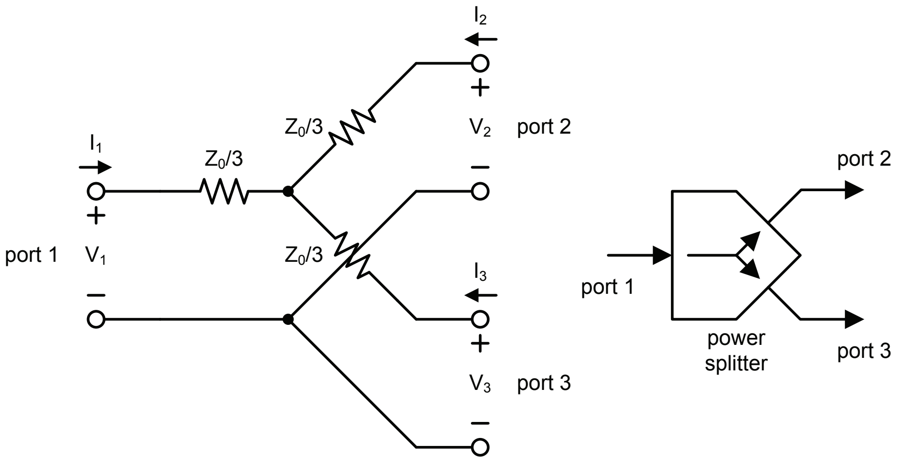


Figure 2. A 3 dB resistive divider

There exists 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

Next, 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, shown in figure 3. This component is designed for an equal (3 dB) split of power over the band of 80 to 120 MHz.

First, 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.

Next, insure that both ports of the FieldFox have Type-N to SMA adapters installed, and then attach an 18-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. The first step is to measure the phase delay for each cable.

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. The display should show a yellow trace that decreases linearly with frequency and which has an abrupt jump between –180° and +180° around 100 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 a quarter 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

$$\Delta t = \frac{1}{4 f_{180^\circ}} .$$

For the 180° frequency found for port 1, compute the one-way time delay Δt_1, which should be close to 2.50 ns.

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 100 MHz, and the corresponding Δt_2 should also be close to 2.50 ns.

Next, 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.

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. 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. 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.

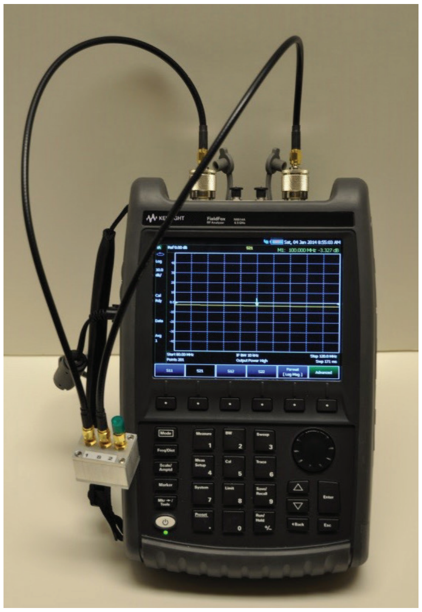


Figure 3. Measurement of the Mini-Circuits ZMSCQ-2-120+ power splitter. This connection maps ports 1 and 3 (labeled S) of the DUT to ports 1 and 2 of the FieldFox, respectively.

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. Figure 3 shows the Mini-Circuits power splitter connected to measure the S-parameters between ports 1 and 3. The green cap is the 50 Ω terminator for port 2. (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. 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 linear magnitude, the phase in degrees, and the log magnitude in decibels. It is easiest to record each of these three values into a matrix in one’s laboratory notebook.

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 between Log Mag, Linear, and Phase. For each measurement record the magnitude to 3 decimal places, the phase to a tenth of a degree, and the log magnitude to a tenth of a dB. Next, 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.

Next, 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, linear magnitude, and phase values for each of these four S-parameters.

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, linear magnitude, and phase values for each of these four S-parameters to complete the overall 3 × 3 S-parameter matrix for the power splitter.

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. Which of the nine values are the most significant? 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?

If this type of power splitter were ideal, its S-parameter matrix would have the form of

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

assuming that all ports could be perfectly matched. Notice that there is a 90° phase difference between the outputs of ports 1 and 2. This S-parameter matrix satisfies the properties for the network to be matched and reciprocal, but is it lossless? A quick check will show that this matrix is not unitary. It would seem that an ideal power splitter of this type would send amplitudes of $1/\sqrt{2}$ or –3.01 dB through to each output port. If half of the power is exiting through each of the output ports, why is the S-parameter matrix not unitary?

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.

Some further analysis

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. Matching at all four ports sets the main diagonal of the scattering matrix to zero, $S_{11} = S_{22} = S_{33} = S_{44} = 0$. Reciprocity makes the remaining off-diagonal elements symmetric about the main diagonal, $S_{ij} = S_{ji}$. A lossless network will have a unitary scattering matrix which places additional restrictions on the remaining six elements in the upper diagonal. Two of these must be zero, and by convention in the labeling the ports of the directional coupler, these are $S_{14} = S_{23} = 0$. By symmetry, this makes the backwards diagonal of the scattering matrix also zero. The unitary requirement in addition forces $|S_{12}| = |S_{34}|$ and $|S_{13}| = |S_{24}|$, as well as placing a restriction on their phase angles. If $S_{12} = S_{34} = \alpha$, $S_{13} = \beta e^{j\theta}$, and $S_{24} = \beta e^{j\phi}$, then $\theta + \phi = \pi$. There are two choices for this: $\theta = \phi = \pi/2$ which produces the symmetric coupler, and $\theta = 0$ and $\phi = \pi$ which produces the antisymmetric coupler. Lastly, the unitary requirement also demands that $\alpha^2 + \beta^2 = 1$.

The detailed mathematics summarized above is presented in several texts on microwave components. The important result is that a matched, reciprocal, and lossless 4-port directional coupler is possible, but that it can only take either of two forms, the symmetric coupler whose scattering matrix is

$$[S] = \begin{bmatrix} 0 & \alpha & j\beta & 0 \\ \alpha & 0 & 0 & j\beta \\ j\beta & 0 & 0 & \alpha \\ 0 & j\beta & \beta & 0 \end{bmatrix},$$

or the antisymmetric coupler whose scattering matrix is

$$[S] = \begin{bmatrix} 0 & \alpha & \beta & 0 \\ \alpha & 0 & 0 & -\beta \\ \beta & 0 & 0 & \alpha \\ 0 & -\beta & \alpha & 0 \end{bmatrix}.$$

Since $\alpha^2 + \beta^2 = 1$, directional couplers have only one degree of freedom, the value of α, or alternatively β. In principle, an ideal directional coupler can be characterized by one single number. Practical implementations of a directional coupler will not have ideal matches, and they can have arbitrary phase offsets on any of their ports. This necessitates a full characterization, but the above structure of the S-parameter matrix should still appear, simplifying the measurement process.

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. Figure 4 illustrates the use of a directional coupler for monitoring forward and reverse power flow through a transmission line. Figure 5 shows 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.

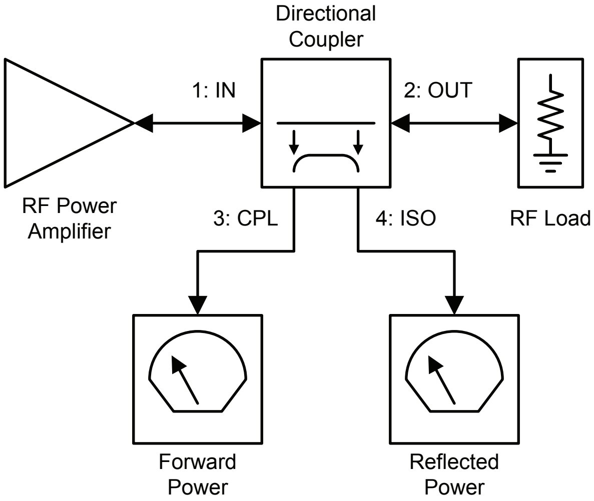


Figure 4. A directional coupler used to monitor forward and reverse power flow through a transmission line.

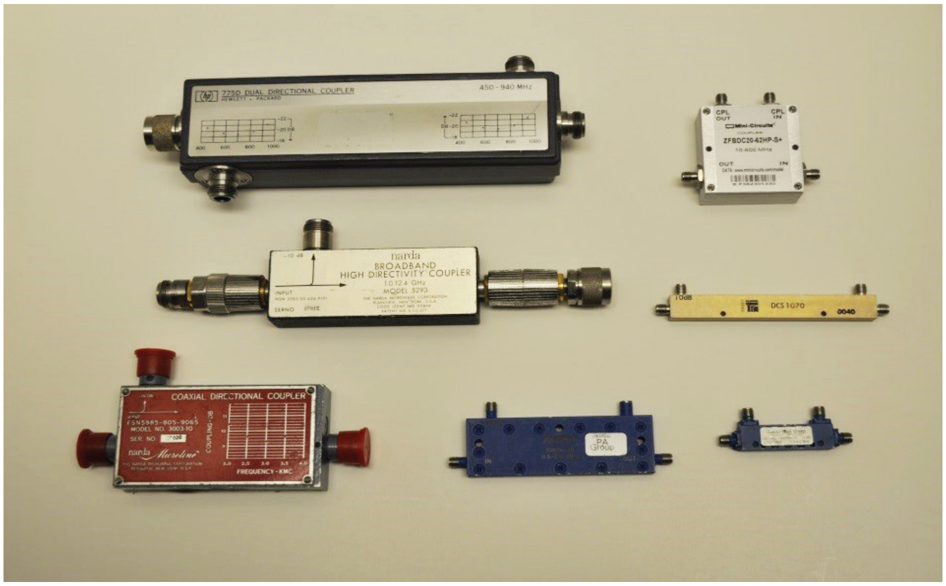


Figure 5. Some representative directional coupler modules

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, $L = P_1/P_2$. The loss is the reciprocal of the gain or forward transfer function. The coupling is the fraction of input power that is directed over to the coupled port, $C = P_1/P_3$. From the form of the S-parameter matrix, it can be seen that C is a direct measure of the parameter β. The directivity is a measure of how much power is coupled into the coupled port versus the isolated port, $D = P_3/P_4$. And finally, the isolation measures how much of the input power makes its way to the isolated port, $I = P_1/P_4$. It can be seen that these measures are not all independent, as $I = CD$. Since each of these four performance measures are power ratios, they are normally expressed in decibels. Because the input power P_1 is always the greatest in magnitude and $P_1 > P_2 > P_3 > P_4$, each of these four performance measures are defined to be greater than unity and thus positive in decibels. Sometimes these may be shown with a negative sign to remind that each successive port receives less power, but the power levels are usually left as implicit, so the sign of a dB measure should just be interpreted in the way that makes physical sense.

Figure 6. Measurement of the Mini-Circuits ZFBDC20-62HP-S+ directional coupler. This connection maps ports 2 and 3 of the DUT to ports 1 and 2 of the FieldFox, respectively.

Measurement assignment – the directional coupler

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 50 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 60 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, the linear magnitude to 3 decimal places, and the phase to a tenth of a degree. 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.

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. Figure 6 illustrate one connection which maps ports 2 and 3 of the DUT to ports 1 and 2 of the FieldFox, respectively. This connection allows measurements of the S_{22}, S_{32}, S_{23}, and S_{33} parameters of the directional coupler.

Once again, it may be noticed that there can be quite a bit of variation between the measurements of S_{11}, S_{22}, S_{33}, and S_{44}, depending upon which connection of the test cables is used. This is again a result of simply using only phase delays to compensate for the test cable effects. The test cables provide a poorer degree of matching to the opposite port than do the 50 Ω termination loads, so the more reliable measurements of these S_{ii} parameters is achieved when the 50 Ω terminator is on the opposite port.

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?

Another closely related device is the quadrature (90°) hybrid (3 dB) coupler. This device has properties that resemble both a power splitter and a directional coupler. The ideal quadrature hybrid coupler will have an S-parameter matrix of the form

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

The zero main diagonal indicates that all ports are matched, and the zero reverse diagonal indicates that it provides isolation between ports 1 and 4 and between ports 2 and 3. The input power is split equally into the two opposite side ports, but with a –90° phase difference between them. A few typical quadrature hybrid couplers are shown in figure 7. If time permits and they are available, use the FieldFox to characterize one of these devices.

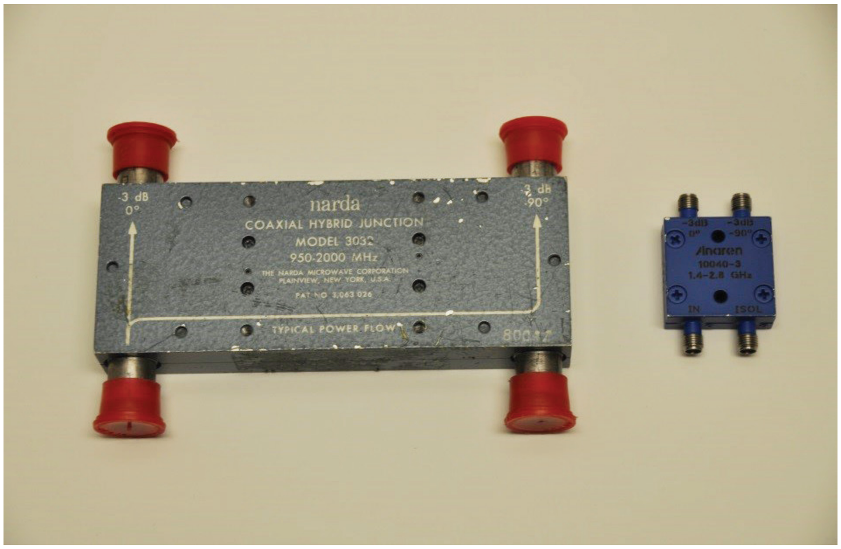


Figure 7. Some typical quadrature hybrid couplers

In the commercial industry, devices such as the power splitter or coupler are generally tested using a multiport network analyzer. A multiport network analyzer is one that has three, four, or more test ports. Furthermore, these modern network analyzers can display many traces, often 100+. So for example, for a coupler, an operator can simply connect all four ports to the network analyzer and view all 16 S-parameters at once.

FieldFox Parts List for Teaching Labs 1 through 6

Teaching labs 1 through 6 all require a FieldFox handheld analyzer and parts listed in the table below. Additionally, Lab 2 requires a Keysight MXG signal analyzer that is used to generate CW, AM and FM signals.

Note regarding the FieldFox handheld analyzer: These Labs were written for the FieldFox N9914A 6.5 GHz analyzer. However, the N9914A can be substituted with any of the following models: N9913A, N9915A, N9916A, or N9917A. The N9918A can also be used but additional adapters will be necessary because it has 3.5 mm test port connectors while the N9914A has Type-N.

Note regarding the MXG RF analog signal generator: Other MXG signal generators can be used but an A Series is simpler to use than a B Series, as the AM modulation scheme is different between the A and B Series. The Lab was written based upon the A Series.

Item no.	Description	Manufacturer	Mfr. part no.	Vendor	Vendor part no.	Qty
C1	SMA (m) to SMA (m) coaxial cable assembly, RG58C/U, 50 ohm, 18 in. long			L-Com	CCS58A-1.5	2
C2	Type-N (m) to BNC (f) coaxial adapter, 50 ohm			L-Com	AXA-NMBF	2
C3	Type-N (m) to SMA (f) coaxial adapter, 50 ohm			L-Com	AXA-NMSF	2
C4	SMA (f) to SMA (f) coaxial adapter, knurled middle			L-Com	BA23	2
C5	SMA (m) to SMA (m) coaxial adapter, Au			L-Com	BA22	2
C6	SMA (m) to SMA (m) to SMA (m) coaxial T adapter			L-Com	BA18	2
C7	SMA (m) terminator, 50 ohm			L-Com	BTS5M	2
C8	SMA (f) terminator, 50 ohm			L-Com	BTS5F	2
D1	Center-loaded telescoping whip antenna with BNC (m) connector, 19 in. long			Radio Shack	20-006	1
D2	800 MHz scanner antenna with BNC (m) connector			Radio Shack	20-283	1
D7	SMA coaxial attenuator, 10 dB, DC to 6 GHz, 50 ohm			Mini-Circuits	VAT-10+	1
D8	SMA coaxial band pass filter, 70 MHz, (63 to 77 MHz), 50 ohm			Mini-Circuits	SBP-70+	1
D9	SMA coaxial power splitter/combiner, 2-way, 90°, 50 ohm, 80 to 120 MHz			Mini-Circuits	ZMSCQ-2-120+	1
D10	SMA coaxial bi-directional coupler, 50 ohm, 50 W, 10 to 600 MHz			Mini-Circuits	ZFBDC20-62HP+	1
C9	SMA male shorting cap, Au	Amphenol Connex	132331_	Digi-Key	ACX2070-ND	1
A1	SMA (f) PCB jack, 50 ohm, 3 GHz, PTFE, Zn alloy/Au plated	TE Connectivity	5-1814832-1	Digi-Key	A97594-ND	1
A2	SMA (f) PCB jack, 50 ohm, 3 GHz, PTFE, brass/Ni plated	Linx Technologies	CONSMA001	Digi-Key	CONSMA001-ND	1
A3	Thumbwheel trimpot, 500 ohm, 0.5 W, PC pin, cermet, single turn, top adjust	Bourns	3352T-1-510LF	Digi-Key	3352T-501LF-ND	1
A4	Resistor, 100 ohm, 1/4 W, 1%, axial lead metal film, 100 ppm/C	Yageo	MFR-25FBF52-100R	Digi-Key	100XBK-ND	1
A5	Capacitor, 22 pF, 100 V, 5%, radial lead ceramic disk, C0G-NP0	Vishay	D220J20C0GH-63L6R	Digi-Key	1429PH-ND	1
A6	DIP8 machine pin socket, 0.100 pitch, 0.300 spacing, 30 µin Au plated	Mill-Max Mfg. Corp.	110-13-308-41-001000	Digi-Key	ED56083-ND	1

FieldFox Parts List for Teaching Labs 1 through 6 *continued*

Item no.	Test equipment	Manufacturer	Mfr. part no.	Vendor	Vendor part no.	Qty
T1	FieldFox handheld analyzer	Keysight	N9914A		N9914A	1
	– Option 233: Spectrum analyzer					1
	– Option 210: VNA transmission/reflection					1
	– Option 211: VNA full 2-port S-parameters					1
T2	MXG RF analog signal generator	Keysight	N5181A		N5181A	1
	– Option UNT: AM, FM, phase modulation					1

This application note was created by Professor Bruce Darling, from University of Washington's Electrical Engineering Department, in collaboration with Keysight Technologies' handheld team within the Component Test Division. The content is designed to complement an introductory course in undergraduate electromagnetics.

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