Basic RF Technic and Laboratory Manual

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April 2002
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Part I

Experiment-7 Directional Coupler
Chapter 1
INTRODUCTION

1.1 Prelab Exercise
1. Suppose you make a measurement with dual directional coupler terminated with
a short, the coupler has the following parameters
coupling-20dB, directivity 30dB, Pin = 1mw incident on port 1. Calculate
(dBm) the power at ports 2, 3, and 4.( refer to Fig-1)

1.2 Directional Coupler
A directional coupler is a four-port network in which portions of the forward and
reverse traveling waves on a line are separately coupled to two of the ports.’ As a
result, it finds extensive use in systems that require the measurement of amplitude
and phase for a traveling wave. In its most common form, the directional coupler
consists of two transmission lines and a mechanism for coupling signals between them.
Its properties may be summarized with the aid of the schematic diagram in Fig.-1
With matched terminations on the output ports,
1. A portion of the wave traveling from port 1 (input) to port 4 (output) is
coupled to port 3 (forward coupled), but not to port 2.
2. A portion of the re
fl
ected wave traveling from port 4 to port 1 is coupled
to port 2, but not port 3.
3. A portion of the wave incident on port 2 to port 3 is coupled to port 4, but
not port 1; and a portion of the wave incident on port 3 is coupled to port 1, but not
port 4.

The performance of a directional coupler is usually described in terms of its
coupling and directivity, which are defined in the following manner.

Coupling - coupling Factor or coupling (C) is defined as the ratio, expressed
in decibels, of the power (incident) at input of the main line to the power coupled
at the output in the auxiliary arm.Thus, coupling is a measure of how much of the
incident power is being sampled.

\[
\text{Coupling (dB)} = 10 \log \frac{P_{inc}}{P_{cp}}
\]

Directivity(dB) = 10log \frac{P_{cp}}{P_{dir}} = 10log K_d
where $p_{inc}$ is the incident power at the input port, $p_{cp}$ is the coupled power,

**Directivity** - Directivity of a directional coupler is defined as the ratio, expressed in decibels, of the power output in the coupled auxiliary arm to the power flowing in uncoupled auxiliary arm. Theoretically, D should be infinite because no power should couple in arm 4 and $p_{dir}$ is the power out of the decoupled port. Note that the directivity factor $K_d$ and $K_c$ are greater than unity. While directivity is a measure of how well the coupler distinguishes between forward and reverse traveling waves. For an ideal directional coupler, $p_{dir} = 0$ and therefore the directivity is infinite. Most applications require directivity values in excess of 30 dB.

### 1.2.1 Application

Some typical applications using directional couplers would be as follows:

1. Directional couplers are used to accurately sample the directional power flow in transmission line. In conjunction with a power meter, an accurate, continuous measurement of power flow can be obtained.

2. Power leveling can be performed when the output of a directional coupler is used in conjunction with a controlled attenuator as a part of a leveling loop.

3. Frequency measurement can be made on continuous basis, when the coupled sample is fed to a suitable frequency counter.

4. Frequency stabilization can be obtained when the coupler output is used as the input to an AFC (automatic frequency control) loop.

5. Continuous power reflection measurements say from an antenna, can be made using couplers as reflectometers.

6. Signal injection can be obtained by inserting the coupler in the line, and feeding the directional signal to be inserted in the system to the coupled output port.
1.3 Main Parameter Definitions

1.3.1 Nominal Coupling & Variation

The ratio, in dB, that the coupled output port is sampled from the input port when all ports are terminated in reflectionless terminations. The nominal coupling is specified as the algebraic average of the maximum and the minimum coupling within the frequency band. The coupling variation specified as The peak to peak deviation, in dB, from the nominal coupling, over the specified frequency range.

1.3.2 Insertion Loss

The net unrecoverable power in dB dissipated within the circuit at any frequency within the specified range.

1.3.3 Directivity

This is a measure of the directionality of the coupler and it is measured as the ratio in dB between the power level at the coupled output when the coupler is fed from the input port and when fed arm the output port, with all ports terminated in reflectionless loads.

1.3.4 SWR

Main Line SWR:- The main line SWR is the standing wave ratio measured looking into the main line input terminals when matched loads are placed at all the other terminals. The main line SWR will remain constant for any orientation of the coupler in the transmission line. The standing wave ratio specified for either the main line path (input to output) and/or the coupled output port(s).

Auxiliary Line SWR: The auxiliary line SWR is the standing wave ratio measured in the auxiliary line looking into the output terminal to which the detector is normally connected when matched loads are placed at all the other ports or terminals.

1.3.5 Average Power Handling

The average CW power handling capability is based on one way transmission through the device under matched load conditions.

1.4 Power Flow Measurement.

Directional couplers are used to accurately sample the directional power flow in a transmission line.

A directional coupler is capable of separately sampling the forward and reverse waves on a transmission line.

The power flow Measurement described at Fig.-2, wherein the power meter at port 3 samples a portion of the transmitter power. The transmitter and the main load, in this case a radiating antenna, are connected to ports 1 and 4, respectively. The coupling factor is chosen so that nearly all the transmitter power is delivered to the antenna port. Typical values of the coupling factor are in the 20 to 50 dB range depend on the transmitter power. For example, a 20 dB coupler samples only
1 percent of the forward power and therefore 99 percent appears at the antenna port. With a perfectly matched load at port 2 and infinite coupler directivity, the meter reading is independent of antenna reflections when $Z_{trans.} = Z_0$. Even shorting the antenna port has no effect on the reading of the power meter, since any reflection at port 4 is absorbed by the internal impedance of the transmitter and the matched load at port 2.

**Ideal Directional Coupler**—Refer to Fig-3 in the ideal case of infinite directivity and $\Gamma_2 = 0$. The coupled signal $b_3 = S_{31}a_1$ where $S_{31}$ define the coupling coefficient associated with transmission from port -1 to port -3. The part of the incident signal reflected at the antenna is $a_4 = \Gamma_4a_4$. A portion of $a_4$ is coupled to port -2 therefore $b_2 = a_4S_{24} = \Gamma_4b_4S_{24}$. We assume $\Gamma_2 = 0$ therefore this wave completely absorb at port-2, and thus

$$P_2 = b_2^2 = |\Gamma_4|^2 |S_{24}|^2 b_4^2 = \frac{|\Gamma_4|^2}{K_c}b_4^2$$

where $K_c = |S_{24}|^{-2} = |S_{31}|^{-2}$ is the coupling factor. For loose coupling ($K_c > 20dB$), $b_4 \approx a_1$ and therefore

$$P_2 \approx P_{trans.}\frac{|\Gamma_4|^2}{K_c}$$

where $p_{trans.} = a_1^2$. With the above assumption (reflectionless directional coupler and infinite directivity), the only signal arriving at port 3 is $S_{31}a_1$, and thus the power delivered to the matched power meter is

$$P_3 = |S_{31}|^2 a_4^2 = \frac{P_{trans.}}{K_c}$$
For the situation described here, the power meter reading is independent of the antenna reflection coefficient and is directly proportional to the transmitted power. Thus, if the coupling factor is exactly known and the meter is accurate, $p_{\text{trans}}$ may be determined accurately from the power meter reading.

**Non Ideal Directional Coupler**—Let us next consider the case where $\Gamma_2 > 0$, and finite directivity. Referring to Fig-3 with $a_3 = 0$, the output wave at port 3 is given by

$$b_3 = S_{31}a_1 + S_{34}\Gamma_4 b_4 + S_{32}\Gamma_2 S_{21}a_1 + S_{32}\Gamma_2 S_{24}\Gamma_4 b_4$$

(1.1)

The first term of equation-1 is the coupled signal between ports 1 and 3. The second and third terms is the directivity errors between ports 4 and 3 and between 1 and 2. The fourth term is the reflected wave coupled to port-2 and rereflected to port-3.

For loose coupling we assume that $b_4 \approx a_1 = \sqrt{P_{\text{trans}}}$ and low losses device therefore $|S_{32}| = |S_{41}| \approx 1$ Thus

$$b_3 = \sqrt{\frac{P_{\text{trans}}}{K_c}} \left[ 1 \angle \phi_1 \pm \frac{|\Gamma_4|}{\sqrt{K_d}} \angle \phi_2 + \frac{|\Gamma_2|}{\sqrt{K_d}} \angle \phi_3 + |\Gamma_4| \angle \phi_4 \right]$$

where $\phi_1$ to $\phi_4$ represent the phase of the individual waves arriving at port 3. Note that $|S_{21}| = |S_{34}| = \sqrt{K_d K_c}$

In most cases, only the magnitude of the reflection and scattering coefficients
are known. This means that only the extreme values of can be determined.

\[
\begin{align*}
P_{3_{\max}} &= \frac{P_{\text{trans}}}{K_c} \left[ 1 + \left( \frac{|\Gamma_2| + |\Gamma_4|}{\sqrt{K_d}} + |\Gamma_2||\Gamma_4| \right) \right]^2 \\
P_{3_{\min}} &= \frac{P_{\text{trans}}}{K_c} \left[ 1 - \left( \frac{|\Gamma_2| + |\Gamma_4|}{\sqrt{K_d}} + |\Gamma_2||\Gamma_4| \right) \right]^2
\end{align*}
\]

(1.2)

(1.3)

where it has been assumed that the first term (the direct coupled wave) is much greater than the others. The plus sign of the symbol is for the case when all the waves arrive at port 3 in phase, while the minus sign represents the case when \( \phi_2, \phi_3 \) and \( \phi_4 \) are 180° out-of-phase with respect to \( \phi_1 \).

Under ideal conditions, the value of transmitter power (\( P_{\text{trans.}} \)) would be determined by merely multiplying the meter reading at port 3 (\( P_3 \)) by the coupling factor (\( K_c \)). Equation -1 shows that such a calculation is in error when the directivity is finite and/or \( |\Gamma_2| \), is non-zero.

By reasoning similar to that used to obtain Eq.-1, the maximum and minimum values of power delivered to port 2 can also be obtained. With \( |\Gamma_2| = 0 \)

\[
p_2 = \frac{P_{\text{trans}}}{K_c} \left[ |\Gamma_4| \pm \frac{1}{\sqrt{K_d}} \right]^2
\]

(1.4)

1.5 Coupler as Reflectometer

Another useful application of the directional coupler involves measuring the reflection coefficient magnitude (and hence SWR) of an unknown Device under Test (DUT) impedance. Refer to Fig-4 the signal source is connected to port 1 and the DUT to port 4. Detectors at ports 3 and 2 sample the forward and reflected waves, respectively. The ratio power meter takes the square root of \( V_r/V_f \) and displays it. The display ranges from zero to unity since it

Directional coupler as reflectometer represents the reflection coefficient magnitude of the DUT (|\( \Gamma_L \)|). The power meter reading is an accurate indication of
load reflection coefficient if the coupler has infinite directivity and the detectors are perfectly matched. As before, finite directivity produces some uncertainty in the measured value of $|\Gamma_L|$. Assuming $|\Gamma_2| = 0$ From Eqs. -1 and 2, replacing $|\Gamma_4|$ with $|\Gamma_L|$

$$P_3 = \frac{P_{\text{trans}}}{K_c} \left[ 1 \pm \frac{|\Gamma_L|}{\sqrt{K_d}} \right]^2$$

$$P_2 = \frac{P_{\text{trans}} |\Gamma_L|^2}{K_c} \left[ 1 \pm \frac{1}{|\Gamma_L| \sqrt{K_d}} \right]^2$$

And the measured $|\Gamma_L| = \sqrt{P_2/P_3}$ or

$$M = |\Gamma_L| \left[ \frac{1 \pm \frac{1}{|\Gamma_L| \sqrt{K_d}}}{1 \pm \frac{|\Gamma_L|}{\sqrt{K_d}}} \right]$$

Notice that with infinite directivity $M$ is exactly equal to $|\Gamma_L|$. While the coupler has finite directivity, there will be error depending on the directivity value.
EXPERIMENT PROCEDURE

2.1 Required Equipment

1. Network Analyzer \(HP − 8714B\).
2. Signal generator \(HP − 8647A\).
3. Spectrum Analyzer \(HP − 8590E\).
4. Offset Termination.
5. Directional coupler.
6. Two termination-50Ω.

2.2 SWR of the Directional Coupler.

We now study the characteristics of a directional coupler. We will measure (i) main line and auxiliary line SWR as a function of frequency, (ii) coupling coefficient as a function of frequency, (iii) directivity as a function of frequency, and (iv) the main line insertion loss as a function of frequency. These parameters are defined as follows:

1. Connect the coupler to the Network Analyzer as indicated in Fig.-5.
2. Set the Network Analyzer to : Reflection measurement, frequency range 700-1000 MHz.
3. Record three graphs according to Table-1 on 3.5” floppy disk or other media, record the minimum and maximum of reflection coefficient, and SWR of the three ports (do not forget to terminate all ports during measurement).

<table>
<thead>
<tr>
<th>Port − No.</th>
<th>(\Gamma) (min, max)</th>
<th>SWR (min, max)</th>
<th>SWR (data sheet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port − 1 (S_{11})</td>
<td>1.12</td>
<td></td>
<td>1.12</td>
</tr>
<tr>
<td>Port − 3 (S_{33})</td>
<td></td>
<td></td>
<td>1.12</td>
</tr>
<tr>
<td>Port − 4 (S_{44})</td>
<td></td>
<td></td>
<td>1.12</td>
</tr>
</tbody>
</table>

Table-1

2.3 Nominal Coupling & Variation

1. Perform a Normalization Calibration according to Appendix-1 to eliminate the cables response while you make a transmission measurement.
2. Connect the coupler to the Network Analyzer as indicated in Fig.-2.
3. Set the Network Analyzer to : Transmission measurement, frequency range 700-1000 MHz.

4. Measure the coupling of Directional Coupler store the Data on 3.5” floppy disk, compare your results to manufacturer data sheet
   Min coupling_____dB, Max. coupling______, manufacturer data sheet 20±0.3 dB.

2.4 Directivity

1. Connect the coupler to the Network Analyzer as indicated in Fig.-2. Exchange the input output ports (connect the Network Analyzer to port-4).

2. Set the Network Analyzer to : Transmission measurement, frequency range 700-1000 MHz.

2. Measure the signal at port-3 $S_{34}$ of Directional Coupler store the Data on magnetic media, for further analysis.

2.5 Power Flow Measurement

In this part of the experiment the source of the Network Analyzer will simulate the transmitter, the receiver of the network analyzer will simulate the power meter, 50Ω termination will simulate perfect matched antenna, and short will be worst case matching.

1. Verify that the coupler is connected to the Network Analyzer as indicated in Fig.-2.

2. Note that the M indicator disappears (normalization is turned off). Otherwise press [Display] Data to eliminate the M indicator.

2. Change the power of the source of Network Analyzer to 5 dBm.
3. Measure the power at the coupled port by pressing $\text{Measure} \rightarrow \text{More}$ and Power.

4. Save your results on magnetic media, for further analysis.

5. Change the 50Ω termination with short and measure the power flow, and save your results on magnetic media, for further analysis.

### 2.6 Coupler as Reflectometer

In this part of the experiment you will measure SWR of unknown load at discrete frequency.

1. Connect the system as indicated in Fig-3.
2. Set the Signal generator to 500 MHz, Amplitude 0 dBm.
3. Set the spectrum analyzer to 500 MHz and span to 1 MHz.
4. Measure incident power, exchange between the output and input of the coupler and fill the following table.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>$P_{\text{incident}}(\text{dBm})$</th>
<th>$P_{\text{REFLECTED}}(\text{dBm})$</th>
<th>SWR(calculated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table-2

### 2.7 Final Report

1. Referring to the stored data plot three graphs of SWR as a function of frequency, find the point of maximum and minimum SWR according to Table-1.

2. Referring to the stored data plot a graph of Coupling as a function of frequency, find the point of maximum and minimum coupling, according to table-2.

3. Plot a graph of Directivity as a function of frequency, find the point of maximum and minimum directivity, compare your results to the Data Sheet of the
coupler (25 dB). According to the graphs, what is the best frequency to use the coupler,

4. Plot two graphs of calculated power flow measurement, one with perfect match antenna, and the other with shorted line,

5. Calculate SWR according to table-2.

2.8 Appendix-1

2.8.1 Normalization Calibration for Transmission Measurement

Normalization is the simplest type of calibration. The analyzer stores data into memory and divides measurements by the stored data to remove frequency response errors.

1. Setup the analyzer for your Transmission Measurement.

2. Connect the system as indicated in Fig-2, but disconnect the Directional Coupler.


4. Notice that the top of the display on the analyzer now shows the type of measurement followed by "/M" to indicate that the displayed data is actually the measurement divided by memory.

5. Be sure to turn off normalization, at the end of measurement, by pressing Display Data. Note that the M indicator disappears when normalization is turned off.

Caution

The normalization Cal will be invalidated if any frequency settings are changed after calibration. There is no correction interpolation with a normalization Cal..