Unit-3

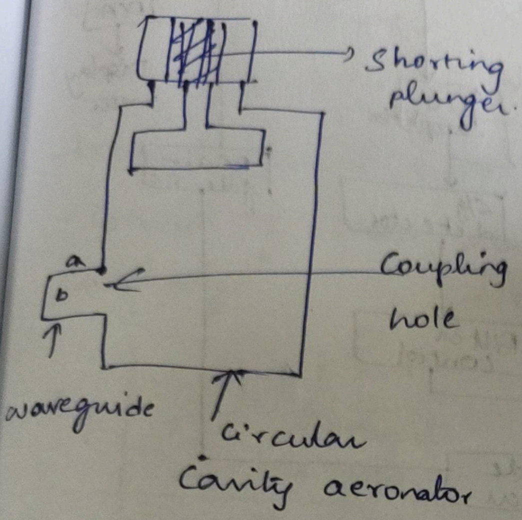
* Terminologies	Low freq	Microwave freq.
Power	Voltage + current can be measured	Difficult to measure V + I in txn line, hence is desirable to measure power directly
Circuit Elements	Lumped elements, hence can be identified + measured	Distributed + impedance of whole circuitry can be measured
Parameters	Can be exactly known	Many parameters can not be measured for their absolute values

* Freq. measurements:-

* Wave meter method:-

- Typically constructed from cylindrical cavity resonator with a variable short circuit termination.
- Shorting plunger is used to change the resonance freq of cavity by changing cavity length.
- TE_{011} mode is used because of its higher Q + absence of axial current. TM_{010} mode is excited in cavity through coupling hole by magnetic field coupling
- Possible oscillation due to plunger can be avoided by placing a block of polytron at its back. For Q ranging from 1000 - 50,000, the accuracy of wavemeter is 1% to 0.005%.

• Since power is absorbed in wavemeter at resonance, this is called as absorption type wavemeter.



(ii) <u>Slotted line Method:-</u>

• Since distance b/w 2 minima $d_{min} = \lambda_g/2$; freq can be determined from relations,

$$\boxed{\lambda_g = 2 d_{min}}$$

For waveguide,

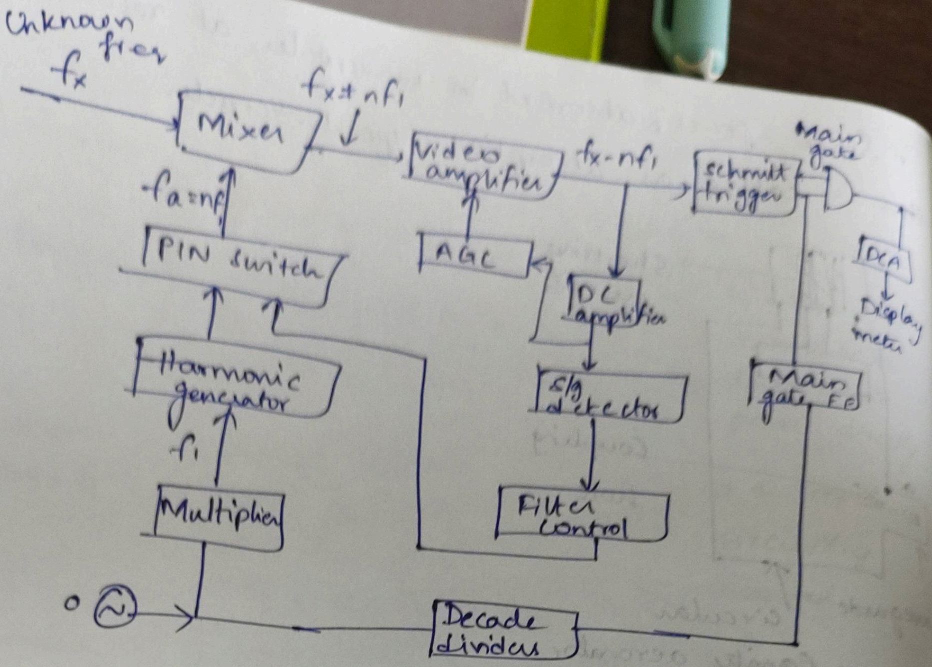
$$\lambda_g = \frac{\lambda_0}{\sqrt{\left[1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2\right]}} \Rightarrow \lambda_g = \frac{\lambda_0}{\sqrt{\left[1 - \left(\frac{\lambda_0}{2a}\right)^2\right]}}$$

For ~~coax~~ coaxial line, $\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_r}}$

(iii) <u>Down - conversion method:-</u>

• Accurate measuring using heterodyne receiver.

• Unknown frequency f_x is down converted by mixing it with known f_a $(f_x - f_a = f_{IF})$ & then is amplified & measured by counter.



• f_a is obtained by = local oscillator freq × f_i
Convenient freq is then passed through harmonic generator to give series of harmonics of f_1

• Appropriate harmonics are then selected by tuning cavity such that f_a can be added with f_{IF} & displays unknown freq f_x.

• Typical value of $f_1 = 100$ to 500 MHz for a range of f_x up to 20 GHz.

* Measurement of power:-

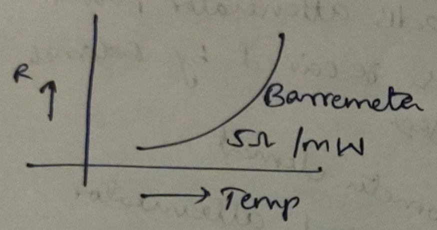
• μw power is avg. power & inside a waveguide, it is invariant with measurement position.

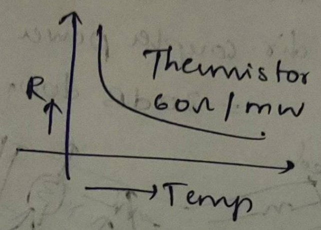
• Techniques used:-

(i) Bolometer (for low μw power [0.01mW–10mW]):

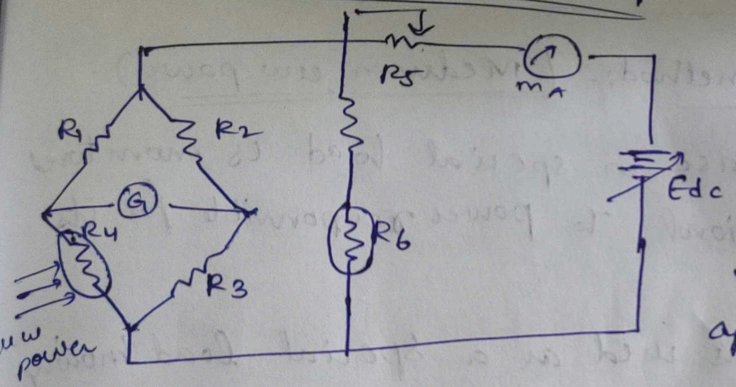
• ~~Meas~~ Bolometers & thermocouples whose resistance changes with applied power are used to measure low μw-power.

- Bolometer is a simple temp. sensitive device whose resistance changes with temp.
- Barremeter & thermistor:- Barremeter have +ve temp coefficient & its resistance ↑ with ↑ in temp.
- Consists of short plantinum wire mounted in a cartridge.





* Balanced bolometer technique:-



- Bolometer is at one arm & initially bridge is balanced by adjusting R5 which varies with DC power applied.
- Let E_1 be voltage of battery at balance. When power is applied ⇒ bolometer heats up + bridge becomes unbalanced.
- New power E_2 is proportional to μw power & detector G can be directly calibrated in terms of μw power.

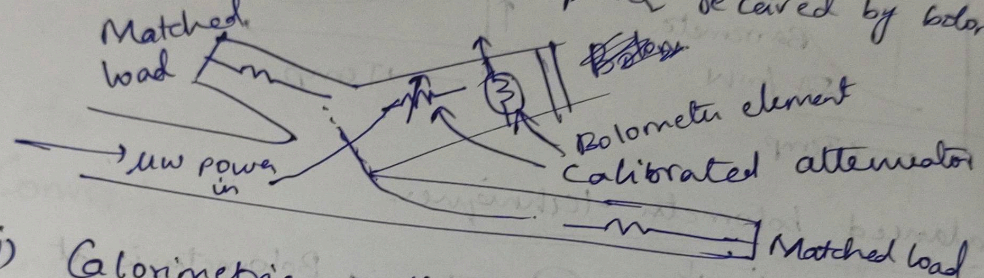
* Errors:- · R6 & R7 are used for temp. compensation
- R6 + R3 are identical & close to bolometer element
- If temp is changed + R3 is reduced, then it will not be termed as μw power change since R6 will reduce.

• Thus more current will flow through R_6 & lesser through bridge & R_3 & thus Bridge is balanced.

* Limitations:- ① Barremeter & thermistor have limited power handling capacity - 10mW

② Power measuring capability can be ↑ by using directional couplers.

③ 20dB dir. coupler power + 10dB attenuator power = 30dB down power received by bolometer.



*(ii) Calorimetric method:- (Medium uw power).

*Principle:- temp rise in special load is monitored which is proportional to power responsible for its rise.

* Working:- Water is used as a special load knowing its mass, specific heat & temp. rise & known rate of fluid flow the power can be measured.

• I/p load & I/p temp gauge are closely placed so that temp gauge will sense change in temp, making bridge ~~to~~ unbalanced.

• s/g due to imbalance is then amplified & is given to comparison load resistor placed near to comparison gauge

• Heat generated is transferred to comparison gauge making bridge rebalanced.

* characteristics:- • For efficient & quick heat exchange components are immersed in oil.

• power measurement accuracy is ±5%.

• 1200Hz source & meter are seperated by means of transformer.

(iii) Calorimetric Watt meter:- (for high μw-power)

• 2 types → Dry type
→ Flow type.

① Dry type:- Consists of coaxial cable filled with dielectric having high hysteresis loss.

② Flow type:- Circulating water, oil or any liquid which is good absorber of μw.

• Fluid changes its temp, when it passes through load because of absorption of μw-power.

• Exact power $P = \frac{RK\rho(T_2 - T_1)}{4.18}$

where R = rate of flow (cm^3/s)

$(T_2 - T_1)$ = temp. diff in °C

K = specific heat in cal/g.

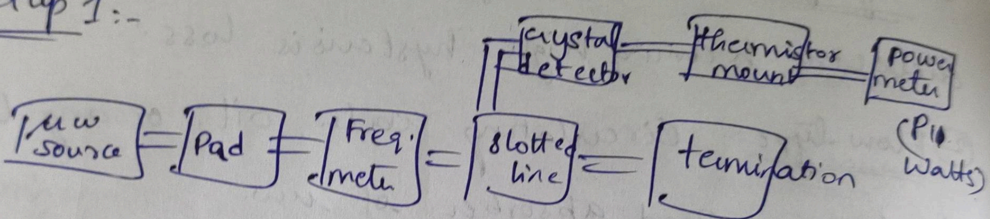
ρ = Specific gravity in ~~cal/g~~ g/cm^3

* Attenuation Measurement:-

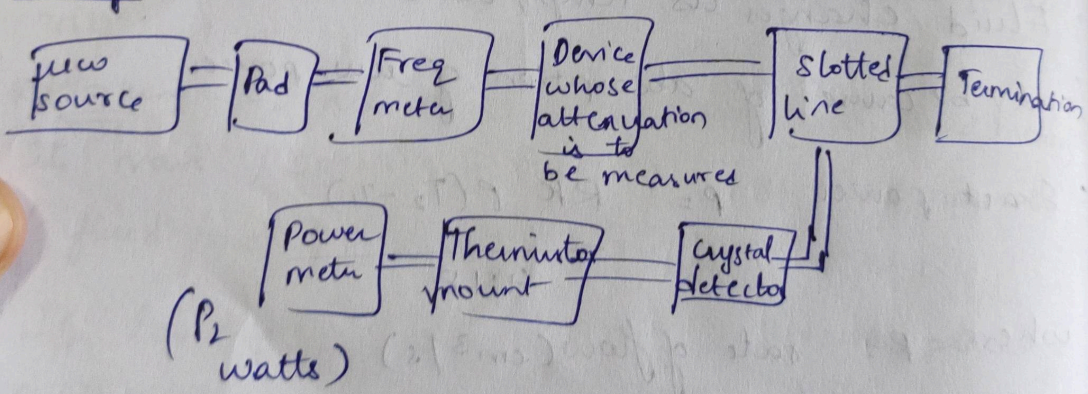
- ratio of i/p power to o/p power expressed in dBs, Attenuation $= 10\log\left(\frac{P_{in}}{P_{out}}\right)$
- amount of attenuation can be measured by 2 methods :
  - Power ratio
  - RF substitution method

(i) **Power-ratio method:-** Measures i/p power & o/p power with & without the device whose attenuation is to be measured.

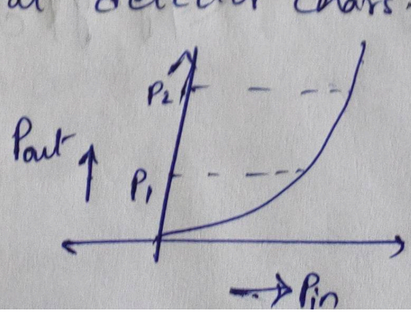
Setup 1:-



Setup 2:-

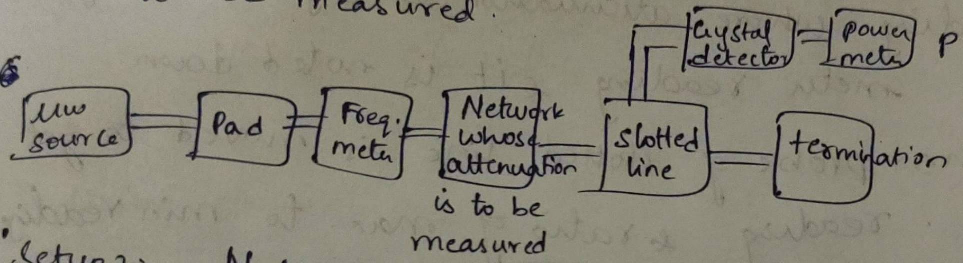


*disadv:- Measured attenuation corresponds to 2 power positions on power meter with sq. law crystal detector chars.

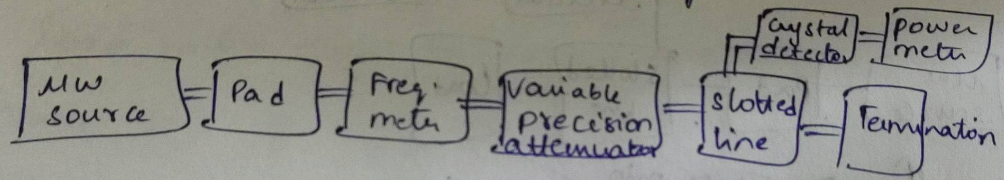


(ii) RF substitution method:-

- Attenuation at single power position is measured.
- Setup 1:- Includes network whose attenuation is to be measured.

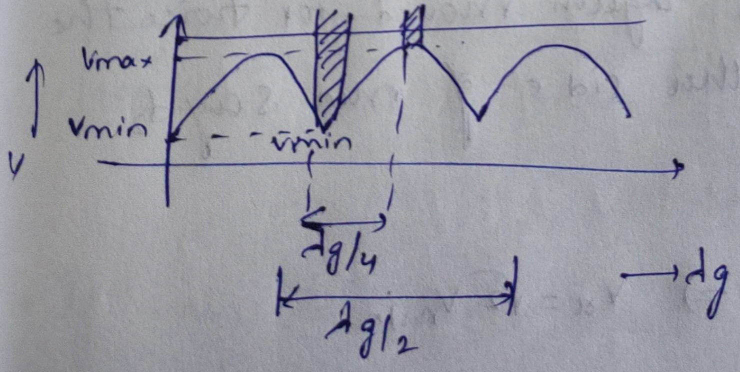


- Setup 2:- Network is replaced by precision attenuator



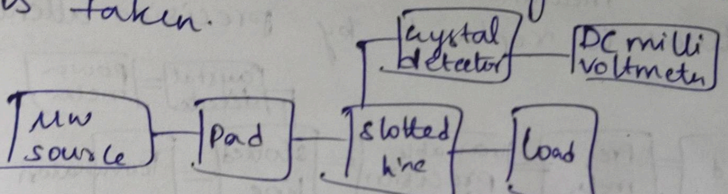
* Measurement of VSWR:-

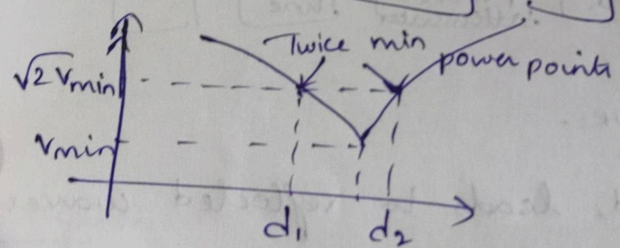
- Mismatched load, leads to reflected waves resulting in standing waves.
- $VSWR \Rightarrow \dfrac{V_{max}}{V_{min}} = \dfrac{1+\rho}{1-\rho}$ where $\rho = \dfrac{P_{reflected}}{P_{incident}}$
- VSWR is varied from 1 to ∞ as ρ varies from 0 to ∞.



* Measurement of Low VSWR ($S < 10$):-

- Adjusting attenuator to give adequate reding on meter
- Probe of slotted line is moved to get max. reading where attenuation is adjusted to get full meter reading & it is noted down.
- Then probe of slotted line is moved to get min. reading & ratio of max. to min reading is taken.





* Measurement of High VSWR ($S > 10$):-

- Double minimum method is used
- Probe is moved to a pt where power is twice the min. and denoted by d_1
- Probe is then again moved for twice the power pt on other side of min say d_2.

$2P_{min} \propto V_x^2$

$\frac{1}{2} = \frac{V_{min}^2}{V_x^2} \Rightarrow V_x = \sqrt{2}\,V_{min}$

$d_1 = 2a \qquad \lambda_0 = c/f$

$\Rightarrow \lambda_g = \dfrac{\lambda_0}{\sqrt{1-\left(\dfrac{\lambda_0}{\lambda_c}\right)^2}}$ $\Rightarrow$ $VSWR = \dfrac{\lambda_g}{\pi(d_2 - d_1)}$

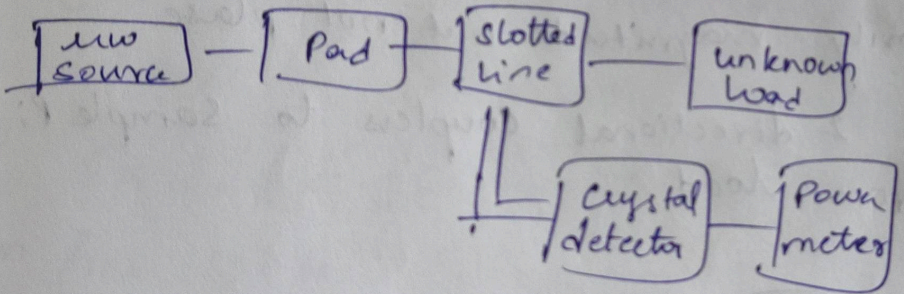
* Measurement of impedance:-

- 3 methods → using magic T / slotted line / reflectometer

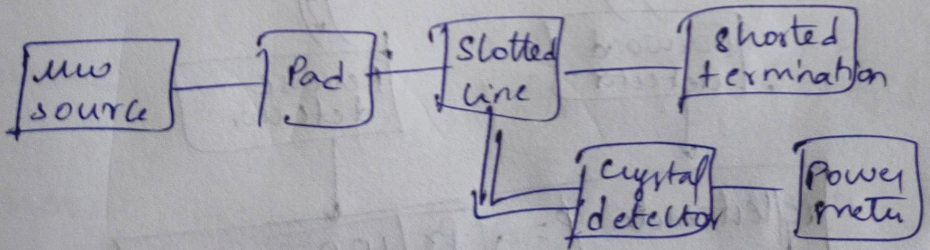
(i) Using slotted line:-

- Incident & reflected waves are due to mismatch of load under test whose impedance is to be measured giving standing wave.

Setup 1:- With Z_L giving V_{max} & V_{min} is shown



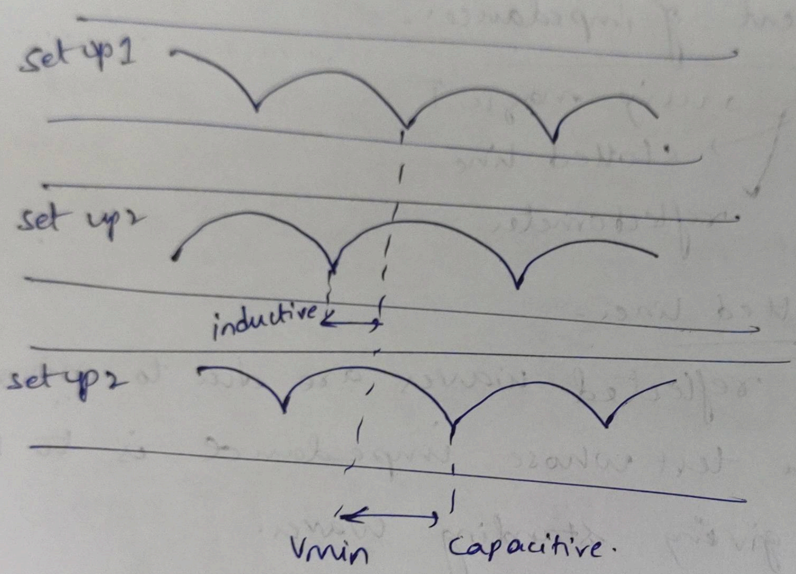
Setup 2:- Z_L is replaced & shift in V_{max} & V_{min} is measured.



- If min. is shifted to left ⇒ impedance is inductive
- If min. is shifted to right ⇒ impedance

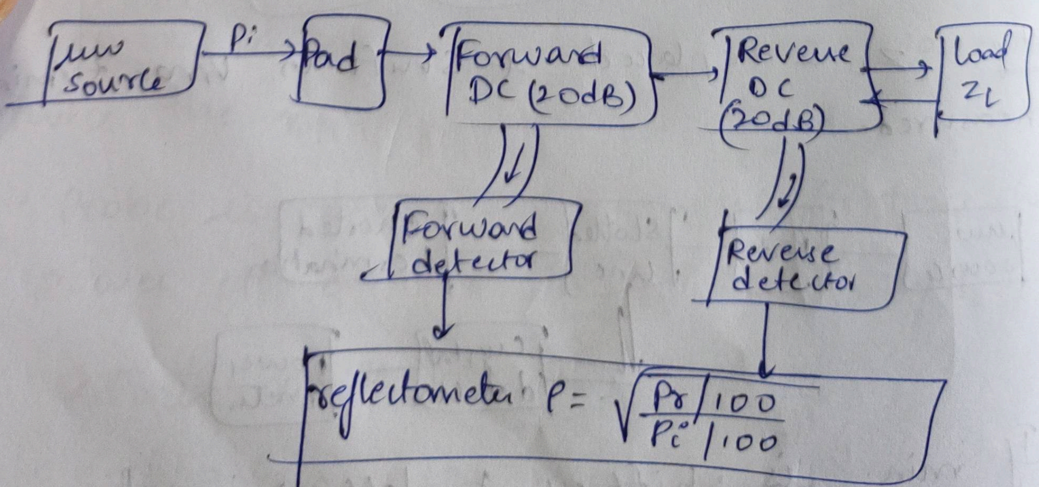
is capacitive.

- Both impedance & reflection coeff can be obtained in magnitude & phase



* Using reflectometer:-

- Gives only magnitude but not phase
- Employs 2 directional couplers to sample P_i & P_r from load.



=) $\rho = \sqrt{\frac{P_r}{P_i}}$

we KT ,

Z_g= kn

* Measuren

- IL = Re
+

- reflected

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* Measureme

- EM prop
is defined
=)
$\varepsilon = \varepsilon_0$
in free sp
ε' = Abil
ε'' = ε_r
where ε_r
where
- it is a
- Method-en

$\Rightarrow \rho = \sqrt{\frac{P_r}{P_i}}$

we KT, $S = \frac{1+\rho}{1-\rho}$ & $\rho = \frac{Z - Z_g}{Z + Z_g}$

Z_g = known impedance, Z = unknown impedance.

* Measurement of Insertion loss :- (IL)

- IL = Reflected power from device due to mismatch + Power attenuated
- reflected power is measured by reflectometer.
- Attenuated power is measured using RF substitution method.

* Measurement of dielectric constant :-

- EM property of non-magnetic material / medium is defined by μ, ε, & σ.

$\Rightarrow$

$\varepsilon = \varepsilon_0 (\varepsilon' - j\varepsilon'')$ where ε = dielectric const in free space $= \varepsilon_r \varepsilon_0$.

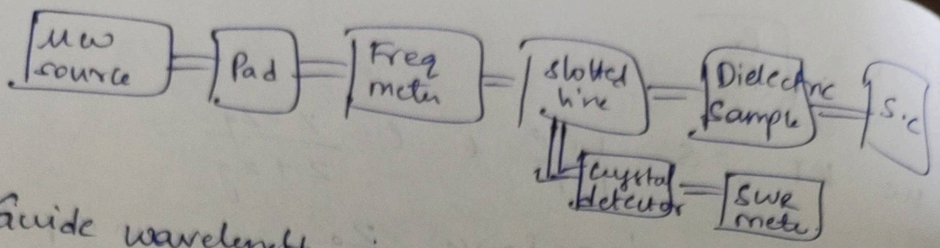
ε' = Ability of dielectric to store energy

ε'' = Energy dissipation in medium.

where $\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \varepsilon' - j\varepsilon'' = \varepsilon'(1 - j\tan\delta)$

where ~~tan~~ $\tan\delta$ = loss tangent $\tan\delta$

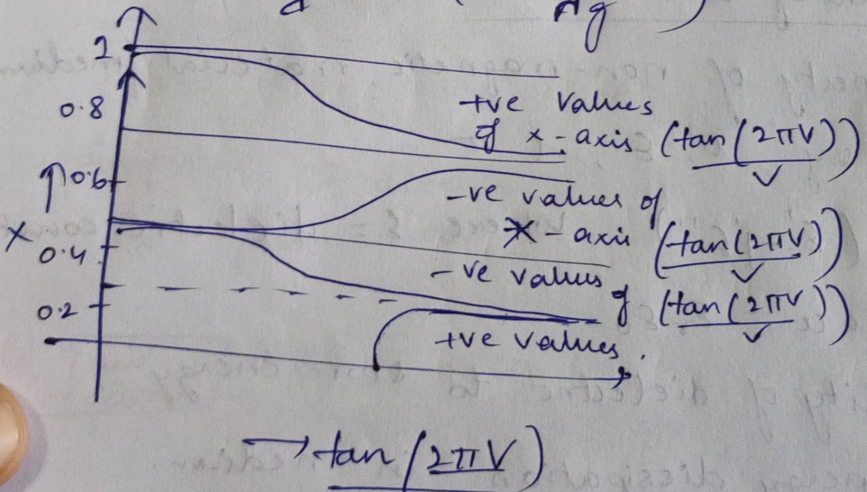
- it is a measure of energy lost in form of heat
- Method employed $\Rightarrow$ Roberts & Von-Hippel.



* Guide wavelength is measured using freq. meter, dielectric thickness is measured using micro-meter.

- micrometer of short circuit is adjusted to read same value as thickness of dielectric.
- Exact position of 2 successive minima's are measured from SWR meter.

- $$X = \frac{\lambda_g}{d} \tan\left(\frac{2\pi(\Delta s + d)}{\lambda_g}\right)$$



unknown quantity $x = \frac{\tan(2\pi V)}{V}$.

where V = no. of wavelengths of μw radiation in distance 'd' of dielectric filled guide.

$$\boxed{\varepsilon_r = 1 - \left(\frac{\lambda_0}{\lambda_g}\right)^2 + \left(\frac{\lambda_0 V}{d}\right)^2}$$

* Numericals:-

① Calculate SER of txn system operating at 10 GHz. Assume TE_{10} wave txn inside a waveguide of dimensions $a = 4\,cm$, $b = 2.5\,cm$. The distance measured b/w twice min. power points = 1mm on slotted line.

(A) Given, $f = 10\,GHz$, $a = 4\,cm$, $b = 2.5\,cm$.

For TE_{10} mode, $\lambda_c = 2a = 2 \times 4 = 8\,cm$.

$$\Rightarrow \boxed{\lambda_0 = \frac{c}{f} \Rightarrow \frac{3\times10^{10}}{10\times10^{9}} = 3\,cm}$$

$\Rightarrow d_2 - d_1 = 1mm$

$$\Rightarrow \lambda_g = \frac{\lambda_0}{\sqrt{1-\left(\frac{\lambda_0}{\lambda_c}\right)^2}} \Rightarrow \lambda_g = \frac{3}{\sqrt{1-\left(\frac{3}{8}\right)^2}} \Rightarrow \boxed{\lambda_g = 3.236\,cm}$$

For double min. method,

$$\boxed{VSWR = \frac{\lambda_g}{\pi(d_2 - d_1)} = \frac{3.236}{\pi(10^{-1})} = 10.3}$$

② You have 2 dir. couplers (20dB) in a guide to sample the incident & reflected power. The o/p of 2 couplers are 3mW & 0.1mW. What is the VSWR ? what is the value of reflected power?

(A) Given, $\frac{P_i}{100} = 3mW \Rightarrow P_i = 300mW$.

$\frac{P_r}{100} = 0.1mW \Rightarrow P_r = 10mW$

reflection coeff.

$$\rho = \sqrt{\frac{P_r}{P_i}} = \sqrt{\frac{10}{300}} = 0.1816$$

$$\Rightarrow VSWR = \frac{1+\rho}{1-\rho} = \frac{1+0.1816}{1-0.1816} = 1.44$$

③ Two identical dir. couplers are used in a waveguide to sample the incident & reflected power. The o/p of 2 couplers is found to be 2.5mW & 0.15mW. Find the VSWR

Ⓐ

$$\rho = \sqrt{\frac{P_r}{P_i}}$$

$$= \sqrt{\frac{0.15}{2.5}}$$

$$\rho = \sqrt{0.06} = 0.244$$

Now, $VSWR = \frac{1+\rho}{1-\rho} = \frac{1+0.244}{1-0.244} \Rightarrow VSWR_s = 1.64$

④ Two identical 30dB dir. couplers are used to sample incident & reflected power in a waveguide. VSWR = 2 & o/p of coupler sampling incident power = 4.5mW. What is the value of reflected power.

Ⓐ

$$VSWR = \frac{1+\rho}{1-\rho} = 2 \Rightarrow (1+\rho) = 2(1-\rho)$$

$$\Rightarrow 3\rho = 1$$

$$\Rightarrow \rho = 0.333$$

Now coupling fac

$\Rightarrow$

$\Rightarrow \frac{P_i}{10^3} = 4.5mW$

$\Rightarrow \rho = \sqrt{\frac{P_r/10^3}{P_i/10^3}}$

$= \sqrt{\frac{P_r}{P_i}}$

$\Rightarrow \rho^2 = \frac{P_r}{P_i}$

$\Rightarrow P_r = \rho^2 \times$

$= (0.3$

$\Rightarrow P_r \simeq 0.5$

Now coupling factor $C = 10 \log \frac{P_i}{P_f} = 30$

$$\Rightarrow \frac{P_i}{P_f} = 10^3 \Rightarrow \boxed{P_f = \frac{P_i}{10^3}}$$

$$\Rightarrow \frac{P_i}{10^3} = 4.5\,mW \text{ (or) } \boxed{P_i = 4.5W}$$

$$\Rightarrow \rho = \sqrt{\frac{P_r/10^3}{P_i/10^3}}$$

$$= \sqrt{\frac{P_r}{P_i}}$$

$$\Rightarrow \rho^2 = \frac{P_r}{P_i}$$

$$\Rightarrow P_r = \rho^2 \times P_i$$

$$= (0.333)^2 \times 4.5 = 0.499\,W$$

$$\Rightarrow \boxed{P_r \simeq 0.5W}$$

$$= \sqrt{\frac{P_r}{P_i}}$$

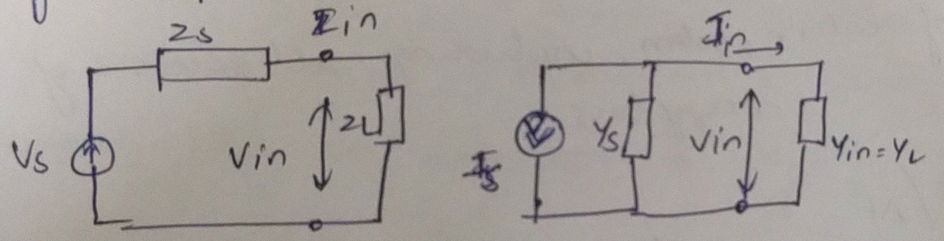
$$\Rightarrow \rho^2 = \frac{P_r}{P_i}$$

$$\Rightarrow P_r = \rho^2 \times P_i$$

$$= (0.333)^2 \times 4.5 = 0.499\ W$$

$$\Rightarrow \boxed{P_r \cong 0.5W}$$

* Impedance matching:- It is necessary to provide max. delivery of RF power to load from source.



$Z_S = R_S + jX_S$ (source impedance)

$Z_L = R_L + jX_L$ (load impedance)

$$\Rightarrow \boxed{P = \frac{1}{2} V_{in}^2 \, Re\left(\frac{1}{Z_L}\right) = \frac{1}{2} V_S^2 \left|\frac{Z_L}{Z_S + Z_L}\right|^2 Re\left(\frac{1}{Z_L}\right)}$$ power delivered to load.

$$\Rightarrow \boxed{P = \frac{1}{2} V_S^2 \frac{R_L}{(R_S + R_L)^2 + (X_S + X_L)^2}}$$

$$\frac{}{I_{D_2}} = \frac{(V_{GS_1} - V_{TH})^2}{(V_{GS_2} - V_{TH})^2}$$

$$\frac{10^{-3}}{I_{D_2}} = \frac{(0.9 - 0.4)^2}{(1.4 - 0.4)^2}$$

$$\Rightarrow I_{D_2} = 10^{-3}\left[\frac{1}{}\right] = \frac{10^{-3}}{}$$

- Power transfer is maximised when source is "conjugate matched" to the load. In case of resistive terminations, the $\boxed{\text{source resistance} = \text{load resistance}}$ for max. power transfer.
- perfect match (zero reflection coeff) can only be achieved at selected single freq.

* Measurement of cavity Q:-

- There are 3 defn of Q, connected to the associated circuit which are summarised below:

① unloaded Q_0:-

$$Q_0 = 2\pi \cdot \frac{\text{Energy stored in cavity}}{\text{Energy lost per cycle in cavity}}$$

Q_0 is selectivity factor of cavity, dependent on geometrical portion of cavity.

② loaded Q_L:-

$$Q_L = 2\pi \cdot \frac{\text{Energy stored in cavity}}{\text{Energy lost per cycle + Energy lost per cycle in external system}}$$

Q_L is Q of entire system, including all sources of energy loss.

$$Q_L = f_0/\Delta f$$

where f_0 = resonance freq.

Δf = 3dB bandwidth.

③ External Q_E:-

$$Q_E = 2\pi \cdot \frac{\text{Energy stored in cavity}}{\text{Energy lost per cycle in external system}}$$

* Measurement

MW source

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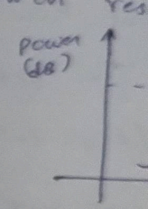
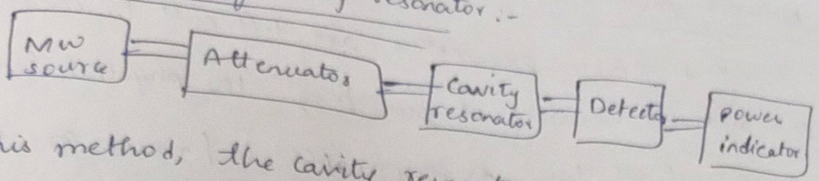


- From setup
keeping the
The cavity
s/g level
notice the
- When o/p
which we ca

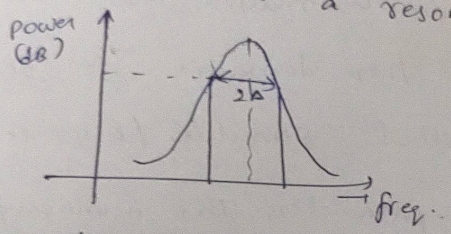
If couplin
Coupling b/w

Drawback:
accuracy
narrow

* Measurement of Q of cavity resonator :-



In this method, the cavity resonator acts as the device that transmits. The o/p signal is plotted as func. of frequency which results in a resonant curve as shown.



. From setup above, the s/g freq. of μw source is varied, keeping the s/g level constant & then o/p power is measured. The cavity resonator is tuned to this frequency & the s/g level and the o/p power is again noted down to notice the diff.

. When o/p is plotted, the resonance curve is obtained, from which we can notice half power bandwidth

$$2\Delta = \pm 1 Q_L$$

$$\Rightarrow \boxed{Q_L = \pm \omega_2(\omega - \omega_0) = \pm \omega_2(\omega - \omega_0)}$$

If coupling b/w μw source & cavity as well the coupling b/w the detector & cavity are neglected then

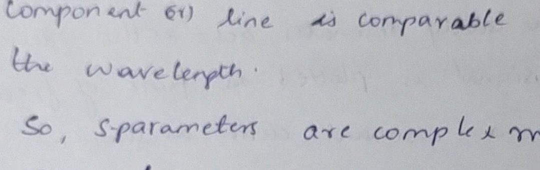
$$\boxed{Q_L = Q_0 \text{ (unloaded Q)}}$$

<u>Drawback</u>:- The main drawback of this system is that accuracy is a bit poor in high Q systems due to narrow band of operation.

* Network parameters:-

- Z, h, Y & ABCD parameters are difficult to measure for μw network because at μw freq. the physical length of component (or) line is comparable to / much greater than the wavelength.
- So, S-parameters are complex matrix that show reflection/txn char. in freq domain. This type of test equipment is called "Stimulus / Response"
- A 2-port device has 4 S-parameters. The numbering convention for S-parameters is that the 1st number following "S" is the port where s/g emerges & 2nd number is the port where s/g is applied ⇒ S_{21} ⇒ port 1 as i/p & port 2 as o/p.
- When no's are same (eg: S_{11}) it indicates a reflection measurement, as i/p & o/p ports are same

⇒



a_i is incident wave at port i
b_i is reflected wave at port i

$$\Rightarrow \left.\begin{array}{l} b_1 = S_{11}a_1 + S_{12}a_2 \\ b_2 = S_{21}a_1 + S_{22}a_2 \end{array}\right\} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$\Rightarrow [b] = [S][a]$$

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} \qquad S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} \qquad (a_2=0, \text{ port 2 is matched})$$

$$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0} \qquad S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0} \qquad (a_1=0, \text{ port 1 is matched})$$

S_{ii} = is the reflec… when other port …

S_{ij} = is the forwa… whereas it re… with other port …

* the steady state …

$V_i = V_{oi}^+ +$ … (incident)

$\Rightarrow V_{oi}^+ = \frac{1}{2}(V_i + Z_o$ …

$V_{oi}^- = \frac{1}{2}(V_i - Z$ …

$\Rightarrow \boxed{P_i^+ = \frac{1}{2Z_{oi}}|V_{oi}|}$ … (incident power)

$\Rightarrow a_i = \frac{V_{oi}^+}{\sqrt{2Z_{oi}}}$; …

$\Rightarrow P_i^+|_{i=1} = P_{avs} =$ …

$P_i^-|_{i=1} = P_{ref} =$ …

$P_{del} = P_{avs} - P_{ref} =$ …

* Characteristic Im…

$\lambda_g = 2(d_1 - d_2) \Rightarrow d_1$ …

$a = 2.2$ cm

$\lambda_c = 2a = 2(2.2$ …

$F_c = c/\lambda_c$

$BA1 = (x-4)$ …

S_{ii} = is the reflection coeff. Γ_i at the i^{th} port port when other port is matched terminated

S_{ij} = is the forward coeff Γ_i, of j^{th} port if i is $> j$ wheareas it represents reverse txn coeff if $i < j$ with other port terminated by matched port.

* the steady state total voltage & current at i^{th} port is,

$$V_i = \underset{\text{(incident)}}{V_{oi}^{+}} + \underset{\text{(reflected)}}{V_{oi}^{-}}$$

$$I_i = I_{oi}^{+} + I_{oi}^{-} = \frac{1}{Z_{oi}}\left(V_{oi}^{+} - V_{oi}^{-}\right)$$

$$\Rightarrow V_{oi}^{+} = \frac{1}{2}\left(V_i + Z_{oi} I_i\right)$$

$$V_{oi}^{-} = \frac{1}{2}\left(V_i - Z_{oi} I_i\right)$$

$$\Rightarrow \boxed{\underset{\text{(incident power)}}{P_i^{+}} = \frac{1}{2Z_{oi}}\left|V_{oi}^{+}\right|^2 \; ; \; \underset{\text{(reflected power)}}{P_i^{-}} = \frac{1}{2Z_{oi}}\left|V_{oi}^{-}\right|^2}$$

$$\Rightarrow a_i = \frac{V_{oi}^{+}}{\sqrt{2Z_{oi}}} \; ; \; b_i = \frac{V_{oi}^{-}}{\sqrt{2Z_{oi}}}$$

$\Rightarrow P_i^{+}\big|_{i=1} = P_{avs} = |a_1|^2$ (power available from source)

$P_i^{-}\big|_{i=1} = P_{ref} = |b_1|^2$ (reflected power from port 1)

$P_{del} = P_{avs} - P_{ref} = |a_1|^2 - |b_1^2|$ (power delivered to port 1)

* <u>Characteristic Impedance Z_0</u>:- using slotted line.

$\lambda_g = 2(d_1 - d_2) \Rightarrow d_1, d_2$ = successive minima.

$a = 2.2\,cm$

$\lambda_c = 2a = 2(2.2) = 4.4\,cm$

$F_c = c/\lambda_c$

$B\lambda| = (x - y)/\lambda g$

$x \Rightarrow 1^{st}$ minima from ref point (for load)

$y \Rightarrow$ " " from ref point (for short)

$$\Rightarrow Z_0 = \frac{120\pi}{\sqrt{1-\left(\frac{f_c}{f_0}\right)^2}}$$

$$Z_L = Z_0 \frac{(1-j(VSWR)\tan\beta\Delta l)}{VSWR - j\tan\beta\Delta l}$$

$$VSWR = \frac{V_{max}}{V_{min}}$$

*① Isolators can be constructed in many

be made by terminating ports 3 & 4