"Optical Measurements"

Master Degree in Engineering
Automation-, Electronics-, Physics-, Telecommunication- Engineering

Optical Measurement Instrumentation

Prof. Cesare Svelto
Politecnico di Milano

Summary

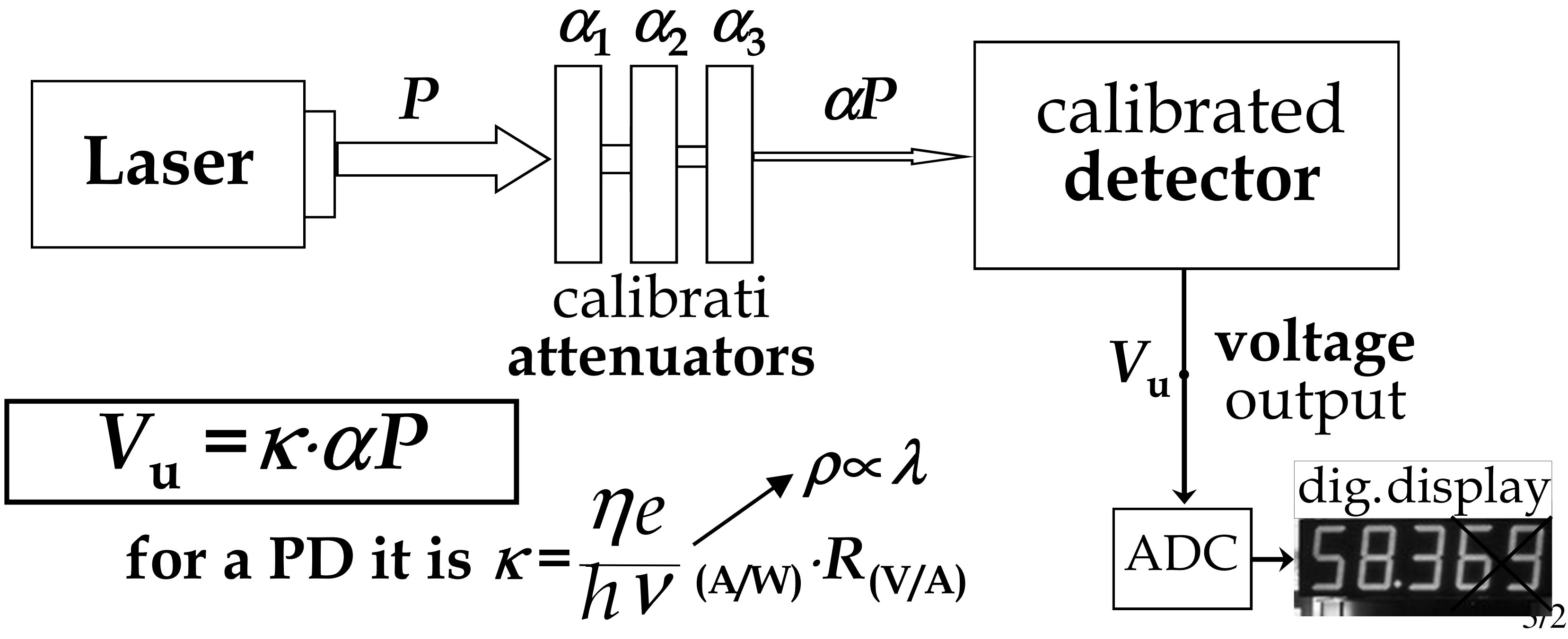
- Optical Power Meter
- CCD detectors (Charge Coupled Device)
  and measurement of laser beam profile
- Wave-Meter and spectrometer/monochromator
- Optical Spectrum Analyzer (OSA)
- Optical Time Domain Reflectometry (OTDR)
- Meas. of Insertion Loss
- Meas. of Polarization Mode Dispersion (PMD)
- Meas. of Bit Error Rate (BER)

Meas. of Optical Power
(DEFINITIONS and METHODS)

- E Electric field [V/m]
- $I = \dfrac{EE^*}{\eta_0}$ Intensity [W/m^2]

$\eta_0 = (\mu_0/\varepsilon_0)^{1/2} = 377\ \Omega$
vacuum impedance

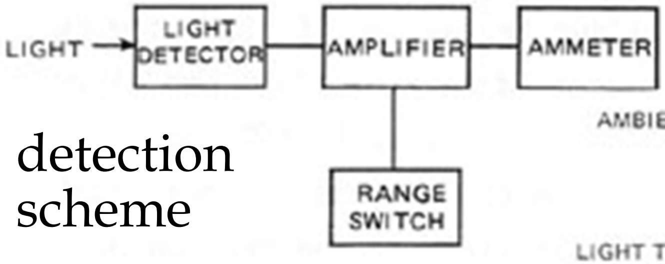
- $P = \int I \mathrm{d}S$ **Power [W]**



$$\boxed{V_{\mathbf{u}} = \kappa \cdot \alpha P}$$

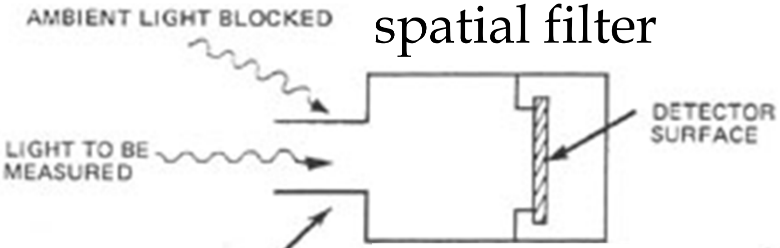
for a PD it is $\kappa = \dfrac{\eta e}{h\nu}_{\mathbf{(A/W)}} \cdot R_{\mathbf{(V/A)}}$ $\nearrow \rho \propto \lambda$

Optical Power Meter (structure)

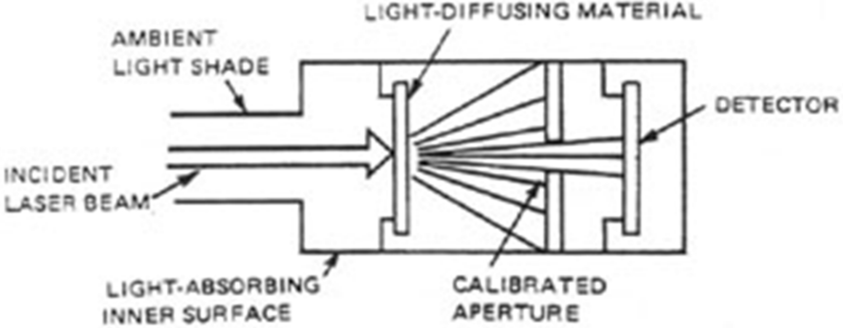


detection
scheme

spatial filter

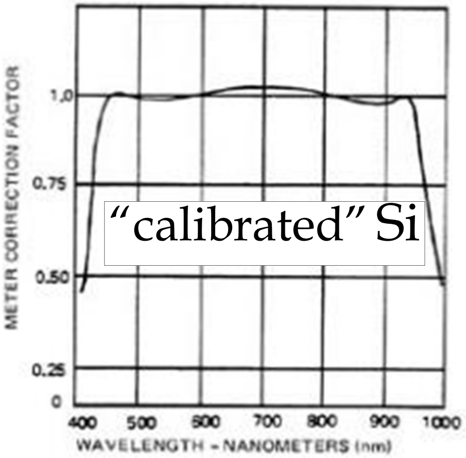


attenuator



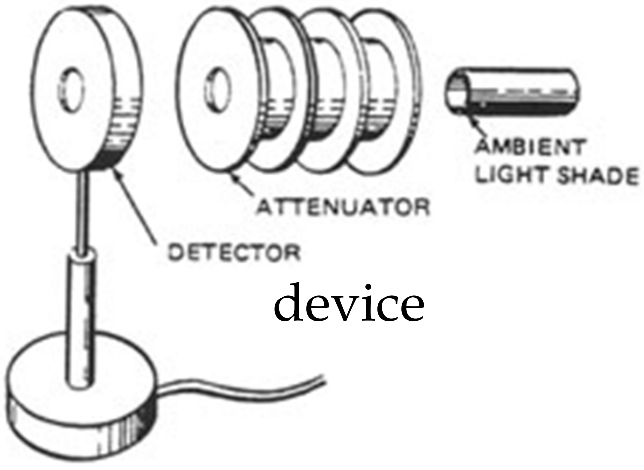
The detector can be THERMAL or SEMICONDUCTOR (thermal detectors have "flat" response)

$$\eta_{abs}P_{opt}=P_{therm}=K\Delta T=K(T-T_{amb})$$
$$\Rightarrow T \propto P_{opt}$$



"calibrated" Si

CALIBRATION



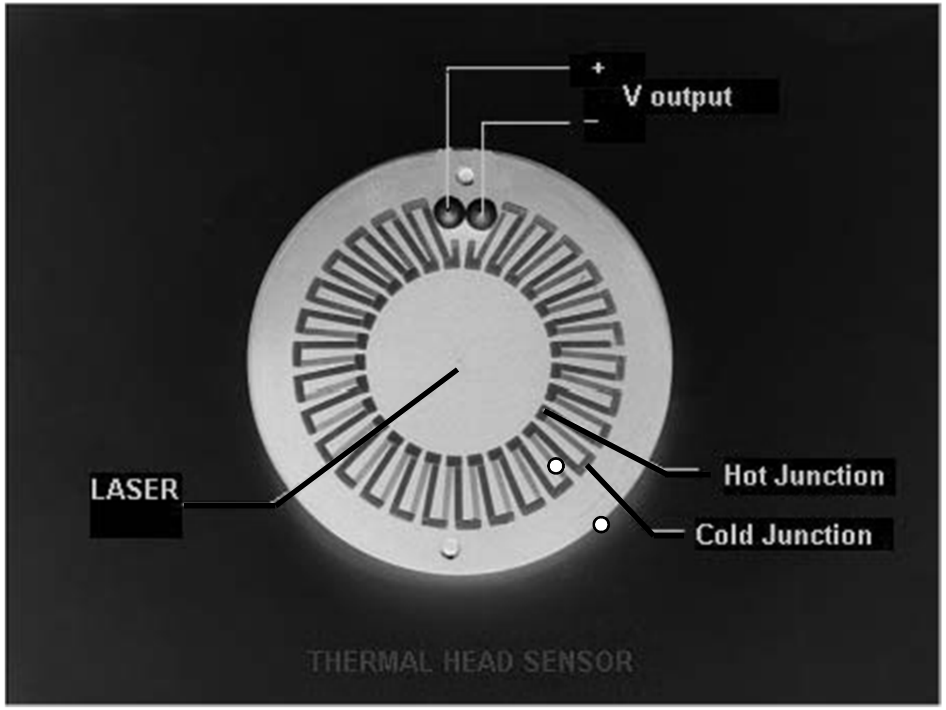
device

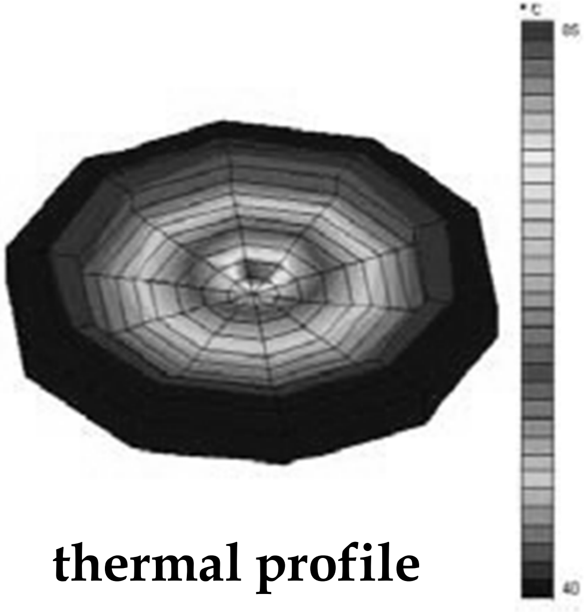
commercial
device

0.1 dB = 2.3×10^{-2}
0.01 dB = 2.3×10^{-3}

Power Meter (thermal sensor)

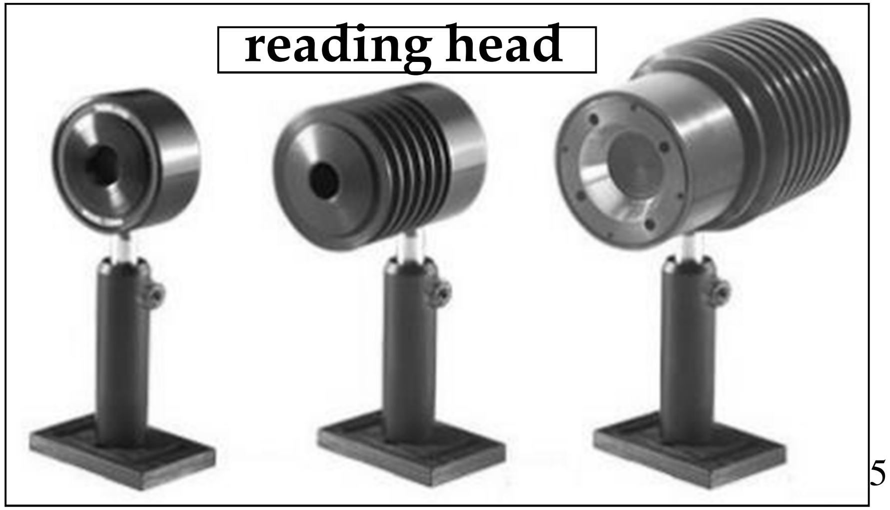
THERMOPILE detector





thermal profile

10W-Sensor Disk

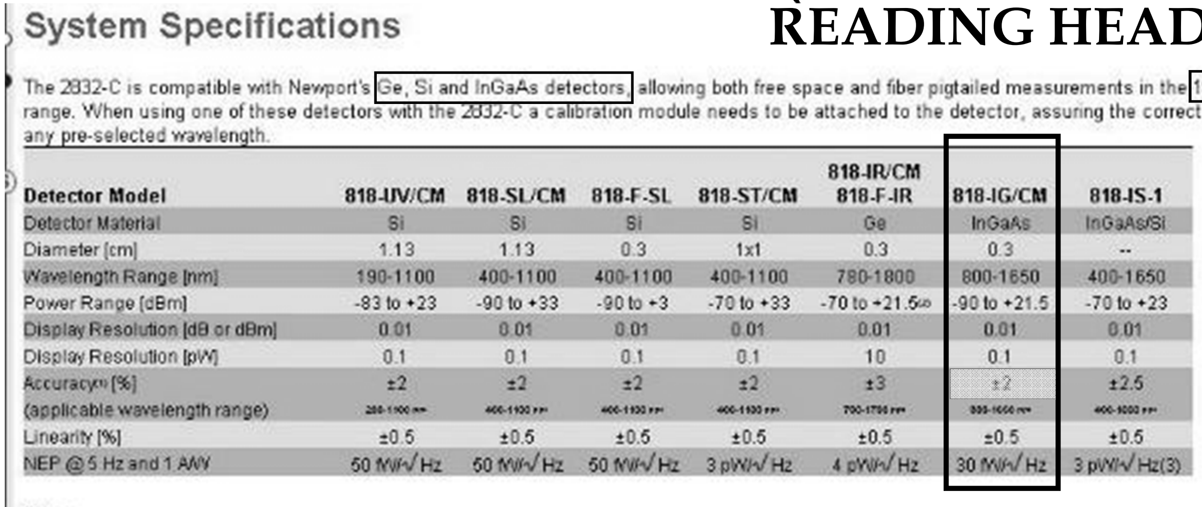


The thermal field has a radial gradient: from central "hot" zone to the "cold" border

Very "slow" (*B*=1 Hz) but accurate for DC power or average meas.

Power Meter (semiconductor specs.)

READING HEAD



System Specifications

The 2832-C is compatible with Newport's Ge, Si and InGaAs detectors, allowing both free space and fiber pigtailed measurements in the 190-1800 nm range. When using one of these detectors with the 2832-C a calibration module needs to be attached to the detector, assuring the correct reading at any pre-selected wavelength.

Detector Model	818-UV/CM	818-SL/CM	818-F-SL	818-ST/CM	818-IR/CM 818-F-IR	818-IG/CM	818-IS-1
Detector Material	Si	Si	Si	Si	Ge	InGaAs	InGaAs/Si
Diameter [cm]	1.13	1.13	0.3	1x1	0.3	0.3	--
Wavelength Range [nm]	190-1100	400-1100	400-1100	400-1100	780-1800	800-1650	400-1650
Power Range [dBm]	-83 to +23	-90 to +33	-90 to +3	-70 to +33	-70 to +21.5(2)	-90 to +21.5	-70 to +23
Display Resolution [dB or dBm]	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Display Resolution [pW]	0.1	0.1	0.1	0.1	10	0.1	0.1
Accuracy(1) [%]	±2	±2	±2	±2	±3	±2	±2.5
(applicable wavelength range)	280-1100 nm	400-1100 nm	400-1100 nm	400-1100 nm	700-1700 nm	800-1650 nm	400-1000 nm
Linearity [%]	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5
NEP @ 5 Hz and 1 A/W	50 fW/√Hz	50 fW/√Hz	50 fW/√Hz	3 pW/√Hz	4 pW/√Hz	30 fW/√Hz	3 pW/√Hz(3)

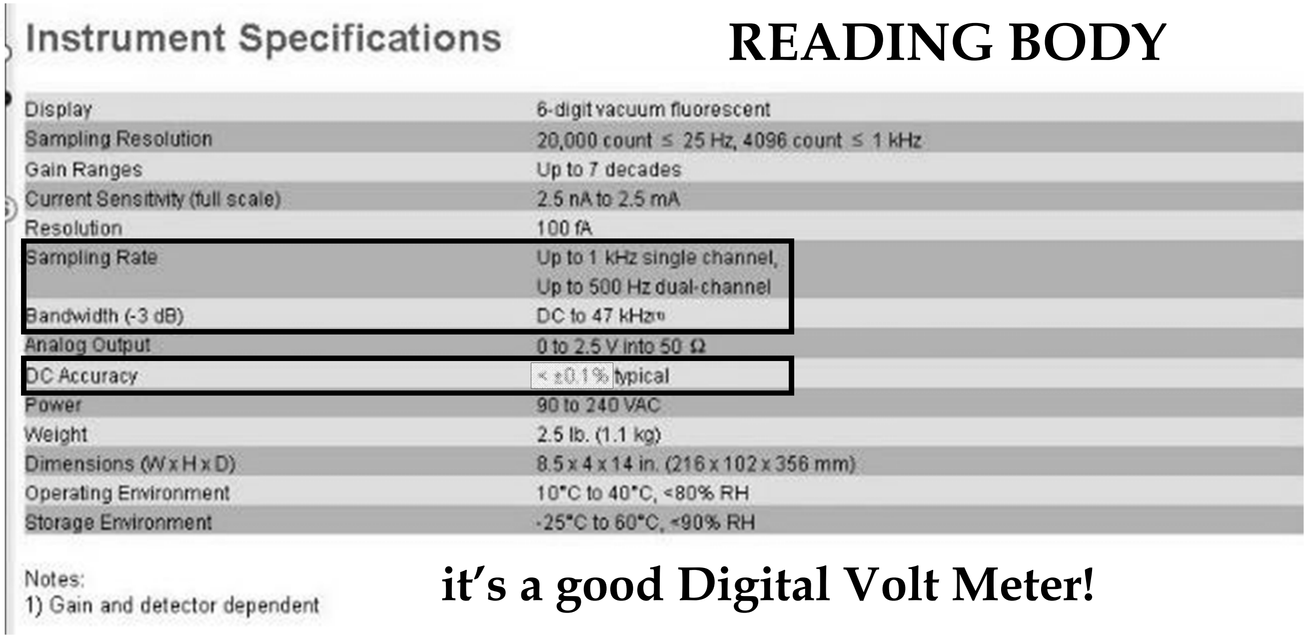
Notes:
1) At calibration temperature, no optical attenuator
2) -70 to +3 dBm for 818-F-IR
3) 0.01 A/W for the 818-IS-1

P_{min}=-90dBm=1pW

P_{max}=+21.5dBm=140mW

11 orders of magnitude!!!

READING BODY



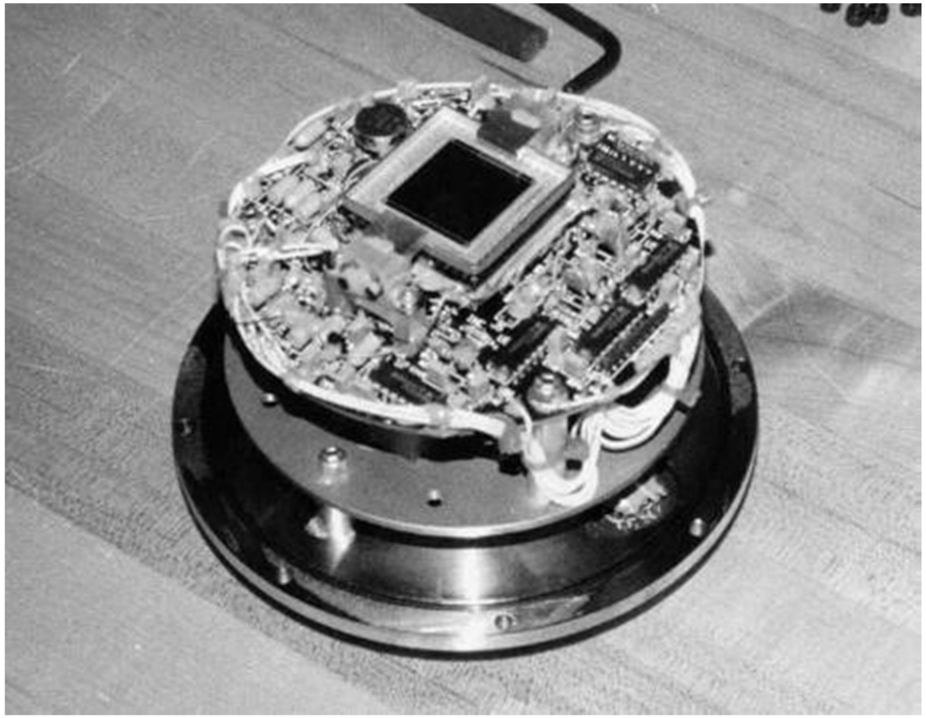
Instrument Specifications

Display	6-digit vacuum fluorescent
Sampling Resolution	20,000 count ≤ 25 Hz, 4096 count ≤ 1 kHz
Gain Ranges	Up to 7 decades
Current Sensitivity (full scale)	2.5 nA to 2.5 mA
Resolution	100 fA
Sampling Rate	Up to 1 kHz single channel, Up to 500 Hz dual-channel
Bandwidth (-3 dB)	DC to 47 kHz(1)
Analog Output	0 to 2.5 V into 50 Ω
DC Accuracy	< ±0.1% typical
Power	90 to 240 VAC
Weight	2.5 lb. (1.1 kg)
Dimensions (W x H x D)	8.5 x 4 x 14 in. (216 x 102 x 356 mm)
Operating Environment	10°C to 40°C, <80% RH
Storage Environment	-25°C to 60°C, <90% RH

Notes:
1) Gain and detector dependent

it's a good Digital Volt Meter!

CCD detectors



A 1024x1024 CCD camera for UV spectrometer

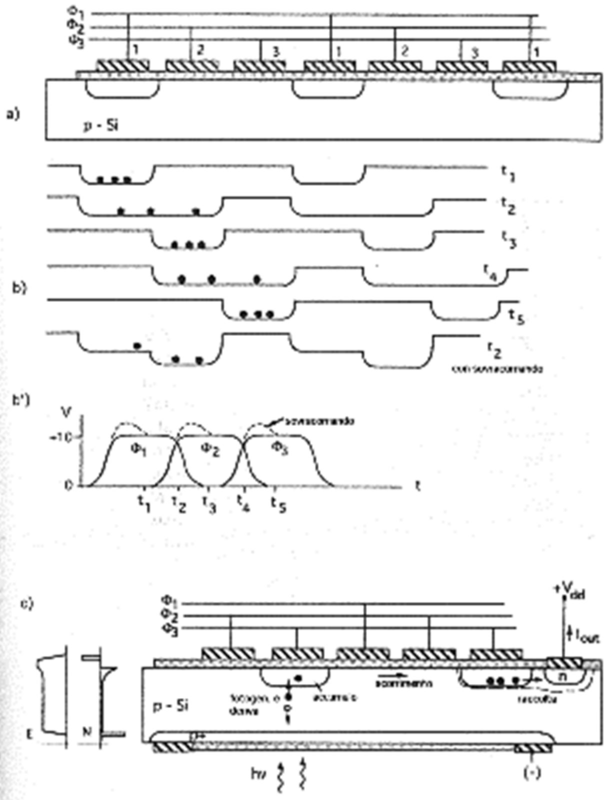


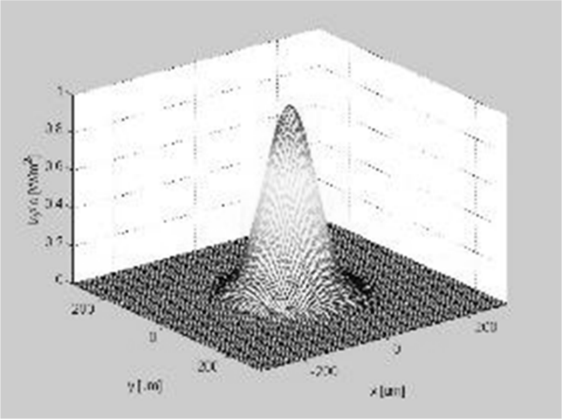
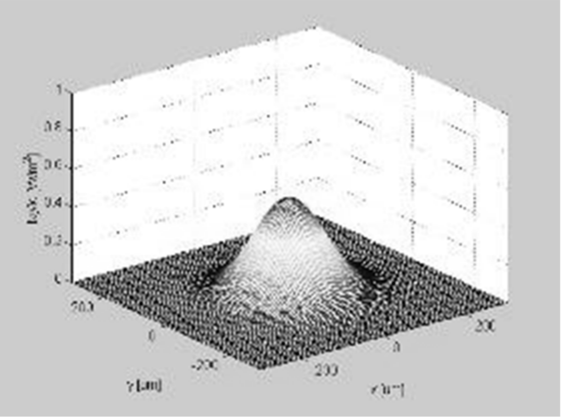
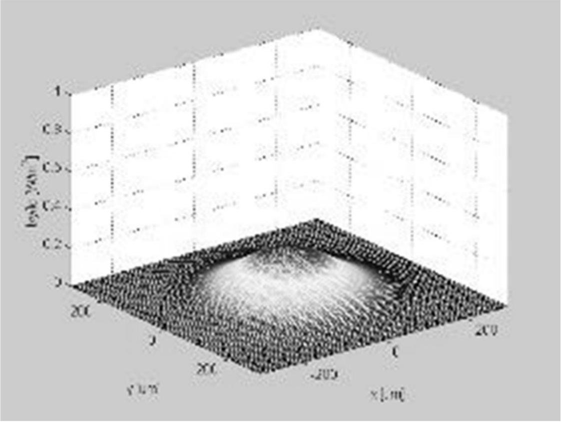
Fig.4.2.2 **a)**: Struttura base del CCD; **b)** sequenza temporale delle buche di potenziale per lo scorrimento della carica quando le fasi sono comandate con i segnali indicati in b'); c) struttura che mostra la fotogenerazione nella regione p, lo scorrimento e la raccolta al pozzo; è indicato l'andamento in profondità della densità di carica e del campo

- **Sliding and collection of photodetected charges**
- Image reconstruction on a **pixel matrix** (visualization by raster display)
- Important: **single pixel dimensions**

Figure from book 'Photodetectors',
by S.Donati, 2nd Ed., AEI Milan 1997.

Meas. of laser beam profile

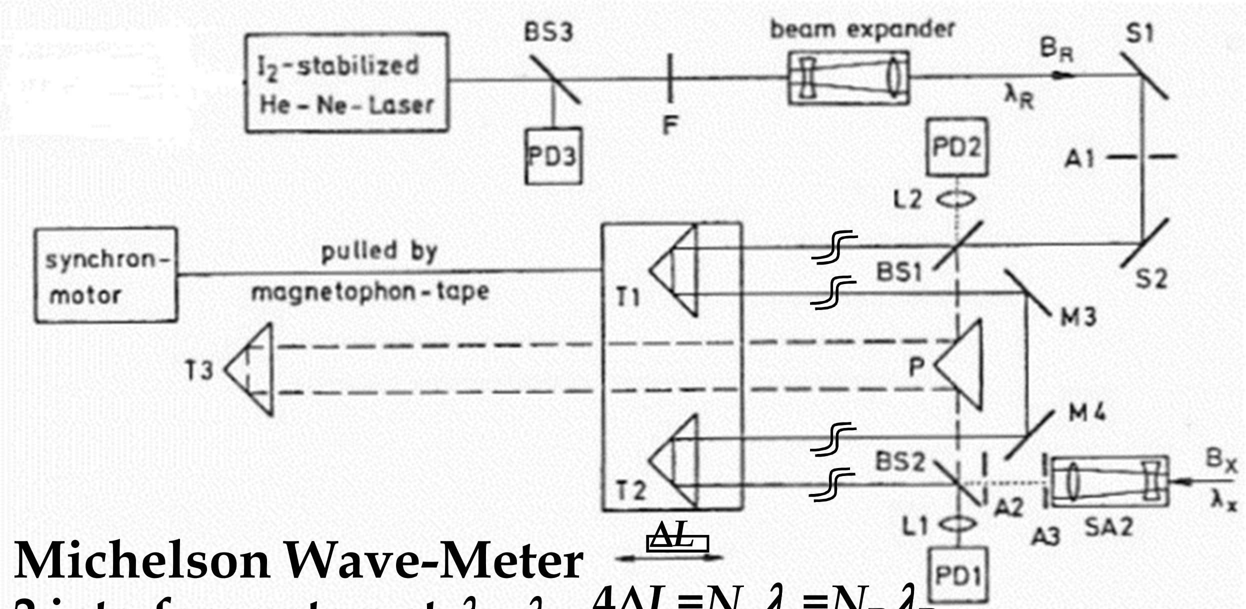
(Analysis in the ***xy*** **plane** during *z*-propagation)

- Meas. of the beam **spot size** $w=w_0\left[1+\left(\frac{z\lambda}{\pi w_0^2}\right)^2\right]^{1/2}$
- Far field ($z>>z_R$): meas. of **divergence** $\theta=\frac{\Delta w}{\Delta z}$
- Meas. of **astigmatism** $w_{0x} \neq w_{0y}$ $\theta_x \neq \theta_y$
- **Meas. of M^2 =** $\frac{\theta_{\text{mis}}}{\theta_{\text{d.l.}}} = \frac{\theta_{\text{mis}}}{\lambda/\pi w_0}$ $\left(M_x^2 \;\; e \;\; M_y^2 \right)$

Laboratory Wave-Meter
(it is a very-accurate interferometer!)

Radiation under test (λ_x) and a reference one (λ_R) travel, in vacuum, along the **same path counted as interference fringes** on the two detectors PD1 e PD2



Michelson Wave-Meter

2 interferometers at λ_x, λ_R **$4\Delta L = N_x\lambda_x = N_R\lambda_R$**

PD2 counts N_x fringes at λ_x

PD1 counts ($N_R+\varepsilon$) fringes at λ_R

$$\Rightarrow \lambda_x = \frac{N_R+\varepsilon}{N_x}\lambda_R \approx \frac{N_R}{N_x}\lambda_R = \kappa\lambda_R$$

Relative uncert. $\left|\frac{\Delta\lambda_x}{\lambda_x}\right| \approx \left|\frac{\Delta\lambda_R}{\lambda_R}\right| = 10^{-10}$ thanks to He-Ne/I$_2$

$u_r(\lambda_R)=2.5\times10^{-11}$

$\Delta\lambda/\lambda=10^{-10} \rightarrow$ ...

λ_x=1.55μm $\Delta\lambda_x$=1.55×10^{-16}m=0.15fm

ν_x≅193THz $\Delta\nu_x$≅19.3kHz ≈20kHz

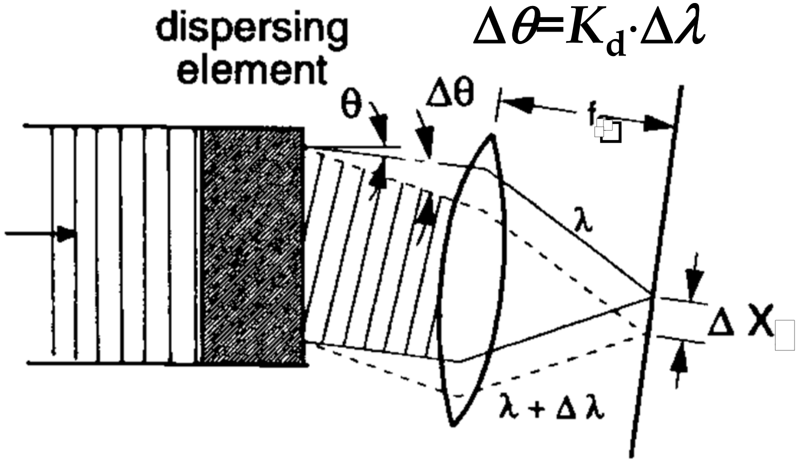
For λ_R=633nm, ΔL=30cm one gets N_R≈1.9×10^6
with λ_x=1550nm one gets N_x≈7.7×10^5

Wave-Meter for DWDM systems

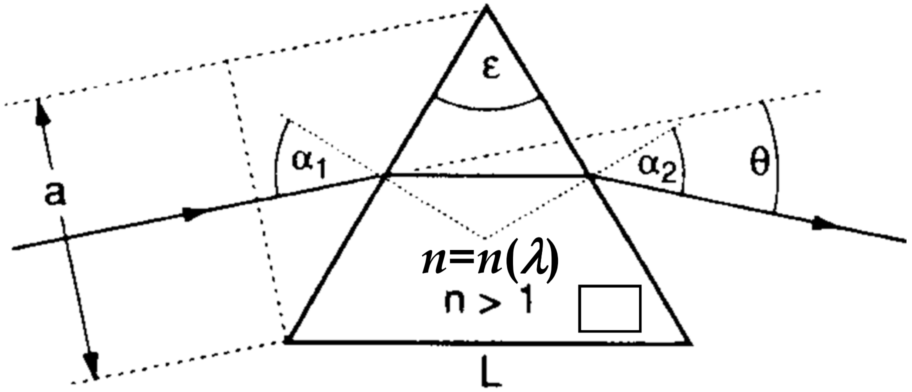
- Simultaneous meas. up to **256 channels**
- **$u(\lambda)$=0.3 pm (300fm!) and $\Delta\lambda$=1÷0.1 pm**
- Meas. **peak power** and **total power**
- Automatic meas. **SNR** and **spacings $\Delta\lambda$**
- **Waterfall diagram** of $\lambda(t)$ and $P(t)$

Spectrometer and monochromator

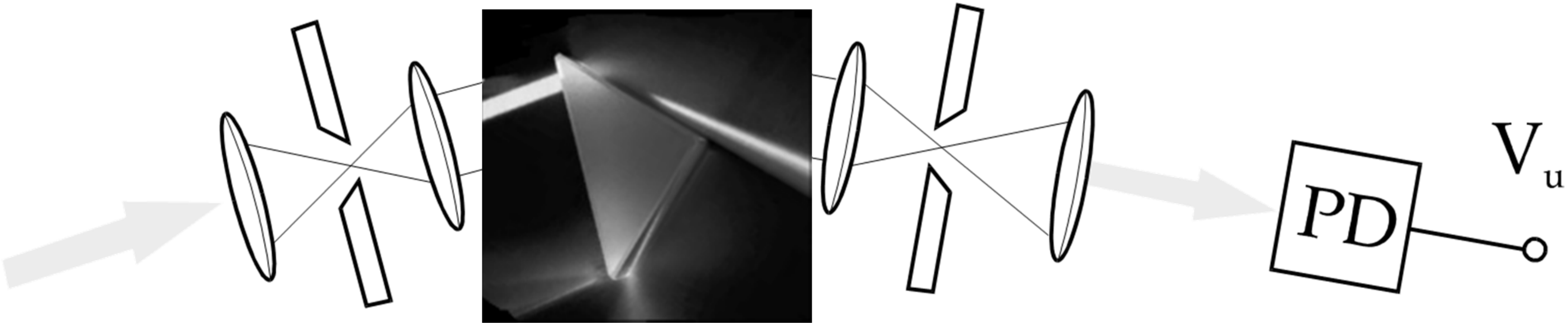
$\Delta\theta = K_d \cdot \Delta\lambda$



$K_d = (d\theta/d\lambda)$
dispersive power



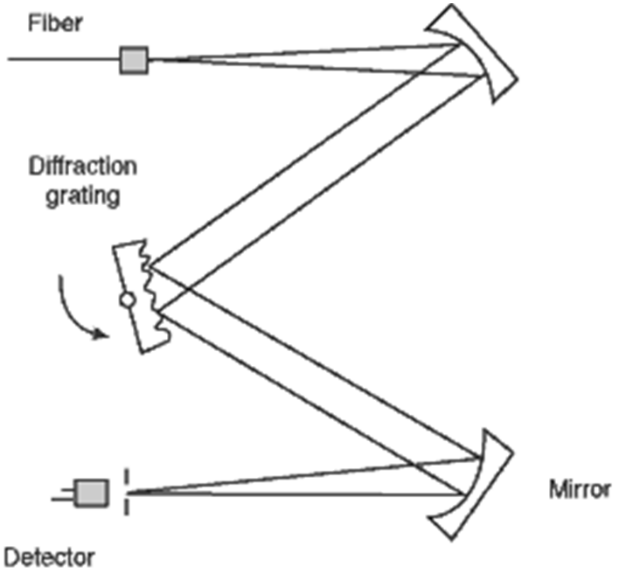
- **Tunable monochromator**

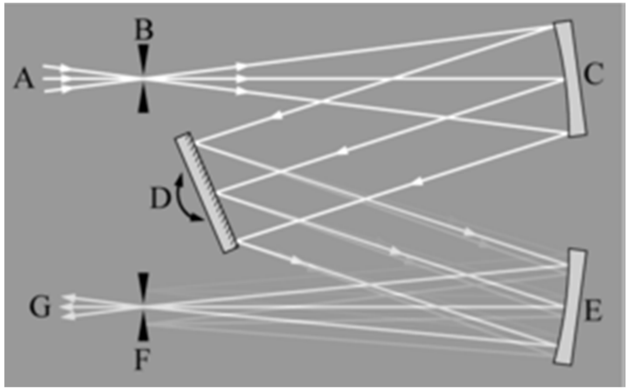


(spectral) resolving power $r = | \Delta\lambda_{min} / \lambda | = | \Delta\nu_{min} / \nu |$
spectral res. (∝ angular res.) $\Delta\lambda_{typ} \approx 0.01$**nm** (10 pm >> 0.1-100 fm=$R_{W\text{-}M}$)

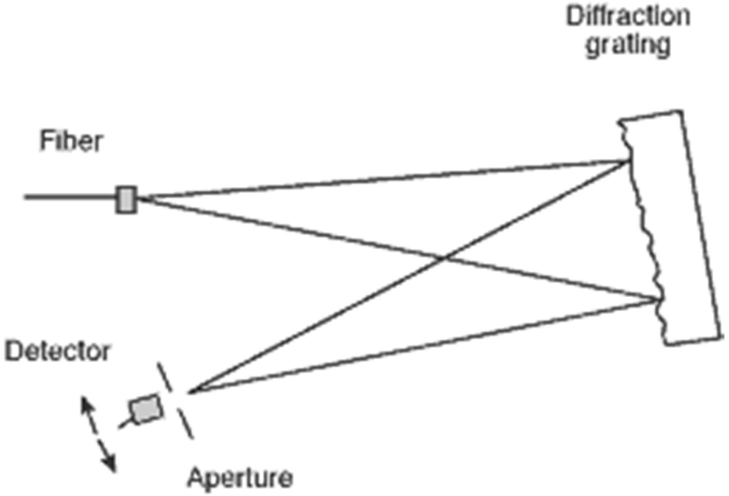
OSA: functional schemes

- **traditional OSA (monochromator with rotating prism/grating)**

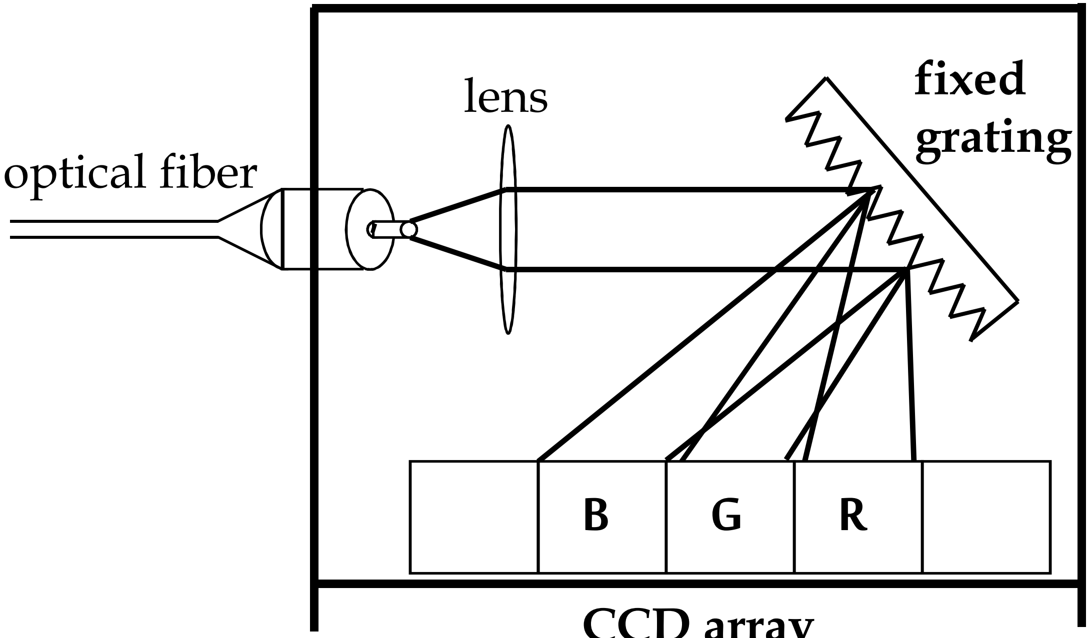




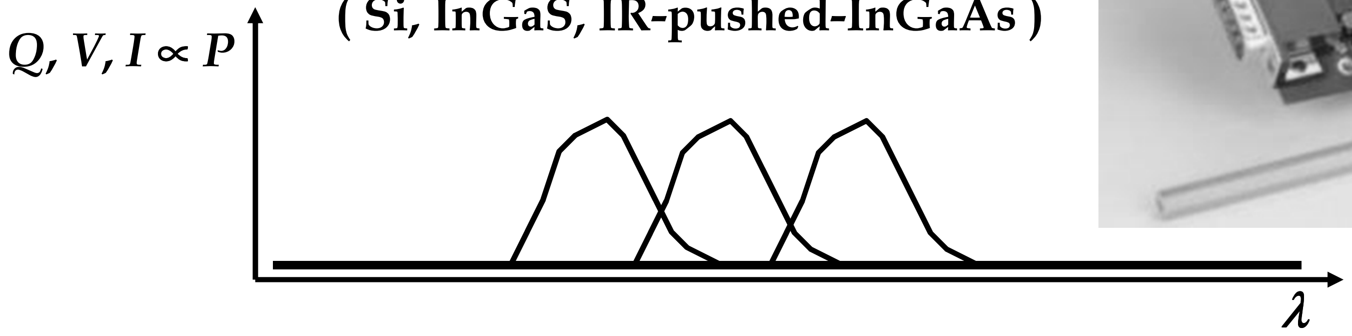
- **narrow-band "field" OSA** ***shock-resistant*** **(fixed *grating* and moving detector or better fixed CCD array)**



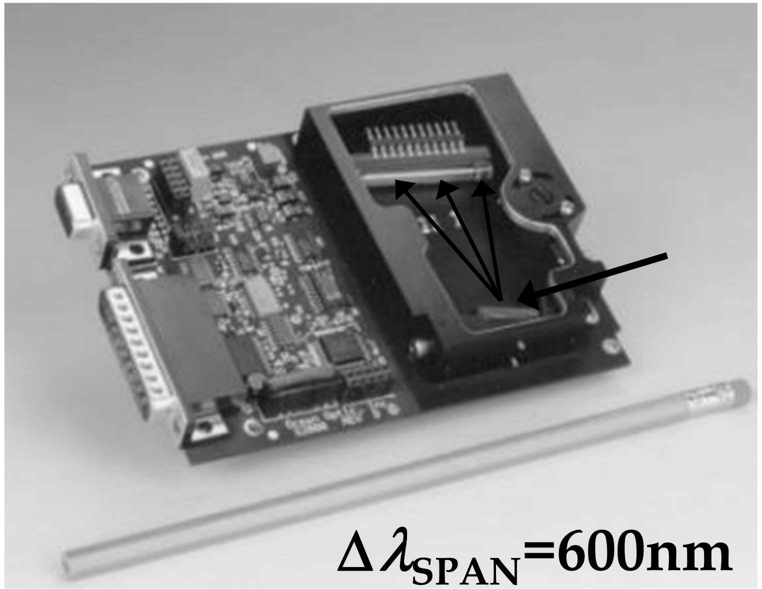
Ultra-compact OSA (PC board)



CCD array
(Si, InGaS, IR-pushed-InGaAs)



2048 ***pixel***
($12.5\mu m \times 200\mu m$)
$\mathbf{L=25.6mm}$
$\mathbf{\Delta\lambda_{res}=0.3nm}$

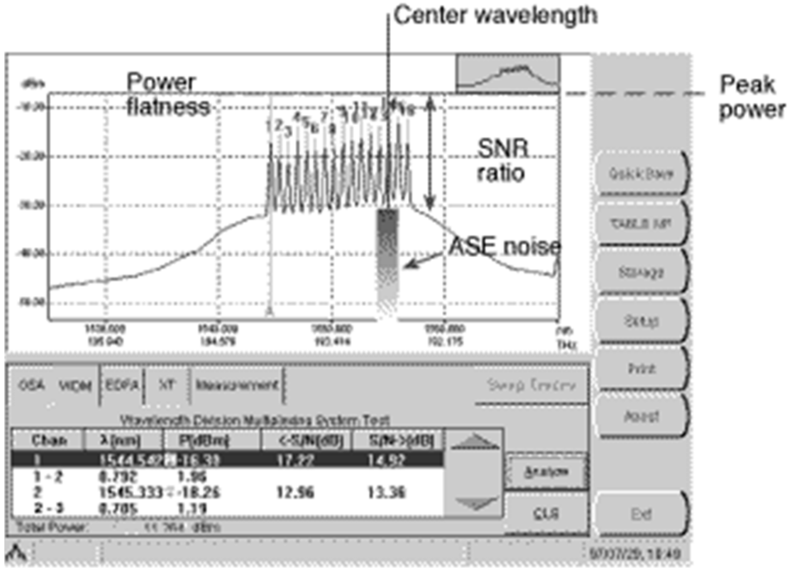


$\mathbf{\Delta\lambda_{SPAN}=600nm}$

Laboratory OSA

- Meas. of **continuum spectrum** (lines+ASE)
- ***u*(*λ*)=10 pm e Δ*λ*=2 pm**
- Meas. of **power: peaks** and **total**
- Automatic meas. of **SNR** and **Δ*λ*** and **Δ*P*** **(*markers*)**
- ***Quantitative graphical representation***

Optical spectrum measurements for laser lines or D–WDM signals



Wavelength Division Multiplexing System Test

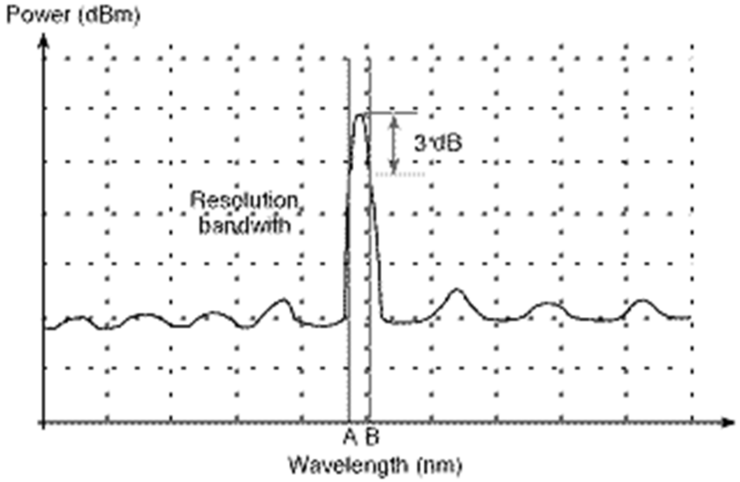
Chan	λ [nm]	P[dBm]	<-S/N[dB]	S/N->[dB]
1	1544.542	-16.33	17.22	14.92
1 - 2	0.792	1.96		
2	1545.333	-18.26	12.96	13.36
2 - 3	0.785	1.19		

Total Power: 11.764 dBm

Parameters to be measured (on the optical WDM signal):

- channel power [dBm]
- center wavelength [nm]
- channel spacing [nm , GHz]
- ASE noise floor [dBm/nm]
- ratio S/N [dB/nm]
- close channels crosstalk [dB]
- global optical power [dBm]

Optical Spectrum Analyzer (OSA)



Measurement parameters of the OSA:

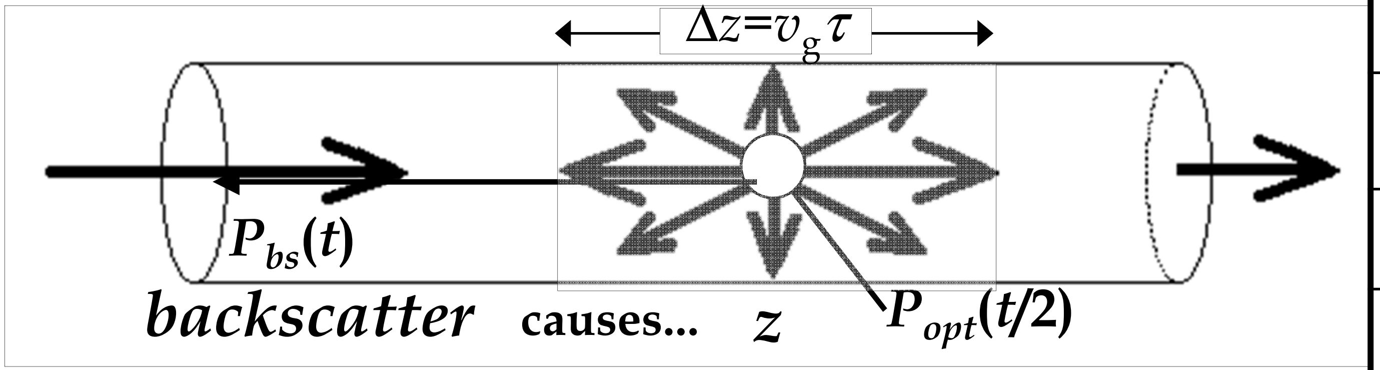
- center wavelength [nm] λ_{START} [nm]
- wavelength span [nm] λ_{STOP} [nm]
- resolution bandwidth (FWHM) [nm]
- wavelength accuracy [nm]
- saturation power [dBm]
- "sensitivity" [dBm]
- dynamic range [dB]
- power accuracy [dB]

Optical Time Domain Reflectometry

Indirect **measurement of local losses** and **distributed attenuation** along an optical fiber cable.

Signal reading is done **in reflection** due to the **backscattering**.

In each “point” scattering is proportional to the available power level and depends inversely on the adopted wavelength.



	α_S [dB/km]	R_S [dB]
MM 850nm	1.9 ×5	-50 ×20
SM 1300nm	0.35	-63
SM 1550nm	×2 0.175	×2 -66

scattering coeff. per unit length

$$P_{bs}(t) = \left[\frac{1}{2}\alpha_S \cdot v_g \tau\right] P_{opt}\left(\frac{t}{2}\right) \quad \text{con} \quad t = \frac{2L}{c/n} = \frac{2z}{c/n} \quad \text{e} \quad \alpha_S \propto \frac{1}{\lambda^4}\,[\text{cm}^{-1}]$$

R_S

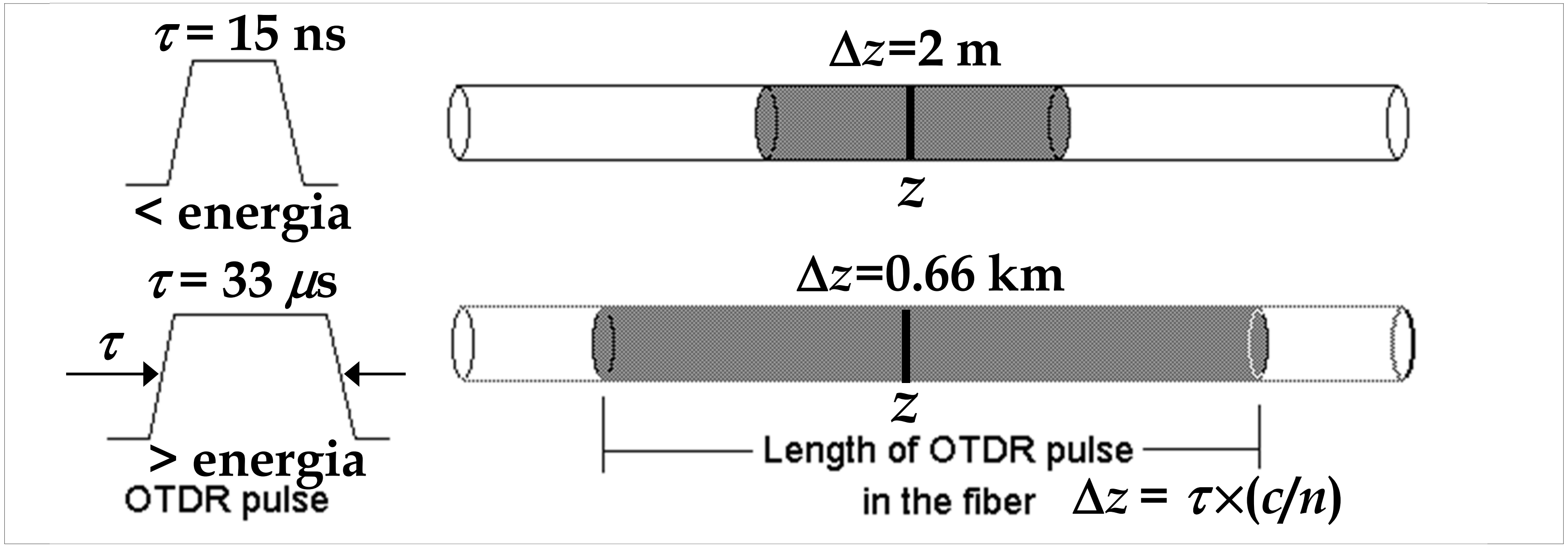
$v_g = \partial\omega/\partial k$ con $k = 2\pi/\lambda$

spatial extension **Δ*z*** of the **“lit” zone** providing for backscattering (with coeff. α_S per unit length)

OTDR Pulse length and resolution

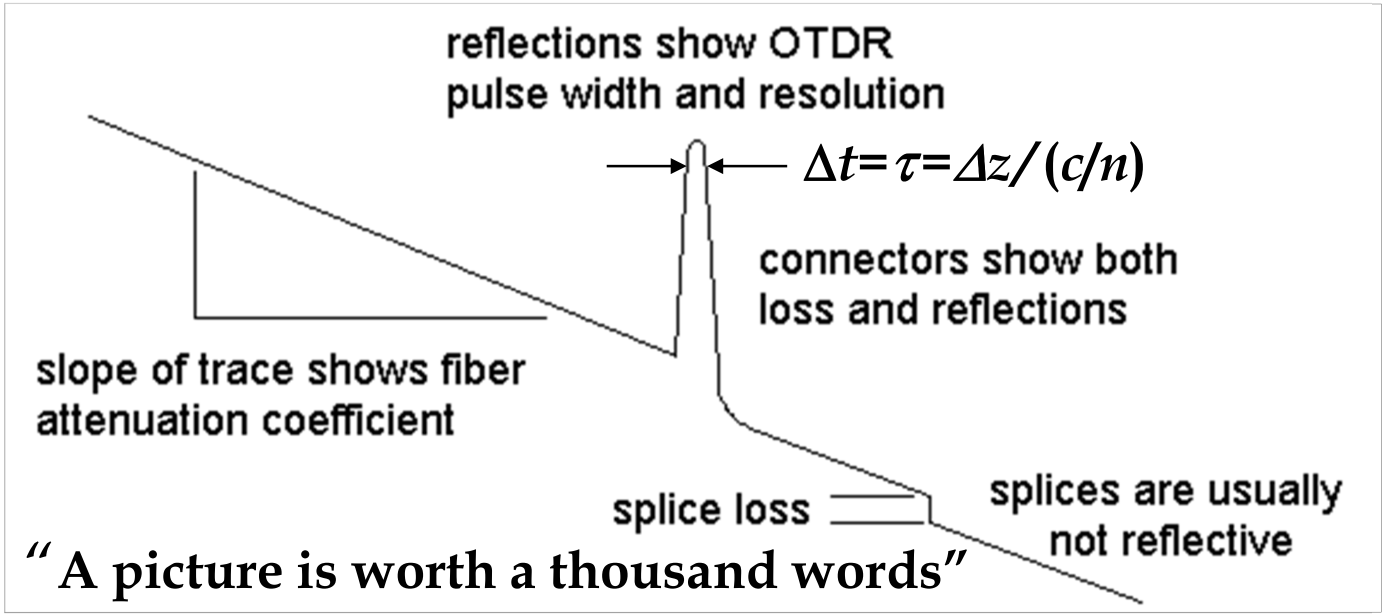
With a **pulsed laser** we inject short (ns) light pulses in the fiber (cable) and we observe the **plot of "back-reflections"** (backscattering) **as a function of time**: recorded time gives the distance z of the fiber length Δz

$$P_{opt}(z) = P_{opt}(0)\exp\left[-\alpha z\right]$$ **attenuation**



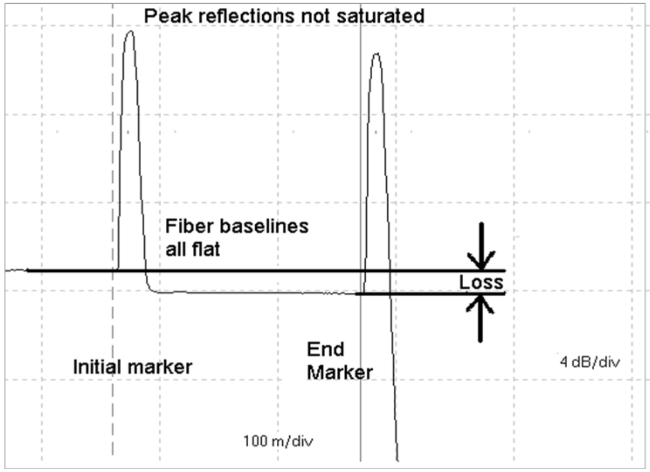
Spatial resolution Δz is poorer when the pulse is larger but SNR gets better with larger/stronger pulses

Information contained in the OTDR trace

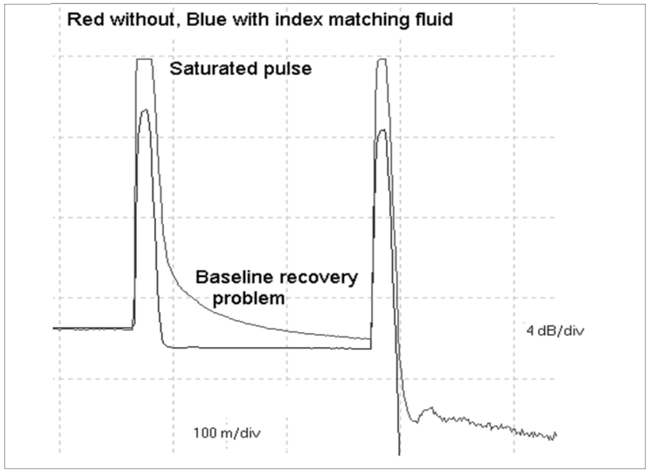


$\Delta t = \tau = \Delta z / (c/n)$

"A picture is worth a thousand words"

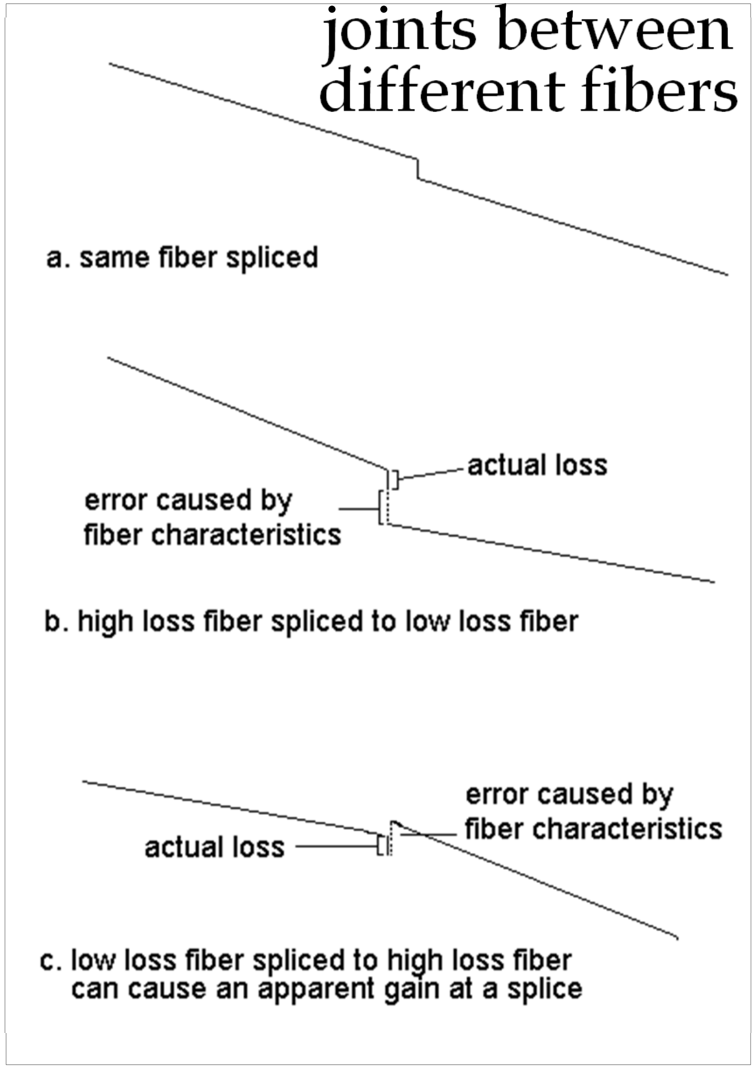


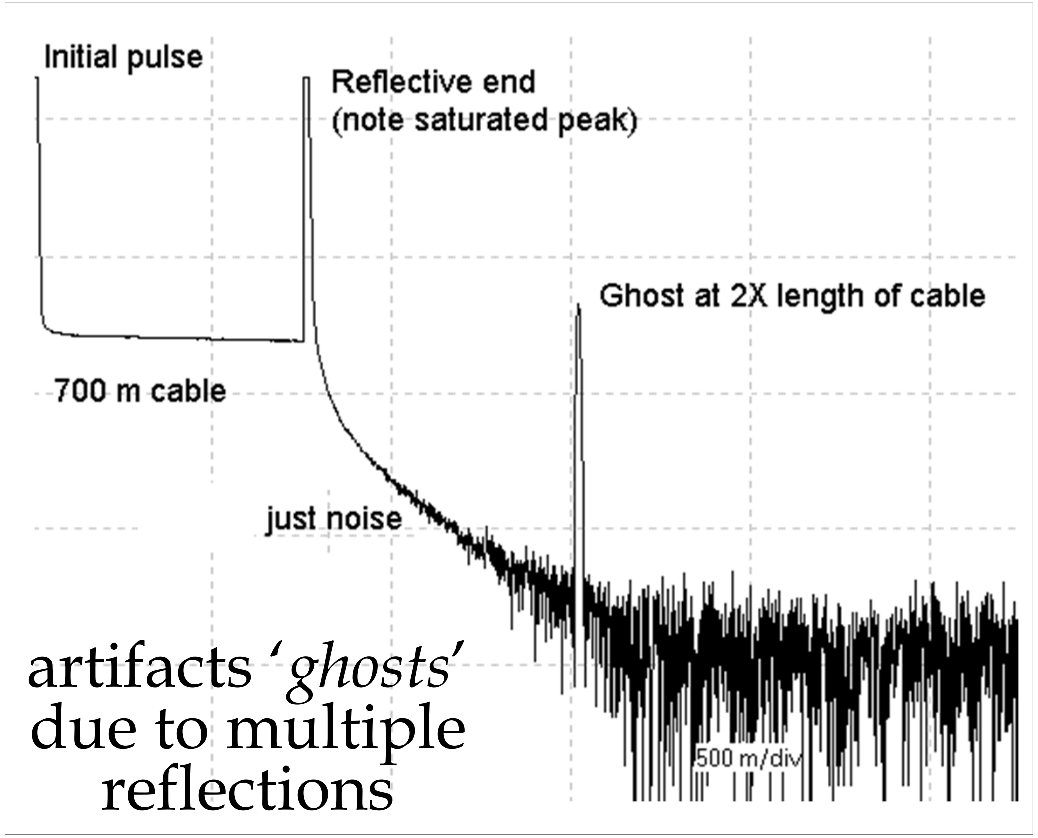
Pb. saturation
and line-base recovering



Tricks in OTDR measurements

joints between different fibers

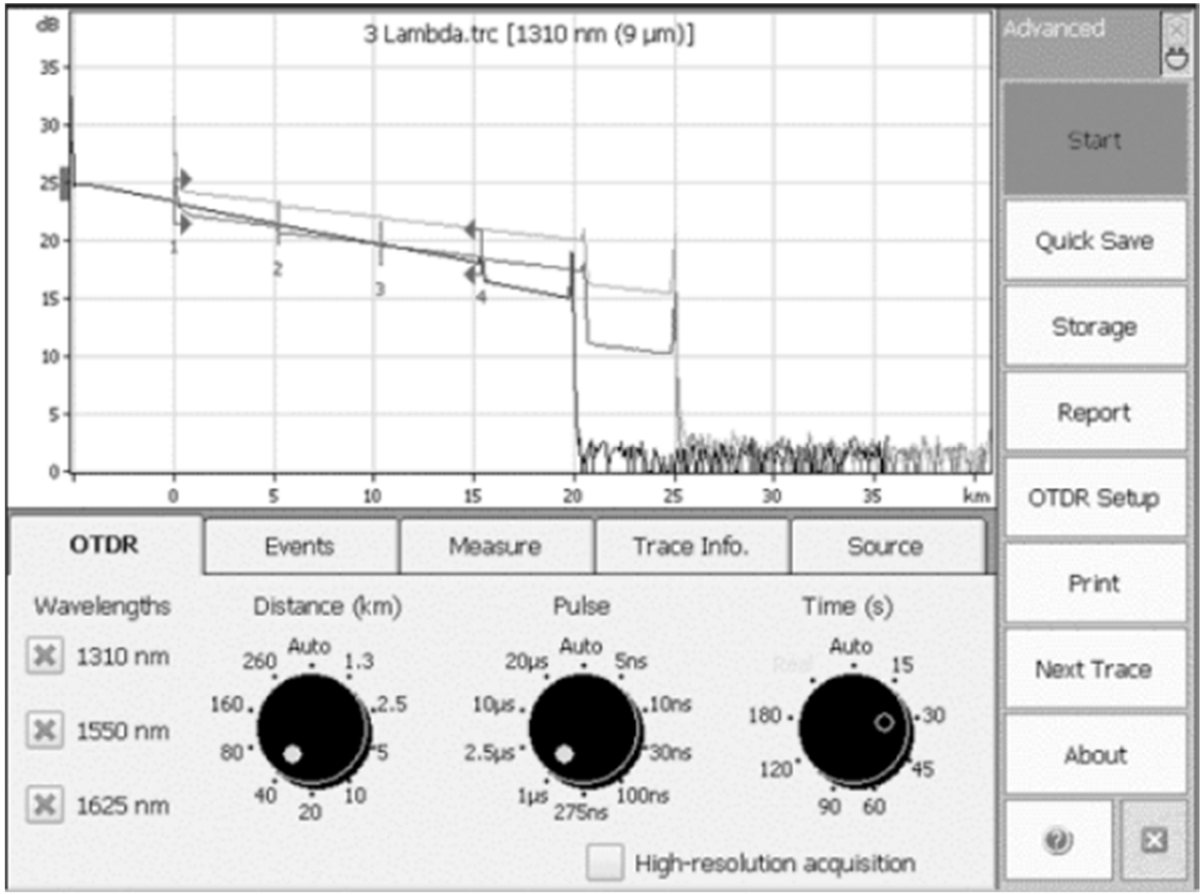




artifacts ‘*ghosts*’ due to multiple reflections

Example of OTDR measurement

portable OTR
for “in-field”
measurements



Wavelengths

☒ 1310 nm

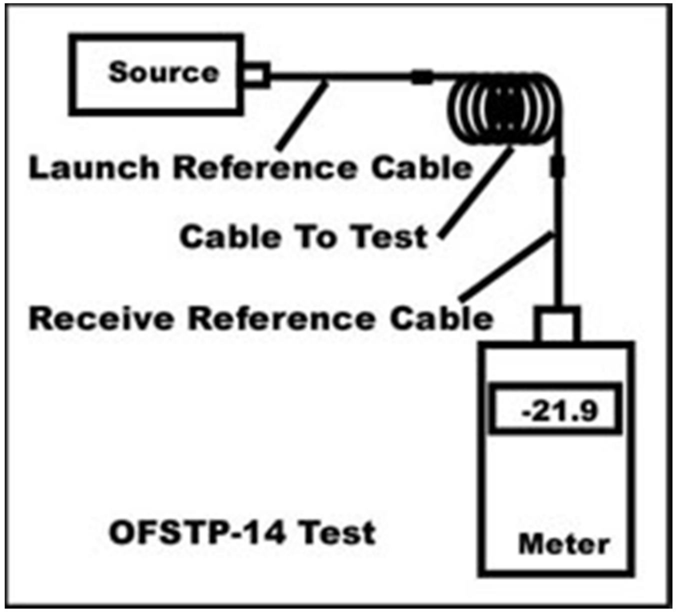
☒ 1550 nm

☒ 1625 nm

☐ High-resolution acquisition

measurement panel of an OTDR

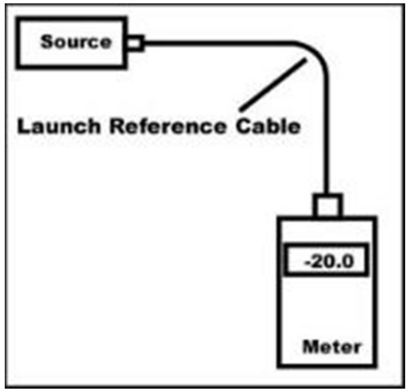
Fiber Insertion Loss measurement

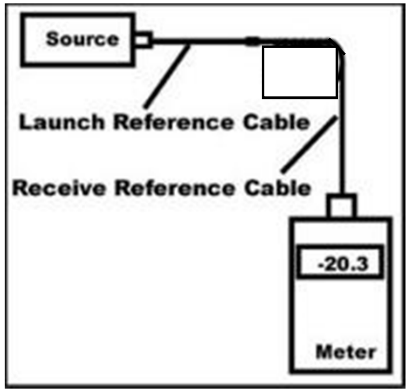


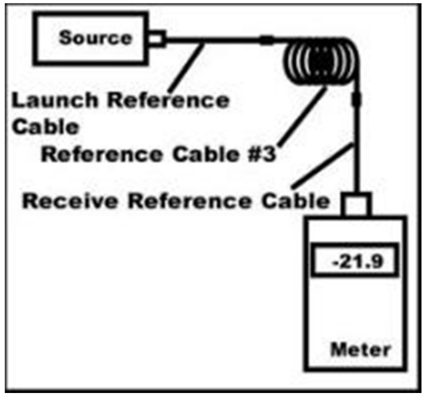
4 standardized methods exist

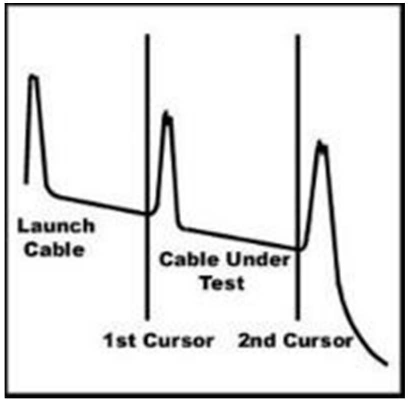
Test	Loss , Std. Dev.
1-Cable Reference	2.96 dB , 0.02 dB
2-Cable Reference	2.66 dB , 0.20 dB
3-Cable Reference	2.48 dB , 0.24 dB
OTDR(1/2 directions)	2.05 dB / 1.91 dB

Results of different measurements at 850 nm on a 520 m cable

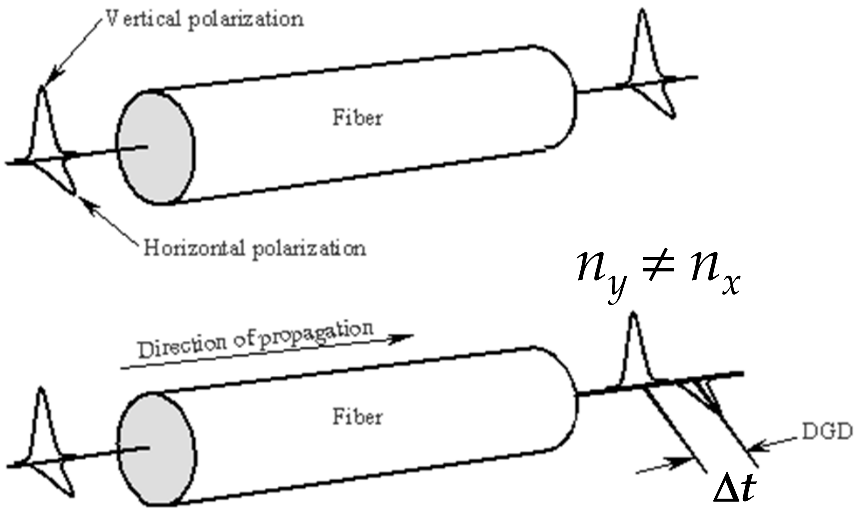








PMD (*Polarization Mode Dispersion*) meas.

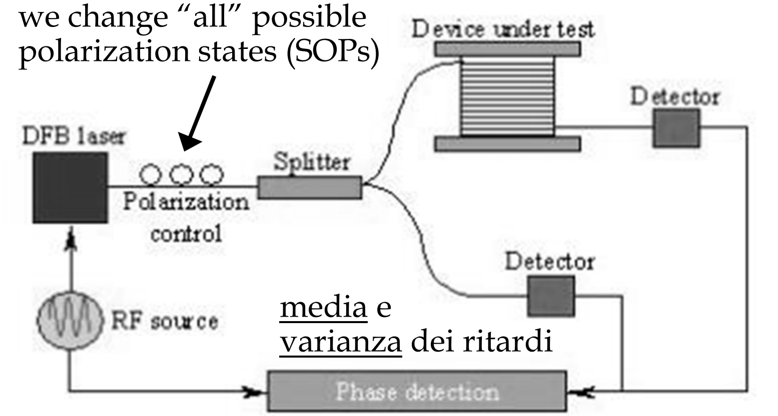


$n_y \neq n_x$

Δt

Opt. Commun. >10 Gb/s
Pb.: polariz. dispersion

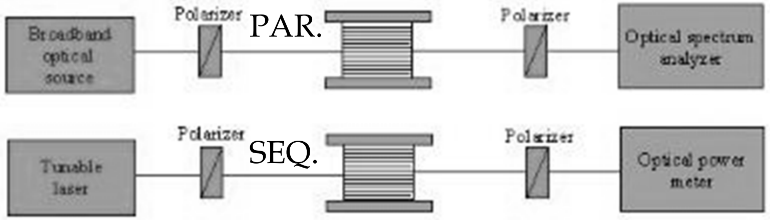
PMD: **STATISTICAL parameter**
Important **Avg Value** and **St.Dev.**
of DGD (Differential Group Delay)
We measure variance per unit length (in time or as a function of SOP or λ): hence we get **σ^2 in [ps^2/km]** and then PMD=σ_{DGD})
Typical values PMD **~0.2 ps/(km)$^{1/2}$**
variability range 0.1÷1 ps/(km)$^{1/2}$



we change “all” possible polarization states (SOPs)

media e varianza dei ritardi

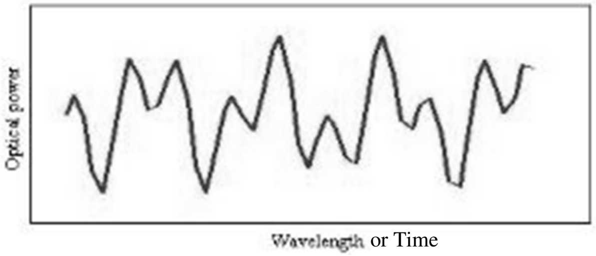
meas. with a single λ



PAR.

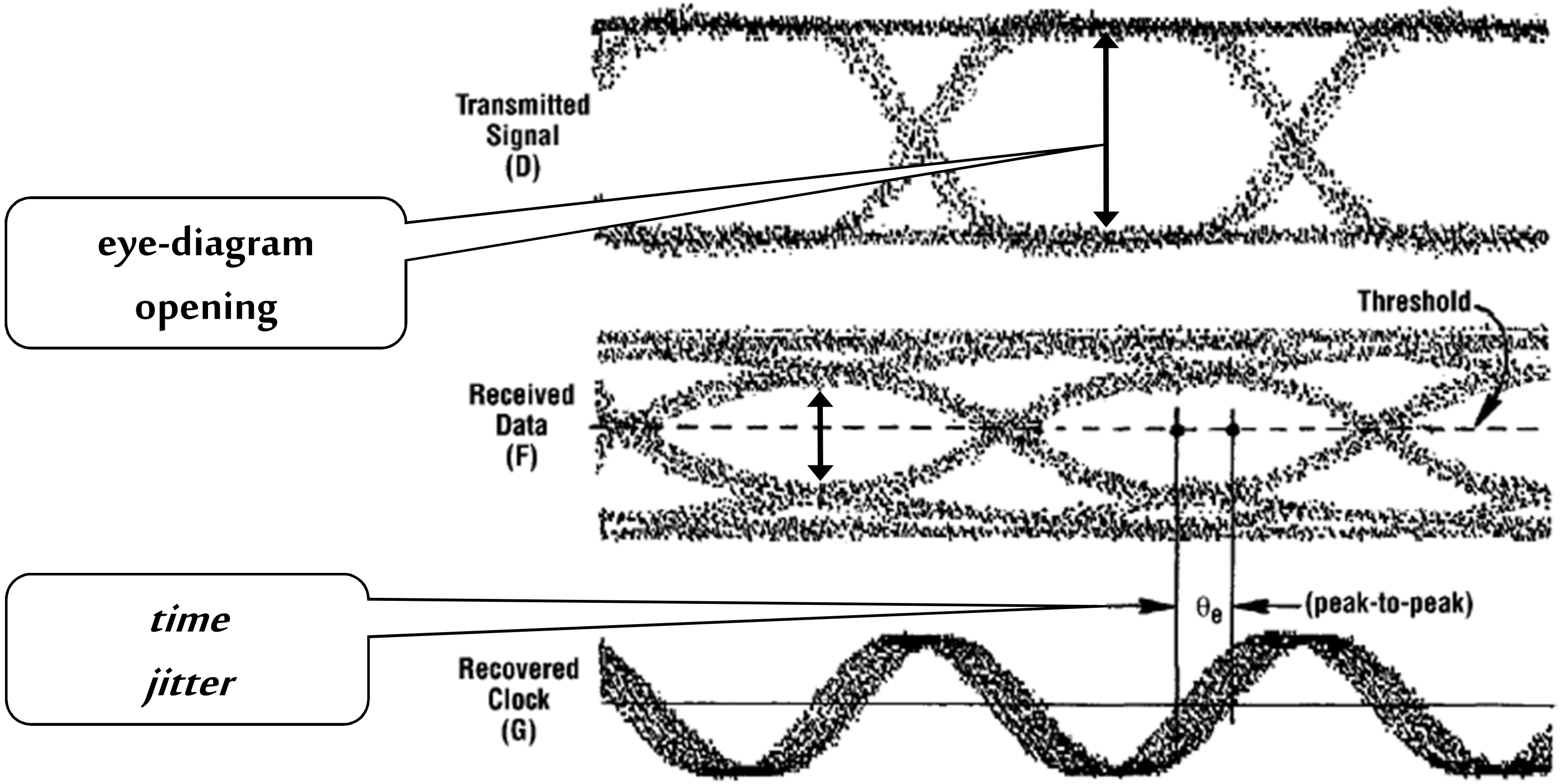
SEQ.

meas. with multiple λ



BER and eye-diagram measurements

For BER<10^{-12} long times are needed (>>20 min at 1 GSa/s)…

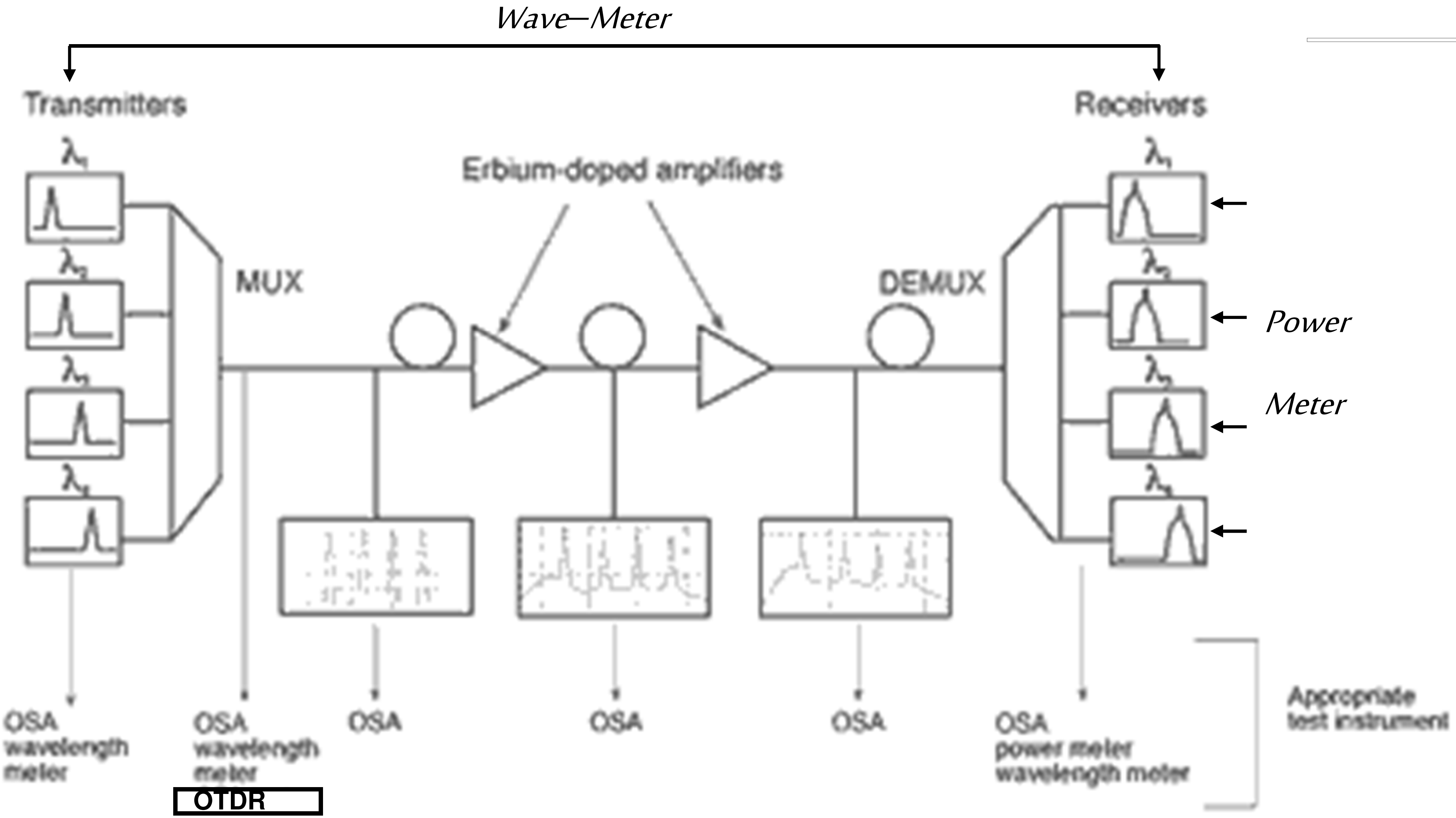


eye-diagram opening

time jitter

BER can be estimated from the **opening** (S/N ratio) **of the eye-diagram**

D-WDM System Monitoring


Wave–Meter

Power

Meter

OTDR

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