Microwave Measurement Techniques

A. Nassiri - ANL

$$P_n = \left(\frac{\nu_n}{2R}\right) R = \frac{\nu_n^2}{4R} = kTB$$

The maximum power delivered from the noisy resistor is $P_n = kTB$, which is considered equally across an entire microwave band.

A resistor temperature at 300^0 k, noise power for a 10kHz bandwidth receiver → $P_n = 4.14 \times 10^{-17}$ W = -176dBW= -146dBm

At the standard temperature of 290^0 k, the noise power available from a lossy passive network in a 1Hz bandwidth is -174dBm/Hz.

$$\left.\frac{S}{N}\right|_{dB} = 10\log\frac{P_s}{P_n}$$

Difficult to measure

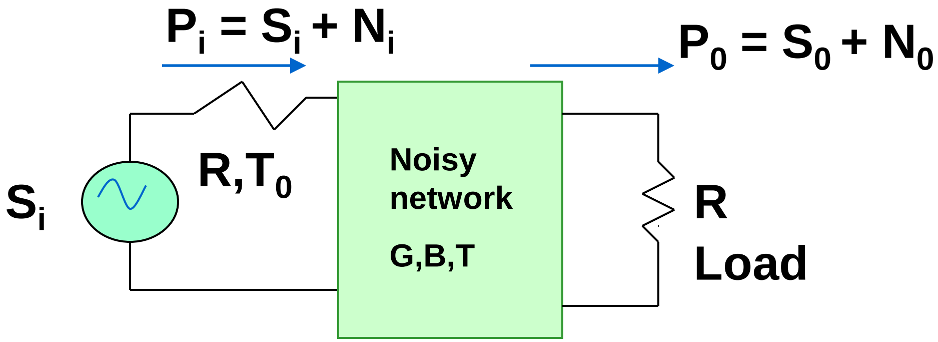
$$\left.\frac{S+N}{N}\right|_{dB} = 10\log\frac{P_s+P_n}{P_n}$$

Measurable quantity

A receiver produces a noise power of 200mW without signal, as signal is applied, the output level becomes 5W.

$$\left.\frac{S+N}{N}\right|_{dB} = 10\log\frac{P_s+P_n}{P_n} = 10\log\frac{5}{0.2} = 14dB$$

A figure of merit to measure the degradation of SNR of a system



$$NF = \frac{(S/N)_i}{(S/N)_o} \geq 1 \qquad NF_{dB} = 10\,log\,NF \geq 0dB$$

For a passive device with G=1/L and in thermal equilibrium at the temperature T, $N_0 = kTB = N_i$, $S_o = GS_i$,

$$NF = \frac{(S/N)_i}{(S/N)_o} = \frac{S_0}{S_i}\frac{N_i}{N_o} = L$$

An amplifier with input signal 100μW and the noise power is 1μW. The amplified signal is 1W with noise power 30mW.

$$signal\ gain = 10\,log\,\frac{1000000}{100} = 40dB$$

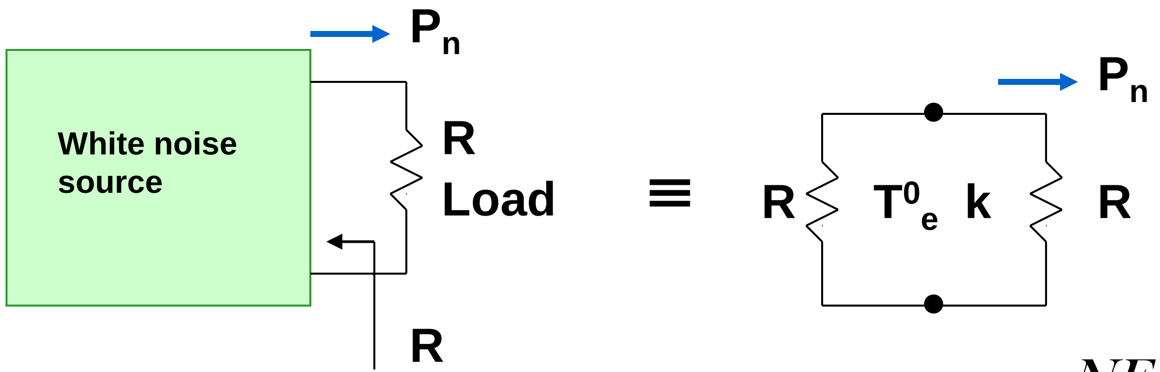
$$noise\ gain = 10\,log\,\frac{30000}{1} = 44.7dB > 40dB$$

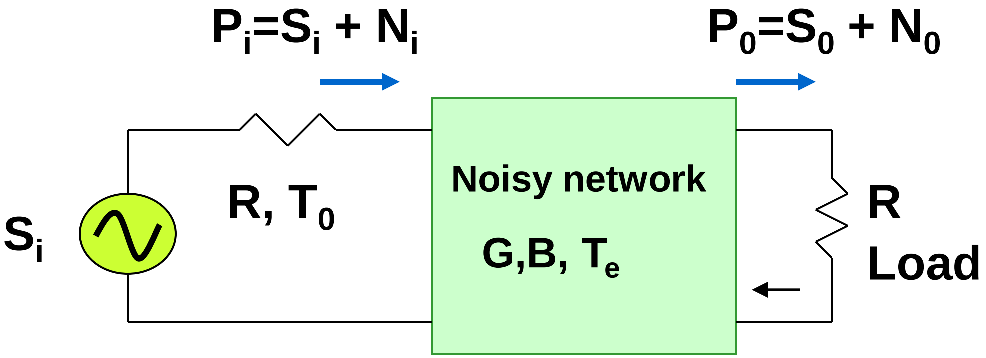
$$NF = \frac{(S/N)_i}{(S/N)_o} = \frac{100/1}{1000/30} = 3 > 1 \qquad NF_{dB} = 4.7dB > 0dB$$

An amplifier with NF 6dB has an input SNR=40dB,

$$NF = \frac{(S/N)_i}{(S/N)_o} \rightarrow \left.\frac{S}{N_o}\right|_{dB} = \left.\frac{S}{N_i}\right|_{dB} - NF_{dB} = 40 - 6 = 34dB$$

Equivalent noise temperature: the absolute temperature to generate the same noise power, not the physical temperature of the device equivalent noise temperature $T_e \equiv P_n / kB$





$$NF = \frac{(S/N)_i}{(S/N)_o}$$

$$= \frac{S_i}{kT_0B}\frac{Gk(T_0+T_e)}{GS_i}B$$

$$= 1 + \frac{T_e}{T_0} \geq 1$$

$$\rightarrow T_e = (NF-1)T_0$$

NF of a cascaded circuit

$$NF = \frac{(S/N)_i}{(S/N)_o} = \frac{S_i}{S_0}\frac{N_0}{N_i}$$

$$= \frac{1}{\prod_{i=1}^{N} G_i}\left\{\frac{kT_0B\prod_{i=1}^{N} G_i}{kT_0B} + \frac{k(NF_1-1)T_0B\prod_{i=1}^{N} G_i}{kT_0B}\right.$$

$$\left. + \frac{k(NF_2-1)T_0B\prod_{i=2}^{N} G_i}{kT_0B} + \cdots + \frac{k(NF_N-1)T_0BG_n}{kT_0B}\right\}$$

A three-stage amplifier

Stage	power gain		noise figure	
1	10	10dB	2	3dB
2	20	13dB	4	6dB
3	30	14.8dB	6	7.8dB

Total gain=6000=37.8dB

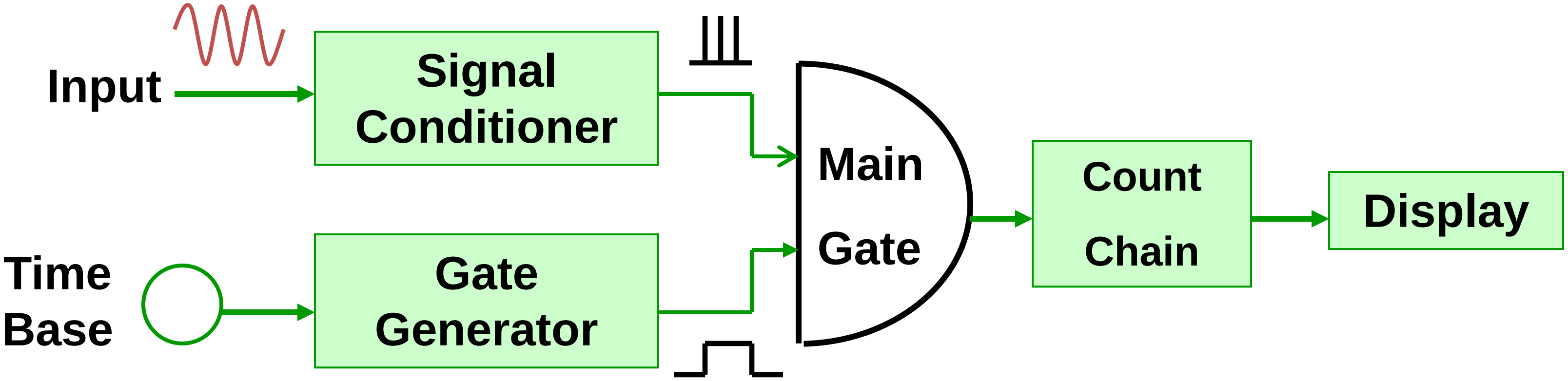
Total NF=2+[(4-1)/10]+[(6-1)/(10×20)]=2.325=3.66dB

Frequency measurements

Two approaches: using frequency counter to measure frequency directly, and using probe to measure the wavelength in a transmission line.

Frequency counter approach

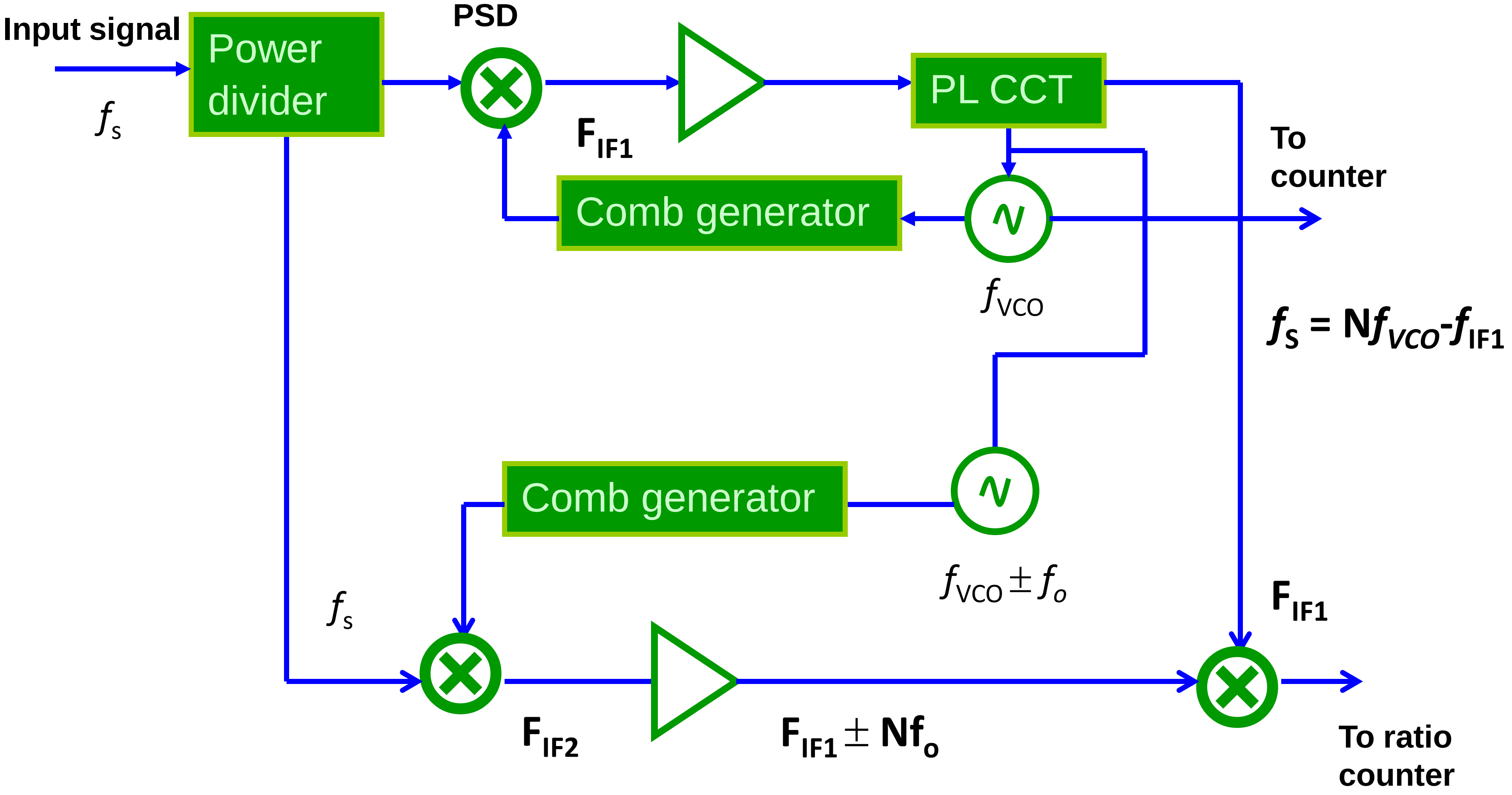
(1) Basic principle: direct counting <500MHz



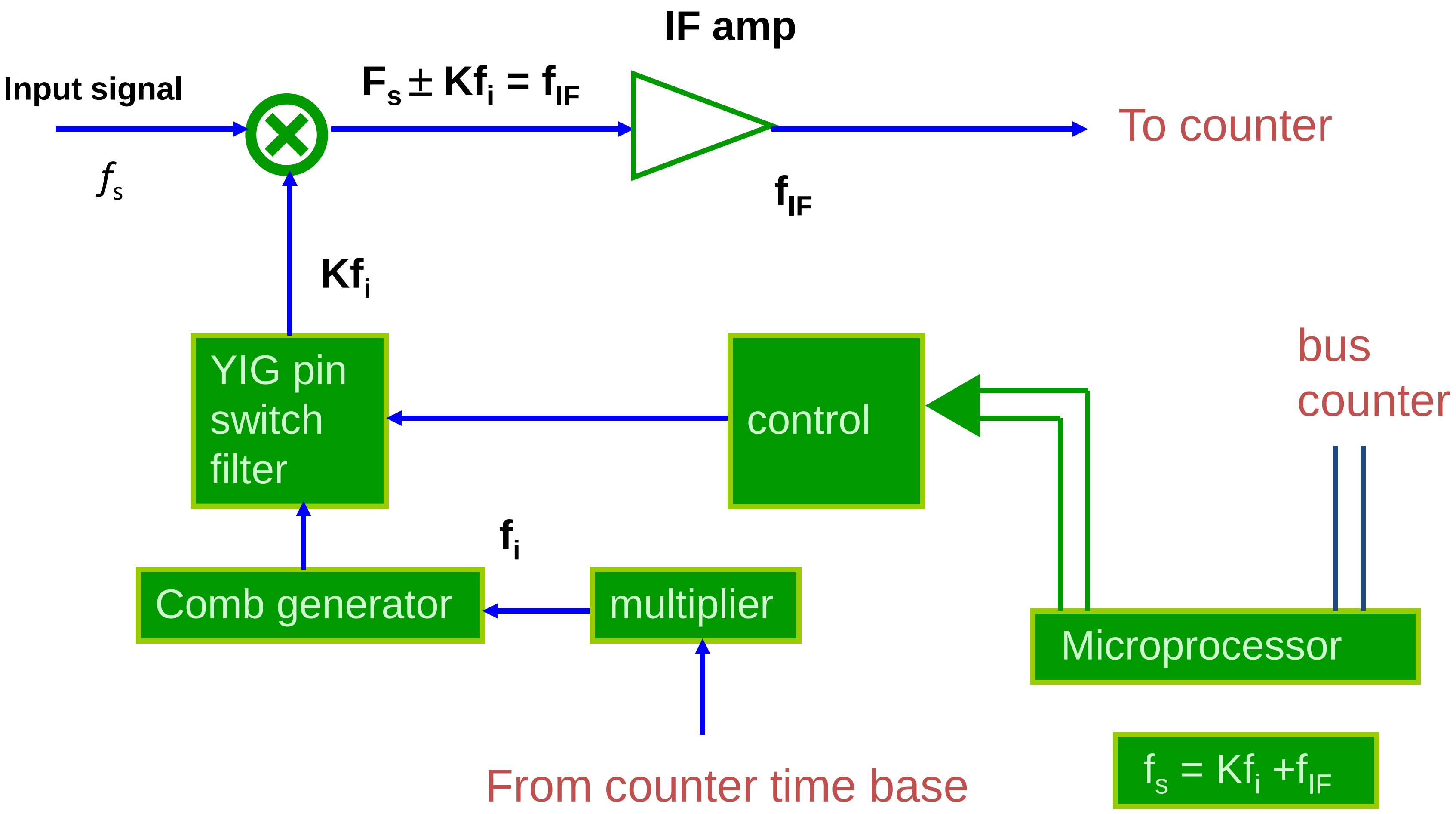
(2) Using frequency down-conversion techniques for microwave signals

- Pre-scaling: divider circuit <2GHz

- Transfer oscillator down-conversion: use PLL to relate the harmonic relationship between the low frequency oscillator and the input microwave signal > 40GHz



Harmonic heterodyne: use mixer to harmonically down convert the input microwave signal <20GHz



IF amp

Input signal

f_s

$F_s \pm Kf_i = f_{IF}$

To counter

f_{IF}

Kf_i

YIG pin switch filter

control

bus counter

f_i

Comb generator

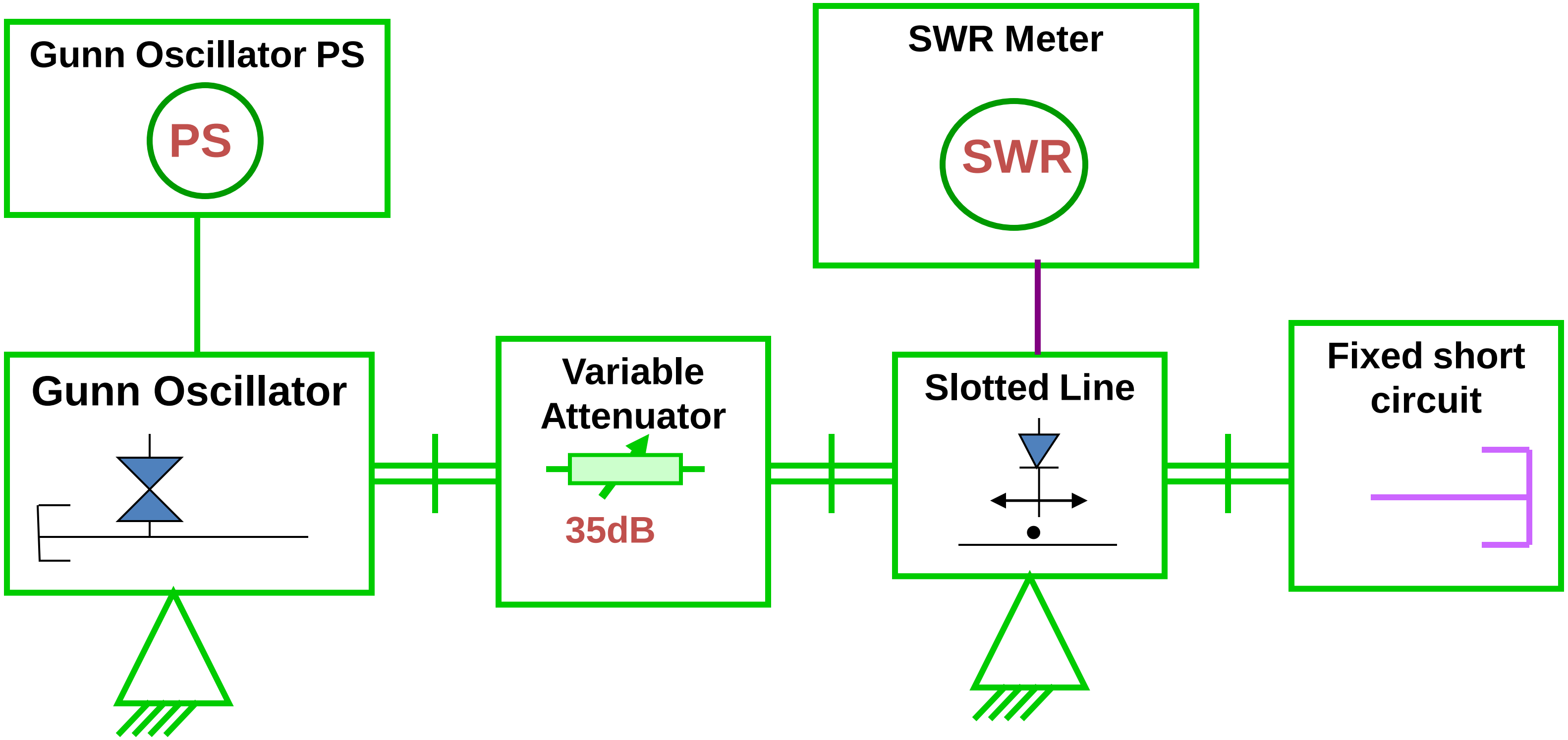
multiplier

Microprocessor

From counter time base

$f_s = Kf_i + f_{IF}$

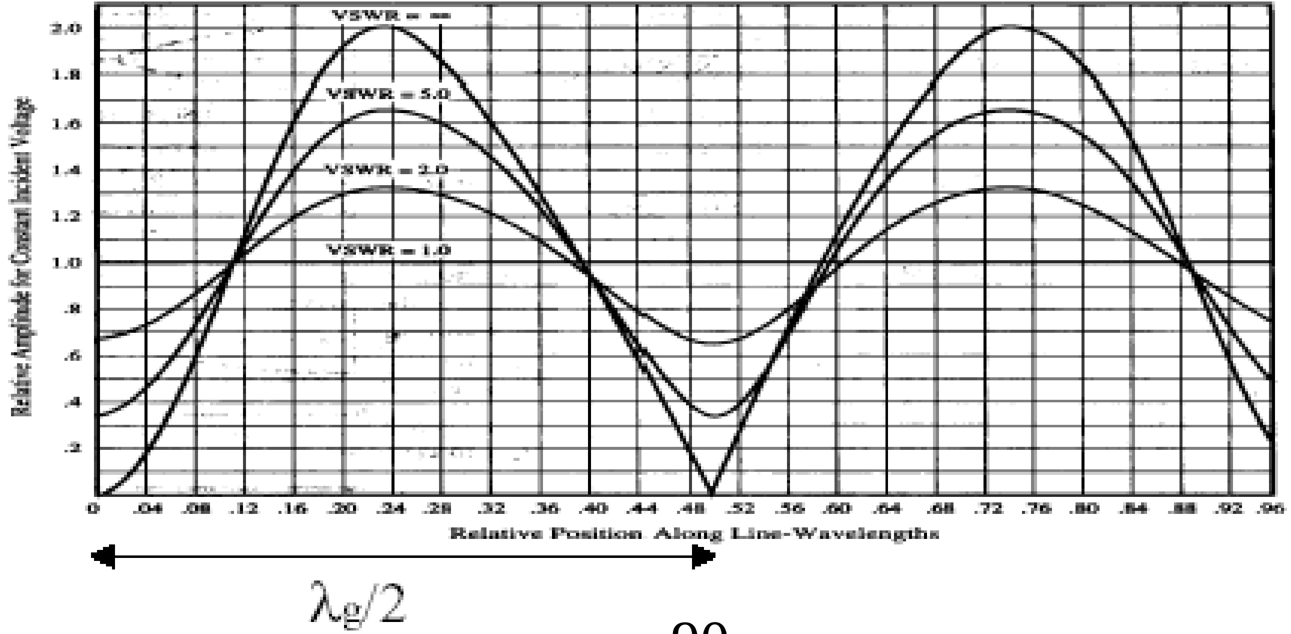
Wavelength measurement approach



$$k_c = \frac{2\pi}{\lambda_c}, \lambda_c = 2a, \beta = \frac{2\pi}{\lambda_g} = \sqrt{k^2 - k_c^2} = \sqrt{\left(\frac{2\pi}{\lambda}\right)^2 - \left(\frac{2\pi}{\lambda_c}\right)^2}$$

Measure $\lambda_g \rightarrow f = c\sqrt{\left(\frac{1}{\lambda_g}\right)^2 + \left(\frac{1}{2a}\right)^2}$

Distance between two adjacent minima is 1.9cm in a WR-90 waveguide.

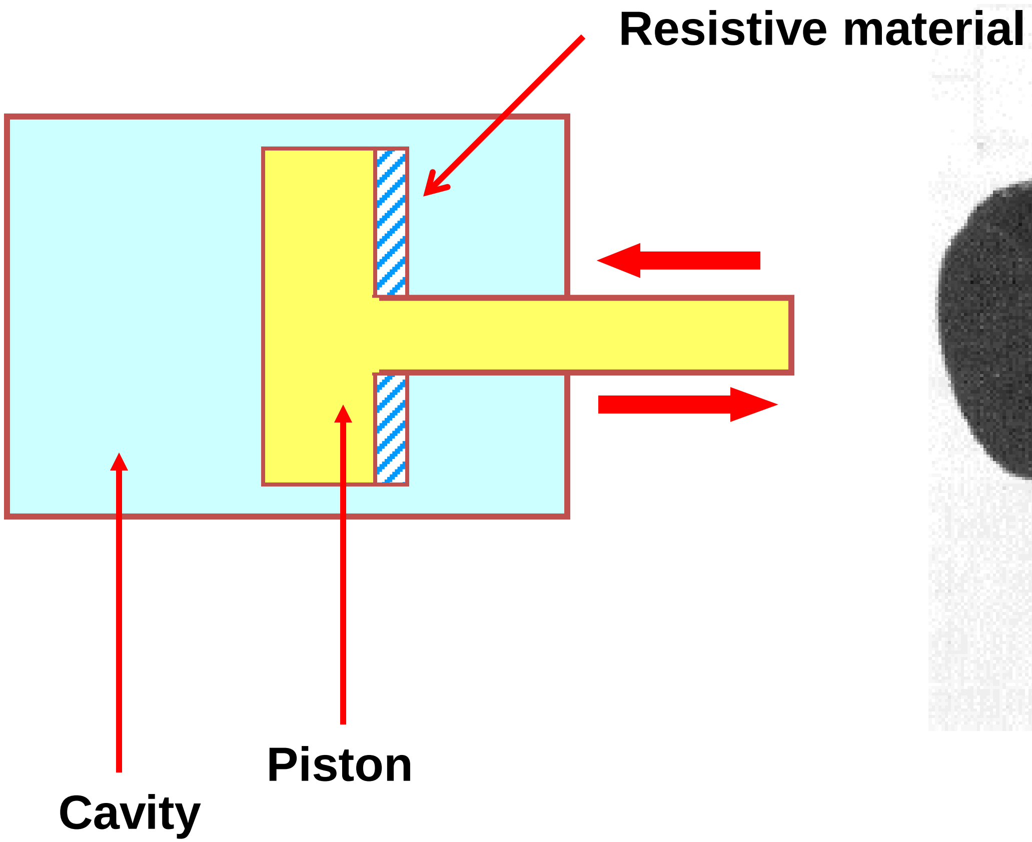


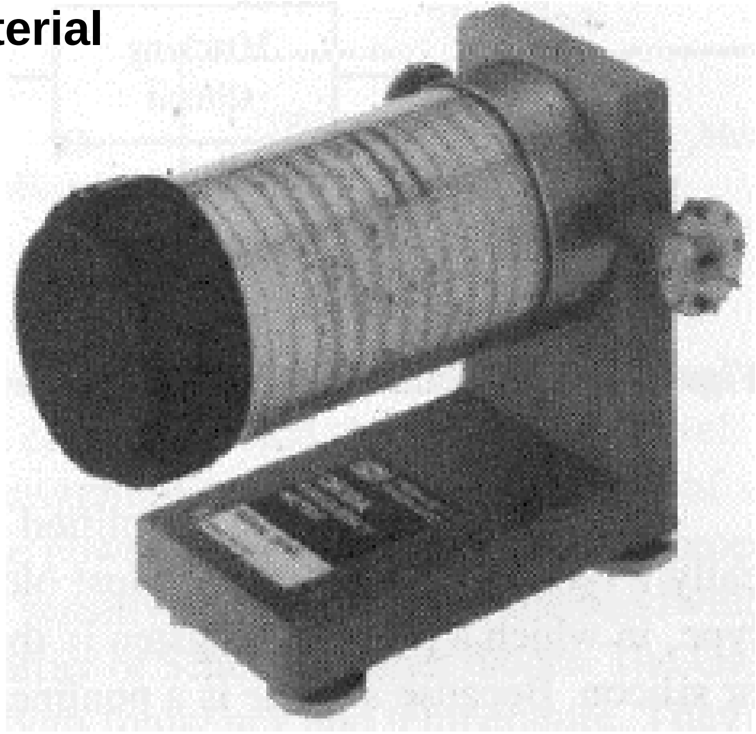
$$\lambda_g = 2\times 1.9cm = 3.8cm,\ \ a = \frac{90}{100}\times 2.54cm = 2.29cm$$

$$f = c\sqrt{\left(\frac{1}{\lambda_g}\right)^2 + \left(\frac{1}{2a}\right)^2}$$

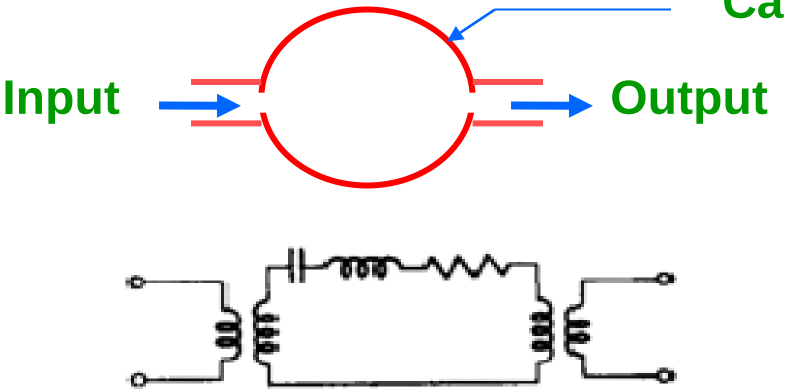
$$= 3\times 10^{10}\,cm/sec\sqrt{\left(\frac{1}{3.8cm}\right)^2 + \left(\frac{1}{2\times 2.29cm}\right)^2} = 10.26\,GHz$$

- **Wavemeter structure**

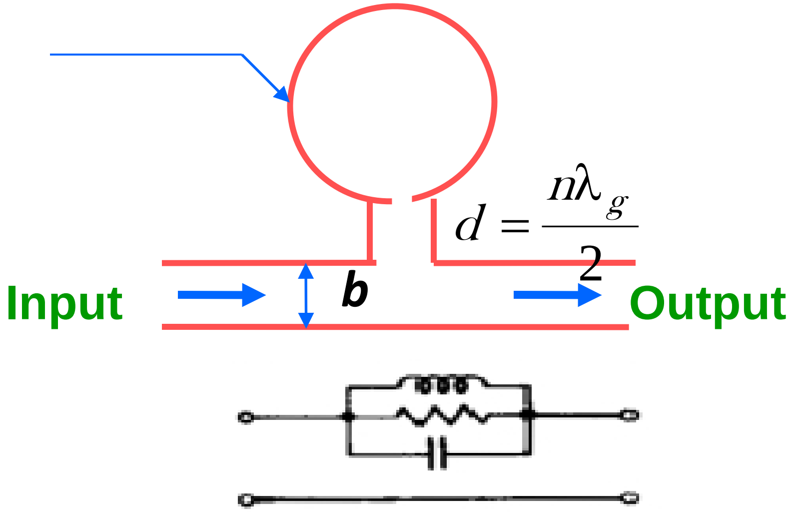




Operating principle

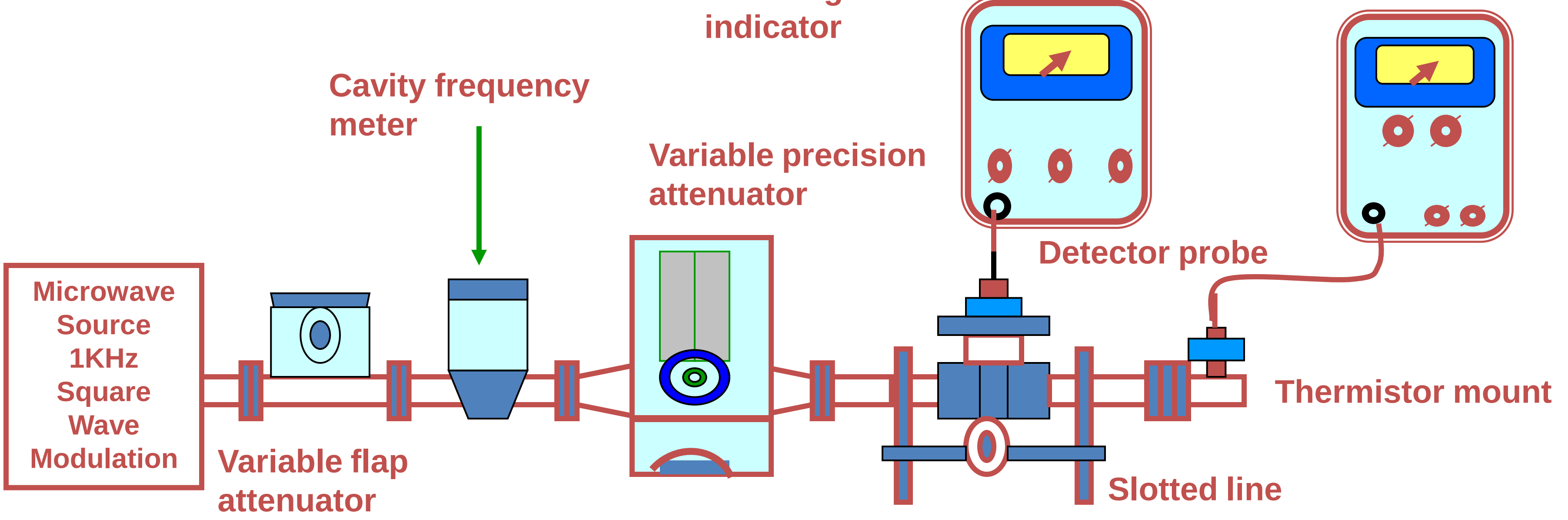


Transmission type



$$d = \frac{n\lambda_g}{2}$$

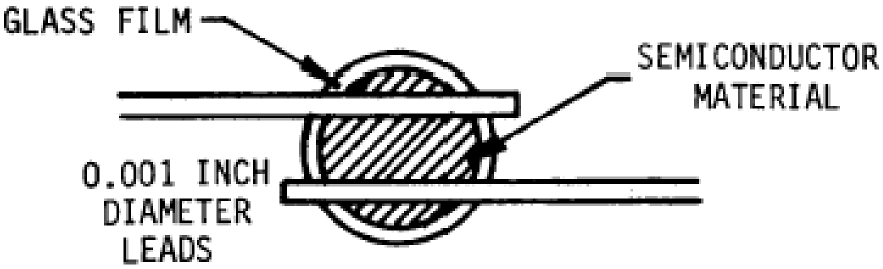
Reaction type



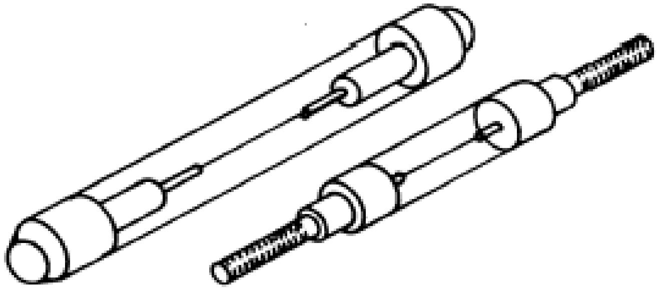
Detection devices

Power detector: bolometer (thermistor and barretter), thermocouple voltage detector: crystal detector, Schottky barrier diode, GaAs barrier diode

Thermistor: a metallic-oxide component with a negative temperature coefficient of resistance



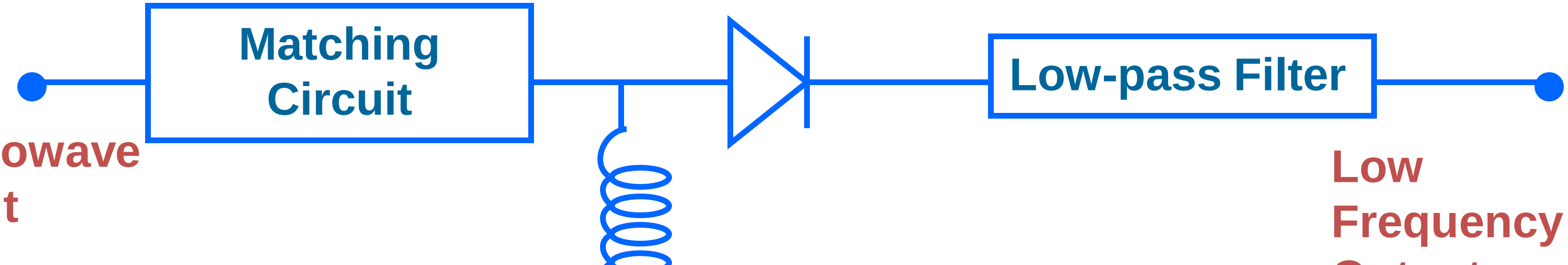
Barretter: a short length of platinum or tungsten wire with a positive temperature coefficient of resistance



Detection devices

Thermocouple: a pair of dissimilar metal (Sb-Bi) wires joined at one end (sensing end) and terminated at the other end (reference end). The difference in temperature produces a proportional voltage.

Crystal detector: use the diode square-law to convert input microwave power to detector output voltage



Diode

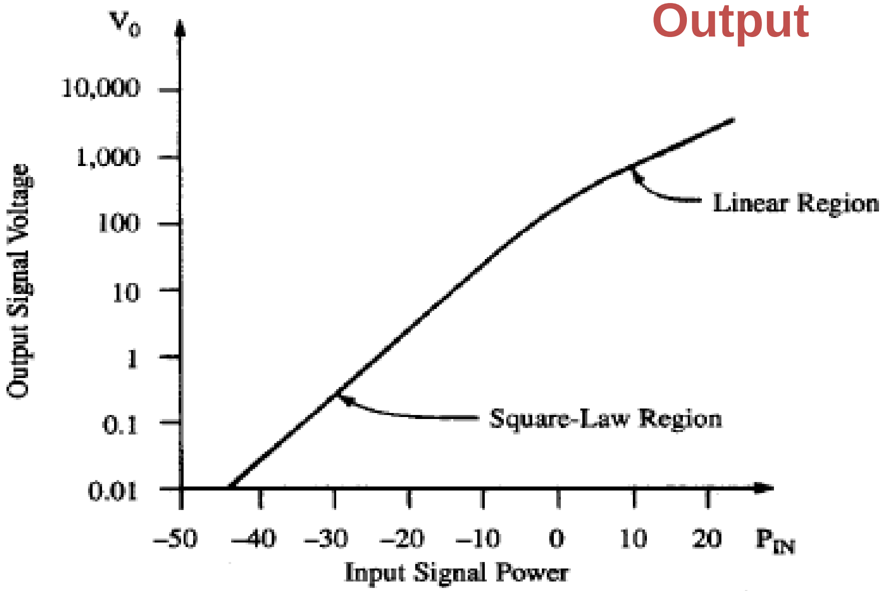
Matching Circuit

Low-pass Filter

Microwave Input

Low Frequency Output

DC Return

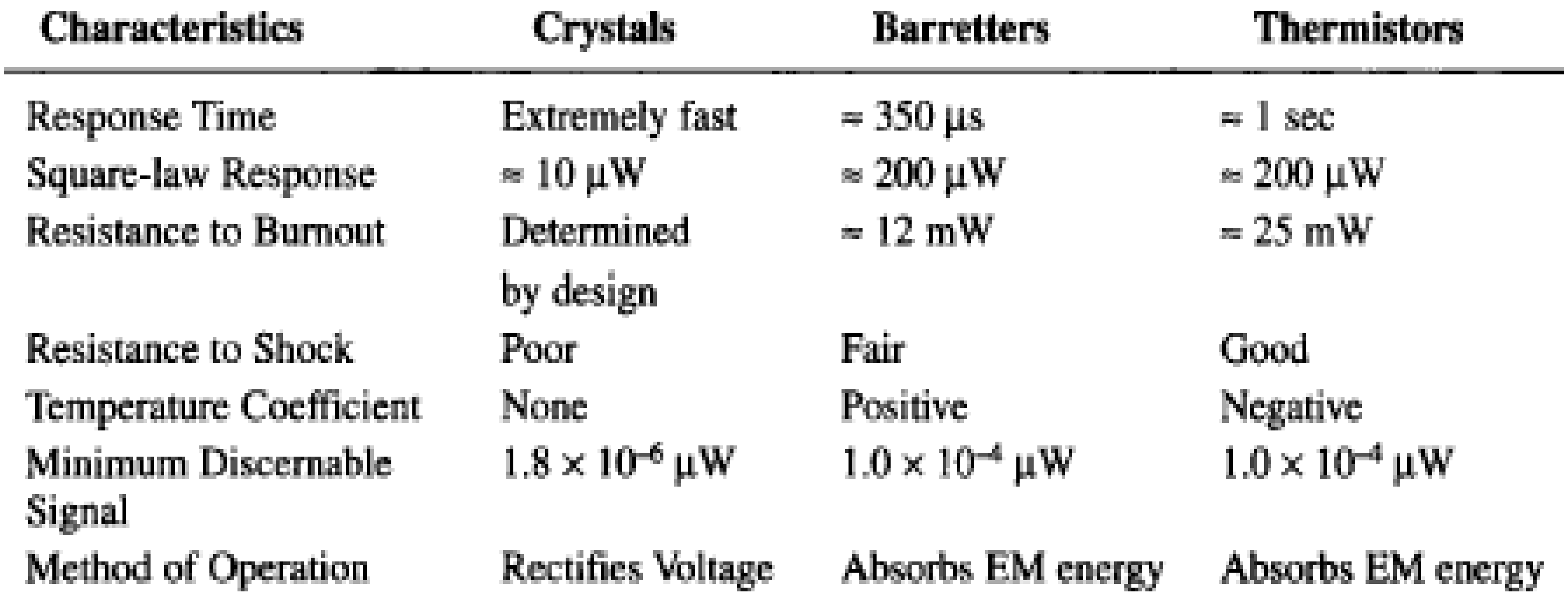


DC return is as a ground for diode and an RF choke.

Detection devices

Schottky barrier or GaAs barrier diode: high sensitivity noise equivalent power (NEP): the required input power to produce, in 1Hz bandwidth, an output SNR = 1 tangential sensitivity (TSS): the lowest detectable microwave signal power

$$NEP = \frac{TSS}{2.5\sqrt{\Delta f}}, \Delta f : Vedio\ Bandwidth$$



Characteristics	Crystals	Barretters	Thermistors
Response Time	Extremely fast	≈ 350 μs	≈ 1 sec
Square-law Response	≈ 10 μW	≈ 200 μW	≈ 200 μW
Resistance to Burnout	Determined by design	≈ 12 mW	≈ 25 mW
Resistance to Shock	Poor	Fair	Good
Temperature Coefficient	None	Positive	Negative
Minimum Discernable Signal	1.8×10^{-6} μW	1.0×10^{-4} μW	1.0×10^{-4} μW
Method of Operation	Rectifies Voltage	Absorbs EM energy	Absorbs EM energy

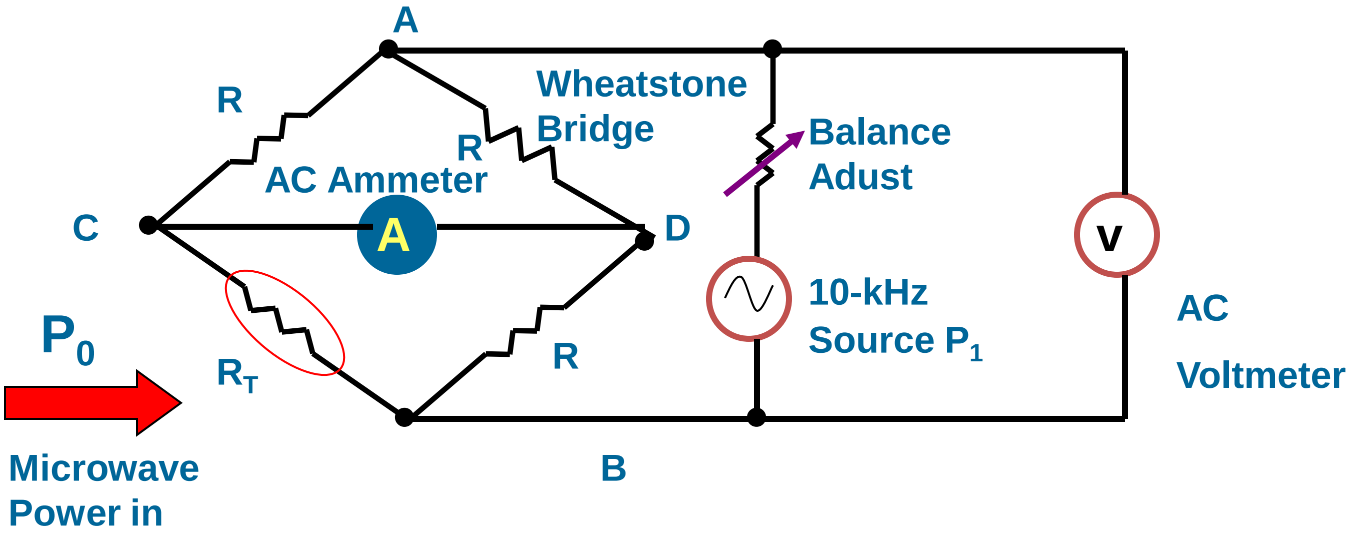
Power Measurements

Difficulty in measuring voltage or current at microwave frequencies → power measurement simpler and more precise

Power range: low power <0dBm, medium power 0dBm~40dBm, high power >40dBm

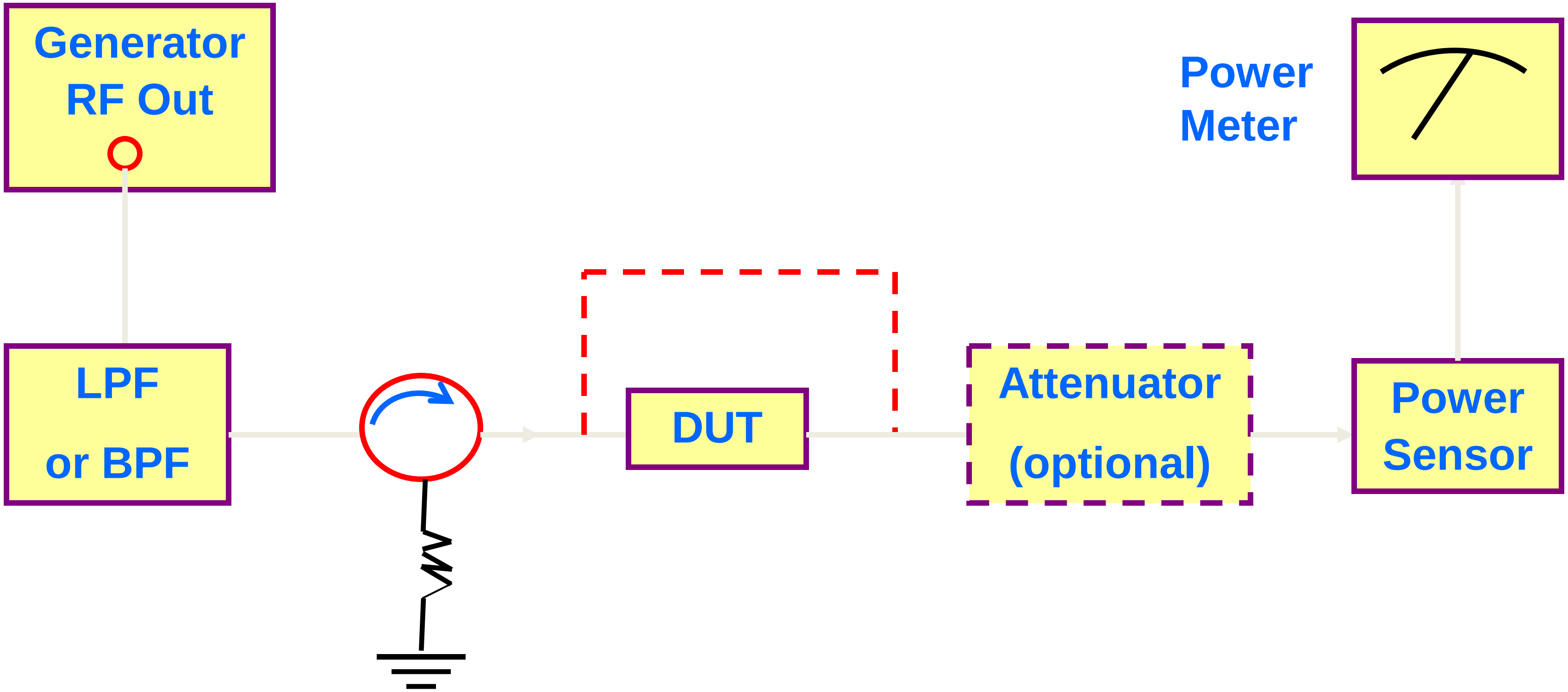
power detector sensitivity: diode ~-70dm, thermistor ~-20dBm

Thermistor power meter

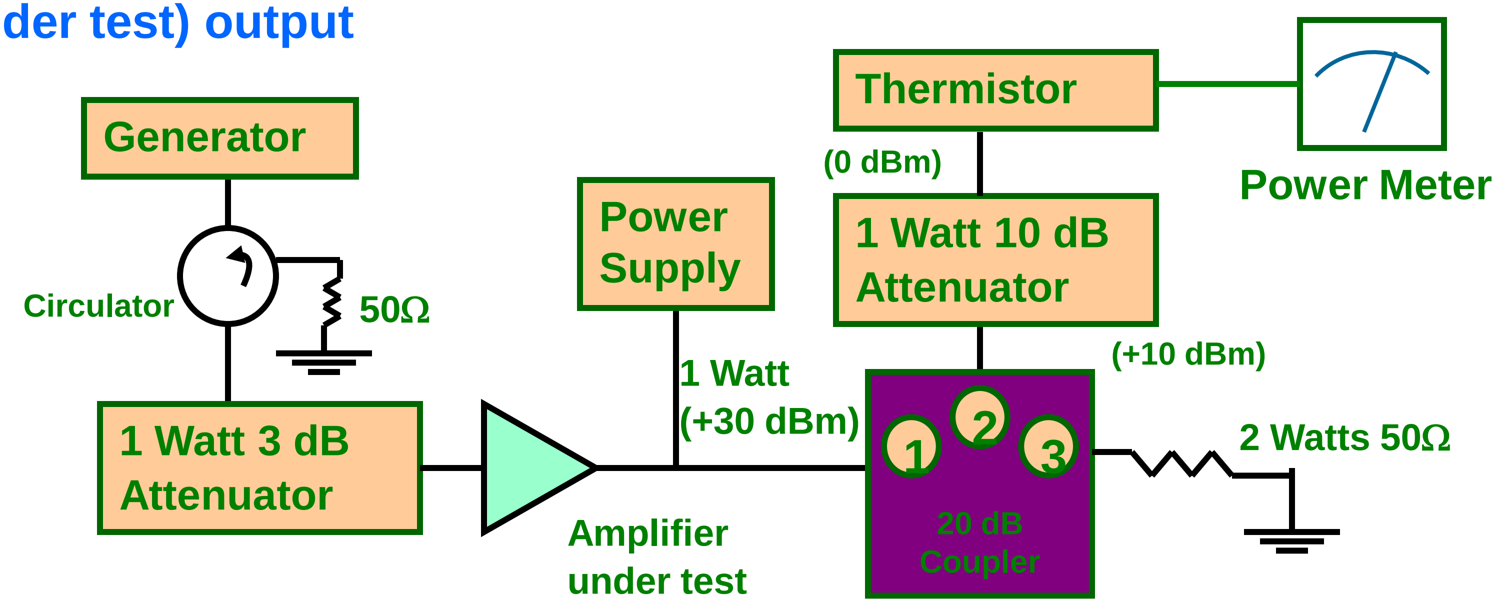


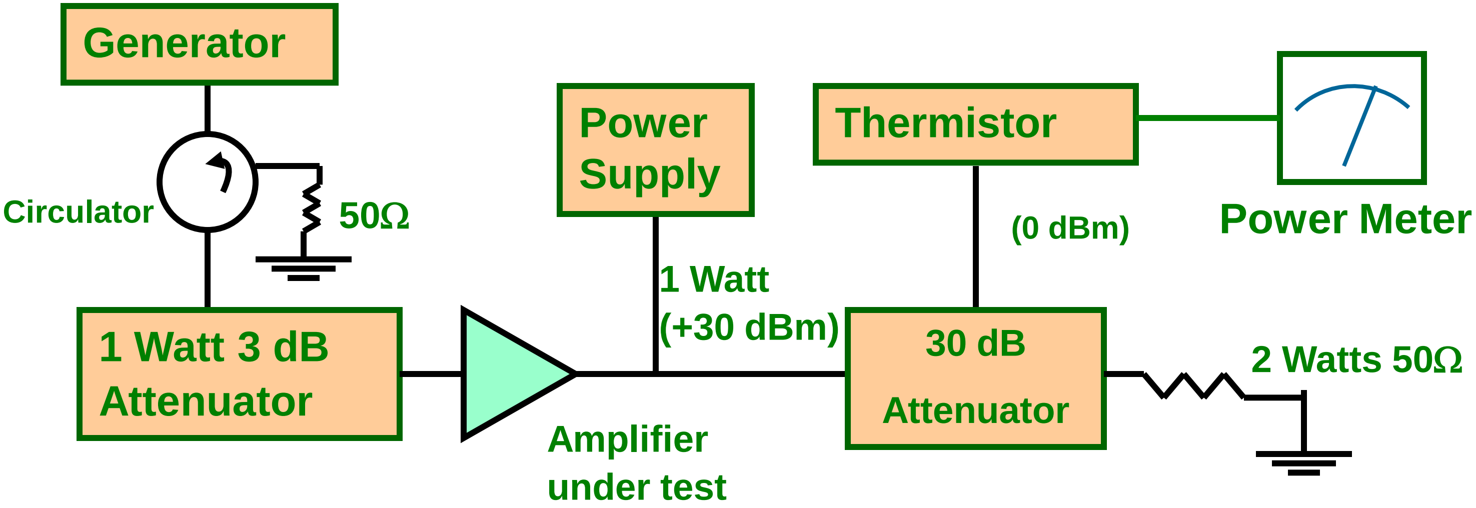
- Low power case

Consider desired frequency spectrum, circuit mismatch, sensor mismatch, sensor safe margin, accuracy, calibration

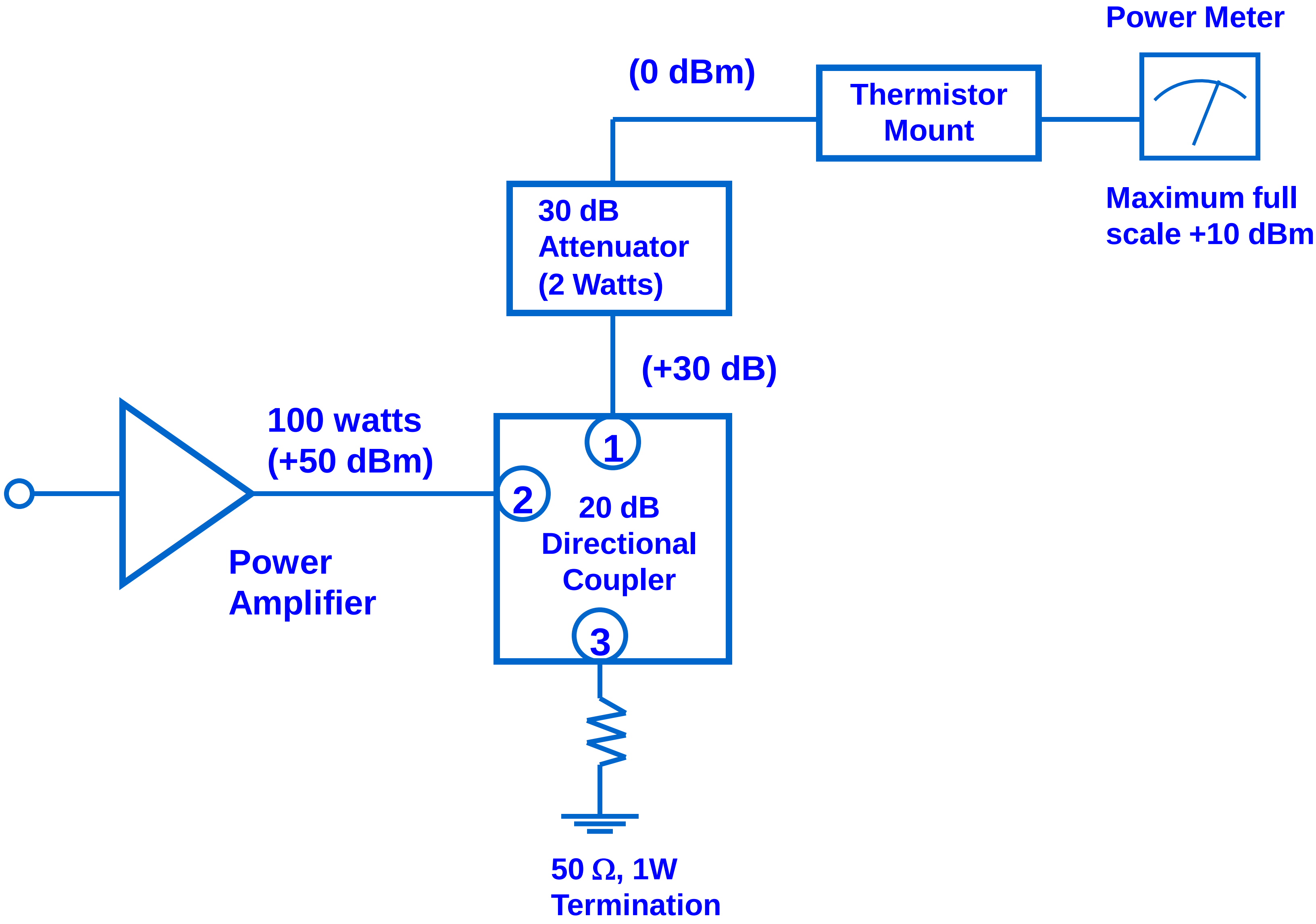


Medium power case: use directional coupler or attenuator at the DUT (device under test) output

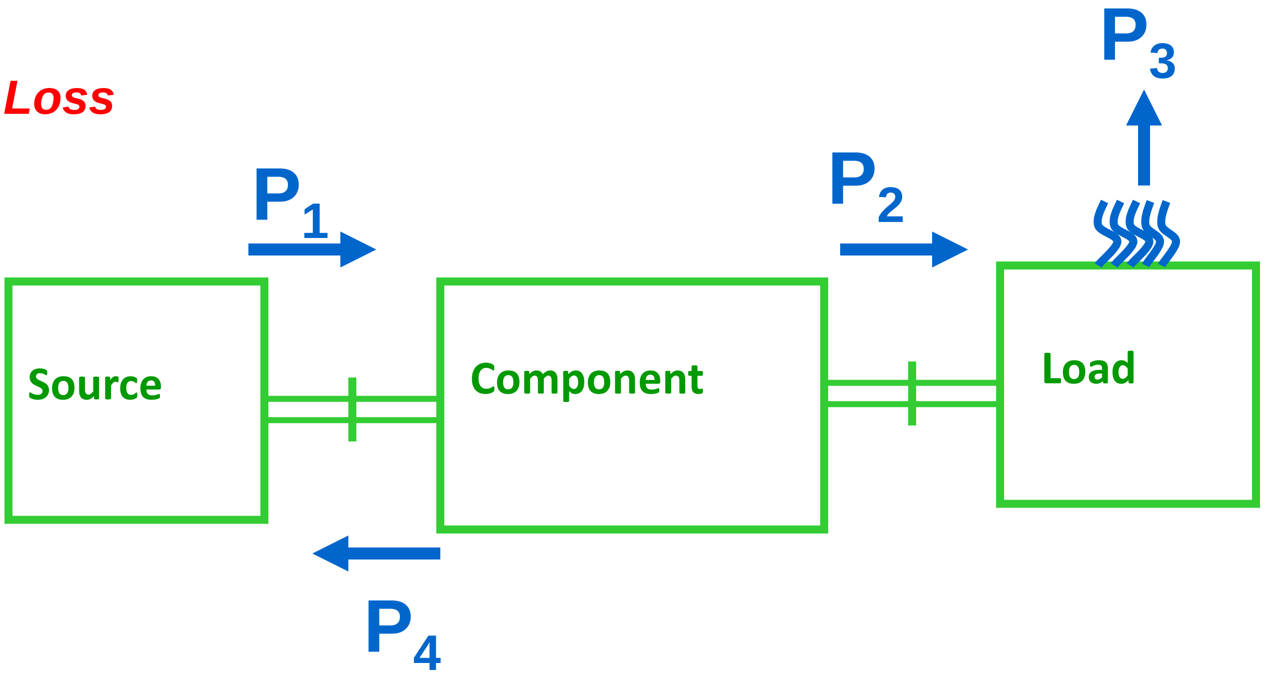




High power case: use directional coupler in reverse direction



Insertion Loss



P1: power to the load without DUT
P2: power to the load after inserting DUT
P3: power dissipated inside DUT
P4: power reflected from DUT

$$IL_{dB} = 10\log\frac{P_1}{P_2} = P_{1(dBm)} - P_{2(dBm)}$$

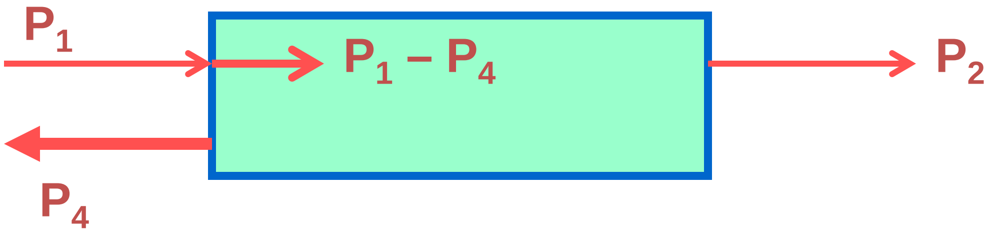
If Γ: DUT reflection coefficient and T: DUT transmission coefficient,

$$IL_{dB} = -10\,log|T|^2 = -10\,log|T|^2\,\frac{1-|\Gamma|^2}{1-|\Gamma|^2}$$

$$= -10\,log\left(1-|\Gamma|^2\right) - 10\,log\,\frac{|T|^2}{1-|\Gamma|^2}$$

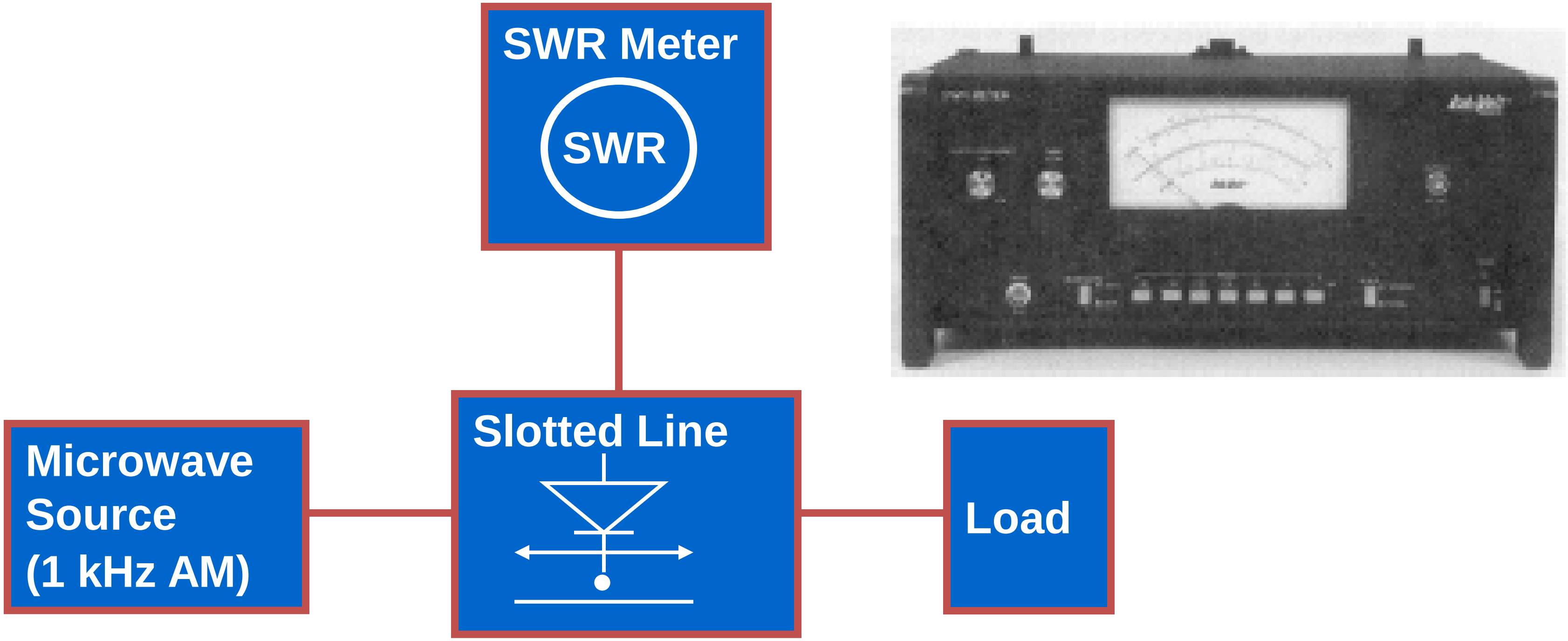
$$= -10\,log\,\frac{P_1 - P_4}{P_1} - 10\,log\,\frac{P_2}{P_1 - P_4}$$

= loss due to reflection + loss due to transmission



Insertion loss is the characteristics of DUT itself. As input port and output ports are matched, IL= attenuation.

VSWR measurements



SWR Meter

SWR

Slotted Line

Microwave Source (1 kHz AM)

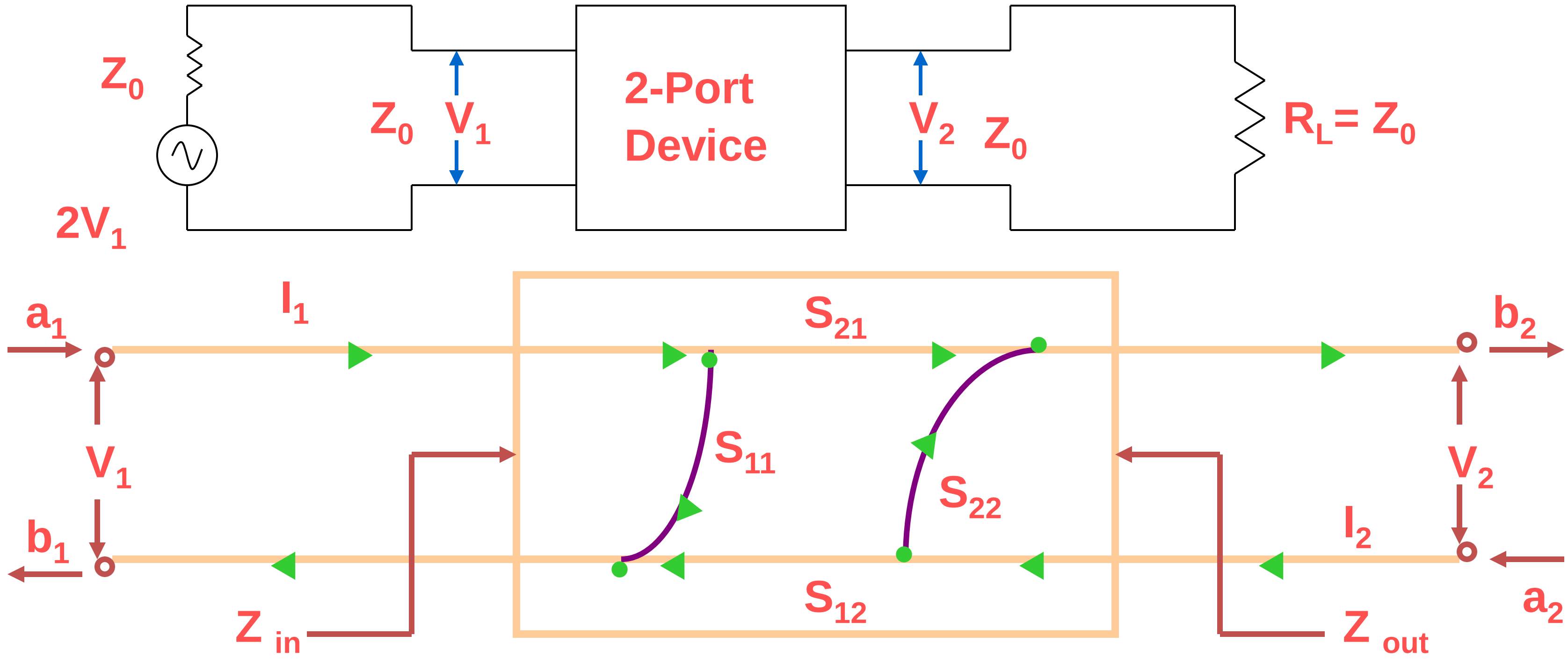
Load

If E probe penetrates too far into the slotted line, → disturb the field distribution and detected signal too strong to drive the detector out of its square-law region.

Problems to use Z- , Y- or H- parameters in microwave circuits

- **Difficult in defining voltage and current for non-TEM lines**
- **No equipment available to measure voltage and current in complex value as oscilloscope**
- **Difficult to make open and short circuits over broadband**
- **Active devices not stable as terminated with open or short circuit.**

S-parameters of a two-port network



$a_1 = V_1^+ / \sqrt{Z_0}$ **: incident (power) wave at port 1**

$b_1 = V_1^- / \sqrt{Z_0}$ **: reflected (power) wave at port 1**

$a_2 = V_2^+ / \sqrt{Z_0}$ **: incident (power) wave at port 2**

$b_2 = V_2^- / \sqrt{Z_0}$ **: reflected (power) wave at port 2**

$$V_1 = V_1^+ + V_1^-, V_2 = V_2^+ + V_2^-, I_1 = \frac{V_1^+}{Z_0} - \frac{V_1^-}{Z_0}, I_2 = \frac{V_2^+}{Z_0} - \frac{V_2^-}{Z_0}$$

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, S_{ij} = \left.\frac{b_i}{a_j}\right|_{a_i = 0, k \neq j} = \left.\frac{V_i^-}{V_j^+}\right|_{V_k^+ = 0, k \neq j}$$

➡ **Incident power to port *i*:** $P_i = \frac{1}{2} \Re e\left\{ V_i I_i^* \right\} = \frac{1}{2}|a_i|^2 - \frac{1}{2}|b_i|^2$

Properties of S- Parameters

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$ **: reflection coefficient at port 1 with port 2 matched**

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$$ **: forward transmission coefficient with port 2 matched**

$$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$$ **: reversed transmission coefficient with port 1 matched**

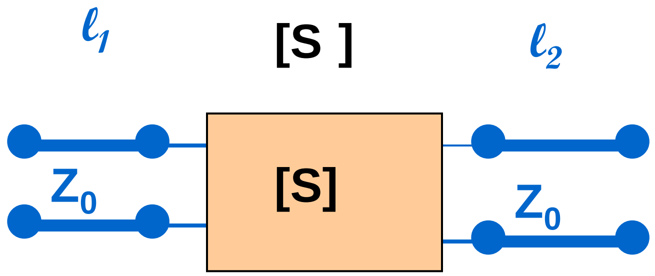
$$S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$ **: reflection coefficient at port 2 with port 1 matched**

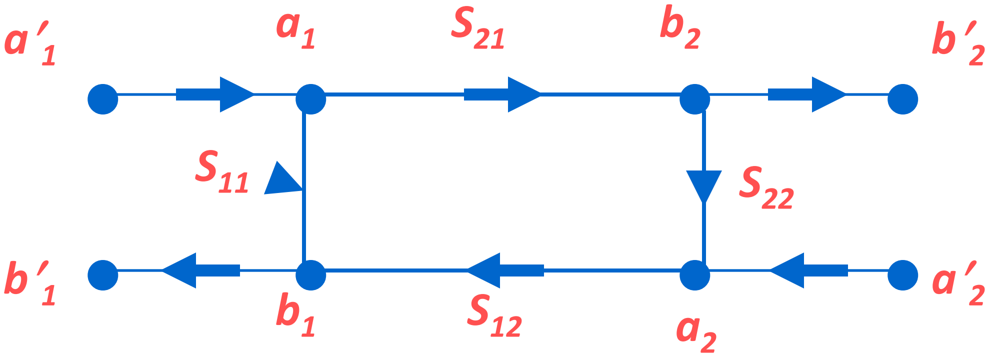
IL **or power gain from port 1 to port 2** $= -10\,log\left|S_{21}\right|^2$

IL **or power gain from port 2 to port 1** $= -10\,log\left|S_{12}\right|^2$

RL **at port 1 or port 2** $= -10\,log\left|S_{11}\right|^2$ **or** $= -10\,log\left|S_{22}\right|^2$

Properties of S- Parameters





$$S'_{11} = S_{11} e^{-j2\beta\ell_1}, S'_{21} = S_{21} e^{-j2\beta(\ell_1+\ell_2)}$$

$$S'_{12} = S_{12} e^{-j2\beta(\ell_1+\ell_2)}, S'_{22} = S_{22} e^{-j2\beta\ell_2}$$

$$b_1 = a_1 S_{11} + a_2 S_{12}$$

$$b_2 = a_1 S_{21} + a_2 S_{22}$$

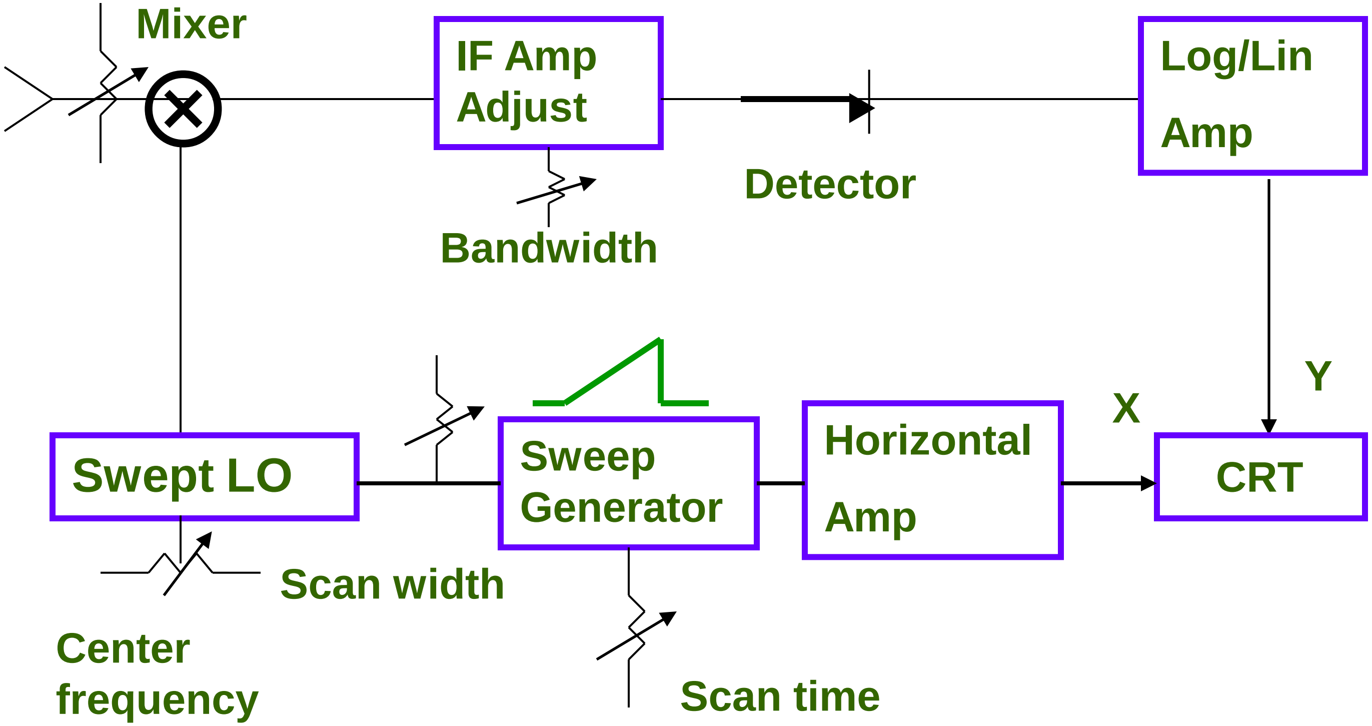
Reasons to use S-matrix in microwave circuit

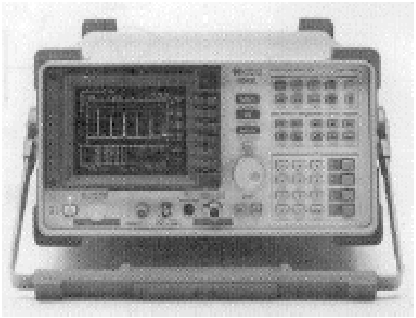
(1) matched load available in broadband application
(2) measurable quantity in terms of incident, reflected and transmitted waves
(3) termination with Z_0 causes no oscillation
(4) convenient to use in the microwave network analysis

Spectrum analyzer

Purpose: measure microwave signal spectrum, can also be used to measure frequency, rms voltage, power, distortion, noise power, amplitude modulation, frequency modulation, spectral purity,...

Operating principle

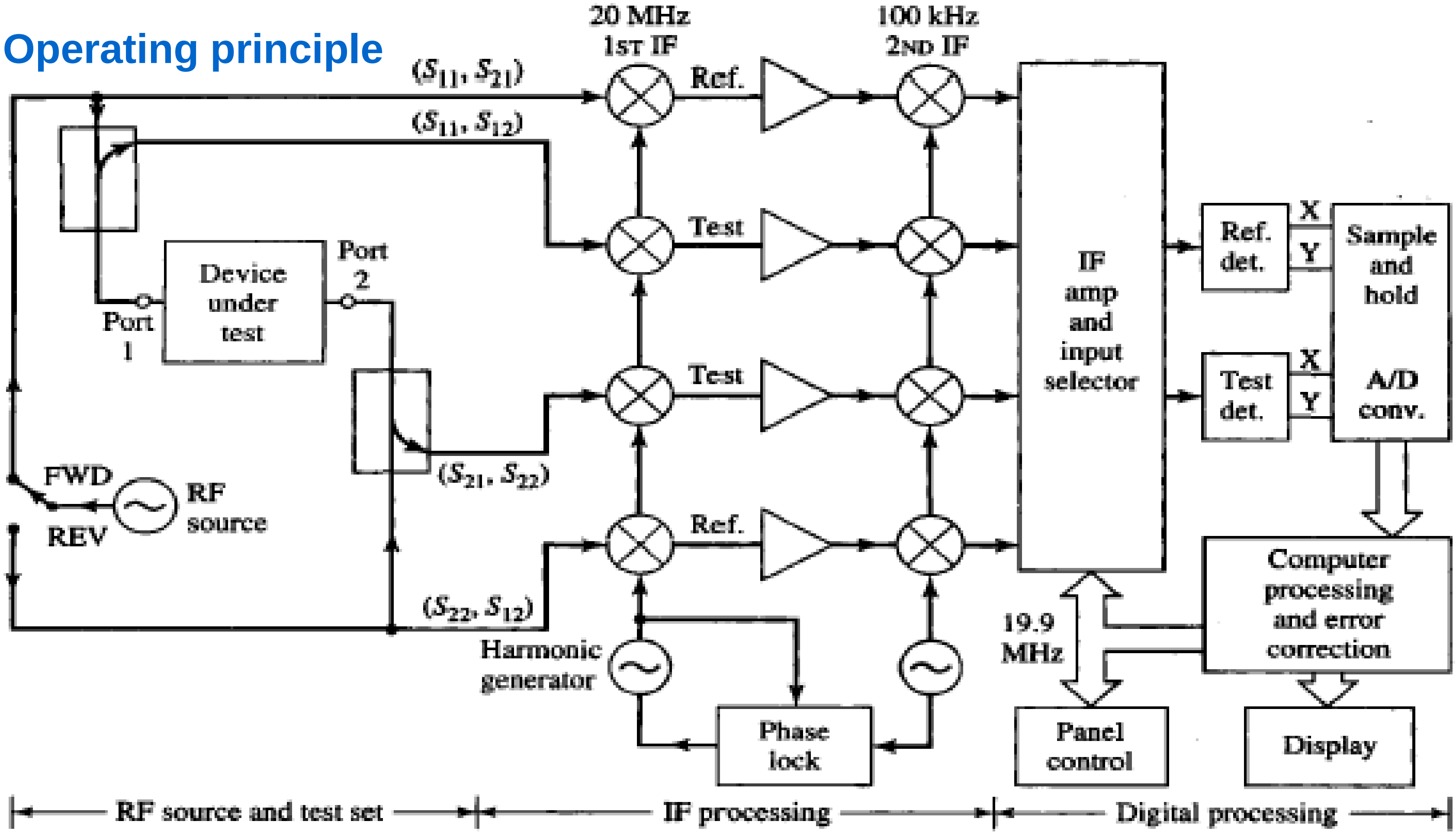




Network analyzer

<u>Purpose:</u> **measure two-port S-parameter of a microwave device or network, can also be used to measure VSWR, return loss, group delay, input impedance, antenna pattern, dielectric constant,….**

Operating principle



Scalar network analyzer measures the magnitude of two-port S-parameters.

Hp8510 vector network analyzer