

Directivity and VSWR Measurements

Understanding Return Loss Measurements

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The characterization of microwave networks requires discriminating between forward and backward traveling waves. Unfortunately no directional device is perfect, leading to potentially dramatic measurement errors. In this note we show that return loss and VSWR measurements are greatly complicated by the finite performance of the directional device used to measure the reflected power. Explicit expressions are derived for measurement error as a function of directivity, return loss, and reflection phase. The only accurate and convenient way to make return loss measurements is with a well matched high directivity directional coupler or bridge.

VSWR and Return Loss

A key performance metric for any microwave or RF network is how well the impedance of the load matches to the impedance of the source. This match determines how much power can be delivered and how much will be reflected back to the transmitter as measured by the return loss, or ratio of reflected power to transmitted power. Traditionally this quality of a component has been described by the voltage standing wave ratio (VSWR), or ratio of maximum to minimum voltage of the standing wave on the line before the component, as this quantity was easier to measure than return loss before network analyzers became commonplace. These two parameters answer the same question: how much power is delivered and how much is reflected from a device under test (DUT)?

In order to measure the power reflected from a DUT, a directional device that can discriminate between forward and reverse travelling waves is necessary. One such directional device¹ is a [directional coupler](#) (Fig. 1). A [directional coupler is a four port device](#) that samples the signal on a through line, but in a way that discriminates between forward and reverse traveling waves.



Figure 1: Schematic diagram of a directional coupler.

In this device, an incoming signal is partially split between the output port and the coupled port, and no signal appears at the isolated port². The isolation that exists between ports 1 and 4 is caused by destructive interference of the odd and even mode internal reflections at the isolated port; constructive interference of these modes creates the coupled signal as well. Couplers are reciprocal circuits which implies that a wave traveling in the reverse direction will be sampled at port 4 (the forward going isolated port) and isolated at port 2 (the forward going coupled port). In practice, the goal of the coupler designer is to obtain as much isolation between the input and isolated port as possible.

The figure of merit that defines how well a coupler discriminates between forward and reverse waves is called directivity. Directivity is defined positively as

$$D = S_{31} + S_{21} - S_{32} \quad (1)$$

where D is the directivity, S_{31} is the coupling ratio, S_{21} is the insertion loss, and S_{32} is the isolation, where all terms are defined negatively in dB. Note that most data sheets use the definition

$$D = S_{31} - S_{32} \quad (2)$$

which does not include insertion loss. This definition is not as meaningful as a figure of merit for return power measurements since it does not include the insertion loss. However, (2) is valid when discussing forward power measurements and is commonly used by the industry.

The importance of directivity is illustrated in the following example. Suppose we want to measure the power traveling down a transmission line terminated by an unknown impedance (Fig. 2). Using a coupler, we can couple off some fraction of power (e.g. 1%) and measure it with a detector. If the DUT impedance is perfectly matched to the transmission line, then no reflection will be generated (therefore regardless of whether the coupler has directivity or not, we will measure the correct power). Now suppose the DUT is non-ideal and generates a reflection as illustrated in Fig. 2. Some of the reflected wave will 'leak' into the coupled port due to non-ideal directivity. This 'leakage' will interfere with the desired forward coupled signal and cause error

¹The most obvious choice would be a circulator, but they are usually narrowband and have insufficient isolation for return loss measurements.

²The coupled port is on the same side as the input port in a directional coupler since it is a backward wave coupler. This is in contrast to Bethe hole couplers and fiber optic couplers which couple power in the forward direction.

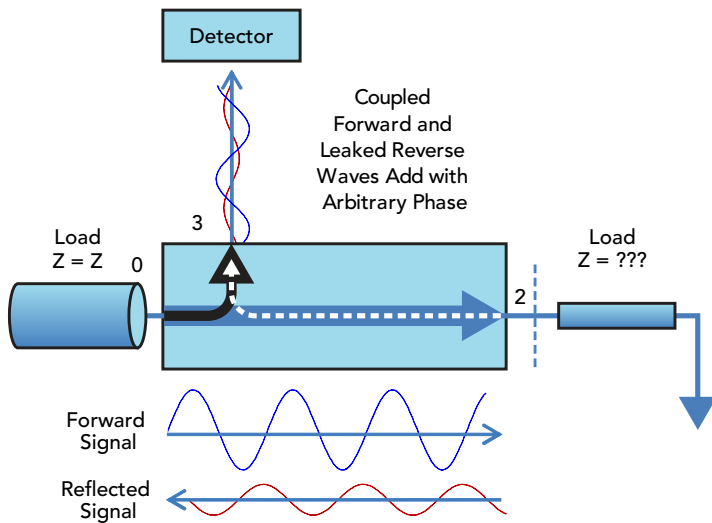


Figure 2: Schematic of a through line power measurement into an unknown impedance. Finite directivity causes the reflected wave to contaminate the coupled signal.

in the forward power measurement. This is a fundamental limitation for 'in situ' power measurements³.

As we show in this paper, choosing a high quality, high directivity coupler is crucial to measuring RF power traveling down a transmission line. We derive expressions to predict error in forward and reverse power measurements, and give rules of thumb to limit the measurement error. As a general trend, we show that forward power measurements are less sensitive than reverse power measurements to coupler directivity.

Forward Power Measurement

In forward power measurements (Fig. 3a), the power detected at the coupled port is the sum of two waves: the desired forward coupled wave and the undesired reverse reflected wave coming from the DUT (as shown in Fig. 2). From interference theory, when two waves with the same frequency combine, the resultant wave is the *vector addition* of the voltages. This means that a small reflected wave can have a significant and variable impact on the measured power depending on the phase rotation in the reflection.

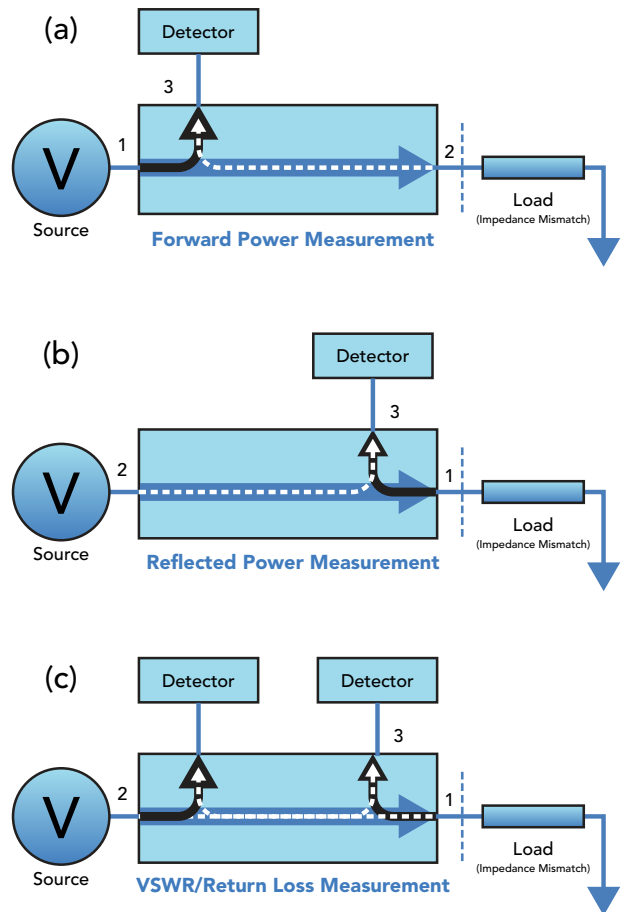


Figure 3: Operation of a directional detector measuring (a) forward power, (b) reverse power, and (c) VSWR/return loss. The large blue arrow represents input power, the black arrow is the power we wish to measure, and the red arrow represents the interfering term due to finite directivity.

Using the definition of directivity and vector voltage addition, we can show that the upper and lower bound power error for a forward power measurement is given by

$$P_{eF} = 10 \cdot \log_{10} \left(10^{\frac{-IL - RL - D}{10}} + 1 \pm 2 \cdot 10^{\frac{-IL - RL - D}{20}} \right) \quad (3)$$

where P_{eF} is the power error, IL and RL are the positive defined insertion and return losses of the device in dB, and D is the directivity defined in (2). This is illustrated in Fig. 4, where high and low power measurement errors for a device with a 1 dB insertion loss are shown for various load return losses.

³The forward coupled and reverse isolated waves add as voltage vectors with unknown phase. Vector network analyzers (VNAs) use the phase information of the detected signals, combined with calibration routines, to correct for reflections and imperfections in the measurement equipment. In this paper we are concerned with scalar, and thus uncorrected measurements only.

This plot shows that

- Reflected power will cause significant power errors when a non-directional device is used.
- The measured power can fall anywhere within a large range, depending on the phase of the reflected signal
- A device with a directivity of 15 dB or better will generally reduce forward power measurement errors below 1 dB.

A directional device should, therefore, have a directivity of at least 15 dB to make it suitable for forward power measurements.

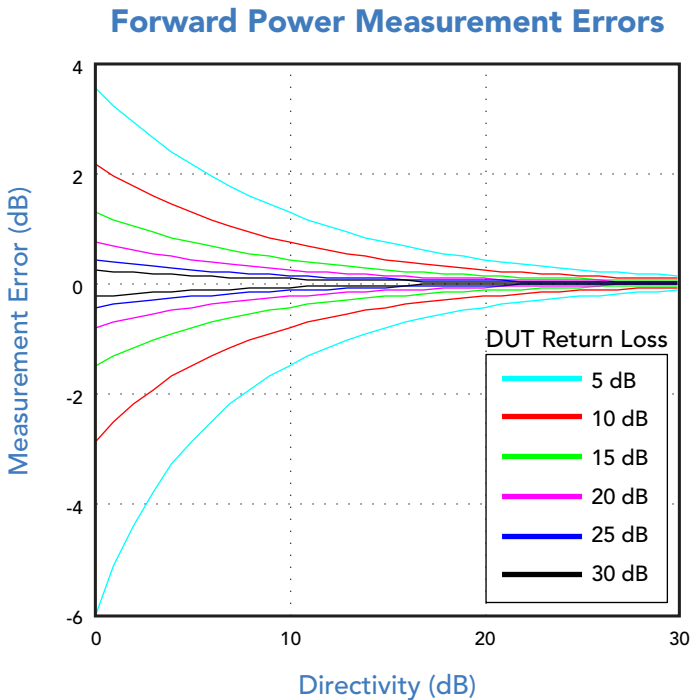


Figure 4: Error in forward power measurement as a function of directivity for various load return loss values.

Reflected Power Measurement

The challenge in reflected power measurements is that the coupler must distinguish between a high forward power signal and a much lower reflected power signal (Fig. 3b). In contrast to forward power measurements, a smaller reflected power will require more directivity to achieve the same measurement certainty. Reflected power measurements require significantly more coupler directivity than forward power measurements to prevent large measurement errors.

As derived in the Appendix, the maximum and minimum reflected power measurement errors are given by

$$P_{eR} = RL + IL + 10 \cdot \log_{10} \left(10^{\frac{-IL - RL}{10}} + 10^{\frac{-D}{10}} \pm 2 \cdot 10^{\frac{-IL - RL - D}{20}} \right) \quad (4)$$

The measurement error versus DUT return loss is shown in Fig. 5, again for a device with a 1 dB insertion loss.

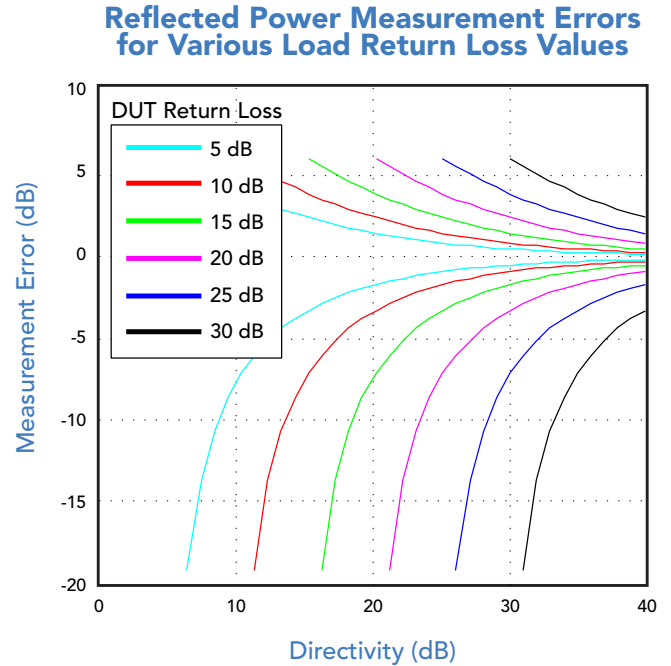


Figure 5: Error in reflected power measurement as a function of directivity.

From this plot we see

- Reflected power measurements are dramatically more sensitive to measurement device directivity than forward power measurements
- When the directivity (minus insertion loss) is equal to the return loss, the leaked forward signal will be equal to the desired coupled reflected signal, resulting in a potentially complete cancellation and infinite error
- A directivity of ~15 dB better than the DUT return loss is necessary to reduce errors to the order of ~1 dB. A directivity of ~5 dB better than DUT return loss will result in errors of ~5 dB.

Thus to accurately measure reflected power from a load with a return loss of less than -15 dB, a directivity of 30 dB or better is required. This is significantly higher than the 15-20 dB typical directivity of most couplers and requires a high directivity measurement device.

VSWR/Return Loss Measurements

A VSWR measurement (Fig. 3c) requires both a forward and reflected power measurement. Therefore, errors from both the forward and reflected power measurements will combine to make the return loss measurement error. When return loss measurements are made with a directional device where the forward and return coupled ports have the same directivity, we can find the error as before. The return loss will be calculated by the user in dB as

$$RL_m = P_{mF} - IL - P_{mR} \quad (5)$$

which, using (3) and (4), gives

$$RL_m = RL + IL + 10 \cdot \log_{10} \left(10^{\frac{-IL-RL}{10}} + 10^{\frac{-D}{10}} + 2 \cdot 10^{\frac{-IL-RL-D}{20}} \cos\theta \right) - 10 \cdot \log_{10} \left(10^{\frac{-IL-RL-D}{10}} + 1 + 2 \cdot 10^{\frac{-IL-RL-D}{20}} \cos\theta \right) \quad (6)$$

The error for the return loss is plotted in Fig. 6 for various directivities and actual return loss values.

Note that the return loss measurement error is almost completely dominated by the reflected power measurement except for very high values of return loss (greater than -5 dB). These plots make it apparent that a directivity of at least 10 dB better, and ideally 15-20 dB better, than the return loss of the device under test is required for accurate measurements.

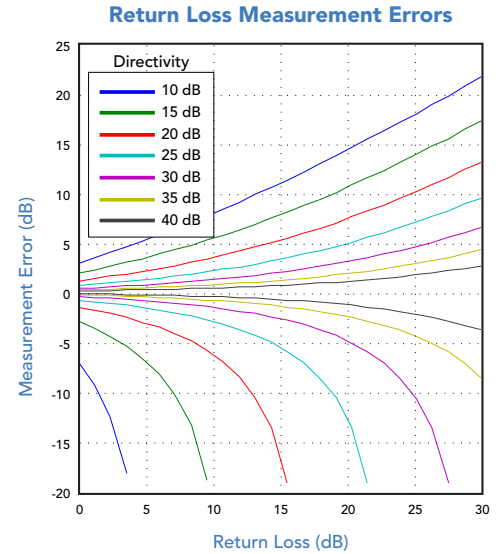


Figure 6: Error in reflected power measurement due to load mismatches for various coupler/bridge directivity values.

The Effect of Output Impedance

A return loss measurement will only detect the reflection from a load, not whether the load is matched to 50 Ω . To ensure the load is 50 Ω , the output impedance of the directional device must be as close to 50 Ω as possible. For example, if a directional device has an output return loss (S22) of 14 dB, this could mean that the impedance is as low as 33 Ω or as high as 75 Ω ⁴ (see Fig. 7). Any subsequent circuit tuned to eliminate the return loss with this coupler would then be matched to a non-50 Ω impedance.

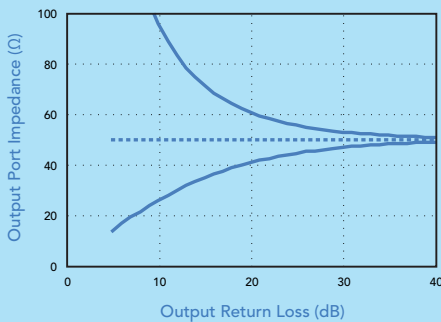


Figure 7: Potential real impedance values for a given output port return loss ($Z_0 = 50 \Omega$).

Measurement errors can also be caused by reflections from mismatches at the source (input) and detector (coupled) ports. These errors can be corrected, as in a network analyzer, if phase information is available (see e.g. [Agilent Network Analyzer Basics](#)), but the correction terms are complicated. For a derivation of the error in reflection measurements due to all of the various terms, see Appendix A of "Swept Frequency Techniques", Ely, Paul C. Jr., Proc. IEEE, vol. 5, no. 6, June 1967.

A directional device that is well matched at all ports combined with a 50 Ω source and detectors will ensure accurate and consistent return loss measurements.

⁴Because Return Loss is actually a vector quantity, with both angle and phase, it could be composed of an infinite range of resistive and reactive components.

Measurement Considerations

Directional Bridge vs. Directional Coupler

A [directional coupler](#), as described at the beginning of this paper (Figs. 1, 8a), uses a coupled line with wave cancellation to make directional power measurements. A [directional bridge](#) is a directional device similar to a directional coupler (Fig. 8b). The directional bridge uses a Wheatstone bridge structure with broadband baluns to achieve significantly higher directivity and a broader bandwidth (lower cutoff frequency) than directional couplers. The tradeoff to achieving multi-decade bandwidth is insertion loss.

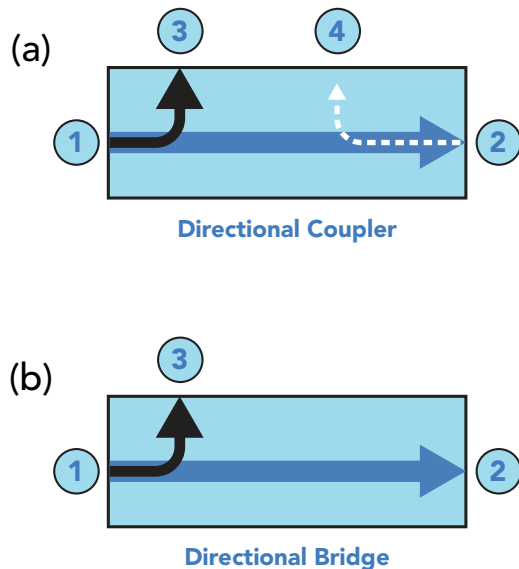


Figure 8: Operation of a directional coupler vs. directional bridge.

[Marki directional bridges](#) use a Wheatstone bridge circuit to achieve extremely high levels of directivity (30-40 dB) down to kHz frequencies. Since the Wheatstone bridge is a resistive circuit, there is extra insertion loss in a directional bridge. For example, a Wheatstone bridge tuned to have a 16 dB coupling will have a 1.6 dB nominal insertion loss⁵. Therefore, one can expect between 2 and 3 dB of total insertion loss in a 16 dB directional bridge when accounting for excess losses caused by material and conductor loss. Furthermore, since most of the power is dissipated in the resistors, directional bridges cannot typically handle more than ≈ 1 Watt of input power. With directivities better than 30 dB from 200 kHz to more than 10 GHz, the directional bridge is indispensable for broadband measurements and significantly simplifies test setups.

[Stripline bidirectional](#) couplers use proximity coupling to provide moderate levels of directivity (15-25 dB) across several octaves up to very high (65 GHz) frequencies. They have lower insertion loss and offer both a through and reflected coupled port.

For high power and low loss applications, [airline couplers](#) offer comparable directivities (15-25 dB) but with a loss less than 0.5 dB and power handling up to 200 W on some units. The tradeoff is a non-flat coupling ratio, which must be calibrated out.

Unidirectional vs. Bidirectional vs. Dual Directional Couplers

Directional couplers are bidirectional. A bidirectional coupler can be used to measure both forward and reverse power simultaneously if both coupled ports are terminated in broadband 50 Ω detectors. Unfortunately, any detector load mismatch will cause errors in the power reading on the other port. Therefore, many directional couplers include a 50 Ω termination internally to make a three port device.

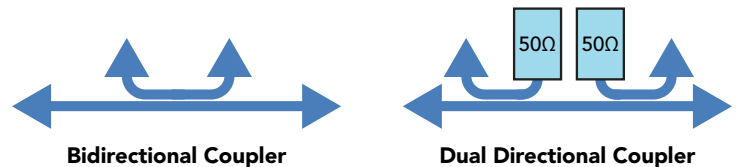


Figure 9: Operation of a bidirectional coupler vs. a dual directional coupler.

A [dual directional coupler](#) minimizes the influence of detector mismatch in VSWR measurements (Fig. 9).

Return Loss Measurement Example

To understand the tradeoffs in selecting a directional device, it is instructive to consider the sources of error that might be present in an actual return loss measurement. As an example we'll measure the return loss of a 10 dB attenuator

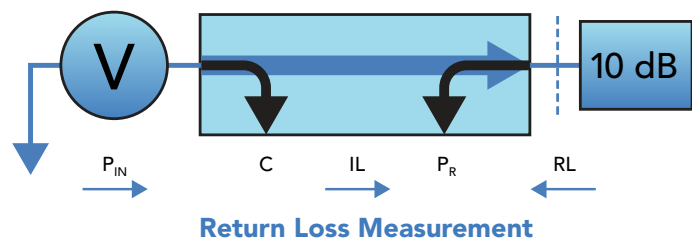


Figure 10: Schematic of the example return loss measurement.

⁵Dunsmore, J., "Network Analyzer Basics", as presented to UC Berkeley EECS 142, 2007.

terminated in an open circuit (Fig. 10). Assuming the open circuit is broadband, the return loss of this device should be 20 dB.

Device	Directivity (dB)	Insertion Loss (dB)	Calculated Error (High)	Calculated Error (Low)	Measured Return Loss (dB)	Measured Return Loss Error (dB)
Competitor Directional Coupler	19.3	0.2	6.5	-19.2	14.0	6.0
Airline Coupler	23.0	0.1	4.7	-10.9	17.5	2.5
Directional Coupler	30.1	0.5	2.4	-3.3	20.9	-0.9
Directional Bridge	37.3	1.9	1.4	-1.6	19.3	0.7

Table 1: Measured return loss values and error values using different measurement devices.

Conclusion

The most reliable and convenient method for making uncorrected return loss measurements is to use a well matched directional device. The directivity and return loss of the directional device determines the accuracy of the return loss measurement. Marki Microwave has a variety of directional devices including high directivity broadband directional bridges, directional and dual directional couplers, and airline directional couplers to suit any measurement application.

Appendix: Derivations and Calculations

Forward Power Measurement

In this case the powers are given by

$$P_F = P_0 - C \quad (7)$$

$$P_R = P_0 - IL - RL - C - D \quad (8)$$

where P_F is the forward coupled power, P_0 is the input power, C is the coupling ratio, P_R is the reflected power that leaks into the coupled port, IL is the device insertion loss, RL is the return loss at the impedance discontinuity, and D is the directivity of (2), with all parameters defined as positive and in dB or dBm as appropriate. The power measured at the coupled port is calculated as the vector addition of the two voltages

$$V_m = \left\{ Z \cdot 10^{\frac{P_0 - C}{10}} \left(10^{\frac{-IL - RL - D}{10}} + 1 \cdot 10^{\frac{-IL - RL - D}{20}} \cos\theta \right) \right\}^{1/2} \quad (9)$$

where θ is the phase angle between the forward and reflected waves at the coupled port determined by the phase length to the reflection point. The power in dBm measured from this voltage will then be

$$P_{mF} = P_0 - C + 10 \cdot \log_{10} \left(10^{\frac{-IL - RL - D}{10}} + 1 + 2 \cdot 10^{\frac{-IL - RL - D}{20}} \cos\theta \right) \quad (10)$$

Reflected Power Measurement

For a reflected power measurement the desired coupled reflected power and undesired coupled forward power are given by

$$P_R = P_0 - IL - RL - C \quad (11)$$

$$P_F = P_0 - C - D \quad (12)$$

which, after vector addition, gives a measured power of

$$P_{mR} = P_0 - C + 10 \cdot \log_{10} \left(10^{\frac{-IL - RL}{10}} + 10^{\frac{-D}{10}} + 2 \cdot 10^{\frac{-IL - RL - D}{20}} \cos\theta \right) \quad (13)$$

In this case the desired power is $P_0 - IL - RL - C$, so the power error can be found by dividing (subtracting in dB) this from the measured power to leave a formula in terms of IL , RL , and D .

$$P_{eR} = RL + IL + 10 \cdot \log_{10} \left(10^{\frac{-IL - RL}{10}} + 10^{\frac{-D}{10}} + 2 \cdot 10^{\frac{-IL - RL - D}{20}} \cos\theta \right) \quad (14)$$

VSWR/Return Loss Measurement

The return loss of a load is defined as the amount of power presented at the port that is reflected back to the source. If a bidirectional or dual directional coupler with reciprocal directivity is used to measure it, the return loss will be calculated as the reflected power divided by the coupling power multiplied by the insertion loss. In dB it is given by

$$RL = P_{mF} + IL - P_{mR} \quad (15)$$

which, plugging in our previously calculated forward and reverse powers, gives

$$RL_m = IL + 10 \cdot \log_{10} \left(10^{\frac{-IL - RL}{10}} + 2 \cdot 10^{\frac{-IL - RL - D}{20}} \cos\theta \right) - 10 \cdot \log_{10} \left(10^{\frac{-IL - RL - D}{10}} + 1 + 2 \cdot 10^{\frac{-IL - RL - D}{20}} \cos\theta \right) \quad (16)$$

When the directivity goes to infinity, this formula reduces to the return loss. It is also apparent that for large values of IL , RL , or D the final term will be very close to zero and the return loss will be dominated by the error in reflected power measurement.

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