Basic RF Technic and Laboratory Manual - Attenuators.

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CONTENTS

PRELAB EXERCISE

1. Define the following terms: Attenuator, ABCD Matrix, Attenuation Range, Attenuation Accuracy and Attenuation Flatness.

2. Design an attenuator (5dB, 8dB, 10dB or 15dB), assume T type attenuator. Find the values of the resistors R_1 and $R_{2.}$

Choose the resistors (should be close to your calculated values) from the existing stock: 1Ω, 10Ω, 15Ω, 20Ω, 22Ω, 27Ω, 33Ω, 47Ω,51Ω, 55Ω, 62Ω, 82Ω or 91Ω and calculate Z_{in}, Γ_{in}, SWR and attenuation (dB) for the chosen resistors.

3. Calculate the width of the microstrip line that you need for 50Ω characteristic impedance of the line, assume that thickness of the FR4 printed circuit board is 1.6 mm and the its dielecric constant is 4.5.

1. BACKGROUND THEORY

The ability to control the amplitude and phase of a signal is a primary requirement in microwave design. Attenuators are used to decrease the power level of a microwave signal without appreciably distorting its waveform. Highly precise versions are utilized in the accurate measurement of power and insertion loss.

In general, Attenuators can be classified as a dissipative network. Attenuators are available with either fixed or variable values of attenuation. Some of these are demonstrate in this experiment.

All kind of attenuators (fixed, step, continuously variable, voltage controlled and digitally controlled) are used in a wide variety of applications, such as:

* Reducing signal levels.
* Matching impedances of sources and loads.
* Measuring gain or loss of a two-ports device.

1.1 Coaxial Attenuators - Fixed T and π Attenuators

Fixed T attenuator is consist of coaxial transmission lines, which have lossy material on a disk extending from the center to the outer conductor and along the center conductor (see Figure 1). This lossy material forms a resistive T, which absorbs some of the microwave power without reflecting any of it.

Coaxial attenuators cover the frequency range from D.C. up to about 50 GHz, and they can have any value of attenuation. Typical values are 3, 6, 10, and 20 dB. Figure 1 shows a T type fixed attenuator with N type connectors.

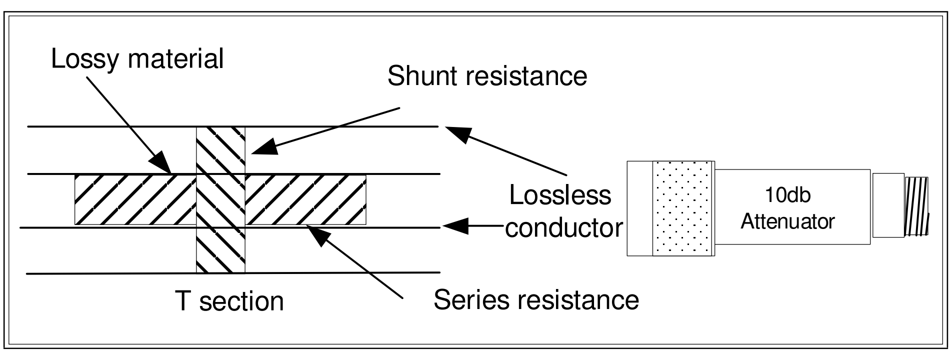

Figure 1 - T Attenuator.

The basic attenuator network is a symmetrical resistive T or π. The series and shunt resistor values R_1 and R$_2$ are chosen so that when the attenuator is terminated in a resistance equal to the transmission-line characteristic impedance, Z$_0$, the input is matched, that is, Z$_{in}$= Z$_0$.

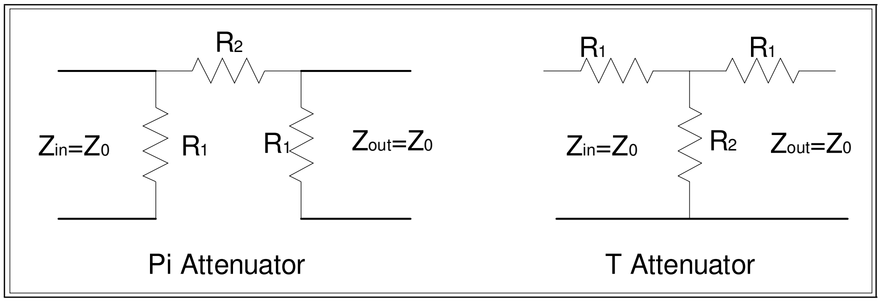

Figure 2 - Equivalent circuits of π and T Attenuators.

1.2 Attenuator as a Two Port Network

Attenuator is a two port device (refer to Figure 3), without Z$_L$.

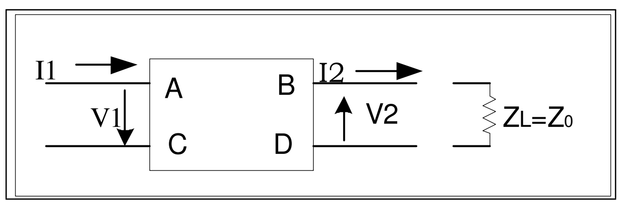

Figure 3 - Attenuator as two port network.

Where:

$$\begin{aligned} V_1 &= AV_2 + BI_2 \\ I_1 &= CV_2 + DI_2 \end{aligned} \quad (1.1)$$

Or in a matrix form:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

Where A and D are dimensionless quantities, B and D represent the impedance and admittance respectively. If we add termination ($Z_L = Z_0$), equation 1 becomes:

$$\begin{aligned} V_1 &= AZ_0I_2 + BI_2 = I_2 (AZ_0 + B) \\ I_1 &= CZ_0I_2 + DI_2 = I_2 (CZ_0 + D) \end{aligned}$$

Or:

$$Z_{in} = \frac{V_1}{I_1} = \frac{AZ_0 + B}{CZ_0 + D} \tag{1.2}$$

The reflection coefficient is equal to:

$$\Gamma_{in} = \left| \frac{Z_L - Z_{in}}{Z_L + Z_{in}} \right| = \left| \frac{Z_0 - \frac{AZ_0+B}{CZ_0+D}}{Z_0 + \frac{AZ_0+B}{CZ_0+D}} \right| = \frac{A + \frac{B}{Z_0} - CZ_0 - D}{A + \frac{B}{Z_0} + CZ_0 + D} \tag{1.3}$$

Electronic circuits may consist of more than one element, the overall ABCD matrix elements for cascade could be obtained by multiplying individual ABCD matrices. For example, if we need to design a π attenuator which consists of three elements, (see Figure 2) we have to multiply three matrices of a single element. The ABCD matrix of series and shunt elements is shown in Figure 4.

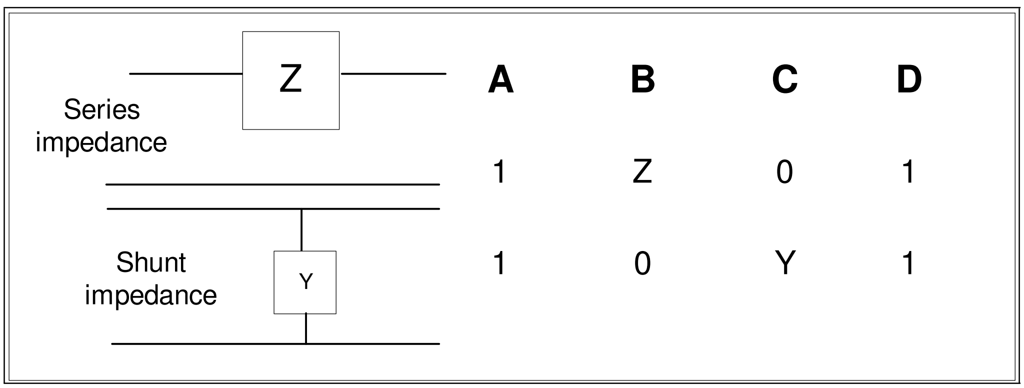

Figure 4 - ABCD matrix elements of series and shunt impedance.

Therefore, the ABCD matrix of a π Attenuator is:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{R_1} & 1 \end{bmatrix} \begin{bmatrix} 1 & R_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{R_1} & 1 \end{bmatrix} = \begin{bmatrix} \frac{R_2+R_1}{R_1} & R_2 \\ \frac{2R_1+R_2}{R_1^2} & \frac{R_2+R_1}{R_1} \end{bmatrix}$$

Ideal attenuator has no reflection, therefore $\Gamma_{in} = 0$, thus equation 3 becomes:

$$A + \frac{B}{Z_0} = CZ_0 + D$$

Which means:

$$\frac{R_2 + R_1}{R_1} + \frac{R_2}{Z_0} = \frac{2R_1 + R_2}{R_1^2} Z_0 + \frac{R_2 + R_1}{R_1}$$

Or

$$R_2 = 2R_1 \frac{Z_0^2}{R_1^2 - Z_0^2}$$

The attenuation $L(dB)$ is defined as:

$$
\begin{aligned}
L &= 10\log\left[CZ_0+D\right]^2 = 20\log\left[\frac{R_2+R_1}{R_1}+\frac{R_2}{Z_0}\right] \\
&= 20\log\left[\frac{2R_1\frac{Z_0^2}{R_1^2-Z_0^2}+R_1}{R_1}+\frac{2R_1\frac{Z_0^2}{R_1^2-Z_0^2}}{Z_0}\right]
\end{aligned}
$$

Or

$$
L = 20\log\frac{Z_0+R_1}{R_1-Z_0} \qquad (1.4)
$$

Figure 5 Shows the value of a shunt resistor R_1 and a series resistor R_2 as a function of attenuation required.

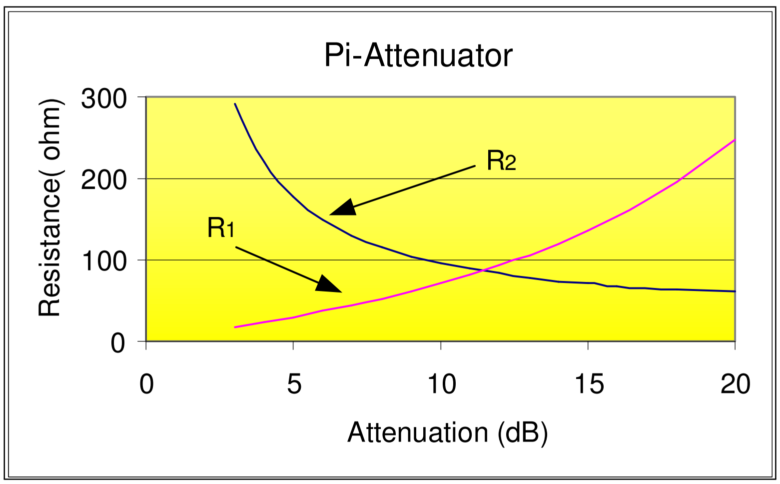

Figure 5 - Value of series R_1 and shunt resistor of R_2 of π attenuator.

1.2.1 T Attenuator

In a similar way, we can determine the value of a series resistor R_1 and a shunt resistor R_2 of a T Attenuator as:

$$
R_2 = -\frac{1}{2}\frac{R_1^2-Z_0^2}{R_1}
$$

And the attenuation as:

$$
L(dB) = 20\log\left[-\frac{Z_0+R_1}{R_1-Z_0}\right]
$$

1.3 Real Resistor

All circuit components, active or passive, are neither purely resistive nor purely reactive, but rather a combination of these impedance elements. The result, as noted, is that all real-word devices have parasitic unwanted inductance in resistor, unwanted capacitance in inductors, etc. Of course, different materials and manufacturing technologies produce varying amounts of parasitics, affecting both a component's usefulness and the accuracy in which you can determine its resistance.

All materials exhibit resistance, except for a few (termed superconductors) whose resistance becomes essentially zero when they are cooled to near absolute zero. An ordinary conductor's resistance is a function of many factors, including material dimension, temperature, current and current frequency. Most common resistor for high frequency are: film types resistors, generally formed by sputtering, sintering or evaporating films of carbon, metals or oxides onto a form. A typical equivalent circuit of a resistor accepted for high frequencies is shown in Figure 6.

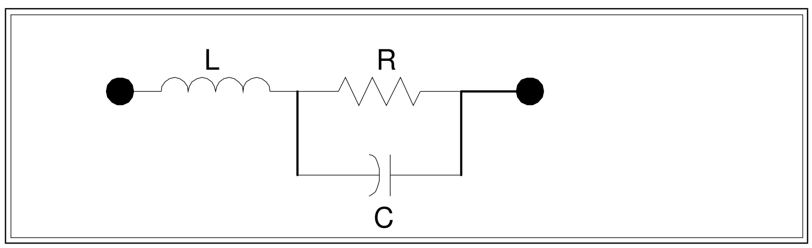

Figure 6 - Equivalent circuit of a resistor at high frequency.

According to this model the equivalent impedance is:

$$Z = jwl + \frac{\frac{R}{jwc}}{R + \frac{1}{jwc}} = \frac{R}{R^2w^2c^2 + 1} + jw\frac{R^2c^2w^2l - R^2c + l}{R^2w^2c^2 + 1} \qquad (1.5)$$

From this model we can observe that both the real and imaginary parts of the impedance are frequency depended. The real part of the impedance is known as the 'Effective Series Resistance' (ESR).

1.4 Microstrip Transmission Line

Microstrip line is one of popular types of planar transmission lines, primarily because simple printed board processes can fabricate it. A conductor of width w

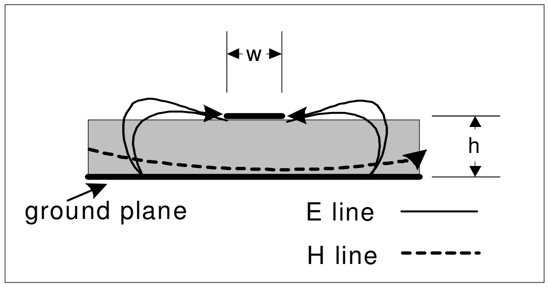

Figure 1-1 Figure 7 - Microstrip Transmission Line Structure.

is printed on a thin, dielectric substrate of thickness h and relative permittivity ϵ_R a sketch of the field lines is shown in Figure 7..

If the dielectric substate was not presented, we could think of the microstrip line as a two-parallel flat strip conductors of width w, separated by a distance of 2h (the ground plane can be replaced by an image line). In this case we would have a simple TEM transmission line, without any substate, therefore $\upsilon_p = c$. The presence of the dielectric substate, and particularly the fact that the electromagnetic wave incident via dielectric and air region above the strip complicates the behavior and analysis of a microstrip line. For this reason, the waves travling in the microstrip line cannot be analyzed as pure TEM waves, and the phase velocity in it becomes:

$$\upsilon_p = \frac{c}{\sqrt{\epsilon_e}} \tag{1.6}$$

Where ϵ_e is the effective dielectric constant of the microstip line and is given aproximately by:

$$\epsilon_e = \frac{\epsilon_R + 1}{2} + \frac{\epsilon_R - 1}{2} \frac{1}{\sqrt{1 + 12\frac{h}{w}}} \tag{1.7}$$

For a given microstrip srructure, the characteristic impedance is defined as:

$$\begin{aligned} Z_0 &= \frac{60}{\sqrt{\epsilon_e}} \ln\left(\frac{8h}{w} + \frac{w}{4h}\right) \qquad \frac{w}{h} \leq 1 \\ Z_0 &= \frac{120\pi}{\sqrt{\epsilon_e}} \left[\frac{w}{h} + 1.393 + 0.667 \ln\left(\frac{w}{h} + 1.444\right)\right] \qquad \frac{w}{h} > 1 \end{aligned} \tag{1.8}$$

For a given characteristic impedance Z_0 and a given dielectric constant ϵ_r ($\epsilon_r \approx$4.5 for FR4), we get:

$$\begin{aligned} \frac{w}{h} &= \frac{8e^A}{e^{2A} - 2} \qquad \frac{w}{h} < 2 \\ \frac{w}{h} &= \frac{2}{\pi}\left[B - 1 - \log_e(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r}\left\{\log_e(2B - 1) + 0.39 - \frac{0.61}{\epsilon_r}\right\}\right] \qquad \frac{w}{h} > 2 \end{aligned} \tag{1.9}$$

Where

$$A = \frac{Z_0}{60}\sqrt{\frac{\epsilon_r + 1}{2}} + \frac{\epsilon_r - 1}{\epsilon_r + 1}\left(0.23 + \frac{0.11}{\epsilon_r}\right) \quad (1.10)$$
$$B = \frac{377\pi}{2Z_0\sqrt{\epsilon_r}}$$

In our laboratory we design a 50Ω microstrip line, using Glass Epoxy (FR4) as dielectric substrate, $\epsilon_r \approx 4.5$, for this special case the impedance of the mcrostrip line, can be approsimate by Figure 8.

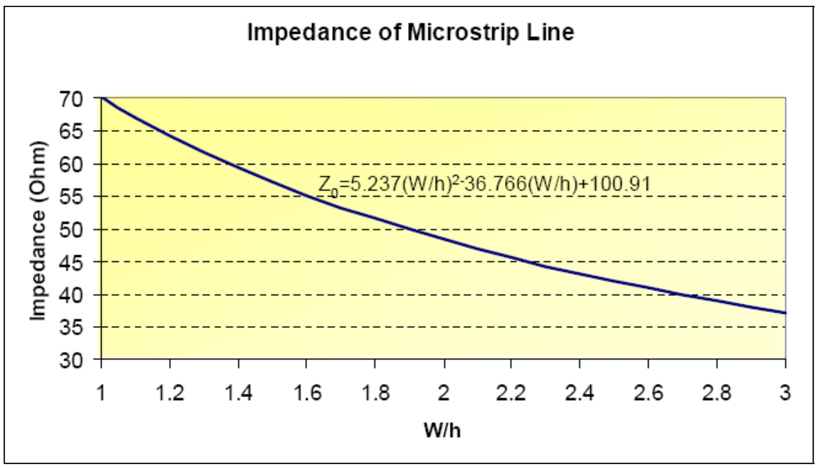

Figure 8 - Characteristic impedance of a FR4 substrate .

1.5 Attenuator Terminology

1.5.1 Attenuation Range

The minimum attenuation change obtainable by varying the manual drive in the case of a mechanically variable attenuator, or the current control in the case of a electronically controlled attenuator, from minimum to maximum setting.

1.5.2 Accuracy

The accuracy is the maximum deviation measured in dB from the displayed attenuation level.

The accuracy of an attenuator directly affects the uncertainty of the measurement, which the attenuator is used in. In many measurements and methodology applications, attenuators are the basic standard against other components and instruments are calibrated. Some manufacturers include the effect of frequency response as part of the accuracy.

1.5.3 Attenuation Flatness

The difference in dB, between minimum and maximum attenuation at a given attenuation setting, over the specified frequency range at ambient temperature, unless otherwise specified on the data sheets.

1.5.4 SWR

SWR is the Standing Wave Ratio for input and output ports. That is to say That the SWR at either port at any attenuation setting with the other port terminated in a reflection-less (i.e. perfectly matched) load. Most attenuators use some forms of distributed thin-film attenuating elements, designed to operate over multi-octave ranges and for low SWR match at input and output. The SWR characteristic is controlled with careful design of the element as well as the transition from RF connector to the element's planar geometry.

1.5.5 Insertion Loss

The loss of the attenuator when it is inserted in a transmission line with the attenuation set to the minimum attenuation position.

1.5.6 Repeatability

Repeatability is define for variable attenuators as the inherent ability to accurately return to a previously noted setting of attenuation on a repeatable basis. In a manual unit, it is a function of the mechanical drive resolution, while in an electronic model it is dependent on the current drive resolution. The typical repeatability value for a step attenuator is less then 0.1 dB maximum over 1 million cycles per section.

1.5.7 Power

The CW average handling capability through the device under matched load conditions.

1.6 Attenuator as an Impedance Matching Network.

At higher microwave frequencies, the performance of the lumped elements attenuator deteriorates quite rapidly since the size of the resistors are no longer small compared to the operating wavelength. The distributed lossy-line attenuator complements the lumped element attenuator in that it has superior performance at higher frequencies. Standard coaxial versions are available with low SWR and flat attenuation versus frequency response from DC to at least 18 GHz. One application of a matched attenuator is to reduce reflection between the source and the load, by inserting an attenuator between the load and the generator. For example, if we connect a RF generator with an internal impedance of 50Ω to a load of 100Ω, we will get:

$$\begin{aligned} \Gamma_L &= \left|\frac{100-50}{100+50}\right| = \frac{1}{3} \text{ and } SWR = \frac{1+\Gamma_L}{1-\Gamma_L} = 2 \\ RL_{load} &= 10\log\frac{1}{|\Gamma_L|^2} = 9.54\ dB \end{aligned}$$

If we add 6 dB matched attenuator between the source and the load, we will change the value of Γ by:

$$\Gamma = |\Gamma_L|\, e^{-2\alpha d}$$

Where αd is the attenuation of the line in neper, therefore

$$RL_{in} = RL_{load} + 2(8.68 * \alpha d) = 9.54 + 2 * 6 = 21.54\ dB$$

A return-loss of 21.54 dB correspond to a SWR of 1.183:1. Thus at the expense of a 6 dB power loss, the input SWR reduce from 2.0:1 to 1.183:1.

2. EXPERIMENT PROCEDURE

2.1 Required Equipment

1. Spectrum Analyzer HP-8590E or HP-8590L.
2. Network Analyzer $HP - 8714B$.
3. Fixed Attenuator.
4. Step Attenuator, JFW 50BR-008.
5. Termination - 50Ω.
6. Coaxial Cable.
7. Keysight ADS simulation software.

2.2 Attenuation

In the first part of the experiment you will use the spectrum analyzer to measure the attenuation of a fixed attenuator using the calibration signal, frequency of 300MHz (or 50MHz) and amplitude of -20dBm, of the spectrum analyzer.

1. Connect a coaxial cable between Cal. out and the input of the spectrum analyzer, as indicated in Figure 9.

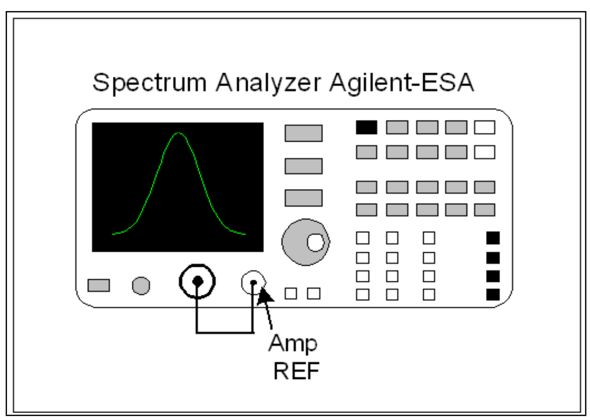

Figure 9 - Generating a calibration signal without attenuator.

2. Set the center frequency to 300MHz (or 50MHz) and the span to 5MHz.

For the spectrum analyzer with the 50MHz calibration signal, press the **Input/Output** key and activate the **Amptd Ref Out (f=50MHz)** softkey to display the calibration signal.

Save the Data on magnetic media. fill in Table-1.

Change the units of the y-axis to Watt and fill in Table-1.

3. Connect the 10 dB fix attenuator with a coaxial cable to the spectrum analyzer, as indicated in Figure 10.

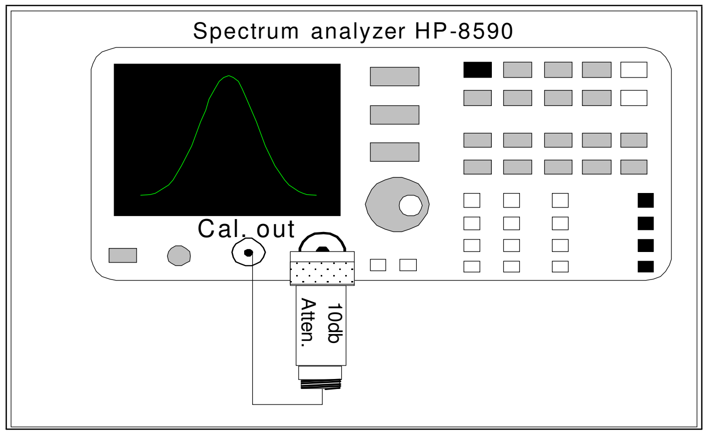

Figure 10 - Generating a calibration signal with attenuator.

Save the Data on magnetic media. Fill in Table-1.

Change the units of the y-axis to Watt and fill in Table-1.

4. Calculate the logarithmic and linear attenuation according to Table-1:

Cal. Sig. (dBm) without attenuator	Cal. Sig. (mW) without attenuator
Cal. Sig. (dBm) with attenuator	Cal. Sig. (mW) with attenuator
Log. attenuation(dB)	Lin. attenuation(K)
(calculated)	(calculated)
Table-1	

2.3 Attenuators Value and SWR

In the this part of the experiment you will use the ADS software and the network analyzer to simulate and measure the two most important characteristic of the attenuator; the attenuation value and the SWR of the attenuator.

2.3.1 Simulation

1. Simulate the system as indicated in Figure 11 (Use the length of the coaxial cable you are going to use in your measurement).

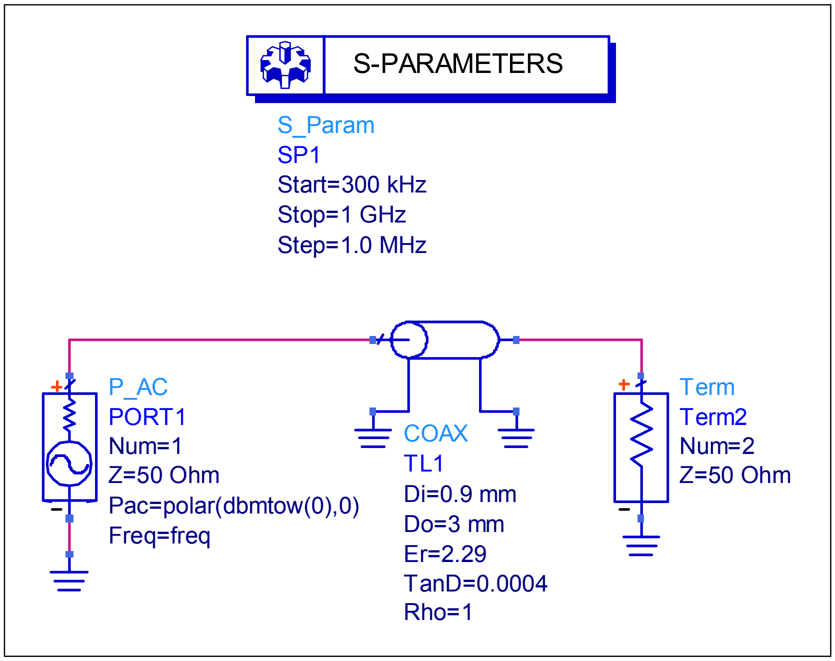

Figure 11 - Simulation without an attenuator.

2. Drew a graph of the attenuation (S21) as a function of frequency. **Save the Data on magnetic media.**
3. Add an attenuator to your simulation, as indicated in Figure 12.

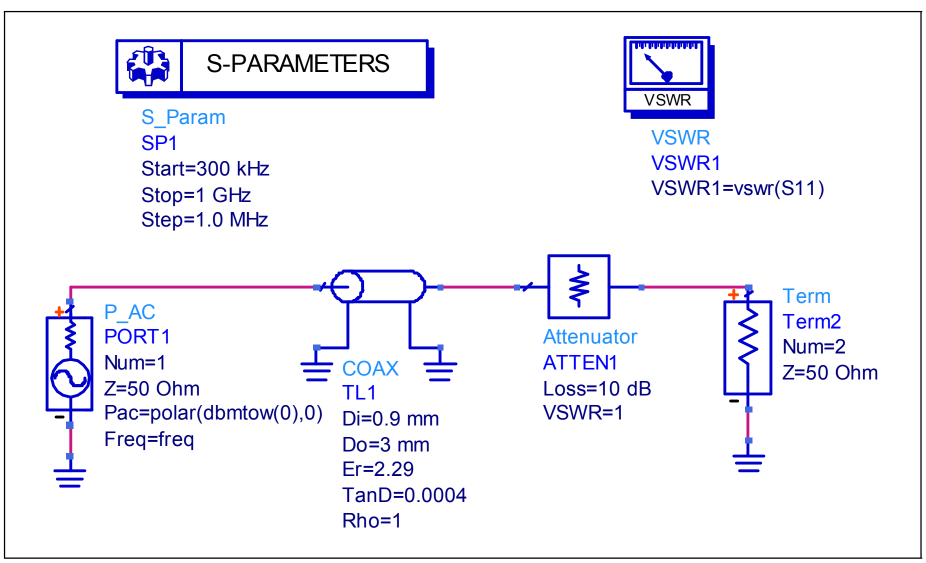

Figure 12 - Simulaion with an attenuator.

4. Drew a graph of the attenuation as a function of frequency. **Save the Data on magnetic media**.

Compare this graph to the graph from paragraph 1.

5. Create the graph of SWR as a function of frequency. **Save the Data on magnetic media**.

2.3.2 Measurament

6. Connect a coaxial cable to the network analyzer, as indicated in Figure 13.

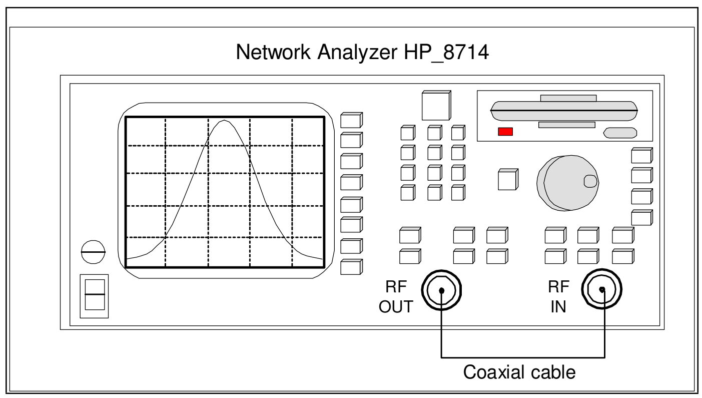

Figure 13 - Transmission measurement without an attenuator.

Set the network analyzer to Transmission measurement, frequency range 0.3-1000 MHz.

7. Measure the attenuation value as a function of frequency. **Save the Data on magnetic media**.

8. Connect the 10 dB fixed attenuator to the network analyzer using the coaxial cable.

9. Measure the attenuation value as a function of frequency. **Save the Data on magnetic media**.

10. Compare the measurement graphs of the attenuation (paragraphs 7 and 9) to the simulation graphs (paragraphs 2 and 4).

11. Set the network analyzer to Reflection measurement, make a reflection calibration and connect the 10 dB fixed attenuator to the network analyzer with a 50Ω termination, as indicated in Figure 14.

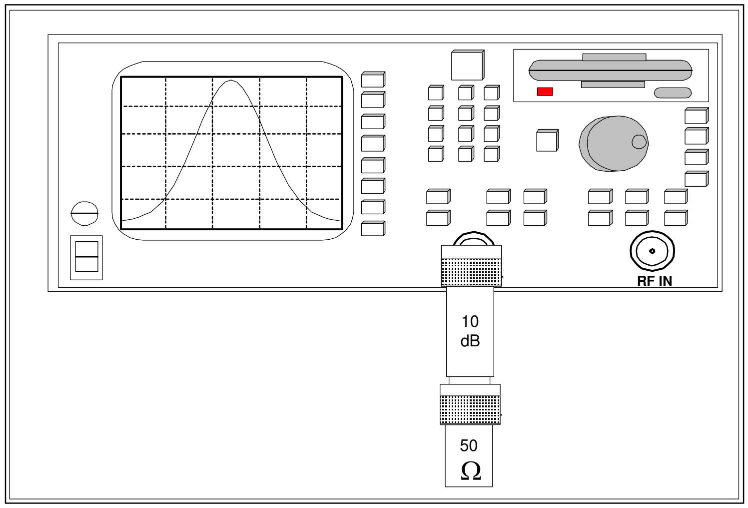

Figure 14 - Measuring the SWR of an Attenuator.

12. Measure the SWR of the input port of the attenuator, as a function of frequency. **Save the Data on magnetic media**.

13. Compare the measurement graph of the SWR (paragraph 12) to the simulation graph (paragraph 5).

14. Exchange the input and output of the attenuator and measure the SWR of the output port, as a function of frequency. **Save the Data on magnetic media**.

Compare this graph to the one from paragraph 12.

2.4 Impedance Matching using Fixed Attenuator

In this part of the experiment you will match a load with SWR of 2:1 to a 50Ω system, by adding a 10dB attenuator.

1. Connect a standard mismatch Maury-2562G directly to the network analyzer, as indicated in Figure 15.

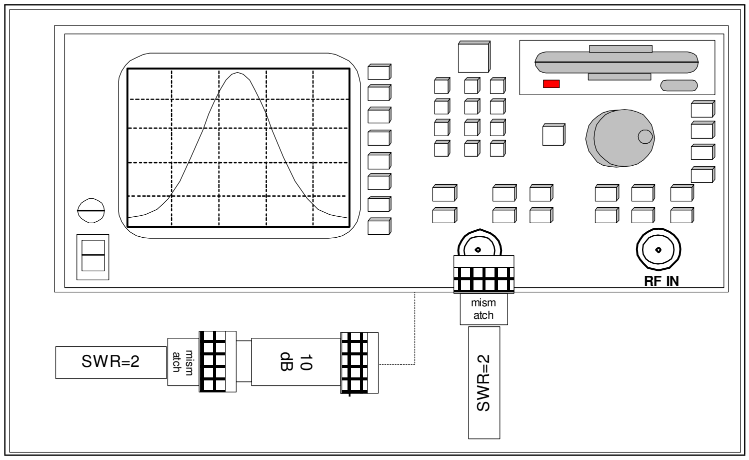

Figure 15 - Impedance Matching using Attenuator.

2. Preform a reflection caliboration and set the network analyzer to Reflection measurement, start frequency 900 MHz stop frequency 1100 MHz.

3. Measure the SWR of the mismatch. **Save the Data on magnetic media** . Fill in Table-2.

4. Disconnect the standard mismatch, make a normalization to remove cable error and measure the attenuation of the 10 dB attenuator at 1 GHz. **Save the Data on magnetic media**.

Fill the in Table-2.

4. Add 10 dB attenuator to the mismatch and connect it to the network analyzer, as indicated in Figure 15 (dashed line).

5. Measure again the SWR and the attenuation of the mismatch. **Save the Data on magnetic media**. Fill in Table-2.

	Return Loss (1GHz)	SWR (1GHz)	Attenuation (1GHz)
Without attenuation			
With attenuation			
Table-2			

2.5 Step-Attenuator

In this part of the experiment you will use the network analyzer to measure two important characteristic of a step attenuator: the SWR for the input and output ports of the attenuator and the accuracy of the attenuator.

1. Replace the mismatch with a step attenuator.

2. Make a reflection calibration, set the network analyzer to SWR measurement, frequency range 0.3 MHz to 1 GHz, and measure the input and output SWR of the attenuator while the attenuator is set to 0 dB attenuation (why?). Don't forget to terminate the attenuator with a 50Ω load. Fill in Table-3:

	Max. SWR	Frequency of Max. SWR
Input SWR		
Output SWR		
Table-3		

3. Set the network analyzer to Transmission measurement and make normalization to remove the coaxial cable response.

4. Measure the attenuation according to Table-4:

Atten. set	Min(dB)	Max(dB)	Atten. set	Min(dB)	Max(dB)
0			10		
1			30		
3			50		
5			70		
Table-4					

.

2.6 Final Report

1. Attached all the results and tables to the report.

2. Compare your SWR, attenuation accuracy and insertion loss measurements to the specification of the step attenuator (see appendix).

3. Compare the calculated attenuation and reflection to the measurements results for the fixed attenuator.

4. Using the data sheet in the appendix, calculate the SWR of the mismatch and the 10 dB attenuator when they are connected to an ideal 50Ω generator (as indicated in dashed line of Figure 14). Compare your calculation to the results of measurements in Table-3.

5. Using Matlab or other simulation software, draw two graphs; the resistors values of a T attenuator, $\overline{R}_1$ as a function of the attenuation (0 to 10 dB) and $\overline{R}_2$ as a function of the attenuation (0 to 10dB).

2.7 Appendix Data Sheet of the Attenuators

2.7.1 Specification of Bench Top Attenuators JFW-Model-50BR-008

Frequency Range - DC-2000 MHz.

Attenuation Range - 0-80 dB in 1 dB steps.

Attenuation Accuracy-

+/- .5 dB maximum or 1% DC-500 MHz

+/- .5 dB maximum or 2% 500-1000 MHz

+/- .5 dB maximum or 3% 1000-2000 MHz

SWR - 1.3:1 maximum DC-1000 MHz. 1.5:1 maximum 1000-2000 MHz.

Insertion Loss - 5 dB maximum DC-1000 MHz and 1 dB maximum 1000 -2000 MHz.

2.7.2 Specification of Fixed Attenuator Mini-Circuit Model-NAT10-60

Frequency Range - DC-6000 MHz.

Attenuation Accuracy - Nom. 10±0.2 dB.

Flatness - DC-2000 MHz ±0.3 dB,
DC-4000 MHz ±0.9 dB,
DC-6000 MHz ±1.9 dB.

SWR-1.2:1 maximum.

2.7.3 Specification of Standard Mismatch Maury Model-2562G

Mismatch value (SWR)-2.00

Accuracy - DC - 8 GHz ±0.12,
8 - 12 GHz ±0.12,
12 - 18 GHz ±0.22.

Calibration Data (Frequency GHz)

S/N-7579		S/N-7580		S/N-7579		S/N-7580	
Freq	SWR	Freq	SWR	Freq	SWR	Freq	SWR
2	2.004	2	1.998	11	2.040	11	2.015
3	2.000	3	1.987	12	1.966	12	1.954
4	2.011	4	1.992	13	1.929	13	1.945
5	2.062	5	2.036	14	1.939	14	1.955
6	2.085	6	2.061	15	1.872	15	1.891
7	2.040	7	2.013	16	1.837	16	1.844
8	1.982	8	1.962	17	1.937	17	1.951
9	1.995	9	1.989	18	2.166	18	2.177
10	2.042	10	2.030				