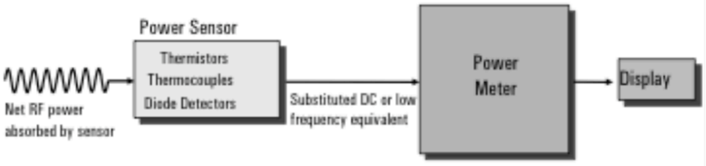
Measurements on Transmission Lines

Power and Attenuation Measurements

Although a variety of instruments measure power, the most accurate instrument is a *power meter* and a *power sensor*. The sensor is an RF power-to-voltage transducer. The power meter displays the detected voltage as a value of power in log (dBm) or linear (watts) units. Typical power meter instrumentation accuracy will be in the order of hundredths of a dB, while other instruments (i.e., *spectrum analyzers*, *network analyzers*) will have power measurement accuracies in the tenths of dBs or more. One of the main differences between the instruments is that of frequency selective measurements. Frequency selective measurements attempt to determine the power within a specified bandwidth. The traditional Power Meter is not frequency selective in the sense that it measures the average power over the full frequency range of the sensor and will include the power of the carrier as well as any harmonics which may be generated. A Spectrum Analyzer provides a frequency selective measurement since it measures in a particular Resolution Bandwidth. The lack of frequency selectivity is the main reason why Power Meters measure down to around -70 dBm and instruments such as a Spectrum Analyzer can measure much lower than this if narrow resolution bandwidths are used.

Average Power provides the average power delivered over several cycles and this is the most common power measurement performed. Average power is defined as the energy transfer rate averaged over many periods of the lowest frequency in the signal. Average power is also defined as the power averaged over a specified time interval. The power meter with sensor only allow to measure the average power, while the Spectrum Analyzer may be used also for more sophisticated power measurements (i.e. peak and pulse power, time-gated power, etc.). We are just interested in average power measurements in the microwave frequency range.

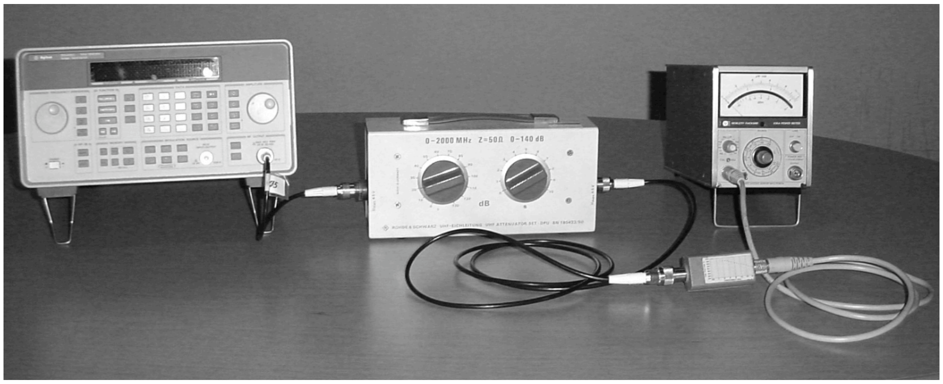
Regarding the hardware used in average power measurements, the basic idea behind the power sensor is to convert high frequency power to a DC or low frequency signal that the power meter can then measure and relate to a certain RF power level. There are two types of power sensor: the end-line power sensor which has just one RF input and a connection to the power meter and basically behaves as a dummy load, and the line-throught power sensor, less common, which has an RF input, and RF output and a connection to the power meter and therefore behaves like a coupler. Often the second type of sensor is integrated in the power meter (line-through power meter).



Experiment 2: Power Measurement with a Power Meter and Power Sensor.

Objective:
We want to use a power meter to measure a reference signal produced by a signal generator.

Equipment Required:
- a signal generator
- a power meter
- an end-line power sensor
- a variable attenuator
- a couple of cables for interconnection



Procedure:
- Before starting the experiment, remember that overloading a device like the power meter may lead to damages or injury. Always estimate the power you are going to apply to the device before connecting it and be sure it fits in the accepted range. If you are not sure, adopt a safe setting.

1) Set the signal generator to output a carrier signal with a value of 0 dBm of average power and a frequency of 2.4 GHz. Disable any modulation. If possible, disable the output of the generator ("RF OFF").

2) Connect the power sensor to the power meter following its instructions before switching it on. Follow the calibration procedure for the power meter, as indicated in its manual. The general procedure consists in switching on the meter for some time in order to stabilize the temperature of the circuits. Then, use the internally generated reference signal to calibrate the gain of the sensor. After the calibration, the instrument should not be switched off. Exit from the calibration mode of the power meter.

3) Set the variable attenuator to an attenuation of -20 dB.

4) Check again the output level of the generator (it should be 0 dBm or 1mW) and the attenuation of the variable attenuator (-20 dB). Estimate the losses of the cables at the working frequency and compute the expected power level at the input of the power meter.

$$\begin{aligned} \mathrm{Power}_{\mathrm{Expected}}(\mathrm{dBm}) = \mathrm{Power}_{\mathrm{Generated}}\ (\mathrm{dBm}) + \mathrm{Losses}_{\mathrm{Cable}}(\mathrm{dB}) \\ + \mathrm{Losses}_{\mathrm{Connector}}(\mathrm{dB}) + \mathrm{Attenuation}(\mathrm{dB}) \end{aligned}$$

In our case the expected value cannot exceed -20 dBm.

5) Be sure that this estimated value fits in the actual measurement range of the power meter, setting the range knob.

6) Connect the signal generator to the power meter passing through the attenuator. Enable the output of the signal generator if it was disabled.

7) If everything is correct, the power meter should indicate the expected value of the power. If you don’t read the expected value or a near one, switch off immediately the generator and check carefully the connections, the setting of the instruments, the calculations and ask for assistance before repeating the measurement.

8) You may observe a small difference, of the order of a few dB, between the estimated and measured value. This difference is given by the losses of the connectors in the RF chain and eventually by the inaccuracy of the instruments. The signal generator is not supposed to be a reference source of power, if not stated explicitly in the manual. You can therefore use this procedure to estimate roughly the losses of the cables and connectors, but you cannot expect to get the exact value.

9) Disable the output of the signal generator, if possible, or reduce the power at the minimum level, then switch the generator off. Disconnect the RF cable from the power sensor but not switch off the power meter.

10) Repeat the calibration procedure for the power meter, in order to validate the measurements. If you notice that the instrument calibration has changed, repeat the whole measurement procedure. Finally switch off the power meter and disconnect the power sensor.

Experiment 3: Power Measurement with a Spectrum Analyzer.

Objective:

We want to use a Spectrum Analyzer to measure a signal produced by a signal generator.

Equipment Required:

- a signal generator
- a Spectrum Analyzer
- a variable attenuator
- a couple of cables for interconnection

Procedure:

- Before starting the experiment, remember that overloading a device like the Spectrum Analyzer may lead to damages or injury. Always estimate the power you are going to apply to the device before connecting it and be sure it fits in the accepted range. If you are not sure, adopt a safe setting.

1) Set the signal generator to output a sine wave (carrier) signal with a value of -20 dBm of average power and a frequency of 2.4 GHz. Disable any modulation. If possible, disable the output of the generator ("RF OFF").

2) Set the variable attenuator to an attenuation of -20 dB.

3) Check again the output level of the generator (it should be -20 dBm or $10\,\mu W$) and the attenuation of the variable attenuator (-20 dB). Estimate the losses of the cables at the working frequency and compute the expected power level at the input of the power meter.

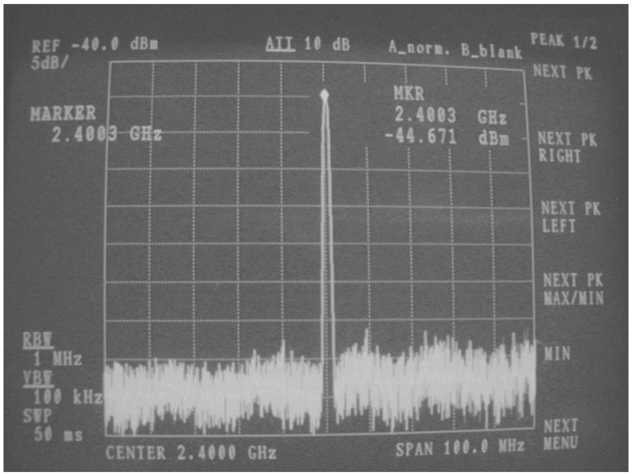
$$\begin{gathered}\mathrm{Power}_{\mathrm{Expected}}(\mathrm{dBm}) = \mathrm{Power}_{\mathrm{Generated}}\,(\mathrm{dBm}) + \mathrm{Losses}_{\mathrm{Cable}}(\mathrm{dB}) \\ + \mathrm{Losses}_{\mathrm{Connector}}(\mathrm{dB}) + \mathrm{Attenuation}(\mathrm{dB})\end{gathered}$$

In our case the expected value cannot exceed -40 dBm.

4) Switch on the Spectrum Analyzer and set the input attenuation of the Spectrum Analyzer to 20dB, the center frequency at 2.4 GHz, the frequency span at 100 MHz, the reference level at -40 dBm, RBW at 1 MHz, VBW at 100 kHz.

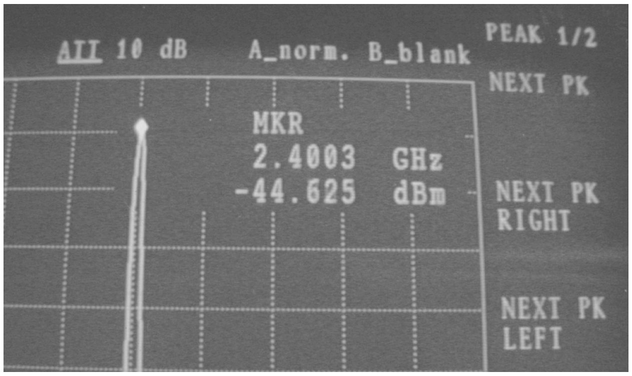
5) Connect the signal generator to the Spectrum Analyzer passing through the attenuator. Enable the output of the signal generator if it was disabled.

6) If everything is correct, the Spectrum Analyzer should display a peak signal centered at 2.4 GHz as shown in figure.



If you don’t see any signal, switch off immediately the generator and check carefully the connections, the setting of the instruments, the calculations and ask for assistance before repeating the measurement.

7) You can read the power level of the signal directly on the screen of the Spectrum Analyzer using the grid as a reference. For a better reading, you may use the marker facilities provided by some Spectrum Analyzers. Check on the instruction manual the correct procedure.



8) You may observe a small difference, of the order of a few dB, between the estimated and measured value. This difference is given by the losses of

the connectors in the RF chain and eventually by the inaccuracy of the instruments. The signal generator is not supposed to be a reference source of power, if not stated explicitly in the manual. You can therefore use this procedure to estimate roughly the losses of the cables and connectors, but you cannot expect to get the exact value.

9) Disable the output of the signal generator, if possible, or reduce the power at the minimum level, then switch the generator off. Disconnect the RF cable from the Spectrum Analyzer and switch it off.

Experiment 4: Measurement of Cable Loss with Power Meter.

Objective:

We want to use the same procedure as experiment number 2 to measure the loss of a cable at a given frequency.

Equipment Required:

- a signal generator
- a power meter
- a power sensor
- the cable under measurement
- eventually, a reference cable with a known loss
- connectors/gender adapters if required

Procedure:

- Be familiar with the procedure of power measurement with the power meter following the instructions of exercise number 2.

In this type of measurement, different scenarios are possible:

1) The power sensor can be plugged directly at the output of the signal generator, and the cable under measurement can also be inserted between the signal generator and the power sensor. In this case, you should first calibrate the signal generator connecting directly its output to the power meter and follow the procedure for power measurement

without any cable in between. Then, you should place the cable under measurement between the signal generator and the power sensor without changing any of the settings of the two instruments. The difference between the two measurements will give a precise value for the loss of the cable (including the losses of the connectors). This method works also if the power meter is not perfectly calibrated because it is based on a difference of values of power, thus eliminating the *bias*.

2) The power sensor cannot be plugged directly at the output of the signal generator or the cable under measurement cannot be inserted between the signal generator and the power sensor. In this case, you should use one or more adapters to match the connector type and gender. In this case you cannot avoid to take into consideration in the total cable loss also the loss of the adapters, possibly using good quality calibrated adapters.

3) In some cases you can measure the loss of a cable relatively to a cable of known loss value. This procedure is also useful in measuring the loss of a very long cable in comparison with a very short one, which is supposed to have a very low loss compared to the long one.

Experiment 5: Measurement of Cable Loss with Spectrum Analyzer and Signal Generator.

Objective:
We want to use the same procedure as experiment number 3 to measure the loss of a cable at different frequencies (called *Frequency Response* of the cable)

Equipment Required:
- a signal generator
- a Spectrum Analyzer
- the cable under measurement
- an interconnection cable
- connectors/gender adapters if required

Procedure:

- Be familiar with the procedure of power measurement with the Spectrum Analyzer following the instructions of exercise number 3.

- This measurement technique works in the same way as the previous one, it just requires an additional cable. It should be a short, good-quality cable. One end of the cable should always be connected to the Spectrum Analyzer, while the other will act like the power sensor of the power meter. With this scheme, the loss of the cable under test can be measured for different values of frequency, varying the frequency of the signal generator and of the Spectrum Analyzer. The calibration of the signal generator should be repeated for the different frequencies used. With enough measurements, you can plot a curve showing the loss at different frequencies: this curve is known as Frequency Response of the cable.

Experiment 6: Measurement of Cable Loss with Spectrum Analyzer and Tracking Generator.

Objective:

We want to use a Spectrum Analyzer with its own Tracking Generator to measure the loss of a cable in a continuous range of frequencies (called *Frequency Response* of the cable)

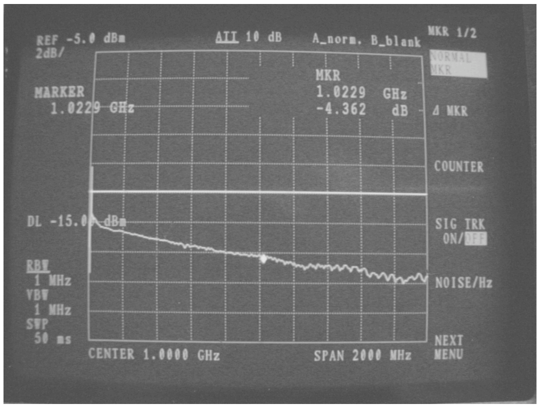
Equipment Required:

- a tracking generator which can be internal to the Spectrum Analyzer or an external accessory
- a Spectrum Analyzer
- the cable under measurement
- an interconnection cable
- connectors/gender adapters if required

Procedure:

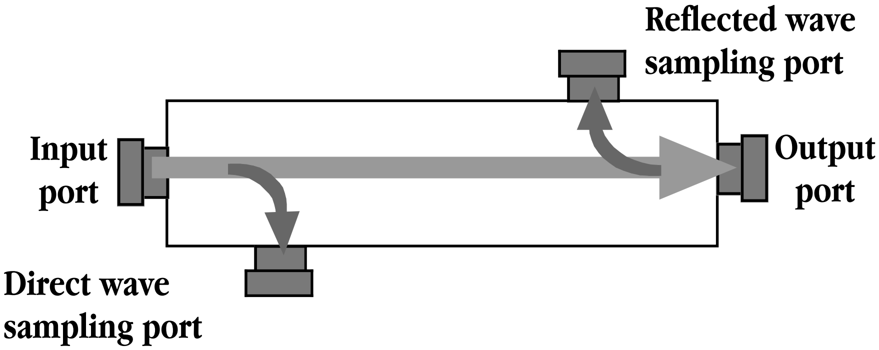
- Be familiar with the procedure of power measurement with the Spectrum Analyzer following the instructions of exercise number 3.

This measurement technique works in the same way as the previous one, but uses the tracking generator instead of the signal generator. It requires an initial calibration of the tracking generator, usually performed connecting the output of the tracking generator and the input of the Spectrum Analyzer with a short cable. Some devices, anyway, do not require this cable and perform automatically the calibration. After the calibration and the proper setting of the Spectrum Analyzer, simply connecting the tracking generator to the Spectrum Analyzer with the cable under test allows to get directly the frequency response of the cable in the chosen frequency range on the display. The difference between this measurement technique and the one with the signal generator is that in this case just one measurement is required instead of many. The usual attention should be given in taking into account the loss of the adapters in the total loss of the cable.



Use of the Directional Coupler for the measurement of Direct Power, Reflected Power and SWR

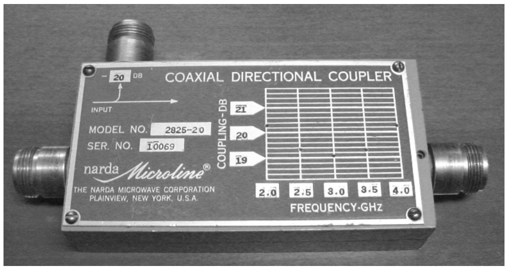
A *directional coupler* is a passive device used to separately extract, through a known *coupling loss*, either the incident (direct) or the reflected wave in a transmission line. The sampling ports have an output 10 to 30 dB less than the signal passing through it, while the pass-through signal is subject to negligible loss, called *insertion loss*.



The coupling factor represents the primary property of a directional coupler and is defined as

$$\text{Coupling factor (dB)} = -10\log\frac{P_c}{P_i}$$

where P_i is the input power and P_c is the output power at the coupled port. Coupling is not constant, but varies with frequency. While different designs may reduce the variance, a perfectly flat coupler theoretically cannot be built. The the graph of the coupling value at different frequencies, given in dB, is usually reproduced on the coupler itself.



A *unidirectional coupler* has available connections for extracting only one direction of transmission; a *bidirectional coupler* has available terminals for extracting both directions.

A function for which couplers offer an ideal solution is the measuring of RF power and comparing incident and reflected signals to calculate the SWR. Common properties desired for all directional couplers are wide operational bandwidth and a good impedance match at all ports when the other ports are terminated in matched loads.

Experiment 7: Measurement of Direct Power, Reflected Power and SWR with Signal Generator, Power Meter and Directional Coupler.

Objective:

We want to use a Directional Coupler to sample the direct and reflected signal to measure its power with a Power Meter. This will allow us to check if the line and the load are matched, having the correct value of impedance.

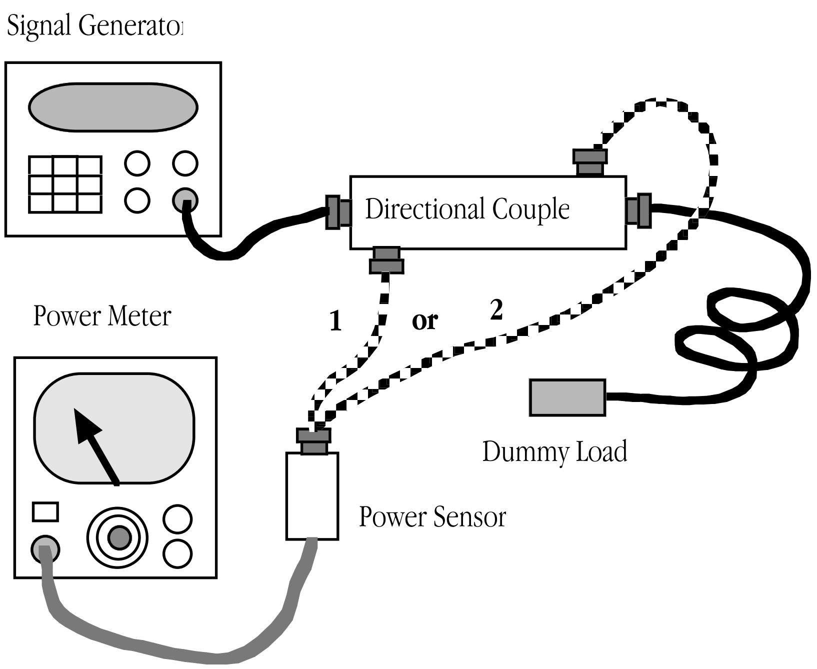
Equipment Required:

- a power meter
- a power sensor
- a signal generator
- an uni-directional coupler
- a bi-directional coupler
- a cable with an impedance of 50 Ω
- a cable with an impedance of 75 Ω
- a dummy load with an impedance of 50 Ω

- a dummy load with an impedance of 75 Ω
- connectors/gender adapters if required

Procedure:

- Be familiar with the procedure of power measurement with the Power Meter following the instructions of exercise number 2.



- Before starting the experiment, remember that overloading a device like the power meter may lead to damages or injury. Always estimate the power you are going to apply to the device before connecting it and be sure it fits in the accepted range. If you are not sure, adopt a safe setting.

1) Set the signal generator to output a carrier signal with a value of 0 dBm of average power and a frequency of 2.4 GHz. Disable any modulation. If possible, disable the output of the generator ("RF OFF").

2) Connect the power sensor to the power meter and calibrate them.

3) Connect the output of the signal generator to the input port of the directional coupler with a 50 Ω cable.

4) Connect the output port of the directional coupler to the 50 Ω dummy load.

5) Connect another 50 Ω dummy load to the reflected signal coupling port of the directional coupler.

6) Check the output level of the generator (it should be 0 dBm or 1mW). Estimate the coupling loss of the directional coupler and the losses of the cables at the working frequency and compute the expected power level at the direct coupling port of the directional coupler.

7) Be sure that this estimated value fits in the actual measurement range of the power meter, setting the range knob.

8) Connect the power sensor of the power meter to the direct signal coupling port of the directional coupler.

9) Enable the output of the signal generator.

10) If everything is correct, the power meter should indicate the expected value of the power. If you don't read the expected value or a near one, switch off immediately the generator and check carefully the connections, the setting of the instruments, the calculations and ask for assistance before repeating the measurement.

11) Disable the output of the signal generator. Disconnect the power sensor from the direct signal coupling port of the directional coupler. Disconnect the dummy load from the reflected signal coupling port of the directional coupler.

12) Connect the power sensor to the reflected signal coupling port of the directional coupler. Connect the 50 Ω dummy load to the direct signal coupling port of the directional coupler.

13) Enable the output of the signal generator, and measure the power with the power meter.

14) Being very low the expected value of the power of the reflected signal, due to the fact that the line is properly matched, modify gradually the setting of the power meter to reach the maximum sensitivity. You should still expect to read a value near to zero.

15) You can repeat the same procedure with a 75 Ω dummy load connected to the output of the directional coupler, or use a 75 Ω cable connected to the output of the directional coupler and terminated with a 50 Ω dummy load, or any other configuration which has an impedance mismatch after the directional coupler. In this case you should measure a reflected power different from zero.

16) With the mismatched configuration you may compute the SWR from the measured values of power of the forward and reflected waves as

$$\mathrm{SWR} = \frac{1 + \sqrt{\frac{P_r}{P_f}}}{1 - \sqrt{\frac{P_r}{P_f}}}$$

Use of the SWR meter for the measurement of SWR

An *SWR meter*, also called *Directional Wattmeter*, is a measuring device that contains a directional coupler for sensing the forward and reflected components of the signal that pass through it. Usually a meter sensitivity control is provides so that when sensing forward power the meter can be set for a full-scale reading. The meter scale can be calibrated to show SWR directly when switched to sense the reflected component. In modern instruments the signal processing and display circuits compute and display the SWR.

One of the most common SWR meters family is the “Bird” one. They provide an easy way to switch between frequency and power ranges by using different plug-in elements, also called “slugs”, which have an arrow over them to indicate the direction of the measured power. The power range goes from 0 to 10kW, and the frequency range is from 450 kHz to 2.7 GHz. There can be place for one or two slugs. With only one slug, two measurements are required to compute the SWR (and you have to rotate the slug of 180°), while in the model with two slugs only one measurement is required to measure both the forward and reflected power and therefore the SWR. An SWR meter can also be used to measure the power as a through-line power meter.

Measures of Impedance of a Coaxial Cable

We are going to calculate the characteristic impedance of a coaxial cable using three different methods:

- Measuring the physical characteristics of the cable

- Using Time Domain Pulse Reflection. With this method we are also going to locate a disturbance along the cable

- Using an SWR meter

To calculate the characteristic impedance of a coaxial cable using its *physical characteristics*, we must consider the values of the distributed capacity and of the distributed inductance. For a coaxial cable, the distributed capacity is equal to

$$C = \frac{2\pi\varepsilon_0}{\log_{10}\frac{b}{a}}\left(\frac{\text{farads}}{\text{meter}}\right)$$

and the distributed inductance is

$$L = \frac{\mu_0}{2\pi}\log_{10}\left(\frac{b}{a}\right)\left(\frac{\text{henries}}{\text{meter}}\right)$$

where b is the inside radius of the outer conductor and a is the outside radius of the inner conductor.

At radio frequency the characteristic impedance becomes a pure resistance if we neglect the ohmic resistance and the shunt conductance of the line. We then have

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\log_{10}\left(\frac{b}{a}\right)\frac{1}{\sqrt{\varepsilon_r}}$$

The characteristic impedance becomes

$$Z_0 = \frac{1}{2\pi} 377 \log_{10}\left(\frac{b}{a}\right)\frac{1}{\sqrt{\varepsilon_r}}$$

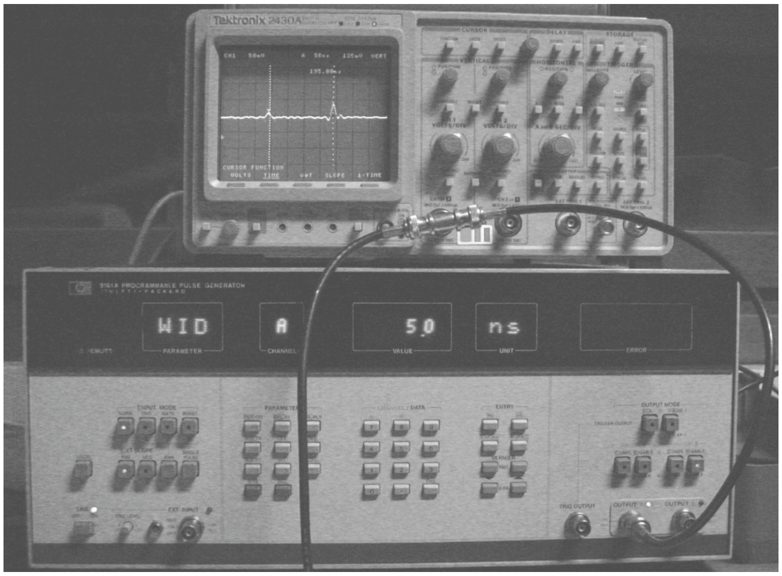
where ε is the dielectric constant of the insulation between the conductors.

For example, if we measure the physical dimensions of the RG-58/U coaxial cable, we find the following values: the inner conductor diameter is 0.8 millimeters and the outer conductor diameter is 5 millimeters. We know that the relative dielectric constants of the polyethylene used in the RG-58/U is equal to 2.3. We then have

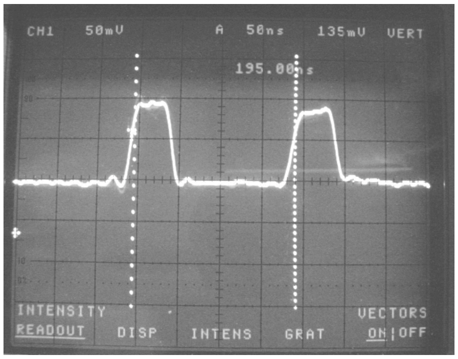
$$Z_0 = 49.7359\Omega$$

This result is very near to the known value of $\mathbf{50\Omega}$.

A *Time Domain Reflectometer (TDR)* is a simple but powerful tool to evaluate transmission lines. The technique used in time-domain reflectometer consists of feeding an impulse of energy into the system and then observing that energy as it is reflected by the system at the point of insertion. A TDR may be assembled using a square wave (or pulse) generator and an oscilloscope.



The generator sends a sequence of pulses down a transmission line, and with the oscilloscope it is possible to sample the signal and observe the incident and reflected pulses. When the fast-rise input pulse meets with a discontinuity or impedance mismatch, the resultant reflections are compared in time and amplitude with the original pulse.



By analyzing the magnitude and shape of the reflected waveform, you can determine the nature of the impedance variation in the transmission system. Also, since distance is related to time and the amplitude of the reflected step is directly related to impedance, the comparison indicates the distance to the fault as well as the nature of the fault. In addition to this, time-domain reflectometer also reveals the characteristic impedance of the line. After the round trip delay of the cable, the reflected voltage arrives back to the oscilloscope and is added to the incident voltage on the oscilloscope to produce the measured voltage value V_m. If we know the impedance of the load Z_l and if we call V_r the value of the reflected voltage and V_i the value of the incident voltage, we can use the following equations to calculate the characteristic impedance of the line:

$$\frac{V_r}{V_i} = \frac{Z_l - Z_0}{Z_l + Z_0}$$

$$\frac{V_m}{V_i} = \frac{V_r + V_i}{V_i} = 1 + \frac{V_r}{V_i} =$$

$$= 1 + \frac{Z_l - Z_0}{Z_l + Z_0} = \frac{Z_l + Z_0 + Z_l - Z_0}{Z_l + Z_0} = \frac{2Z_l}{Z_l + Z_0}$$

A TDR can be also used to determine the position of a disturbance along a line, for example the position of a short circuit. The location of the disturbance is calculated with a simple proportional method. The round-trip time to the disturbance can be read from the oscilloscope grid. Thus, you need only to read the time, multiply it by the velocity of the radio wave on the specific cable (which is given by the speed of light multiplied by a factor called the velocity factor of the cable, VF) and divide it by two. The distance of the disturbance is then calculated as

$$l = \frac{300 \times VF \times t}{2}$$

Where *l* is the length in meters, *t* is the time delay in microseconds and VF is the velocity factor of the line.

Experiment 8: Measurement of the characteristic impedance of a coaxial cable with a TDR.

Objective:

We want to measure the characteristic impedance of a coaxial cable with a TDR.

Required equipment:

- a piece of RG-58/U coaxial cable with connectors
- a square wave generator
- an oscilloscope
- a load impedance of known value

Procedure:

We must first of all know the value of the load impedance. For example, it can be a 75Ω impedance. We must then set the Amplitude of the incident voltage waveform on the square wave generator. To make calculations easier, we can set this value to 1 V. The oscilloscope has then to be synchronized to the pulses. We are now ready to measure the value of the resulting step. If we measure a step of 1.2 V on the oscilloscope, we can use the formulas and obtain:

$$\frac{1.2}{1} = \frac{2 \times 75}{75 + Z_0}$$

The value of the unknown characteristic impedance is then 50Ω.

Experiment 9: Location of a disturbance along a coaxial cable with a TDR.

Objective:

We want to determine the position of a disturbance along a line with a TDR, for example the position of a short circuit.

Required equipment:

- a piece of RG-58/U coaxial cable with connectors
- a square wave generator
- an oscilloscope
- a pair of scissors

Procedure:

- If we want to determine the position of a disturbance, we must first of all create a "simulated" disturbance, for example with an open circuit at the end of the cable. We must use a pulse generator capable of generating short and fast rising pulses. For cable lengths in the order of meters, the pulses width should be in the range of 10 ns. We must synchronize the oscilloscope with the pulses. We can then measure on the oscilloscope grid the time it takes at the incident pulse to come back from the disturbance. If we measure a time of 0.16 μs, we are able to determine the position of the disturbance as

$$l = \frac{300 \times 0.66 \times 0.16}{2} = 15.84 \text{ meters}$$

where 0.66 is the velocity factor of the coaxial cable.

To calculate the characteristic impedance of a coaxial cable using an SWR meter, we must find the relationship between the value of the SWR and the characteristic impedance. We know that

$$r = \frac{Z_a - Z_0}{Z_a + Z_0} = \frac{(R_a \pm jX_a) - (R_0 \pm jX_0)}{(R_a \pm jX_a) + (R_0 \pm jX_0)}$$

In most cases, the characteristic impedance is completely resistive, meaning that $Z_0=R_0$ and $X_0=0$. We can choose a known load impedance which is resistive too, meaning that $Z_a=R_a$ and $X_a=0$. In this way we have

$$|\rho| = \sqrt{\frac{(R_a - R_0)^2}{(R_a + R_0)^2}}$$

We know that the relationship between the absolute value of ρ and the SWR is

$$|\rho| = \frac{SWR - 1}{SWR + 1}$$

Combining the two equations, we have

$$\frac{SWR - 1}{SWR + 1} = \sqrt{\frac{(R_a - R_0)^2}{(R_a + R_0)^2}}$$

$$\left(\frac{SWR - 1}{SWR + 1}\right)^2 = \frac{(R_a - R_0)^2}{(R_a + R_0)^2}$$

$$\frac{(SWR - 1)^2}{(SWR + 1)^2} = \frac{(R_a - R_0)^2}{(R_a + R_0)^2}$$

$$\gamma = \frac{(SWR - 1)}{(SWR + 1)} = \frac{(R_a - R_0)}{(R_a + R_0)}$$

If we measure the SWR with an SWR meter, and we indicate the ratio on the left as γ, we can calculate the value of R_0 as

$$R_0 = R_a \frac{1 - \gamma}{1 + \gamma}$$

For example, if we want to determine the characteristic impedance with an SWR meter, we must first of all place a 50 Ω load at the end of the cable. Using the SWR meter, we measure the value of SWR. Assuming that it is 1.4, then we calculate γ as

$$\gamma = \frac{(\text{SWR} - 1)}{(\text{SWR} + 1)} = \frac{0.4}{2.4} = 0.166$$

We can then determine the characteristic impedance as

$$R_0 = R_a \frac{1 - \gamma}{1 + \gamma} = 35.7143\Omega$$