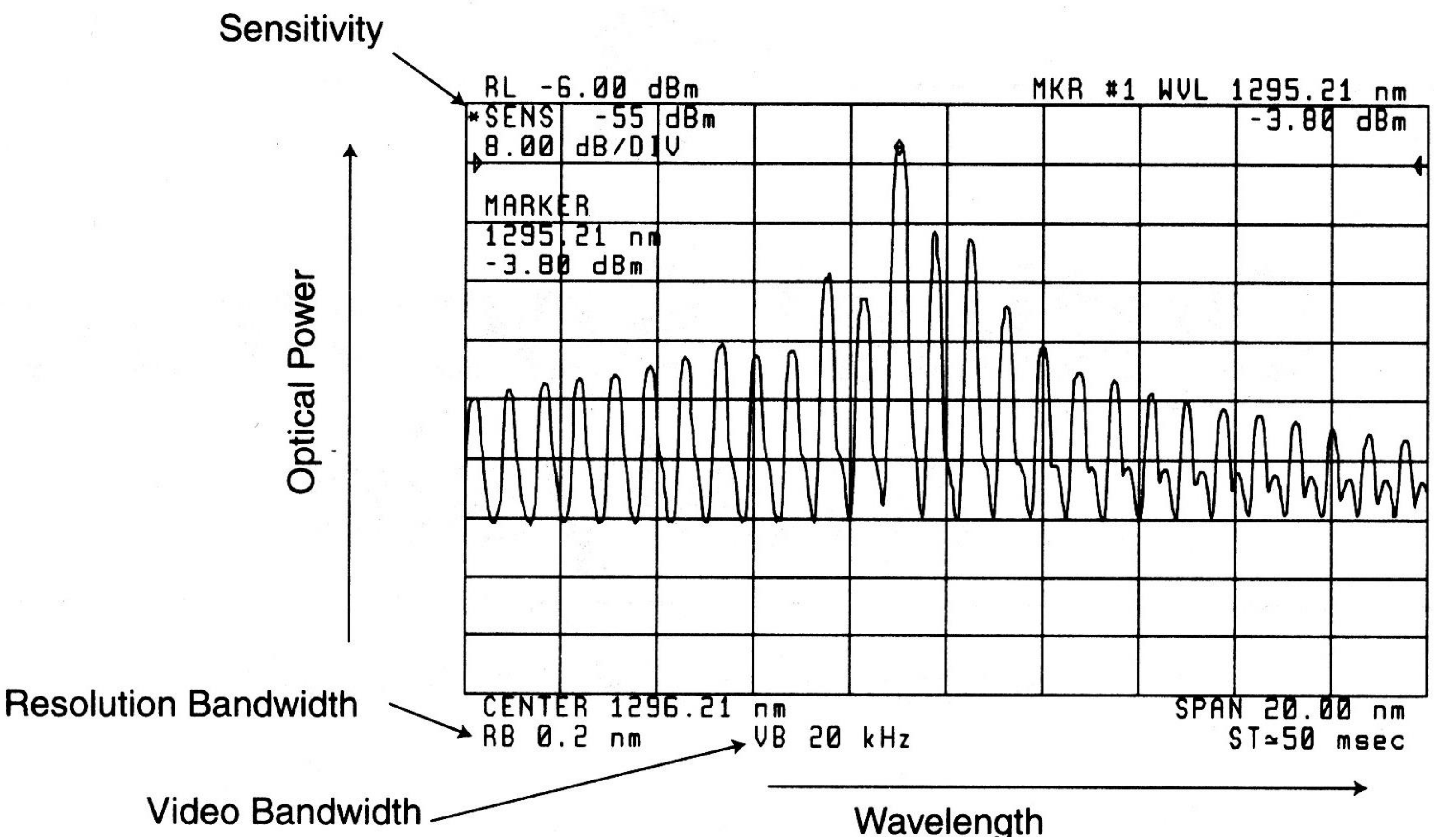
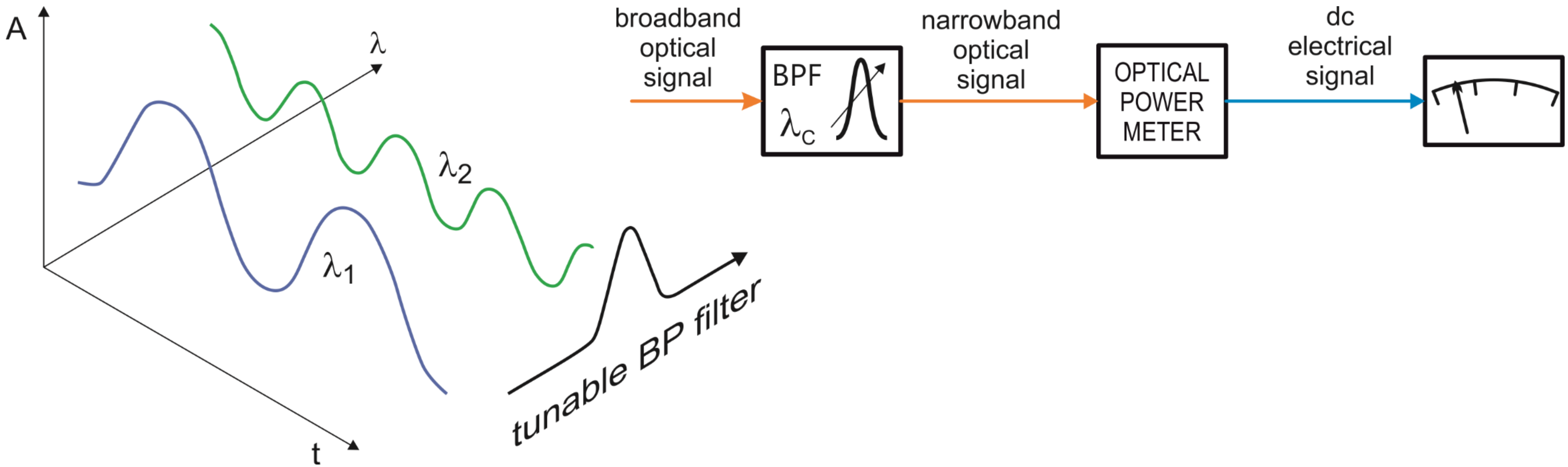
Optical spectrum analysis

- example of measured optical spectrum

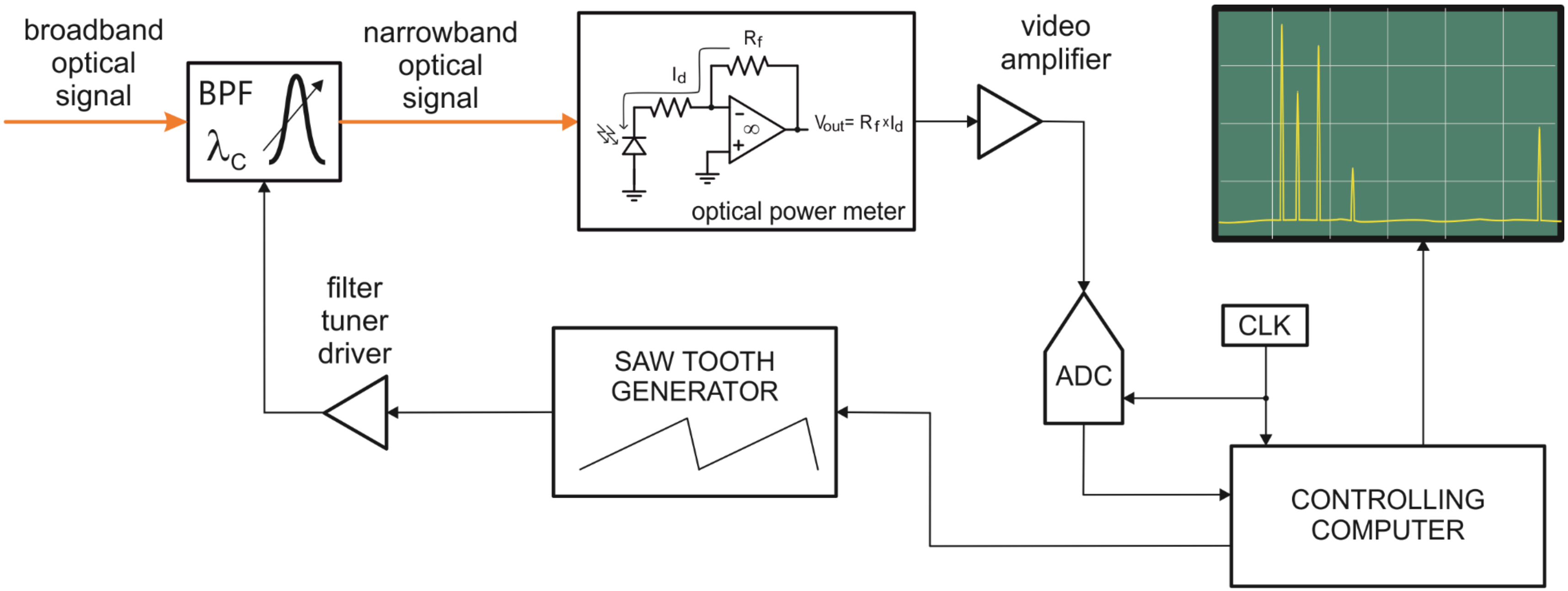


Optical Spectrum Analyzer (OSA): principle scheme



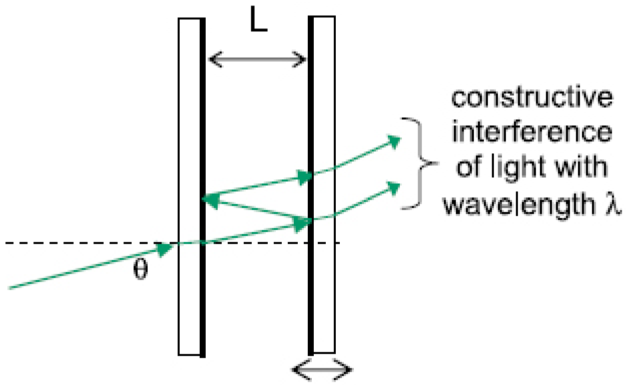
- there is an analogy, as far as the principle of operation is concerned, with the radiofrequency spectrum analyzer
- however, from the point of view of the physical realization, the two instruments are completely different due to the different properties of the optical radiation with respect to the radio-frequency radiation

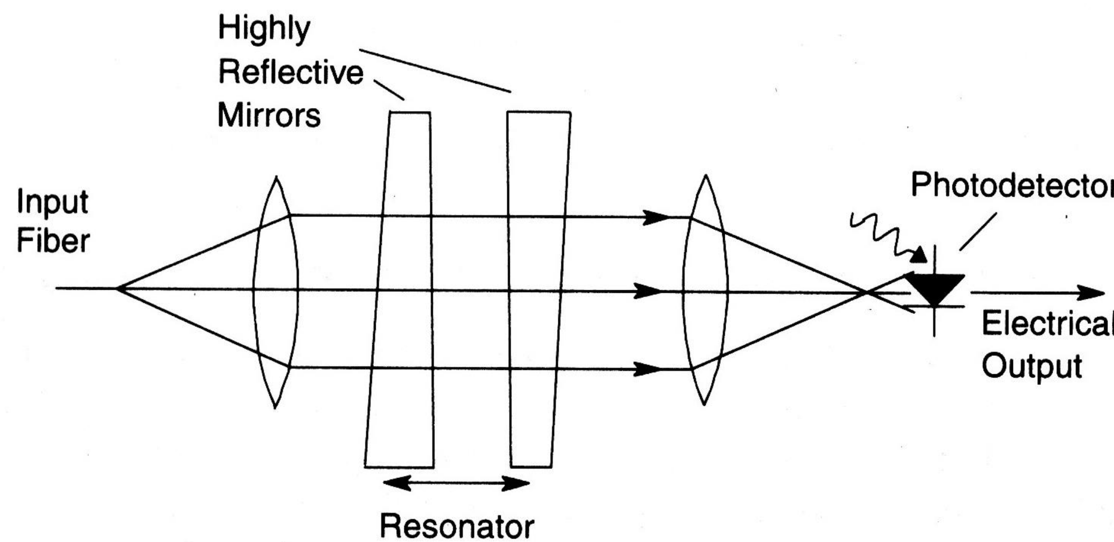
Optical Spectrum Analyzer (OSA): principle scheme



prof. U. Minoni

Fabry-Perot filter (etalon)

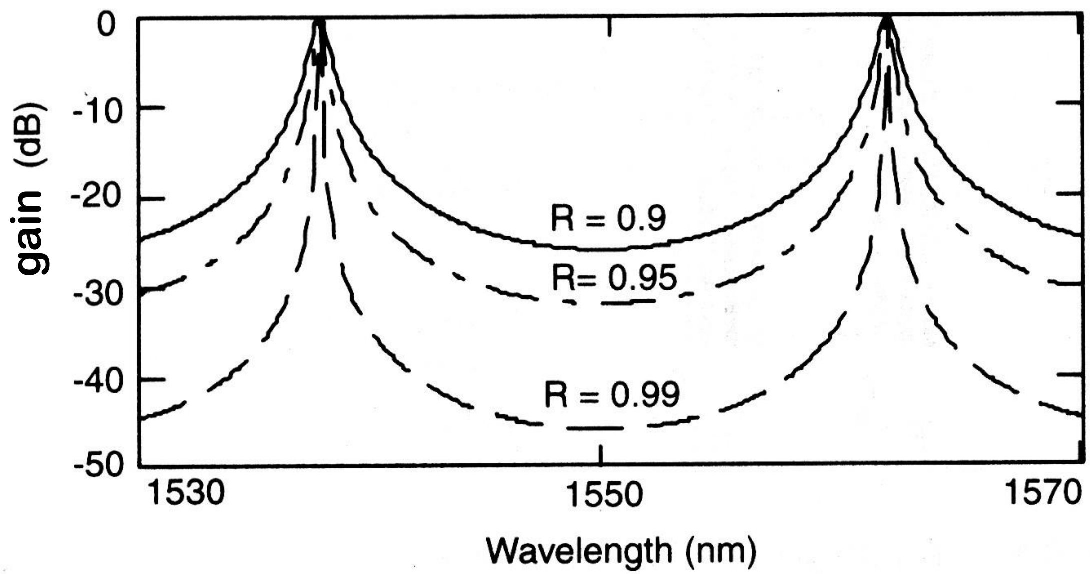




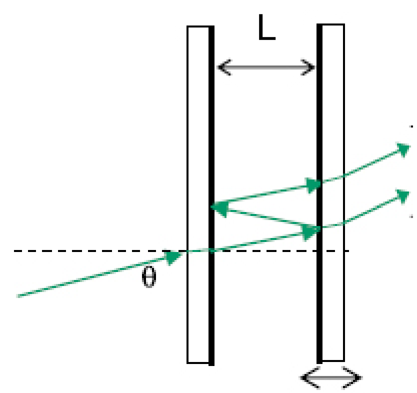
- the Fabry-Perot interferometer acts as a resonant cavity
- the incoming light is band-pass filtered, just the resonant wavelength passes through the filter
- the filter can be tuned by changing the mirror spacing or by rotating the interferometer with respect to the optical axis of the incoming beam

Fabry-Perot filter

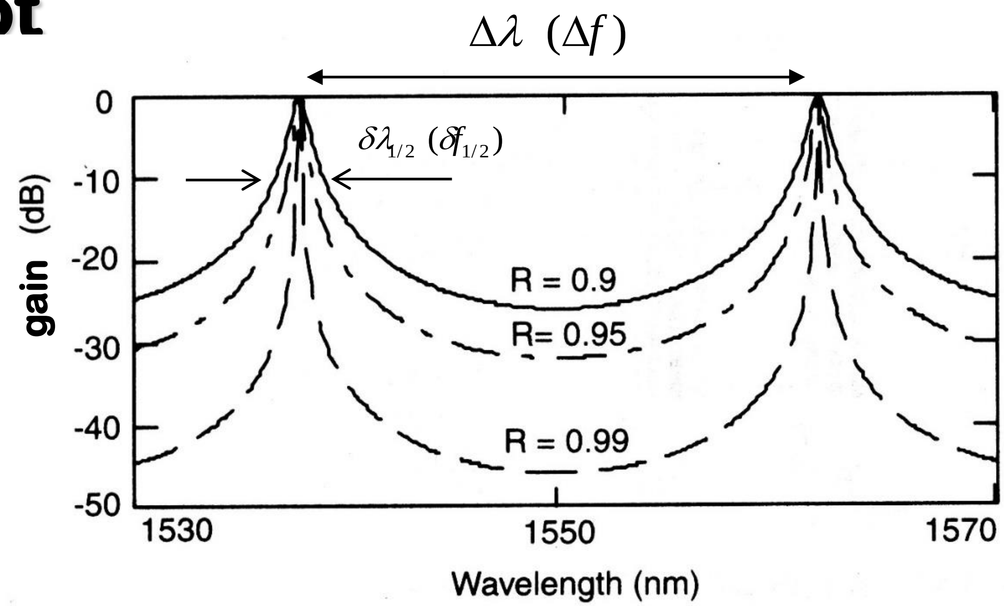
- Transmission function: $T = \dfrac{(1-R)^2}{(1-R)^2 + 4R \cdot sin^2\left(\dfrac{2\pi L n \cos\vartheta}{\lambda_{vacuum}}\right)}$
  R = reflectivity
  L = mirrors spacing
  n = refractive index of the medium
  θ = incidence angle of the light beam measured respect to the optical axis



L = 50 μm



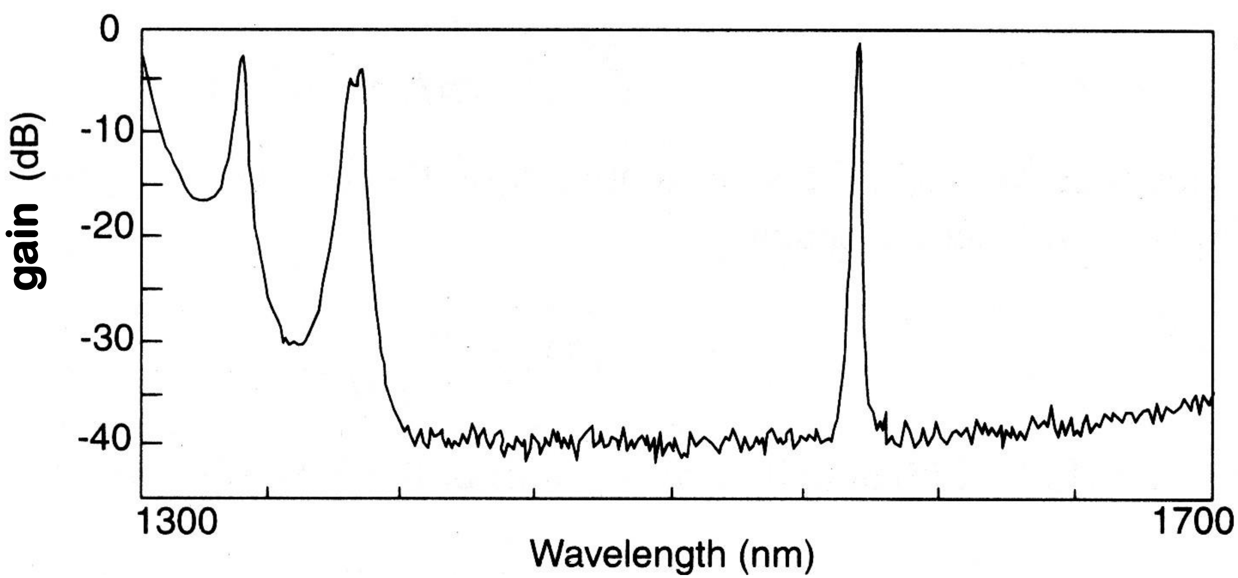
Fabry-Perot



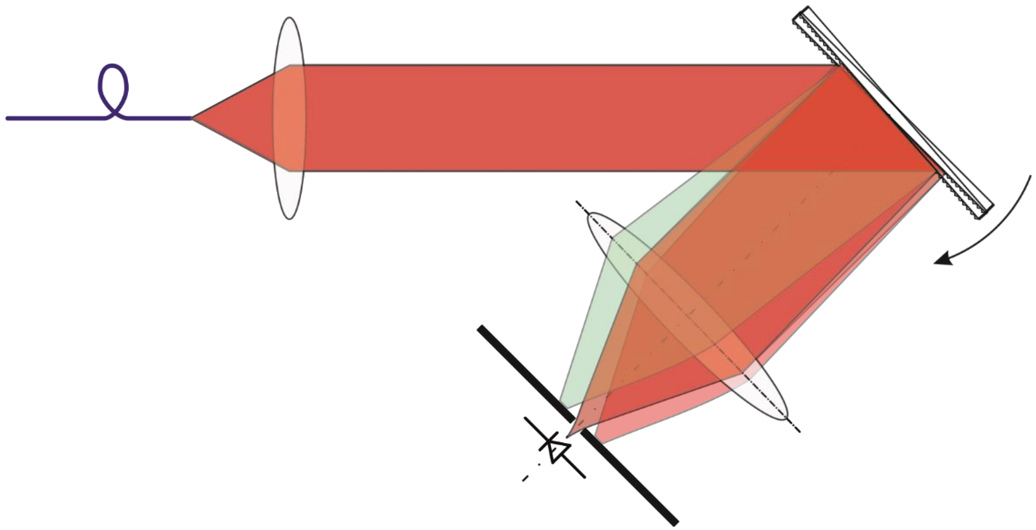
- peaks spacing of the transmission function: $\Delta f = \dfrac{c}{2Ln\cos\vartheta}$
- free spectral range (FSR): $|\Delta\lambda| = \dfrac{\lambda^2}{2Ln\cdot\cos\vartheta}$
- width of the peaks measured at half height: $\delta f_{1/2} = \dfrac{(1-R)c}{2\pi Ln\sqrt{R}\cos\vartheta}$
- finesse: $F = \dfrac{\Delta f}{\delta f_{1/2}} = \dfrac{\pi\sqrt{R}}{(1-R)}$, values up to some thousands for the best filters

Fabry-Perot filter

- very high wavelength resolution
- narrow wavelength range, due to the transmission function periodicity
- the periodicity of the pass-band filtering can be highly reduced by using mirrors having a great reflectivity in a region of the optical spectrum narrower than the peaks spacing of the transmission function

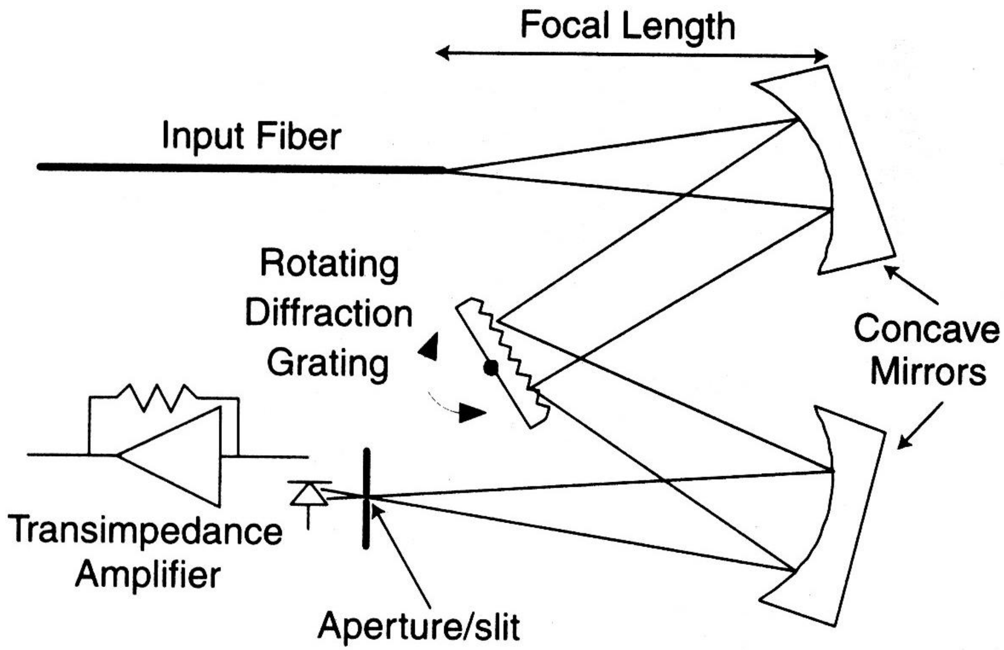


Diffraction-grating-based OSA (a)



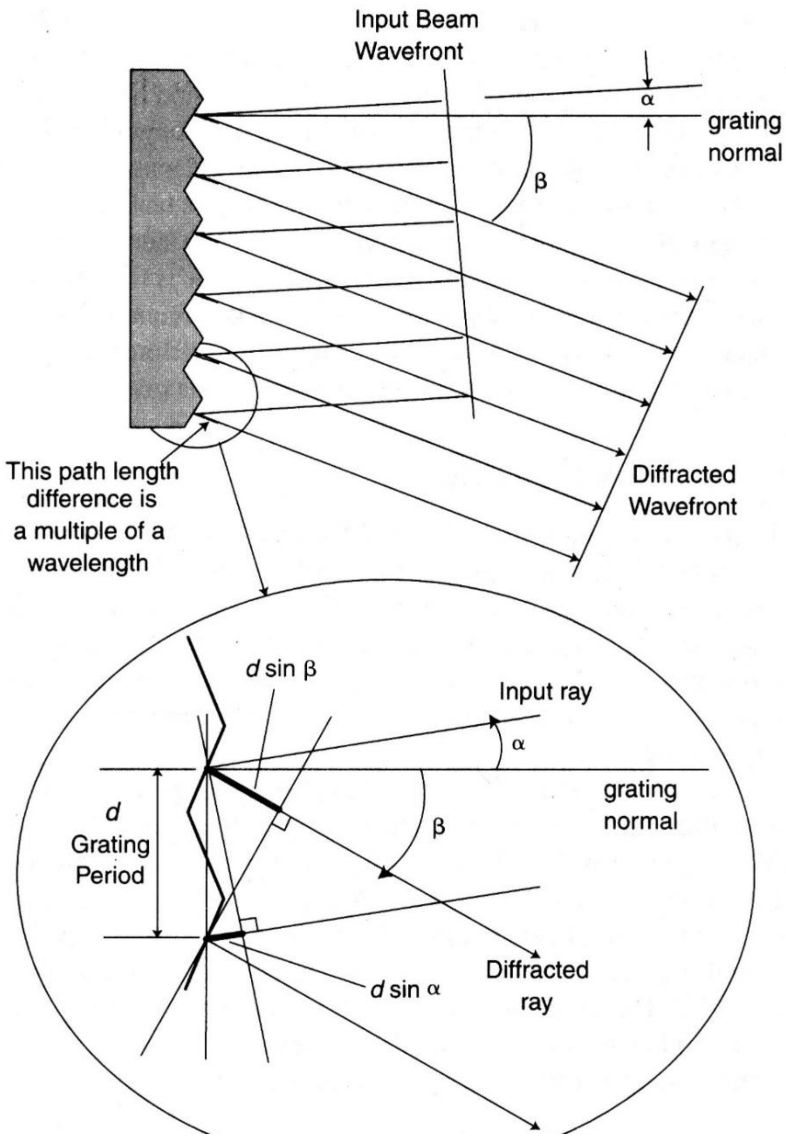
- a diffraction grating is able to spatially separate the different spectral components of the input optical signal
- by rotating the diffraction grating it is possible to select the optical wavelength that is aligned to the slit in front of the photo-detector

Diffraction-grating-based OSA (b)



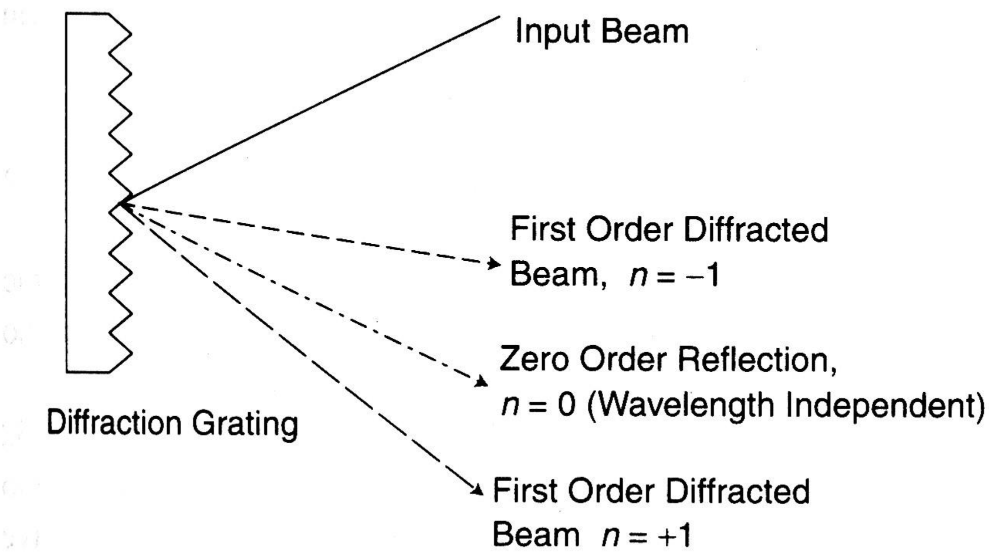
- the optical component set realizes a monochromator that, in conjunction with a photo-detector, is named spectrometer
- an OSA includes a spectrometer and all the auxiliary optical and electronic components required to automate the measurement

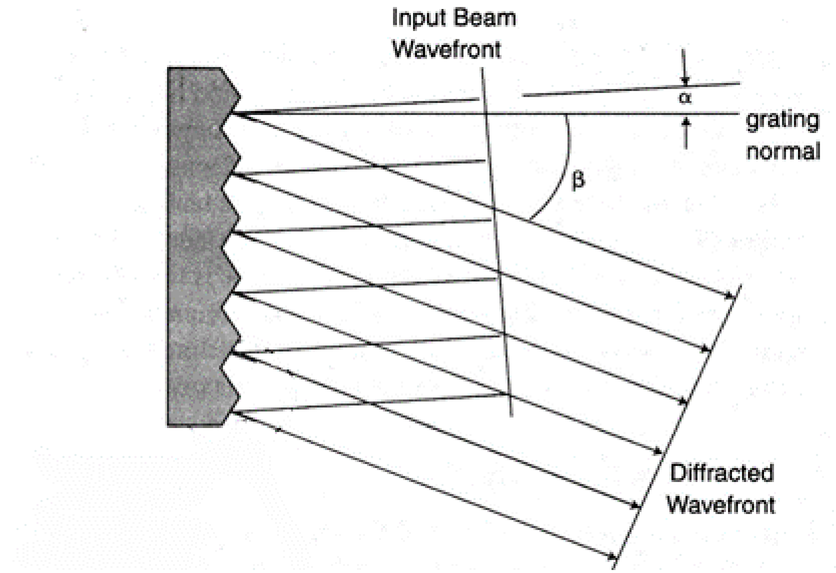
Diffraction grating



- $n \cdot \lambda = d(sin\beta - sin\alpha)$
  - **α = angle of the incident light**
  - **β = angle of diffracted light**
  - **d = grating spacing**
  - **λ = optical wavelength**
  - **n = integral number: diffraction order**

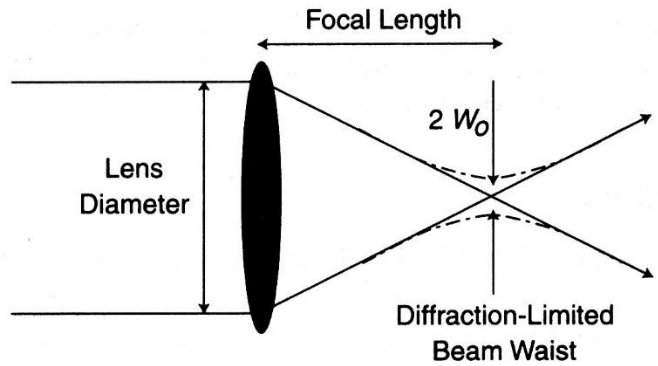
Diffraction grating





- **divergence angle of the diffracted beam:** $\Delta\beta_{min} = \frac{\lambda}{N \cdot d \cdot \cos\beta}$
  N is the number of illuminated lines
- **dispersion (rad/m):** $D = \frac{\Delta\beta}{\Delta\lambda} = \frac{n}{d \cdot \cos\beta}$
- **best resolution:** $\Delta\lambda_{min} = \frac{\lambda}{N \cdot n}$

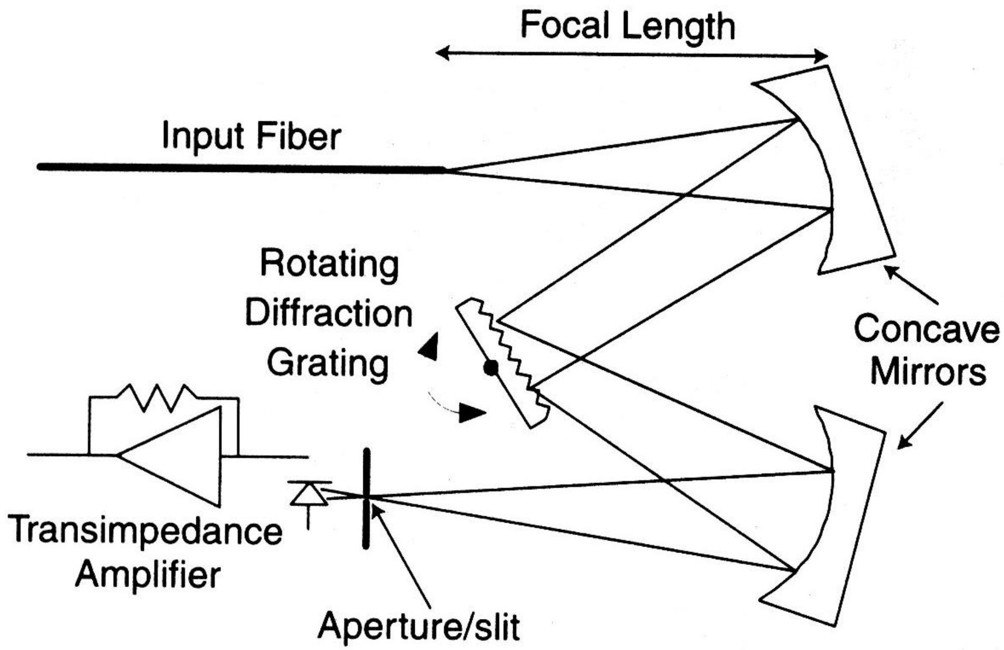
Collimating optics



- this optic accepts the diverging beam at the monochromator input and collimates it to form a plane wave that then illuminates the diffraction grating
- we can use either reflective optics (mirrors) or refractive optics (lenses)
- the collimator focal length must be independent of the optical wavelength λ (no chromatic aberration)
- the diameter of the collimated beam should be as large as possible to achieve high wavelength resolution.

- the optics must be "diffraction-limited": $w_0 = \frac{2\lambda F}{\pi D}$

Diffraction-grating-based OSA (b)



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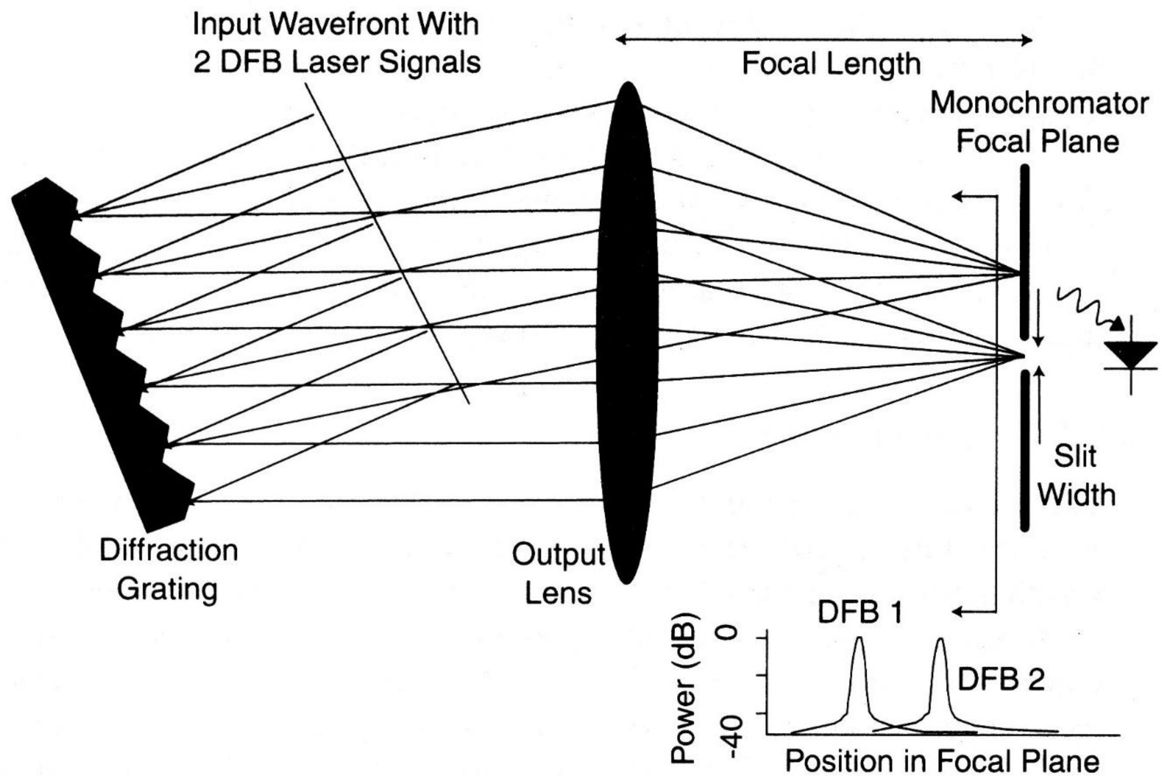
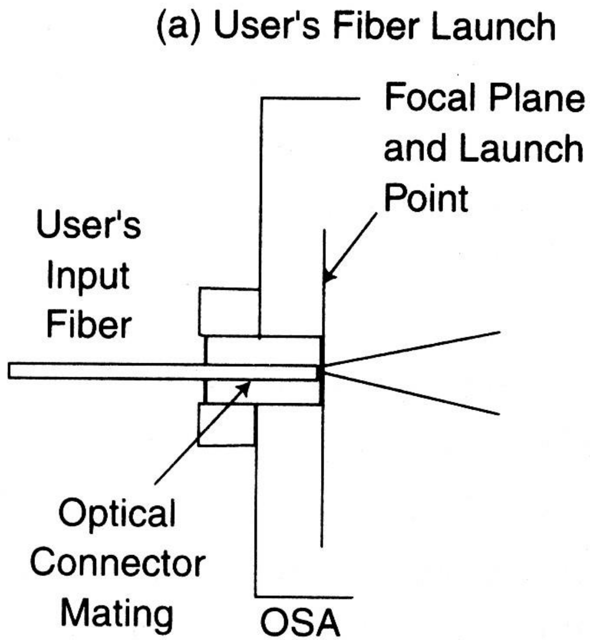
Focusing optics



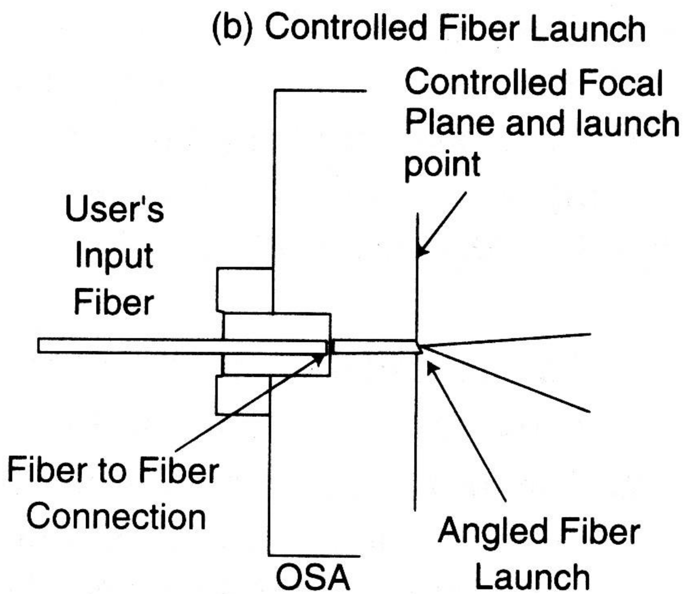
- the focusing optics converts the diffraction angle into a position of the light spot on the focal plane where the photo-detector is placed.

Input stage of an OSA



- a) the fiber carrying the signal to be analyzed coincides with the input slit of the OSA
  - ☺No insertion loss
  - ☺No hazard of damage while connecting the fiber
  - ☹Risk of pollution of the monochromator
  - ☹Low accuracy of the image positioning at the monochromator input
  - 😐The fiber/air interface causes a typical return loss of 14 dB

Input stage of an OSA

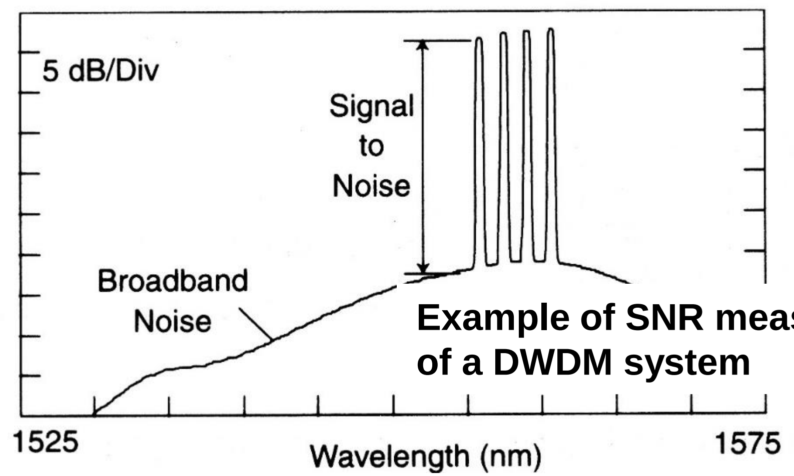


- a short fiber section forms the input of the OSA
  - ☹Insertion loss difficult to evaluate
  - ☹Risk of damage during the fiber connection
  - ☺No possibility to pollute the monochromator
  - ☺Perfect positioning of the image at the monochromator input
  - ☹The interface fiber/fiber causes a typical return loss of 28 dB
  - ☺The reflection at the end of the input fiber can become negligible by using an angled cut

Light detection

- output slit: together with the input slit and the diffraction grating it determines the wavelength resolution of the OSA
- the output slit can be realized with a receiving fiber
- detector: photomultiplier for λ < 1 μm, PIN for λ > 1 μm
- the bandwidth of the amplifier determines the sweep velocity and the instrument sensitivity

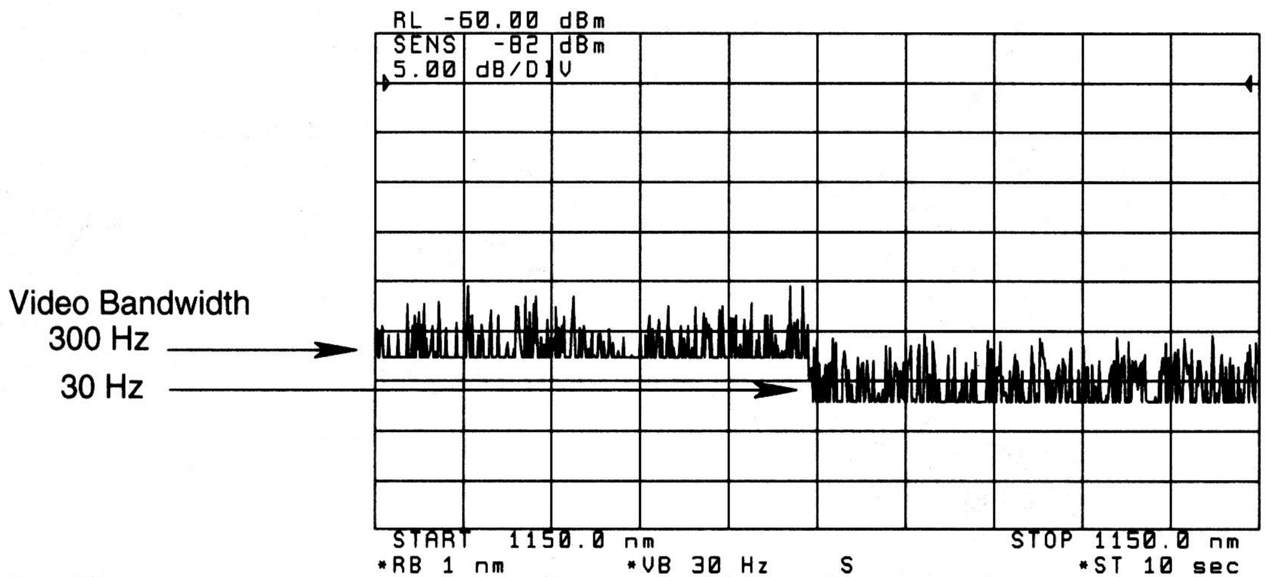
- dynamic range:
  very important for the DWDM systems
  (> 40dB)



Example of SNR measurement of a DWDM system

Sensitivity

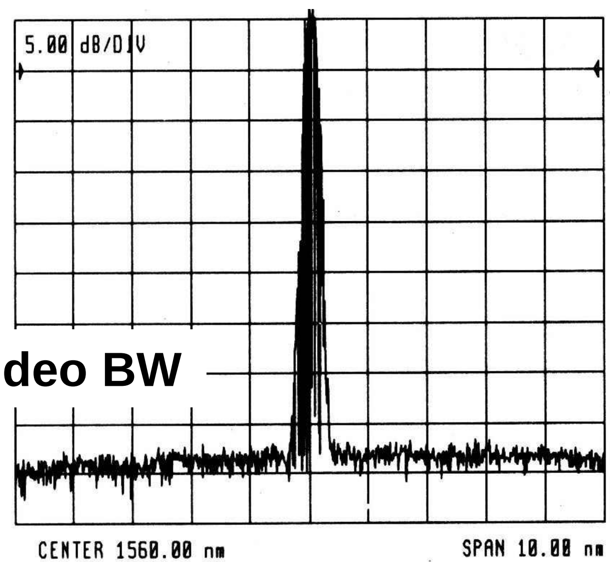
- Limiting factors:
  - power loss of the monochromator: from 3 to 8 dB
  - the detector sensitivity
  - the electronic bandwidth of the photo-detector signal processing chain (video bandwidth)



Spectral measurements on modulated signals

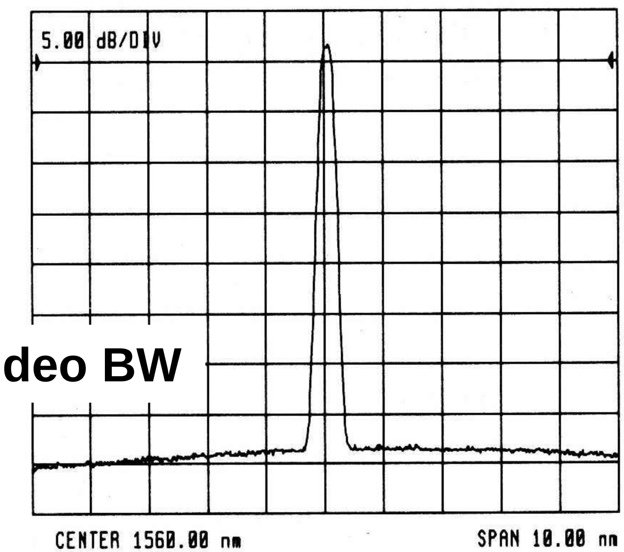
- if the modulation of the optical signal is fast with respect to the sweep time of the OSA the visualized spectrum is the time-average of the input spectrum
- the video bandwidth must be small with respect to the smallest frequency of the modulating signal

excessive video BW



VBW = 700 kHz

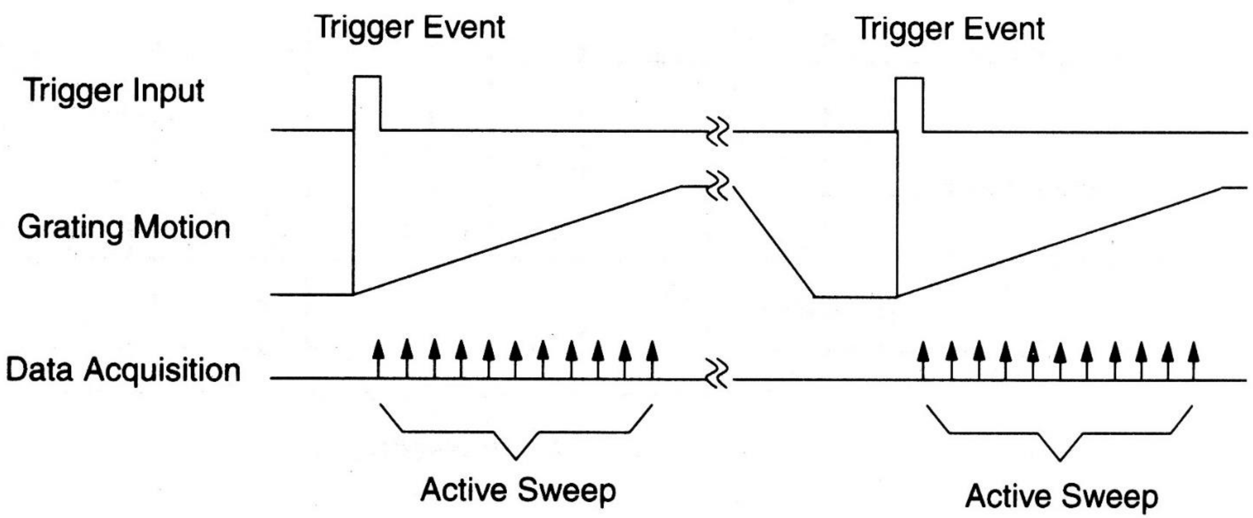
correct video BW



VBW = 100 Hz

Triggered-Sweep mode

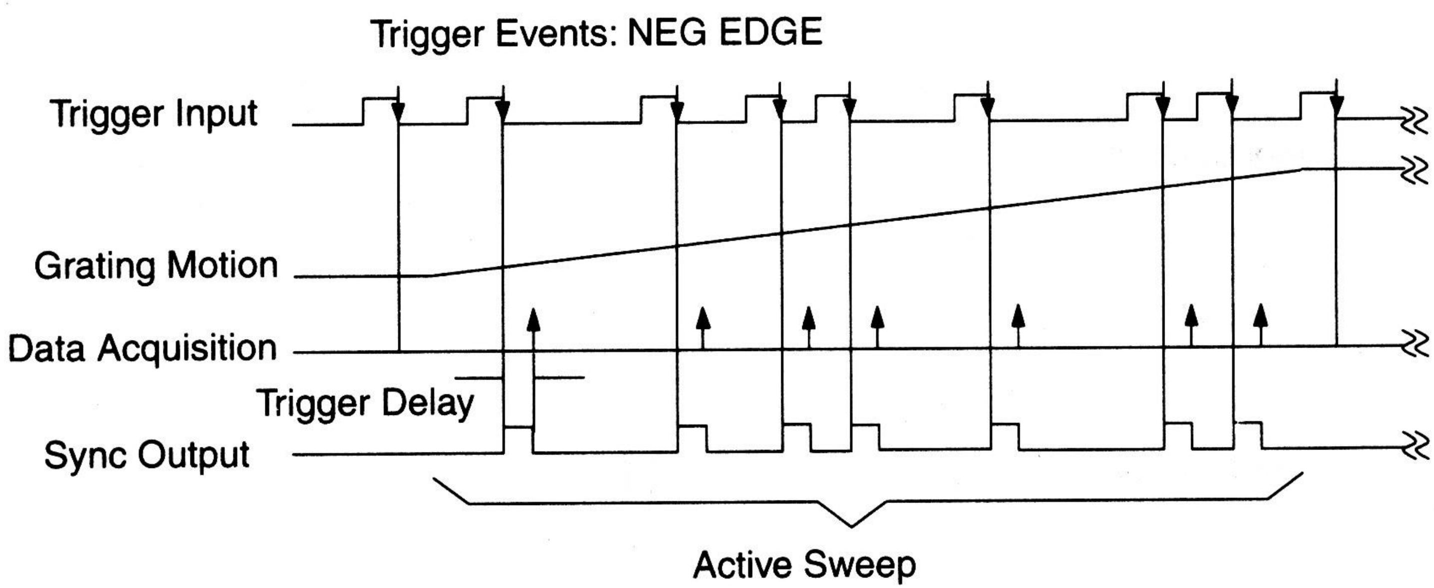
- the sweep is synchronized by a trigger signal



- application example: recording of the spectra emitted by a tunable source. For each step of the signal controlling the laser source, that is for each spectrum change, a trigger pulse is generated and sent to the OSA.

ADC-trigger mode

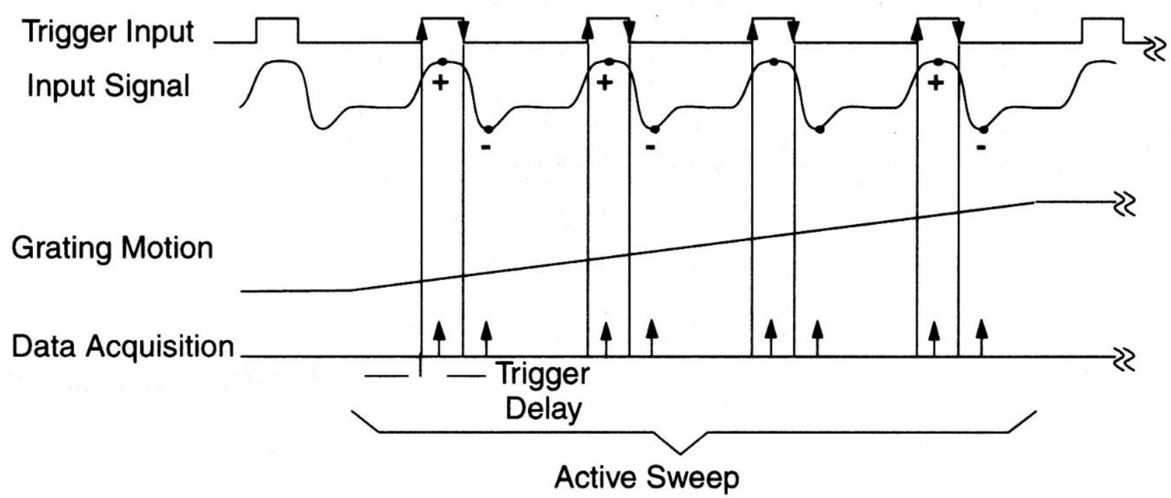
- the sweep is asynchronous, the detector sampling is synchronized with the input optical signal



- application example: the laser source is driven by a pulse train signal. The signal sampling is activated only when the light source is ON.

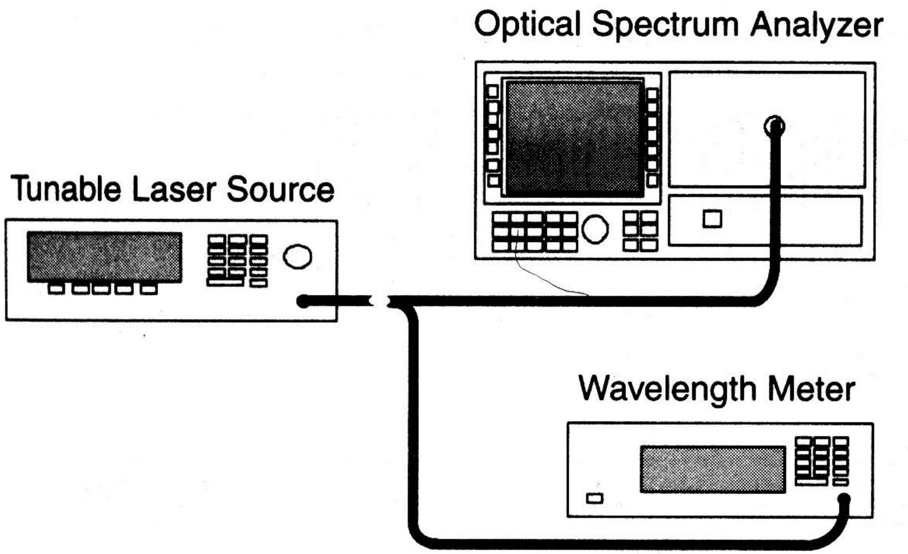
ADC-AC mode

- the sweep is asynchronous, the detector sampling is synchronized with the input optical signal. For each pulse, two samples are acquired: the first one at the rising edge and the second one at the falling edge of the optical pulse. The sample difference is used to build the trace: from the trace it is cancelled the continuous signal component.



- the non-modulated component is suppressed.

Wavelength calibration of the OSA



- A) by comparison to a reference λ meter
- B) by comparison with known absorption lines of a gas