Microwave signal measurements

Introduction

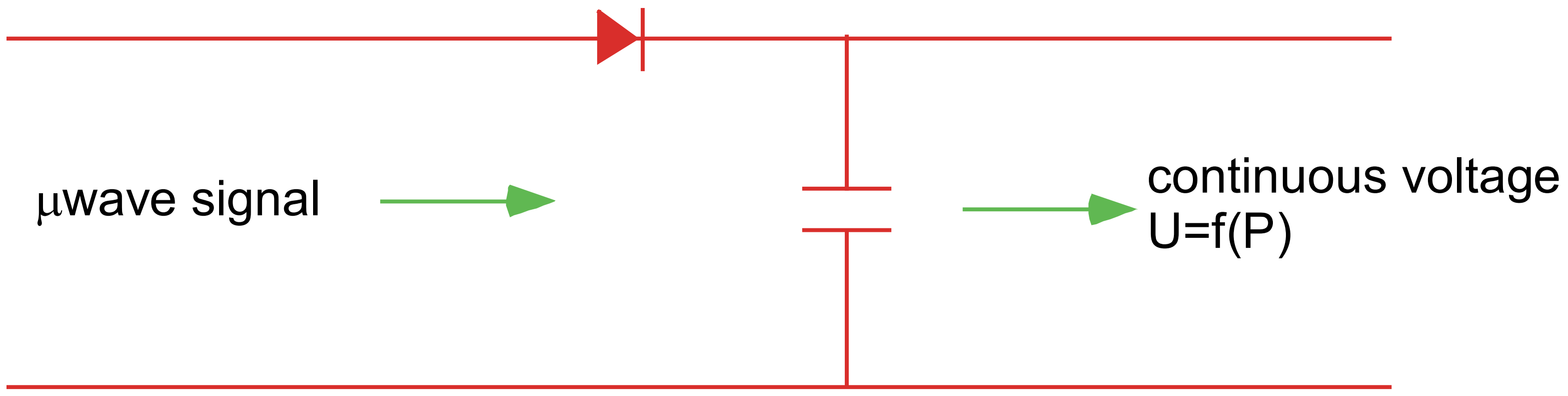
- In non TEM lines, V and I are not defined physically
- In TEM lines, V and I are difficult or impossible to measure
- P is always defined
- f is always defined

Microwave signals are characterized by their power and frequency

Power measurement

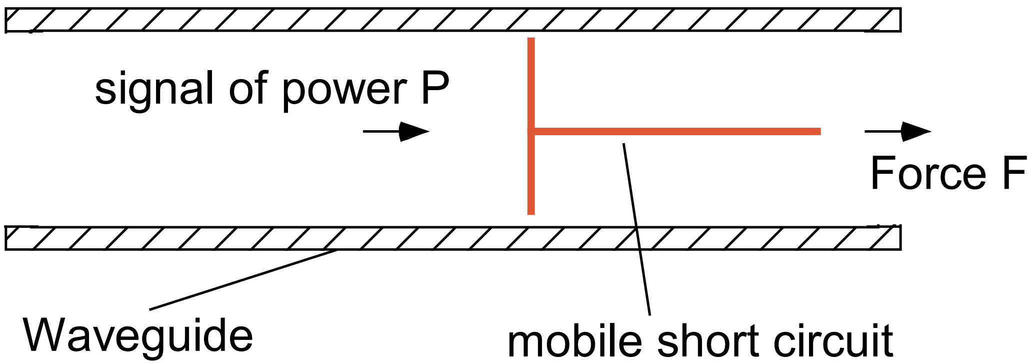
- Physical means used :
  - Rectifying the signal
  - Convert microwave power to mechanical force
  - Convert microwave power to heat

Rectifying



- Problems : stability, precision, matching, harmonics. Thus filtering and calibration are necessary
- Advantage : fast

Mechanical measurement



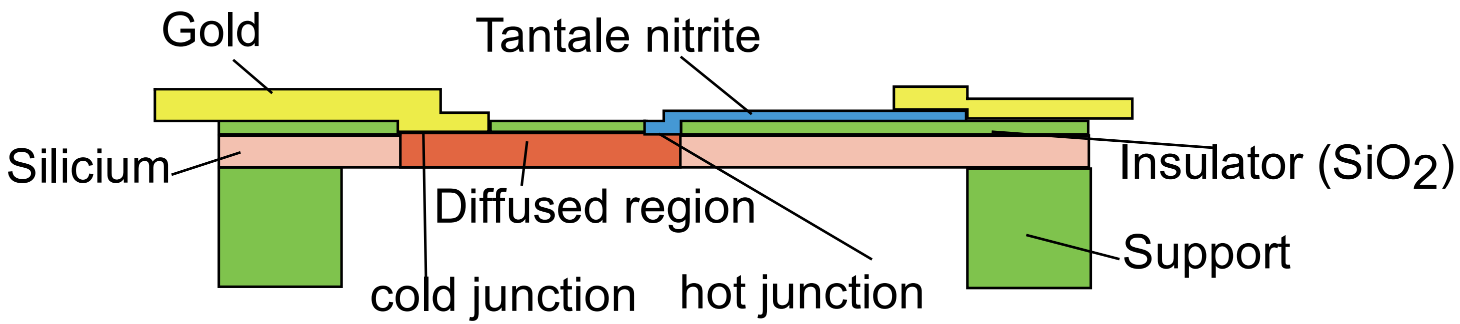
$$F = \frac{2P\lambda}{c_o \lambda_g}$$

- Problems : very weak force, total reflection of the signal

Thermal conversion

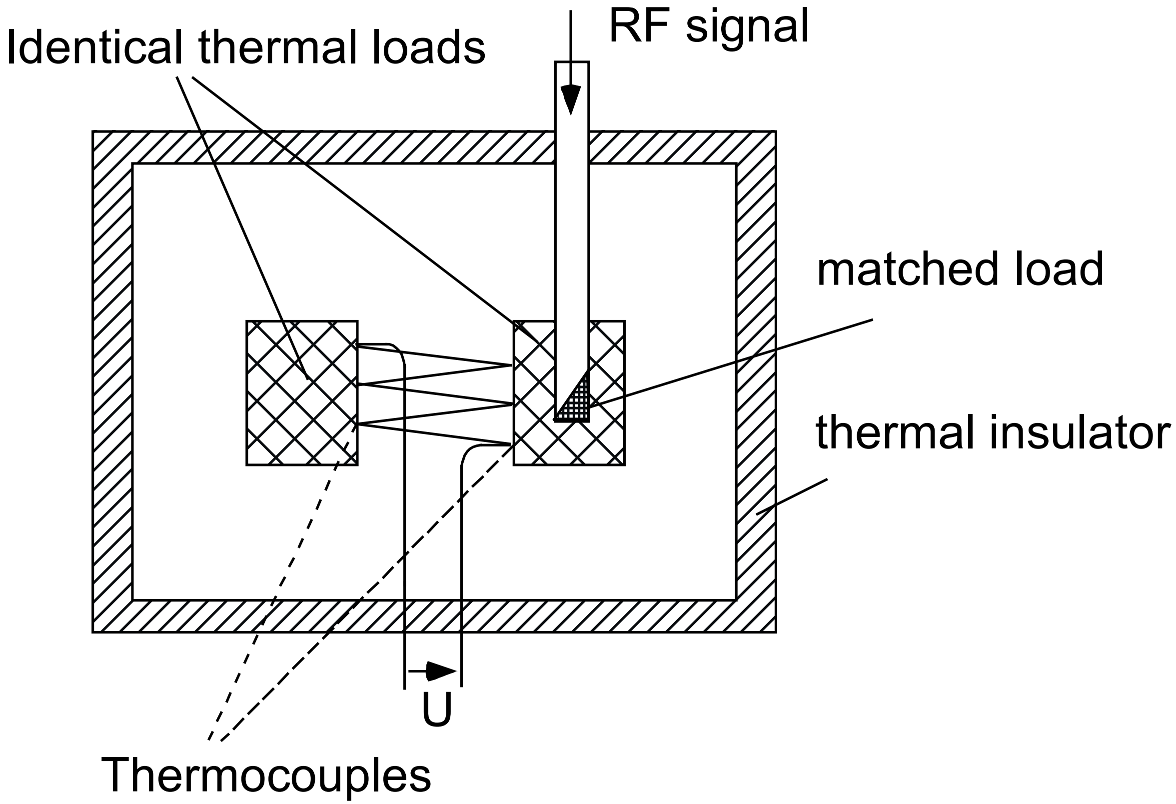
- The microwave power is converted to heat (use of absorbers or thermistors)
- The variation of temperature is measured
  - calorimeters (precision measurements)
  - Electronical measurement (usual measurements)

Thermocouples



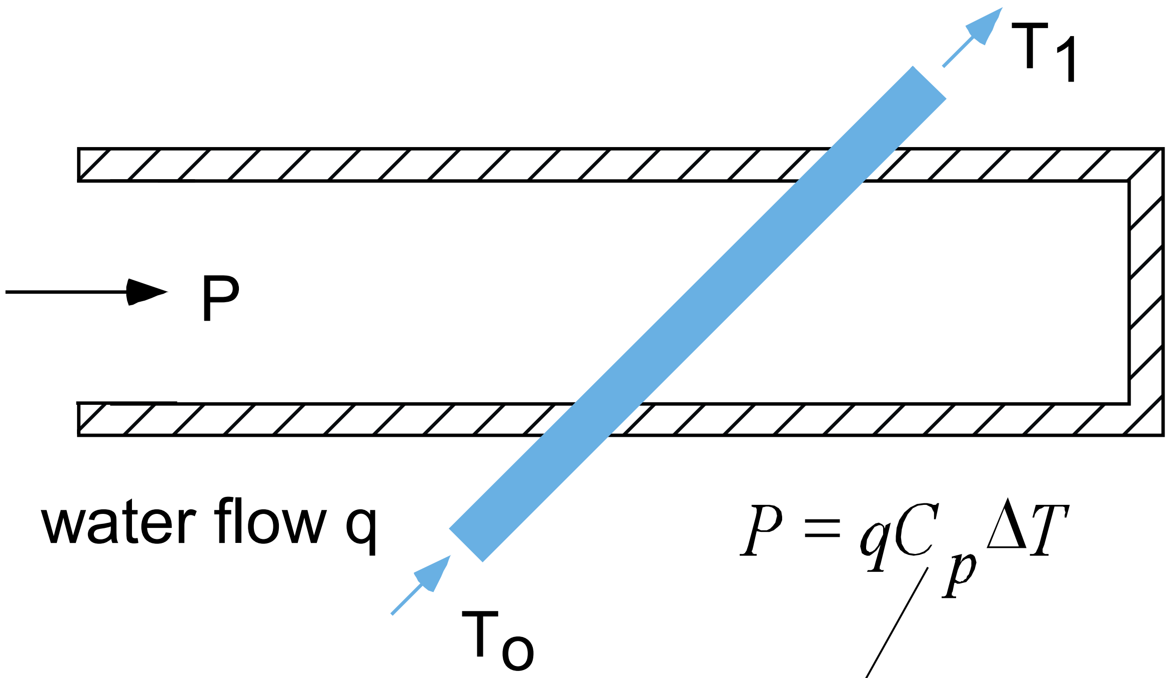
- A voltage U exists at each junction between two different conductive materials (electrochemical potential)
- This voltage is temperature dependant
- Thus the "hot " junction is compared to the temperature of a reference "cold" junction

Calorimeter



$$U \sim T_1 - T_o \sim P$$

Water calorimeter

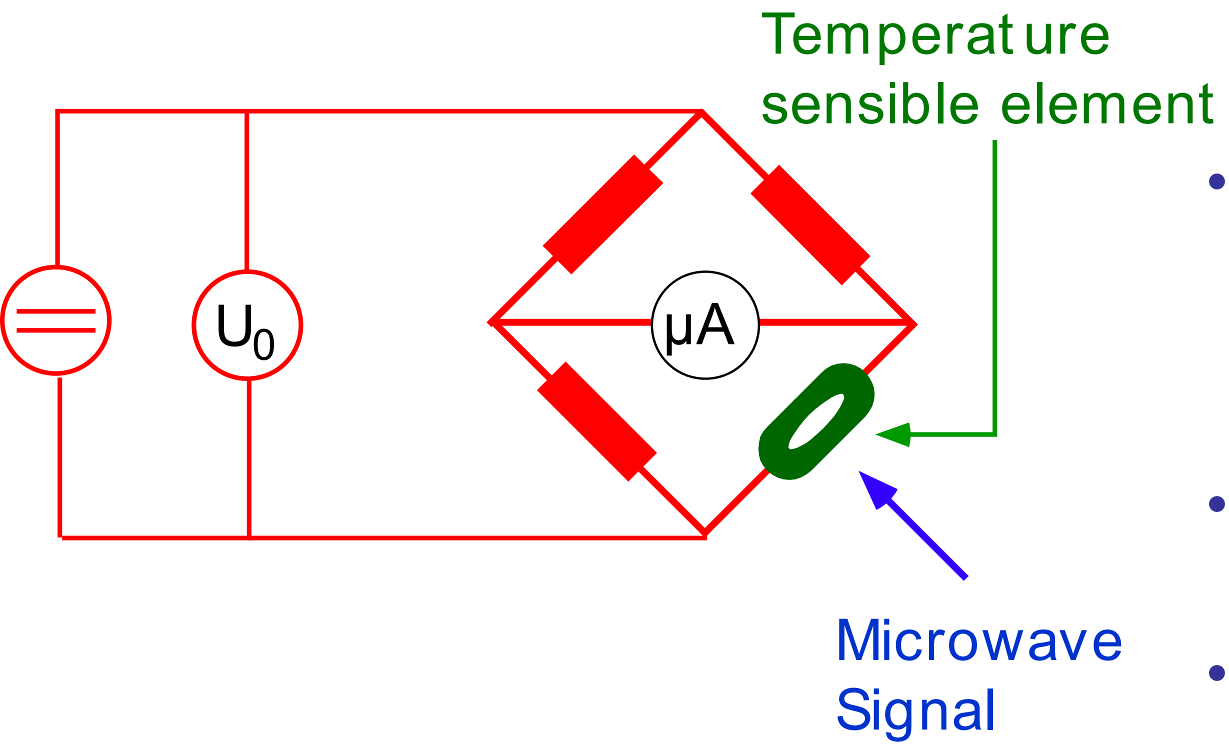


$$P = qC_p\Delta T$$

specific heat

- The flow must be constant
- High precicsion measurements for standards
- Bulky setups, and slow measurements

Milliwattmeter using a wheatstone bridge



- The equilibrium is sought for until having i=0 in the μAmpmeter
- Without the μwave signal (calibaration)
- With the μwave signal (measurement)

Milliwattmeter using a wheatstone bridge

- At the equilibrium, without μwave signal

$$P_o = \frac{U_o^2}{4R}$$

- In presence of the μwave signal, the voltage is reduced to reach the equilibrium again.

$$P_1 = \frac{\left(U_o - \Delta U\right)^2}{4R}$$

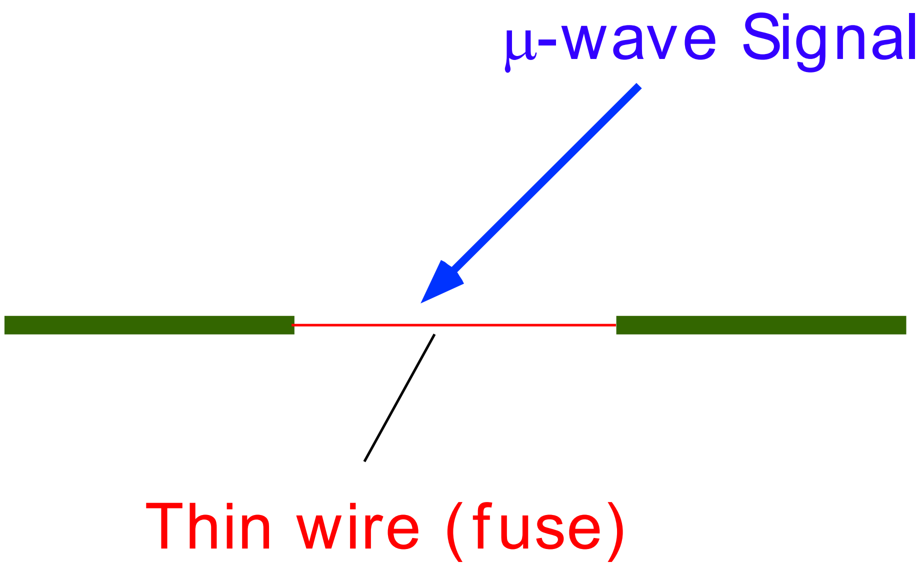
Milliwattmeter using a wheatstone bridge

- Thus, the μwave power is equal to

$$P = P_o - P_1$$
$$= \frac{\Delta U\left(2U_o - \Delta U\right)}{4R}$$

Thermosensible elements : Bolometers or thermistors

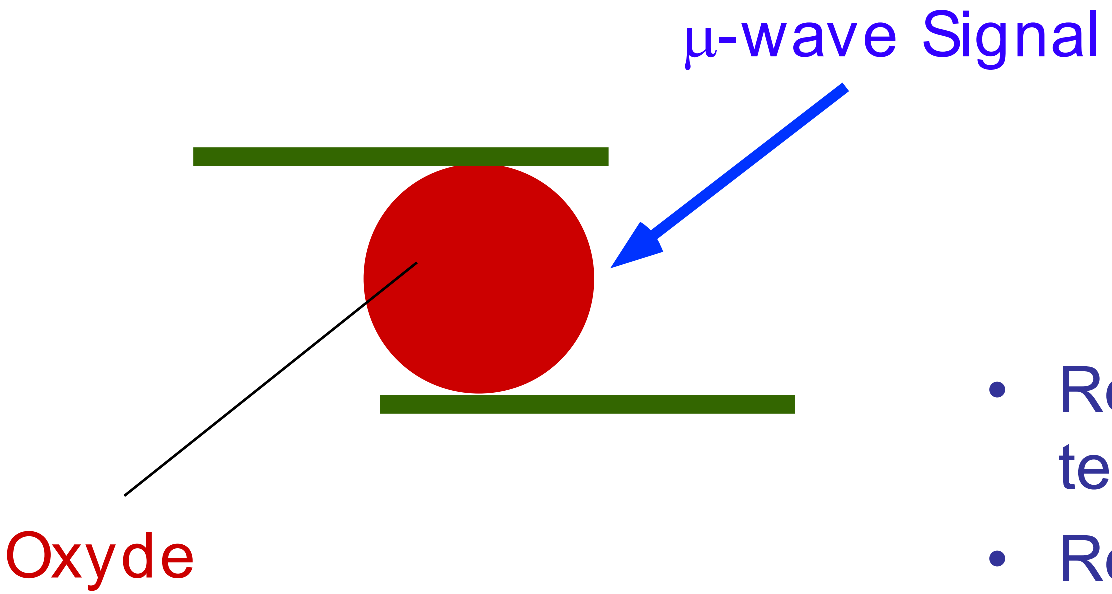
Bolometer



R ↗ when T ↗

- Thin wire conductor
- When P increases, T and R increase
- Response time : < 1ms

Thermistor



- Resistor with negative temperature coefficient
- Response time : 0.5-1 s

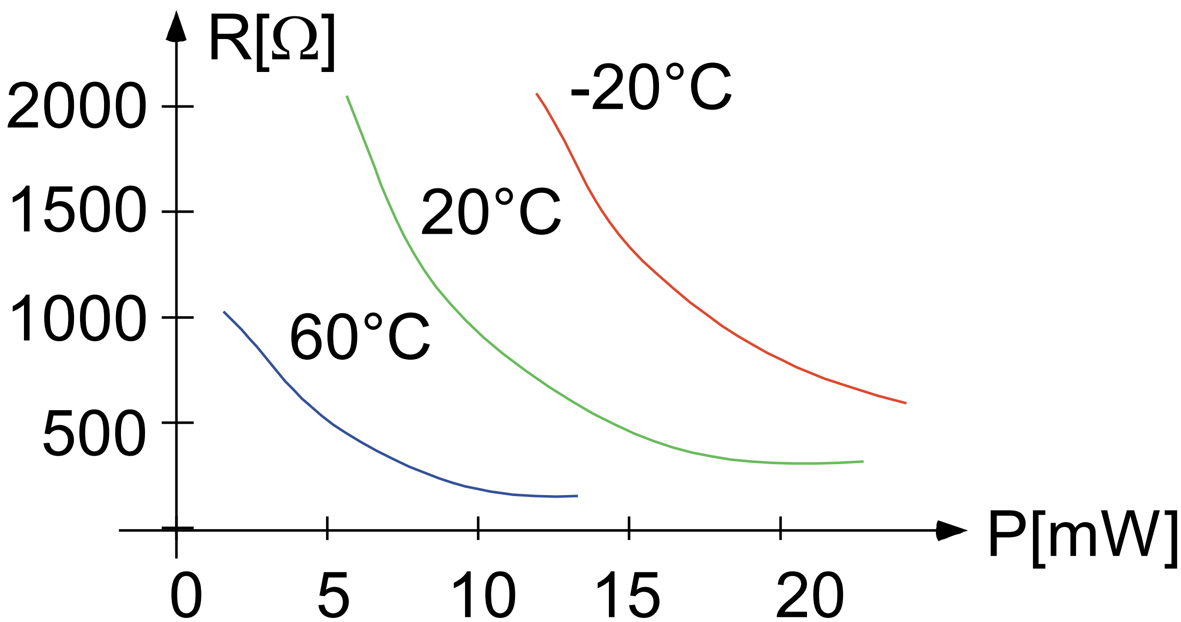
R ↘ quand T ↗

Sources of measurement errors

- mismatch
- Thermal drift
- Substitution errors
- μ–wave losses
- Thermoelectrical effect
- Precision of the powermeter
- Pairing of the sensitive elements

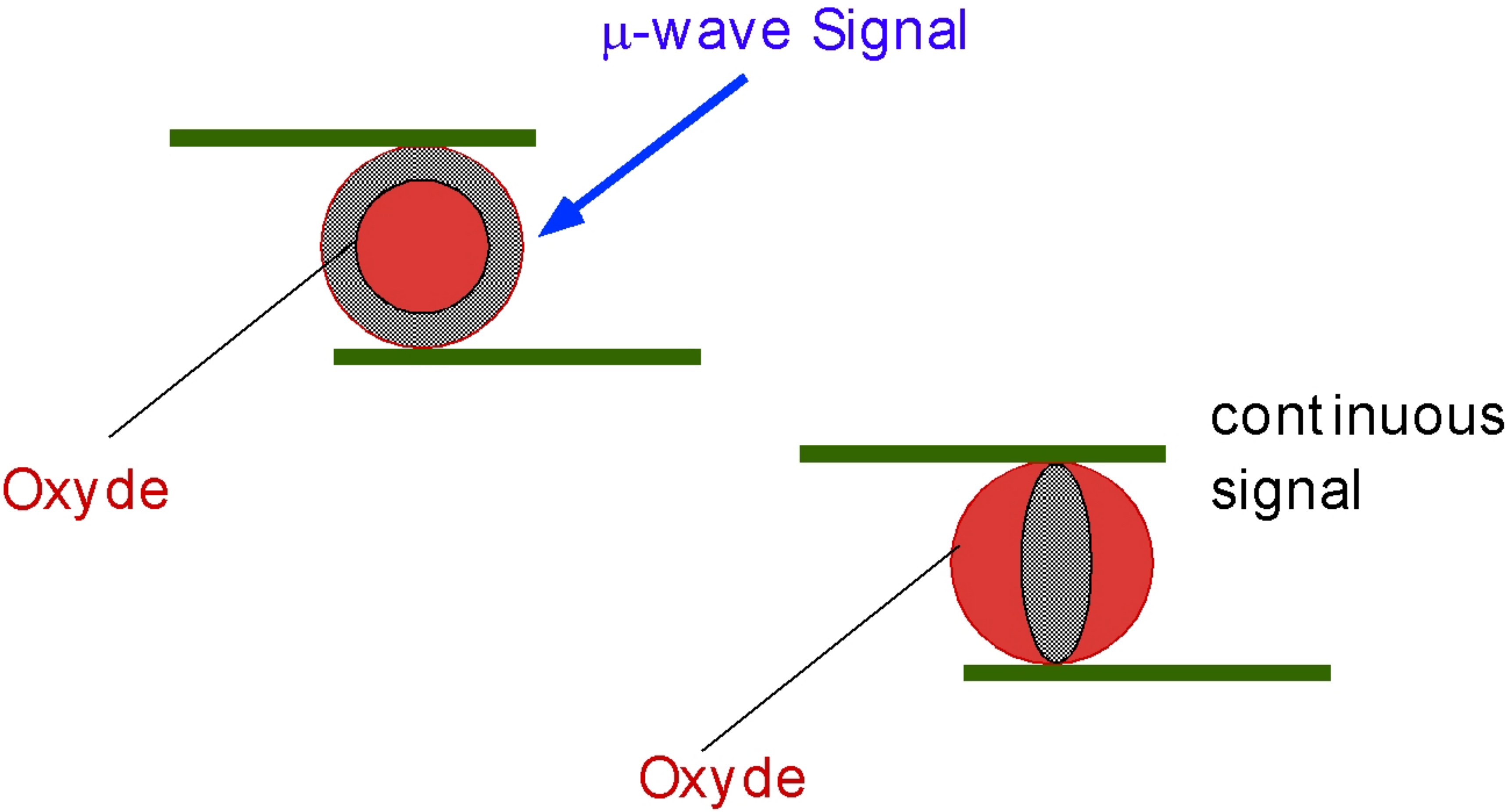
calibration

Thermal drift



Compensation : measure at the same time the reference and the signal (paired sensitive elements)

Substitution losses

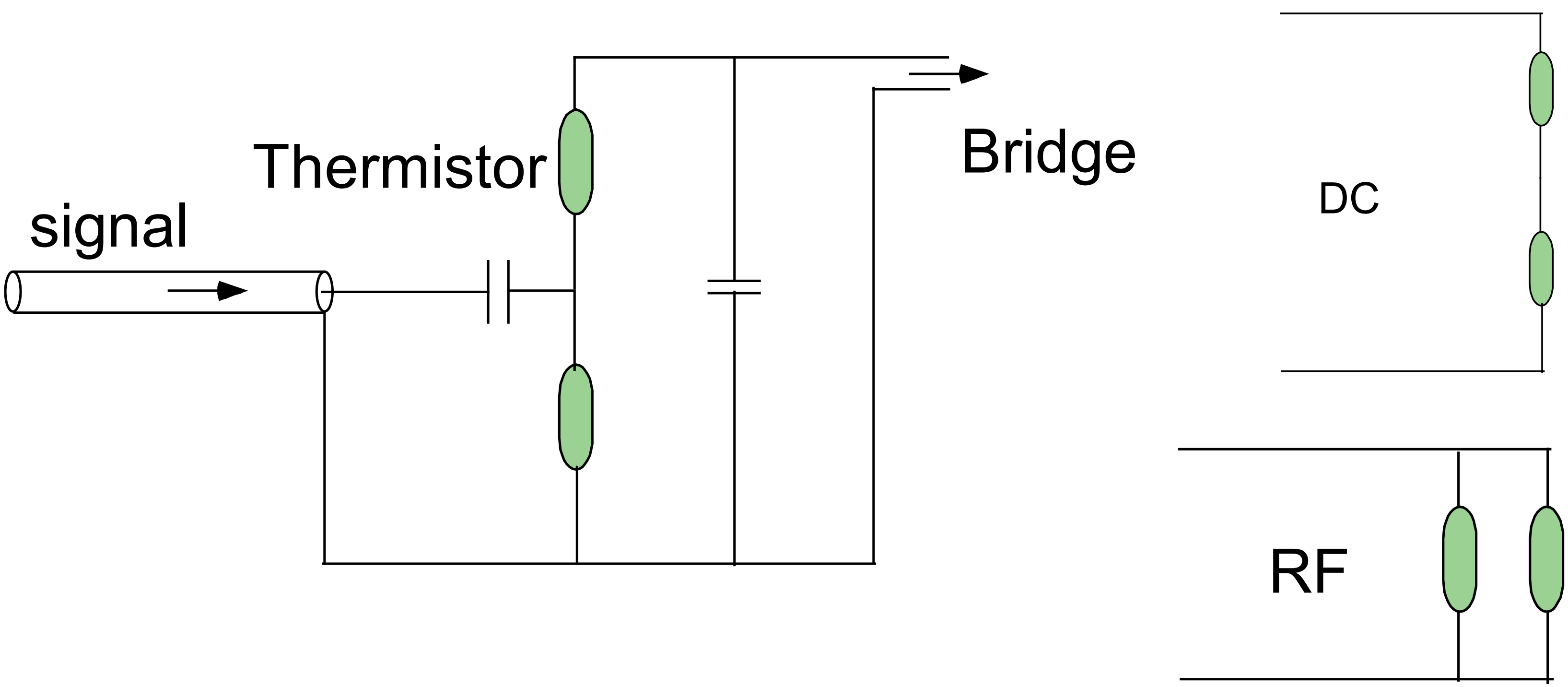


Subsitution efficiency

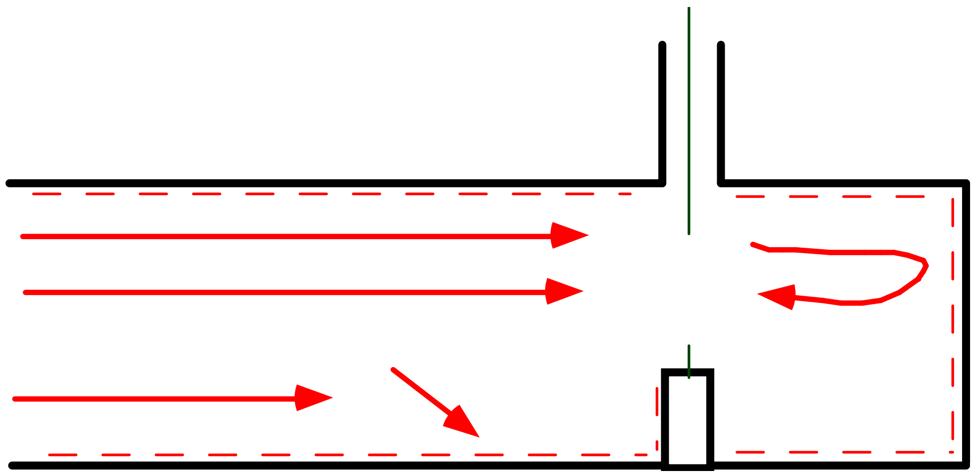
$$\eta_s = \frac{P_o - P_1}{P_{\mu w}} = \frac{\text{Continuous power}}{\text{microwave power}}$$

Pairing of elements

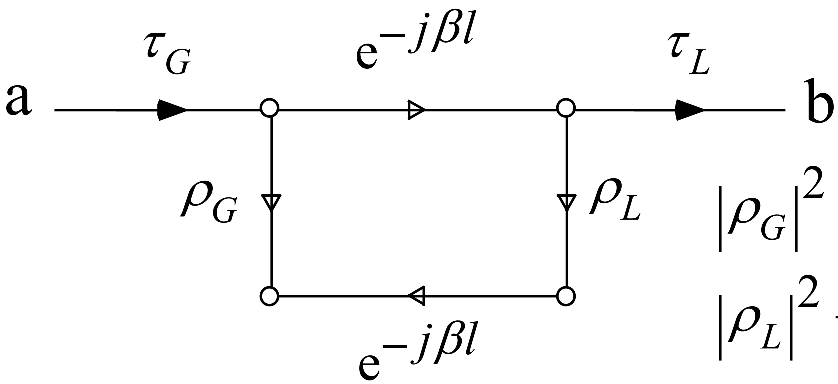
In coaxial systems , we need to avoid that the continuous signal flows into the transmission line : use of paired elements and decoupling capacitors.



RF losses



Mismatch errors : flow chart



$$|\rho_G|^2 + |\tau_G|^2 = 1$$

$$|\rho_L|^2 + |\tau_L|^2 = 1$$

$$P_a = |a|^2\left(1 - |\rho_G|^2\right)$$

Power that would be absorbed by a matched power meter

$$P_m = \frac{|a|^2\left(1 - |\rho_G|^2\right)\left(1 - |\rho_L|^2\right)}{\left|1 - \rho_G \rho_L \, e^{-2j\beta l}\right|^2}$$

Power absorbed by the unmatched power meter

Mismatch errors

we define the mismatch efficiency as

$$\frac{P_m}{P_a} = \frac{\left(1-\left|\rho_L\right|^2\right)}{\left|1-\rho_G\rho_L\,\mathrm{e}^{-2j\beta l}\right|^2} = \eta_d$$

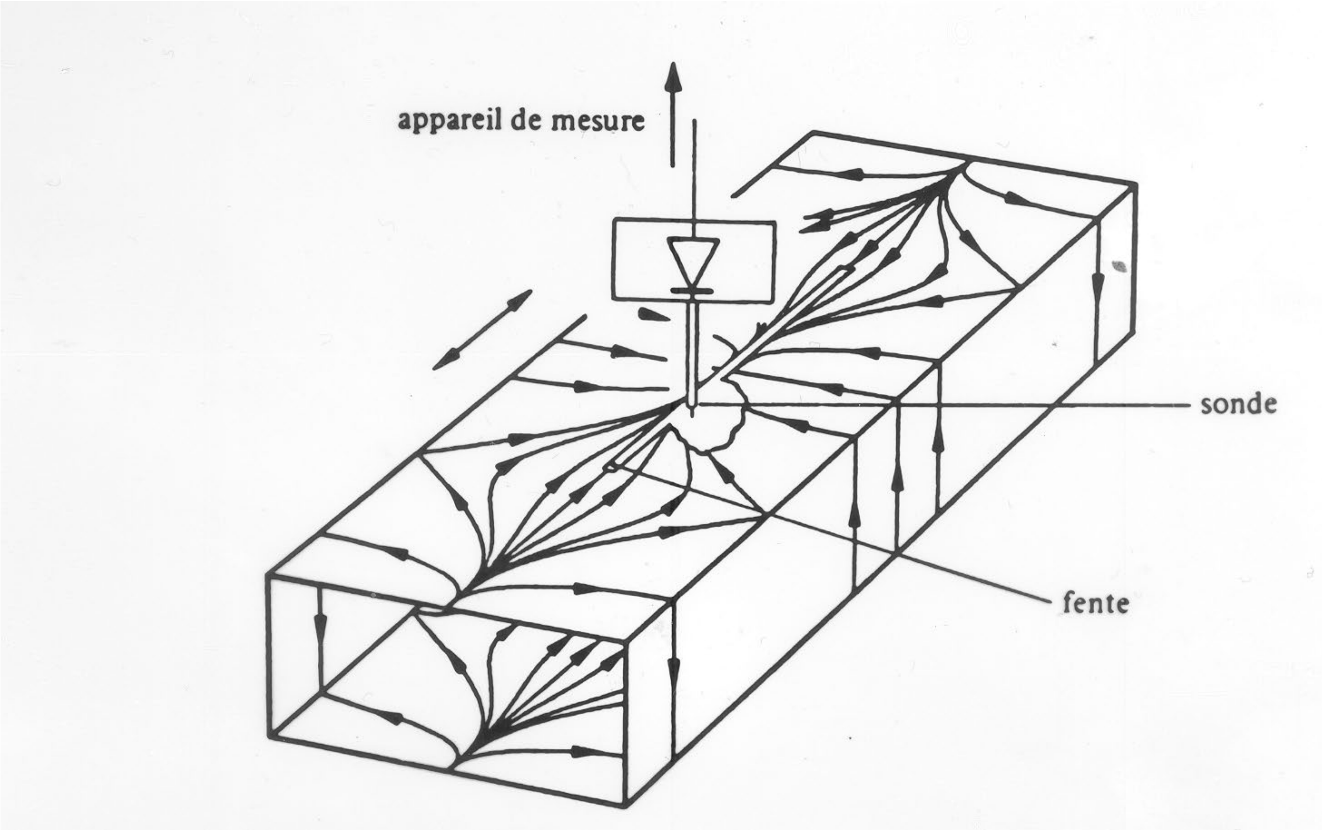
Thus

$$\frac{\left(1-\left|\rho_L\right|^2\right)}{\left(1+\left|\rho_G\rho_L\right|\right)^2} \le \eta_d \le \frac{\left(1-\left|\rho_L\right|^2\right)}{\left(1-\left|\rho_G\rho_L\right|\right)^2}$$

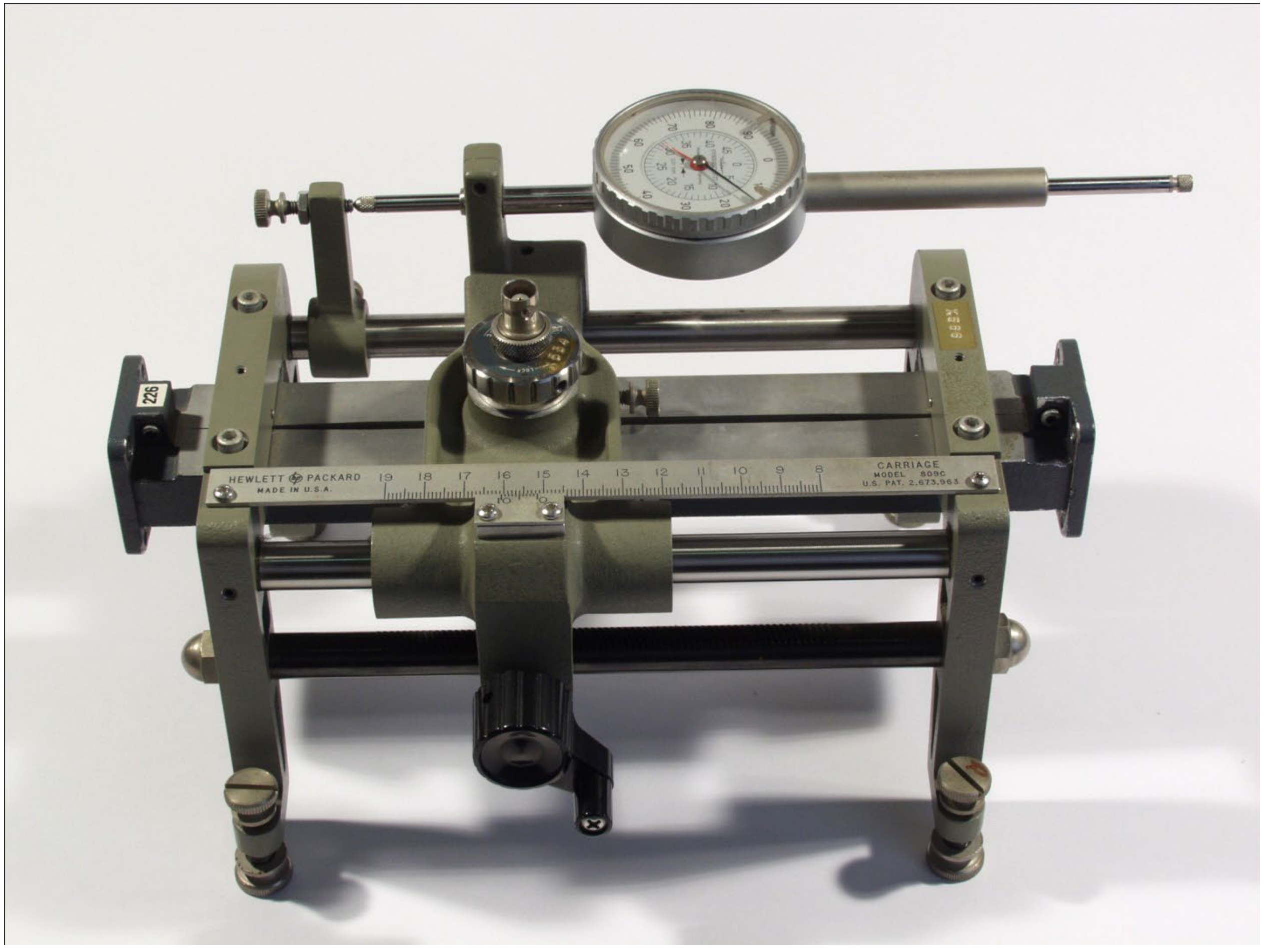
Frequency measurements

- Geometrical measurements (wavelength, cavity resonance)
- Electronic measurement

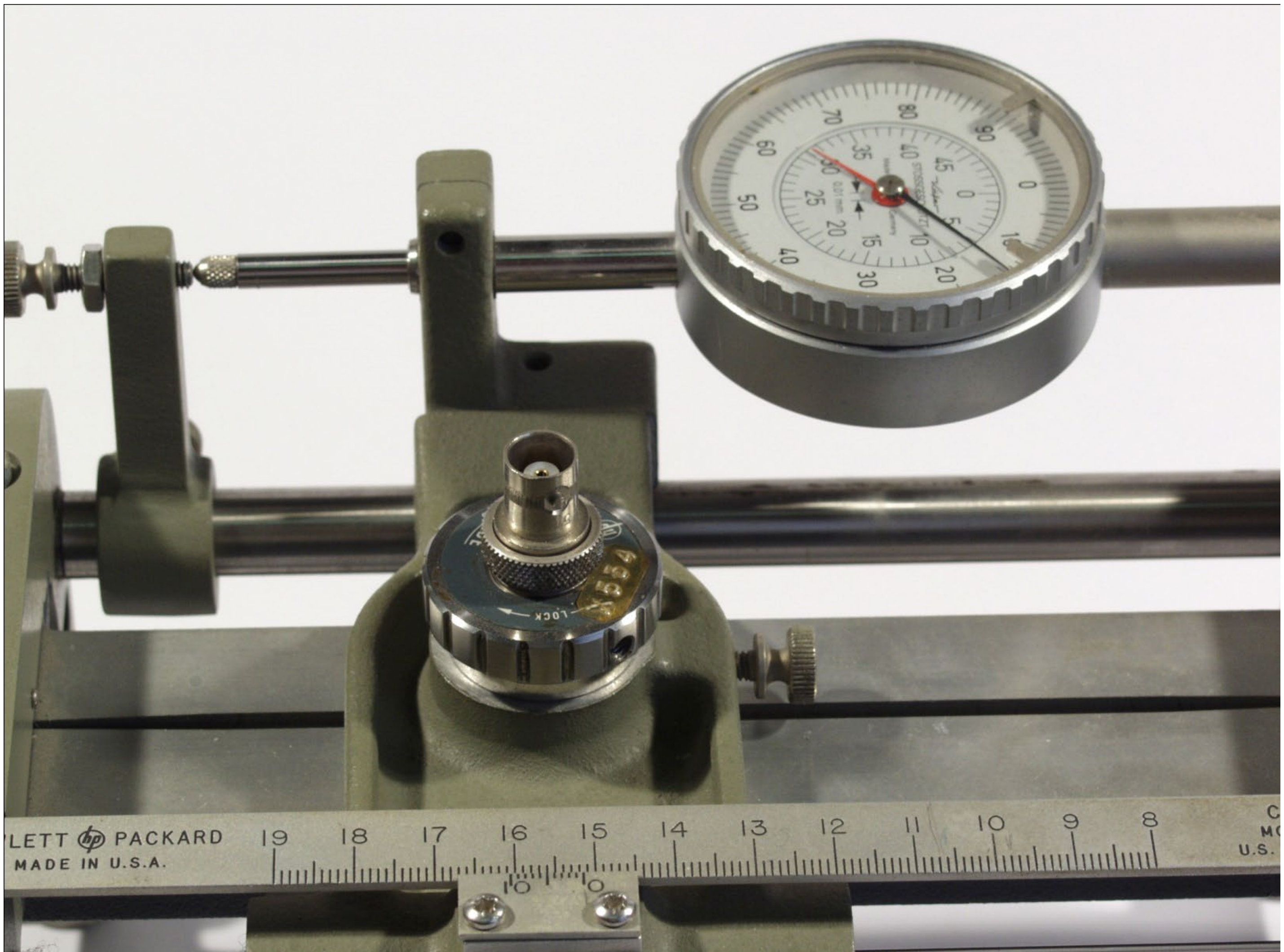
Slotted line



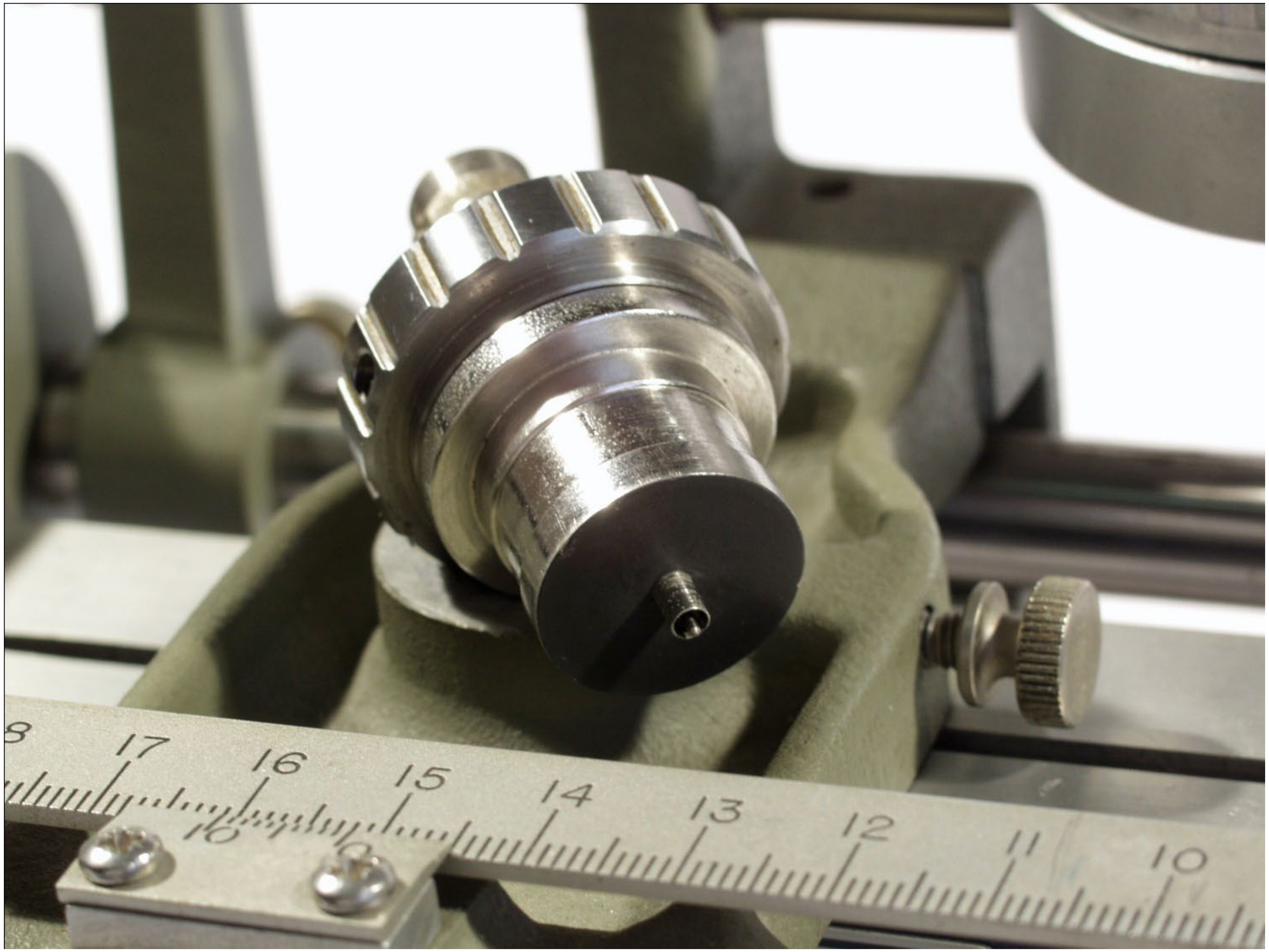
Slotted line



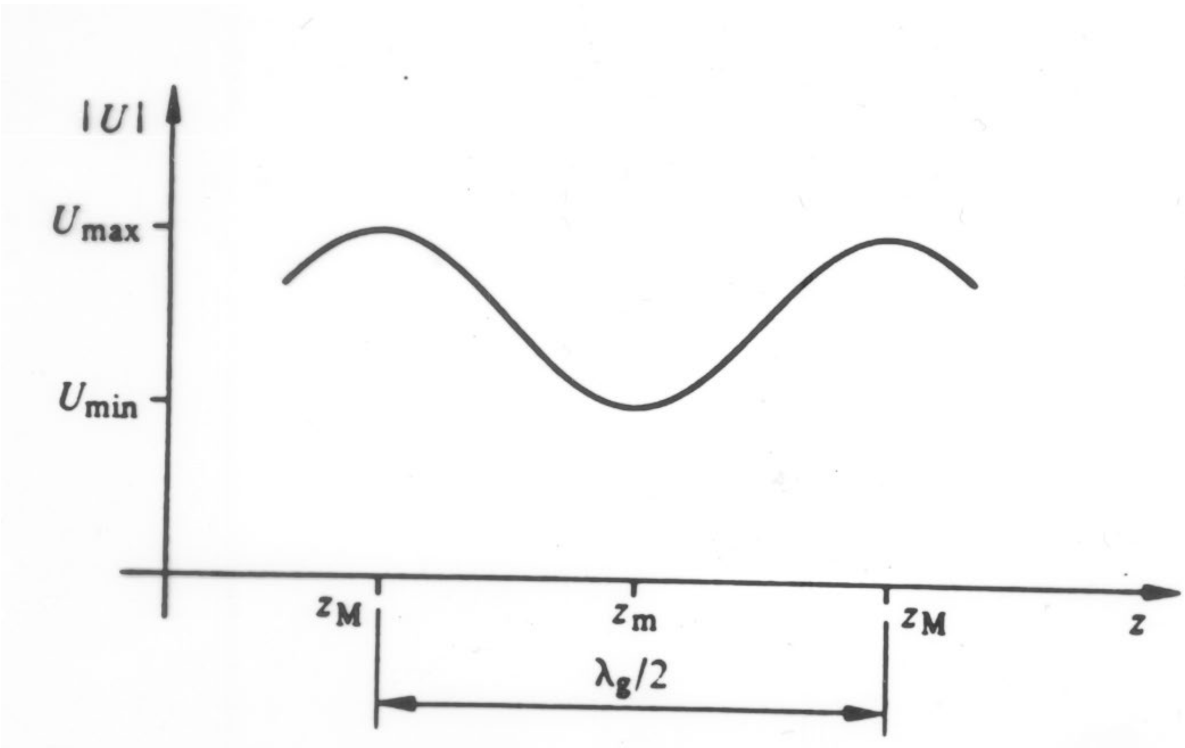
Slotted line



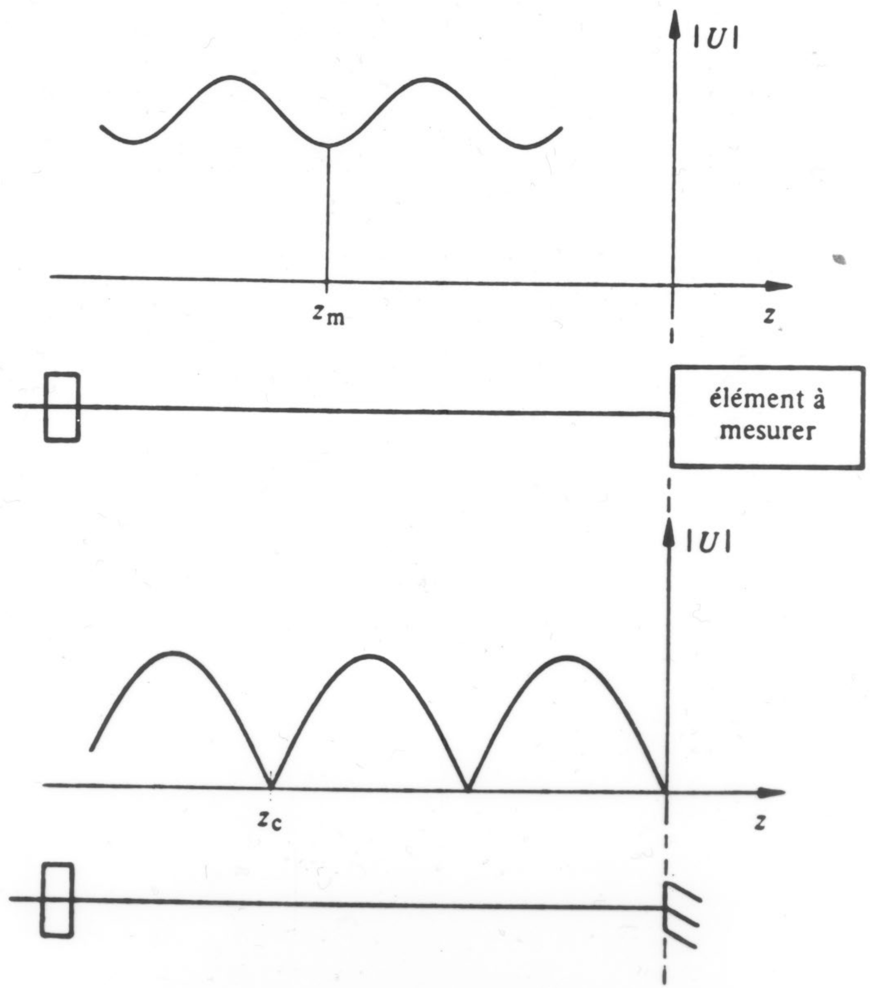
Slotted line



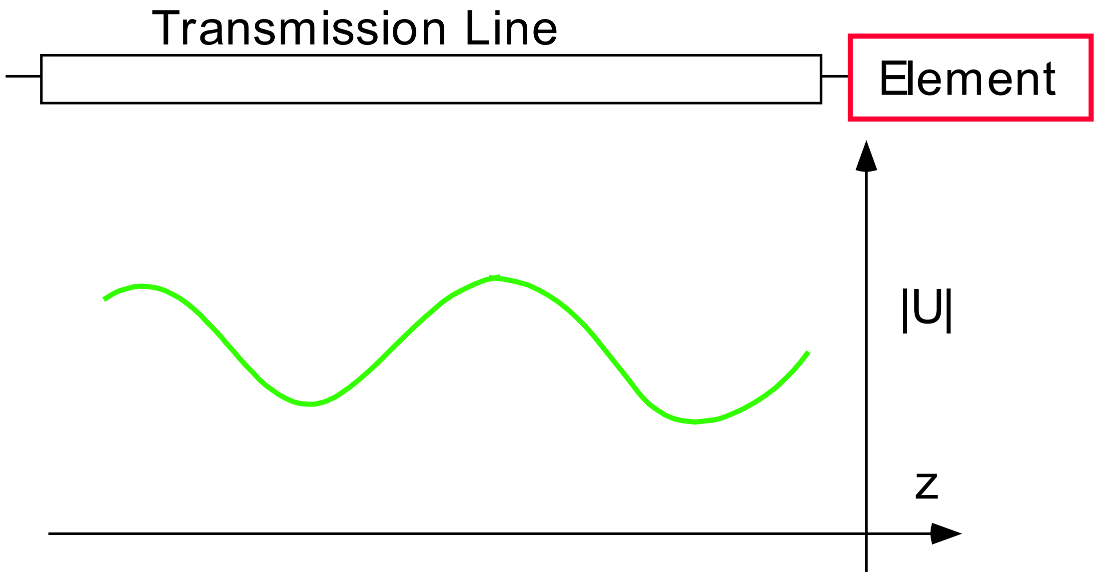
Slotted line



slotted line



Slotted line



$$U_i = \sqrt{Z_{ci}}\left(a_i + b_i\right) = \sqrt{Z_{ci}}\left(a_i + s_{ii}a_i\right)$$

$$U_i\left(z\right) = \sqrt{Z_{ci}}a_i\left(z\right)\left[1 + s_{ii}e^{2j\beta z}\right]$$

$$\left|U_i\left(z\right)\right| = \sqrt{Z_{ci}}\left|a_i\left(z\right)\right|\sqrt{\left[1+\left|s_{ii}\right|\cos\left(\varphi+2\beta z\right)\right]^2 + \left|s_{ii}\right|^2\sin^2\left(\varphi+2\beta z\right)}$$

$$\left|U_i\left(z\right)\right| = \sqrt{Z_{ci}}\left|a_i\left(z\right)\right|\sqrt{1+\left|s_{ii}\right|^2 + 2\left|s_{11}\right|\cos\left(\varphi+2\beta z\right)}$$

VSWR

Extrema of |Ui| :

$$U_{\max} = \sqrt{Z_{ci}}\,|a_i|\left(1+|s_{ii}|\right) \quad for \;\; \varphi + 2\beta z_i = 2n\pi$$

$$U_{\min} = \sqrt{Z_{ci}}\,|a_i|\left(1-|s_{ii}|\right) \quad for \;\; \varphi + 2\beta z_i = (2n+1)\pi$$

$$ROS = VSWR = \frac{|U_{\max}|}{|U_{\min}|} = \frac{1+|s_{ii}|}{1-|s_{ii}|}$$

slotted line

- Measure position of two minima in the slotted line. The guided wavelength is given by twice this distance

$$f = \frac{c_o}{\lambda}$$

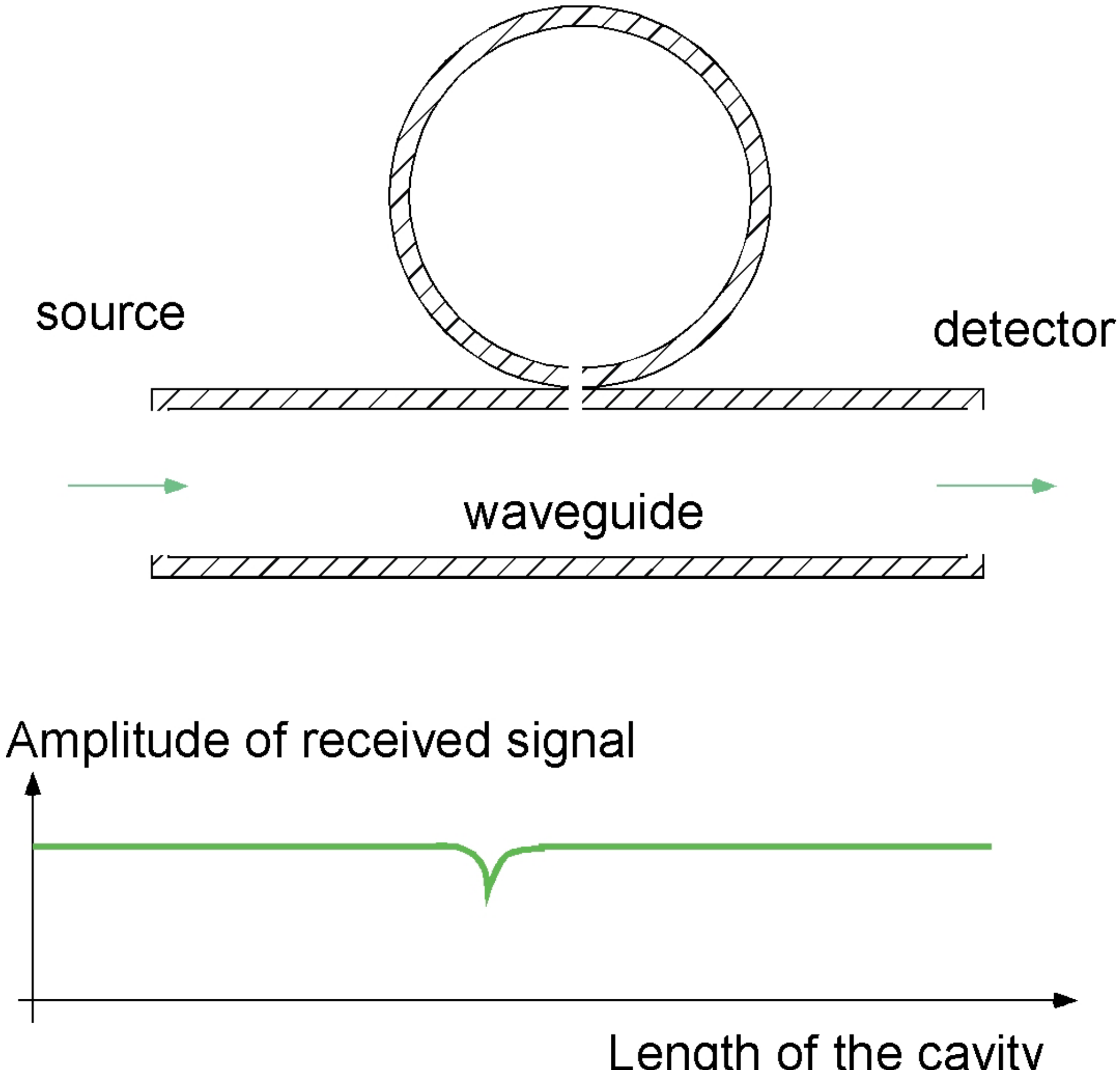
- In the case of a rectangular waveguide of section a x b in the dominant mode, we have

$$\lambda = \frac{\lambda_{10}}{\sqrt{1 + \left(\frac{\lambda_{10}}{2a}\right)^2}}$$

- Where λ_{10} is the measured guided wavelength

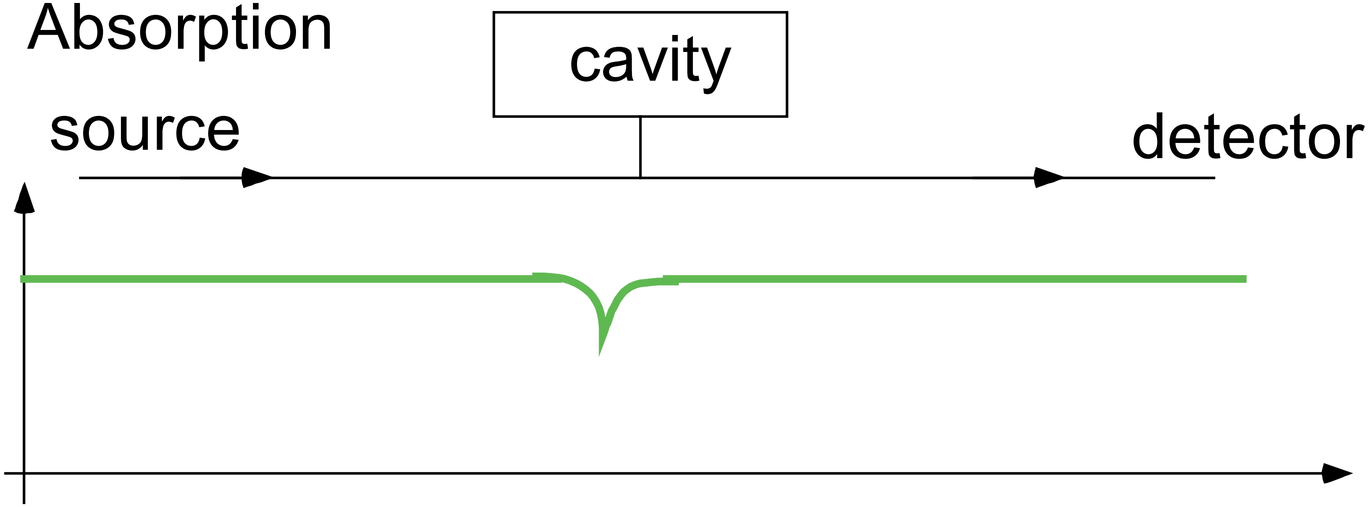
Wavemeter

Wavemeter : principle

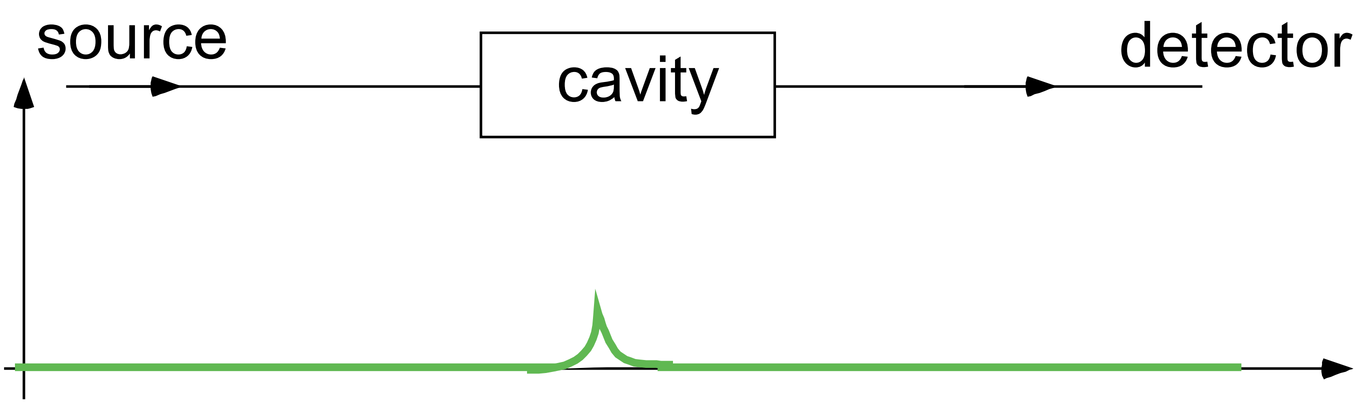


Wavemeter : different layouts

Absorption

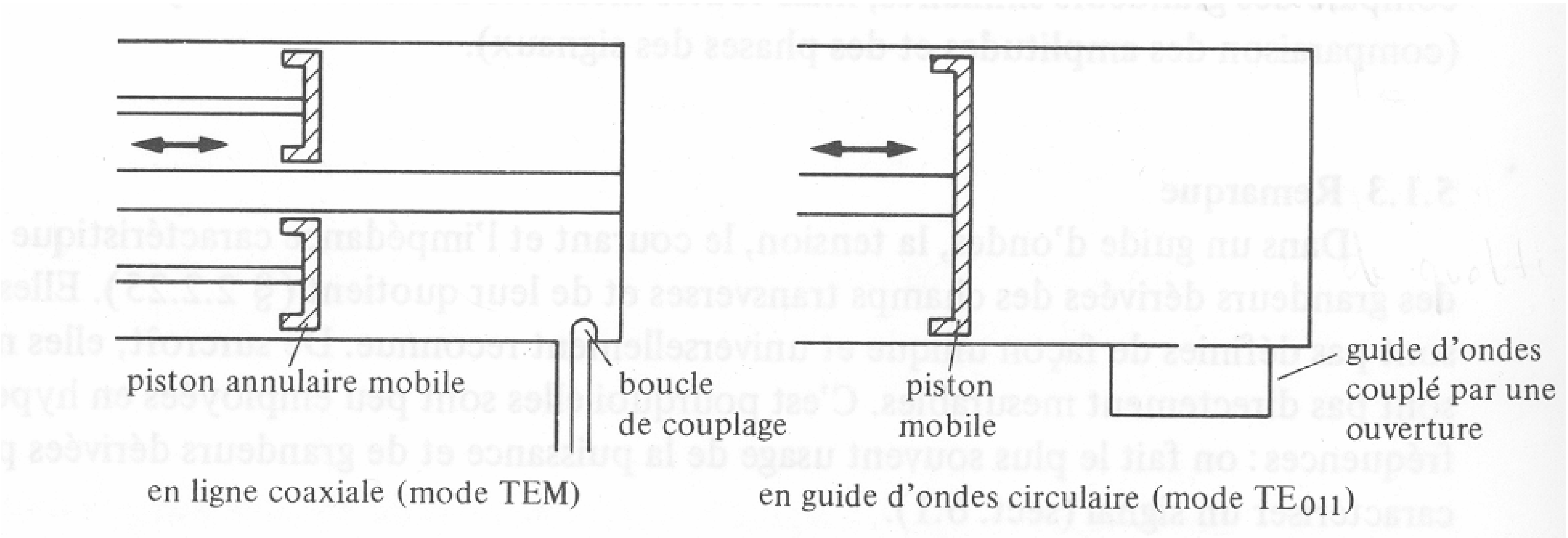


Transmission



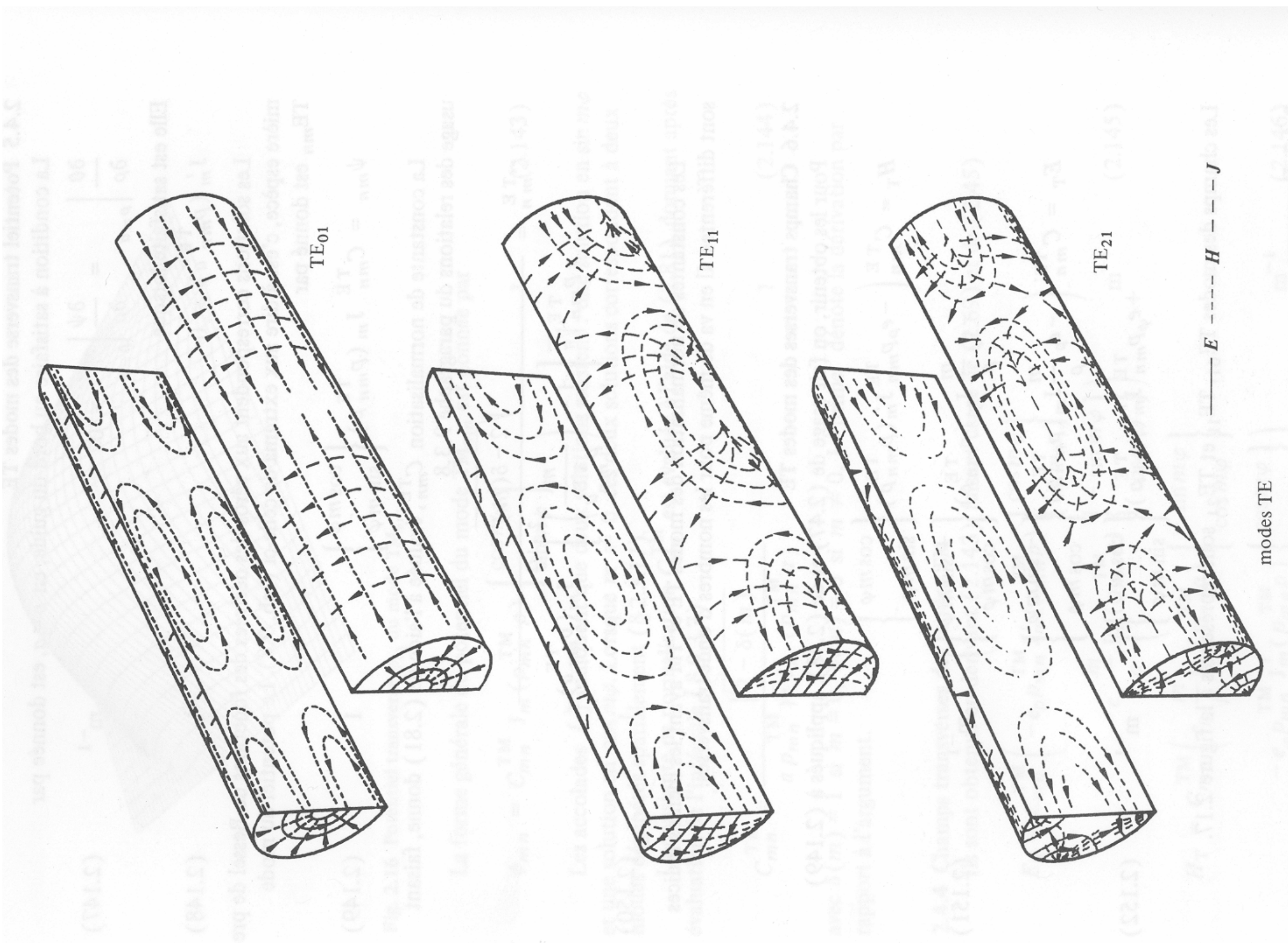
Wavemeter : example

Type of wavemeters



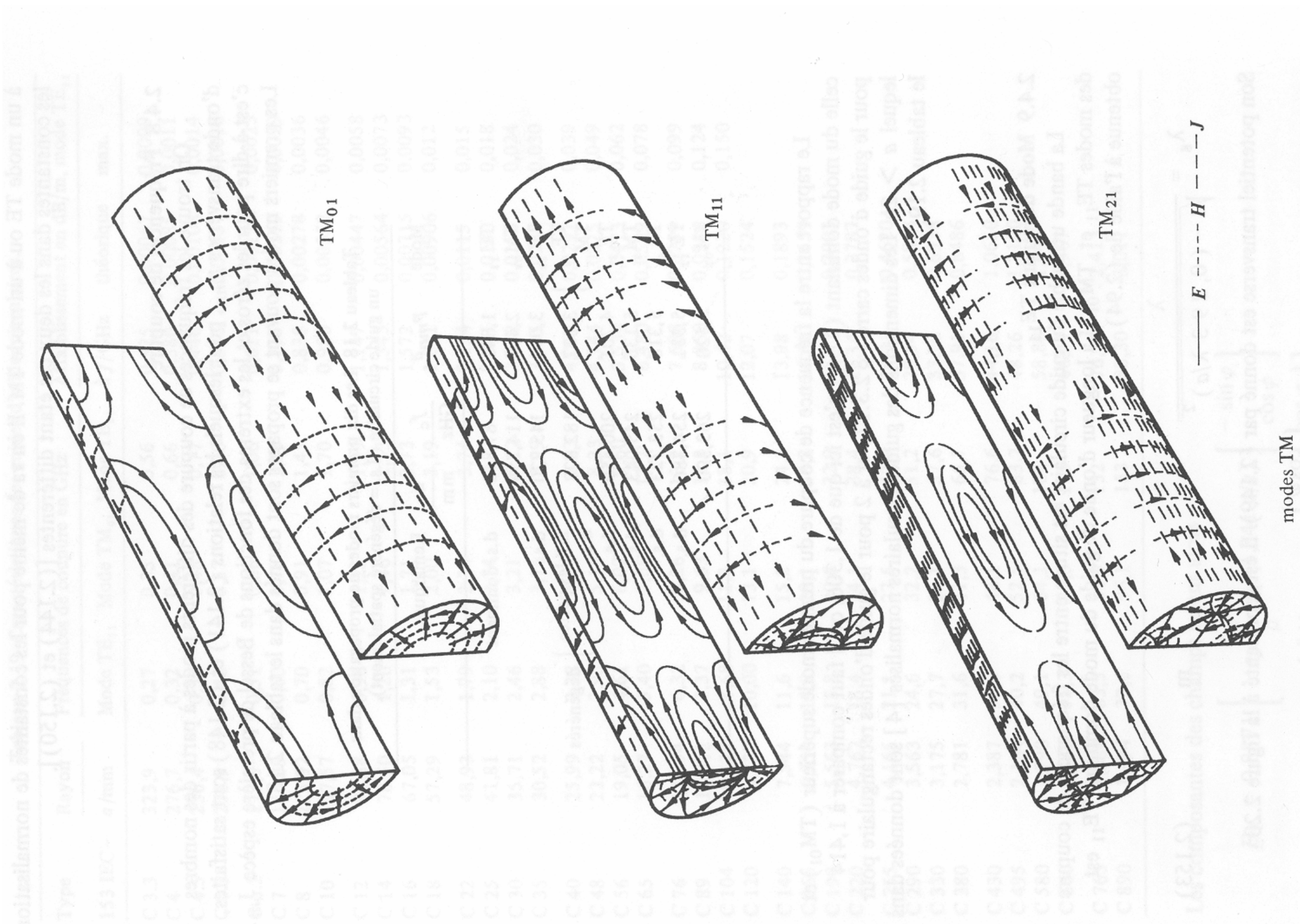
Microwaves and Antennas Group

TE Cavity modes

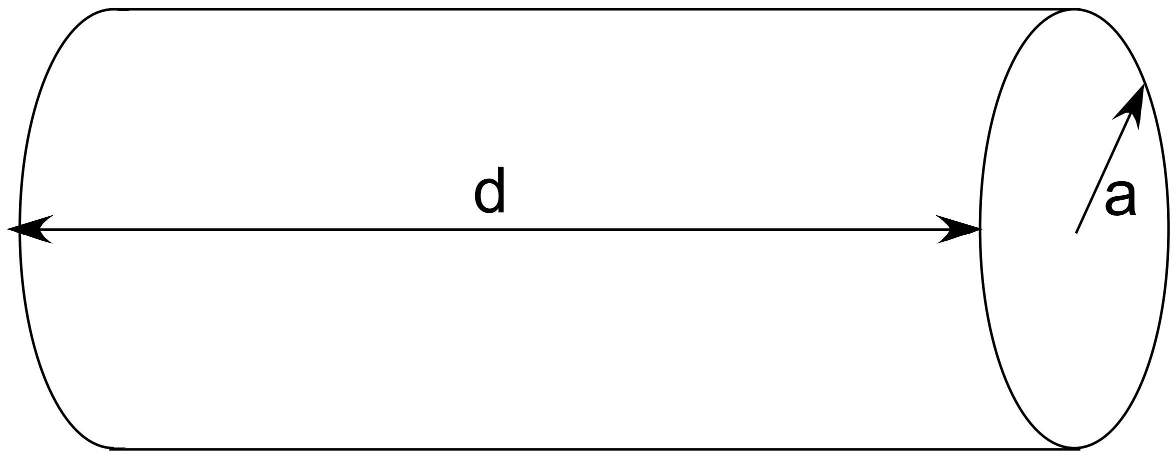


EPFL

TM Cavity modes



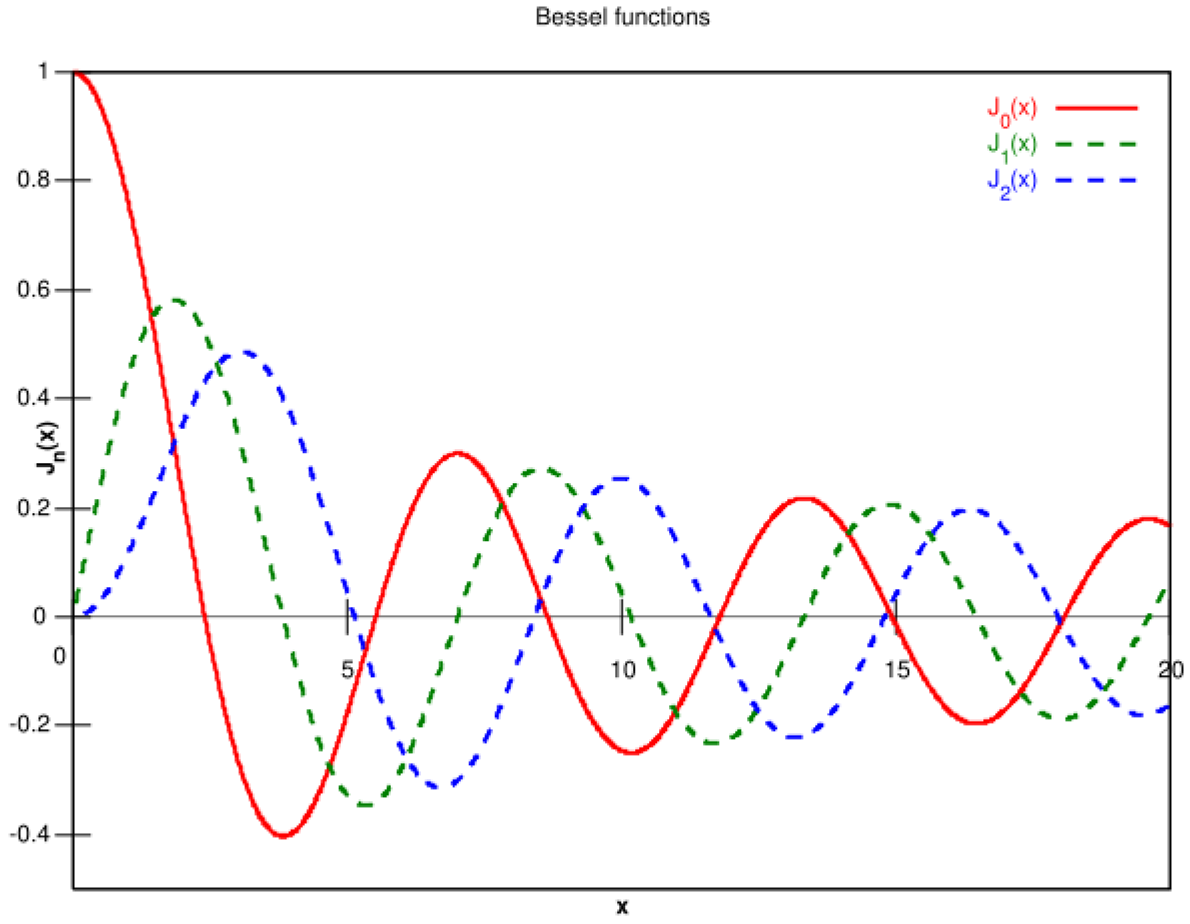
resonance of a cylindrical cavity



$$f_{mnl} = \sqrt{\frac{c_o}{2\pi}\left(\frac{x_{mn}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2}$$

x_{mn} is : the n_{th} zero of J'm (TEmn mode)
the n_{th} zero of Jm (TMmn mode)

Bessel function of the first kind (Jm)



zero of Jm (Bessel function of the first kind)

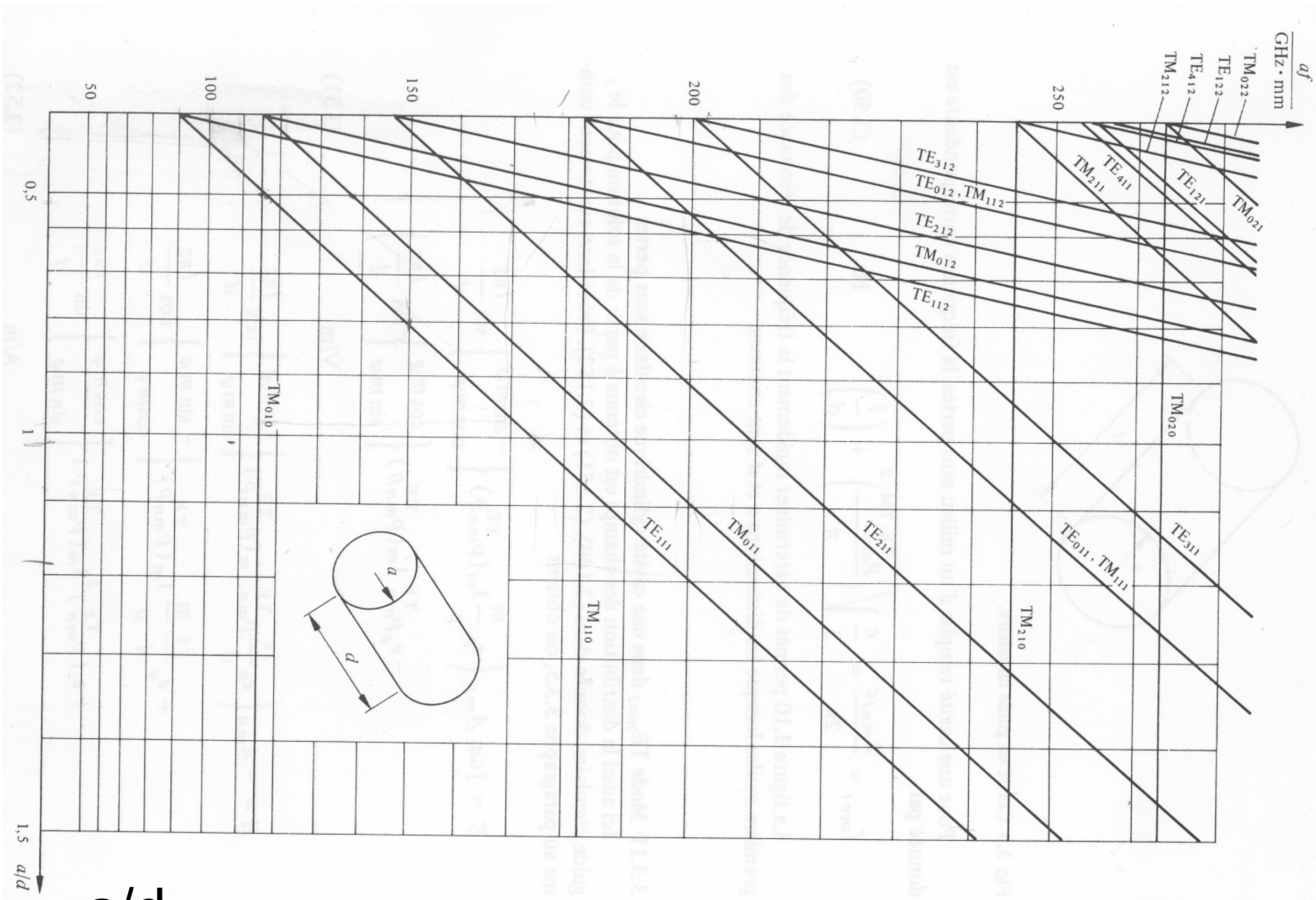
n	x_{n1}	x_{n2}	x_{n3}
0	2.405	5.520	8.654
1	3.832	7.016	10.174
2	5.135	8.417	11.620

zero of J'm (derivative of the Bessel function of first kind)

n	p'n1	p'n2	p'n3
0	3.832	7.016	10.174
1	1.841	5.331	8.536
2	3.054	6.706	9.970

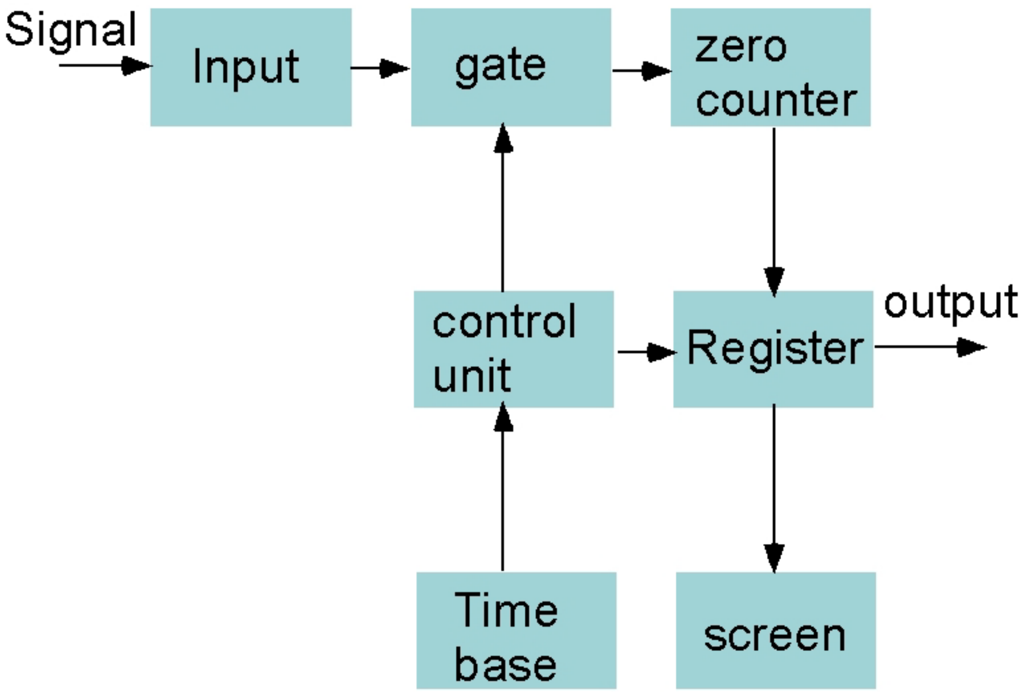
Resonance frequency in cylindrical cavities

af [GHzmm]



a/d

Frequency counters



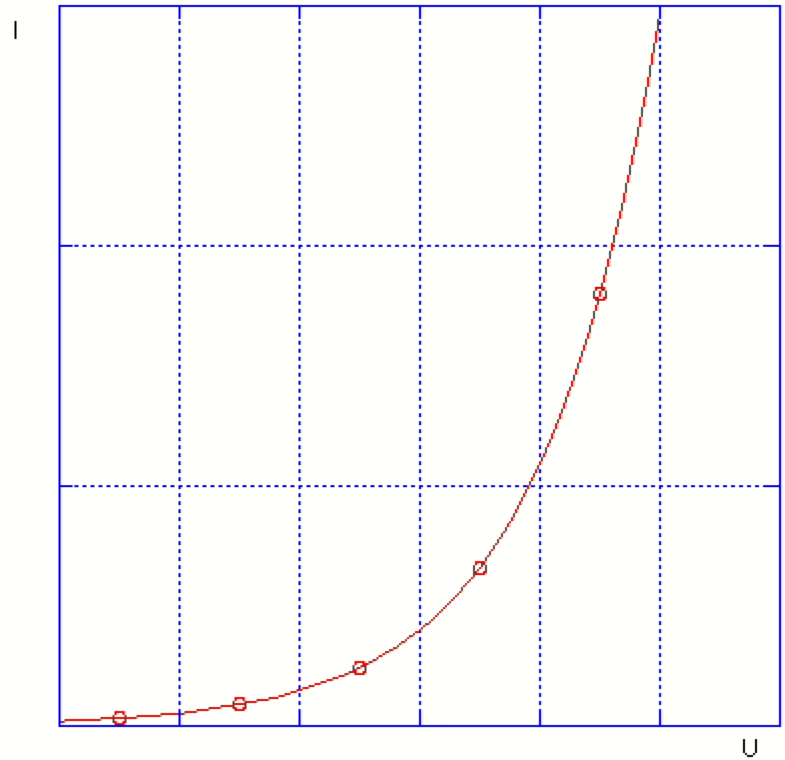
Frequency counters

- Periods are counted during a specified time
- A high precision time base is required
  - Quartz : 1 error in 10^8-10^9
  - Cesium : 1 error in 10^{13}
- The frequency being inversely proportional to the time, a counter can be used up to
  - 1 ns => 1GHz
- At higher frequencies :
  - Change of frequency (heterodyning)
  - Transfer oscillator
  - Frequency division

Frequency changements

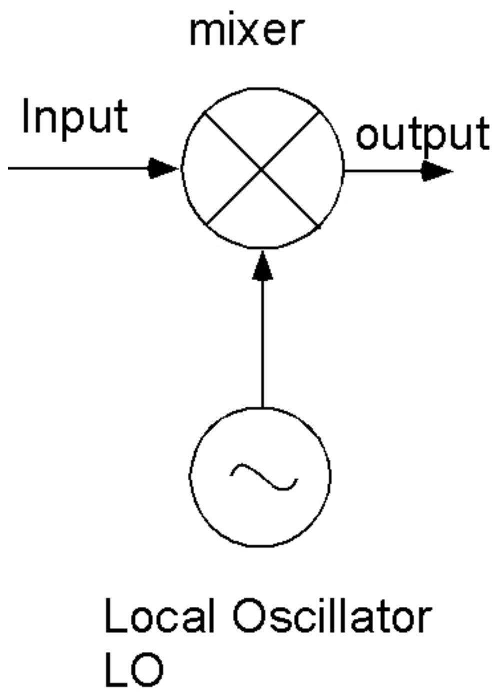
- Need of a non linear element
  – diode
  – transistor
- The non linearity will lead to intermodulation products
- Frequency mixing

Mixer : principle



$$I = I_s\left(e^{\alpha U} - 1\right) = I_s\left[\alpha U + \frac{(\alpha U)^2}{2!} + \frac{(\alpha U)^3}{3!} + \ldots\right]$$

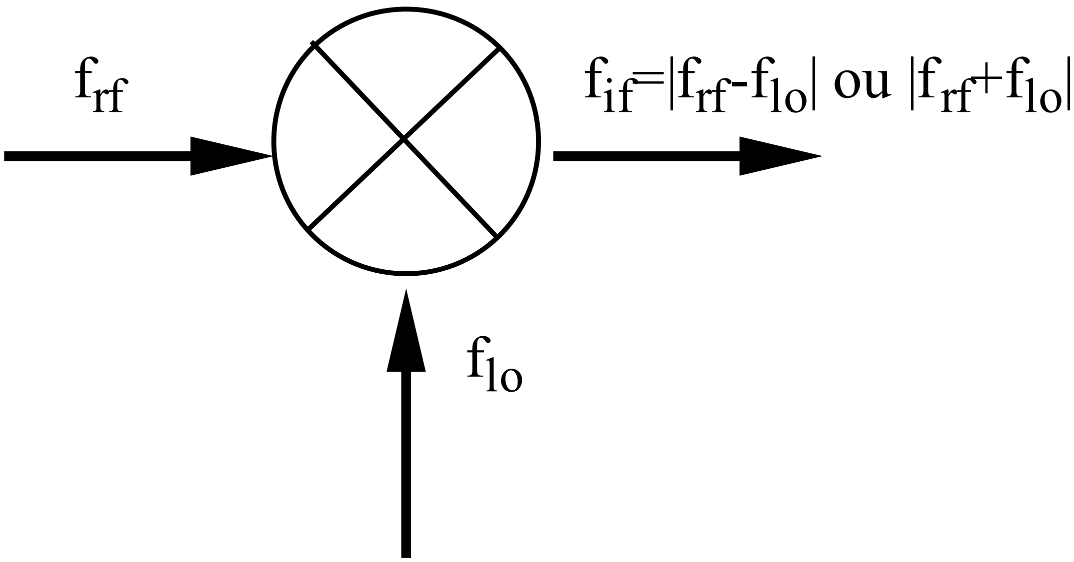
Mixer Principle



$$I(V) = I_s\left(e^{\alpha V} - 1\right) \qquad \alpha = \frac{q}{nKT}$$

$$v(t) = V_1 \sin \omega_1 t + V_2 \sin \omega_2 t$$

Mixer Principle

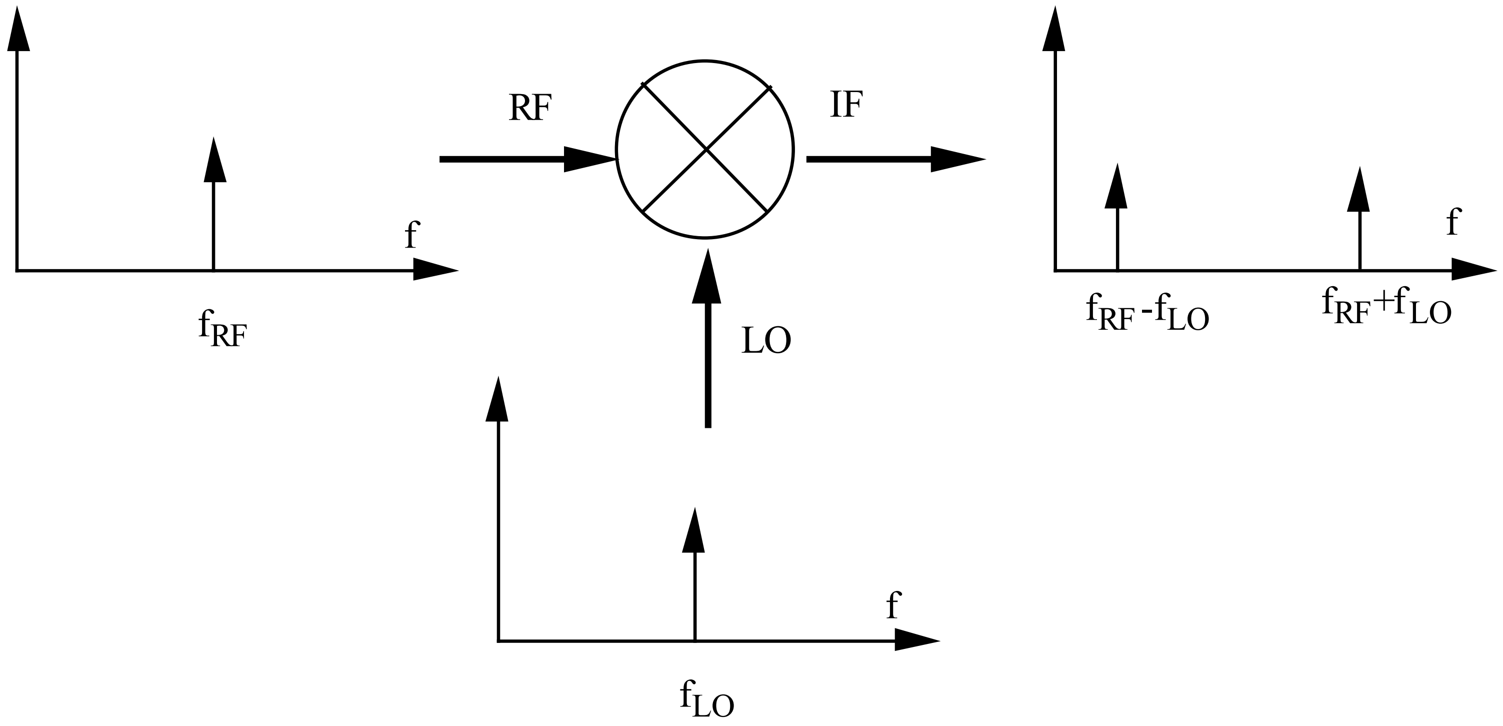


$$i(t) = I_s\left[\alpha\left(V_1 \sin\omega_1 t + V_2 \sin\omega_2 t\right) + \frac{\alpha^2}{2}\left(V_1 \sin\omega_1 t + V_2 \sin\omega_2 t\right)^2 + \ldots\right]$$

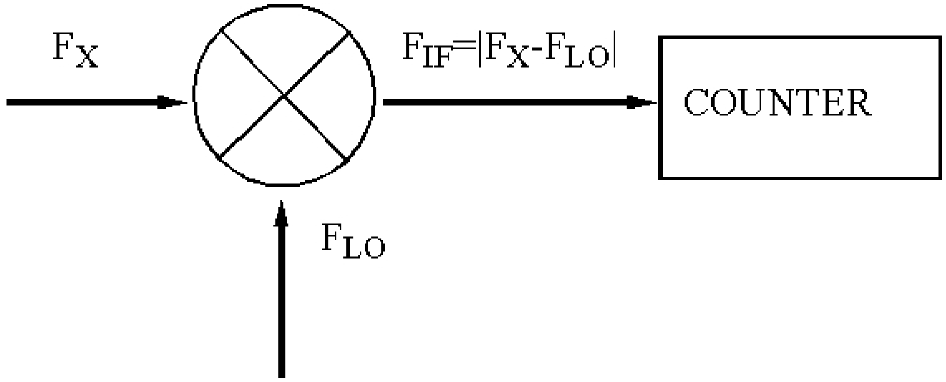
$$= I_s\alpha\left[V_1 \sin\omega_1 t + V_2 \sin\omega_2 t\right] +$$

$$I_s\frac{\alpha^2}{2}\left[V_1^2 \sin^2\omega_1 t + V_2^2 \sin^2\omega 2t + V_1V_2\cos(\omega_1-\omega_2)t - V_1V_2\cos(\omega_1+\omega_2)t + \ldots\right]$$

Mixer Principle

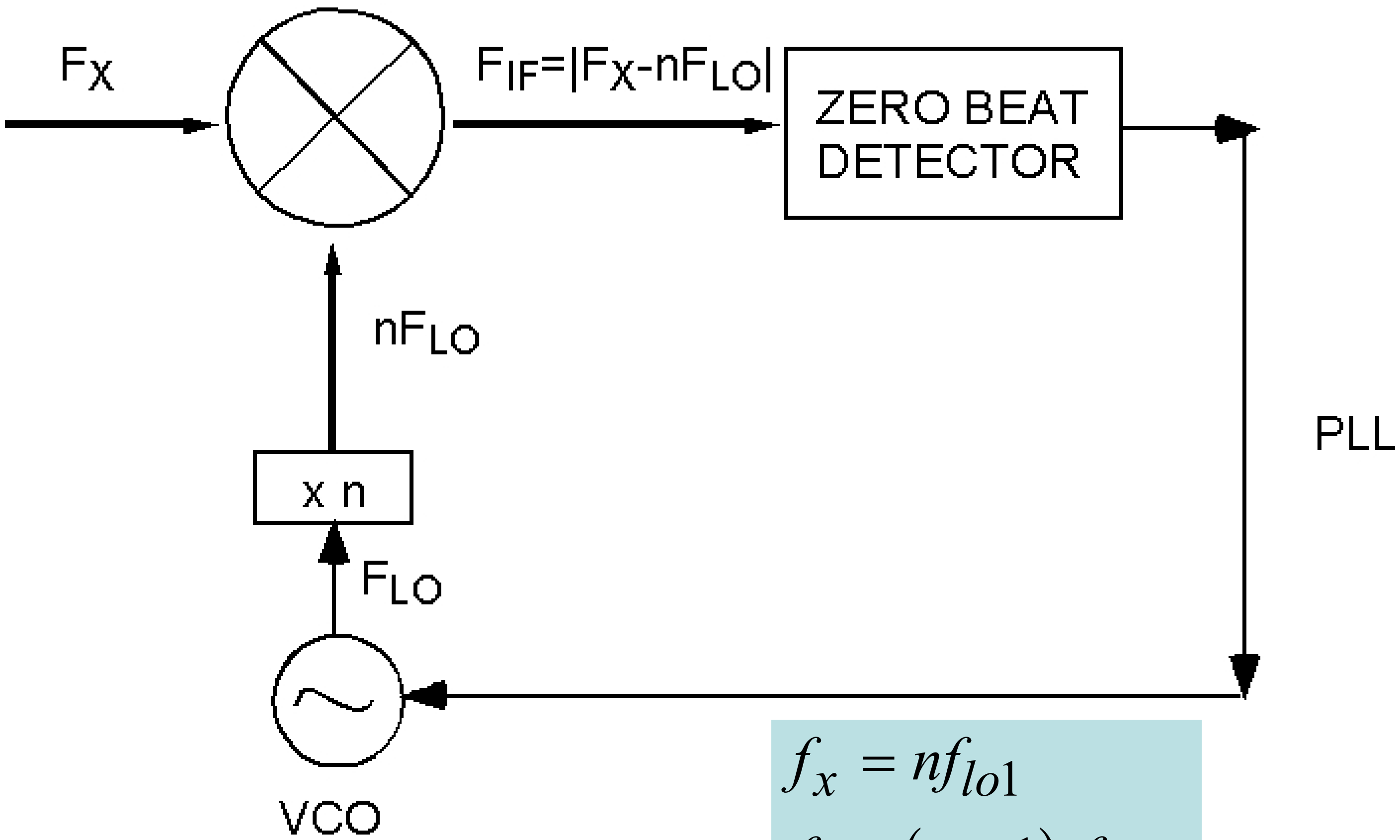


Heterodyne counter



- Sign ambiguity
- 2 measure-ments are necessary

Transfer oscillator

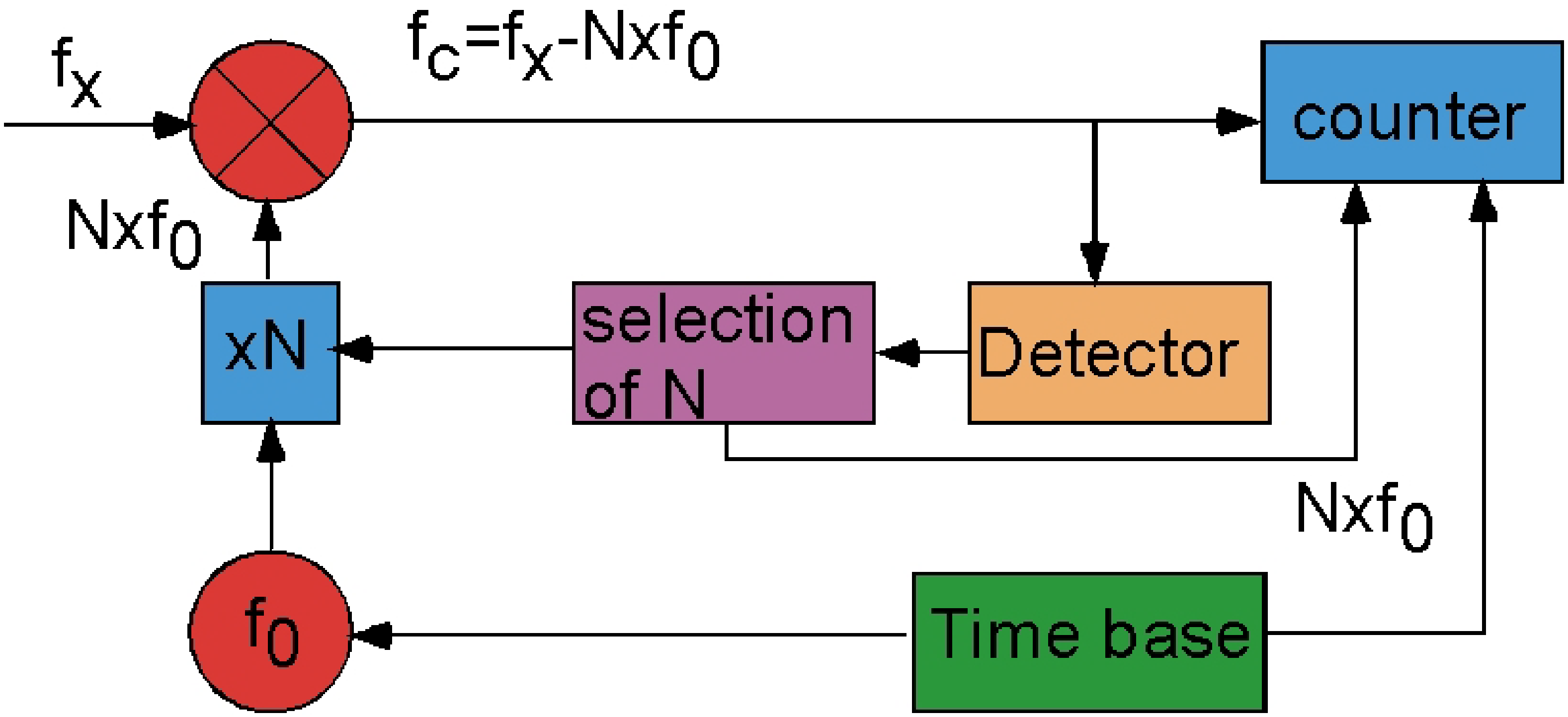


$$f_x = nf_{lo1}$$

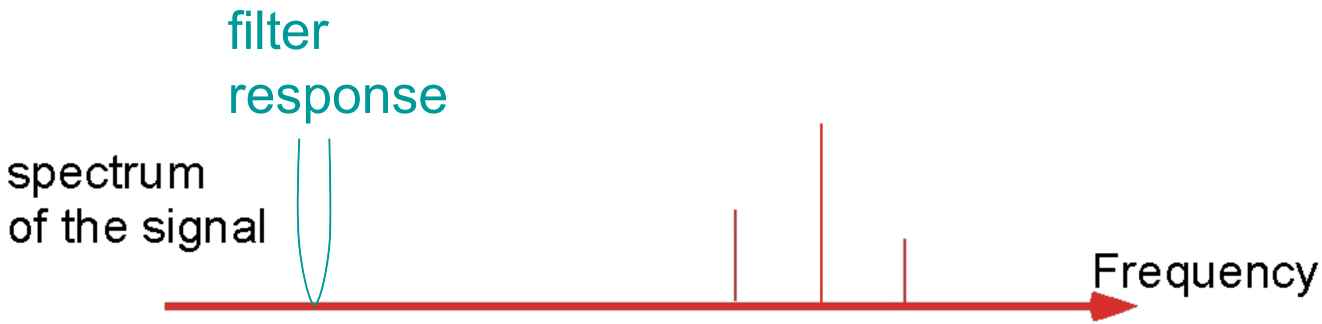
$$fx = (n-1)\,f_{lo2}$$

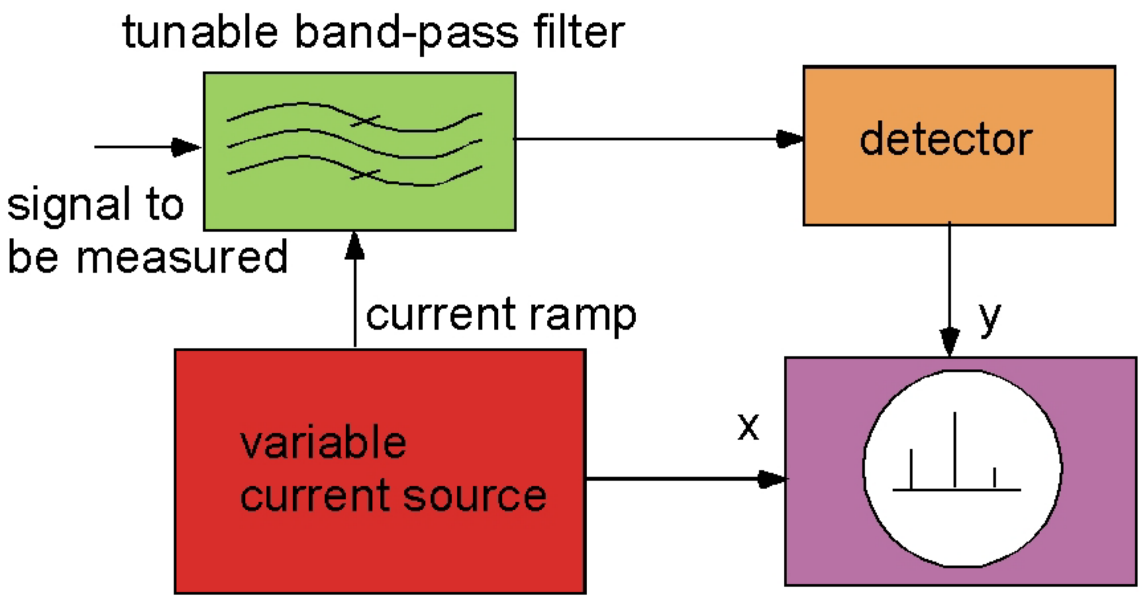
$$n = \frac{f_{lo2}}{(f_{lo1} - f_{lo2})}$$

"Modern" frequency counter



Spectrum analysor : the principle





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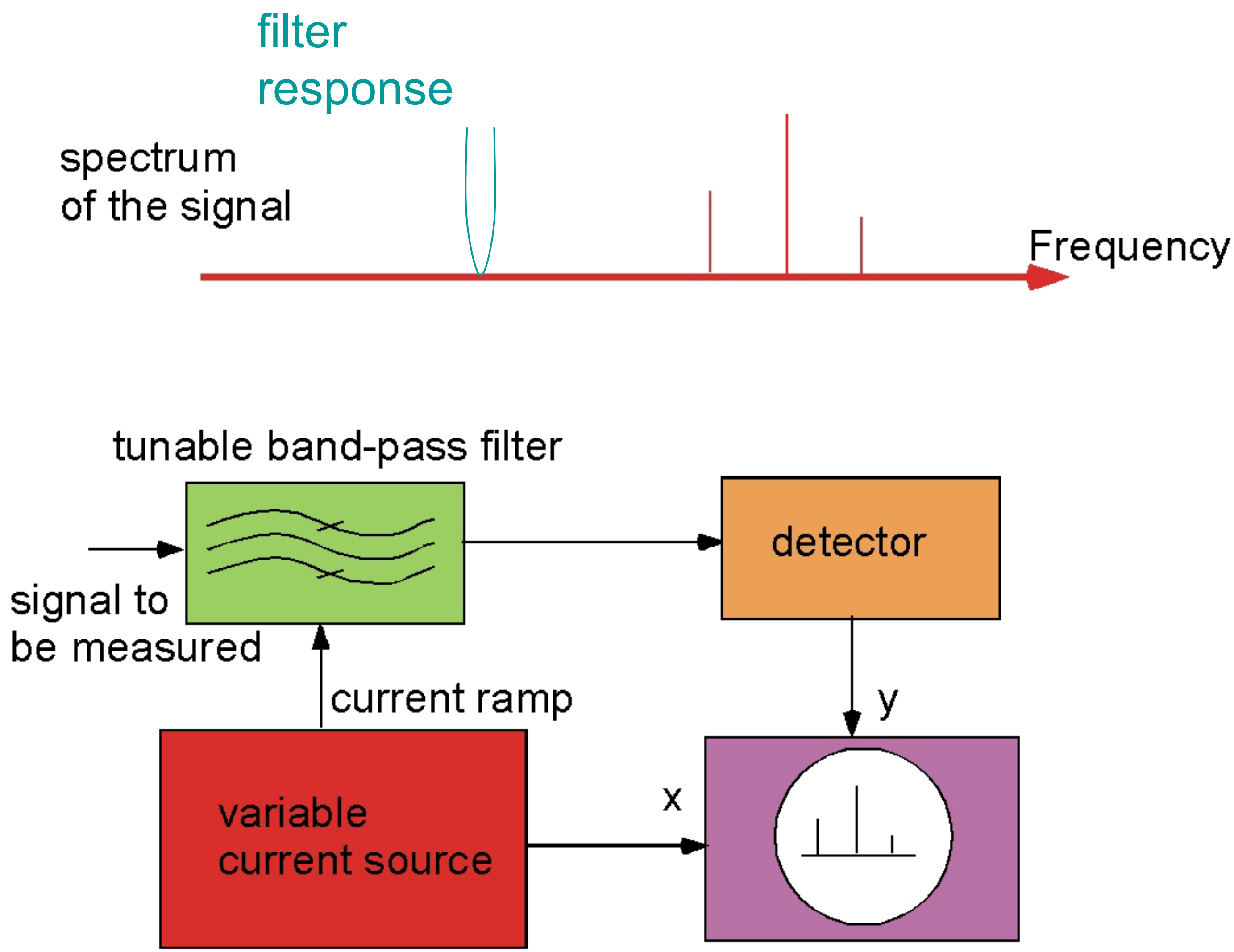
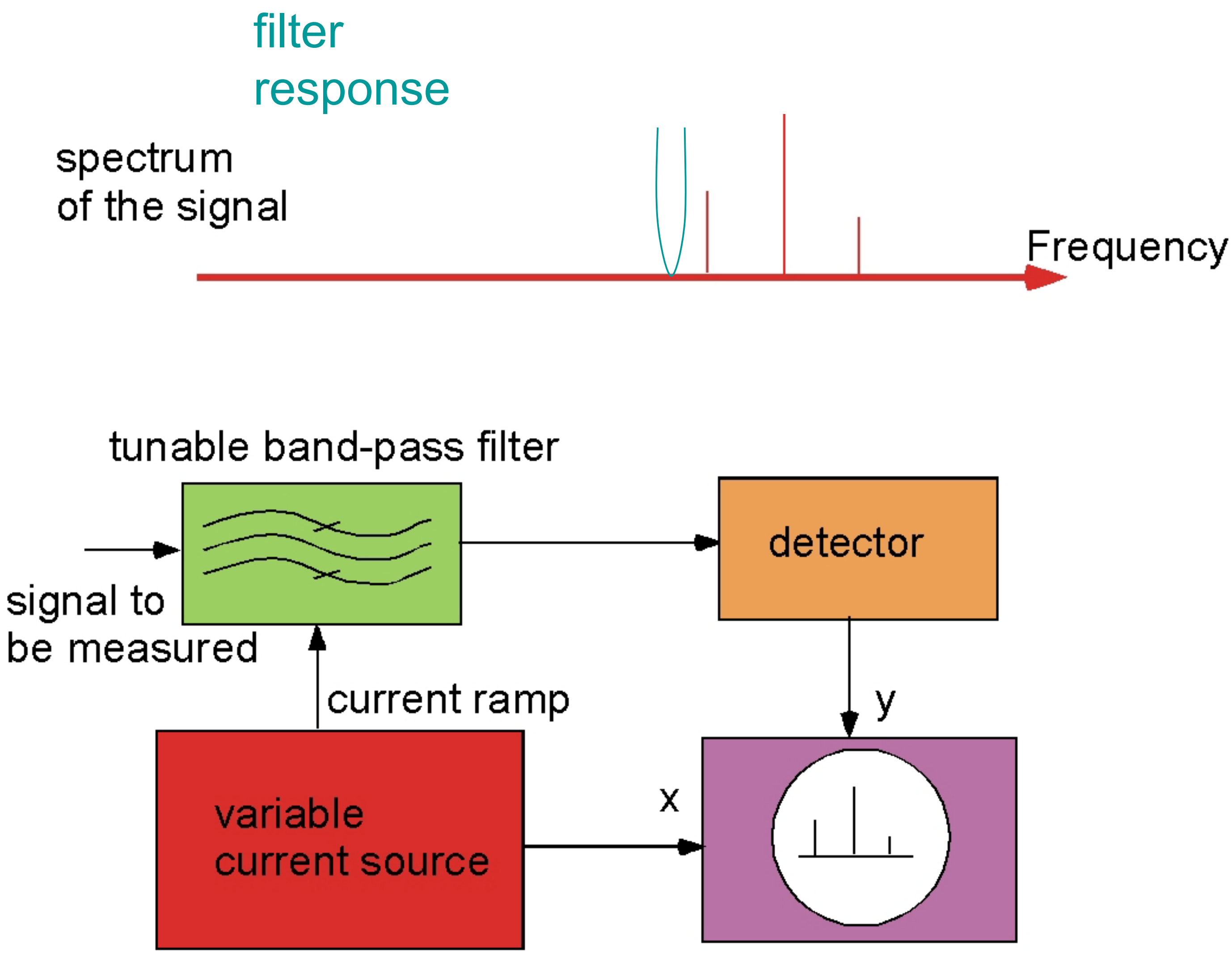


Spectrum analysor : the principle



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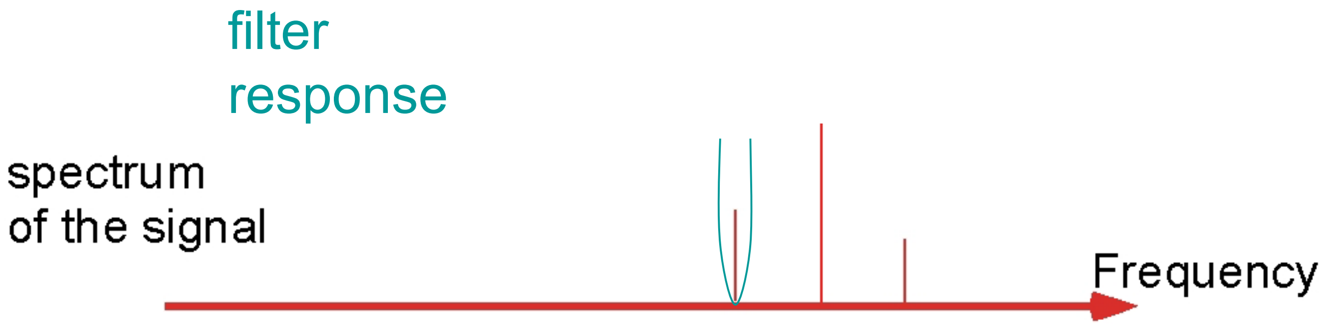

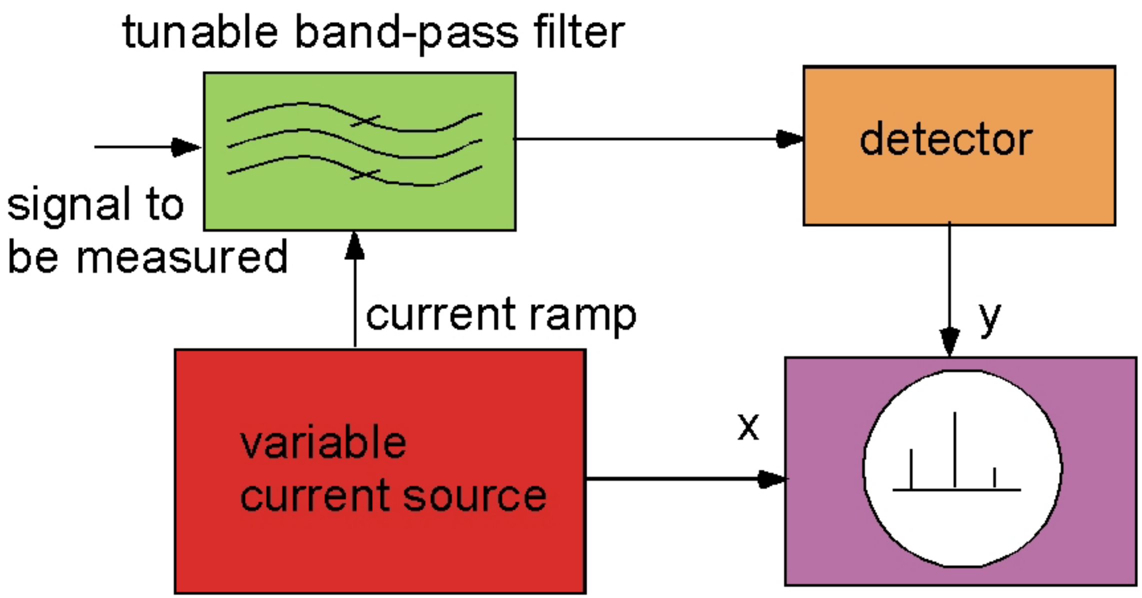

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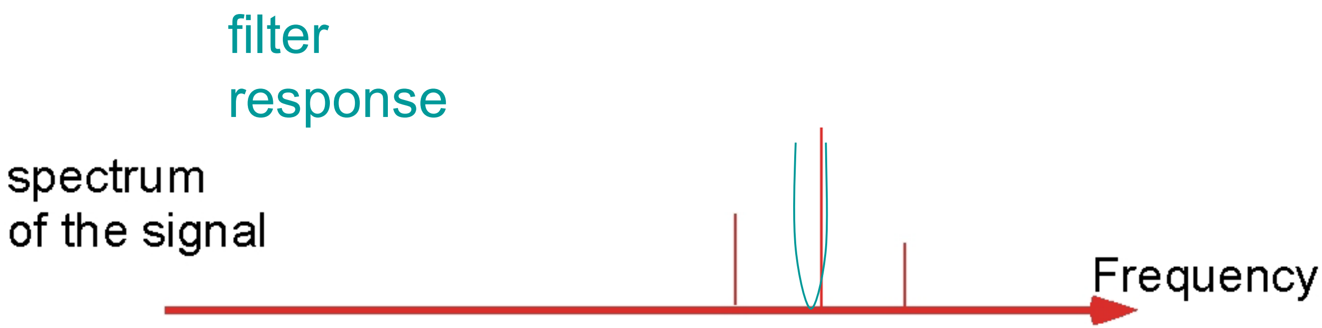

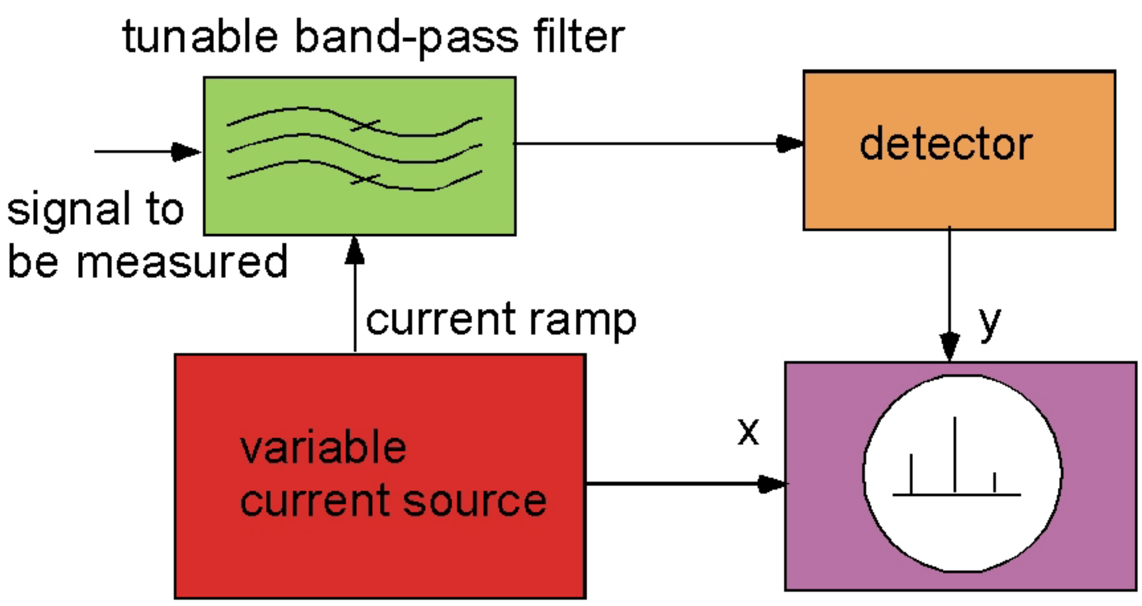

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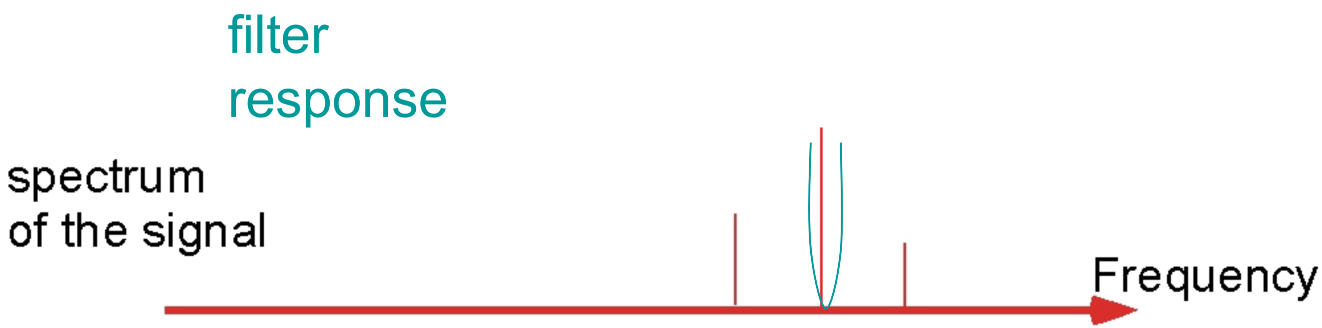

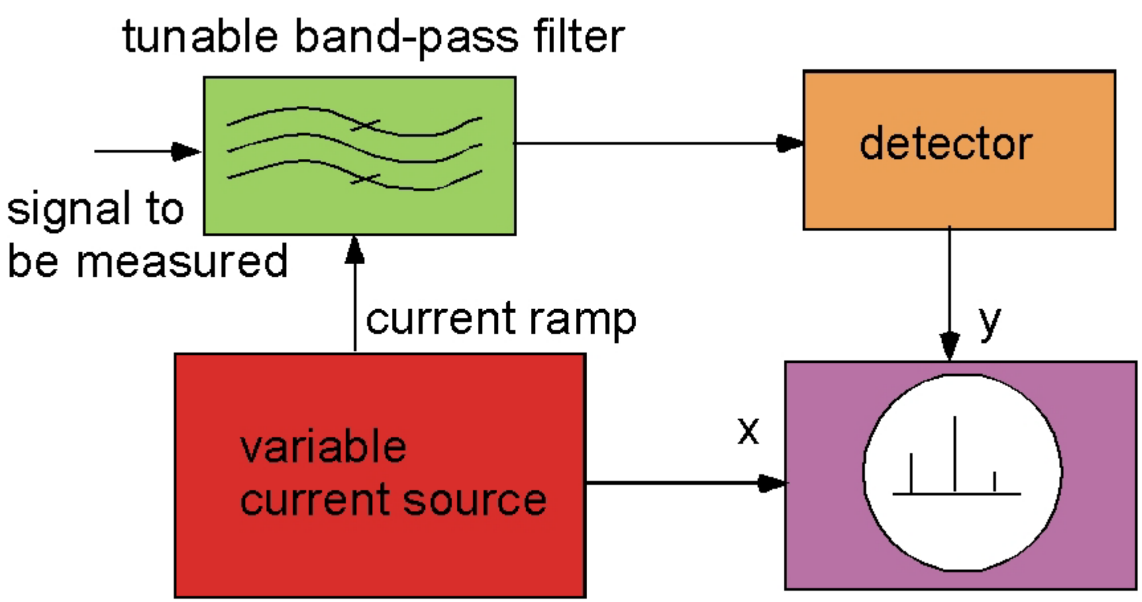

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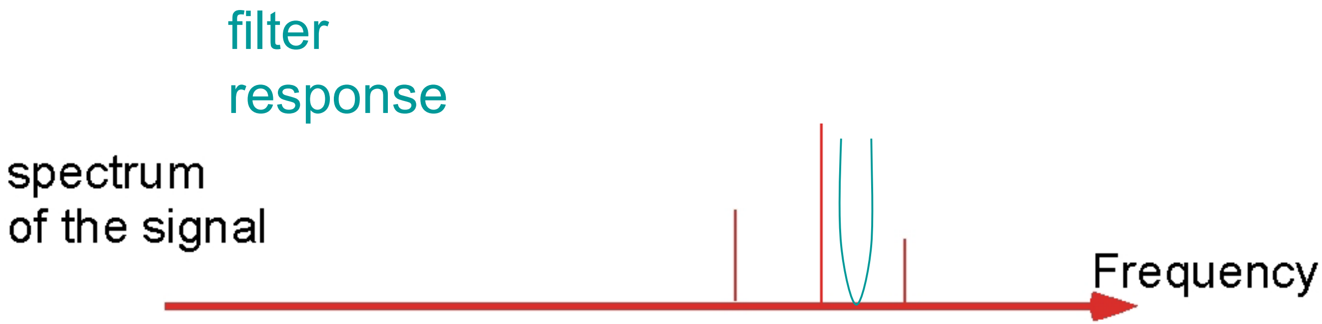

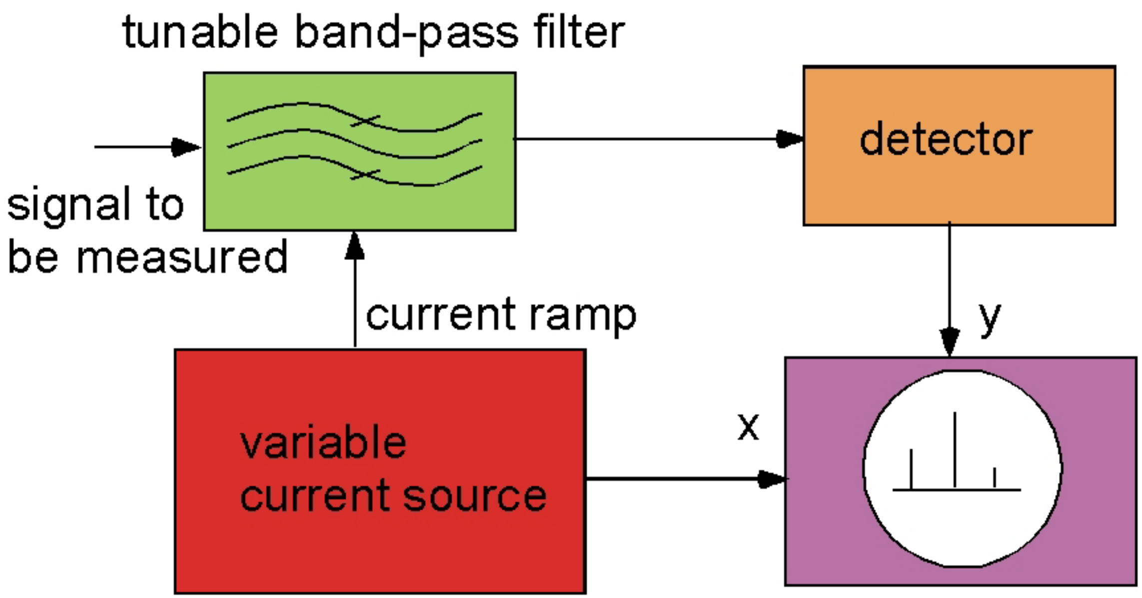

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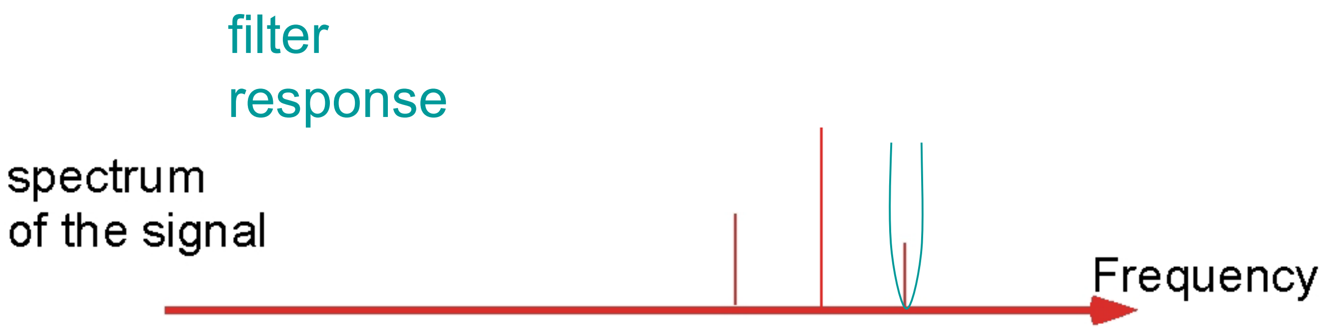
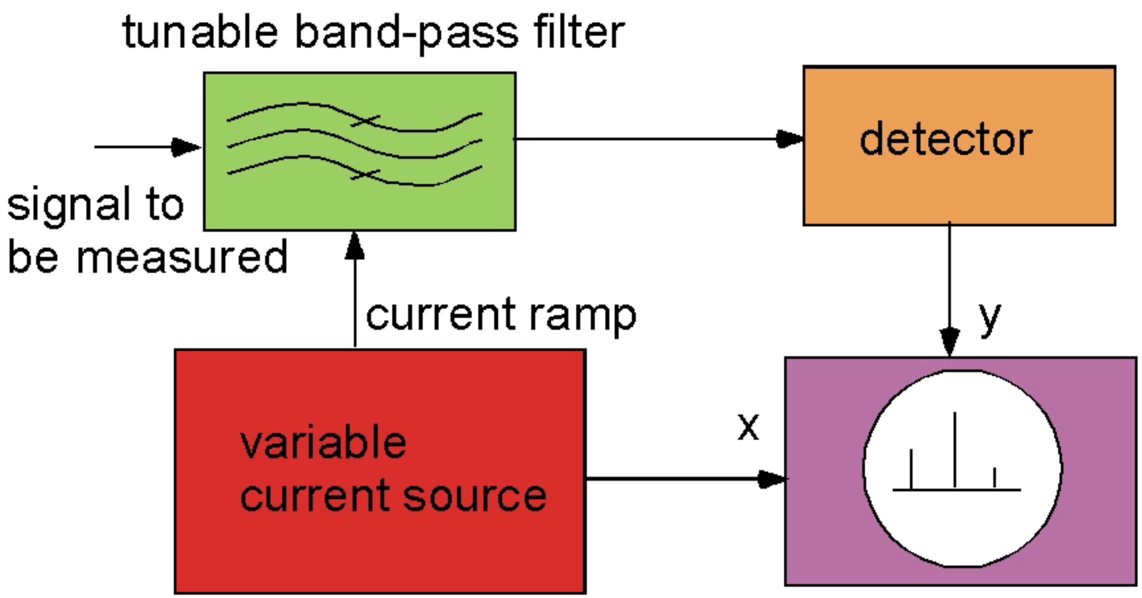
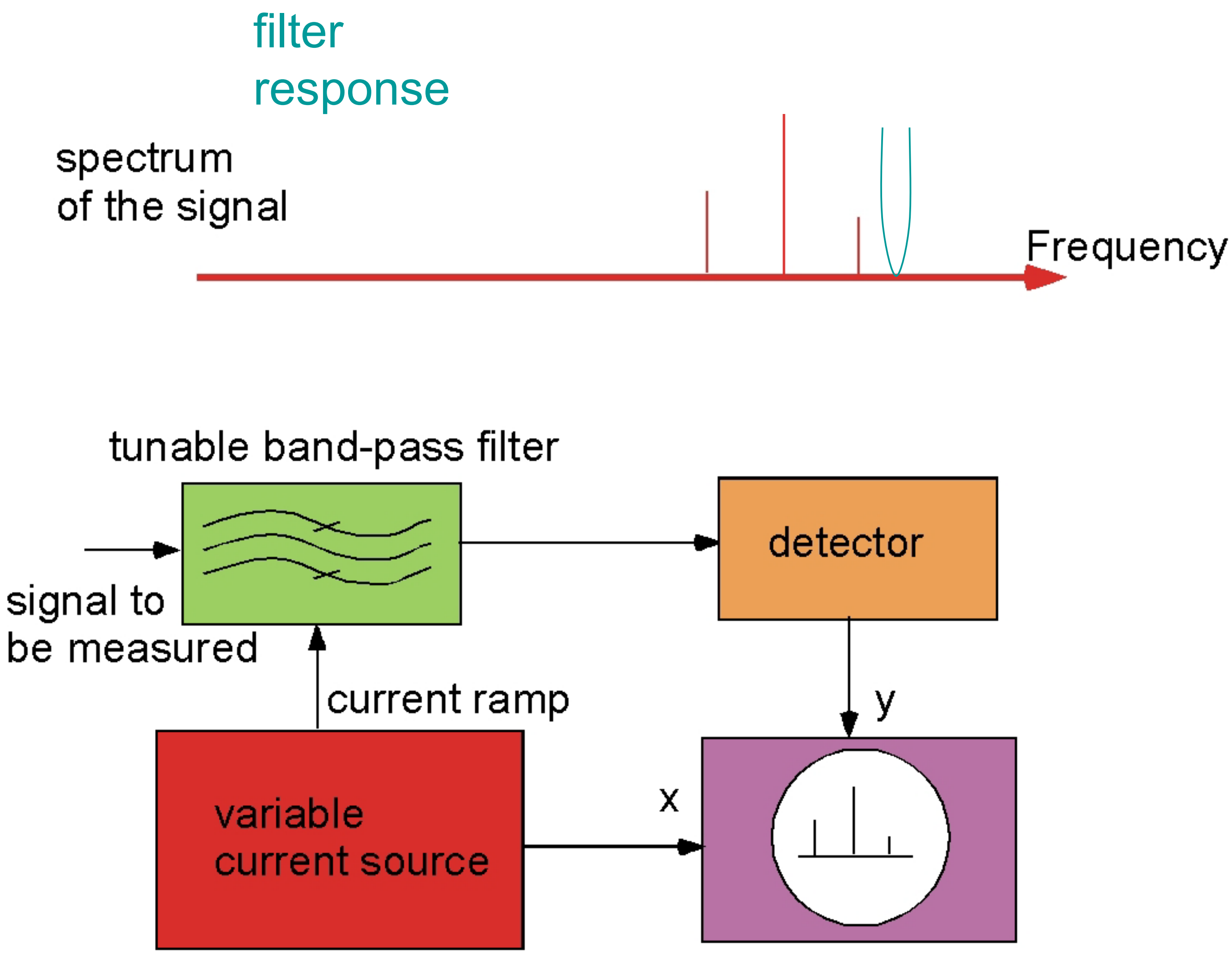
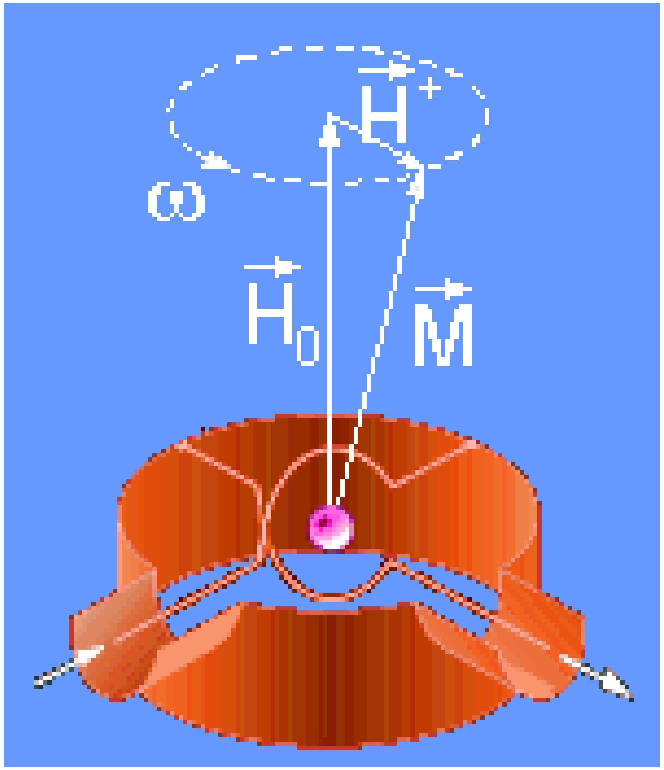




Spectrum analysor : the principle



The YIG filter



Typical Yig filter response

500MHz to 18GHz YIG Filters

STANDARD OCTAVE BANDS[6]

TYPE[1,8]	OMNIYIG MODEL No.[3]	FREQ RANGE (GHz)	INSERTION LOSS (dB)	BANDWIDTH at 3dB[4] (MHz)	OFF RESONANCE SPURIOUS MINIMUM (dB)	COMBINED PASSBAND RIPPLE & SPUR MAX (dB)	FREQ DRIFT 0° TO 60°C (MHz)	OFF RESONANCE ISOLATION MINIMUM (dB)	DIMENSIONS CUBED (INCHES)	WEIGHT (oz)	FREQ TRACKING BETWEEN CHANNELS (MHz)	DRAWING NUMBER
2-STAGE	P102	0.5-1.0	4.0	17-30	30	1.0	5	45	1.4	9.8	-	01
	L102	1.0-2.0	3.5	24-35	30	1.5	5	45	1.4	9.8	-	01
	S102	2.0-4.0	2.5	25-40	25	1.5	5	50	1.4	9.8	-	01
	C102	4.0-8.0	2.5	25-40	25	1.5	9	50	1.4	9.8	-	01
	X102	8.0-12.4	2.5	25-40	25	1.5	10	50	1.69	17.5	-	02
	Ku102	12.4-18.0	2.5	30-45	25	1.5	12	45	1.69	17.5	-	02
3-STAGE	P103	0.5-1.0	5.0	14-25	35	1.0	5	70	1.4	9.8	-	01
	L103	1.0-2.0	3.5	20-35	35	1.5	5	70	1.4	9.8	-	01
	S103	2.0-4.0	3.0	20-35	30	1.5	5	70	1.4	9.8	-	01
	C103	4.0-8.0	3.0	25-40	30	1.5	9	70	1.4	9.8	-	01
	X103	8.0-12.4	3.0	25-40	30	1.5	10	70	1.69	17.5	-	02
	Ku103	12.4-18.0	3.5	30-45	30	1.5	12	65	1.69	17.5	-	02
4-STAGE	P104	0.5-1.0	6.0	12-23	38	1.0	5	80	1.4	9.8	-	01
	L104	1.0-2.0	4.5	20-35	38	1.5	5	80	1.4	9.8	-	01
	S104	2.0-4.0	4.0	20-35	38	1.5	5	80	1.4	9.8	-	01
	C104	4.0-8.0	4.0	25-40	38	1.5	9	80	1.4	9.8	-	01
	X104	8.0-12.4	4.0	25-40	38	1.5	10	80	1.69	17.5	-	02
	Ku104	12.4-18.0	4.0	28-45	38	1.5	12	80	1.69	17.5	-	02
DUAL 2-STAGE (Per Channel)	P1022	0.5-1.0	3.5	17-30	30	1.0	5	45	1.4	9.8	5	03
	L1022	1.0-2.0	3.5	24-35	30	1.5	5	45	1.4	9.8	6	03
	S1022	2.0-4.0	2.5	25-40	25	1.5	5	50	1.4	9.8	6	03
	C1022	4.0-8.0	2.5	25-40	25	1.5	9	50	1.4	9.8	7	03
	X1022	8.0-12.4	2.5	25-40	25	1.5	10	50	1.69	17.5	8	04
	Ku1022	12.4-18.0	2.5	30-45	25	1.5	12	45	1.69	17.5	7	04

STANDARD MULTI-OCTAVE BANDS[6]

2-STAGE	M102[5]	1.0-12.4	5.0	25-60	25	2.5	13	50	1.69	17.5	-	02
3-STAGE	M103[5]	1.0-12.4	6.5	25-60	33	2.5	13	70	1.69	17.5	-	02
4-STAGE	M104B			25-60		2.5	13	80	1.69	17.5	-	02
DUAL 2-ST.	M1022			25-55		2.0	13	50	1.69	17.5	10	04
3-STAGE	M203[5]			25-70		2.5	13	70	1.69	17.5	-	02
2-STAGE	M1611			25-65		2.5	13	52	1.69	17.5	-	02
4-STAGE	M1612			25-65		2.5	13	80	1.69			

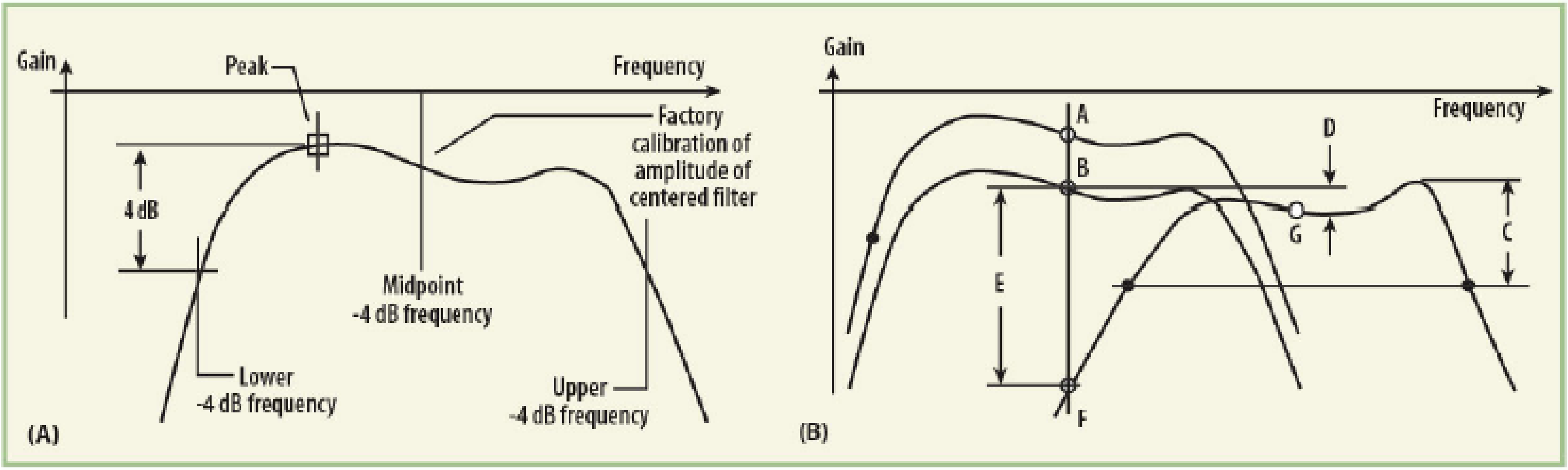
Typical Yig filter response

STANDARD MULTI-OCTAVE BANDS[6]

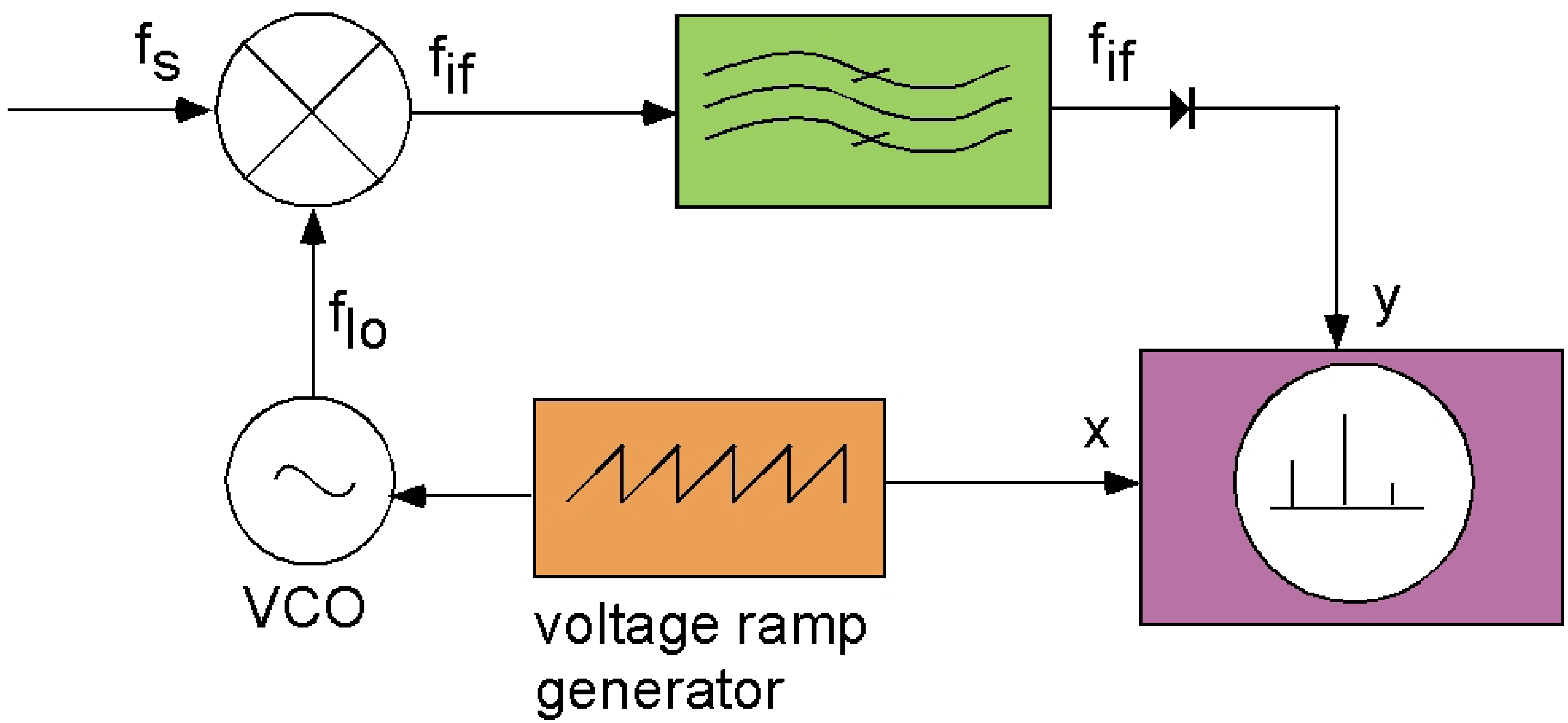
2-STAGE	M102[5]	1.0-12.4	5.0	25-60
3-STAGE	M103[5]	1.0-12.4	6.5	25-60
4-STAGE	M104B			25-60
DUAL 2-ST.	M1022			25-55
3-STAGE	M203[5]			25-70
2-STAGE	M1611			25-65
4-STAGE	M1612			25-65

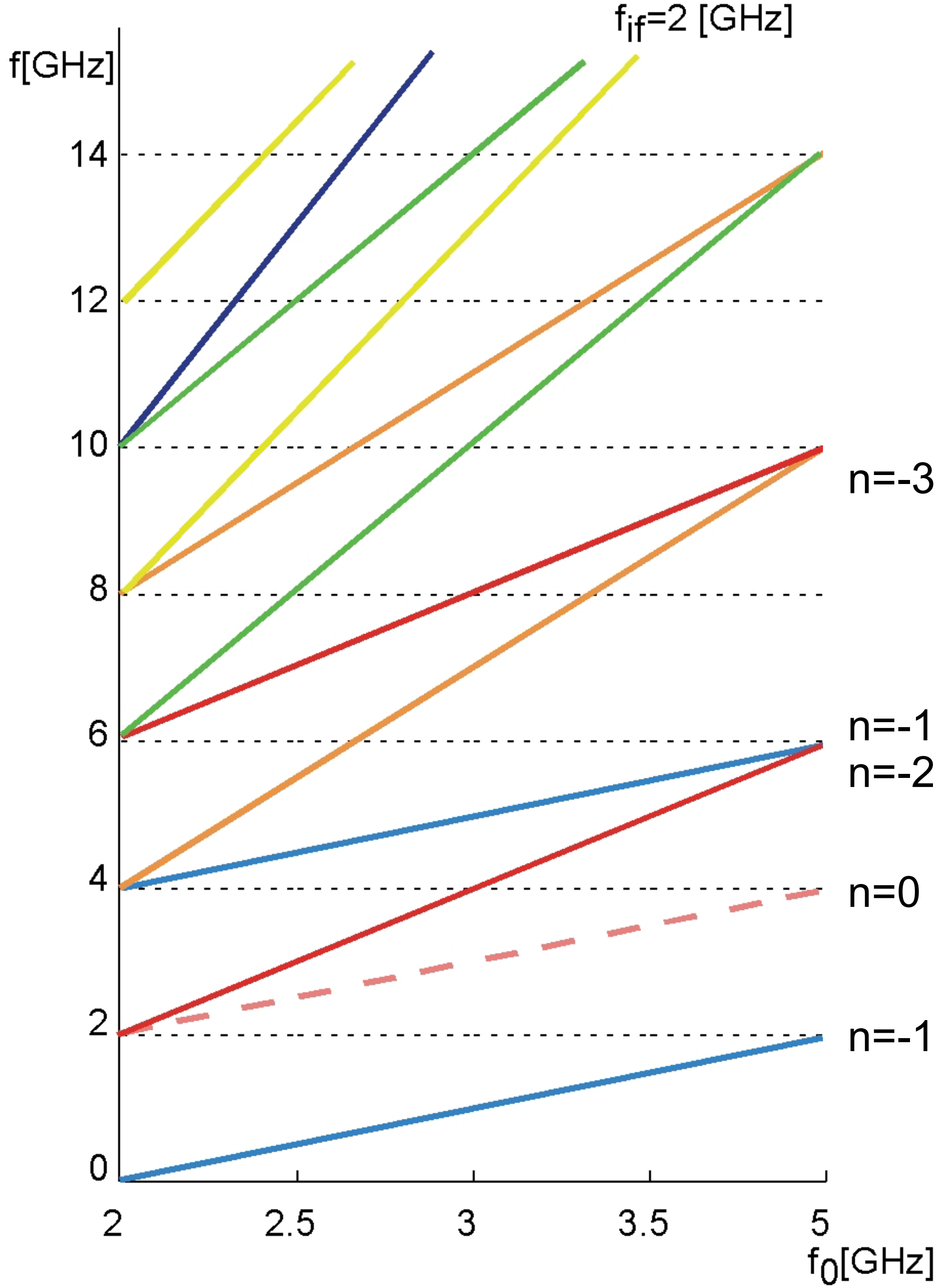
source : Omniyig filters : http://www.omniyig.com/

Typical Yig filter response



Solution : fixed filter



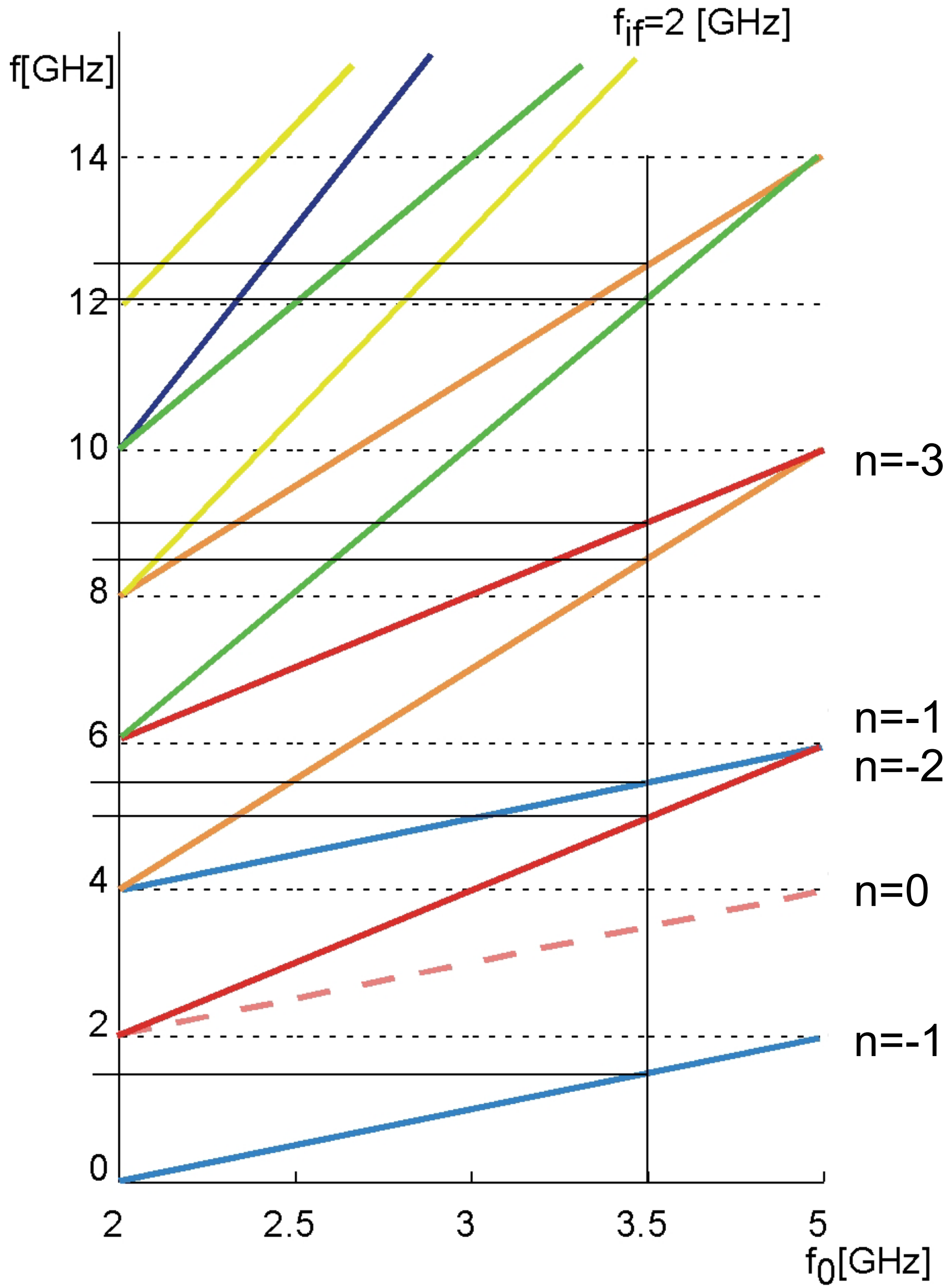


$$\left|f + nf_0\right| = f_{if}$$

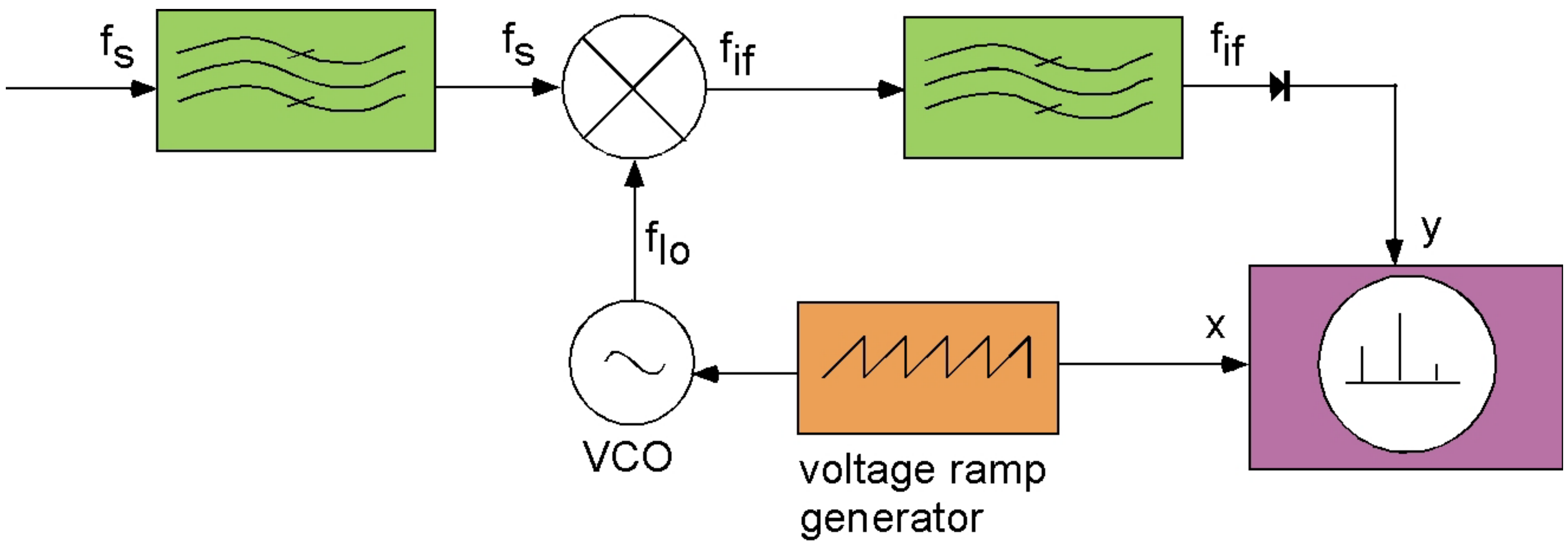
Spectrum analyser : problems

- ambiguity
- spurious images

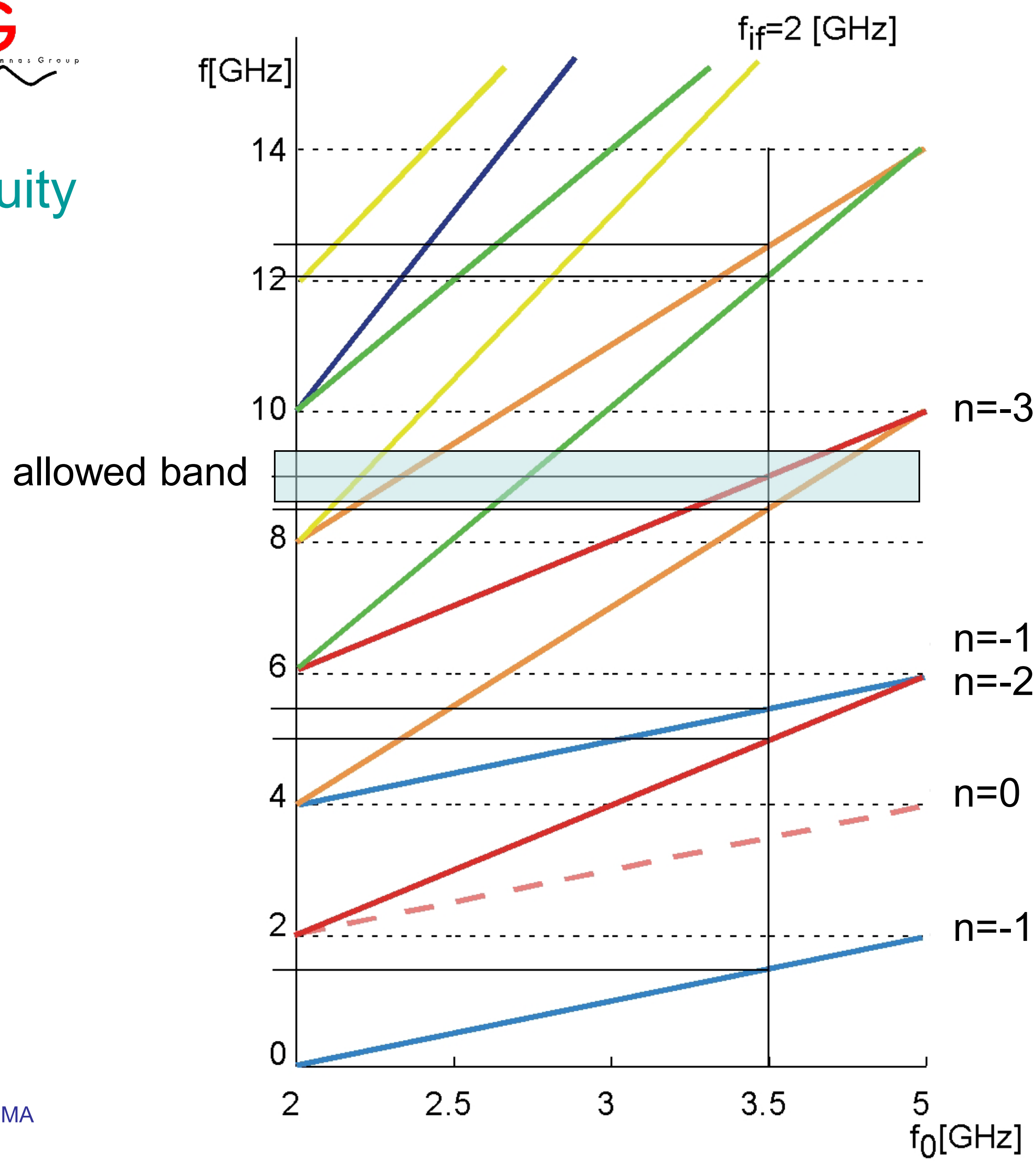
ambiguity



Ambiguity : solution

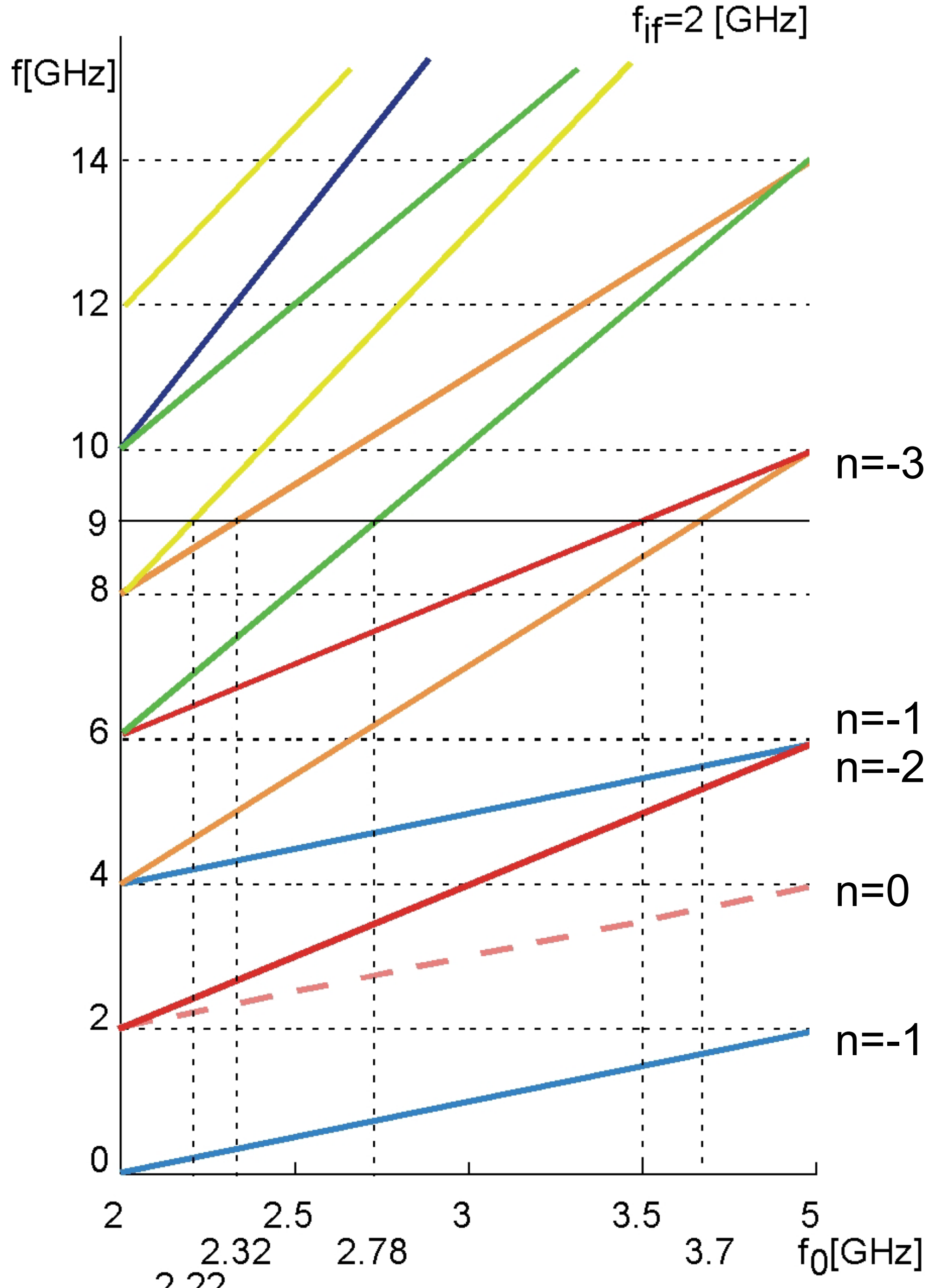


ambiguity

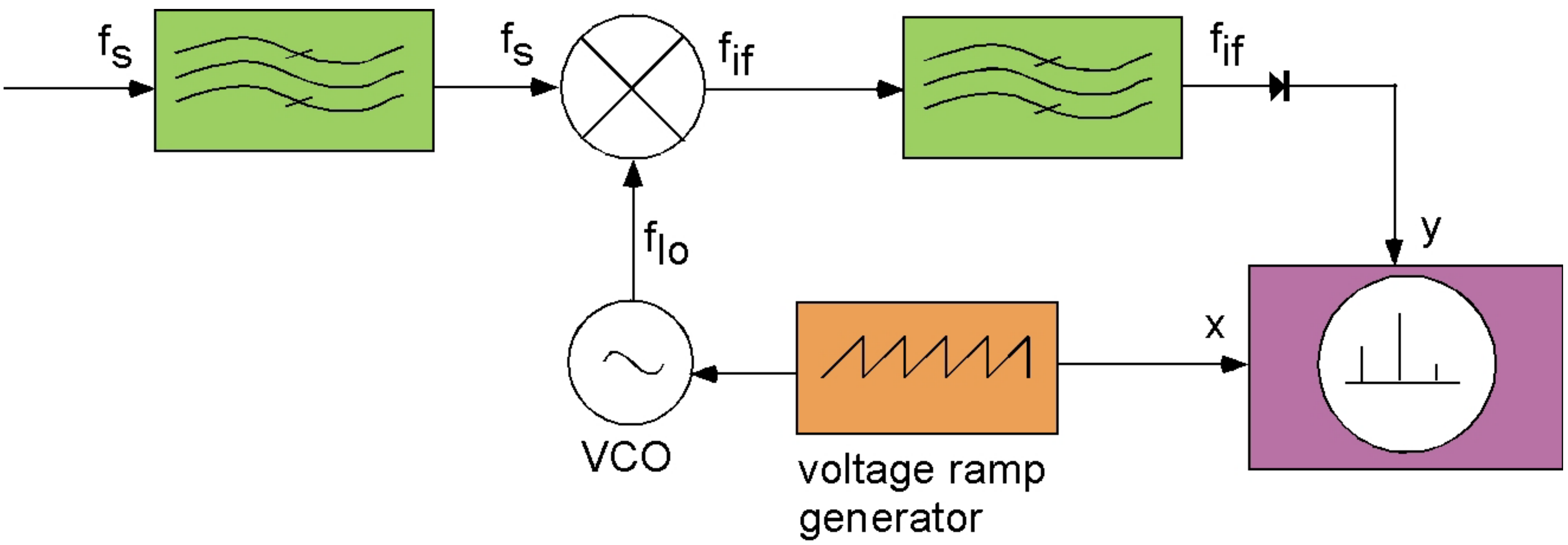


f_{if}=2 [GHz]
f[GHz]
14
12
10
8
6
4
2
0
allowed band
n=-3
n=-1
n=-2
n=0
n=-1
2
2.5
3
3.5
5
f_0[GHz]

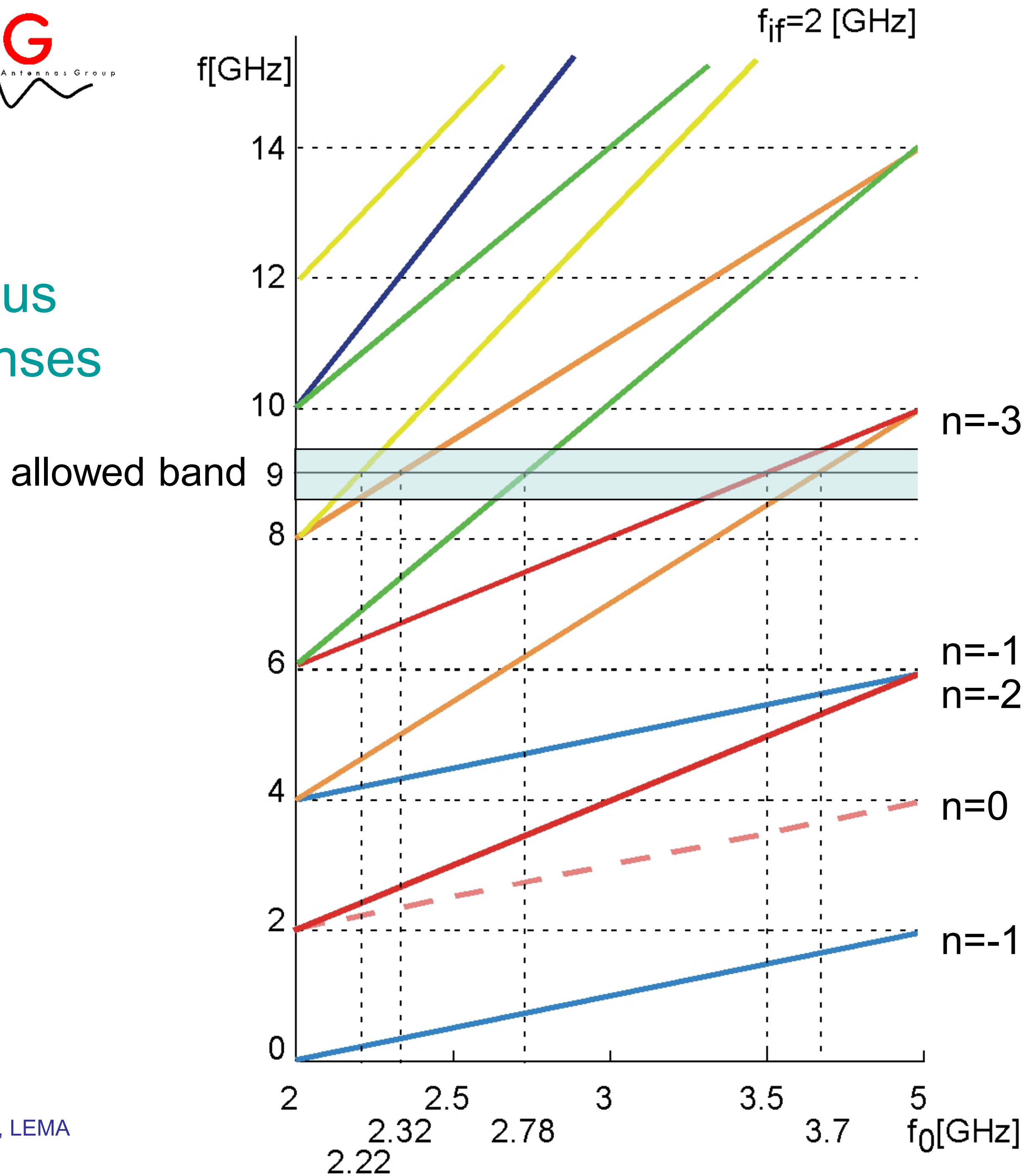
spurious responses



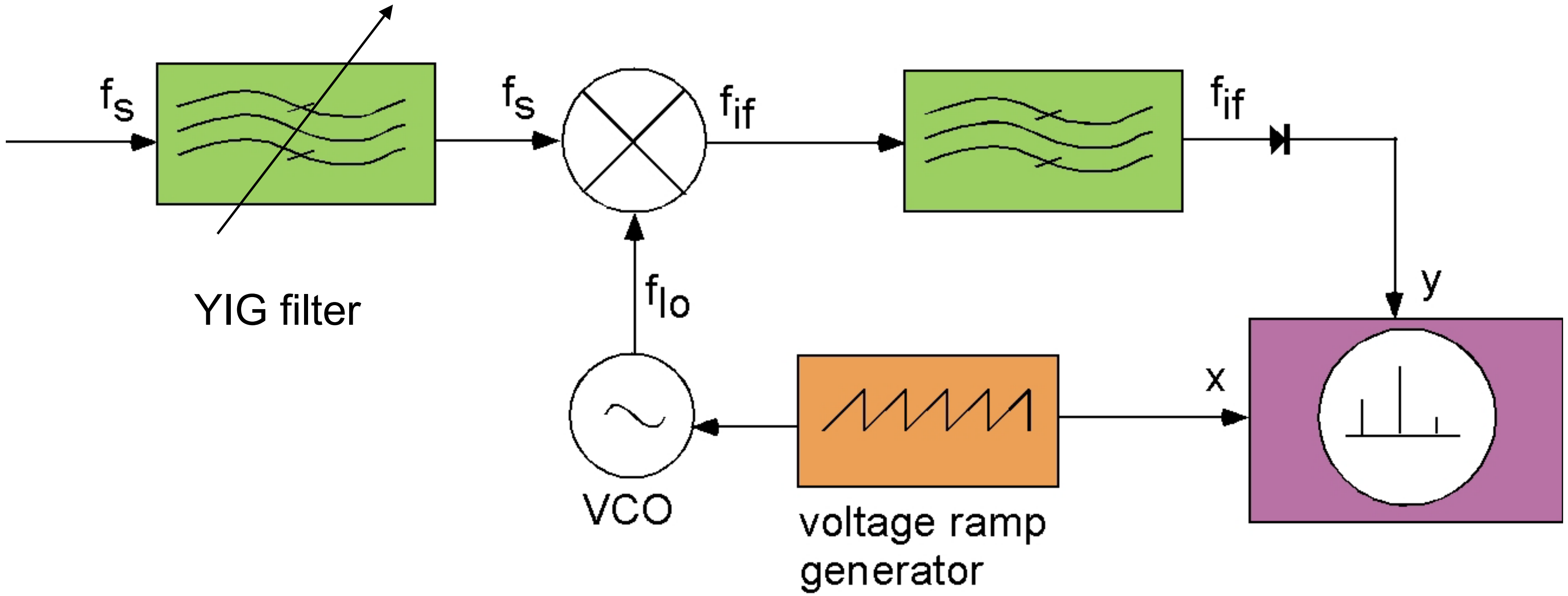
Spurious responses : pre-filter is not a solution



spurious responses



Spurious responses : pre-selector is the solution



spurious responses