MICROWAVE ENGINEERING

UNIT 6

Basics of the microwave sources

Fundamental principles of working of microwave tubes:

- During interaction between particle and field energy transfer takes place.
- When the field favours the particle motion, energy transfer takes place from the field to particle.
- If the field opposes the particle motion, the particle loses and field gains the energy.
- The gain of the energy by one is equal to the loss by the other.
- The amount of energy transferred is proportional to
  - The charge on the particle
  - Intensity of the field.
  - Length or duration of the interaction.
- When the gap voltage is sinusoidal time varying and the charge is distributed
  - If the particle crossing at positive peak effects maximum transfers of energy to field, the crossing of particle at negative peak effects maximum energy transfer to particle
  - the distributed charge must be compressed into a thin sheet or *bunch*, where it requires lesser amount time to cross the gap for effecting maximum amount of energy transfer.

- When the gap voltage is sinusoidal time varying and bunch-crossing is at a constant rate:
  - For maximum unidirectional flow of energy there is only one instant, either at positive peak or negative peak where the *bunch* has to cross the gap. So the *bunch* crossing must be once per cycle of the gap voltage.

- In case of *bunch*-crossing at a uniform rate f , maximum energy transfer can takes place only to a component of grid gap field whose frequency is also

GUNN DIODE

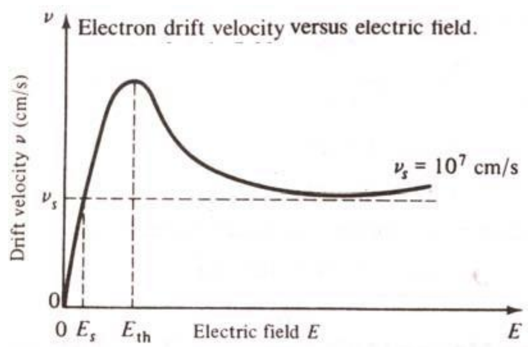
- Gunn oscillators and amplifiers are most important microwave devices that have been extensively used as local oscillators and power amplifier covering the frequency range 1 to 100 GHz in which Gunn diode is a critical part.
- Gunn diode is an n-type slab of GaAs, InP, InAs, InSb and CdTd.
- Gunn diode exhibits dynamic negative resistances when it is biased to a potential gradient more than a certain value known as threshold field E_{th} due to Gunn effect or Transferred Electron Effect (TEE).
- In any n-type semi-conductor the drift velocity, the following relations govern current, field and drift velocity.

  $$v_d = \mu E \rightarrow \frac{dv_d}{dE} = \mu \quad and \quad J = nq\mu E \rightarrow \frac{dJ}{dE} = nq\mu$$

  - When the field is less than the E_{th}, increase in the field E causes the v_d to increase resulting in the positive mobility . Hence an increase in the E causes J to increase resulting in positive resistance.
  - When the field is in between E_{th} and E_v increase in the field E causes the v_d to decrease due to the onset of TEE resulting the negative mobility . Hence an increase in the field E causes J to decrease resulting in the manifestation of differential negative resistance.
  - When the field is more than E_v increase in field E causes v_d to increase resulting in the positive mobility due to the disappearance of the TEE. Hence an increase in the E causes J to increase resulting in positive resistance.
- The threshold field values are GaAs-3.3kv/cm, InP-10.53kv/cm, InAs-1.63kv/cm, InSb-0.63kv/cm CdTd-13.03kv/cm
- TEE is ‘a field induced transfer of conduction band electrons from a high mobility lower energy satellite valley to low mobility higher energy satellite valley’
  - It is bulk material property i.e. it takes place at each and every point in the body of the Gunn.
  - Due to this effect the mobility of the electrons in the diode become negative.
- In the InP diode
  - There exists three satellite valleys in its conduction band where as in others it two.
  - The peak to valley current ratio is larger because the electron transfer proceeds faster with increasing field.
  - Thermal excitation of the electrons has less effect leading to the lower degradation of the peak to valley

current ratio because the larger energy separations between lower and its nearest valley.

- In the InAs and InSb diodes TEE can be observed only under hydrostatic pressures that reduce the energy difference between the satellite valleys. Their energy difference is more than that of the forbidden gap under normal pressures.
- The electrons drift through the diode with velocities depending upon the field intensity and its maximum when the diode is biased to threshold value.



- Peak velocities in various diodes are GaAs-2.2, InP-2.5, InAs-3.6, InSb-5.0 and CdTd-1.5 times 10^7 cm/sec.
- Noise is due to 'AM noise' normally small, due to amplitude variations plus 'FM noise' which is due to frequency deviations.
- The upper frequency of the TEDs is limited to 150GHz mainly due to the 'finite response time'.
- The output power falls as $\frac{1}{f^2}$
- Gunn oscillators and amplifiers are being widely used as local oscillators and power amplifiers covering 1 to 100GHz range

GUNN DOMAINS

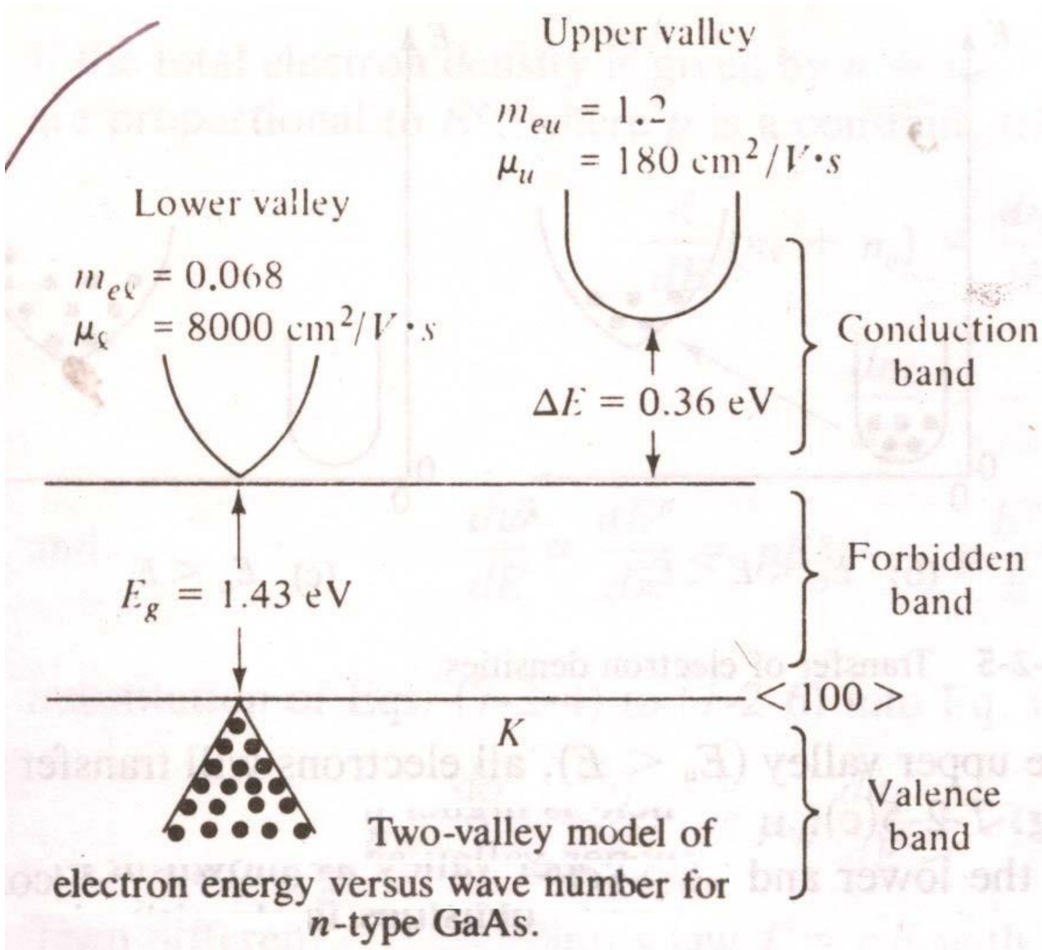
The transfer to lower mobility valley starts with the electrons located in a small region where the field intensity is more due to lower carrier concentration. These regions are called high field domains. The domains travel to anode shifting all the electrons in their path to lower mobility valley. The velocity of the domains is slightly more than the drift velocity of the electrons.

- Domains start to form whenever the electric field in a region of the sample increases above the threshold value and with the stream through the device.
- If additional voltage is applied to the diode with a domain then the domain will increase in size and absorb more voltage than was added and the current will decrease.

- The domain disappears after reaching the anode or in the mid-way if the field drops to a value less than sustain field value E_s.
- Decreasing the field slightly lower than the threshold value can prevent the formation of new domain.
- The domain modulates the current through the device as the domain passes the regions of different doping and cross-sectional areas.
- The domain length is inversely proportional to the doping concentration.

TWO-VALLEY MODEL THEORY:

- It has been proposed by Kroemer to explain the manifestation of negative resistance in certain type of bulk semiconductor materials.
- In the conduction band of n-type GaAs a high mobility lower valley is separated from a low mobility upper valley by an energy difference of 0.36ev.
- Under equilibrium conditions the electron densities in both the valleys remain same.
- When the applied field is lower than the field corresponding to the energies of the electrons in the lower valley then the no transfer of electrons takes place from one to other valley. The mobility of the carriers is positive.
- When the applied field is higher than the field corresponding to the energies of the electrons in the lower valley and lower than the field corresponding to the energies of the electrons in the upper valley, then transfer of electrons takes place from high mobility lower to low mobility upper valley. The mobility of the carriers becomes negative.
- When the applied field is higher than the field corresponding to the energies of the electrons in the higher valley, then no transfer of electrons takes place because by that time all the electrons of the lower valley must have been transferred to the upper valley. The mobility of the carriers is positive.



Two-valley model of electron energy versus wave number for *n*-type GaAs.

- The nobilities of the electrons in the two valleys must satisfying the relation

$$\left[\left(\frac{\mu_l - \mu_u}{\mu_l + \mu_u f}\right)\left(-\frac{E}{n_l}\frac{dn_l}{dE}\right) - P\right] > 1 \qquad where \quad f = \frac{n_u}{n_l},\ \mu = E^P$$

RWH THEORY

Ridley, Watkins and Hilsum proposed this theory to explain the phenomenon of Negative Differential Resistance (NDR) in bulk materials. Its salient features are

- Bulk NDR devices are classified into two groups. One voltage controlled NDRs and second current controlled NDRs.

- The characteristic relation between Electric field *E* and the current density *J* of voltage controlled NDRs is 'N' shaped and that of the current controlled NDRs is 'S' shaped.
- The electric field is multi-valued in the case of voltage controlled NDRs and it is electric current that is multi-valued in case of current controlled NDRs.
- The differential resistivity increases with field in case of voltage controlled NDRs and decreases in case of current controlled NDRs.
- A semi-conductor exhibiting bulk NDR is inherently unstable because a momentary space charge, which might have been created due to random fluctuation in the carrier density, grows exponentially with time because the relaxation time is negative.
- Because of NDR, the initially homogeneous semi-conductor becomes heterogeneous to achieve stability. It results in 'high field domains' in voltage controlled NDRs and 'high current filaments' in current controlled NDRs.
- The high field domain starts forming at a region where the field intensity is higher extending further perpendicular to the direction of current flow separating two low
- The high current filament starts forming at a region where the field intensity is higher extending further along the direction of the current flow separating two low

According to RWH theory for the semiconductor to exhibit negative resistance,

- The separation energy between the lower valley and the upper valley must be several times larger than the thermal energy of the electrons at room temperatures i.e.
- The separation energy between the valleys must be smaller than forbidden energy gap between the conduction band and valence band.
- Electrons in the lower valley must have high mobility, small effective mass and low density of state whereas those in the upper valley must have low mobility, large effective mass and high density of state.

As Si and Ge don't meet these criteria, they can not exhibit dynamic negative resistance.

<u>GUNN MODES</u>

- Major factors that determine the modes of operation are
  - ✓ Concentration and uniformity of the doping
  - ✓ Length of the active region
  - ✓ Operating bias voltage
  - ✓ Cathode contact property

✓ Type of the circuit used.

- An important boundary separating the various modes of operation is $n_0 L = 10^{12} cm^{-2}$
- The TEDs with $n_0 L$ products smaller than $10^{12} cm^{-2}$ exhibit a stable field distribution.

<u>Gunn oscillation mode</u>: $\left[\dfrac{fL \cong 10^7 \, cm/\sec}{nL > 10^{12} cm^{-2}}\right]$

- This mode is operated with the field more than the threshold value i.e. $E > E_{th}$
- The high field domain drifts along the specimen until it reaches anode or low field value drops to below the sustaining field value ie $E < E_s$
- The frequency of oscillation is given by $f = \dfrac{v_{dom}}{L_{eff}}$ where v_{dom} is the velocity of the domain and L_{eff} is the effective length the domain travels before a new domain gets nucleated.

✓ Transit time domain mode: $[fL \approx 10^7 \, cm/\sec]$

- The high field domains are stable in the sense that they propagate with a particular velocity but don't change in any way with time.
- When the high field domain reaches the anode the current in the external circuit increases.
- The frequency of the current oscillations depends on among other things, the velocity of the domain across the sample. If the velocity increases the frequency increases and vice versa. It also depends upon the bias voltage.
- The shape of the domains in GaAs and InP TEDs is triangular.
- In this mode the oscillation period is transit time. The efficiency is below 10%.

✓ Delayed domain mode:$[10^6 \, cm/\sec < fL < 10^7 \, cm/\sec]$

- In this mode the domain is collected by the anode when $E < E_{th}$ and the new domain formation gets delayed until the rise of the field to above threshold.
- The oscillation period is greater than the transit time.
- The oscillations occur at the frequency of the resonant circuit.

- The efficiency of this mode is about 20%

✓ Quenched domain mode: [$10^6\,cm$ / sec< $fL < 10^7\,cm$ /sec]

- While the domain is traveling, the bias field drops to a value less than E_S during negative half cycle quenching the domain. A new cannot form until the field again rises above the E_{th} .
- Oscillations occur at the frequency of the resonant circuit rather than the transit time frequency.

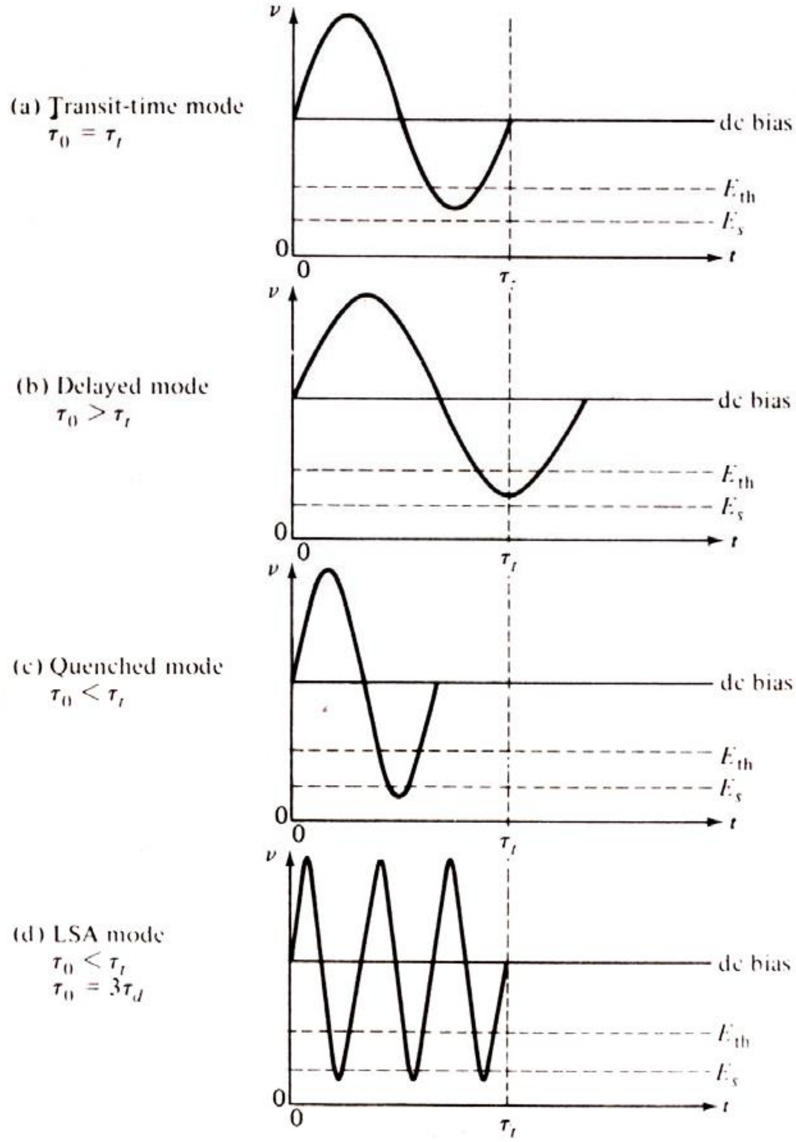


Figure Gunn domain modes.

- The operating frequencies are higher than the transit time frequency.
- Formation of multiple high field layers takes place.
- The upper frequency limit for this mode is determined by the speed of quenching.
- In this mode the efficiency can be 13%.

LSA mode: $\left[\frac{fL > 2X10^{7}\ cm/\sec}{2x10^{4} < \frac{n_0}{f} > 2x10^{3}}\right]$

- This is the simplest mode of operation.
- As the frequency is high the domains do not get sufficient time to form.
- Most of the domains find them selves in the negative conduction state during a large fraction of voltage cycle.
- A large portion of the device exhibits a uniform field resulting in efficient power generation at the circuit controlled frequency.
- This mode is suitable to generate short pulses of high peak power
- Its maximum operating frequency is much lower than the that of the TT devices.

In this mode the devices exhibits stable amplification at the transit time frequency.

- Negative conductance is utilized to prevent the formation of the domains.
- There exists three regions of amplification depending on the fL product range from $10^{7}\ to\ 0.5x10^{8}$

Bias ciruit oscillation mode:

- This mode occurs when there is either GUNN or LSA oscillation and fL is small.
- When the diode is biased to the threshold GUNN oscillation begin leading to sudden decrease in the average current of the circuit driving it to oscillations.
- The frequency of the oscillations may be in the range from 1KHz to 100 MHz.

IMPATT

- The IMPATT diode is now one of the most powerful solid-state sources for the generation of microwaves. It can generate higher CW power outputs in millimeter-wave frequencies i.e. above 30 GHz of all solid-state devices. These are compact, inexpensive, moderately efficient and with improved device fabrication technology these diodes also have become reliable under high temperature operation
- IMPATT stands for ‘IMPact ionization Avalanche Transit Time’.
- IMPATT diodes employ ‘impact ionization’ and ‘transit time’ properties of semi-conductor structures to get negative resistance at microwave frequencies.

- Impact ionization or avalanche multiplication: 'it is a process related to semi-conductors in which the generation and multiplication of hole-electron pair takes place due to knocking off the valence electrons into conduction band by the highly energetic carriers when the electric field is increased above certain value'.
  The rate of pair production is a sensitive non-linear function of field.
- The negative resistance occurs from the delay, which cause the current to lag behind the voltage by half cycle time, have two components:
  - One is Avalanche time delay caused by 'finite buildup time of the avalanche current.'
  - Other is transit time delay by the finite time for the carriers to cross the drift region.
- These diodes are made from GaAs, Ge, Si.
- Extremely high voltage gradient 400kv/cm back biasing the diode is required for its operation.
- In all the structures there exists two regions
  - Avalanche region: in this region avalanche multiplication takes, doping concentration and field intensity are high.
  - Drift region: in this region avalanche multiplication does not take place, doping concentration and field levels are low.
  - Depletion region is AR plus DR.

- Maximum negative resistance is occurs when the transit angle θ = π at which the operating frequency becomes $f = \frac{v_d}{2L}$ where v_d is drift velocity of the carriers and L length of the drift region.
- IMPATT is the name of a diode family. It's basic members are
  - Read diode $p^+ - n - i - n^+$ *or its dual* $n^+ - p - i - p^+$
  - Single drift diode $p^+ - n - p^+$
  - Double drift diode or RIMPATT diode $p^+ - p - n - n^+$
  - Pin diode $p^+ - i - n^+$

- The noise measure in GaAs is low when compared to Si and for Ge it is in between GaAs and Si. The main reason for the low noise behavior of GaAs is that for a given field the electron and hole ionization rates are essentially same, where as in Si these are quite different.
- The highest powers, frequency and efficiency are obtained from double drift diodes that are also known as RIMPATTs. The power-frequency^2 product is highest for these diodes. The improved performance results mainly from the fact that holes and electrons produced by the avalanche are allowed to give energy to RF signal while

traversing the drift region. In the case of single drift diodes only one type of carriers is so utilized.

- Comparison:
  - When compared to GUNN diode these diodes have more efficiency around 30%, more powerful around 15w CW and their frequency can reach up to 200GHz where as in the case of GUNN it is only 100GHz.
  - But when compared to GUNN diodes these are more noisy.
  - Below 40GHz GaAs IMPATTs have higher powers and efficiency than do Si IMPATTs.
  - Between 40-60 GHz GaAs IMPATTs show higher power and efficiency whereas Si IMPATTs give high reliability and yield.
  - Above 60GHz Si IMPATTs outperform the GaAs IMPATTs.
  - Around 10GHz efficiency is close to 40%.
- Power output:
  - At lower frequencies the power output is thermal-limited and varies as f^{-1};
  - At higher frequencies (>50 MHz) the power is electronic limited and varies as f^{-2}
- Difficulties:
  - The noise is high mainly because of the statistical nature of the generation rates of electron-hole pairs in the avalanche region.
  - Highly sensitive to operational conditions.
  - Large electronic-reactance, which can cause detuning or even burnout of the device unless proper care is taken.
- Applications:
  - In microwave links
  - In CW radars
  - In electronic counter measures.

TRAPATT

- TRAPATT stands for 'TRApped Plasma Avalanche Triggered Transit'
- TRAPATT diode is a high power, high efficiency device.
- For a TRAPATT diode, the design and performance are more complicated because of strong device-circuit interaction that dictates most of the device performance.
- Silicon $p^+ - n - n^+ \; or \; n^+ - p - p^+$ structures are used to get high powers. The doping of the depletion region is generally such that the diodes are well punched through at break down i.e. depletion region extends from $p^+ - n \; to \; n - n^+$ junction.

- OPERATION:
  - It is mounted at a distance of $\lambda_g/4$ from a short in a wave-guide or coaxial line so that a high RF field exists across the diode
  - Initially the diode charges up like a linear capacitor, driving the magnitude of the field above the breakdown voltage.
  - High field avalanche zone or shock front passes through the diode and fills the depletion layer with a highly conductive dense plasma of electrons and holes whose space charge depresses the voltage to low values.
  - The plasma generated takes time to get removed from the depletion region followed by the residual charge from the ends of the depletion layer, raising the voltage across the diode.
  - The diode once again charges up like a fixed capacitor until current moves to zero. The same voltage is maintained across the diode until the current rises again.
  - As the voltage across the diode is low during the drift of the pulse, drift velocity becomes less leading to more transit time, dissipation becomes less giving rise to higher efficiencies, operating frequencies lower and active regions become thinner.
  - This diode requires a circuit that can support harmonics of fundamental frequency of high voltage amplitudes. The rich harmonic content is necessary to get the required phase delay in the current at such low frequencies.

- Difficulties:
  - It has higher noise figure when compared to IMPATT diodes.
  - Its operation is quite complicated and requires good control over the device and circuit.
  - The upper operating frequencies are practically limited to below millimeter-wave range i.e. 10GHz.
  - It is highly sensitive even to small changes in circuit or operating conditions or temperature.
- Performance:
  - The output power of a series connection of five diodes under pulse condition reaches 1.2kw with a efficiency of 25%.
  - The upper frequency limit is close to 10GHz and highest obtained efficiency is 75%
  - Its high pulse power output is much larger than most other microwave semi-conductor devices.

BASICS OF MICRO-WAVE LABORATORY

Microwave bench in the lab is a rectangular wave-guide run over which various components like source, attenuator, frequency meter, tunable probe etc. are mounted. It provides an unexcelled tool for learning basic concepts of standing waves and mismatched transmission lines at microwave frequencies. Its length is proportional to wavelength, as a result at low frequencies it becomes unwieldy long and at high frequencies it becomes too small to work comfortably with it.

The mode of the wave that exists in the bench of the lab is TE_{10} i.e. dominant mode. So the cut-off wavelength is $\lambda_C = 2a$ where ' a ' is the inner distance between the sidewalls of the wave-guide. The equipment is designed to work in the X-band, which ranges in frequency from 8.2 to 12.4 GHz, wavelength from 2.5 cm to 3.75 cm. The guide wavelength ranges from 2.98cm to 6.47cm, the guide dimensions are 2.286 X 1.016 cm with cut-frequency 6.557 GHz and cut-off wave length is 4.56 cm.

If the source is Reflex Klystron, it is required to be operated in $1\frac{3}{4}$ made giving max possible power output. To achieve this condition set the beam voltage to around 300 V and increase repeller voltage until max deflection is observed in the VSWR meter. If the source is Gunn, it must be operated in the middle of its negative resistance region by varying its bias voltage until max deflection is observed in VSWR meter.

The micrometer head provided at the source end of the bench is to change to the frequency of the microwave source. The power output and frequency of the source are dependent upon the output impedance and power reflected. The isolation must be sufficient to prevent reflected wave entering back into the source.

While measuring guide wavelength, the termination should be short, which can give sharp and hence easily locatable minima leading to accurate measurements. Even though the distance between two consecutive maxima is $\lambda_g/2$ only minima should be used to measure λ_g as they are more accurately locatable than the maxima.

VSWR meter consists of an ac amplifier tuned to 1 KHz approximately. For VSWR meter to be of any use its input and hence the output of the microwave source must be a modulated signal to this frequency. If the source is RK the modulation is done internally, in case of Gunn oscillator it is performed externally with PiN diode.

VSWR meter is designed to measure VSWR. Its scale is calibrated to read VSWR directly. It can also be used as a reference to measure power levels. Most of the measurements require a power level in the bench at which it can give a deflection in VSWR meter when its gain is 30 db. For the double min method to be used, the VSWR on the line must be more than 3 db. Other wise 3db points do not exist over the standing wave pattern.

Slide-screw tuner is a wave guide equivalent of transmission line stub with two degrees of freedom. It is designed to provide the necessary mismatch to establish high VSWR over the line. If the depth of insertion $d < \lambda/4$ it provides capacitive susceptance and for $d > \lambda/4$ it is inductive susceptance.

In the wave-guide detector or tunable probe, for better response the short must be maintained at a distance of $\lambda_g/4$ from the diode and also in the tunable probe. The diodes of the wave-guide detector and movable probe give voltage or current proportional to the power incident over the surface of the diode. This fact can be used to measure microwave power ratio with ammeter or voltmeter. Relative power in db is P = 10 log $\frac{I_1}{I_2}$ db or 10log $\frac{V_2}{V_1}$ db .

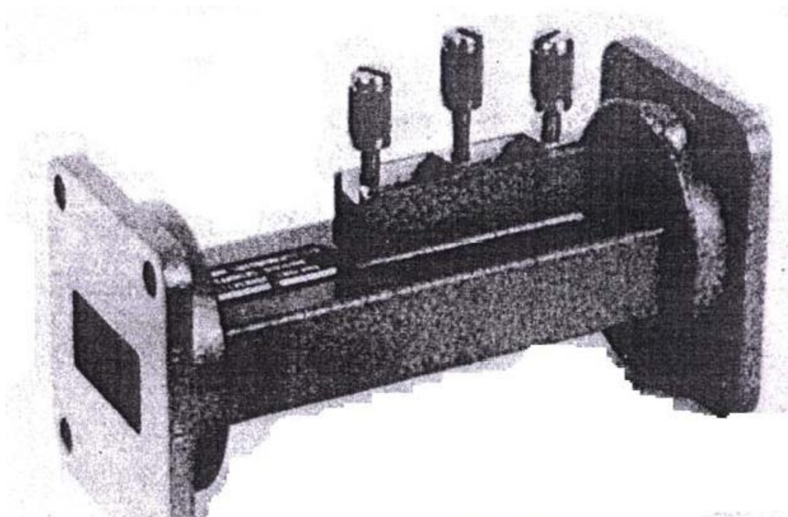
The length of the slotted section is such that to accommodate at least three minima (one guide wavelength) at the lowest frequency of operation. Low power levels in the bench necessitate too much insertion of the probe leading to distortion of the standing wave pattern giving rise to erroneous results. So attenuation of the wave should not be too high.

BLOCKS OF THE BENCH

- The source used in the microwave bench is either Reflex Klystron or Gunn oscillator. In either case the frequency of the wave can be varied using the micrometer head provided at one end of the bench.
- Isolator always follows the source. Its purpose is to prevent the reflected wave entering back into the source. In the lab the Isolator that is configured with three port circulator and matched termination is used.

- The attenuator used in the bench set up is flap attenuator providing attenuation of 0 to 25 db. The amount of attenuation provided by the device can be read from the micrometer scale provided.
- Wave-meter: It is designed to measure the microwave frequencies in the X band *directly*. Outwardly it is cylindrical in shape with a rotary cap at the top, rotary scale which is a tuning dial directly calibrated in frequency and a vertical pointer over a transparent plastic enclosure attached to the fixed base which has a wave-guide through it. In the grooves over its surface two rings move upwards when the scale is rotated clock-wise and downwards when it is rotated anti-clockwise. At the top of the scale it is 12.4 and at the bottom of the scale it is 8.2 frequencies in GHz. Inside it is a circular cavity with a movable short attached to the cap to allow the mechanical tuning of the resonant frequency, and the cavity is loosely coupled to wave-guide with a small aperture. In operation, power will be absorbed by the cavity as it is tuned to the frequency of the wave travelling through the wave-guide. The absorption can be monitored by a 'dip' in the deflection of the VSWR or power meter connected to the system.
- The standing wave detector is designed to observe the standing wave pattern existing in the slotted section and consists of
    - Slotted wave-guide: It is a piece of rectangular wave-guide with a non-radiating slot over its broad wall. Probe can be inserted through the slot into the guide to sense the field
    - Tunable probe: It is movable with its probe into the slot along the slotted section. The output of the tunable probe is proportional to the power of the wave into which its probe is inserted and it is normally given to the VSWR meter. The cap of the tunable probe can be pulled out or pushed in to match the slotted section to the wave-guide.
    - Vernier scale: This is provided along the length of the slotted section to locate the position of the tunable probe exactly thereby the nodes or antinodes of the sw pattern.
    - Rack and pinion arrangement: it is to move the probe and place it at any desired location over the SW pattern.
- VSWR meter: It is basically a high gain voltmeter consisting of basic meter movement and a high (to be able to measure low quantities) variable (to have multi-range facility) gain (60db) ac (to avoid the drift problems associated with dc amplifiers) amplifier. To vary the gain three knobs are provided one in steps of 10db and the remaining two in continuous manner. Its scale has two parts one to measure absolute VSWR: top '1' to '∞'and just below to it '3' to '10', another part below the ordinary scale to measure VSWR in db's: from '0' to '10'. In addition both have extended scales to measure 'accurately' the VSWR in between '1.3'to '2'.

- Wave-guide detector: It consists of a diode across, with a movable short inside a piece of wave-guide. For maximum response the short must be maintained at a distance of $\lambda_g/4$. It is designed to detect the presence of wave. Its output is proportional to the power of the wave incident. So it is a square law device.

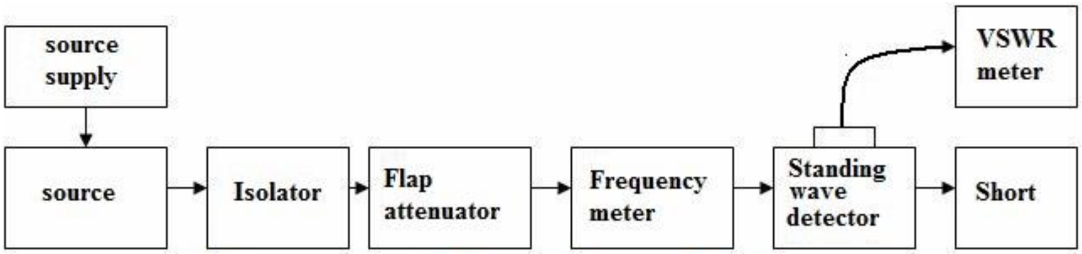


three-screw tuner.

FREQUENCY

- **Dip method or wave meter method**:
  - The wave meter is connected in the bench with attenuator on one side and the waveguide detector on the other side. The output of the wave-guide detector is given to the VSWR meter and power flow in the bench is adjusted until proper deflection is observed in the meter.
  - The wave meter is rotated until it is one end of the scale i.e. the indication of the meter is either 12 or 8 GHz.
  - Rotate the wave meter in the opposite direction slowly but continuously by pressing the centre finger of the left hand over its cap while observing the deflection in the VSWR meter.
  - At one point of time a ‘dip’ in the deflection of the meter can be observed. Stop the rotation of the wave meter and note down the indication of the meter in between rings against the pointer. This is the frequency of the wave running in the bench.
- **Slotted line method**:
  - This method uses cut-off wavelength and guide wavelength to calculate the free space wave length. From the free space wave length frequency can be calculated.

- $f = \frac{c}{\lambda}$ *and* $\lambda_g = \frac{\lambda}{\sqrt{1-(\lambda/\lambda_0)^2}}$
- As the mode of the wave in the bench is dominant, the cut-off wavelength is twice the inner distance between the sidewalls of the wave guide. By measuring this distance using a scale and multiplying it with two cut-off wavelength can be obtained.



Measurement of the guide wave length

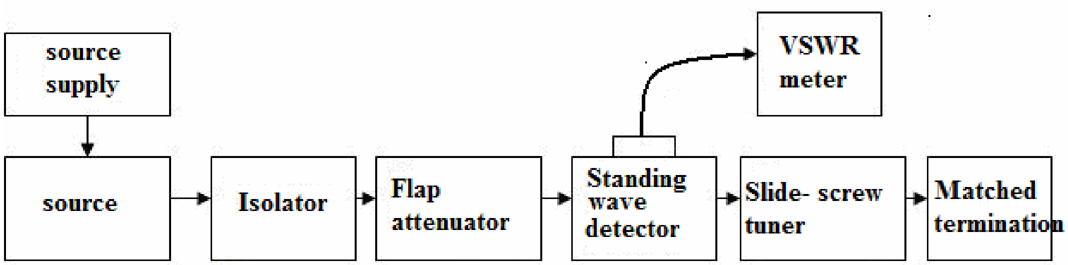
- To find the guide wavelength terminate the bench with a short resulting in the formation of the standing wave pattern in the slotted section. The output of the tunable probe is given to the VSWR meter and the distance between two consecutive minima is measured using the Vernier scale provided. Twice this amount gives the guide wavelength.

<u>VSWR</u>

- **<u>Low VSWR</u>**:
  - This method can be used to measure the VSWR when it is less than ten with reasonable accuracy.
  - The bench is terminated with the DUT for which VSWR is to be determined resulting in the formation of the standing waves in the slotted section. In the laboratory, the DUT is usually a Horn antenna. The output of the tunable probe is connected to the VSWR meter.
  - Place the probe over a maximum and using the gain varying knobs provided over the front panel of the VSWR meter move the pointer of the meter to '1' over the scale.
  - Then move the probe to minimum and note down the indication of the pointer over the scale which gives the VSWR of the wave over the bench.
  - In the case of the pointer drops to no deflection position while moving to minimum, then increase the gain of the meter by 10db, move the probe to minimum, note down the indication of the pointer on the scale 3-10 which is the VSWR of the wave.
- **<u>Double minimum method</u>**:
  - Double minimum method can be used only if the SWR over the line is more than 3db and it requires to be used only when SWR is more than 10. To be able to apply this method, a VSWR more than 10 has to be established first over the line. In the laboratory it is done using a match terminated slide screw tuner. With match terminated slide screw tuner connected to the slotted section, place the tunable probe

over a maximum of the standing wave pattern and move the pointer of the VSWR meter over to ‘1’ by varying the gain. Now move the probe to a minimum and vary the position and depth of the probe of the slide screw tuner until the pointer in the VSWR meter is over ' ∞ ' of the top scale. Increase the gain of the meter by 10db and if the pointer is still over' ∞ ' (or 10 of the scale below) then the SWR over the line is 10 or more. If the pointer stays over in between two extreme positions of the scale even after increasing the gain, then the setting of the slide screw tuner should be changed in such an amount in such a direction so that the pointer is over ' ∞ '. Now the VSWR over the line is 10 or more and we can use the double minimum method to measure it accurately.

- The bench is to be terminated with the DUT, which can establish high VSWR i.e. more than 3db over the slotted section. The output of the tunable probe is given to the VSWR meter.
- Move the tunable probe over to a minimum and by varying the gain place the pointer



Measurement of high VSWR

on ‘3’ in the db scale of the VSWR meter.

- Move the tunable probe to either side until the pointer moves to ‘0’ in the db scale. Note down the position of the tunable probe over the Vernier scale. Let it be d_1.
- Now move the probe in the opposite direction until the pointer again stands over the ‘0’ after passing over the ‘3’ in the db scale. Note down the position of the probe. Let it be d_2.
- Now replace the termination of the bench with short and measure the distance between two consecutive minima. Twice this distance gives the guide wavelength λ_g.
- The VSWR can be obtained using the formula $\text{VSWR} = \frac{\lambda_g}{\pi(d_1 \quad d_2)}$

To establish to high VSWR in the lab:

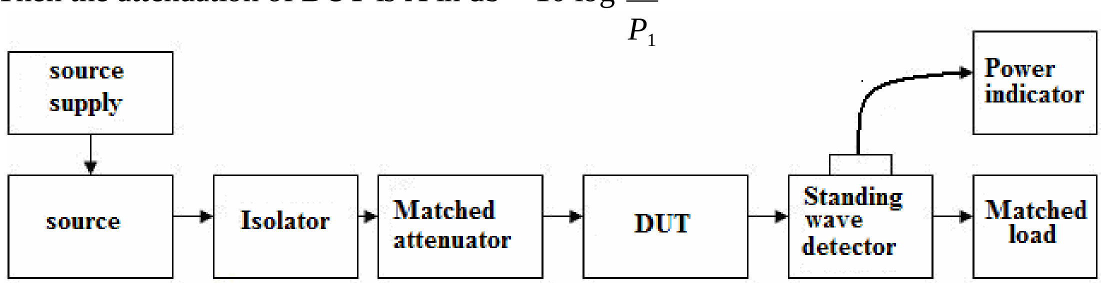
ATTENUATION:

Power ratio method:

- The DUT for which attenuation is to be measured is placed before the slotted section of the bench terminated with matched load.
- The output of the tunable probe is given to a power meter.

- Let us suppose the indications of the power meter are P_1 and P_2 with the DUT and with out DUT in the bench.

- Then the attenuation of DUT is A in db = 10 log $\frac{P_2}{P_1}$

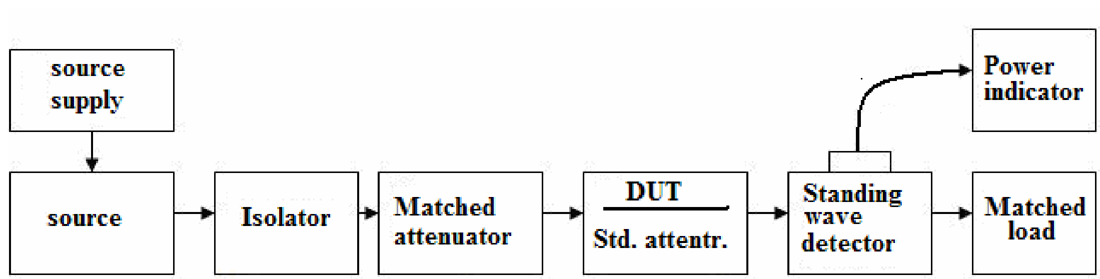


Power Ratio method

- In case of the non-availability of the power meter, the power ratio can still be obtained by measuring the output current or voltage of the tunable probe using multi-meter or CRO. The ratio $P_1/P_2 = V_1/V_2 = I_1/I_2$ as
- This method uses two different points on the characteristic of curve of the diode detector at which the detector may not be obeying square law characteristic leading to erroneous readings.

RF substitution method:

- Place the DUT before the slotted section and connect the tunable probe output to VSWR meter. Termination of the bench must be matched. Note down the deflection of the pointer in the VSWR meter.



RF substitution method

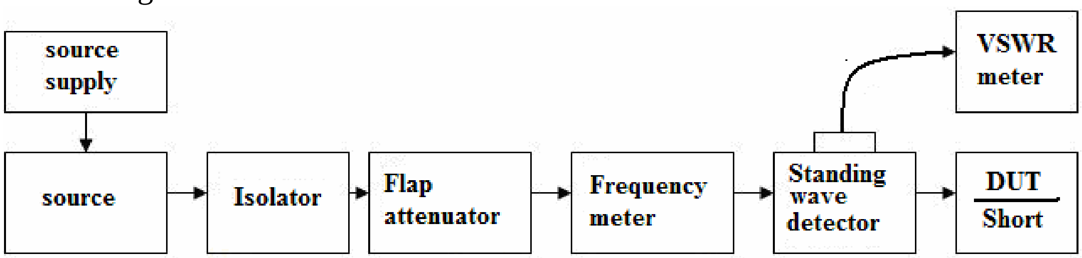
- Replace the DUT with standard variable precision attenuator and vary its attenuation until the deflection of the pointer is same as that in the previous step.
- At this position the attenuation of the standard attenuator which can be noted down gives the attenuation of the DUT

IMPEDANCE

Slotted line method:

- The bench is terminated with the DUT for which impedance is to be measured. And the position of a minimum is located along with the measurement of SWR .

- Replace the termination with a short. Measure the guide wavelength and shift in minimum both in magnitude and direction.



Measurement of the impedance

- If the shift is towards left the load is inductive and if it is right the load is capacitive.
- Use the formula shown below to calculate the impedance of the DUT. $\frac{Z_L}{Z_0} = \frac{1+|\Gamma|e^{j\theta}}{1-|\Gamma|e^{j\theta}}$

  where the magnitude of the reflection coefficient $|\Gamma| = \frac{\rho - 1}{\rho + 1}$ and $\theta = \pi \pm 2\beta d$ where d is shift in the minimum and $\beta = \frac{2\pi}{\lambda_g}$ phase shift constant, + in case of right shift and – in case of left shift. Z_0 is characteristic impedance of the slotted section.

Magic Tee method:

- The matched source and null detector are connected to the side arms of the magic tee.
- The standard variable precision impedance and unknown impedance are connected to the coplanar arms of the magic tee.
- The standard variable precision impedance is varied until the null is observed in the detector.
- The indication over the standard variable precision impedance is the impedance to be known.

PowerBridge methods:

- Bolometers are devices which change their resistance with temperature. When wave power falls over its surface, it gets converted into heat rising its temperature. With change in temperature the resistance changes. The change in the resistance, which can be measured conveniently using bridge methods, is a measure of the wave power incident.
- Bolometers can be divided into two categories one *Barretters* whose resistance rises with temperature and *thermistors* whose resistance falls with temperatures.
- Barretters are thin short platinum wires used to measure low wave power levels. They change 5ohm per milli-watt of incident wave power. These are very delicate and sensitive devices useful to measure very low power levels less than few milli-watts. They have

positive temperature coefficient of resistance. Thermistors are semi conductor devices with negative temperature coefficient of resistance. Used to measure low and medium wave power levels. The change in resistance is 60 ohm per milli-watt of incident wave power.

- Power meter: it is a balanced bridge circuit in which one of the arms is a bolometer. The wave power incident over this arm changes its resistance driving the bridge into unbalance. The amount of unbalance which is proportional to the incident wave power is amplified using the bridge amplifier and measured using a voltmeter. The voltmeter is calibrated to read the power directly.
- Single bridge circuits give erroneous readings due to mismatch at the wave input port and also due to sensitivity of thermistor to ambient temperature. These shortcomings can be overcome by adopting double identical bridge.

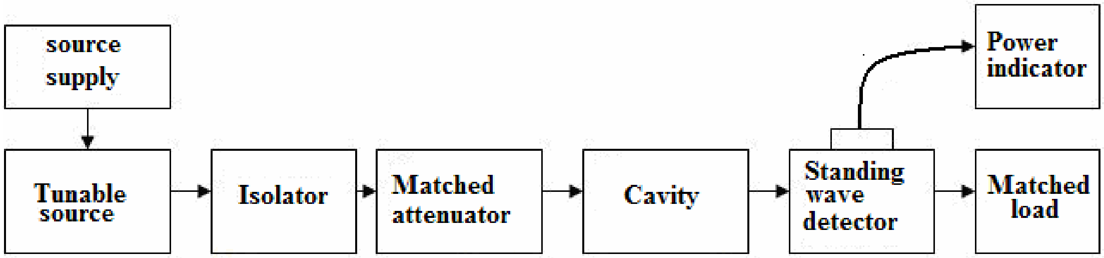
Calorimetric methods:

- This method is useful to measure high wave powers. It involves conversion of the wave energy into heat, absorption of heat by some liquid or dielectric and then measurement of the rise of the temperature of the liquid/dielectric.
- Static calorimeter: it consists of a 50ohm coaxial cable filled with a dielectric load with a high hysterisis loss. The incident wave power is dissipated in the load. The average input is $P = \frac{4.18\, mC_pT}{t}$ watts where t is time in sec, T is the temperature in ^{0}C and m is the mass of the medium in gms.
- Circulating calorimeter: in this method the power is made to incident on the water flowing at a constant rate through a water load. The heat introduced into the fluid makes the exit temperature to be higher than the input temperature. The incident power is then measured using the relation $P = 4.18 v\, d\, C_p\, T$ watts where v is rate of the flow of the fluid in cc/sec, d is the specific gravity of the fluid in gm/sec, C_p is the specific heat in cal/gm.

'Q' of cavity:

By transmission:

- This method is used when the cavity for which 'Q' is being measured has two ports or openings. It is to be connected before the slotted section in the bench with tunable source. The termination of the bench must be matched and the output of the tunable probe is given to a power meter.
- The power that is transmitted by the cavity is measured using the power meter at different frequencies and a graph is drawn. It resembles inverted 'U'.



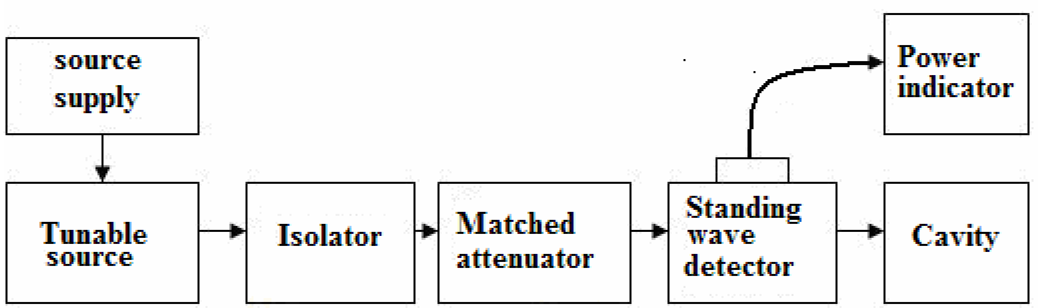
Transmission method

- From the graph find the resonant frequency, the frequency at which the transmitted power is maximum and also the half-power frequencies at which the transmitted power half of the maximum.
- Using the relation

$$Q = \frac{\text{resonant frequency}}{\text{bandwidth}}$$ find the Q of the cavity.

<u>By measuring VSWR</u>:

- This method is useful when the cavity has single opening or port. The bench with tunable source is terminated with the cavity and output of the tunable probe is connected to VSWR meter.
- The VSWR due to the cavity is measured at different frequencies and graph is drawn whose shape is similar to 'U'.



VSWR method

- The resonant frequency S_r, frequency at which the VSWR is lowest and the lowest VSWR both can be noted down from the graph
- From the lowest VSWR using one of the following relations which ever gives more than one find the half-power VSWR. $\rho_{1/2} = \rho_r + \frac{1}{2\rho_r} + \sqrt{\rho_r^2 + \frac{1}{4\rho_r^2}}$ or

$$\rho_{1/2} = \frac{1}{\rho_r} + \frac{\rho_r}{2} + \sqrt{\frac{1}{\rho_r^2} + \frac{\rho_r^2}{4}}$$

- Using the computed $\rho_{1/2}$ from the already drawn graph find the half-power frequencies and from them band-width.
- Now using the formula $Q = \frac{\text{resonant frequency}}{\text{bandwidth}}$ find the Q of the cavity.

Parameters of DC

The important characteristics of the DC are coupling factor, directivity and isolation.

- Measure the output power of the source P_{in}. In case of non-availability of the power meter, use the wave-guide detector –CRO combination to measure the voltage proportional to the power. Let it be V_{in}
- Give input at the port 3. Measure the output power at port 1 with port 2 match terminated. Let it be P_c. If the voltage proportional to power is measured using wave-guide detector–CRO combination, let it be V_c
- Give input at the port 2. Measure the output power at port 1 with port 3 match terminated. Let it be P_d. If the voltage proportional to power is measured using wave-guide detector–CRO combination, let it be V_d
- Give input at the port 2. Measure the output power at port 3 with port 1 match terminated. Let it be P_T. If the voltage proportional to power is measured using wave-guide detector–CRO combination, let it be V_T
- Now coupling in db $C = 10\log\left(P_{in}/P_c\right) = 10\log\left(V_{in}/V_c\right)$, directivity in db $D = 10\log\left(P_c/P_d\right) = 10\log\left(V_c/V_d\right)$ and isolation in db $I = 10\log\left(P_{in}/P_d\right)$ $= 10\log\left(V_{in}/V_d\right)$. If the measurements of correct $I = C + D$
- Precaution: After the power output of the source P_{in} in measured, the settings of the source, attenuator or waveguide detector should not be changed.

s-parameters

- S-parameters are complex quantities and to measure them network analyzer is required. If the device is assumed an ideal, reciprocal with equal arm lengths, then the s-parameters become pure real quantities.
- Let us try for the s-matrix of the magic tee assuming it an ideal one. As power meters are not usually available, we can use wave-guide-CRO combination to measure the relative powers.

- Step I: Measure the output of source. Let it be V_{in}. The settings of the sources and attenuator should not be varied until the completion of the experiment.
- Step II: Give input to port1 and measure output at ports 2,3 and 4 while maintaining matched terminations at the other ports. Let them be V_{21}, V_{31} and V_{41}.
- Step III: Give input to port3 and measure output at ports1,2 and 4 while maintaining matched terminations at the other ports. Let them be V_{13}, V_{23} and V_{43}.

Now $s_{31} = \sqrt{V_{31}/V_{in}}$, $s_{21} = \sqrt{V_{21}/V_{in}}$, $s_{41} = \sqrt{V_{41}/V_{in}}$, $s_{23} = \sqrt{V_{23}/V_{in}}$, $s_{43} = \sqrt{V_{43}/V_{in}}$. As the device is reciprocal $s_{31} = s_{13}$, $s_{21} = s_{12}$ etc. Then the diagonal elements of the s-matrix can be found using unity property. If the measurements are correct them the diagonal elements must be zeros.