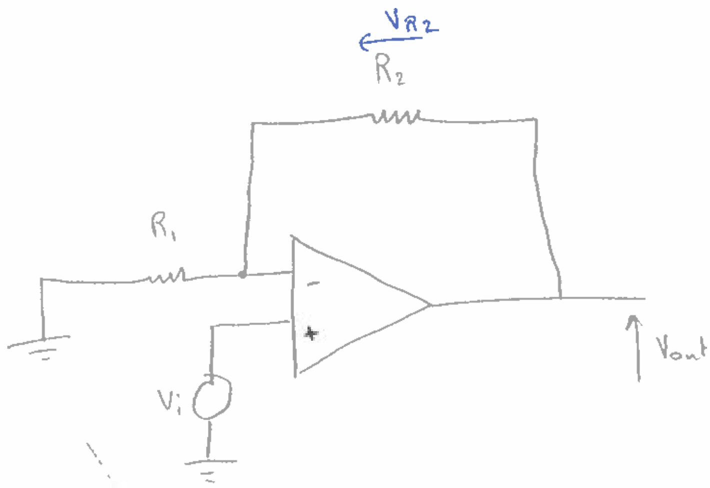
Non inverting amplifier



$$V^- = V_{out} \frac{R_1}{R_1 + R_2}$$

$$V_{out} = \frac{R_1 + R_2}{R_1} V_i$$

if $V^+ = V^-$ $\quad (V^+ = V_i)$

$$\begin{cases} I_1 = \dfrac{V_i}{R_1} \\ V_{R2} = R_2 \cdot I_1 \end{cases}$$

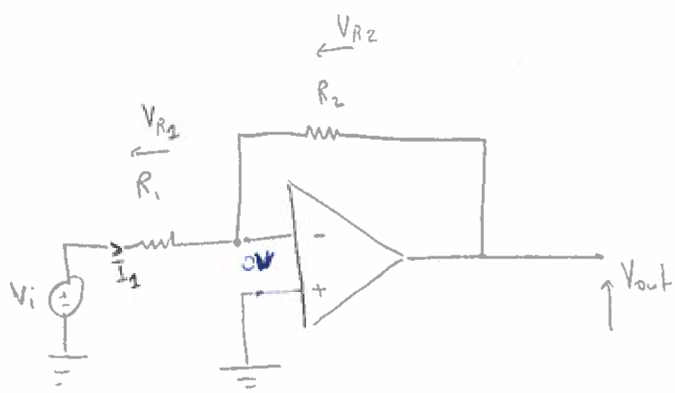
$$\rightarrow V_{out} = V_i + V_{R2}$$

$$= V_i + R_2 I_1$$

$$= V_i + R_2 \frac{V_i}{R_1}$$

$$\boxed{V_{out} = V_i \left(1 + \frac{R_2}{R_1}\right)} \rightarrow \boxed{G = 1 + \frac{R_2}{R_1}}$$

Inverting amplifier



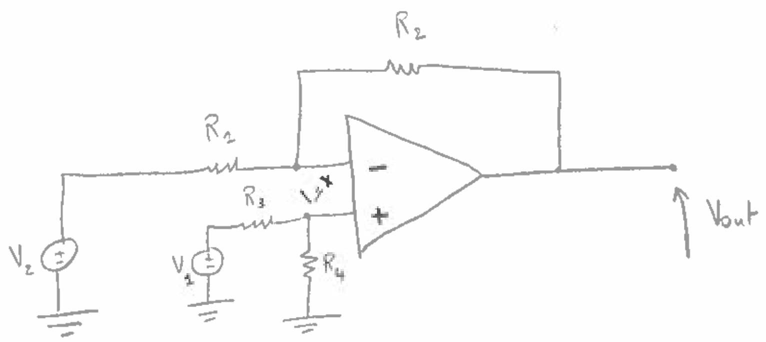
assume $V^+ = V^-$ [when $G \rightarrow \infty$]

$$I_1 = \frac{V_i - 0}{R_1} = \frac{0 - V_{out}}{R_2}$$

$$\boxed{V_{out} = -\frac{R_2}{R_1} V_{in}}$$

Difference amplifier

use of superposition principle



① $V_2 = 0$

$$V^+ = V_1 \frac{R_4}{R_3 + R_4}$$

$$V_{out}' = V^+ \cdot \left(1 + \frac{R_2}{R_1}\right)$$ [non-inverting amplifier]

$$V_{out}' = V_1 \frac{R_4}{R_3 + R_4} \left(1 + \frac{R_2}{R_1}\right)$$

② $V_1 = 0$ (similar to inverter amplifier)

$$V_{out}'' = -\frac{R_2}{R_1} V_2$$

$$\Rightarrow V_{out} = V_{out}' + V_{out}''$$

$$= V_1 \underbrace{\frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right)}_{G^+} - \underbrace{\frac{R_2}{R_1}}_{G^-} V_2$$

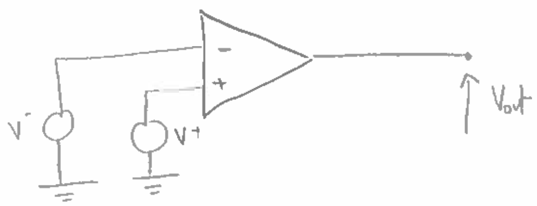
$$G = G^+ = G^- \longrightarrow V_{out} = G\,(V_1 - V_2)$$

$\downarrow$

$$\begin{cases} R_2 = R_4 \\ R_1 = R_3 \end{cases}$$

Common Mode Rejection Ratio

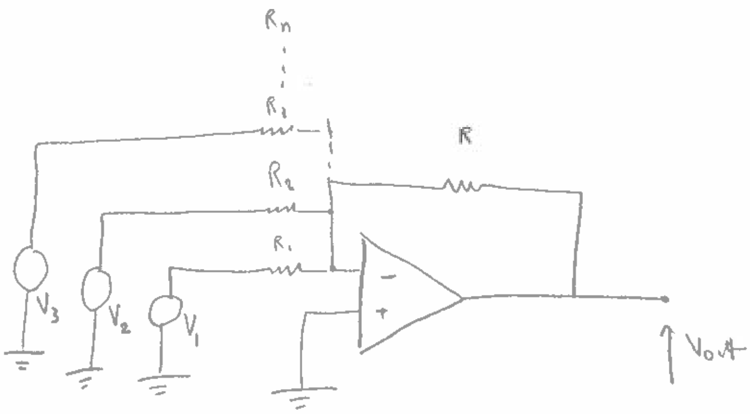
$$V_{out} = G^+ V^+ - G^- V^-$$



$$\begin{cases} G_d = \dfrac{G^+ + G^-}{2} \\ G_c = G^+ + G^- \end{cases}$$

$$CMRR = \frac{G_d}{G_c}$$

Summing amplifier



assume

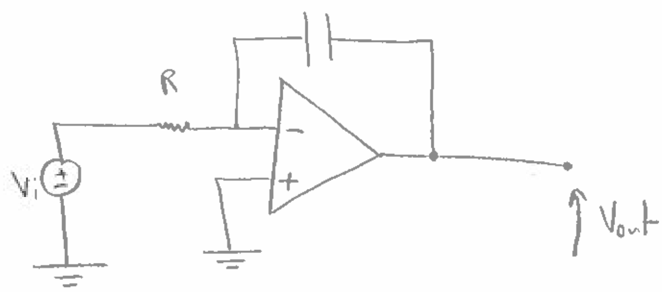
$$R_1 = R_2 = R_3 = \dots = R_n$$

$$V_{out} = -R\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \dots \frac{V_n}{R_n}\right)$$

$$\boxed{V_{out} = \frac{-R}{R_1}\left(V_1 + V_2 + \dots + V_n\right)}$$

Integrator

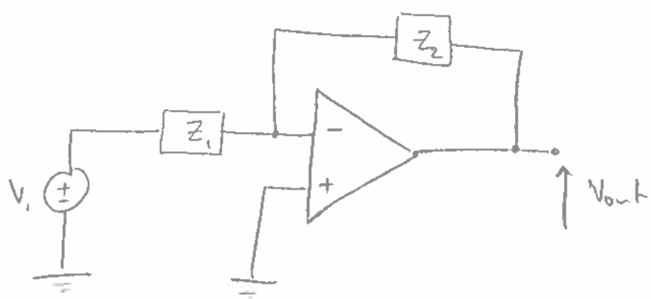
↳ similar to inverter amplifier



$$V_{out} = -\frac{Z_2}{Z_1} V_i$$

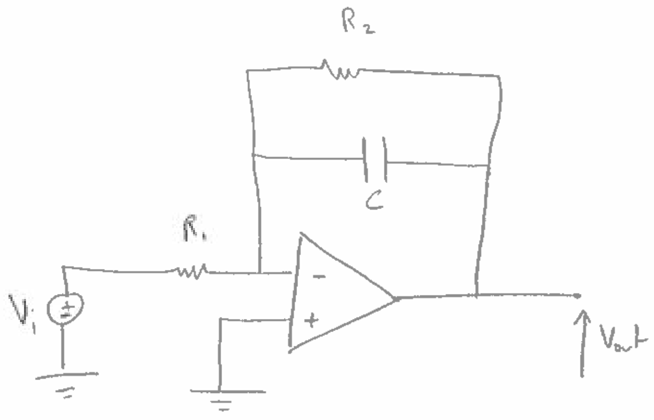
$$V_{out}(s) = -\frac{1}{sC \cdot R} V_i(s)$$

$$V_{out}(s) = -\frac{1}{s} \cdot \frac{1}{RC} V_i(s)$$



→ if there is a continuous component of the input → the system will saturate
↳ the solution is approximate integrator

Approximate integrator



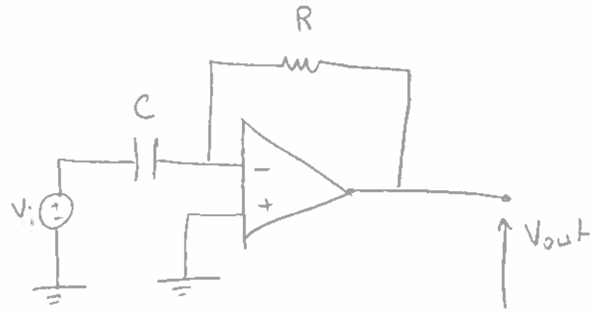
$$V_{out} = -\frac{Z_{eq}}{Z_1} \cdot V_i$$

$$Z_{eq} = \frac{Z_2 Z_3}{Z_2 + Z_3} \quad / \quad Z_1 = R_1, \quad Z_2 = R_2, \quad Z_3 = \frac{1}{sC}$$

$$V_{out}(s) = -\frac{1}{R_1} \cdot \frac{\frac{1}{sC} \cdot R_2}{\frac{1}{sC} + R_2} \cdot V_i(s)$$

$$\boxed{V_{out}(s) = -\frac{1}{R_1} \frac{R_2}{1 + sR_2C} V_i(s)}$$

Approximate differentiator

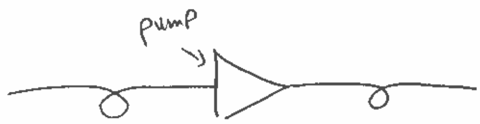


$$V_{out}(t) = -RC \frac{dV_i(t)}{dt}$$

$$V_{out}(s) = -\frac{R}{1/sC} V_i(s)$$

$$\boxed{V_{out}(s) = -sRC\, V_i(s)}$$

OA : to increase the power of the optical signal.



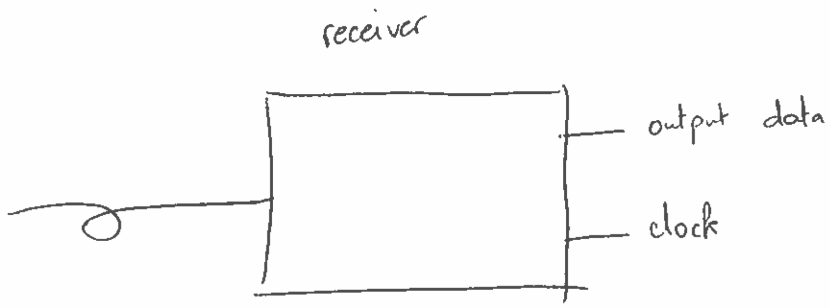
→ noisy component. → high output power.

→ worse SNR.

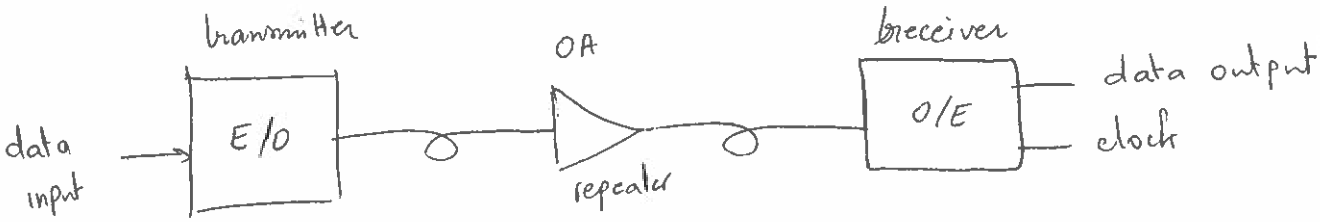
Repeater : optical signal → converted to electrical signal, it is reshaped

→ then converted back to optical signal.

→ SNR same as original signal from transmitter.



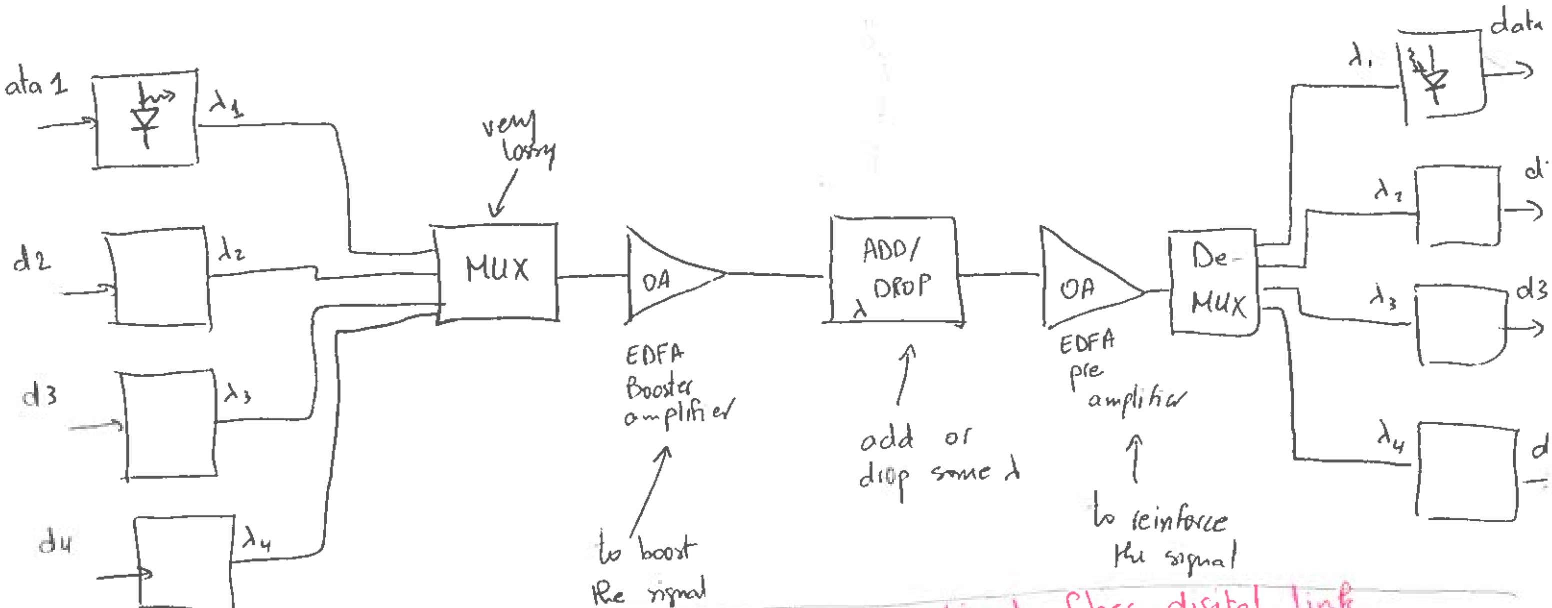
→ convert optical power → to electrical power : (based on photodetectors)



WDM

λ

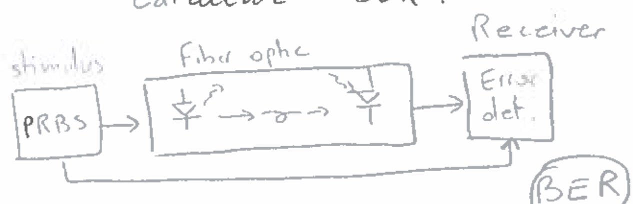
EDFA → 1530 ~ 1565 nm



characterization of an optical fiber digital link

→ Send : pseudo Random Binary sequence : to compare with the output [receiver] and calculate BER.

length : $2^{23} - 1$



BER ≈ 10^{-9} — 10^{-13}

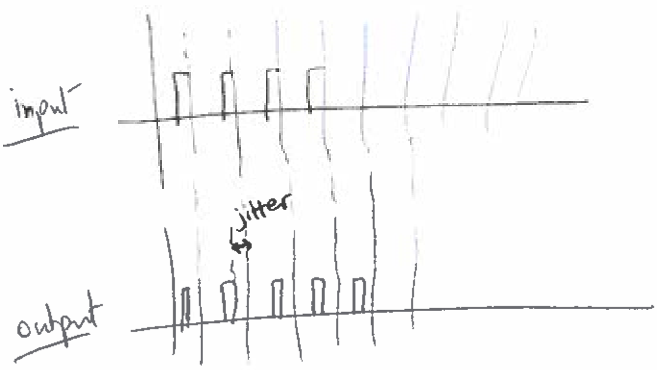
BER ∝ losses of the fiber.

→ Waveform analysis : compare the in and out signals to find where is the loss coming from. [check the form of the signal].

Clock jitter : how much the period of the clk is changing

tolerance : limit of max jitter → garantees that the receiver is working as expected

and : BER < 10^{-13}



Optical power → ~~optique~~ power meter.

optical power meters

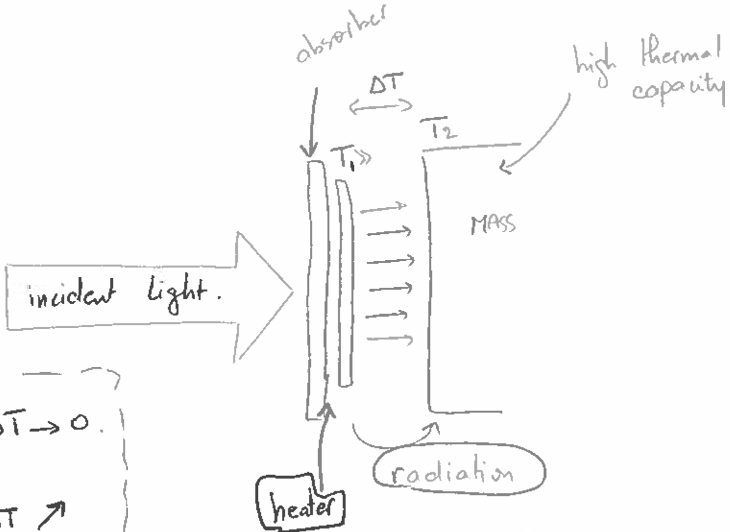
	thermoelectric detectors	electronic photo-detectors
λ	low dependence	high dependance.
auto-calibration	YES	NO
sensitivity	low / > 10 mW	high / < 1 pW
uncertainty	1%	2%

idea: absorb the light.

thermopile
↓
measures ΔT

→ when light = off → $\Delta T \to 0$.

heater: to increase T_1 and ΔT ↗



→ thermal equilibrium → ΔT stable.
→ measure the P_{opt} AND $P_{electrical}$ ~~and compare~~.

$P_e = R.I^2$

$\boxed{P_{opt} = P_e}$ → so, we have P_{opt}.

PIN Photo-detectors

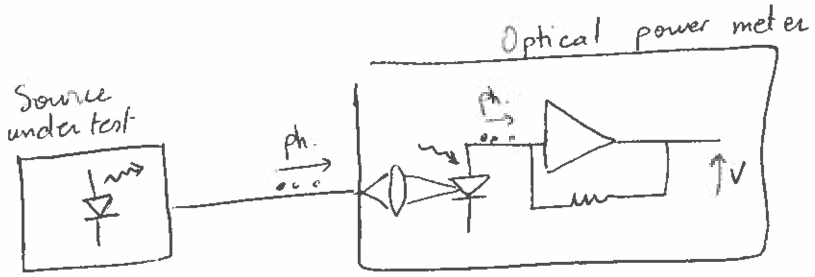
↳ converts photons to electrons → generates current

↳ photons absorbed by "intrinsic" Layer Ge, Si, InGaAs

↳ efficiency 90%. ↳ fast response time.

↳ Avalanche Photo-diode (APD)

↳ lower speed ↳ higher sensitivity.

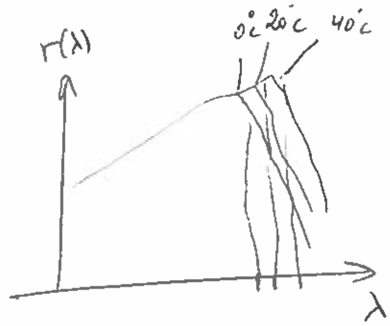


PIN photodiode

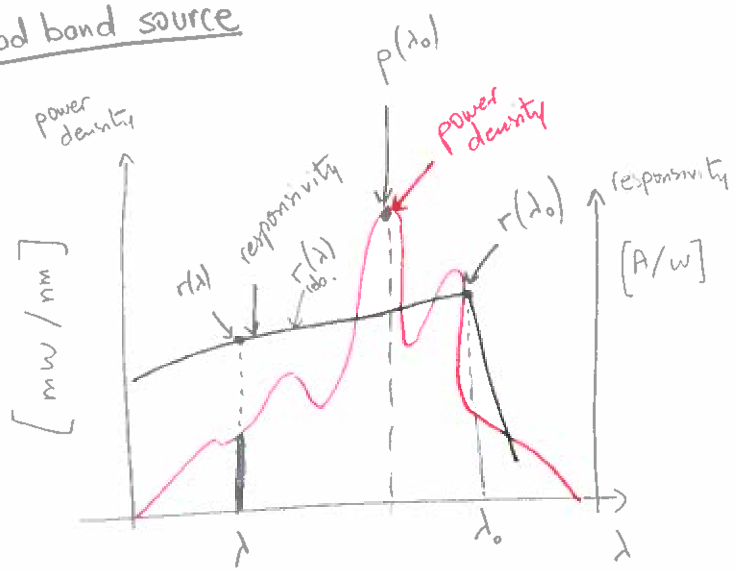
responsivity : how much current produced per unit of optical power.

$$r = \frac{I}{P_{opt}} = r(\lambda) \quad \left[\frac{A}{W}\right]$$

→ responsivity depends on the wave length.



Broad band source



→ the total photo-current

$$\boxed{I_{Tot} = \int r(\lambda) \cdot p(\lambda) \, d\lambda}$$

→ Relative responsitivity :

$$r(\lambda) = r(\lambda_0) \cdot \underbrace{r_{rel} f(\lambda)}_{\text{relative resp.}}$$

→ relative power spectral density

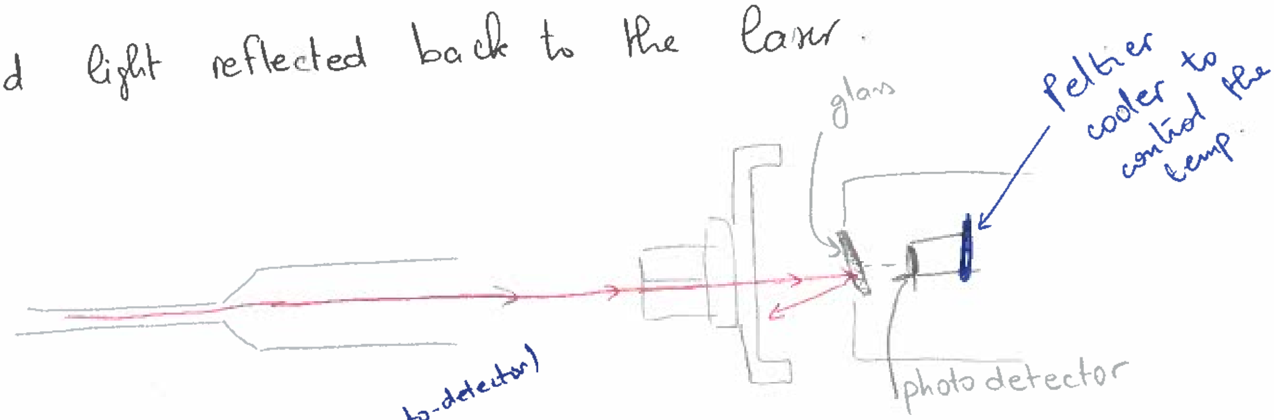
$$p(\lambda) = p(\lambda_0) \cdot \underbrace{f(\lambda)}_{\text{relative power density}}$$

$\boxed{r(\lambda_0) : \text{sensitivity}}$

$\boxed{p(\lambda_0) : \text{absolute power of the light source}}$

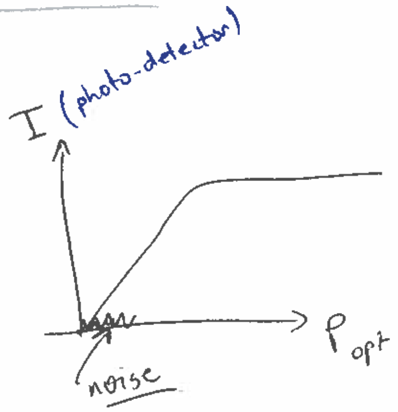
Power meters with photo-detectors

→ avoid light reflected back to the laser.



High dynamic range :

ratio of max I / I noise ~~Popt max~~



$$\frac{I_{max}}{I_{noise}} = \text{dynamic range.}$$

$$\approx 10^5$$

[Photo-detector]

power noise ⟶ noise equivalent power (NEP)

$$NEP = \frac{1}{r}\sqrt{[i_n^2]} = \frac{1}{r}\sqrt{2eB_n\,(2I_{dark} + r \cdot P_{opt})}$$

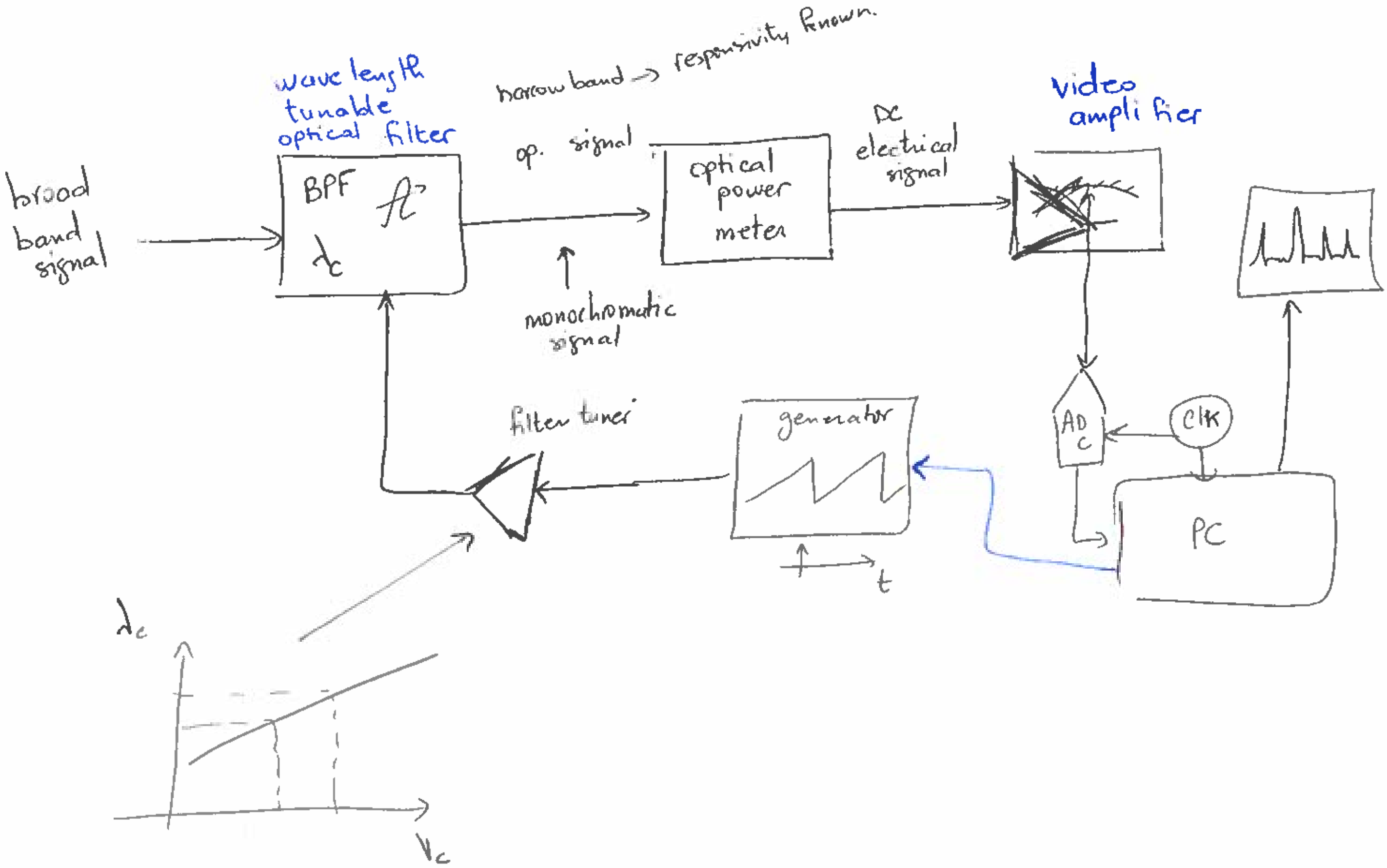
I_{dark} : dark current ~~even~~ in the output even when $i_n = 0$.

$$SNR = \frac{P_{opt}}{NEP}$$

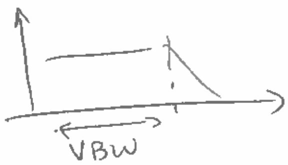
I_{dark} : dark current is the current at the output ~~even~~ when we have no input optical power.

OSA

VBW : BW of the final stage of the processing chain.

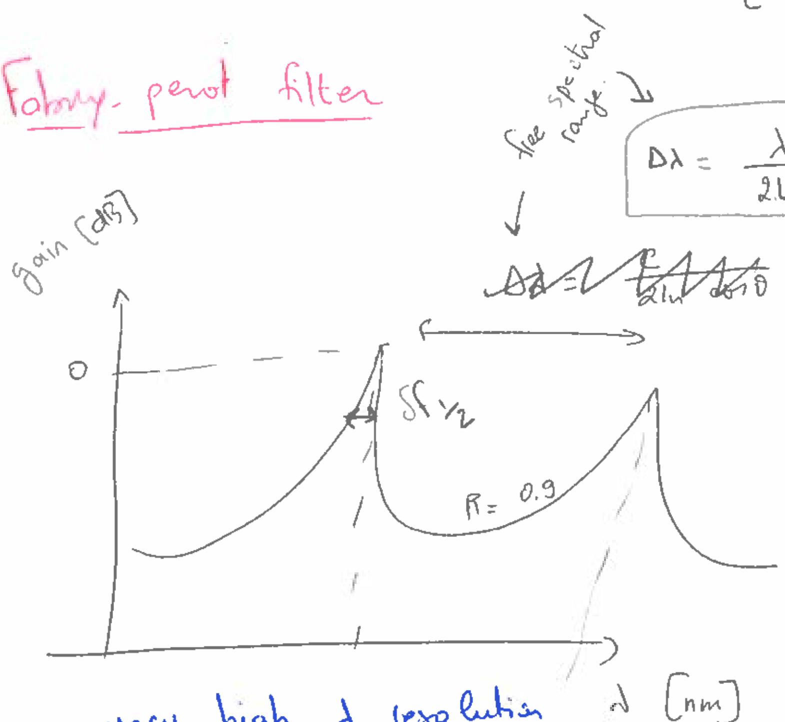


VBW



related to the velocity of the scan [the generator].

Fabry-perot filter



$$\boxed{\Delta\lambda = \frac{\lambda^2}{2L.n.\cos\theta}}$$

~~$\Delta\lambda = \frac{\lambda^2}{2Ln\cos\theta}$~~

Finess $F \approx 10^3$

→ good F.P. filter

$$F = \frac{\Delta f}{\delta f_{1/2}}$$

resolution

→ very high λ resolution

→ narrow λ range due to the periodicity of Transmission function

Diffraction grating

$$n.\lambda = d(\sin\beta - \sin\alpha)$$

periodic

divergence angle : $\Delta\beta_{min} = \dfrac{\lambda}{N.d.\cos\beta}$

N : nbr of illuminated lines

dispersion $D = \dfrac{\Delta\beta}{\Delta\lambda} = \dfrac{n}{d\cos\beta}$

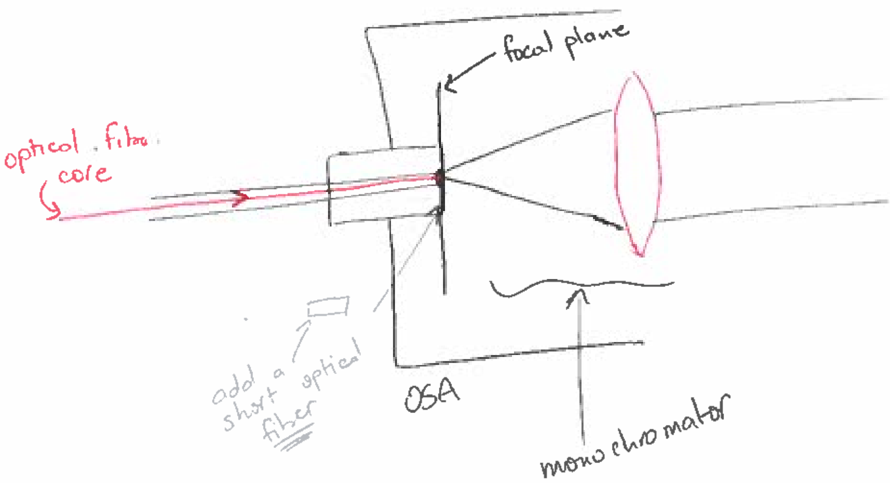
best resolution : $\Delta\lambda_{min} = \dfrac{\lambda}{N.n}$

---

monochromator : input : many wavelengths.
output : one single λ.

monochromator + photo-detector $\Rightarrow$ spectrometer.

Input stage of OSA



→ no insertion loss
→ no damage of connector
→ dirt can enter to the monochromator.
→ low accuracy
→ fiber / air interface causes a return loss = 14 dB.

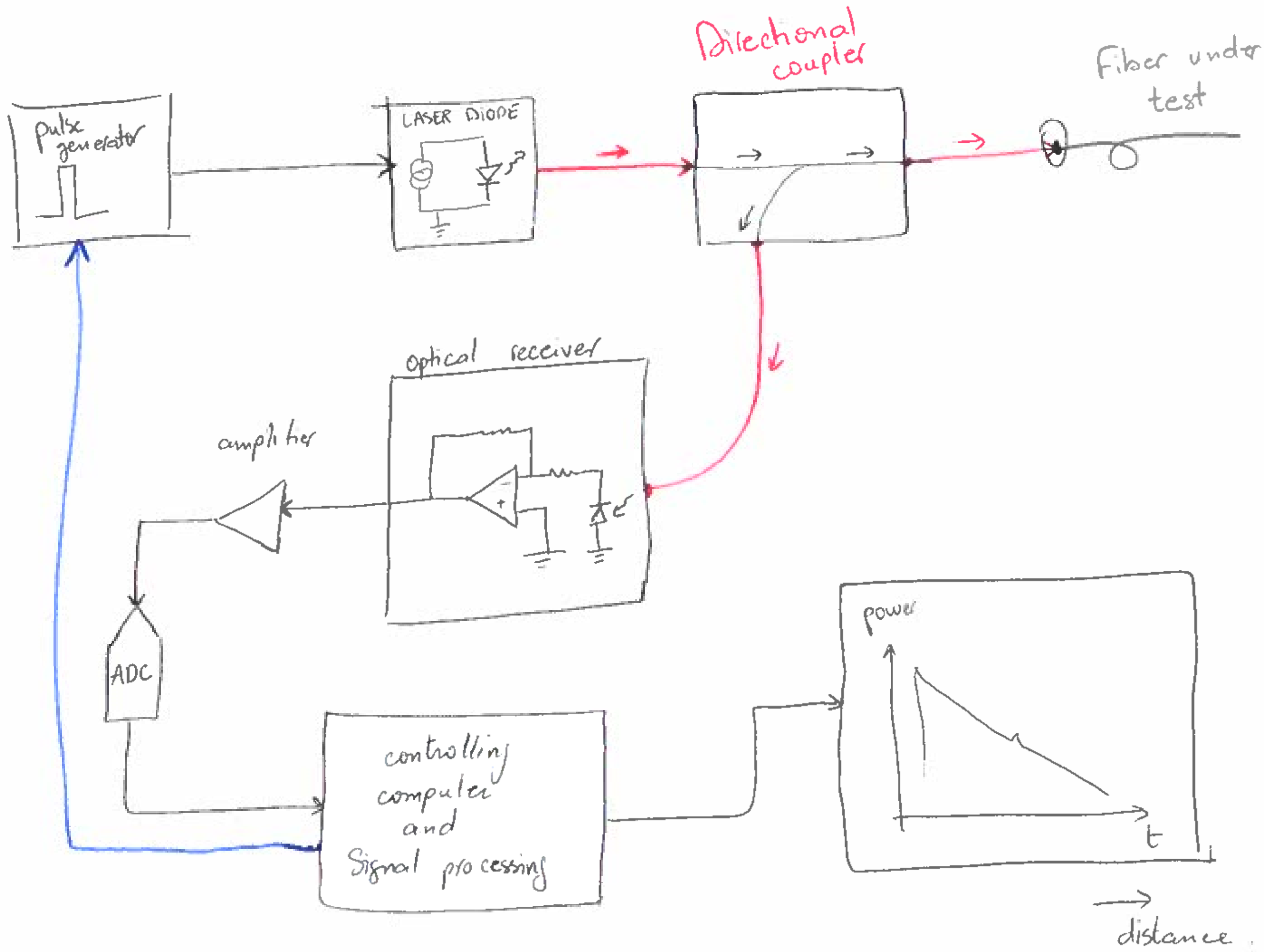
solution : add an optical fiber.

↳ λ resolution of OSA : determined by input slit + diffraction grating + output slit

↳ BW of amplifier → determines the sweep velocity AND sensitivity

↳ the Total loss determines the quality of the transmission system.

↳ OTDR : solution for monitoring installed optical fibers.



→ back propogation light : loss in fiber

↳ because of macro discontinuities : connectors / splices / bending...

↳ back scattering

$$P(z) = \underbrace{P_0 \cdot e^{-\alpha z}}$$

α : attenuation coeff $[km^{-1}]$

$$\underset{[dB/km]}{\alpha} = 10 \log \left(\frac{P_0}{P(z)} \right) \cdot \frac{1}{z}$$

$$\underset{\substack{\uparrow \\ \text{absorbance}}}{\alpha_a}$$

$$\alpha = \alpha_a + \alpha_s \leftarrow \text{scattering.}$$

the scattered intensity

$$\alpha_s \approx \frac{1}{\lambda^4}$$

backscatter factor $S = 10 \log \dfrac{P_0}{P_s(0)} = -10 \log (K \cdot W)$

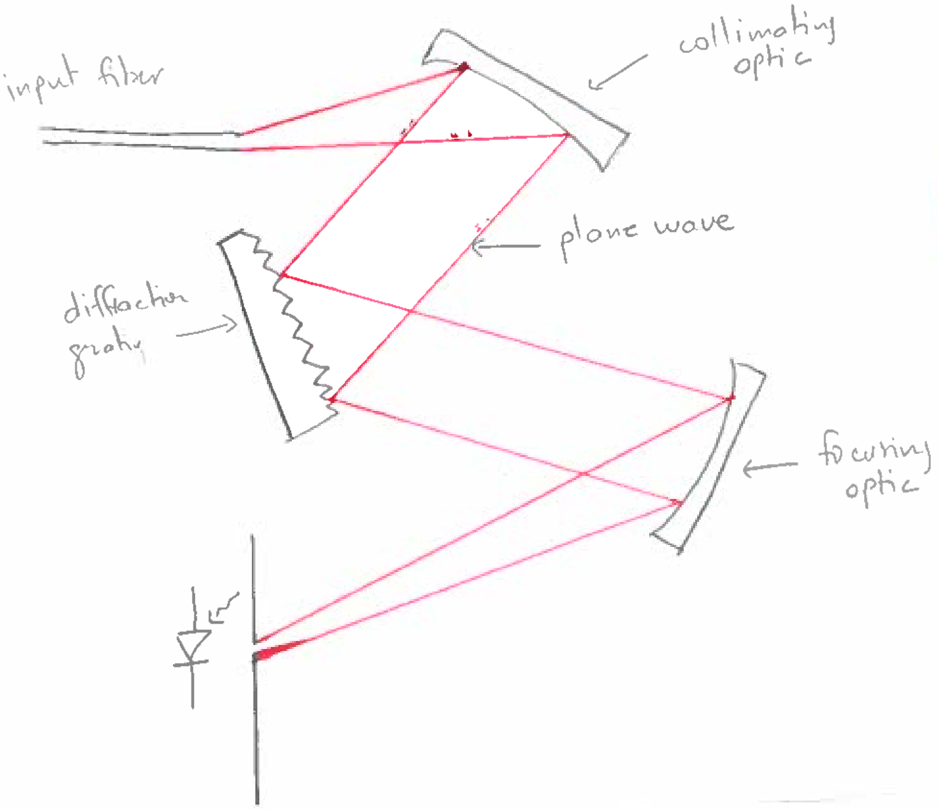
↳ a parameter characterizing the fiber.

Sensitivity of the OSA : limiting factors :

- the power loss of the monochromator $(3 \rightarrow 8 \text{ dB})$
- sensitivity of the detector
- BW of the photo ~~diode~~ - detector signal (Video BW).

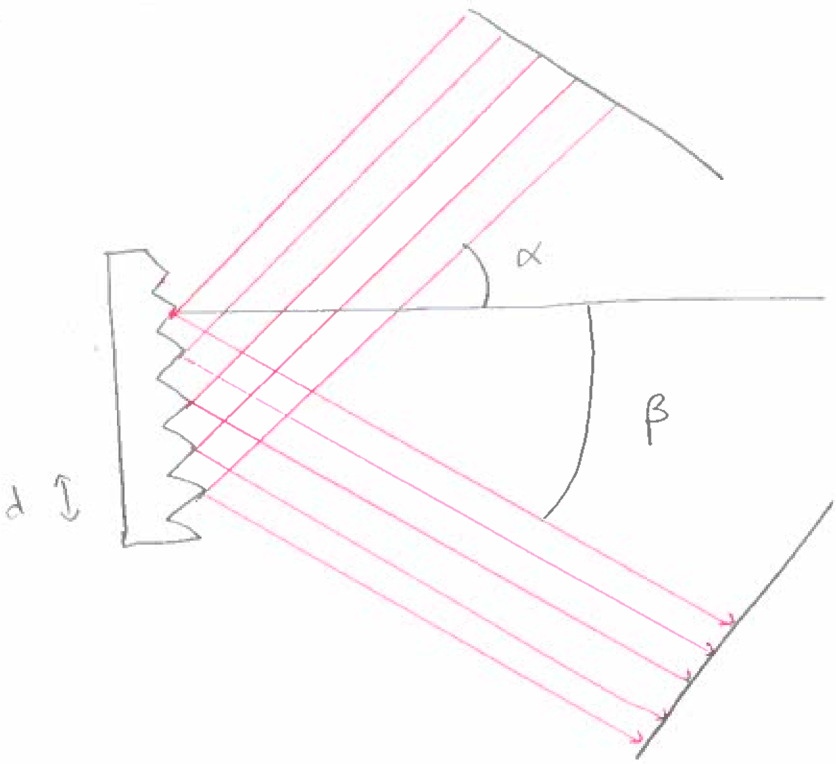
S : fraction

Diffraction grating



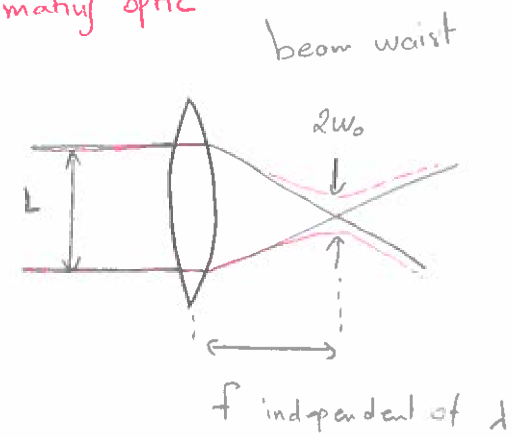
→ output & input slit + the diffraction grating → determine the resolution of the OSA.

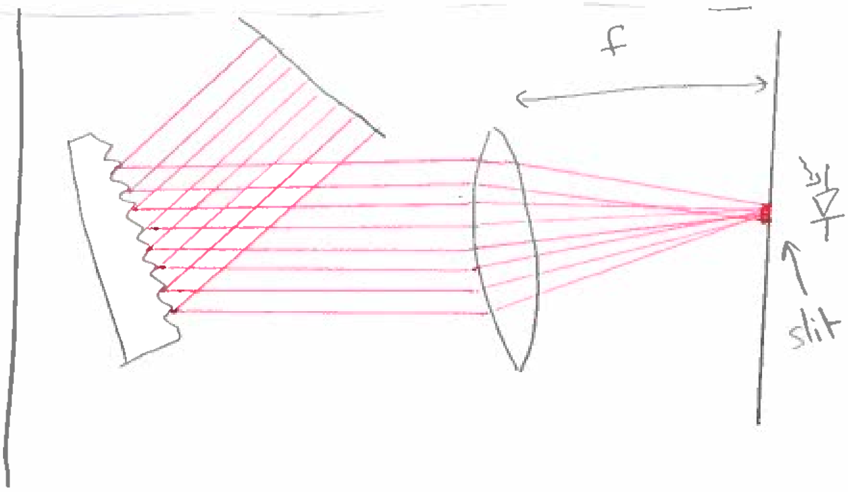
→ BW of the amplifier determines the sweep velocity & the instrument sensitivity.



$$n\lambda = d\,(\sin\beta - \sin\alpha)$$

collimating optic





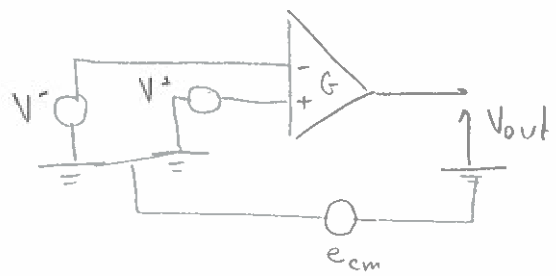
Difference amplifier

$$V_{out} = V_1 G^+ - V_2 G^-$$

→ Study of the unwanted source (e_{cm})

→ the difference amplifier will amplifie $(V_1 - V_2)$ but will reject (e_{cm})

$$\begin{cases} G_d = \dfrac{G^+ + G^-}{2} \\ G_c = G^+ - G^- \end{cases}$$



$$\begin{cases} G^+ = G_d + \dfrac{G_c}{2} \\ G^- = G_d - \dfrac{G_c}{2} \end{cases}$$

→ we replace in V_{out}

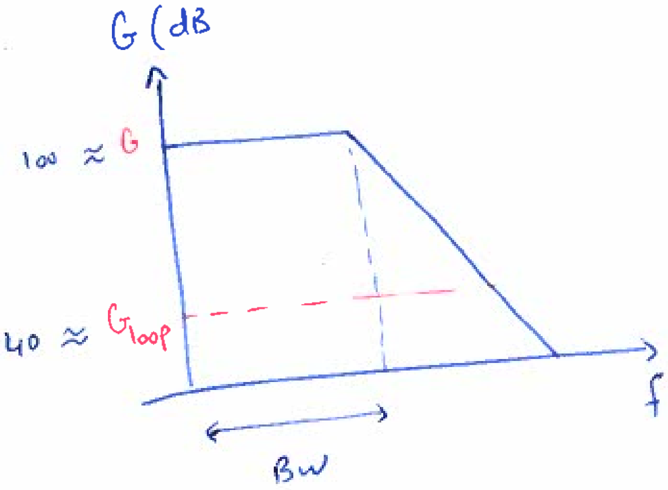
$$V_{out} = V_1 \left(G_d + \frac{G_c}{2}\right) - V_2 \left(G_d - \frac{G_c}{2}\right)$$

$$V_{out} = G_d (V_1 - V_2) + G_c \left(\frac{V_1 + V_2}{2}\right)$$

$$V_{out} = G_d (V_1 - V_2) + G_c (e_{cm})$$

$$CMRR = \frac{G_d}{G_c}$$

(Common Mode Rejection Ratio)



es :

$$V_{out} = \underbrace{-\frac{R_2}{R_1}}_{G_{loop}} V_{in}$$

$$= -100\ V_{in}$$

$$G_{loop} = 100 = 20\log(100)$$

$$= 40\ dB$$

→ The signals used by the Network analyzer to stimulate the DUT during the measurement of its TF :

① Sinusoid signal : we have to iteratively set the ~~center~~ frequency of the sinusoid at the center freq. of every filter. we have to make as many measurements as there are bins.

② Broadband signal : can simultaneously produce energy in each of the FFT bins, which can be captured in one FFT measurement

③ Chirp sine signal : is a swept sine burst designed to fill the time record of the FFT analyzer. It has a relatively high average power → produces a better SNR compared to random noise.

④ Broadband random noise : has equal energy in all of the ~~frequency~~ FFT bins.

⑤ PRN signal : periodic ~~with~~ within the time record of the analyzer so that it does not produce leakage.

⑥ Random noise source : usefull with non-linear networks. The non-linear measurements can be averaged out since they produce a different response for each measurement

$1 \to 8$

$2 \to 6$

$3 \to 6$

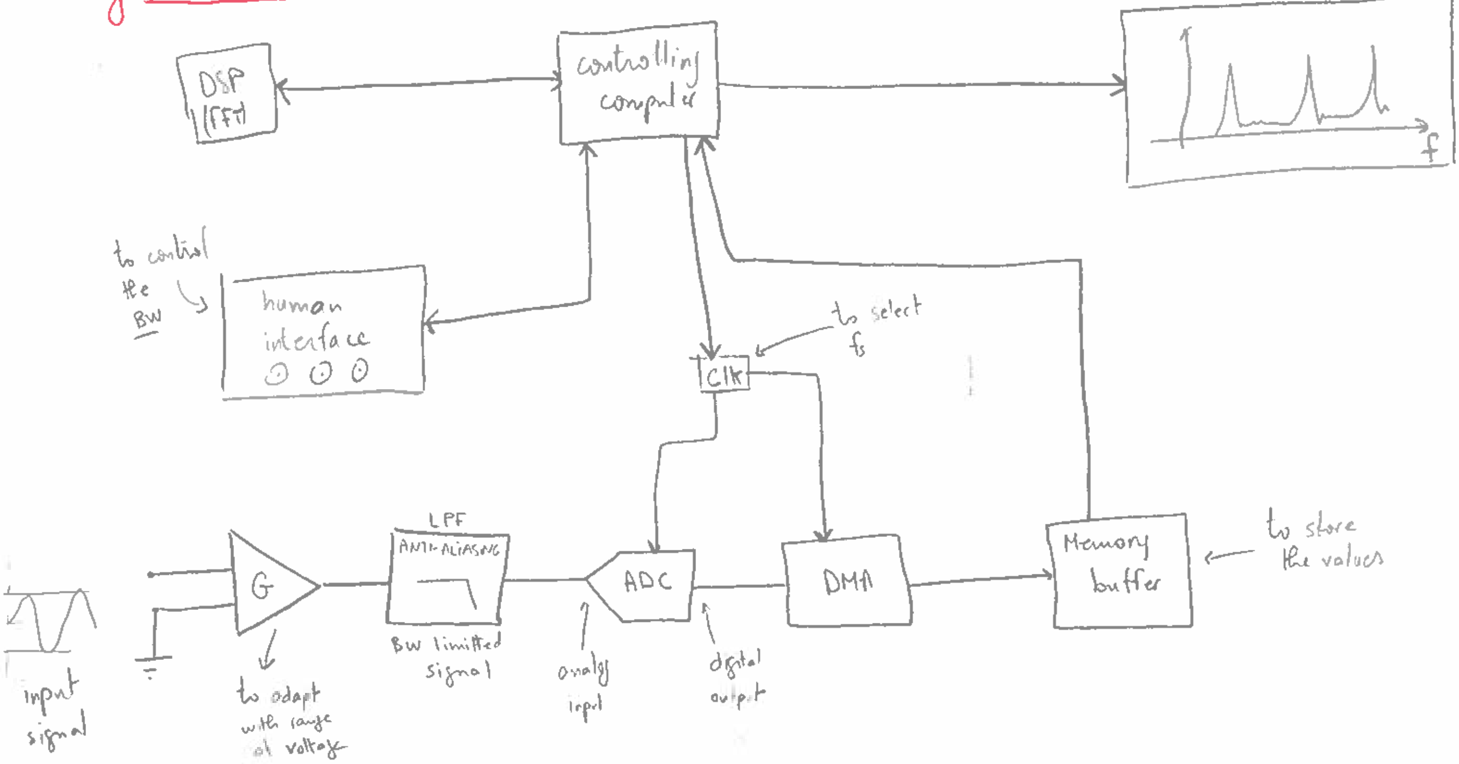
$50 \to 33$

15

$25 \to 17$

19

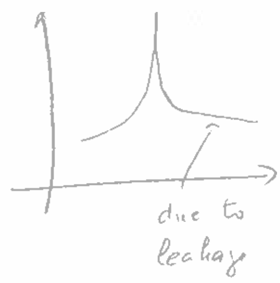
Digital (FFT based) spectrum analyzer



FFT : works in the Baseband $f = [0\,Hz \longrightarrow \frac{f_s}{2}]$.

resolution : $\delta f = \frac{f_s}{N}$ / $f_n = n\,\frac{f_s}{N}$ / $f_{max} = \frac{f_s}{2}$

computation time : [number of computations $= N \log_2(N)$].



Leakage: discontinuity $\rightarrow$ source of new frequency components.

↳ use windows to force the ends of waveform $= 0$.

↳ reduce leakage $\rightarrow$ better resolution.

Mean : $\bar{x} = E(x) = \int_{-\infty}^{+\infty} x \,.\, PDF(x)\, dx$.

Variance : $S^2 = E(x - \bar{x})^2 = \overline{x^2} - \bar{x}^2$

Noise power : when $R = 1\,\Omega$ $\quad P_{noise} = V^2 = I^2$

signal power $\longrightarrow P_{12} = \int_{f_1}^{f_2} S_x(f)\, df$ $\quad$ power spectral density

Wiener - Khinchin theorem

→ auto correlation function : $R_{xx}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x(t)\, x(t+\tau)\, dt$

→ power spectral density $S_x(f) = 2 \int_{-\infty}^{+\infty} R_{xx}(\tau)\, e^{-j2\pi f \tau}\, d\tau$.

→ Noise power for ideal filter

$P_n = N_0 \cdot G_0 \cdot BW_N$

(N_0: input PSD)

Noise Equivalent BW

$BW_N = \frac{1}{G_0} \int_0^{\infty} \underbrace{G(f)}_{\text{power gain of the filter}}\, df$

G_0: power gain of ideal filter

Heterodyne (swept) spectrum analyzer [analog heterodyne].

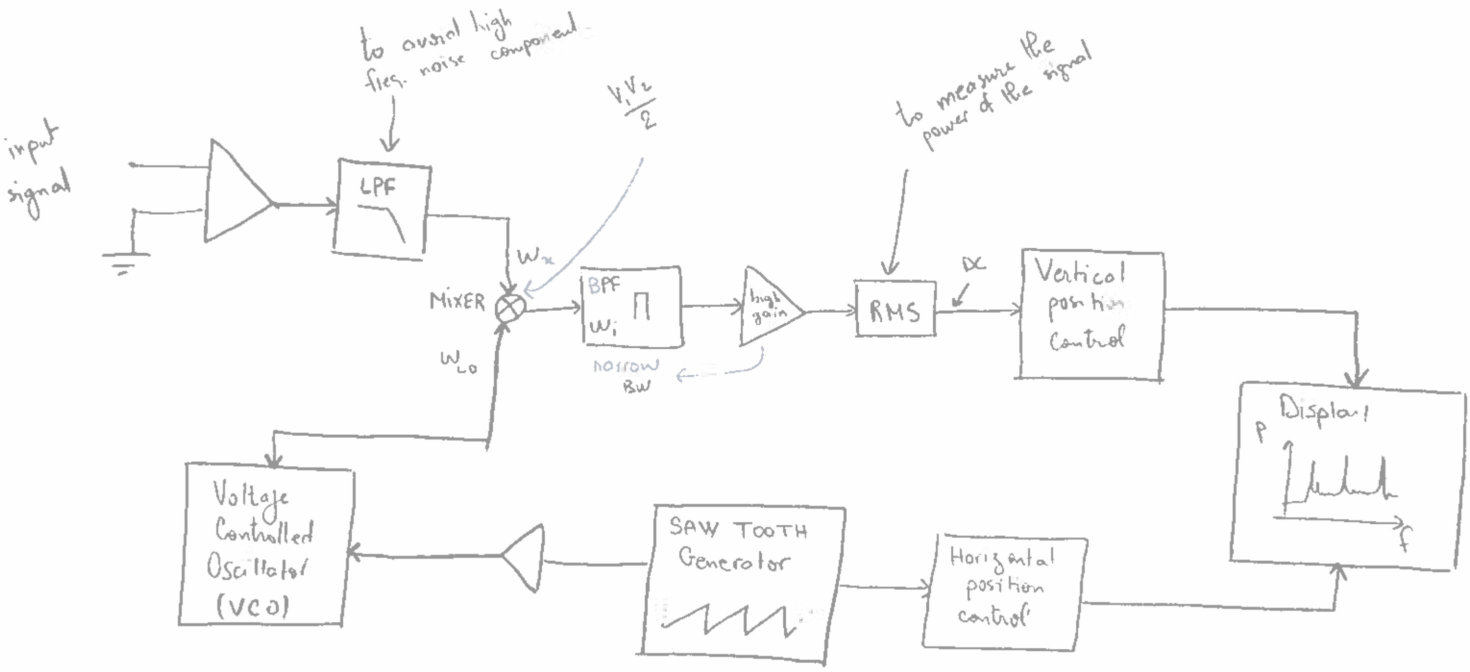
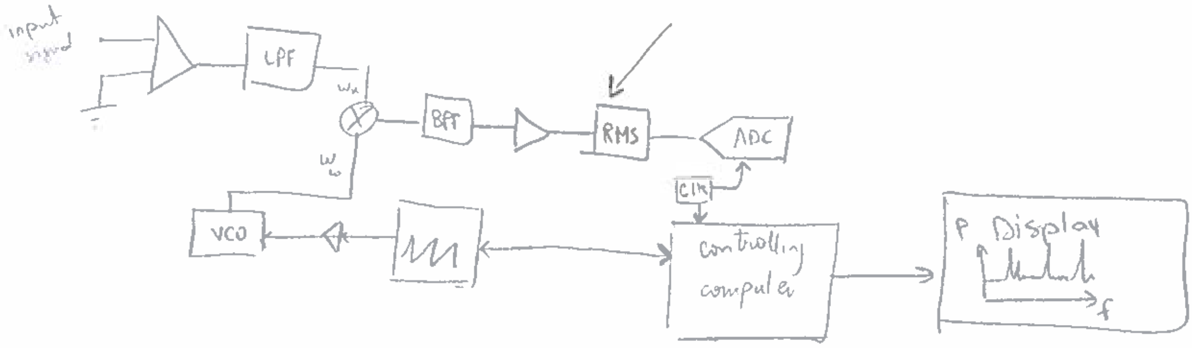
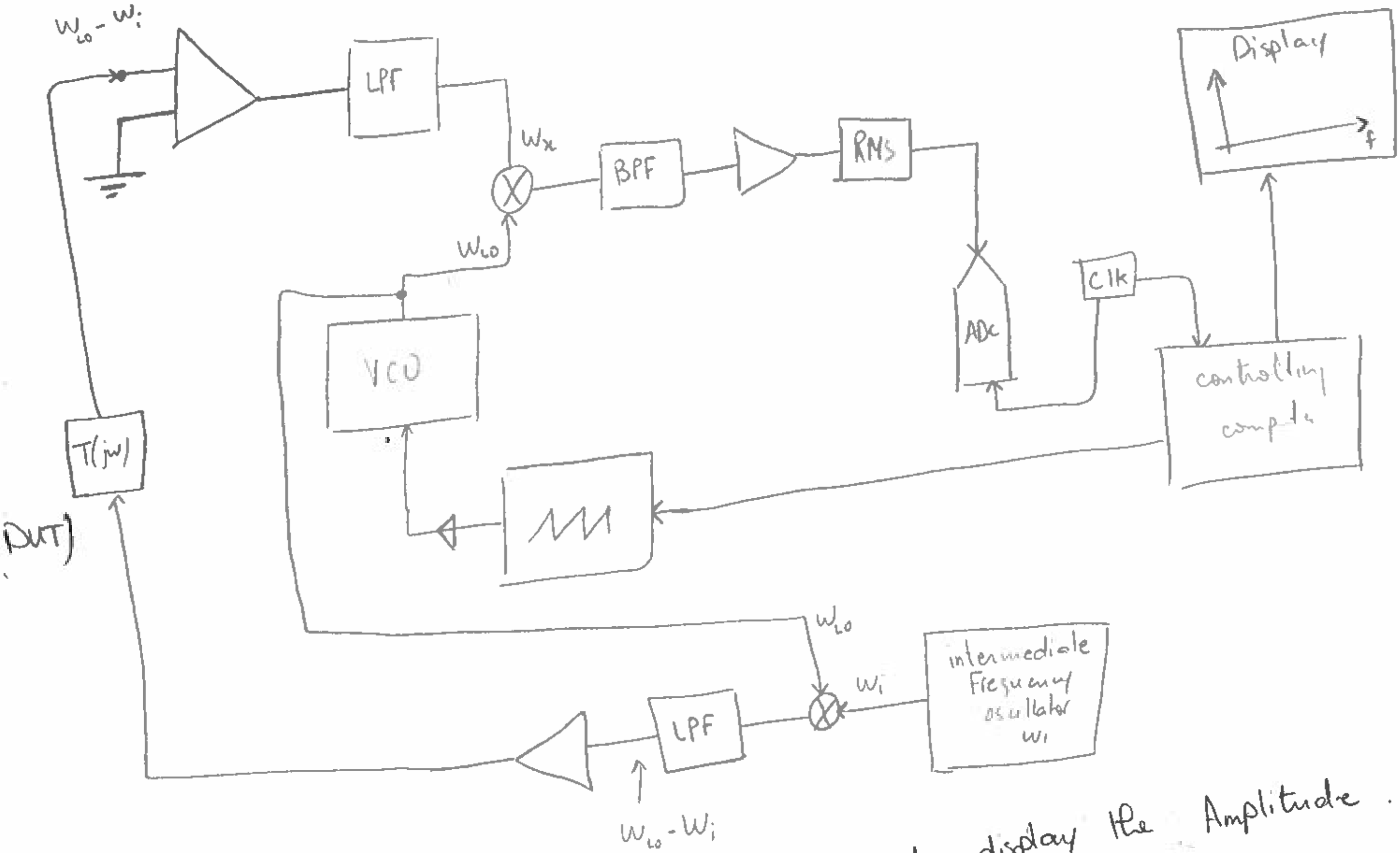


image frequency : high freq component that should be taken away using a LPF.



Frequency response analysis : Amplitude

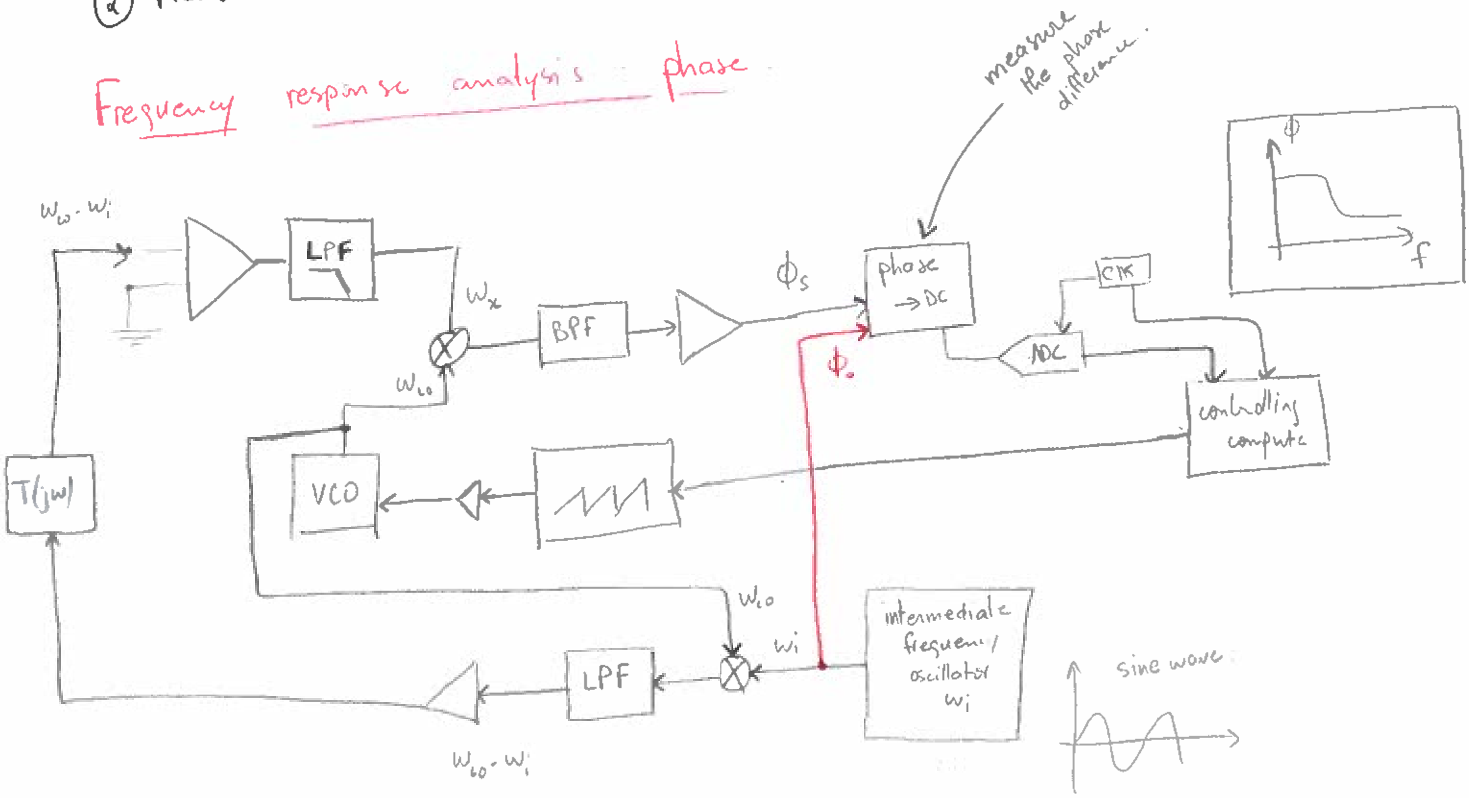


display the Amplitude.

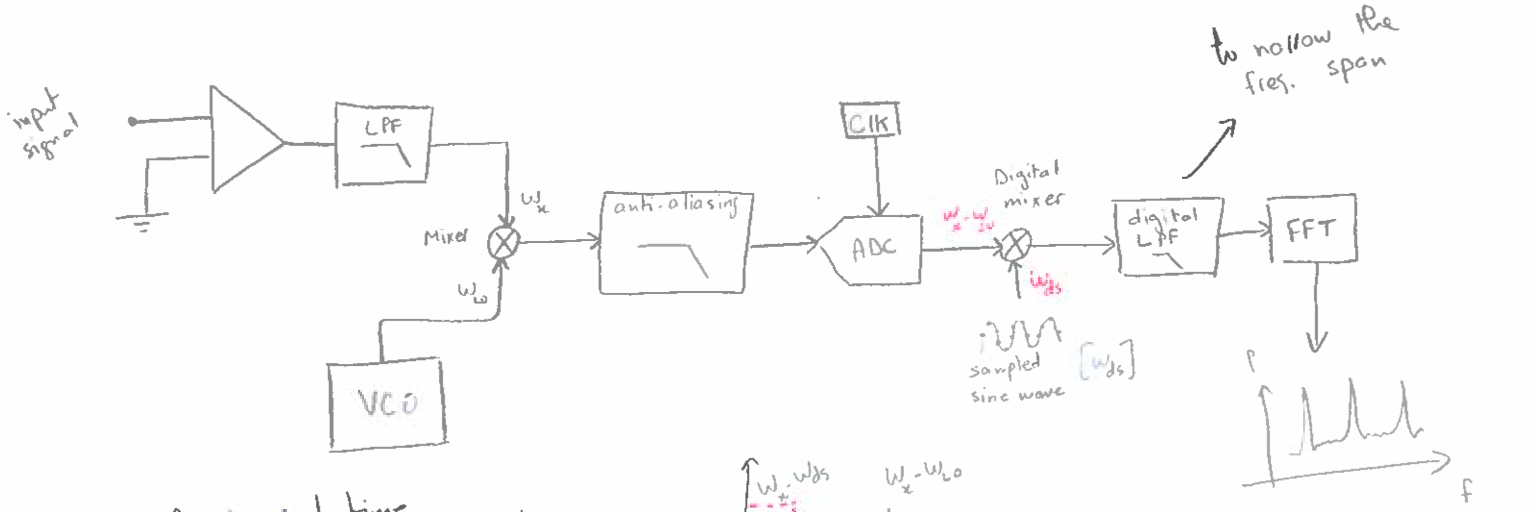
① Calibration: we take off the DUT and measure the displayed Amplitude.

② Measurement: add the DUT and

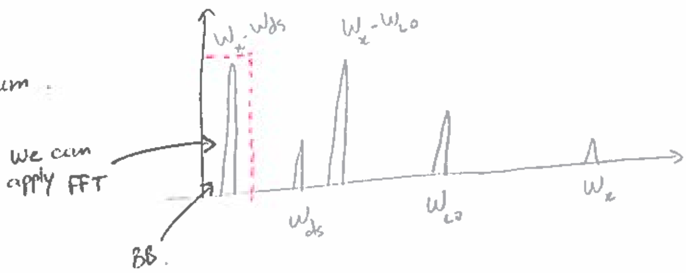
Frequency response analysis phase



Real time spectrum analyzer : combination of heterodyne and FFT.



→ works in real time
→ any location in the spectrum.



Distortion : [single tone input]. $V_{in} = A\cos(wt)$.

→ reduce the input amplitude A by 1 dB

→ reduce of 1dB the fundamental harmonic.

→ " " 2dB " 2^{nd} "

→ " " 3 dB " 3^{rd} "

(intermodulation distortion) [two tone input] $V_{in} = A_1\cos(w_1 t) + A_2\cos(w_2 t)$

→ the frequencies in the output : $W_{nm} = |nw_1 \pm m w_2|$.

order of component = ~~sum~~ $(n+m)$ → f_{21} → 3^{rd} order comp.

f_{11} → 2^{nd} " "

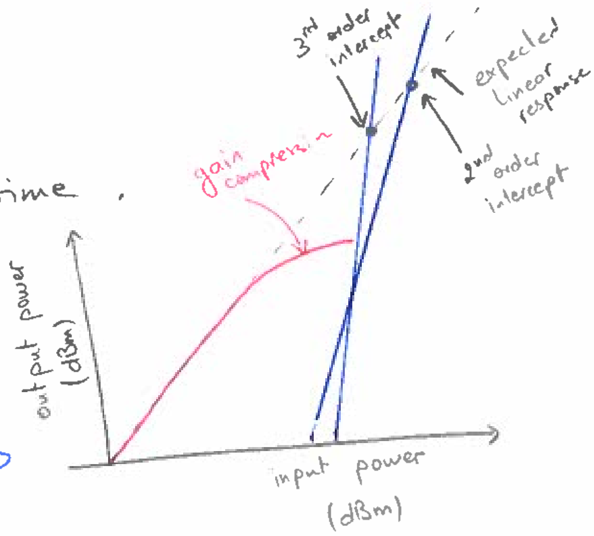
→ To increase the sensitivity :

↳ improve the SNR

↳ reduce the VBW.

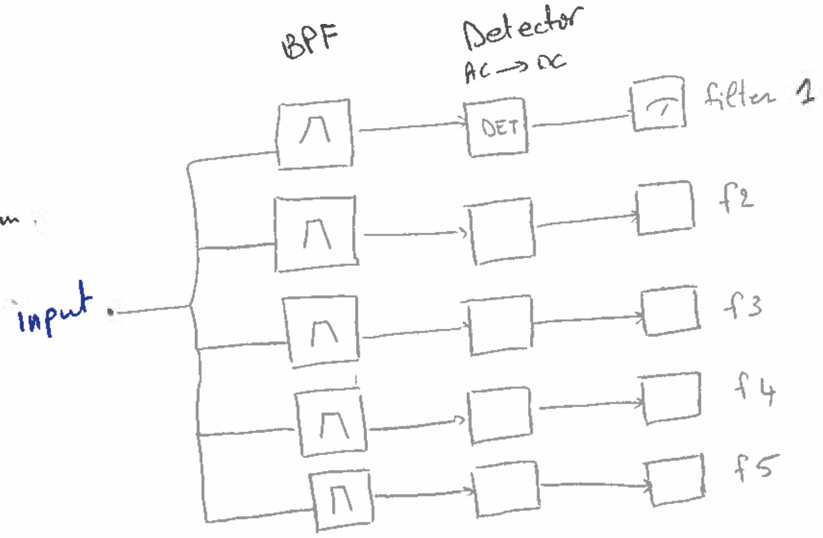
↳ the measurement will take more time.

The intercept concept



Bank of filters :

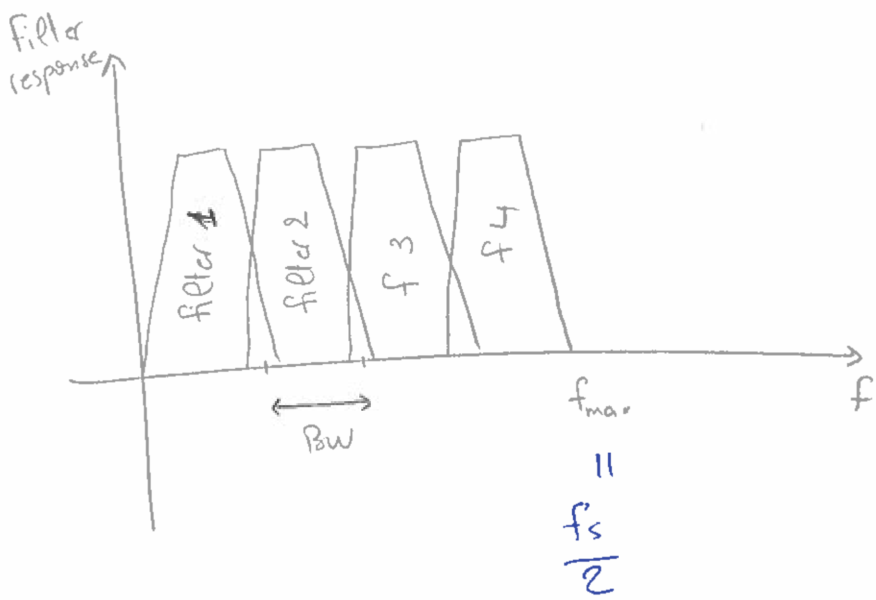
→ simple.
→ fast
→ real time measurement system.



To implement a spectrum analyzer, we connect a bank of electronic filters together, each with its own output.

Each filter is a Band pass filter tuned at a different center frequency. The Bandwidths and center frequencies are aligned to cover the entire range of frequency of interest with minimal overlap of filter shape.

The output of the filters are connected to detectors that convert the AC signal to DC level, then displayed by a meter.



$$\delta_f = \frac{f_s}{N}$$

resolution

→ Noise level of the analyzer depends on the frequency resolution of the measurement.

OTDR

→ provide info about attenuation & loss of the fiber
→ by exploiting backscattered light from fiber.
→ we use "directional coupler" to prevent the laser signal from saturating the receiver.

→ $\approx 10\ \mu s / Km$.

→ Dynamic range: the difference between the initial backscattered level & the noise level after 3 min of measurement time.

→ High spatial resolution → short pulse width → wide receiver BW. ⇒ leads to a reduced SNR

Long pulse wide → low noise ⇒ improve sensitivity but bad spatial resolution

→ S: the fraction of light scattered

$$S = \left(\frac{NA}{n_0}\right)^2 \cdot \frac{1}{m}$$