ELEC 453/6391 Microwave Engineering

Experiment #2

Impedance Measurement Using the Vector Voltmeter

Note:
1.You must do the Item 3, the Preliminary Exercise, before coming to the laboratory.
2.Bring a diskette to the lab so that you can take your data home with you.

1. Equipment

Bench #2 (Near the door)

- HP8350B with HP83592A 0.01 to 20 GHz plug in.
- HP8405A Vector Voltmeter
- HP394A variable attenuator
- HP76D (450 to 945 MHz) dual directional coupler or HP77D-012 (0.1 to 2.0 GHz) dual directional coupler
- Two HP11536A 50-ohm tees
- Loads: short circuit load, matched load, VSWR 2:1 load, VSWR 1.2:1 load.
- N-type tee with two 50-ohm loads with N connectors.
- Resistor mounted on an N-type bulkhead connector
- Monopole antenna and small ground plane.
- GR 874-LA adjustable air line and GR 874-D20 adjustable stub.

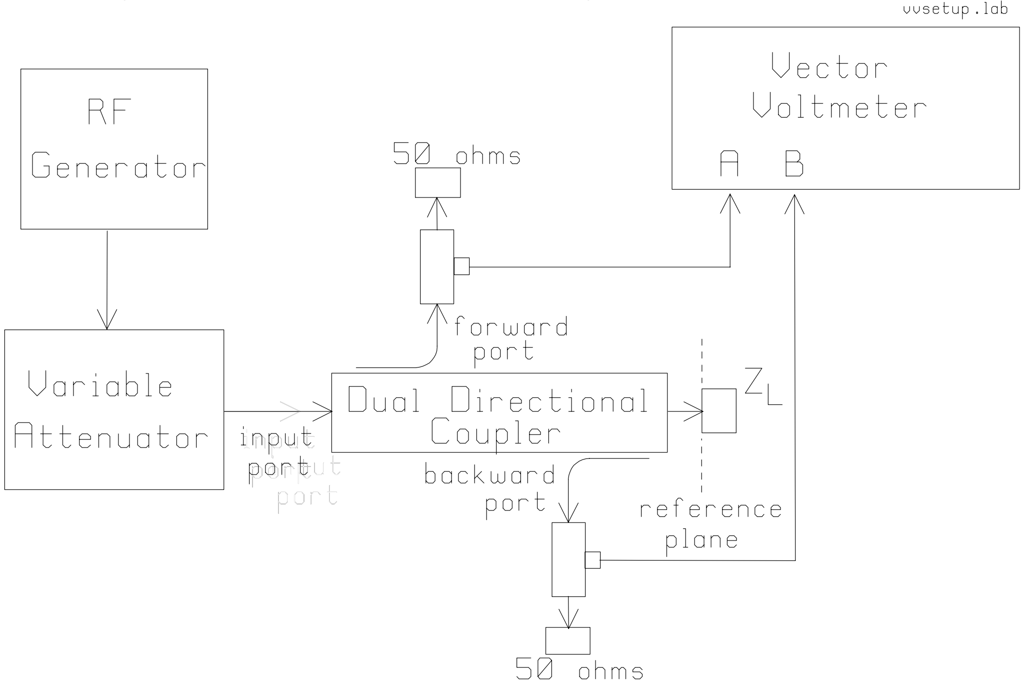

Fig. 2.1 Circuit for impedance measurement using a vector voltmeter.

Fig. 2.2 The HP8405A vector voltmeter.

2. Introduction

Fig. 2.1 shows the measurement setup for measuring the impedance of an unknown load Z_L using the HP8405A "vector voltmeter" (VVM) of Fig. 2.2. A vector voltmeter measures both the RMS value of an RF voltage, and the phase of the voltage relative to a reference voltage at the same frequency. Thus, the VVM has two inputs or "channels": channel "A" is called the reference channel; and channel "B" is the test channel. Set the channel selector switch to "A" to measure the RMS voltage at probe A. Set the channel switch to "B" to measure the RMS voltage at probe B, and the phase of the voltage at probe B, assuming that the voltage at probe A has zero phase, i.e., is the phase reference. The instrument is said to be "vector" because it measures phase as well as amplitude.

The vector voltmeter is designed to work with radio-frequency (RF) voltages at HF, VHF and UHF, up to 1 GHz. Between 100 MHz and 1 GHz, RF circuits are usually implemented using "transmission lines" such as coaxial cable or microstrip. The vector voltmeter measures voltages in 50-ohm coaxial circuits with the aid of HP11536A 50-ohm probe tees. A probe tee allows one of the VVM's probes to sample the RF voltage on a 50-ohm coaxial transmission line having N-type connectors, without giving rise to impedance mismatch.

Fig. 2.3 HP394A variable attenuator.

In the block diagram of Fig. 2.1, the RF generator's signal is fed to the variable attenuator of Fig. 2.3. This is quite convenient for adjusting the level of the RF signal. Also the variable attenuator provides a much better impedance match for the RF generator than does a direct connection to the directional coupler, which is terminated with a short circuit load for calibration, so is an awful impedance match.

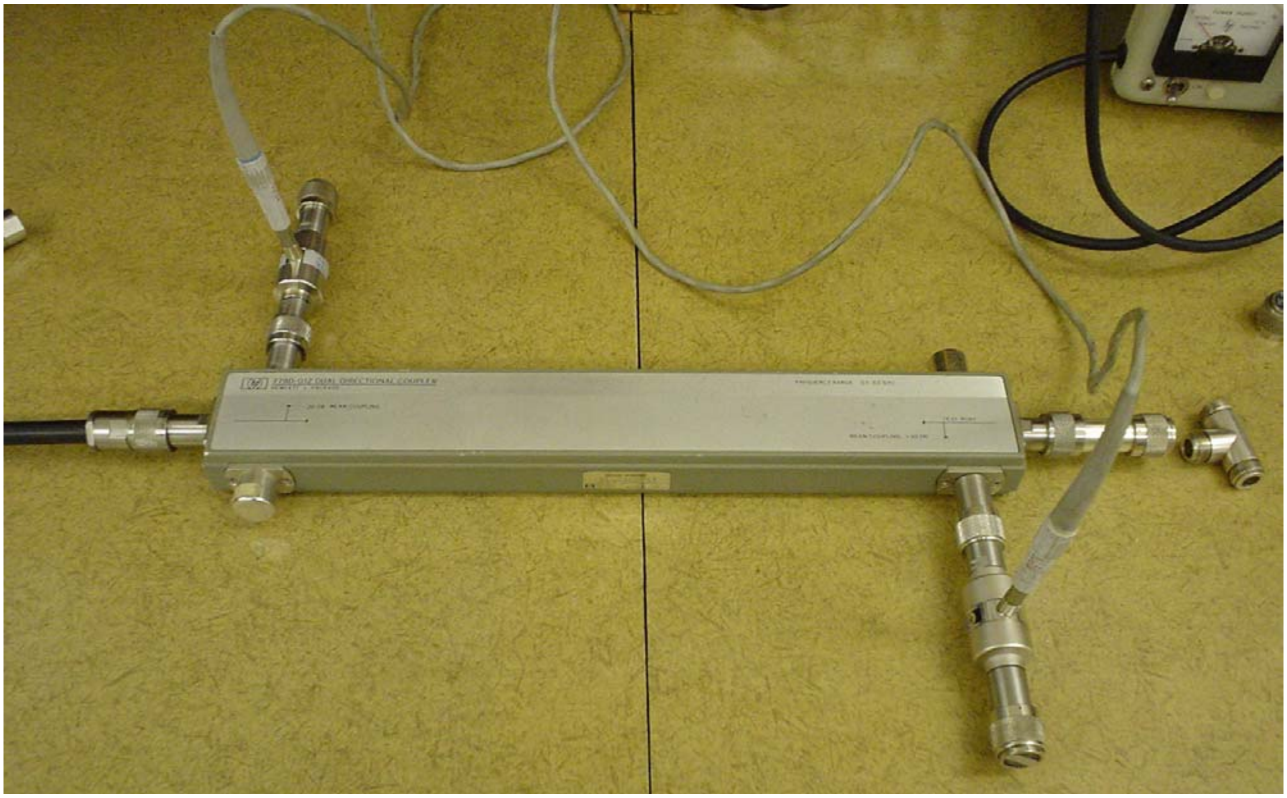

Fig. 2.4 HP77D-012 dual directional coupler.

We can use the VVM to measure the impedance of load Z_L with the aid of the "dual directional coupler[1]" shown in Figure 2.4. The directional coupler behaves as a length of transmission line between the input port and the load port where Z_L is connected. The voltage on the transmission line is made up of the forward-traveling wave $V^+e^{-j\beta z}$ and the backward-traveling wave $V^-e^{j\beta z}$ reflected from the load, and is given by

$$V(z) = V^+e^{-j\beta z} + V^-e^{j\beta z}$$

The directional coupler lets us separate the forward-traveling wave from the backward-traveling wave. Magic! The directional coupler "samples" the forward-traveling wave and provides a voltage $V_A = C_f V^+$ at the "forward" coupled port, and samples the backward-traveling wave and provides a voltage $V_B = C_b V^-$ at the "backward" port. Coupling coefficients C_f and C_b are complex-valued, and typically have magnitudes of about -20 dB. The "forward" port of the directional coupler is fed to channel A of the vector voltmeter, and the voltage is used both to phase-lock the receiver and as a phase reference for channel B. With the selector switch set to "channel A", the VVM measures the RMS value of the voltage on probe A, which is proportional to V^+. The voltage from the directional coupler's backward port is fed to channel B, and with the selector to "channel B" the VVM measures the RMS voltage on probe B, proportional to V^-, and the phase of the voltage at probe B relative to that at probe A.

To measure impedance Z_L, the magnitude and phase of the reflection coefficient Γ is derived from the voltages read from the VVM, and then the impedance is found by solving $\Gamma = \dfrac{Z_L - R_c}{Z_L + R_c}$, where

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[1] Pozar, "Microwave Engineering", 3rd edition, Wiley, pp. 311-314.

$R_c = 50$ ohms is the characteristic resistance of the coaxial transmission line. The reflected voltage is given by[2] $V^- = \Gamma e^{-j2\beta L} V^+$. Take the ratio $V_B / V_A = C_b V^- / \left(C_f V^+\right)$ and express it in decibels to get

$$V_B\,(\text{dB})\text{-}V_A\,(\text{dB}) = (C_b\,(\text{dB})\text{-}C_f\,(\text{dB})) + (V^-\,(\text{dB})\text{-}V^+\,(\text{dB}))$$

Since $|\Gamma| = |V^-| / |V^+|$, we have Γ (dB)= V^- (dB)-V^+ (dB) so

$$V_B\,(\text{dB})\text{-}V_A\,(\text{dB}) = (C_b\,(\text{dB})\text{-}C_f\,(\text{dB})) + \Gamma\ (\text{dB})$$

so

$$|\Gamma|\,(\text{dB}) = (C_f\,(\text{dB})\text{-}C_b\,(\text{dB})) - (V_A\,(\text{dB})\text{-}V_B\,(\text{dB})) \qquad \ldots(1)$$

For an ideal directional coupler $C_b = C_f$, so with the load on the measurement port, $|\Gamma|$ (dB)= V_B (dB)-V_A (dB).

The phase meter on the VVM reads $\theta =$ (phase of V_B -phase of V_A), that is, the phase of the voltage at probe B relative to the voltage at probe A. To measure the phase θ_Γ of the reflection coefficient $\Gamma = |\Gamma| e^{j\theta_\Gamma}$, we must compensate for the difference in electrical path length between L_f from the input to the "forward" port, and L_b from the input to the load and from there to the "backward port". The VVM's phase meter reads

$$\theta = \theta_\Gamma + \theta_c + (-\beta L_b + \theta_b) - (-\beta L_a + \theta_a) \qquad \ldots(2)$$

where θ_c is a phase compensation that is chosen by adjusting the "phase meter offset" knob on the VVM. We will choose θ_c to make the meter read $\theta = \theta_\Gamma$, using a short circuit as a reference. We say that the short circuit is used to "establish the location of the measurement plane". Mount the short circuit on the measurement port. Then the phase of the reflection coefficient is $\theta_\Gamma =$-180 degrees. Adjust the phase offset knob so that the meter reads $\theta = -180$ degrees; this sets the phase compensation as $\theta_c = -[(-\beta L_b + \theta_b) - (-\beta L_a + \theta_a)]$ which cancels terms in Equation (2), so $\theta = \theta_\Gamma$.

The VVM implements phase offset electronically. Sometimes, it is convenient to implement phase offset mechanically by putting a "line stretcher" in series with either the forward port or the backward port of the directional coupler. A "line stretcher" is sometimes called an "extendable air line", and is a coaxial cable whose length can be extended from some minimum value $d_{\min}$ (typically 20 cm) to some maximum value $d_{\max} \approx 2d_{\min}$. By extending the length of the air line from $d_{\min}$ to d, we change the phase delay from $-\beta d_{\min}$ to $-\beta d$. With the short circuit load, we can choose the line-stretcher length d so that $-\beta d = \theta_c = -[(-\beta L_b + \theta_b) - (-\beta L_a + \theta_a)]$ and then $\theta = \theta_\Gamma$. In Experiment 4, you will use the HP8410 Network Analyzer, which incorporates a mechanical "line stretcher" into the reflection/transmission test set.

Since we need to calibrate the phase using a short-circuit load as a reference, we can derive information about C_f and C_b from the voltages at channel A and channel B. With the short circuit, we expect $\Gamma = -1$ so $|\Gamma|$ is zero dB, and we have

$$0 = (C_f\,(\text{dB})\text{-}C_b\,(\text{dB}))\text{-}(V_{As}\,(\text{dB})\text{-}V_{Bs}\,(\text{dB}))$$

where V_{As} and V_{Bs} are the "calibration" voltages in channel A and channel B with the short circuit in place. Then

$$C_f\,(\text{dB})\text{-}C_b\,(\text{dB}) = V_{As}\,(\text{dB})\text{-}V_{Bs}\,(\text{dB})$$

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[2] Trueman, ELEC453 lecture notes, set #3.

The value of V_{As} - V_{Bs} is typically 0.1 dB. Then mount the unknown load and measure the voltage in channel A, V_A , and in channel B, V_B . The reflection coefficient in dB is given by Eqn. (1) and substituting C_f (dB)-C_b (dB)=V_{As} (dB)-V_{Bs} (dB) obtains

$$|\Gamma|\text{(dB)}=(V_{As}\text{(dB)}-V_{Bs}\text{(dB)})-(V_A\text{(dB)}-V_B\text{(dB)})$$

This compensates for the difference in the C_f (dB)-C_b (dB)=V_{As} (dB)-V_{Bs} (dB) coupling factor between the "forward" and the "backward" port and significantly improves the accuracy of the VVM measurement of the impedance. To make the measurement simpler, use the variable attenuator to make the "channel A" voltage equal to 0 dB with both the short-circuit load and the unknown impedance. Then

$$|\Gamma|\text{ (dB)}=V_B\text{(dB)} - V_{Bs}\text{(dB)} \qquad \ldots(3)$$

This is the formula we will use in the laboratory.

In practice directional couplers do not achieve perfect isolation between the forward and backward port: some of the signal in the "forward" path appears at the "backward" port, and some "backward" signal appears at the "forward" port. The "directivity" measures the amount of unwanted signal, and is typically -30 dB or -35 dB. Because of imperfections in the coupler, the simple "short circuit" calibration method used in this experiment can lead to poor accuracy. More elaborate calibration procedures use several reference standards: a short circuit, an open circuit and a matched load. A matrix equation must be solved to derive the reflection coefficient from the magnitude and phase measured on the VVM. Such three-standard calibration is much more accurate than our simple short-circuit method, but it is beyond the scope of this introductory experiment.

The circuit of Fig. 2.1 is very similar to that used in a modern network analyzer for impedance measurement. This experiment will help us to understand what a network analyzer actually measures, how the location of the "reference plane" is established, and the purpose of the three-standard calibration procedure. In Experiment 5 the HP8720 will be used to re-measure some of the loads you will measure in this experiment, and you will be asked to compare your measured values from this experiment with those from Experiment 5.

3. Preliminary Exercise

Answer these questions before you come to the lab. The lab demonstrator will check that you have answered these questions before he permits you to do the experiment.

1. The short-circuit termination is attached to the measurement port of the directional coupler in Fig. 2.1. The vector voltmeter is adjusted so that the voltage on channel A is zero dB. Then channel B reads -0.2 dB. The VVM's phase compensation is adjusted so that the channel B has a phase of -180 degrees relative to channel A. Then the unknown load impedance is mounted on the measurement port, and the voltage on channel A is adjusted to 0 dB. The voltage on channel B is measured and is -10.1 dB, with a phase of 127 degrees. Calculate the reflection coefficient magnitude and phase. Calculate the value of the load impedance, assuming that the characteristic impedance is 50 ohms.
2. The "Vector Voltmeter Calculator" vvcalc.exe is available to help you do the calculations for this experiment. Fetch vvcalc.exe from the course web site and use it to solve problem 1 above, and to verify that your answer is correct.

Fig. 2.5 HP 8350B RF Oscillator

4. Procedure in the Laboratory

Setting up the HP 8350B RF Oscillator with the HP83592A 0.1-20 GHz RF Plug-in

The HP 8350B RF oscillator is shown in Fig. 2.5. Follow these instructions to set up the instrument:

1. Push the CW or "continuous wave" button on the front panel of the HP8350B.
2. Set the frequency to 750 MHz by pressing the "MHz" key, then typing "750" on the keypad and then pushing the "MHz" key again.
3. To set the power level, push "power level" on the RF plug-in below the knob, then use the keypad to enter 15 dBm. You can also turn the knob until the display reads 15 dBm.
4. The RF on/off button is just above the output jack. When the power is off the button is not lit, but when the power is on the button is lit. See the note about RF On/Off, below.

RF On/Off

You should keep the RF "off" most of the time to protect the RF oscillator against operating into a high impedance load by accident. This can damage some RF generators severely, especially costly, high-power generators! Also, if you were working with high-power RF equipment, there can be health hazards when you are exposed to strong RF fields. In our lab experiments, the power levels are extremely small so there is no risk. But it is good practice to keep the RF "off" most of the time, except when you need to excite the circuit to do a measurement. Make sure the RF is "off" when you are changing the load on the slotted line. Then turn the RF "on", make your measurement, and turn the RF "off" again.

Setting up the Circuit

Connect the RF generator to the input of the HP394A variable attenuator, Fig. 2.3, using a coaxial cable with N-type connectors. Terminate the "unattenuated output" port and the "termination" port with 50-ohm loads. Connect the "attenuated output" port to the input of the dual directional coupler. Connect the short circuit load to the coupler's output port. Connect an HP11536a 50-ohm tee to the "forward" port, and terminate the tee with a 50-ohm load. Carefully push the probe for channel A into the tee; the pin on the probe is easily broken. Connect another 50-ohm tee to the "backward" port, and terminate it with a 50-ohm load. Gently push the channel B probe into the tee. Set the frequency to 750 MHz, and the power to 15 dBm. You are ready to measure!

Operating the Vector Voltmeter

Make sure the frequency-range selector on the VVM is set to 500-1000 MHz. Set the HP394A attenuator to 60 dB, and turn on the RF power. Gradually decrease the attenuation until the APC locks.

On the older grey VVM, the APC light will go out when the APC is locked. Note that when the APC is unlocked the phase needle swings randomly, but becomes steady when the APC locks. The newer beige VVM has a burned-out APC light, but otherwise the instrument works perfectly. You know the APC is locked when the phase needle is steady.

Calibration

Terminate the measurement port with a short circuit. Turn on the RF power and make sure the APC is locked. Set the channel selector switch to A, and adjust the HP394A variable attenuator so that the magnitude needle reads 0 dB. Then switch the selector to channel B. Read the voltage: it will be between -0.2 and +0.2 dB, depending on the frequency. This is V_{Bs} in Equation (3). Select the phase range as +-180 degrees. Center the red knob labeled “Phase range zero”. Set the “meter offset +/-“ switch to “+”. Then each clockwise click of the black “meter offset” knob 10 degrees of phase. Use the “meter offset” knob to set the phase needle to be close to either -180 or +180 degrees. You might need to change the “+/-“ switch to “-“. Then use the red “phase range zero” knob to adjust the needle to precisely +180 or -180. This calibrates the VV so that the “measurement plane” is at the location of the short circuit termination. So when we mount the unknown load, the phase meter will read $\theta = \theta_\Gamma$, the angle of the reflection coefficient of the load.

Measuring the Impedance of an Unknown Load

Turn off the RF power, disconnect the short circuit, and attach the load. Then turn the RF power back on. Make sure the APC is locked by noting that the phase needle is steady rather than randomly wavering. Set the selector switch to channel A and use the variable attenuator to adjust the amplitude to 0 dB. Then set the selector to channel B, and read V_B. Sometimes you need to add gain to the VVM by clicking the “amplitude range” knob, to get a reading that lies within the decibel scale on the meter. Use Equation (3) to calculate the magnitude of the reflection coefficient.

Read the phase from the phase meter. Sometimes the phase meter is off scale. Don’t adjust the black “meter offset” knob, or you will lose your calibration. You can bring the needle back on-scale by clicking the red “meter offset -/+” switch, which changes the sign of the phase compensation. Suppose that, at the calibration step, the meter offset is set to “+” and 70 degrees. Then suppose the load is mounted, and the phase meter reading is off scale. Click the “+/-“ switch to “-“; this brings the needle back on scale. You have changed the phase compensation from +70 to -70 degrees, so subtract 140 degrees from the meter reading to get the phase. Thus if the needle reads -56 degrees, the actual phase is -56-140=-196 degrees; add 360 and record the phase as θ_Γ=164 degrees.

4.1 Confidence Checks

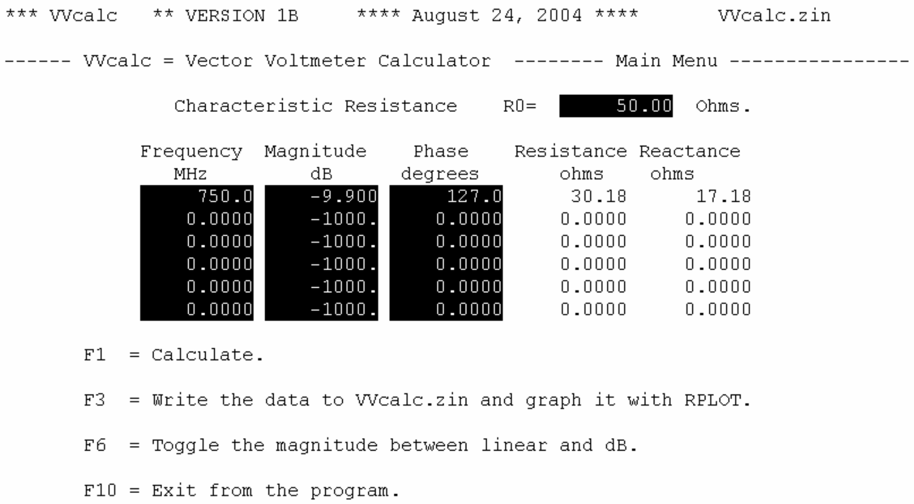
Set the frequency to 750 MHz and calibrate the VVM as described above, using the short-circuit termination. Record V_{Bs} in the table below. Then put a matched load on the measurement port, set the channel A amplitude to 0 dB, and record the magnitude of the channel B voltage, V_B, and the phase, θ_Γ, in the table. Calculate the load impedance; since the load is “matched” you expect a value of close to (50+j0) ohms. Repeat for the 2:1 termination, and the 1.2:1 termination. Record your data in Table 4.1 in Section 5, below.

4.2 Impedance of a “Tee” Load as a Function of Frequency

A “tee-50” load is made using an N-type tee junction and two 50-ohm loads. We expect the input impedance of this load to be approximately 25 ohms. Similarly, a “tee-75” load uses two 75-ohm loads on a tee. We use these “tee” load2 in lab 1 and lab 2. Measure the impedance of a “tee” load at 650, 700, 750, 800, 850, and 900 MHz using the vector voltmeter. Note that at each frequency you must:

1. Set the frequency
2. Mount the short-circuit termination; adjust the variable attenuator so that the channel A voltage is 0 dB; record the channel B voltage and record it in the table; adjust the phase offset so that the phase meter reads +180 or -180 degrees.
3. Mount the tee-25 load; adjust the channel A voltage to 0 dB; measure the channel B voltage magnitude and phase and record the values in the table.

Record your data in Table 4.2, in Section 5.



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*** VVcalc   ** VERSION 1B     **** August 24, 2004 ****       VVcalc.zin

------ VVcalc = Vector Voltmeter Calculator  -------- Main Menu ----------------

                Characteristic Resistance    R0=      50.00  Ohms.

             Frequency  Magnitude    Phase    Resistance Reactance
                MHz        dB       degrees      ohms      ohms
                 750.0    -9.900      127.0      30.18      17.18
                0.0000    -1000.     0.0000     0.0000     0.0000
                0.0000    -1000.     0.0000     0.0000     0.0000
                0.0000    -1000.     0.0000     0.0000     0.0000
                0.0000    -1000.     0.0000     0.0000     0.0000
                0.0000    -1000.     0.0000     0.0000     0.0000

       F1  = Calculate.

       F3  = Write the data to VVcalc.zin and graph it with RPLOT.

       F6  = Toggle the magnitude between linear and dB.

       F10 = Exit from the program.
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Fig. 2.6 VVcalc main menu.

You can evaluate the load impedance with the formula $Z_L = R_c \frac{1+\Gamma}{1-\Gamma}$. But since there are a lot of points to calculate for this lab, you can use the "Vector Voltmeter Calculator" program "VVcalc.exe" to evaluate the formula quickly. The main menu is shown in Fig. 2.6. Enter your measurement frequency, your reflection coefficient magnitude in dB (a negative number) and your measured phase, and then press F1 to calculate the impedance. The "VVcalc" program lets you enter data for all six frequencies. After you enter each data point, push F1 to calculate the impedance. Look at the impedance values: they change smoothly from one frequency to the next. When you have entered all six points, push F3 to write the data to a file called "vvcalc.zin". VVcalc starts program RPLOT to graph the resistance and reactance as a function of the frequency. In RPLOT, push F10 to see the graph. You will want to save your data file for use in Experiments 1 and 5. You should RENAME the data file "vvcalc.zin" to some convenient name such as "Lab_2_1.zin", and SAVE it because you will need to use it in Lab 2 and Lab 5.

You can run the "vvcalc" program on the "Darwin" computer in the lab. Log in with user name "Maxwell" and no password. There is a directory for your lab group, and you can use it to you're your data. Analyzing your data in the lab is good practice: you can graph it immediately and if the resistance and reactance do not change smoothly with frequency, your data is in error and you can go back to the "bench" to verify your measurement. When you are confident that your data is correct, copy your "zin" data file to your diskette and take it home. Darwin is *not* connected to the internet so you cannot email the data file to yourself!

At home, you can download "vvcalc.exe" from the course web site to analyze your data, if you have not done so in the lab. You can download the RPLOT program to graph the data. Also, download program SMTHCHT to plot your impedance data on a Smith Chart. The User's Guide for SMTHCHT describes the format of the "zin" file.

4.3 Impedance of a Resistor

The lab demonstrator will give you a resistor mounted on an N-type “bulkhead” connector. There are two resistors. One is a five-watt resistor with a beige body, of resistance 23.9 ohms at D.C. The other is a ½-watt resistor with a value of about 100 ohms at D.C. Measure the impedance of one of the resistors as a function of frequency from 650 to 900 MHz.

Half of the lab groups do lab 1 first and lab 2 second. If your group has already done lab 1, make sure you measure the *same* resistor that you did in lab 1, because you will be asked to compare your measurement on the vector voltmeter with your measurement using the slotted line.

Record your data in Table 4.3 in Section 5. Enter your data into the VVcalc program and calculate the impedance at each frequency. Save your “zin” data file with a convenient name such as Lab2_2.zin.

Fig. 2.7 Monopole antenna on a small square ground plane.

4.4 Input Impedance of a Monopole Antenna

A monopole antenna consists of a wire or rod standing above a ground plane, as shown in Fig. 2.7. The base of the monopole is an N-type bulkhead connector. The monopole itself is simply an extension of the center conductor of the coaxial cable. The monopole is a length of brass tubing that fits over the base; there are various lengths of tubing to make monopoles of various heights. The demonstrator will give you a monopole. Fit it to the base and measure its height above the surface of the ground plane carefully.

Connect the monopole to the “measurement port” of the dual directional coupler with a long coaxial cable. The impedance is sensitive to the presence of your body, so you want to move it away from the area where you will be working. Also, tipping it on edge, as shown in the figure, tends to isolate the monopole from the “proximity effects” of the people in the room. In Fig. 2.7, the instruments near the monopole are very close, and their presence will affect the impedance. Ideally, antenna impedance should be measured in an “anechoic chamber”, where the antenna is surrounded by microwave absorbing material, which simulates a free-space environment for the antenna. Sometimes antenna impedance is measured on an “open-field” site. This can be the roof of a building, where there is nothing near the antenna, or even a rural site such as a farm. Even though we don’t have microwave absorber, it is still interesting to measure the antenna’s impedance to obtain an approximate value.

Fig. 2.8 Bulkhead connector with a short-circuit to ground.

After you set the frequency of the RF generator, you must establish the location of the "measurement plane". We want to measure the impedance at the base of the monopole. Fig. 2.8 shows a bulkhead connector similar to that used to make the monopole. The center conductor has been short-circuited to the connector body with four small wires. This will be used to calibrate the vector voltmeter at each frequency. Install this short circuit at the end of the long coaxial cable, in place of the monopole. Calibrate the VVM by setting the voltage in channel A to 0 dB, noting the voltage in channel B, and adjusting the phase offset for ± 180 degrees. Then remove the short and replace it with the monopole, and readjust the channel A voltage to 0 dB. Note the voltage in channel B and the phase, and calculate the impedance in the usual way. Repeat the measurement at six frequencies to fill up Table 4.4 in Section 5. Enter your data into the VVcalc program and calculate the impedance at each frequency. Save your "zin" data file with a convenient name such as Lab2_3.zin. You will compare your VVM measurement of the monopole impedance with a measurement using the HP8720 network analyzer, in Experiment 5.

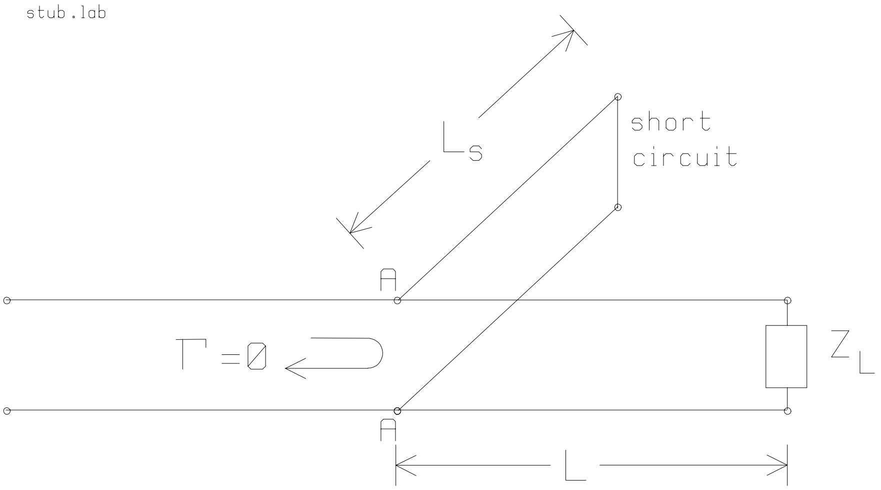

Fig. 2.9 The single-stub matching circuit.

4.5 Single-Stub Matching

Single-stub matching[3] is a technique for providing an impedance match between a generator and transmission line of characteristic resistance R_c and a load Z_L. As shown in Fig. 2.9, the load Z_L is connected to the feed cable with a transmission line of variable length L, and a "tuning stub" is connected at the junction. The tuning stub is simply a length L_s of coaxial transmission line terminated in a short circuit. The length of the stub L_s is also variable. Later in the course, we will study the design of the single-stub matching circuit[4]. The purpose of this part of the lab is to convince yourself that it is possible to obtain an approximate impedance match by varying both the distance L between the measurement port AA and the load, and the length of the stub, L_s.

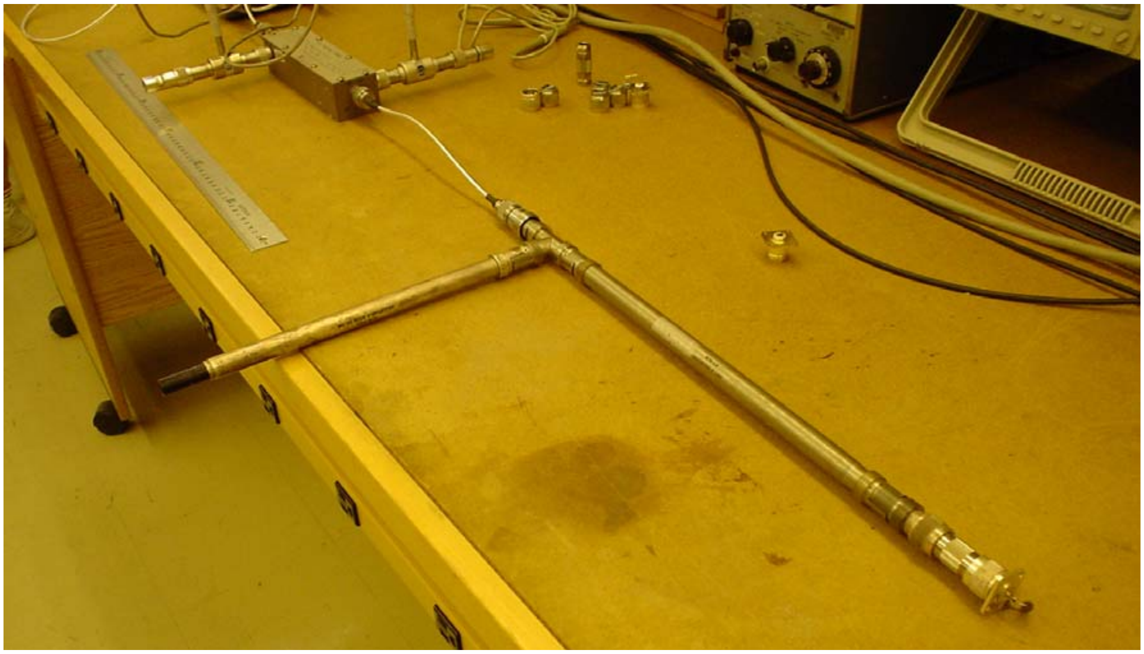

Fig. 2.10 Single-stub matching circuit using a line stretcher and a tuning stub.

Set up a single-stub matching circuit using an adjustable air line (874-LA) or "line stretcher" and an adjustable stub (874-D20), as shown in Fig. 2.10. In this lab, you will adjust the circuit by trial-and-error. Use the resistor measured in part 4.3 as the load.

We will adjust the single-stub tuning circuit to get the best possible match at 800 MHz, and then find the bandwidth of the match by measuring the input impedance from 700 to 900 MHz.

At 800 MHz, put the short circuit termination at the measurement port of the directional coupler, and calibrate the VV. Then attach the stub-matching circuit terminated by the resistor. To adjust the circuit at 800 MHz, set both the stub and the line stretcher to their minimum lengths. Then gradually pull out the line stretcher until you get a minimum voltage on channel B of the vector voltmeter. Change the stub length to make the minimum deeper. Then once again, pull out the line stretcher a little more to reduce the reflected voltage, and then re-adjust the tuning stub. You should be able to reduce the reflected voltage to be less than -30 dB. See if you can do better! Unfortunately the GR connectors themselves reflect the signal so it is difficult to obtain a really good match. Record your values at 800 MHz in Table 4.6.

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[3] Pozar, Section 5.2, page 228.

[4] C.W. Trueman, ELEC 453 Lecture Notes, set 11.

Once you have adjusted the line stretcher and the stub for a good match at 800 MHz, determine the bandwidth of the match by measuring the input impedance at nearby frequencies without readjusting the line stretcher or the stub. Measure the input impedance at 700, 750, 850 and 900 MHz, and record your values in Table 4.6. Use the Vector Voltmeter Calculator program to calculate the input impedance at each frequency, and the "return loss", defined as $RL = -20\log|\Gamma|$.

5. Tables of Data

Student name:	
Student I.D.:	
Lab Section:	
Lab Instructor's Signature:	

Table 4.1
Confidence Checks for Part 4.1

Load	Short Circuit	Unknown Load		Reflection coefficient Γ (linear scale)	Load Impedance $Z_L = R_c \frac{1+\Gamma}{1-\Gamma}$
	V_{Bs} (dB)	V_B (db)	θ_Γ (deg)		
Matched load					
2:1 termination					
1.2:1 termination					

Table 4.2
"Tee" Load Data for Part 4.2

Frequency	Short Circuit	Unknown Load		Load Impedance
MHz	V_{Bs} (dB)	V_B (dB)	θ_Γ (deg)	R+jX (ohms)
650				
700				
750				
800				
850				
900				

Table 4.3
Resistor Data for Part 4.3

Frequency	Short Circuit	Unknown Load		Load Impedance
MHz	V_{Bs} (dB)	V_B (dB)	θ_Γ (deg)	R+jX (ohms)
650				
700				
750				
800				
850				
900				

Table 4.5
Monopole Data for Part 4.5

Frequency	Short Circuit	Unknown Load		Load Impedance
MHz	V_{Bs} (dB)	V_B (dB)	θ_Γ (deg)	R+jX (ohms)
650				
700				
750				
800				
850				
900				

Table 4.6
Stub-Matching Data for Part 4.6

Frequency	Short Circuit	Unknown Load		Load Impedance	Return Loss
MHz	V_{Bs} (dB)	V_B (dB)	θ_Γ (deg)	R+jX (ohms)	dB
Adjustment of the single-stub matching circuit for the best possible match at 800 MHz:					
800					
Find the bandwidth of the single-stub matching circuit:					
700					
750					
850					
900					

6. Questions to Answer in your Lab Report

Your lab report must include a signed “Expectations of Originality” form.

Your lab report must include the tables from Section 5, filled in with your data, and “signed off” by your lab demonstrator at the end of the lab session.

Your lab report will consist of the answers to the following questions:

1) The matched load should have an SWR of 1. What is your measured value for the impedance of the matched load at 750 MHz? What is the corresponding SWR?
2) The 2:1 load should have an SWR of 2. What is your measured value of the impedance of the 2:1 load at 750 MHz? What is the corresponding SWR?
3) The 1.2:1 load should have an SWR of 1.2. What is your measured value of the impedance of the 2:1 load at 750 MHz? What is the corresponding SWR?
4) Plot the resistance and reactance of the “tee” load as a function of frequency from 650 to 900 MHz. We might expect that two 50-ohm loads in parallel would make a 25 ohm load. Why do the measured values differ from 25 ohms? For the “tee-75’ load, why does the impedance differ

from 37.5 ohms? You can model the "tee" load with the "TRLINE" transmission-line solver and compare the predicted performance with your measurements.

5) Plot the resistance and reactance of the carbon-composition resistor as a function of frequency from 650 to 900 MHz. Note that the measured values are very different from the D.C. resistance.
6) Plot the input impedance of the monopole antenna at five frequencies. The monopole is "resonant" when its height is approximately quarter of a free-space wavelength. A better estimate is 0.475/2 of the free-space wavelength. At resonance, the reactance of the monopole is zero. Use linear interpolation with your measured data to estimate the frequency where the reactance is zero. How tall is the monopole at this frequency, in free-space wavelengths? Does this agree with the "rule-of-thumb" formulas?
7) Plot the return loss of the single-stub matching circuit at five frequencies. What is the best return loss you achieved? Use your data at five frequencies to estimate the bandwidth of the tuning circuit for a return loss of better than 20 dB.

Some lab groups do experiment 1 before experiment 2. If your group has already done experiment 1, answer these questions.

8) Make a graph comparing the measured impedance of the "tee" load using the slotted line and the vector voltmeter. Plot resistance as a function of frequency, and the reactance as a function of frequency. Explain any differences between the impedance values measured by the two methods.
9) Make a graph comparing the measured impedance of the carbon-composition resistor, using the slotted line and the vector voltmeter.

Optional Question for Expert Users

(Recommended for students taking ELEC456 "Antennas")

You can obtain a copy of the "Numerical Electromagnetics Code" (NEC) from the web at address: For a Pentium with Microsoft Windows, you can get an "exe" file for NEC-2 from "The Unofficial Numerical Electromagnetics Code (NEC) Archives" at
http://www.qsl.net/wb6tpu/swindex.html
See the ELEC456 "Antennas" lecture notes set 12, at
http://emclab.concordia.ca/~trueman/elec456/ANT_Lecture12w.pdf
You can calculate the impedance of a monopole antenna with the input file:

```
CM 10 cm monopole antenna
CM 3 mm diameter
CE
GW    1 21    0.        0.        0.        0.         0.       0.1       0.0015
GE  1
GN  1
EX  0    1    1    0    1.        0.
FR  0    6    0    0  650.0000   50.
RP  0    1    1    0       90.    360.00        0.        1.
EN
```

This input file asks NEC to calculate the impedance of the 10 cm monopole at 6 frequencies, starting at 650 MHz, with a step size of 50 MHz. You can use the Notepad (or a text editor) to "grovel" through NEC's output file to find the impedance values. Search for the word "impedance". Type the frequency, the resistance and the reactance into a three-column data file and graph it with RPLOT. The calculated values are very similar to the measured impedance.