**SİVAS UNIVERSITY OF SCIENCE AND TECHNOLOGY**
**FACULTY OF ENGINEERING AND NATURAL SCIENCES**

# INTRODUCTION TO RF AND MICROWAVE ENGINERING

**Experiments Manual Report**

**Supervisor:** Prof. Dr. Fatih KABURCUK
**Research Assistant:** Kağan Murat PÜRLÜ
**Research Assistant:** Şekip DALGAÇ

Spring 2024-2025

# Content

**Basic Concepts and Theoretical Background**
**1. Introduction**

A slotted transmission line is a type of transmission line used to sample the electric field intensity of the standing wave formed on a terminated line. The characteristic impedance of the slotted transmission line employed in this experiment is 50 Ω.

As shown in Figure 1, the slotted transmission line comprises three ports: the generator port, the load port, and the probe port. By transmitting an RF signal from the generator port and sampling the standing wave produced whose pattern depends on the match at the load port at various positions along the line via the probe port, one can calculate the Voltage Standing Wave Ratio (VSWR). From the VSWR and the electrical distance between a null of the standing wave and the load, the load impedance can be determined. The spatial period of the standing wave is proportional to the wavelength of the RF signal on the transmission line.

Figure 1.1. Slotted Transmission Line

**1.1 Characteristic Impedance**

A transmission line can be represented as a circuit of capacitance and inductance, as shown in Figure 1.2. Although the series resistance due to conductor losses and the shunt conductance due to dielectric losses would normally be uniformly distributed, they are neglected here. The characteristic impedance is defined as

$$Z_0 = \sqrt{\frac{L}{C}} \quad (1)$$

where L is the inductance per unit length and C is the capacitance per unit length.

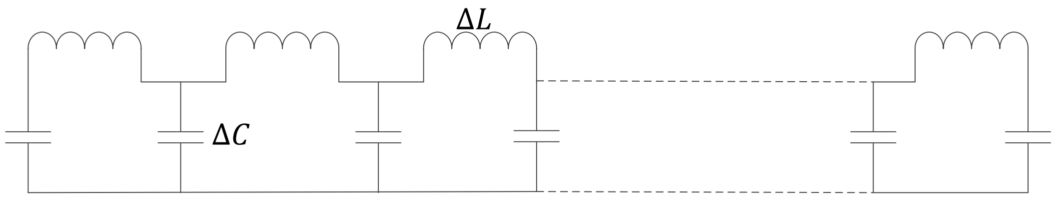



Figure 1.2. Transmission Line

The speed of electromagnetic waves is known to depend on the medium through which they propagate. For a transmission line, this speed is defined as

$$v = \frac{1}{\sqrt{LC}} \quad (2)$$

If the wave propagates in a dielectric medium whose effective relative permittivity $\varepsilon_r$ is greater than unity, then

$$v = \frac{c}{\sqrt{\varepsilon_r}} \quad (3)$$

**1.2 Standing Waves**

The performance of transmission lines can be explained by the behavior of electromagnetic waves within the line. The wave sent by the signal generator at one end is partially or fully reflected at the load, depending on the load impedance at the other end. The reflected waves travel back toward the generator with a 360° phase delay.

The pattern formed by the incident and reflected waves is called a standing wave. The maxima of the standing wave occur when the incident and reflected waves are in phase, and the minima occur when these waves are 180° out of phase.

The amplitude and phase of the reflected wave are related to those of the incident wave and can be characterized as a function of the load. In a slotted transmission line, the load impedance can be determined by directly observing the parameters of the standing wave.

The amplitudes and phases of the reflected and incident waves

$$\frac{E_i}{I_i} = Z_0 \tag{4}$$

$$\frac{E_r}{I_r} = Z_0 \tag{5}$$

In these equations, $E_i$ represents the complex voltage of the incident wave, $I_i$ the complex current of the incident wave, $E_r$ the complex voltage of the reflected wave, and $I_r$ the complex current of the reflected wave. $Z_0$ denotes the characteristic impedance of the slotted transmission line, which in this experiment is 50.

In the relation between the incident and reflected waves, the reflection coefficient where $Z_x$ is the complex impedance of the load is defined as:

$$\Gamma = \frac{Z_x - Z_0}{Z_x + Z_0} \tag{6}$$

Additionally, the relationships between the voltages and currents of the reflected and incident waves can be expressed as:

$$E_r = E_i\Gamma \tag{7}$$

$$I_r = -I_i\Gamma \tag{8}$$

The maximum voltage of the standing-wave pattern on the transmission line is $E_{max} = |E_i| + |E_r|$ or $E_{max} = |E_i|(1 + |\Gamma|)$ and the minimum voltage is $E_{min} = |E_i| - |E_r|$ or $E_{min} = |E_i|(1 - |\Gamma|)$.

The voltage standing-wave ratio (VSWR), defined as the ratio of the maximum to minimum voltages, is

$$VSWR = \frac{E_{max}}{E_{min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{9}$$

The spectrum analyzer trace of the sample taken on the slotted transmission line displays the power profile of the electromagnetic wave. For a sinusoidal wave, the relationship between power and voltage is

$$p_{max}(watt) = \frac{\left( E_{max} / \sqrt{2} \right)^2}{Z_0} \qquad (10)$$

from which the standing-wave voltage $E_{max}$ can be determined.

In a lossless transmission line, the input impedance $Z_p$ at any point toward the load is the ratio of the complex voltage to the complex current. As shown in Figure 1.4, this impedance repeats every half-wavelength. The reflected voltage and current waves are 180° out of phase: where the standing-wave voltage reaches its maximum, the current is at its minimum, and vice versa. The incident voltage and current waves, by contrast, remain in phase at all points.

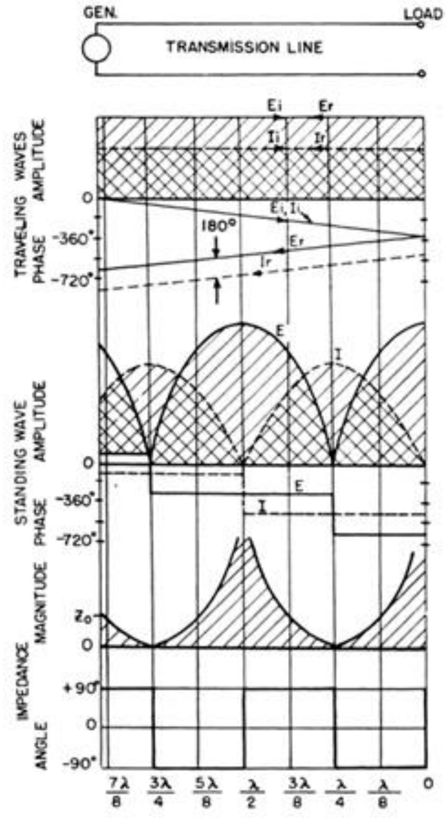



Figure 1.4. Open-Circuited Transmission Line

As shown in Figure 1.4, the behavior of the incident and reflected voltage and current waves visualized for an open-circuit load on an open-terminated transmission line is analogous for any unknown load. The effective voltage and current waves—resulting from the superposition of the incident and reflected waves—are in phase at the points where the voltage is maximum. At those locations, the effective impedance is purely resistive and can be expressed as

$$R_{p\,max} = Z_0 \cdot VSWR \tag{11}$$

Where the voltage is minimum, the incident and reflected voltage waves are 180° out of phase, while the incident and reflected current waves remain in phase. Under these conditions, the effective impedance is again purely resistive and is given by

$$R_{p\,min} = \frac{Z_0}{VSWR} \tag{12}$$

The impedance at an arbitrary point p on the transmission line can be written as

$$Z_p = Z_0 \cdot \frac{Z_x + jZ_0 tan\theta}{Z_0 + jZ_x tan\theta} \tag{13}$$

where $Z_0$ is the characteristic impedance of the line, $Z_x$ is the load impedance, and θ is the electrical distance between the load and point p.

Similarly, the load impedance can be expressed in terms of a known impedance $Z_p$ measured at point p:

$$Z_x = Z_0 \cdot \frac{Z_p - jZ_0 tan\theta}{Z_0 - jZ_p tan\theta} \tag{14}$$

By using the standing-wave parameters measured on the slotted line, the impedance of an unknown load can be determined. In particular, the load impedance can be shown to satisfy

$$Z_x = Z_0 \, . \frac{1 - j(VSWR)tan\theta}{VSWR - jtan\theta} \tag{15}$$

$$= Z_0 \, . \frac{2(VSWR) - j(VSWR^2 - 1)\sin 2\theta}{(VSWR^2 + 1) + (VSWR^2 - 1)\cos 2\theta} \tag{16}$$

Here, θ is obtained from the electrical distance between the load and the nearest voltage minimum on the standing-wave pattern. To find θ, one first terminates the slotted line in a short circuit (see Figure 1.5) and marks the voltage minimum closest to the load. Then, with the unknown load connected, one locates the nearest voltage minimum and measures the electrical separation between these two minima; that separation is θ.

If the VSWR is much larger than tanθ, the load's equivalent resistance and reactance can be approximated by

$$R_x \cong \frac{Z_0}{VSWR\ cos^2\theta} \tag{17}$$

$$X_x \cong -Z_0 tan\theta \tag{18}$$

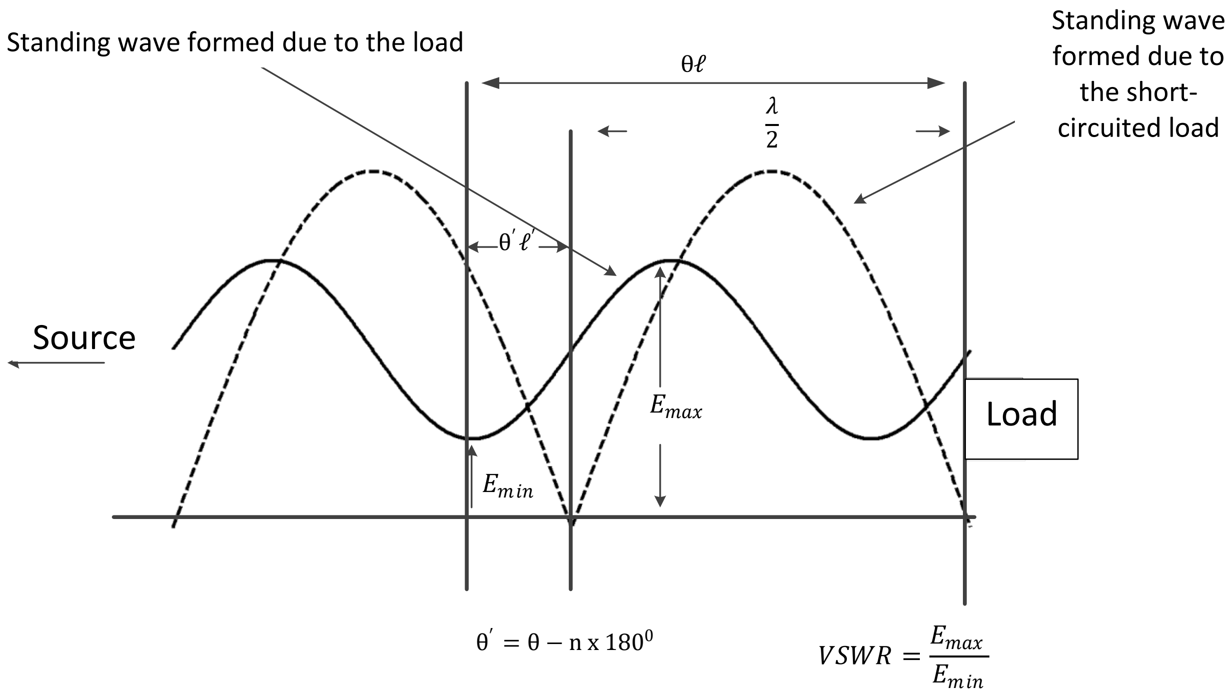



Figure 1.5. Relationship between Load Impedance and Standing Wave Pattern

Additionally, the VSWR and the electrical distance θ can be determined using a load with a known impedance.

$$VSWR = \frac{1}{2Z_0\ Re\{Z_x\}}\left(m \pm \sqrt{m^2 + 4{Z_0}^2 Im\{Z_x\}}\right) \tag{19}$$

$$\theta = arctan\left[\frac{1}{2Z_0\ Im\{Z_x\}}\left(m \pm \sqrt{m^2 + 4{Z_0}^2 Im\{Z_x\}}\right)\right] \tag{20}$$

$$m = {Z_0}^2 - |Z_x|^2 \tag{21}$$

## 1.3 Smith Chart

The Smith Chart, developed by P. H. Smith, is a method that simplifies the procedures outlined in the previous section for determining the load impedance on a slotted line. In the attached Smith Chart, the horizontal axis passing through the center of the circle—representing constant resistance values—is called the Resistance Component axis. The circles intersecting the Resistance Component axis correspond to constant reactance values. Using the Smith Chart, all impedance values from zero to infinity can be mapped. By locating a point on the chart, the corresponding resistance and reactance define the unknown impedance. As the distance from any point on the transmission line to the unknown load changes, the corresponding point for the load impedance rotates around the Smith Chart. This angular movement is proportional to the electrical length along the line; one full revolution around the chart corresponds to half a wavelength. The radius of the circle to be drawn is a function of the VSWR.

### 1.3.1 Calculation of the Load Impedance from VSWR and the Voltage Minimum

When an unknown load is connected to the slotted line, the impedance at the point of minimum measured voltage is purely resistive. This resistance equals $\frac{Z_0}{VSWR}$ . Normalize this resistance by $Z_0$ (the characteristic impedance of the line) and plot it on the Smith Chart along the Resistance Component axis. If you draw a circle through this point centered at the Smith Chart's center, then every point on that circle corresponds to the impedance at some location along the transmission line.

On the Smith Chart, the directions labeled "WAVELENGTH TOWARDS LOAD" and "WAVELENGTH TOWARDS GENERATOR," which are scaled in wavelength units, indicate the direction to move along the circle of radius $\frac{Z_0}{VSWR}$ (centered on the chart) when locating the unknown load.

The load impedance can also be determined by using the electrical distance from the voltage minimum to the generator. This electrical distance specifies the angular displacement to move along the circle of radius $\frac{Z_0}{VSWR}$ in the "WAVELENGTH TOWARDS GENERATOR" direction. From the point marked on that circle, a line drawn to intersect the Resistance Component axis gives the load's resistance value. Similarly, a line drawn from the marked point to intersect the inductive or capacitive Reactance Component circles gives the load's reactance value.

Figure 1.6 shows that, for a slotted-line measurement with VSWR = 5 and an electrical distance of 0.14 λ from the voltage minimum to the load, the load impedance is found to be 23 – j55 Ω. As also seen in Figure 1.6, the load admittance lies 0.25 λ away from the corresponding impedance point. From the admittance point, the ray intersecting the conductance-component axis gives the conductance value, and the ray intersecting the susceptance-component axis gives the susceptance value.

### 1.3.2 Calculation of Impedance from One Point to Another on the Transmission Line

If the impedance $Z_p$ at a point p on the transmission line is known, and you wish to find the impedance $Z_x$ at another point whose electrical distance from p is known (for example, the load point), you can use the Smith Chart as follows.

First, plot the known impedance $Z_p$ on the Smith Chart and draw a circle centered at the chart's center passing through that point. If the point whose impedance you wish to find lies toward the load, move along this circle in the "WAVELENGTH TOWARDS LOAD" direction by an angular amount corresponding to the electrical length (expressed in wavelengths). The point you land on gives the impedance $Z_x$ at the desired location.

If the point at which the impedance is to be determined lies toward the signal generator, the impedance $Z_x$ can be found by moving along the circle in the "WAVELENGTH TOWARDS GENERATOR" direction by an angular amount corresponding to the electrical length (expressed in wavelengths).

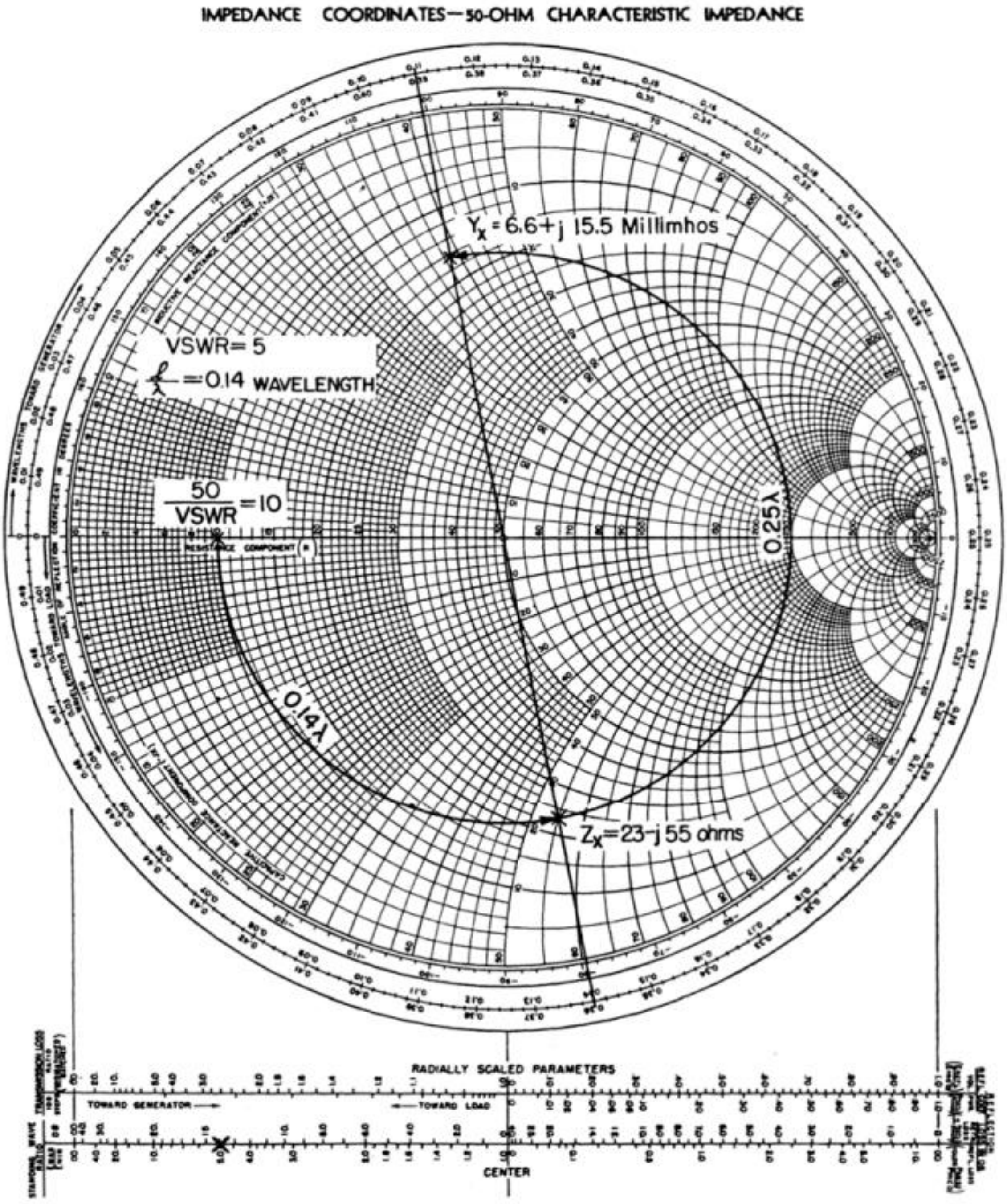



Figure 1.6. Smith Chart example illustrating impedance calculation from VSWR and the minimum-voltage point.

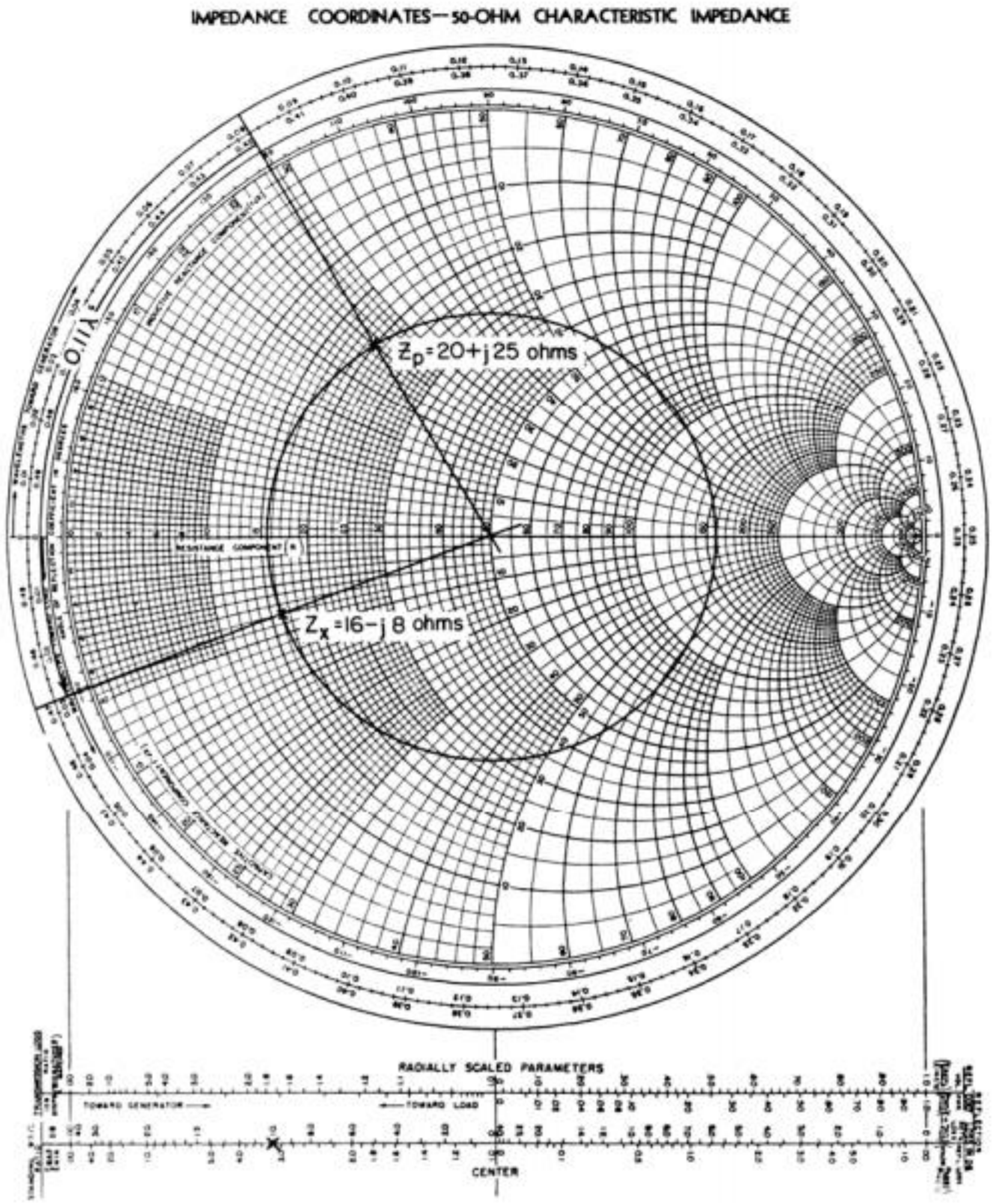



Figure 1.7. Smith Chart example illustrating impedance calculation from one point to another on the transmission line.

## 2. Equipment and Connection Diagram

- Y-8004-01 Slotted Transmission Line*

- Y-8005-09 RF Generator & Measurement Unit (Spectrum Analyzer with optional Tracking Generator)
- Tablet, Android Phone, or Computer (optional)
- One 45 cm SMA male to SMA male RF cable
- One 90 cm SMA male to SMA male RF cable
- Open-circuit load, short-circuit load, 50 Ω load, unknown load

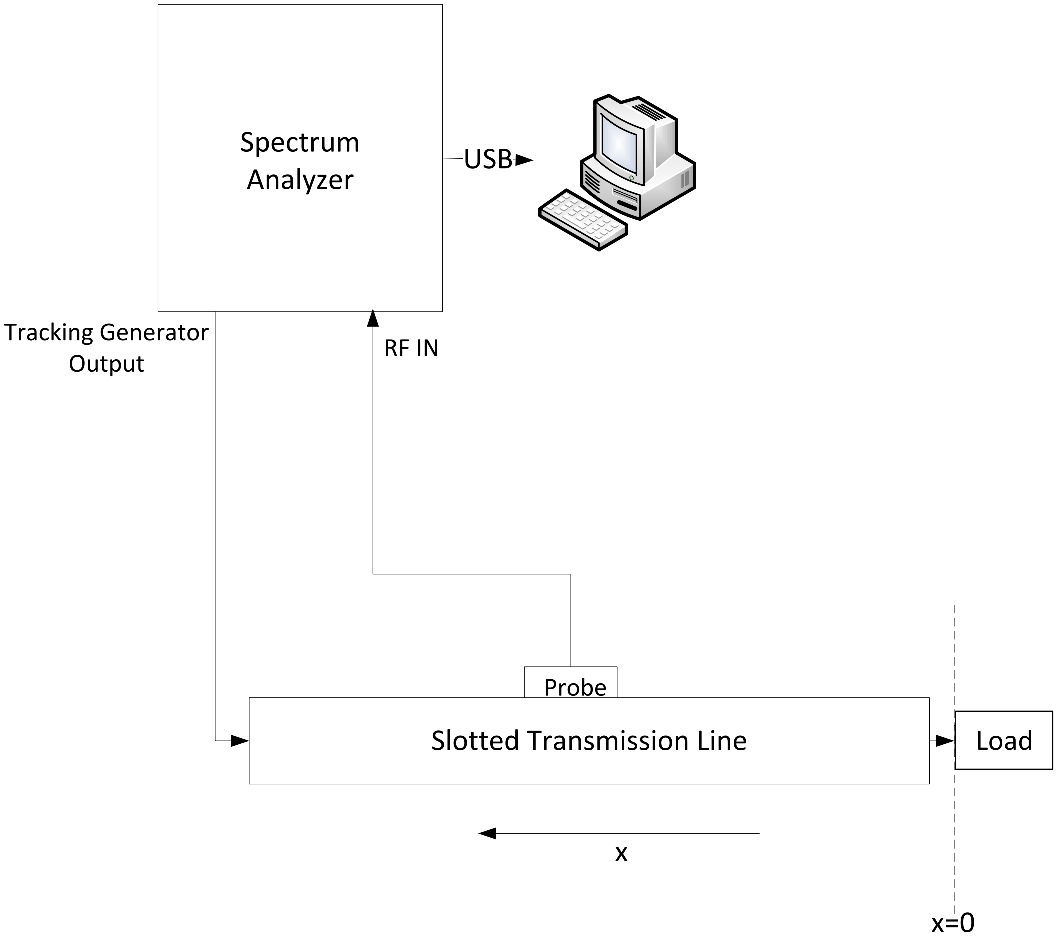



Figure 2.1. Experimental Connection Diagram

*The load port and generator port are not marked on the slotted transmission line. In the experiments, the end corresponding to the 0 cm mark on the scale is assumed to be the load port.

**Experiments**
**1. Standing Wave Experiment**
**1.1. Objective**

The aim of this experiment is to demonstrate the formation of standing waves on a slotted transmission line by using a movable probe to map out the voltage minima and maxima along the line. By accurately measuring the distances between successive minima, you will determine the guided wavelength and calculate the propagation velocity of the wave. Through this procedure, you will deepen your understanding of wave interference, impedance mismatches, and their effects on power transfer in RF transmission lines.

**1.2. Experimental Setup**

As shown in Figure 2.1.

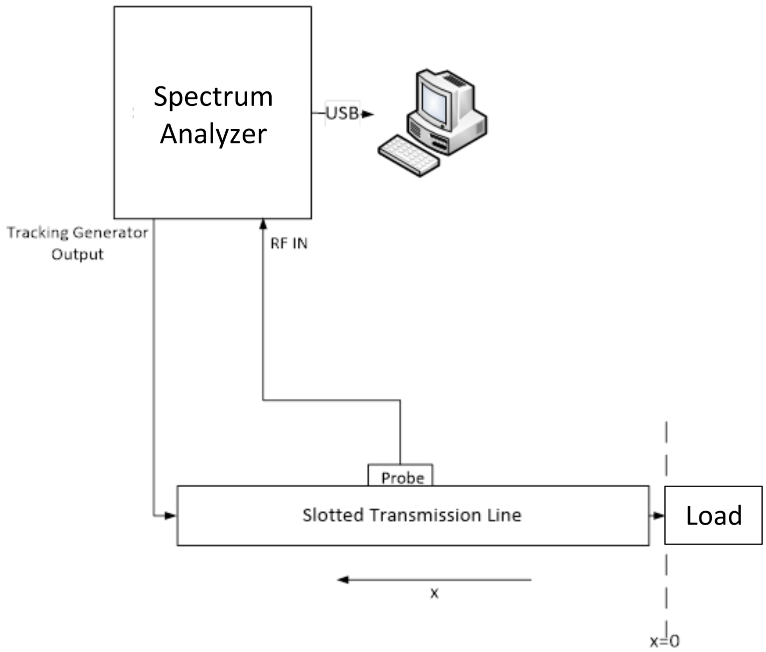



Figure 2.1. Experimental Connection Diagram

**1.3. Procedure**

- Set the RF signal generator to 2 GHz and –15 dBm output power. Configure the spectrum analyzer with a center frequency of 2 GHz, a span of 0.5 MHz, and a reference level of –20 dBm.

- Connect the Port-1 side of the unknown load to the load port.

- Slide the probe from 0 cm to 30 cm in 1 cm increments. At each position, record the power value displayed on the spectrum analyzer, mark it on the graph in Appendix 1, and plot the curve.

- In the vicinity of each minimum point (±1 cm), use millimeter precision to locate the absolute minimum power. Mark both its position and power value clearly on the graph.

- From the graph, determine the relationship between the positions of successive standing-wave minima.

…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………
………………

- What is the reason the y-axis of the graph is not divided into equal intervals?

## 2. Wavelength Experiment
### 2.1. Objective

The objective of this experiment is to determine the RF signal's wavelength by measuring the standing-wave period on a slotted transmission line. By recording the positions of successive voltage minima, you will calculate the guided wavelength and use it to compute the signal frequency. This procedure will reinforce your understanding of wave propagation and standing-wave formation in transmission lines.

### 2.2. Experimental Setup

As shown in Figure 2.1.

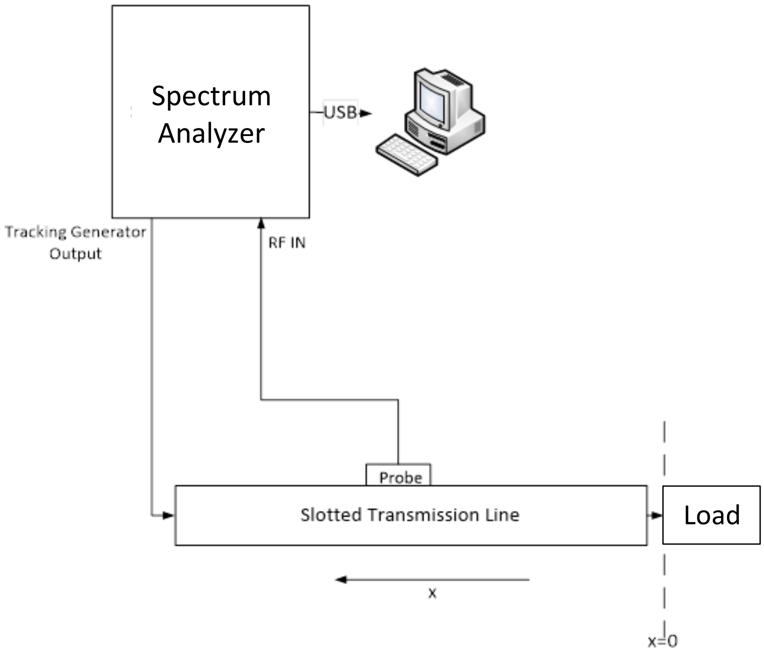



Figure 2.1. Experimental Connection Diagram

### 2.3. Procedure

- Set the RF signal generator to 2 GHz and the output power to –15 dBm. Configure the spectrum analyzer with a center frequency of 2 GHz, a span of 0.5 MHz, and a reference level of –20 dBm.

- Connect a 50 Ω load to the load port.

- When you move the probe from end to end of the slotted transmission line and back, can you clearly observe the maximum and minimum signal levels on the spectrum analyzer display? Why?

……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………

- Connect an open-circuit load to the load port.
- Move the probe along the slotted transmission **line toward the signal generator** until the lowest level appears on the spectrum analyzer display. Record the position of this lowest level as $l_{min1}$.

  $l_{min1}$ : ........................................................
- Move the probe along the slotted transmission line toward the signal generator (in the X direction) until the highest level appears on the spectrum analyzer display. Record the position of this highest level as $l_{max}$.

  $l_{max}$ : ........................................................
- Can you determine the wavelength of the signal from the values of $l_{min1}$ and $l_{max}$?

  $\lambda_1$ : ........................................................
- What is the wavelength in air corresponding to the frequency you set on the RF signal generator?

  $\lambda_{teo}$ : ........................................................
- Are the values of $\lambda_{teo}$ and $\lambda_1$ consistent?

……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………
………………

- Starting from the point $l_{max}$ on the slotted transmission line, move the probe toward the signal generator (in the X direction) until the lowest level appears on the spectrum analyzer display. Record the position of this lowest level as $l_{min2}$.

  $l_{min2}$ : .......................................................

- Using the points $l_{min1}$ and $l_{min2}$ determine the wavelength of the RF signal.

  $\lambda_2$ : .......................................................

- Which of the values $\lambda_1$ and $\lambda_2$ is more consistent with the theoretical value $\lambda_{teo}$? Why?

  …………………………………………………………………………………………
  …………………………………………………………………………………………
  …………………………………………………………………………………………
  …………………………………………………………………………………………
  …………………………………………………………………………………………
  …………………………………………………………………………………………
  ………………………………

  Hold the probe at the $l_{min2}$ position on the slotted transmission line.

- Connect a short-circuit load to the load port.
- Move the probe along the slotted transmission **line toward the load port** until the lowest signal level appears. Record the position of this lowest level.

  $l_{min3}$ : .......................................................

- What is the relationship between the points $l_{min2}$ and $l_{min3}$ and the wavelength of the RF signal? How can you explain this relationship?

  …………………………………………………………………………………………
  …………………………………………………………………………………………
  …………………………………………………………………………………………
  …………………………………………………………………………………………
  …………………………………………………………………………………………
  …………………………………………………………………………………………
  ………………………………

### 3.VSWR Measurement

### 3.1. Objective

The objective of this experiment is to determine the Voltage Standing Wave Ratio (VSWR) of an unknown load using a slotted transmission line and movable probe. By measuring the highest and lowest signal levels along the line, you will calculate the reflection coefficient and from it the VSWR. This procedure will deepen your understanding of impedance mismatches and standing-wave behavior in RF systems.

### 3.2. Experimental Setup

As shown in Figure 2.1.

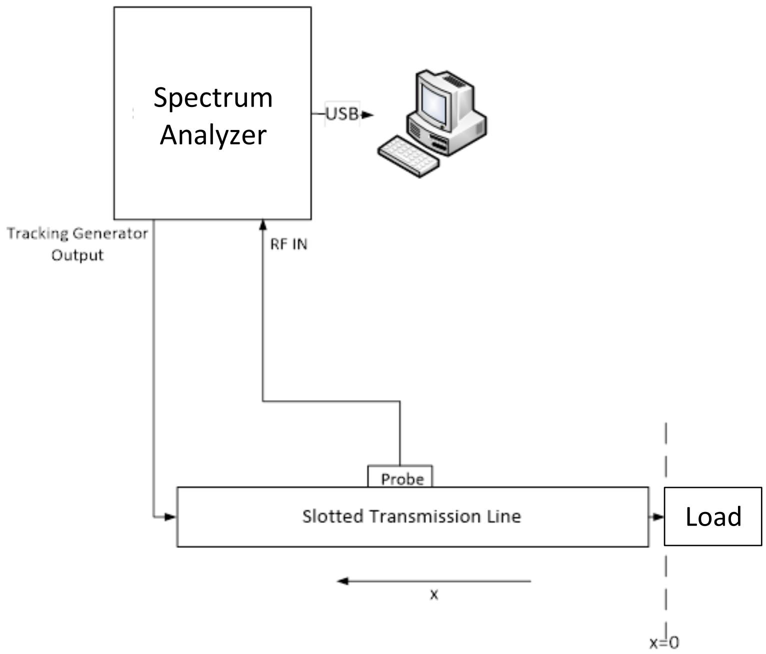



Figure 2.1. Experimental Connection Diagram

### 3.3. Procedure

- Set the RF signal generator to 2 GHz and the output power to –15 dBm. Configure the spectrum analyzer with a center frequency of 2 GHz, a span of 0.5 MHz, and a reference level of –20 dBm.
- Connect the Port-1 side of the unknown load to the load port.
- Move the probe toward the signal generator until the lowest signal level appears on the spectrum analyzer display. Record this minimum level.

$p_{1-min}$(dBm): ........................................................

- Move the probe toward the signal generator until the highest signal level appears on the spectrum analyzer display. Record this maximum level.

  $p_{1-max}$(dBm): ........................................................

- Using the values $p_{1-min}$(dBm) and $p_{1-max}$(dBm) calculate the VSWR of the load.

  $VSWR_1$: ........................................................

- Connect the Port-2 side of the unknown load to the load port.
- Move the probe **toward the signal generator** until the lowest signal level appears on the spectrum analyzer display. Record this minimum level.

  $p_{2-min}$(dBm): ........................................................

- Move the probe toward the signal generator until the highest signal level appears on the spectrum analyzer display. Record the highest level value.

  $p_{2-max}$(dBm): ........................................................

- Using the values $p_{2-min}$(dBm) and $p_{2-max}$(dBm) calculate the VSWR of the load.

  $VSWR_2$: ........................................................

## 4. Impedance Measurement

### 4.1. Objective

The objective of this experiment is to determine the complex impedance of an unknown load by using a slotted transmission line and movable probe. By locating the positions of successive minima (and maxima) along the line and calculating the corresponding reflection coefficient, you will derive both the magnitude and phase of the load impedance. This procedure will deepen your understanding of impedance matching and standing-wave behavior in RF transmission lines.

### 4.2. Experimental Setup

As shown in Figure 2.1.

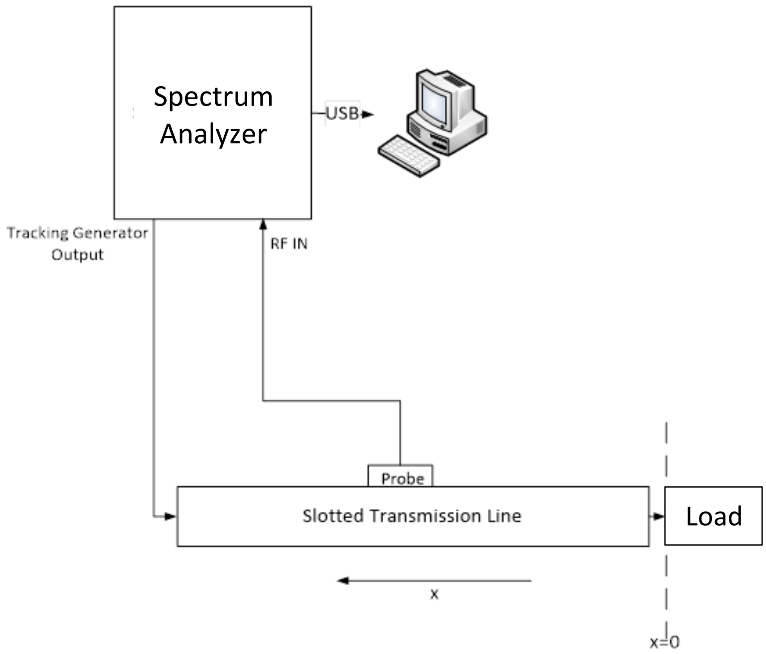



Figure 2.1. Experimental Connection Diagram

### 4.3. Procedure

- Set the RF signal generator to 2 GHz and the output power to –15 dBm. Configure the spectrum analyzer with a center frequency of 2 GHz, a span of 0.5 MHz, and a reference level of –20 dBm.
- Connect the short-circuit load to the load port.

- From X=0, move the probe **toward the signal generator** until the lowest signal level appears on the spectrum analyzer display. Record the position of this minimum:

$k_{min1}$ : ........................................................

- Connect the Port-1 side of the unknown load to the load port.
- From $k_{min1}$, move the probe **toward the signal generator** until the lowest signal level appears on the spectrum analyzer display. Record the minimum level and its position:

$p_{min}$(dBm): ........................................................
$k_{min2}$ : ............................................................

- From $k_{min2}$, move the **probe toward the signal generator** until the highest signal level appears on the spectrum analyzer display. Record the maximum level and its position:

$p_{max}$ (dBm):........................................................
$k_{max}$ : ................................................................

- Calculate the load's VSWR from $p_{min}$(dBm) and $p_{max}$(dBm):

$VSWR$: ............................................................
- Compute the electrical distance between $k_{min1}$ and $k_{min2}$:
$\theta$ : .....................................................................
- From the values of VSWR and θ, calculate the load impedance:
$Z_L$ : .....................................................................

## 5. Smith Chart

### 5.1. Objective

The objective of this experiment is to use a Smith Chart to determine the impedance of an unknown load from standing-wave measurements. By plotting the measured reflection coefficient on the chart, you will directly read both the resistive and reactive components of the load impedance. This exercise will enhance your ability to interpret and apply Smith Chart techniques for RF impedance analysis.

### 5.2. Experimental Setup

As shown in Figure 2.1.

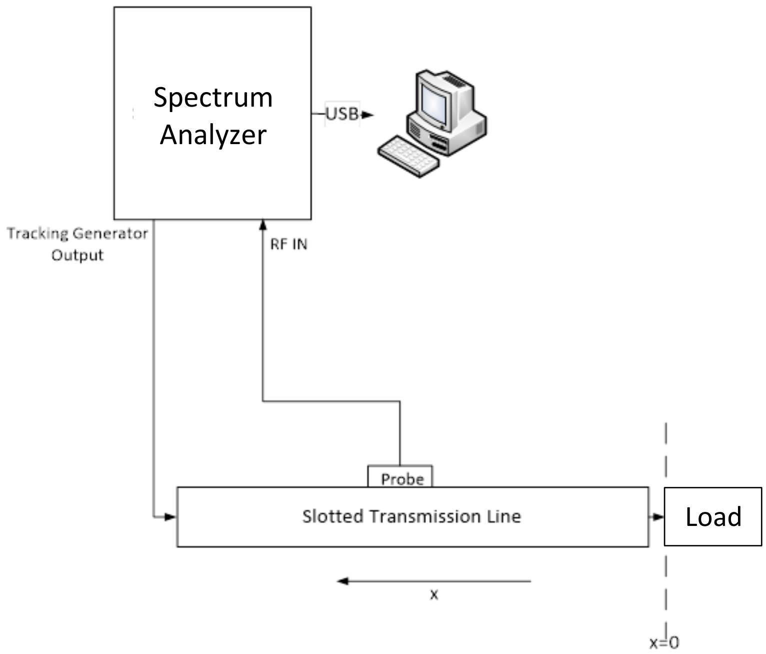



Figure 2.1. Experimental Connection Diagram

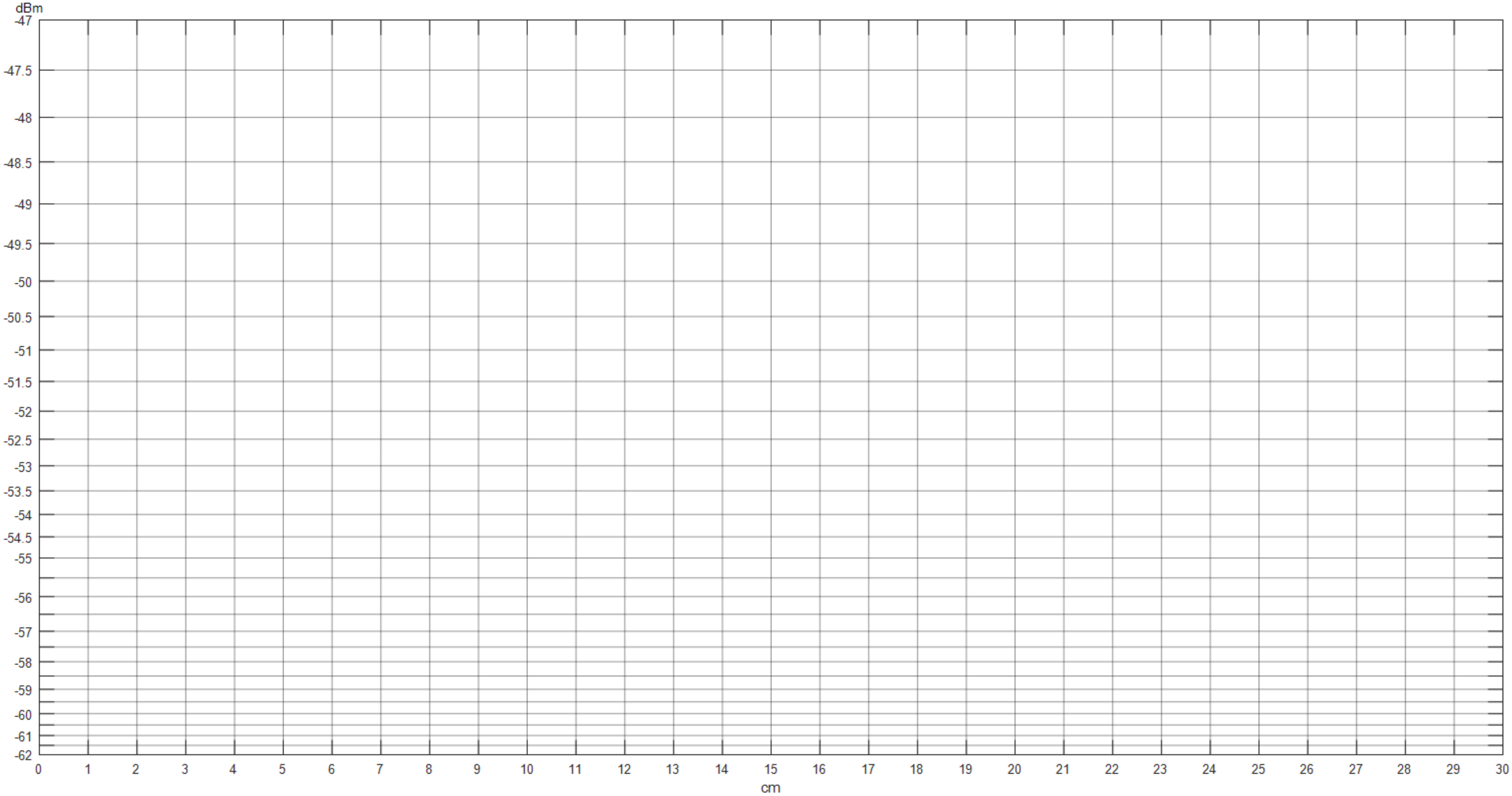
### 5.3. Procedure

- Using the values you found in Experiment 3 and the Smith Chart, determine the impedance of the unknown load's Port-1 side:
  $Z_{L(sc)}$ : ............................................................
- Is the impedance you found here the same as the impedance you calculated in Experiment 3? If not, explain why.

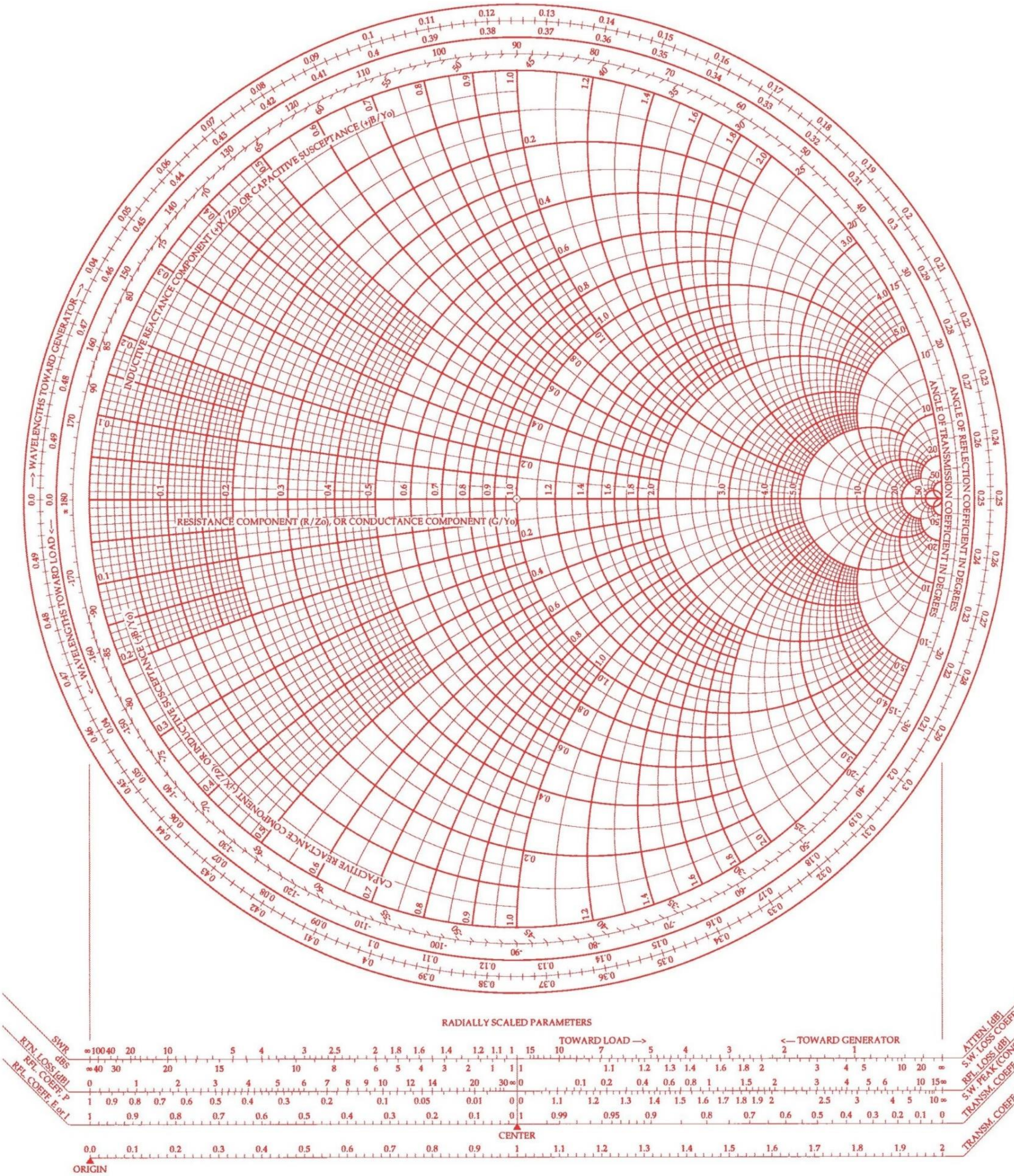
  ……………………………………………………………………………………………

………………………………………………………………………………………………
………………………………………………………………………………………………
………………

- Using the Smith Chart, determine the admittance of the unknown load's Port-1 side: $Y_{L(sc)}$ : ..........................................................................................................................
- Ensure that the unknown load's Port-1 side is connected to the load port as in Experiment 3.
- Mark on the Smith Chart the impedance $Z_p$ measured at p=12 cm (toward the load) and record its value:
  $Z_{p(sc)}$ : ..........................................................................................................................
- Calculate $Z_p$ analytically from your previous experiment results and record it:
  $Z_p$ : ..........................................................................................................................
- Are the values $Z_p$ and $Z_{p(sc)}$ the same? If not, explain why.
  ………………………………………………………………………………………………
  ………………………………………………………………………………………………
  ………………………………………………………………………………………………
  ………………


dBm
-47
-47.5
-48
-48.5
-49
-49.5
-50
-50.5
-51
-51.5
-52
-52.5
-53
-53.5
-54
-54.5
-55
-56
-57
-58
-59
-60
-61
-62
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
cm

# The Complete Smith Chart



**Instruments and Equipment**

**1. Slotted Transmission Line Module**

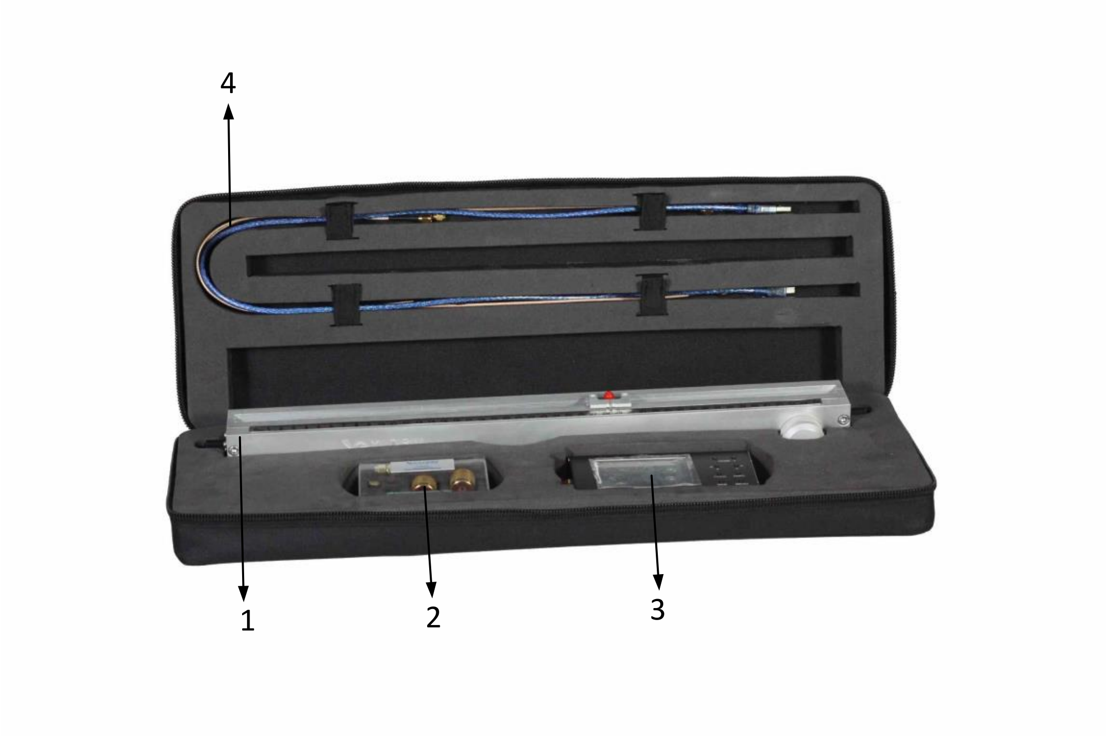



Figure 1

1. **Slotted Transmission Line Module**

2. **Load Module**, containing:

- 1× Short Load
- 1× Open Load
- 1× 50 Ω Load
- 1× Unknown-Impedance Load
- 2× N-Male to SMA-Female adapters

3. Tracking Generator Optional Spektrum Analyzer
4. Cables

- 2× 45 cm SMA-Male to SMA-Male RF cables
- 1× 90 cm SMA-Male to SMA-Male RF cable
- 1× Mini-USB Type-A to USB cable

## 2. Slotted Transmission Line Module

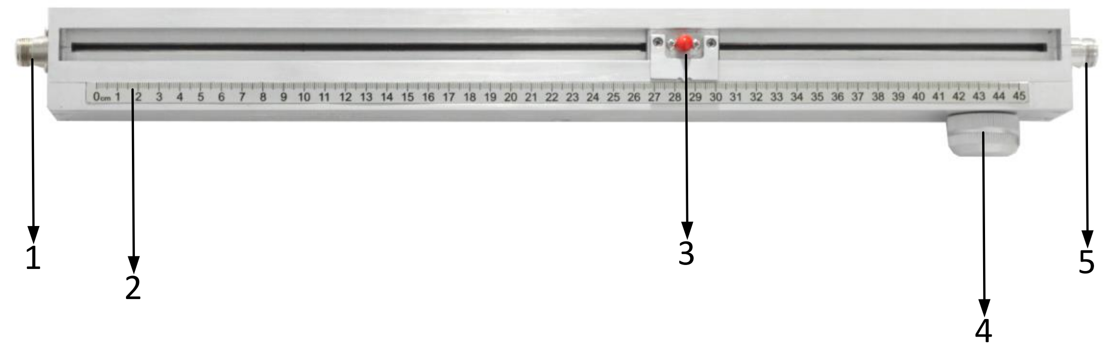
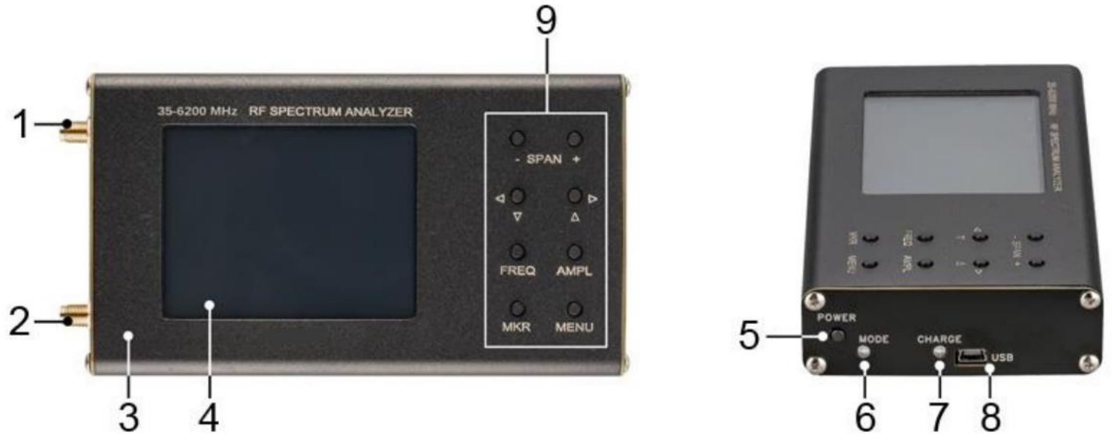



Figure 2.1

1. N-Female Connector
2. Scale (Ruler)
3. Probe Port (SMA-Female)
4. POT
5. N-Female Connector

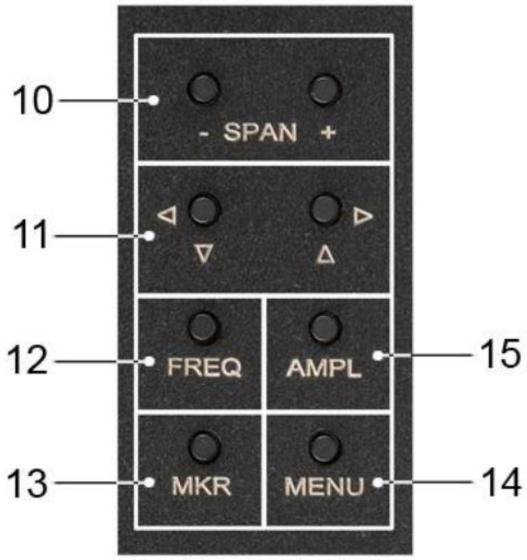
**3. Tracking Generator Spectrum Analyzer Optional**




1. RF Signal Output (Tracking Generator Out) **TG OUT**
2. RF Signal Input **RF IN**
3. Box
4. Display And Menu Navigation
5. On/Off Button **POWER**
6. Operating-Mode Indicator **MODE**
7. Battery-Charge Indicator **CHARGE**
8. Mini-USB Connector
9. Control Buttons

**Note:** For greater measurement stability, it is recommended to connect the portable spectrum analyzer via USB to a 5 V adapter or a PC’s USB port.

### 3.1. Control-Button Functions




10. **SPAN ±** (“+” and “–” keys): Adjust the frequency span along the horizontal axis.

11. **FREQ**: Display current frequency settings. Hold > 2 s to open frequency-adjustment window.

12. **MKR**: Marker control. Hold > 2 s to open marker-adjustment window.

13. **MENU**: Access the main menu.

14. **AMPL**: Display current amplitude settings. Hold > 2 s to open amplitude-adjustment window.