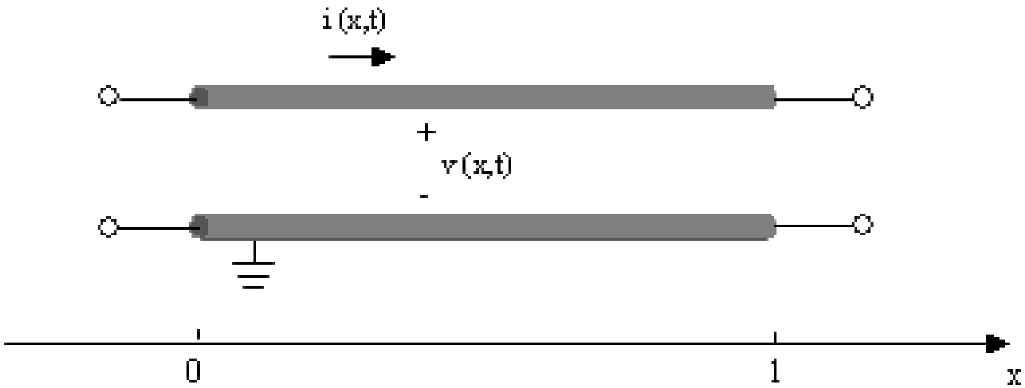
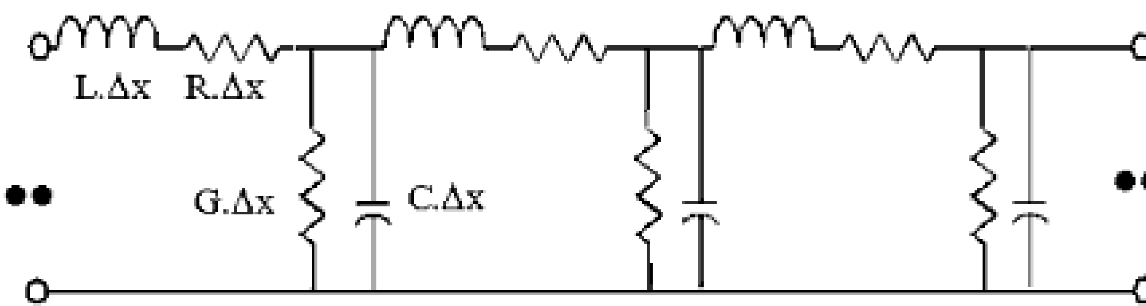
MICROWAVE MEASUREMENTS

Transmission line characteristics

Transmission Line- In the microwave frequency region, power is considered to be in electric and magnetic fields that are guided from place to place by some physical structure. Any physical structure that will guide an electromagnetic wave place to place.

Transmission lines are distributed devices. RLCG type models are commonly used to approximate the distributed behavior of a transmission line.





RLCG Model for Single Transmission Line

The single transmission line shown below can be modeled by a network consisting of a series resistance and inductance with parallel capacitance and conductance

- **R Resistive** loss of the conductor (transmission line trace). Determined by the conductance of the metal, width, height, and length of the conductor.
- **L Inductive** part of the circuit resulting from the layout of the conductors.
- **C Capacitive** part of the circuit resulting from the layout of the conductors. Determined by the permittivity and thickness of the board material and the area of the conductor.
- **G Shunt** loss of the dielectric. Determined by the layout of the conductors, permittivity, loss tangent and thickness of the board material.

General Characteristics of Transmission Line

- Propagation delay per unit length (T_0) {time/distance} [ps/in] Or Velocity (v_0) {distance/time} [in/ps]
- Characteristic Impedance (Z_0)
- Per-unit-length Capacitance (C_0) [pf/in]
- Per-unit-length Inductance (L_0) [nf/in]
- Per-unit-length (Series) Resistance (R_0) [W/in]
- Per-unit-length (Parallel) Conductance (G_0) [S/in]

Transmission Line Equations
Propagation equation

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta$$

α is the attenuation (loss) factor
β is the phase (velocity) factor

Characteristic Impedance equation

$$Z0 = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}}$$

Characteristics of transmission line

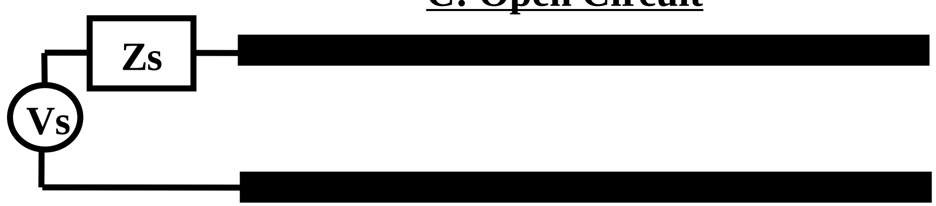
A: Terminated in Zo

$$\rho = \frac{Zo - Zo}{Zo + Zo} = 0$$

B: Short Circuit

$$\rho = \frac{0 - Zo}{0 + Zo} = -1$$

C: Open Circuit



$$P = \frac{\infty - Zo}{\infty + Zo} = 1$$

The Reflection and Transmission Losses

- When the resistive load termination is not equal to the characteristic impedance, part of the power is reflected back and the remainder is absorbed by the load
- . The amount of voltage reflected back is called *voltage reflection coefficient.*

$$\Gamma = V_i/V_r$$

where Vi is incident voltage and vr is reflected voltage.

The reflection coefficient is also given by :

$$\Gamma = (Z_L - Z_O)/(Z_L + Z_O)$$

VOLTAGE STANDING WAVE RATIO (VSWR)

- A standing wave is formed by the addition of incident and reflected waves and has nodal points that remain stationary with time.
- *Voltage Standing Wave Ratio:*

$$\mathbf{VSWR = V_{max}/V_{min}}$$

Voltage standing wave ratio expressed in decibels;

SWR (dB) = $20\log_{10}VSWR$

- The maximum impedance of the line is given by:
- $Z_{max} = V_{max}/I_{min}$

- The minimum impedance of the line is given by:
- $Z_{min} = V_{min}/I_{max}$

or alternatively:

- $Z_{min} = Z_o/VSWR$

- Relationship between VSWR and Reflection Coefficient:

$$\mathbf{VSWR = (1 + |\Gamma|)/(1 - |\Gamma|)}$$

$$\mathbf{\Gamma = (VSWR - 1)/(VSWR + 1)}$$

- 3.2 Understand types of measurements.
- 3.2.1 Draw the block diagram of instrument in microwave testing.
- 3.2.2 Explain the function of each block and the overall measurement process:

a. Frequency measurement using wave meter.

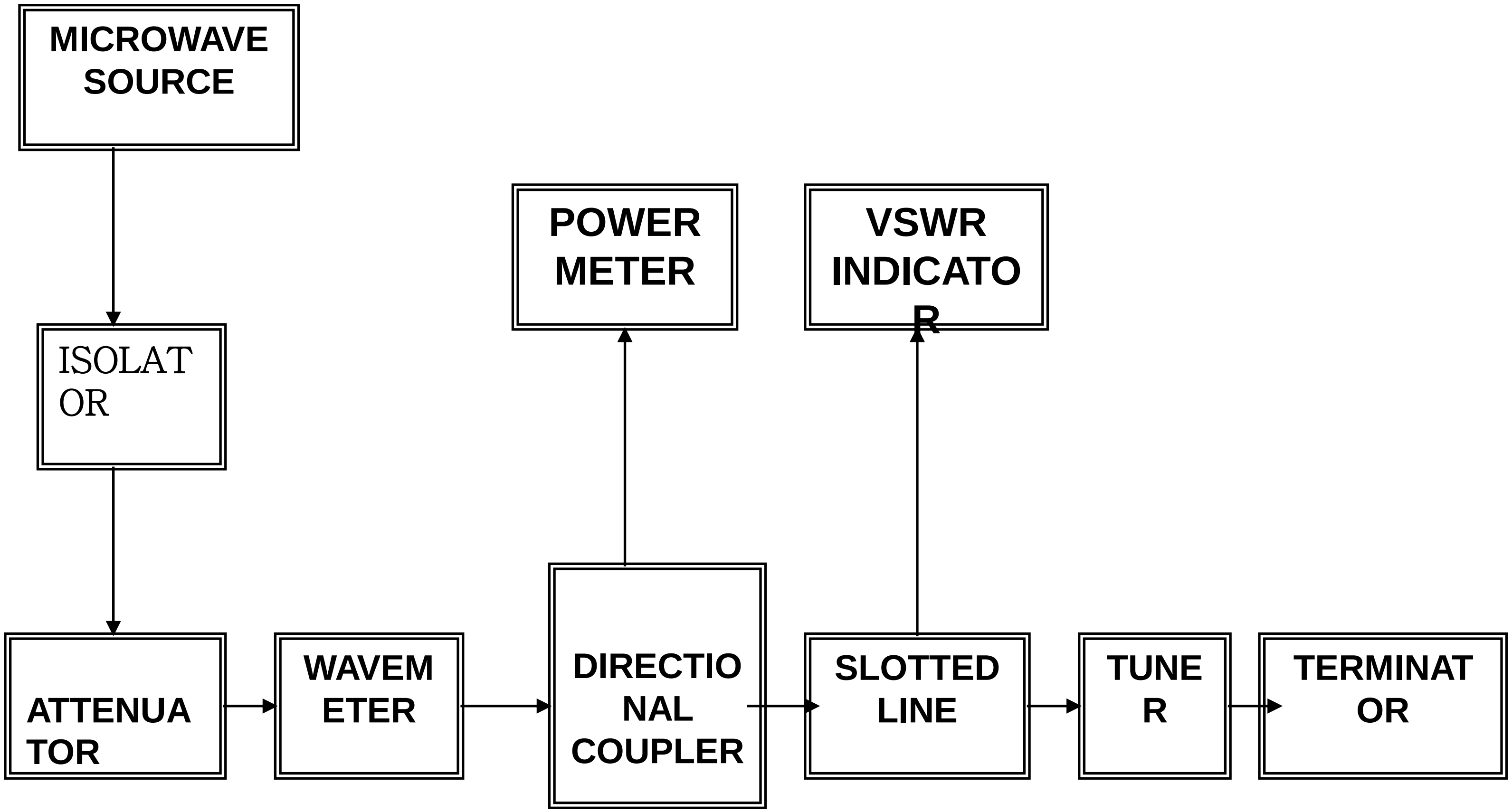
b. VSWR measurement using slotted line.

c. Power measurement using low powered Bolometer or Crystal Rectifier.

TYPES OF MEASUREMENT

TYPES OF MEASUREMENT	EQUIPMENTS
FREQUENCY-DOMAIN	➢ Wavemeter s (absorption, transmission or reaction). ➢ Slotted lines. ➢ Spectrum analyzer, frequency sweepers and frequency counters.
DISPLAY OF TIME-DOMAIN	➢ Sampling oscilloscope. ➢ Oscilloscope.
VSWR	➢ Slotted lines (direct method or double minimum method)
POWER	➢ Power meters. ➢ Detectors with oscilloscopes. ➢ Spectrum analyzers.
WAVELENGTH	➢ Coaxial and waveguide slotted lines
NOISE	➢ Noise meters.
	➢ Network analyzer – multifunctional test equipment.

BLOCK DIAGRAM OF INSTRUMENT IN MICROWAVE TESTING.



FUNCTION OF EACH BLOCK

MICROWAVE SOURCE – generates microwave source in X-band (8 – 12 GHz);

e.g klystron, magnetron or TWT

ISOLATOR /CIRCULATOR - Allow wave to travel through in one direction while being attenuated in the other direction or it is use to eliminate the unwanted generator frequency pulling (*changing the frequency of the generator*) due to system mismatch or discontinuity. (*to prevent reflected energy from reaching the source*)

- **ATTENUATOR** - Control the amount of power level in a fixed amount, variable amount or in a series of fixed steps from the from the microwave source to the wavemeter.
- **WAVEMETER** - Used to select / measure resonant cavity frequencies by having a plunger move in and out of the cavity thus causes the the cavity to resonate at different frequencies.
- **DIRECTIONAL COUPLER** - Samples part of the power travelling through the main waveguide and allows part of its energy to feed to a secondary output port. Ideally it is used to separate the incident and reflected wave in a transmission line.
- **SLOTTED LINE -** Used to determine the field strength through the use of a detector probe that slides along the top of the waveguide.

- **VSWR INDICATOR -** Denotes the value of VSWR measured by the slotted line.

- **TUNER -** Allows only the desired frequency to appear at the output. Any harmonic frequencies that appear at the output are reduced to an acceptable level.

- **TERMINATOR -** May range from a simple resistive termination to some sort of deep-space antenna array, active repeater or similar devices. 3 special cases of transmission line i.e short circuit, open circuit, match impedance.

FREQUENCY MEASUREMENT

- The frequency meter used has a cavity which is coupled to the waveguide by a small coupling hole which is used to absorb only a tiny fraction of energy passing along the waveguide.

- Adjusting the micrometer of the Frequency Meter will vary the plunger into the cavity. This will alters the cavity size and hence the resonance frequency.

- The readings on the micrometer scales are calibrated against frequency. As the plunger enters the caviy, its sized is reduced and the frequency increases.

- The wavemeter is adjusted for maximum or minimum power meter readings depending on whether the cavity is a transmission or absorption type device. With the transmission-type device, the power meter will be adjusted for a maximum. It only allows frequency close to resonance to be transmitted through them. Other frequencies are reflected down the waveguide. The wavemeter acts as a short circuit for all other frequencies.

- For the absorption-type wavemeter, the power meter will be adjusted for a minimum. Its absorp power from the line around resonant frequency and act as a short to other frequencies.

- The absorbing material used is to absorb any unwanted signal that will cause disturbance to the system.

VSWR (VOLTAGE STANDING WAVE RATIO) MEASUREMENT

- Used to determine the degree of mismatch between the source and load when the value VSWR ≠ 1.
- Can be measured by using a slotted line. **Direct Method Measurement** is used for VSWR values upto about 10. Its value can be read directly using a standing wave detector .
- The measurement consists simply of adjusting attenuator to give an adequate reading, making sure that the frequency is correct and then using the dc voltmeter to measure the detector output at a maximum on the slotted section and then at the nearest minimum.

The ratio of the voltage maximum to the minimum gives the VSWR i.e

$$VSWR = V_{max} / V_{min}$$

$$ISWR = I_{max} / I_{min}$$

$$= k (V_{max})^2 / k (V_{min})^2$$

$$= (V_{max} / V_{min})^2$$

$$= VSWR^2$$

$$VSWR = \sqrt{(I_{max} / I_{min})} = \sqrt{ISWR}$$

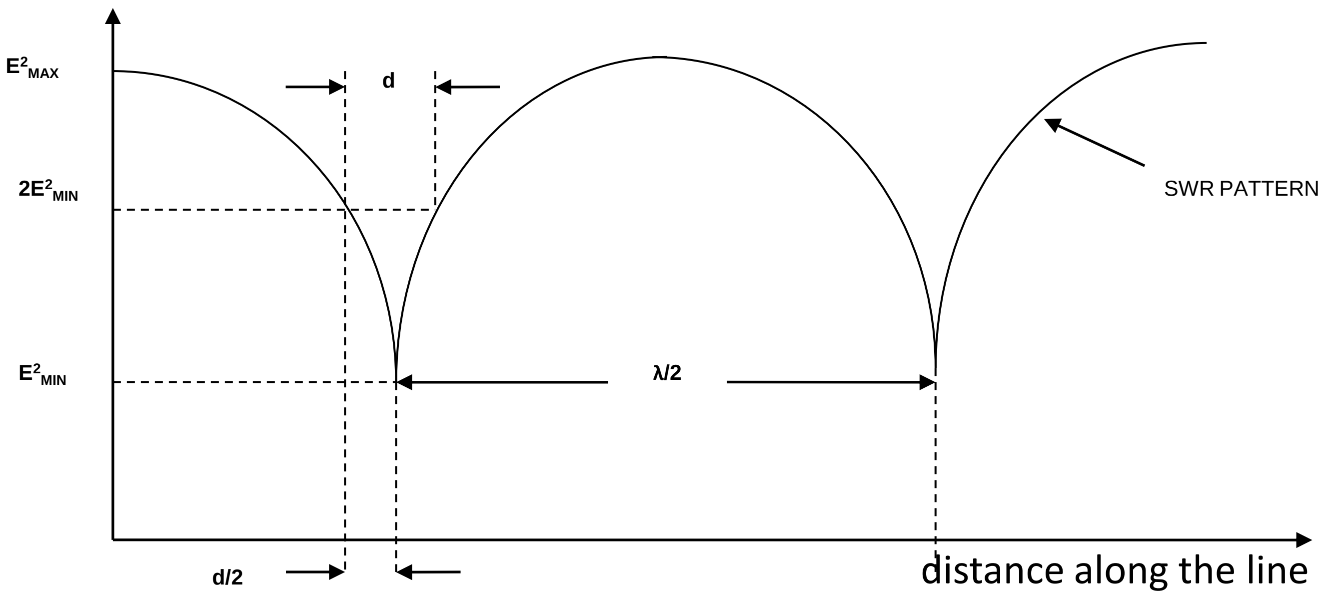
- Methods used depends on the value of VSWR whether it is high or low. If the load is not exactly matched to the line, standing wave pattern is produced.

- Reflections can be measured in terms of voltage, current or power. Measurement using voltage is preffered because it is simplicity.

- When reflection occured, the incident and the reflected waves will reinforce each other in some places, and in others they will tend to cancel each other out.

DOUBLE MINIMUM METHOD MEASUREMENT (VSWR > 10)

- ‘Double Minimum’ method is usually employed for VSWR values greater than about 10.



- The detector output (proportional to field strength squared) is plotted against position. The probe is moved aling the line to find the minimum value of signal.

- It is then moved either side to determine 2 positions at which twice as much detector signal is obtained. The distance d between these two positions then gives the VSWR according to the formula :

$$S = \sqrt{1 + 1/\sin^2(\pi d/\lambda)}$$

POWER MEASUREMENT

- Power is defined as the quantity of energy dissipated or stored per unit time.
- Methods of measurement of power depend on the frequency of operation, levels of power and whether the power is continuous or pulsed.
- The range of microwave power is divided into three categories :-

  i. Low power (< 10mW @ 0dBm)

  ii. Medium power (from 10 mW - 10 W @ 0 – 40 dBm)

  iii. High power (> 10 W @ 40 dBm)
- The microwave power meter consists of a power sensor, which converts the microwave power to heat energy.
- The sensors used for power measurements are the Schottky barrier diode, bolometer and the thermocouple.

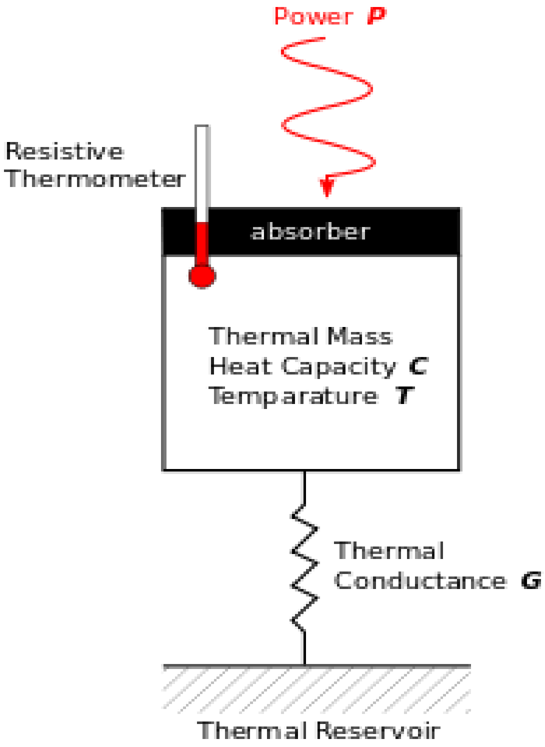
SCHOTTKY BARRIER DIODE

- A zero-biased Schottky Barrier Diode is used as a square-law detector whose output is proportional to the input power.
- The diode detectors can be used to measure power levels as low as 70dBm.

BOLOMETERS

- A Bolometer is a power sensor whose resistance changes with temperature as it absorbs microwave power.
- Are power detectors that operate on thermal principles. Since the temperature of the resistance is dependent on the signal power absorbed, the resistance must also be in proportion to the signal power.
- The two most common types of bolometer are, the barretter and the thermistor. Both are sensitive power detectors and is used to indicate microwatts of power. They are used with bridge circuits to convert resistance to power using a meter or other indicating devices.

BOLOMETER


Power P
Resistive
Thermometer
absorber
Thermal Mass
Heat Capacity C
Temparature T
Thermal
Conductance G
Thermal Reservoir

BARETTERS

- Are usually thin pieces of wire such as platinum. They are mounted as terminating devices in a section of transmission line. The section of transmission line with the mounting structure is called a detector mount.
- The increase of temperature of the baretter due to the power absorbed from the signal in the line causes the temperature of the device to increase.
- The temperature coefficient of the device causes the resistance to change in value in proportion to the change in temperature of the device (positive temperature coefficient i.e the resistance increases with increasing temperature; $R \alpha t$).

BARETTER


LGC
LGC
MODEL 2677
0.1-20 GHz SWITCH
S/N
J1
J2
GENERAL ®
MICROWAVE
08415-60057
MADE IN ISRAEL
J3-COM

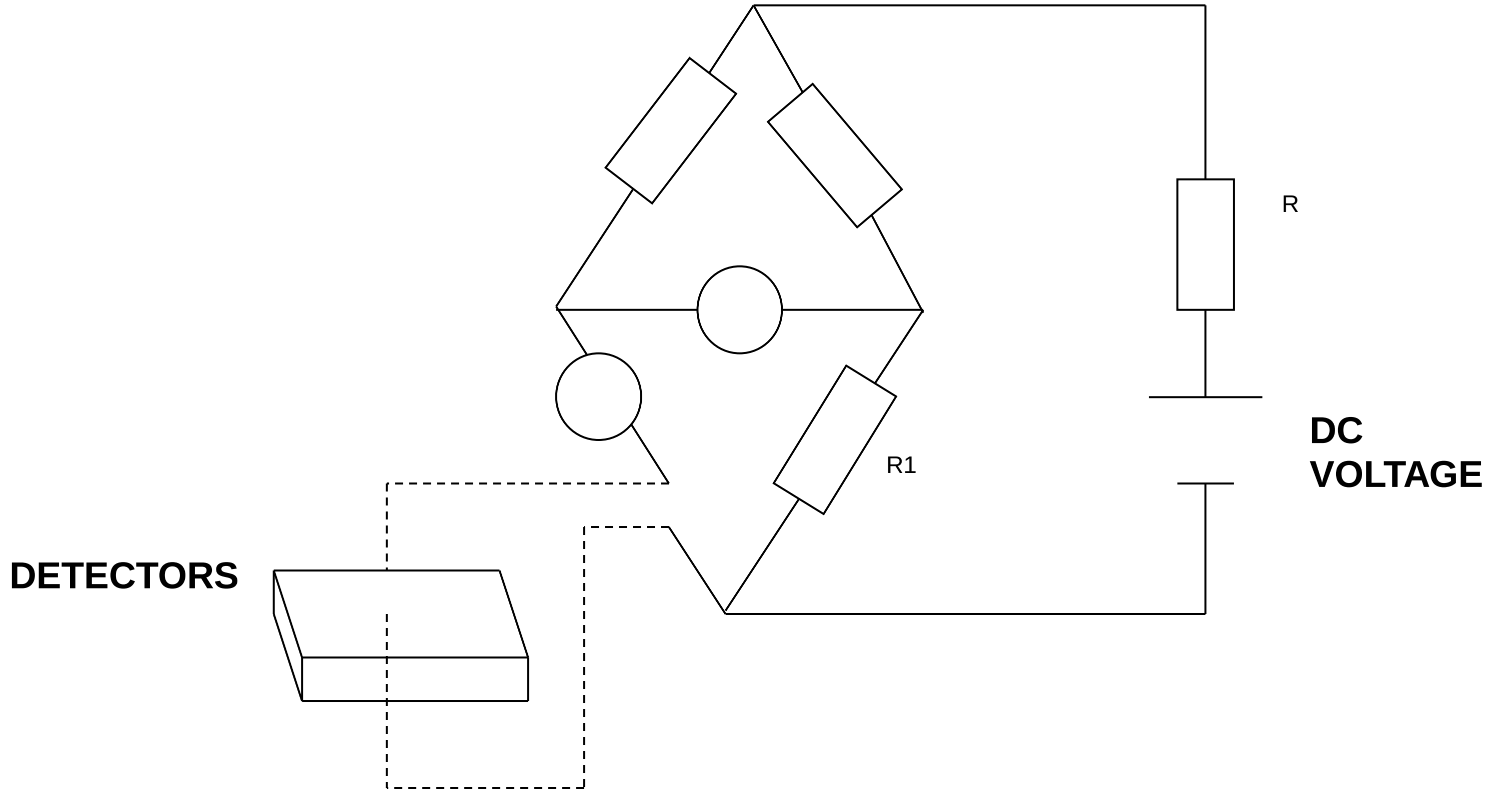
THERMISTOR

- Are beads of semiconductor material that are mounted across the line. They have a negative temperature coefficient i.e the resistance decreases with increasing temperature; $R \alpha 1/ t$.

- The impedance of baretters and thermistors must match that of the transmission so that all power is absorbed by the device.

Thermistor mount

- Variations in resistance due to thermal-sensing devices must be converted to a reading on an indicating device such as a meter. This can be done accurately using a balanced bridge arrangement as shown below:-



- With no power to the detector that contains the sensor element, the sensor-line R1 is adjusted to zero reading through the meter M1 and the bridge circuit is balanced.

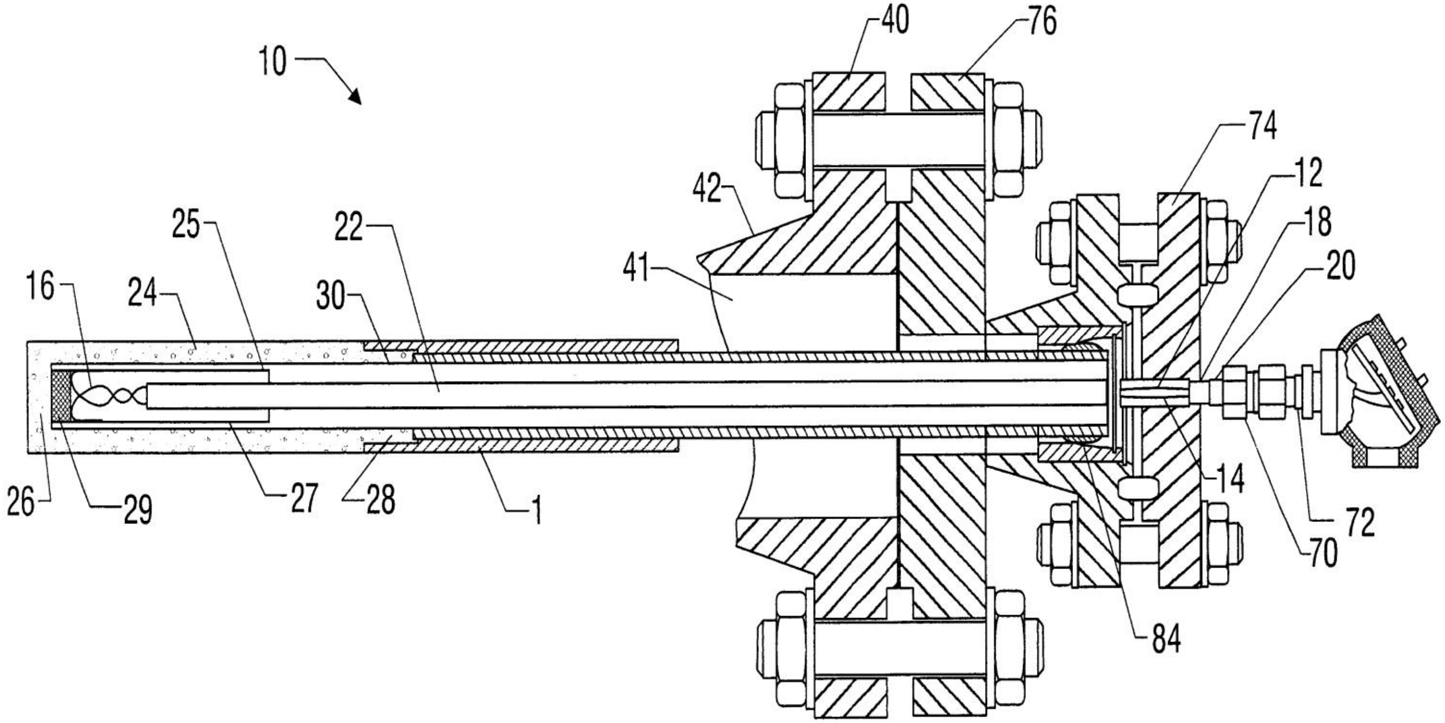
- When signal is applied to the sensor element, causing its temperature to change, the sensor resistance changes, causing the bridge to become unbalanced.

- Resistor R1 is adjusted to balance meter M1. The change in the reading of meter M2 in the sensor element leg is a direct measure of the microwave power.

THERMOCOUPLES

- Are used as power monitors in the low-to-medium power regions and are very sensitve.
- Is a thin wire made of two disimilar metals. Hence there will be two junctions (hot & cold).
- When the temperature at two junctions are different, a voltage is developed across the thermocouple (i.e across both junctions). This developed voltage is proportional to the difference between the two junction temperatures.
- When the temperature at both junctions are the same, the difference in voltage = 0.

Thermocouple



MICROWAVE CRYSTALS

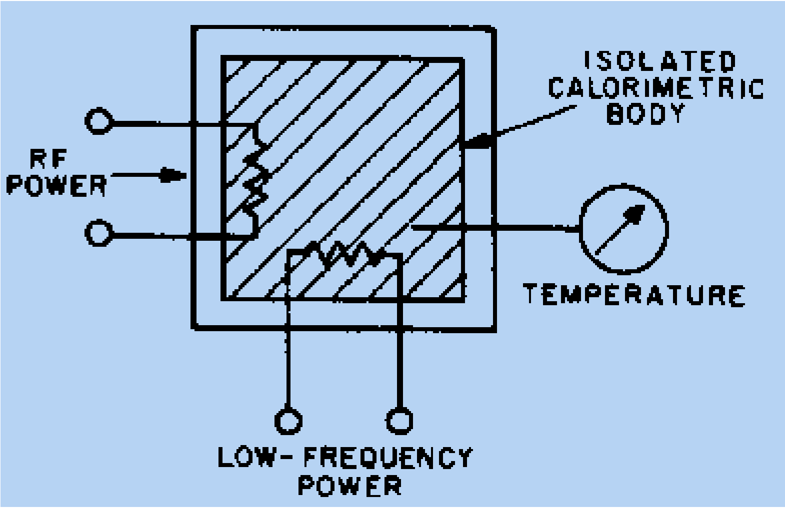
- Are non-linear detectors that provide current in proportion to the power. It is limited to making low-power measurements.
- The current is proportional to the power due to the square-law characteristic of the crystal. This square-law characteristic only occurs for small signal levels.
- At larger signal levels the relationship is linear, as with any diode. Therefore the proportional relationship between power and current output is only true at power levels below 10mW.

Microwave Crystal

CALORIMETERS

- The calorimeters are the most accurate of all instruments for measuring high power. Calorimeters depend on the complete conversion of the input electromagnetic energy into heat. Direct heating requires the measurement of the heating effect on the medium, or load, terminating the line. Indirect heating requires the measurement of the heating effect on a medium or body other than the original power-absorbing material. Power measurement with true calorimeter methods is based solely on temperature, mass, and time. *Substitution* methods use a known, low-frequency power to produce the same physical effect as an unknown of power being measured. Calorimeters are classified as STATIC (non flow) types and CIRCULATING (flow) types.

CALORIMETER



SMITH CHART

DEFINITION :-

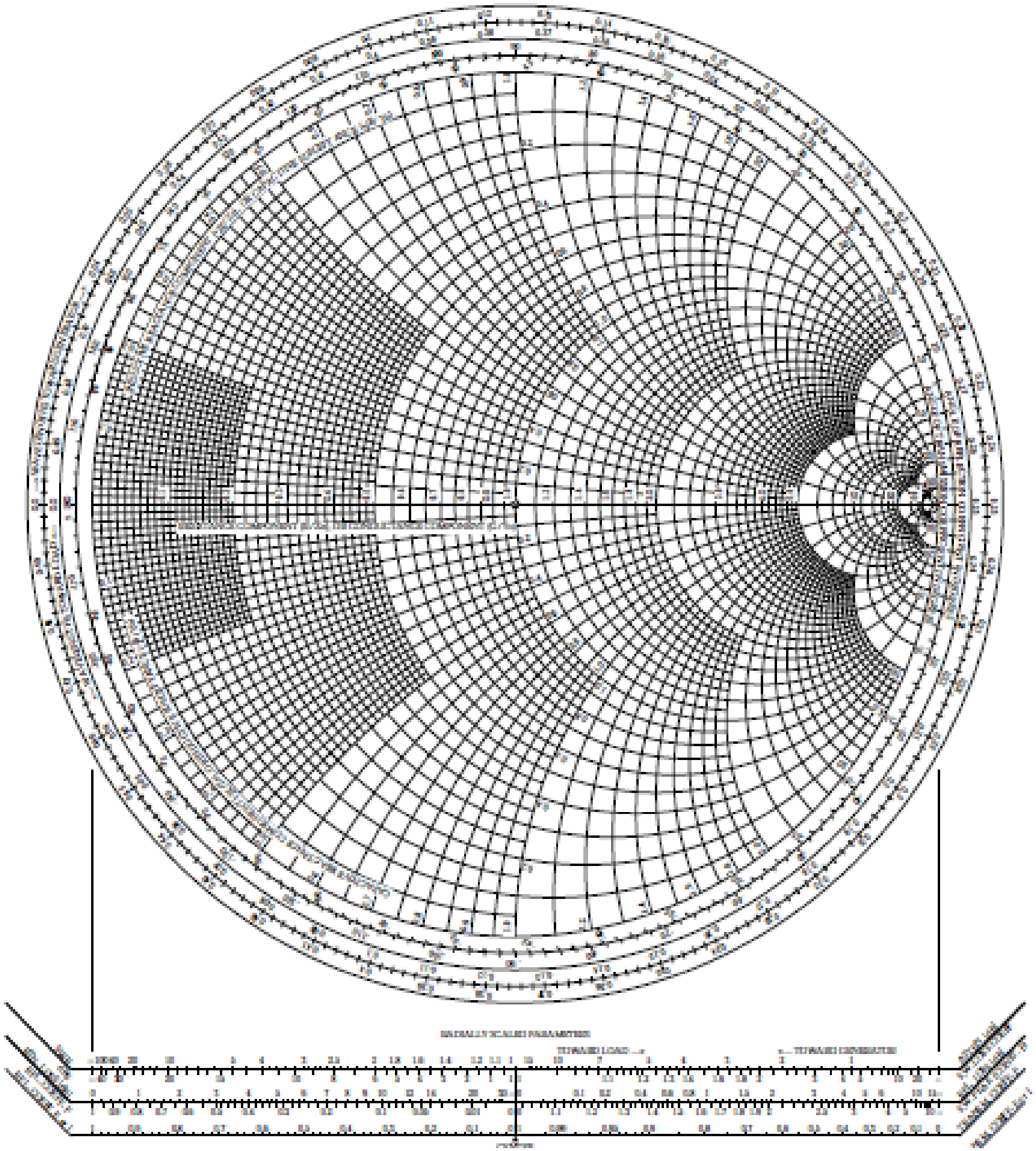
- plot of complex reflection overlaid with an impedance and/or admittance grid referenced to a 1-ohm characteristic impedance.

- Contains almost all possible impedances, real or imaginary, within one circle.

- Represent all imaginary impedances from - infinity to + infinity.

The Complete Smith Chart

Black Magic Design



COMPONENTS OF A SMITH CHART

- Horizontal center line – resistance / conductance.
- Zero resistance / conductance – located on the left end of the line.
- Infinite resistance / conductance - located on the right end of the line.
- Horizontal centerline – resistive / conductive horizontal scale of the chart. It is independent of the characteristic impedance of the transmission line by normalizing the input values.

COMPONENTS OF A SMITH CHART

Normalized impedance, $z_L = \frac{R \pm jX}{Z_0}$

Normalized resistance, $r_L = R / Z_0$

Normalized conductance, $g_L = G / Z_0$

- The center of the line and also of the chart is 1.0 point, where $R = Z_0$ or $G = Y_0$. ($Z_0 = 1 / Y_0$)
- At point 1.0, the line termination = characteristic impedance of the line and no reflection will occur.

COMPONENTS OF A SMITH CHART

- Circles tangent to the right side of chart – circles of constant resistance / conductance.

- Are drawn on the SC tangent to the right-hand side of the chart and its intersection with the centerline.

- The curved lines from the outer circle that terminate on the centerline at the right side are lines of constant impedance / susceptance.

COMPONENTS OF A SMITH CHART

- Lines of Constant Reactance and Susceptance.

- Shown on SC with curves that start from a given reactance value on the outer circle and end at the right hand side of the centerline.

- Upper half of the outer circle scale of SC represents:

  Inductive reactive component / Capacitive reactive component

$$x_L = +\frac{j X_L}{Z_0} \qquad \text{OR} \qquad b = +\frac{j B}{Y_0}$$

COMPONENTS OF A SMITH CHART

- Lower half of the outer circle scale of SC represents the :

Capacitive reactive component / Inductive susceptance component

$$x_C = -\frac{j X_C}{Z_0} \qquad \text{OR} \qquad b = -\frac{j B}{Y_0}$$

IMPEDANCE, Z AND ADMITTANCE, Y

- Z is the steady state AC term.

- Combined effect of both resistance (R), and reactance (X),

  where

$$Z = R + jX$$

(X = jwL for an inductor, and

X = 1 / jwC for a capacitor,

where w is the radian frequency or 2 π f.)

Generally, Z is a complex quantity having a real part (resistance) and an imaginary part (reactance).

- In terms of impedance and its constituent quantities of resistance and reactance refers to series- connected circuits where impedances add together

- Circuits have elements connected in parallel or "shunt" are a natural fit for the "acceptance" quantity of admittance (Y) and its constituent quantities of conductance (G) and susceptance (B), Where

$$Y = G + jB$$

($B = jwC$ for a capacitor, and

$B = 1/jwL$ for an inductor.)

- Admittances add together for shunt-connected circuits.

Remember that

$$Y = 1/Z = 1/(R+jX),$$

so that $G = 1/R$

only if $X = 0,$

and $B = -1/X$

only if $R = 0$

- When working with a series-connected circuit or inserting elements in series with an existing circuit or transmission line, the resistance and reactance components are easily manipulated on the **"impedance"** Smith chart.

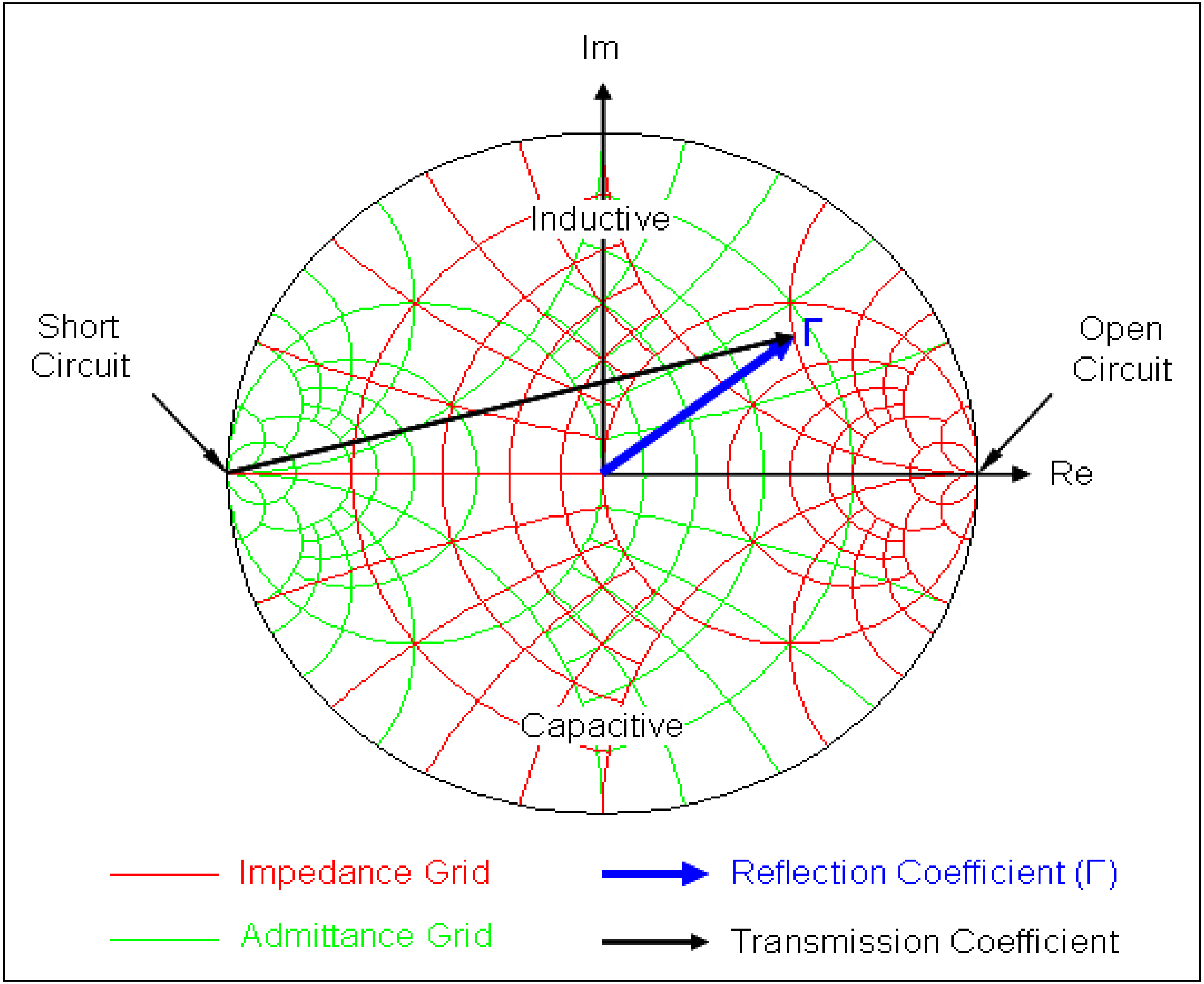
- When working with a parallel-connected circuit or inserting elements in parallel with an existing circuit or transmission line, the conductance and susceptance components are easily manipulated on the **"admittance"** smith chart.

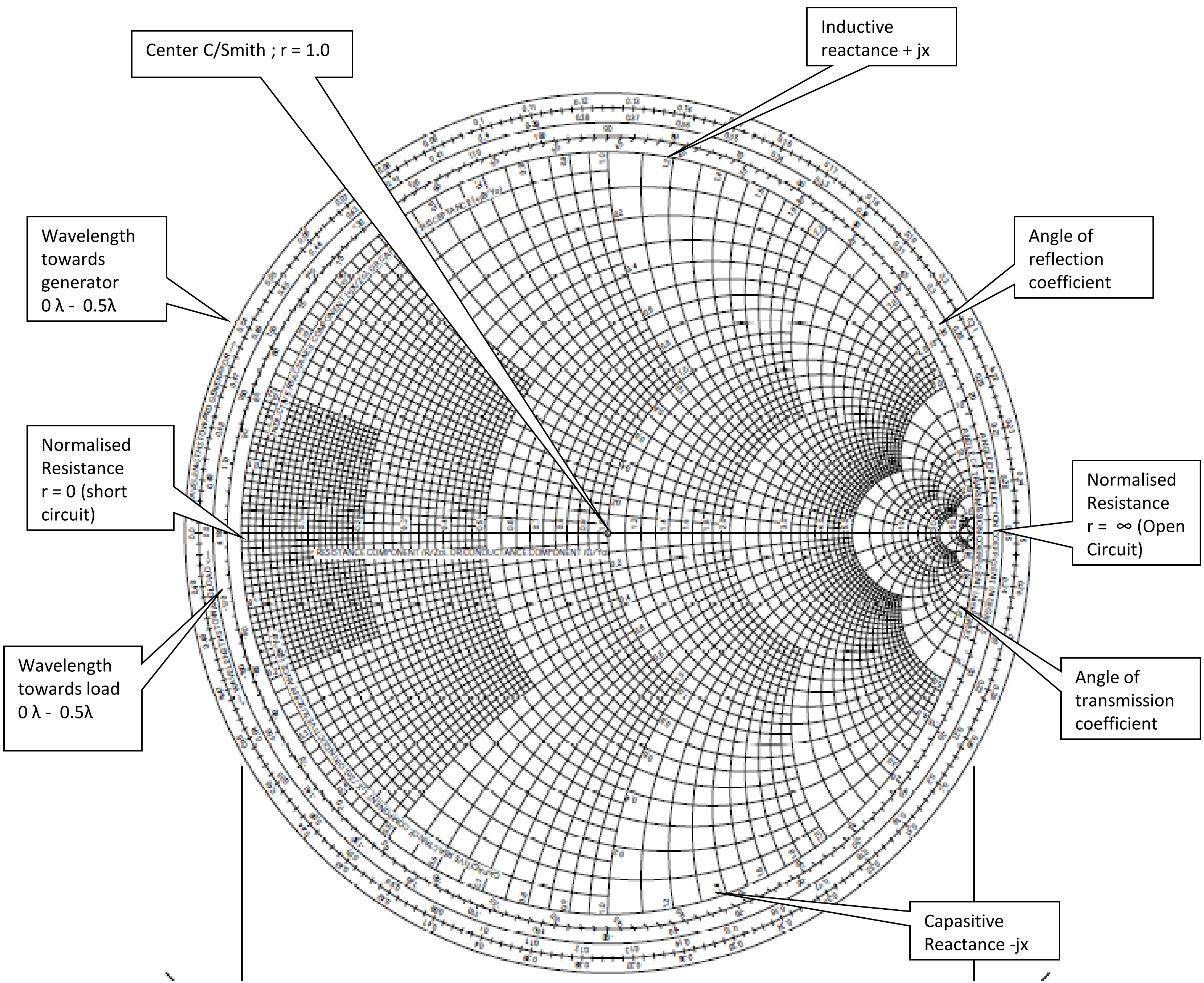
ORIENTATION OF THE SMITH CHART

- Places the resistance axis horizontally with the short circuit (SC) location at the far left.
- The voltage of the reflected wave at a short circuit must cancel the voltage of the incident wave so that zero potential exists across the short circuit.
- In other words, the voltage reflection coefficient must be -1 or a magnitude of 1 at an angle of 180°.

FOR AN OPEN CIRCUIT (OC),

- The reflected voltage is equal to and in phase with the incident voltage (reflection coefficient of +1) so that the open circuit location is on the right.
- In general, the reflection coefficient has a magnitude other than unity and is complex.


Im
Inductive
Short Circuit
Γ
Open Circuit
Re
Capacitive
Impedance Grid
Reflection Coefficient (Γ)
Admittance Grid
Transmission Coefficient


Center C/Smith ; r = 1.0
Inductive reactance + jx
Wavelength towards generator 0 λ - 0.5λ
Angle of reflection coefficient
Normalised Resistance r = 0 (short circuit)
Normalised Resistance r = ∞ (Open Circuit)
Wavelength towards load 0 λ - 0.5λ
Angle of transmission coefficient
Capasitive Reactance -jx
RESISTANCE COMPONENT (R/Zo), OR CONDUCTANCE COMPONENT (G/Yo)

SOLUTIONS TO MICROWAVE PROBLEMS USING SMITH CHART

1. Plotting a complex impedance on a Smith chart
2. Finding VSWR for a given load
3. Finding the admittance for a given impedance
4. Finding the input impedance of a transmission line terminated in a short or open.
5. Finding the input impedance at any distance from a load Z_L.
6. Locating the first maximum and minimum from any load
7. Matching a transmission line to a load with a single series stub.
8. Matching a transmission line with a single parallel stub
9. Matching a transmission line to a load with two parallel stubs.

PLOTTING A COMPLEX IMPEDANCE ON A SMITH CHART

- To locate a complex impedance, Z = R+-jX or admittance Y = G +jB on a Smith chart, normalize the real and imaginary part of the complex impedance.
- Locating the value of the normalized real term on the horizontal line scale locates the resistance circle.
- Locating the normalized value of the imaginary term on the outer circle locates the curve of constant reactance.
- The intersection of the circle and the curve locates the complex impedance on the Smith chart.

FINDING THE VSWR FOR A GIVEN LOAD

1. Normalize the load and plot its location on the Smith chart.
2. Draw a circle with a radius equal to the distance between the 1.0 point and the location of the normalized load and the center of the Smith chart as the center.
3. The intersection of the right-hand side of the circle with the horizontal resistance line locates the value of the VSWR.

FINDING THE INPUT IMPEDANCE AT ANY DISTANCE FROM THE LOAD

1. The load impedance is first normalized and is located on the Smith chart.
2. The VSWR circle is drawn for the load.
3. A line is drawn from the 1.0 point through the load to the outer wavelength scale.
4. To locate the input impedance on a Smith chart of the transmission line at any given distance from the load, advance in clockwise direction from the located point, a distance in wavelength equal to the distance to the new location on the transmission line.

SMITH CHART USAGE :

- Plot real, imaginary & complex load
- Find VSWR for a given transmission line transmission.
- Find input impedance at any point in front of a transmission line terminated in an open, short or complex load.
- Locate the distance to the minimum and maximum points of standing waves in front of any line termination.

SMITH CHART USAGE :

- Locate the distance to the minimum and maximum points of standing waves in front of any line termination.
- Match a line termination to the transmission line using single- and double-stub tuners.

REFLECTION COEFFICIENT

REFLECTION COEFFICIENT, ρ	LOAD, Z_L	VSWR, σ	REMARK
$\rho = -1$	short circuit, $Z_L = 0$;	$\sigma = 0$	Due to phase reversal i.e change of phase thus the incident and reflected wave will be cancelled.
$\rho = 1$	open circuit , $Z_L = \infty$	$\sigma = \infty$	Total refelection occurs because the 2 waves are in phase.
$\rho = 0$	Matching load, $Z_L = Z_0$	$\sigma = 1$	No reflection occurs only have incident wave.

STUB MATCHING

•When a line is 'matched' the reflection coefficient $\rho = 0$ and so the standing wave ratio, $S = 1$. Most system are therefore designed to work with S as near to 1 as possible.

•A value of $S > 1$, represent mismatched and end to loss of power at the receiving end. In other cases it may caused a voltage breakdown as in high power radar system or distortion in tv.

•It it therefore necessary to match a line. Matching in the case of two wire lines, may be done by using one or more stub and is called 'stub matching' or by the use of quarter wave transformer.

- The use of stub in matching a complex load to the line is to achieve a complete power transfer (VSWR = 1.0).The stub used has to be placed in parallel with the line and load, thus has to deal with admittance, not impedance