Influence of a directional coupler's parameters on the results of forward and reflected power measurements
White Paper

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A directional coupler is typically used to make nonintrusive measurements of the output power of an amplifier system or the reflected power of a sink such as a load impedance, an antenna or some other device under test (DUT).

The accuracy of the displayed result is highly dependent on the directional coupler's physical characteristics. We distinguish between quantities that we can determine with test equipment and calibrate out, vs. factors that we cannot influence and which invariably corrupt the measurement result. Such latter factors that highly corrupt power measurements and which cannot be calibrated out include the directivity and isolation of a directional coupler.

This White Paper examines the influence of the frequency response of the directivity on the results of measurements of the forward and reflected power.

White Paper
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ROHDE&SCHWARZ

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1 Introduction

A directional coupler is typically used to make nonintrusive measurements of the output power of an amplifier system and/or the reflected power of a sink (load impedance, antenna or other DUT) (Fig. 1).

Part of the forward or reflected power is decoupled with a fixed coupling factor and fed to a measuring system.

The accuracy of the displayed result is highly dependent on the physical characteristics of the directional coupler.

In terms of the measurement uncertainty of the results, we must distinguish between quantities we can determine with test equipment and calibrate out vs. other factors that invariably corrupt the measurement result.

2 Parameters of a directional coupler

The following parameters are used to characterize a directional coupler:

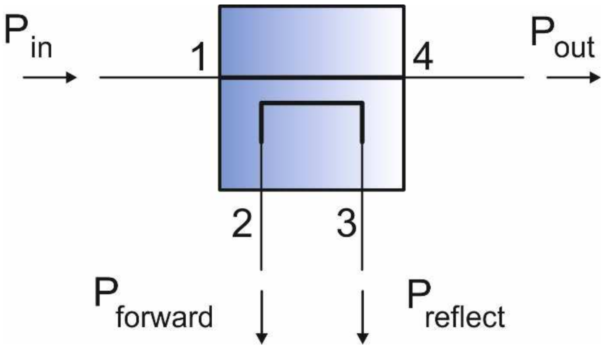


Fig. 1: Block diagram of a directional coupler.

Coupling, forward: $$10\log\left(\frac{P_{in}}{P_{forward}}\right)$$

Coupling, reflected: $$10\log\left(\frac{P_{out}}{P_{reflect}}\right)$$

Directivity: $$10\log\left(\frac{P_{forward}}{P_{reflect}}\right)$$

Isolation: $$10\log\left(\frac{P_{in}}{P_{reflect}}\right)=10\left(\log\left(\frac{P_{in}}{P_{forward}}\right)+\log\left(\frac{P_{forward}}{P_{reflect}}\right)\right)$$

For symmetrical systems, the forward and reflected coupling are identical.

The isolation then has the following symmetry:

$$10\log\left(\frac{P_{in}}{P_{reflect}}\right)=10\log\left(\frac{P_{out}}{P_{forward}}\right)$$

Especially for reflected measurements, the result is dependent on the magnitude of the isolation and is thus highly dependent on the magnitude of the directivity.

2.1 Influence of the frequency response on the measurement result

The frequency response of a directional coupler is one of the constant factors that is largely independent of the test configuration (see Figs. 2 and 11 ff.).

The directional coupler's specified coupling factor is normally valid only for a single frequency. However, it is possible to measure the frequency response of the coupling factor using test equipment (or sometimes it is specified in the data sheet). Since this quantity is constant, the frequency response can be calibrated out or otherwise eliminated as part of a power measurement. It is a constant factor that is independent of the test configuration.

As is conventional with physical systems, the coupling varies at the rate of 20 dB/decade or 6 dB/octave.

If we wish to implement a broadband measuring system, the appropriate frequency response correction must be realized at the test ports for the forward and reflected power. The simplest approach is to use lowpass circuits.

The example here shows the real frequency response of the coupling attenuation without any frequency response compensation.

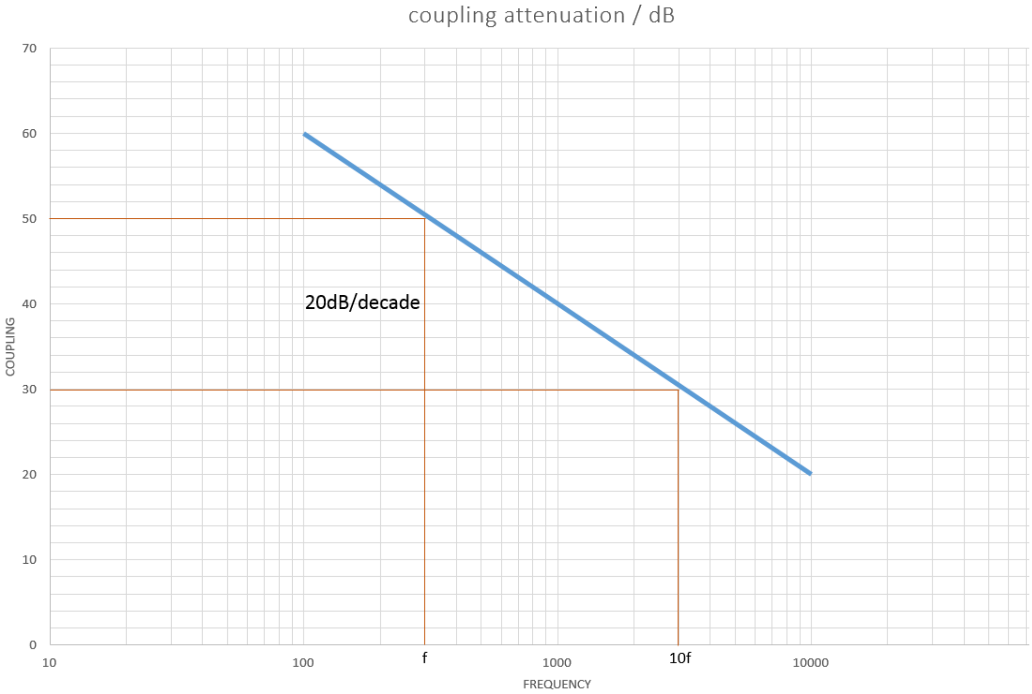


Fig. 2: Coupling attenuation vs. frequency for a directional coupler without any frequency response compensation.

Example: Calculation of the coupling attenuation at a different frequency:

$$a_k(f_2) = a_k(f_1) + 20\log\left(\frac{f_1}{f_2}\right) \qquad \text{für} \quad f_1 \le f_2$$

2.2 Influence of the directivity on the measurement result

The factors that highly corrupt power measurements and which cannot be calibrated out include the directivity and isolation of a directional coupler.

Directivity is a fixed (unchangeable) physical system characteristic of a directional coupler. When making power measurements, the test setup that is used also plays a key role.

The measurement uncertainty due to low directivity becomes apparent especially during measurement of the reflected power since the reflected power is generally much lower than the forward power.

Numerical example:

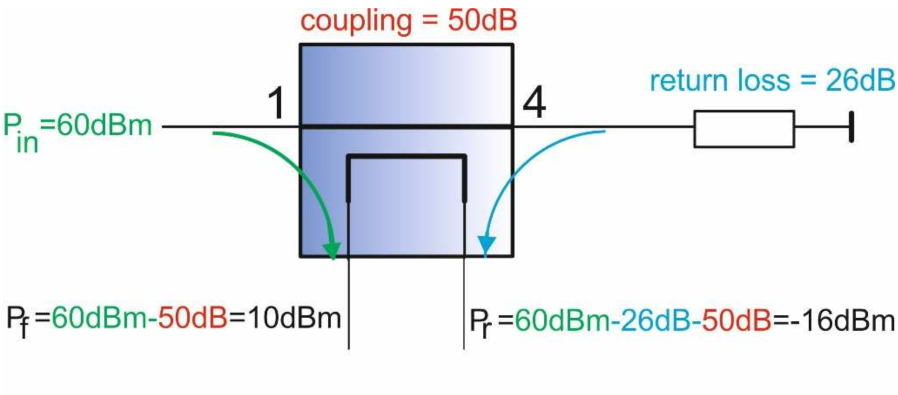


Fig. 3: Example of a real-world directional coupler.

If our directional coupler had perfect isolation, the return loss of the load would equal the difference between the reflected and forward measurements:

$$P_r - P_f = -16dBm - 10dBm = -26dB = return\,loss\;of\;load$$

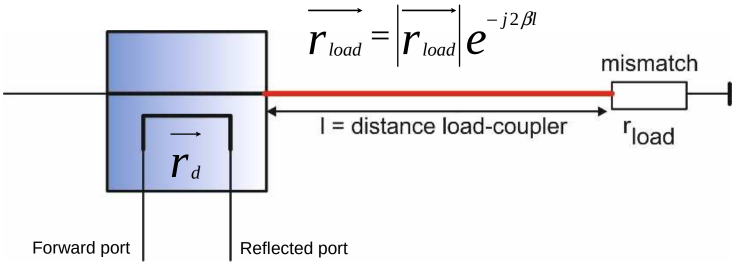
However, in real-world systems the directivity is finite and it typically causes a substantial measurement error. Since the forward and reflected waves are complex vectors, the phase angle (between the directional coupler and DUT) is just as relevant as the magnitude. The phase angle is determined by the wavelength of the signal and the distance between the load and the directional coupler.

The following figures should help to clarify this situation:

Fig. 4 shows a typical test setup. The DUT and the directional coupler are separated by a distance l which is typically realized with a coaxial cable that also serves to transform the load impedance.

At the directional coupler's reflection port, two components are added vectorially:

- The DUT's input impedance transformed by the phase angle Φ
- The vector of the measurement system's directivity



$$\overrightarrow{r_{load}} = \left|\overrightarrow{r_{load}}\right| e^{-j2\beta l}$$

$$\overrightarrow{r_r} = \overrightarrow{r_d} + \left|\overrightarrow{r_{load}}\right| e^{-j2\beta l}$$

Fig. 4: Typical test setup.

$\overrightarrow{r_r}$ = Reflection coefficient at directional coupler's reflection port

$\overrightarrow{r_d}$ = Directivity of directional coupler

$\overrightarrow{r_{load}}$ = Reflection coefficient of load / DUT

$\beta = \frac{2\pi}{\lambda}$ β = Phase coefficient λ = Wavelength

Fig. 5 shows the correlation.

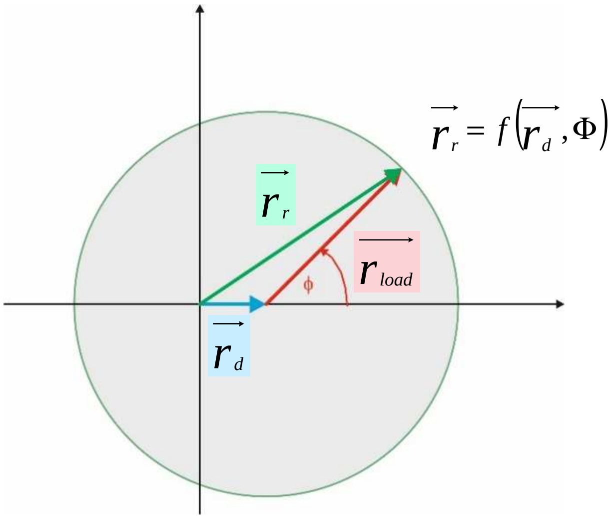


Fig. 5: Vector addition of measurands at the reflection port.

The measurement result at the reflection port is dependent on the magnitude of the load's reflection coefficient ($\vec{r}_{load}$) as well as especially on the phase angle Φ (= 2βl) between the directional coupler and the load. It can lie at **any** point on the circumference of the circle (Fig. 5).

The maximum measured value is attained if the two vectors are in phase (Φ = 0°). The minimum measured value occurs if the two vectors are out of phase (Φ = 180°).

$$\left|\vec{r}_{r,\max}\right| = \left|\left|\vec{r}_d\right| + \left|\vec{r}_{load}\right|\right|$$

$$\left|\vec{r}_{r,\min}\right| = \left|\left|\vec{r}_d\right| - \left|\vec{r}_{load}\right|\right|$$

From this discussion, it should be clear that for a given directivity, the measurement error increases as the DUT's reflected power decreases.

2.2.1 Example 1: Directional coupler with good directivity (typ. 1 octave)

$$\text{Directivity of directional coupler} = 34\,\text{dB} \Rightarrow \left|\overrightarrow{r_d}\right| = 0.01995$$

$$\text{Return loss load} = \text{-26 dB} \Rightarrow \left|\overrightarrow{r_{load}}\right| = 0.0501$$

$$\text{Input power} = 5\,\text{kW} \quad \Rightarrow \quad \text{Expected reflection} = 12.6W$$

$$\left|\overrightarrow{r_{r,\max}}\right| = \left|\left|\overrightarrow{r_d}\right| + \left|\overrightarrow{r_{load}}\right|\right| = 0.01995 + 0.0501 = 0.07 \Rightarrow \text{-23 dB}$$

$$\left|\overrightarrow{r_{r,\min}}\right| = \left|\left|\overrightarrow{r_d}\right| - \left|\overrightarrow{r_{load}}\right|\right| = 0.03015 \Rightarrow \text{-30.4 dB}$$

$$\text{Measured values: min.} = 4.55\,\text{W, max.} = 25.06\,\text{W}$$

Instead of the expected value of 12.6 W, the measured value can assume any value between 4.55 W and 25.06 W.

2.2.2 Example 2: Broadband directional coupler with typical directivity found in EMC measuring systems

$$\text{Directivity of directional coupler} = 23\,\text{dB} \Rightarrow \left|\overrightarrow{r_d}\right| = 0.0708$$

$$\text{Return loss load} = \text{-}2.92\,\text{dB} \Rightarrow \left|\overrightarrow{r_{load}}\right| = 0.7145 \Rightarrow \text{VSWR} = 6$$

$$\text{Input power} = 10\,\text{kW} \quad \Rightarrow \quad \text{Expected reflection} = 5105W$$

$$\left|\overrightarrow{r_{r,\max}}\right| = \left\|\overrightarrow{r_d}\right| + \left|\overrightarrow{r_{load}}\right\| = 0.0708 + 0.7145 = 0.7853 \Rightarrow \text{-}2.10\,\text{dB}$$

$$\left|\overrightarrow{r_{r,\min}}\right| = \left\|\overrightarrow{r_d}\right| - \left|\overrightarrow{r_{load}}\right\| = 0.6437 \Rightarrow \text{-}3.83\,\text{dB}$$

$$\text{Measured values}: \text{min.} = 4144\ \text{W}, \text{max.} = 6166\ \text{W}$$

As we might expect due to the worse directivity, the measurement error is relatively large. Instead of the correct value of 5105 W, a value between 4144 W and 6166 W can be displayed.

If we use the directional coupler from Example 2 to measure a small reflection value like in Example 1 (–26 dB), a value between a minimum of 2.14 W and a maximum of 73.11 W can be displayed instead of the correct value of 12.6 W.

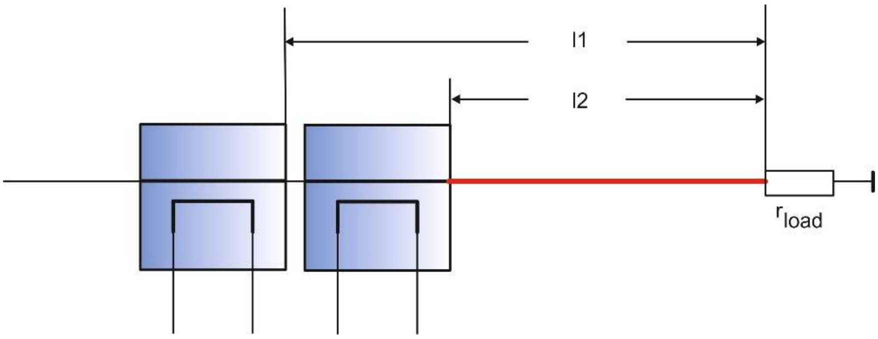
Since the phase angle to the DUT has different values at different frequencies, the displayed result will also vary as a function of the frequency.

2.2.3 Example 3: Two identical directional couplers in series at the output of an amplifier system

We will now discuss a further practical example which illustrates the dependency of the measurement result on the distance between the directional coupler and the DUT/load.

At the output of our amplifier system, two identical directional couplers are connected in series (Figs. 6 and 10) due to the need for multiple power samples for different test instruments or for monitoring applications.

Since the directional couplers each have a different phase angle to the DUT, they will display different measured values.



$$\overrightarrow{r}_{r1} = \overrightarrow{r}_{d} + \left|\overrightarrow{r}_{load}\right| e^{-j2\beta l1} \qquad \overrightarrow{r}_{r2} = \overrightarrow{r}_{d} + \left|\overrightarrow{r}_{load}\right| e^{-j2\beta l2}$$

Fig. 6: Divergent measured values due to different phase angles to the DUT.

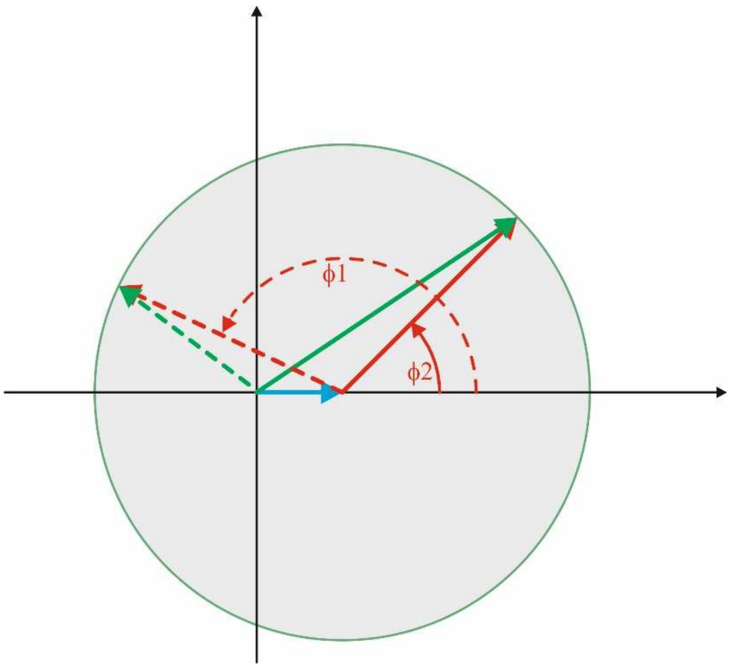


Fig. 7: Vector display of the measurement uncertainty for Fig. 6.

As seen in Fig. 7, different measured values (green vectors) are obtained due to the finite directivity and the different phase angle (distance to DUT, blue vector) despite the fact that the reflected wave (red vector) has the same magnitude at both directional couplers.

The following example illustrates this problem:

For the two directional couplers connected in series, the (mechanical) distance between the two reflection ports is assumed to equal 375 mm. If we now compare a measurement at 200 MHz on the two reflection ports, we obtain the following phase difference for the reflected wave:

$$\Delta\Phi = \frac{2\pi}{\lambda} 2 * \Delta l \qquad \lambda/m = \frac{300}{f/\text{MHz}} = 1.5m$$

$$\Delta\Phi = \frac{2\pi}{1.5} 2 * 0.375 = \pi \quad \text{or } 180°$$

We expect to find the maximum deviation between the two measured values here since the reflected waves are out of phase on the two reflection ports.

If we now compare a second measurement at 100 kHz, we obtain the following phase difference on the reflection ports:

$$\Delta\Phi = \frac{2\pi}{\lambda} 2 * \Delta l \qquad \lambda/m = \frac{300}{f/\text{MHz}} = 3000m$$

$$\Delta\Phi = \frac{2\pi}{3000} 2 * 0.375 = 0.00157 \quad \text{or } 0.09°$$

The measured values at the two reflection ports should not exhibit any significant deviation since the phase difference is only 0.09° (Fig. 7).

This example makes it clear just how much the test setup can impact the measurement result.

2.2.4 Example 4: Measurement uncertainty for different VSWR values and directivities in a measuring system

Figs. 8 and 9 below represent a typical case for EMC applications. The expected range of values is shown for a reflection measurement with antenna system matching as follows:

VSWR = 6 and 1 kW forward power (Fig. 8)
VSWR = 10 and 1 kW forward power (Fig. 9)

As we can see in Figs. 8 and 9, the results vary widely as a function of the directivity and VSWR.

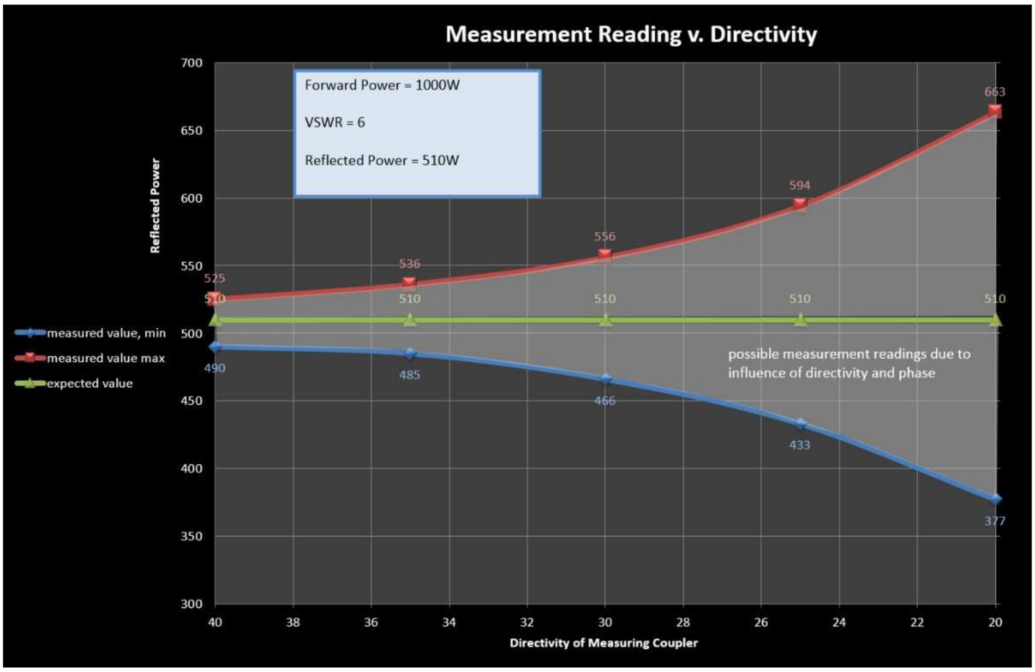


Fig. 8: Range of measured values for a reflection measurement with finite directivity, VSWR = 6 and 1 kW forward power.

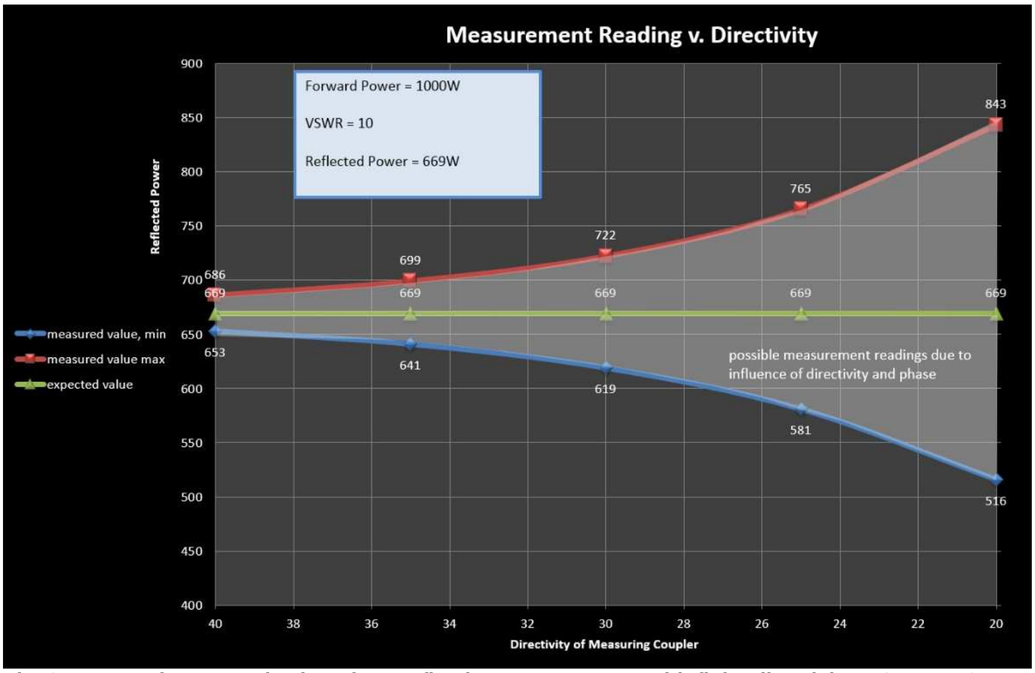


Fig. 9: Range of measured values for a reflection measurement with finite directivity, VSWR = 10 and 1 kW forward power.

2.3 Rohde & Schwarz directional coupler systems

2.3.1 Example for broadcast transmitters

Fig. 10: Directional coupler with two measuring systems and air line connection.

R&S®GD998 - 26 kW UHF directional coupler, frequency range 470 MHz to 862 MHz

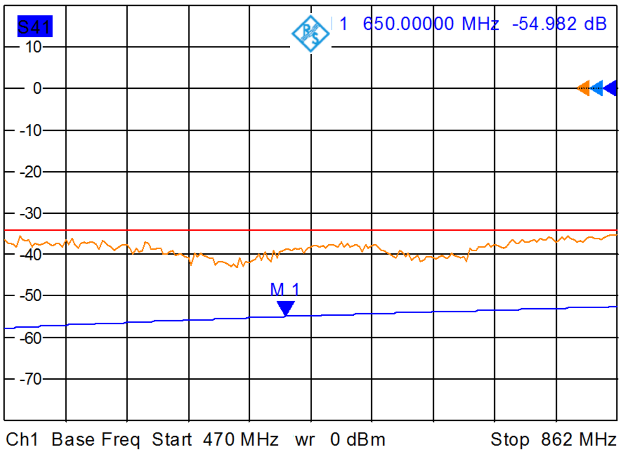


Fig. 11: Coupling attenuation –55 dB (blue), directivity < –34 dB (orange).

R&S®GD998 - 42 kW VHF directional coupler, frequency range 170 MHz to 254 MHz

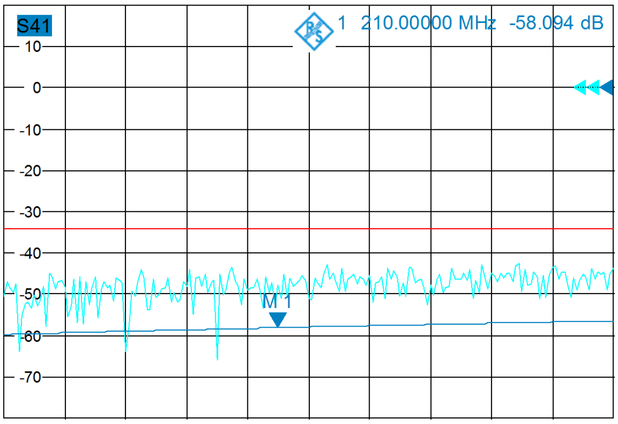


Fig. 12: Coupling attenuation –58 dB (blue), directivity < –40 dB (light blue).

2.3.2 Example for EMC systems

10 kW directional coupler, frequency range 9 kHz to 250 MHz

Fig. 13: Broadband directional coupler, 9 kHz to 250 MHz.

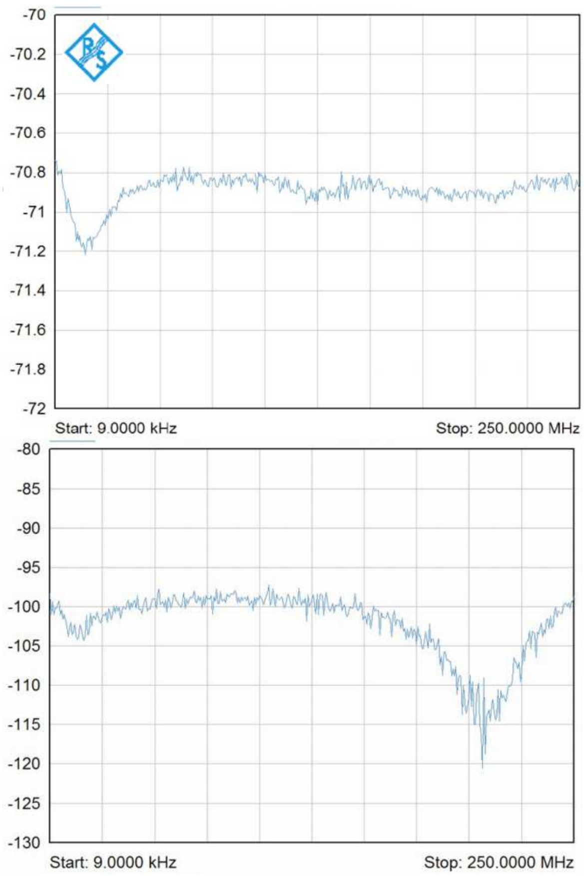


Fig. 14: Coupling attenuation approx. –71 dB and isolation < –98 dB (→ directivity < –27 dB).

1 kW directional coupler, frequency range 80 MHz to 1 GHz

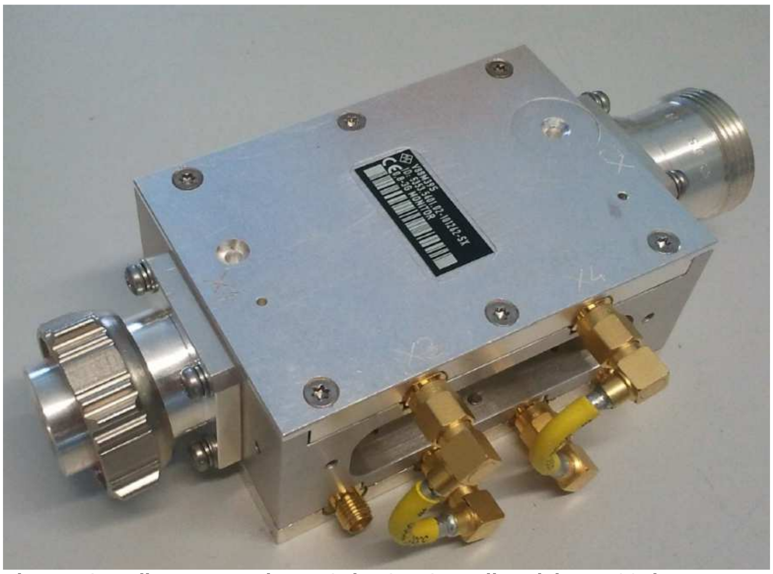


Fig. 15: Coupling attenuation –58 dB @ 1 GHz, directivity < –26 dB.

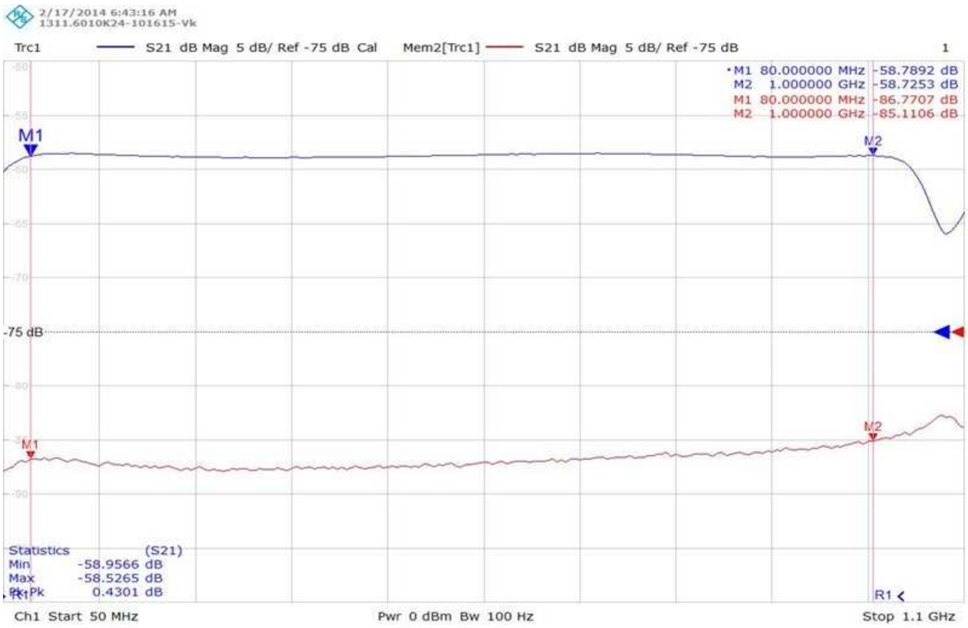


Fig. 16: Coupling attenuation (blue) approx. –58.7 dB and isolation (red) < –85 dB (→directivity < –26.3 dB).

3 Formulas

Reflection coefficient to VSWR	$s = \frac{1+\lvert r \rvert}{1-\lvert r \rvert} \qquad r \in [-1;1] \qquad s \in [1;\infty]$
VSWR to reflection coefficient	$\lvert r \rvert = \frac{s-1}{s+1} \qquad r \in [-1;1] \qquad s \in [1;\infty]$
Reflection coefficient in dB	$a/dB = 20\log\lvert r \rvert$

4 Summary

This White Paper examined the physical factors that can influence measurements of the reflected power in an amplifier system.

The test setup plays a major role when determining the reflected power.

The directional coupler's directivity can be used to estimate the expected error when measuring the reflected power. As the magnitude of the directivity decreases, we are able to make more accurate measurements of the power reflected by a DUT.

Since the reflected wave and the finite directivity represent two different vectors, they are added vectorially in the directional coupler's reflection port (Figs. 5 and 7). Accordingly, the measured value is highly dependent on the phase angle between the directional coupler and the DUT.

The phase angle is determined by the distance between the directional coupler and the DUT as well as by the frequency.

This means that when using directional couplers with finite directivity, each reflected power measurement must be reevaluated in terms of the distance to the DUT as well as the frequency.

This applies especially to test setups with several identical directional couplers connected in series to increase the number of measurement samples available for different test instruments.

As we have discussed, reflected power measurements on a DUT with a constant VSWR should not be expected to produce a constant value on the directional coupler at different frequencies. Instead, the results will fall somewhere in a tolerance band, as illustrated in Figs. 8 and 9.

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