Optical power measurements (1)

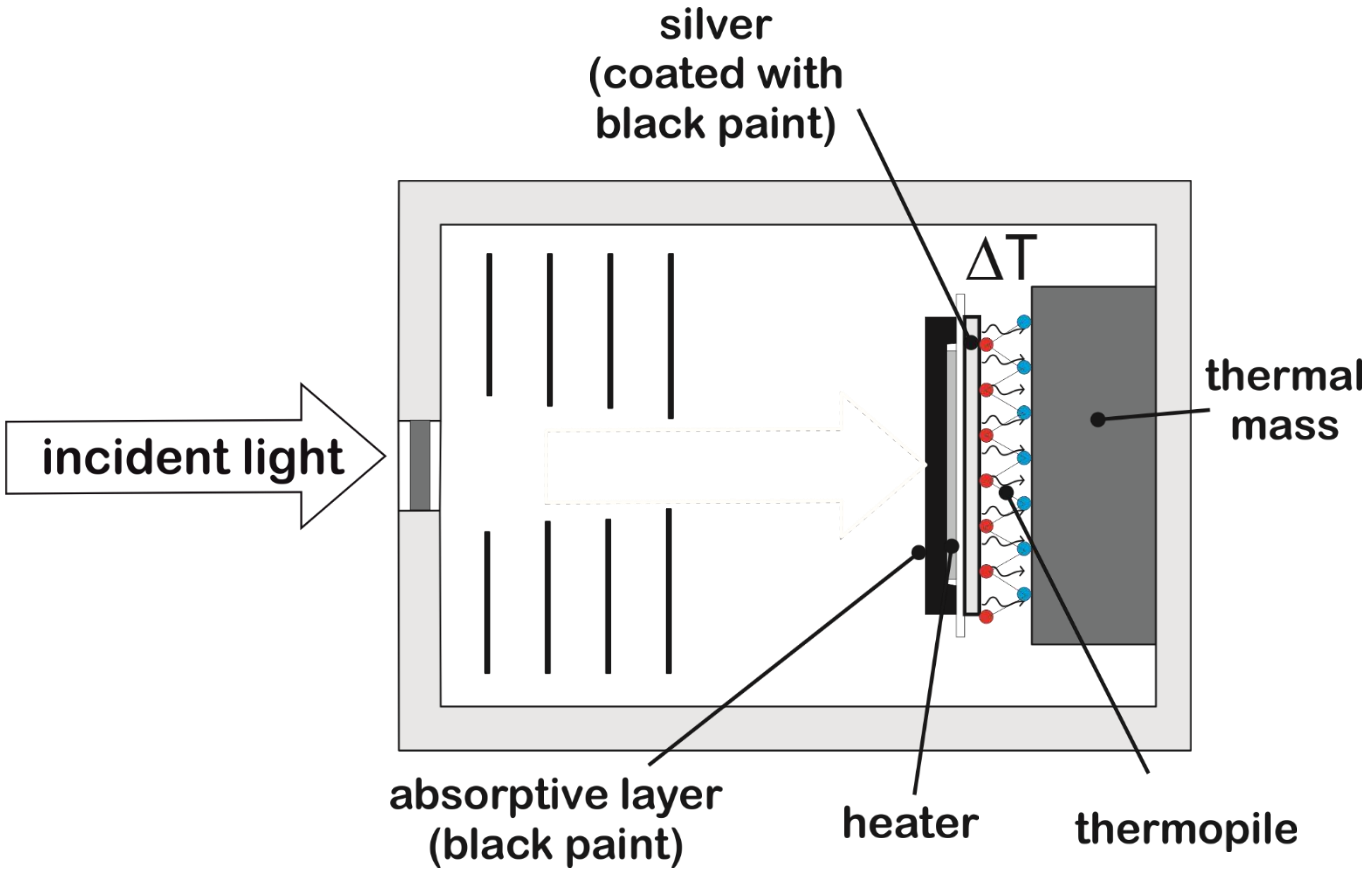
- The optical power measurement is fundamental for the metrology of the optical fibers: almost all the optical instruments include a power meter
- Absolute measurements: traceable to the International System of Units (SI)
  - optical sources characterization
  - characterization of optical detectors and receivers
  - safety measurements (laser safety)
- Relative measurements: not necessarily traceable measurements
  - loss/attenuation measurements
  - gain measurements
  - insertion loss measurements

Optical power measurements (2)

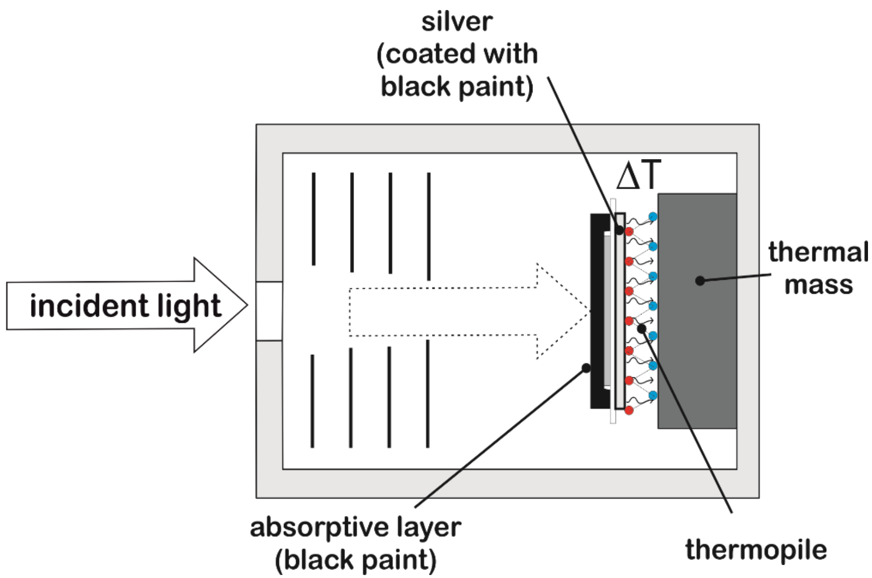
- The optical power measurements are commonly based on electrical power measurements.
- An optical power measured value must be traceable to the international unit of power which is defined by means of electrical quantities (electrical power reference).
- The optical power measurement can be based on thermoelectric detectors or on electronic photo-detectors.

feature	thermoelectric	electronic
dependence on wavelength	very low, wide range	very high, short range (2:1)
auto-calibration	yes	no
sensitivity	low, >10mW	very high, < 1 pW
uncertainty	down to +/-1%	down to +/-2%

Thermoelectric detectors: substitution radiometry



Thermoelectric detectors: substitution radiometry



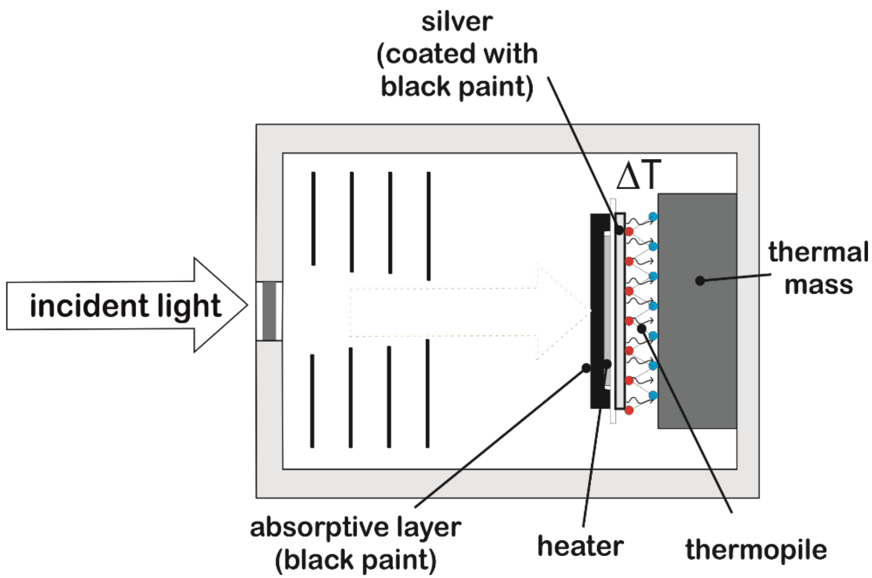
a) the light beam, whose power has to be measured, enters the detector

b) at the thermal equilibrium, the temperature difference between the absorber and the thermal mass is proportional to the incident optical power:

$$\Delta T \propto P_{opt}$$

c) this temperature difference ΔT is measured by means of a thermopile

Thermoelectric detectors



d) the light beam is stopped with a shutter and the electrical heater is switched on

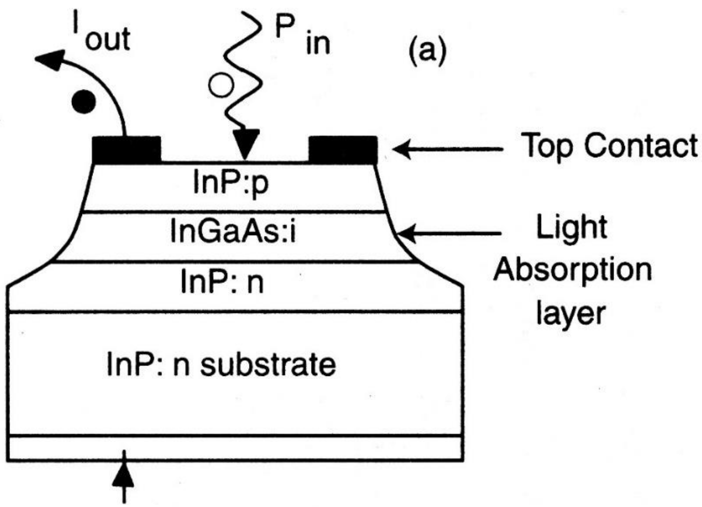
e) the supply power of the heater is regulated in order to stabilize a new thermal equilibrium at the same temperature difference ΔT previously recorded (in step b)

f) the electrical power P_e now supplying the heater is measured: it is the result of the measurement since we can say that

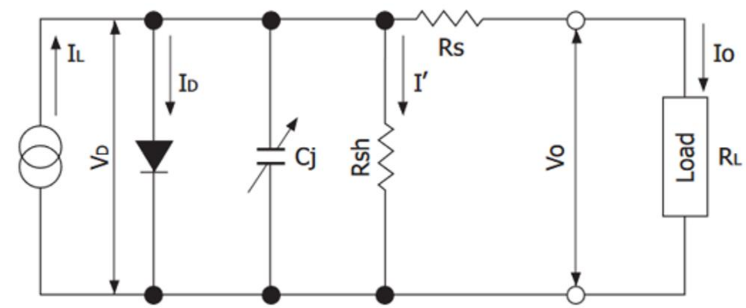
$$P_{opt} = P_e$$

the measurement is therefore based on the direct comparison between an optical power and an electrical power

p-i-n photo-detectors



- the pin photodiode is a photon-to-electron converter: the incoming photons are absorbed by the intrinsic (i) layer made by a low band-gap material
- equivalent circuit

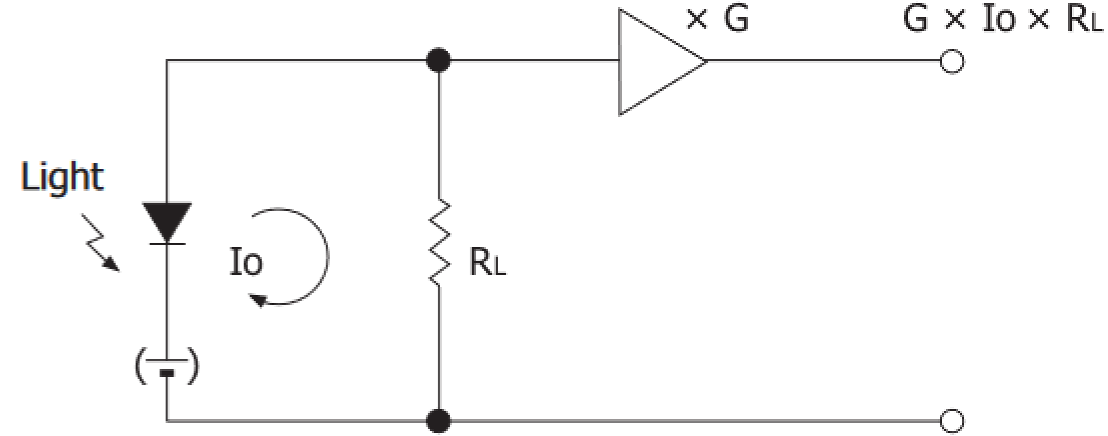


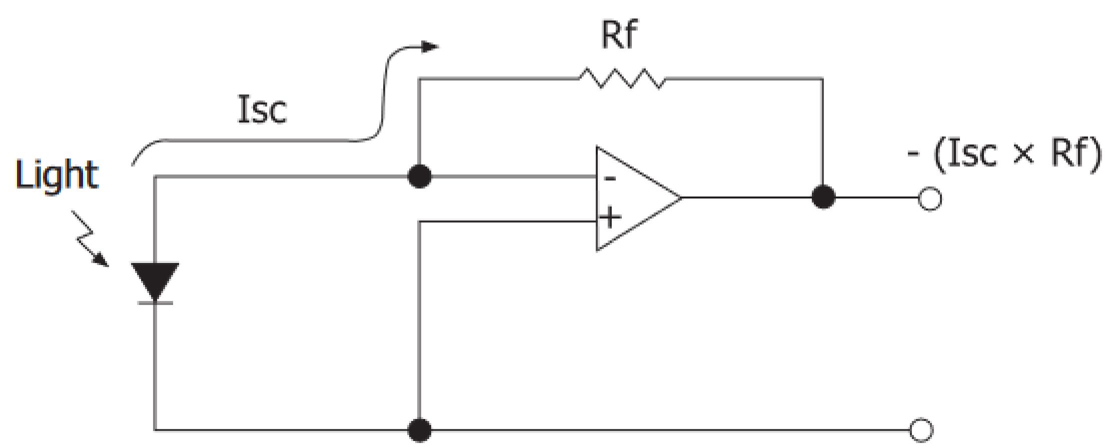
IL : current generated by incident light (proportional to light level)
VD : voltage across diode
ID : diode current
Cj : junction capacitance
Rsh: shunt resistance
I′ : shunt resistance current
Rs : series resistance
Vo : output voltage
Io : output current

- MATERIAL: Si, Ge, InGaAs
- Efficiency up to 90%
- Fast response time, bandwidth up to 100 GHz
- Avalanche photo-detectors (APD): lower speed (few GHz BW), higher sensitivity

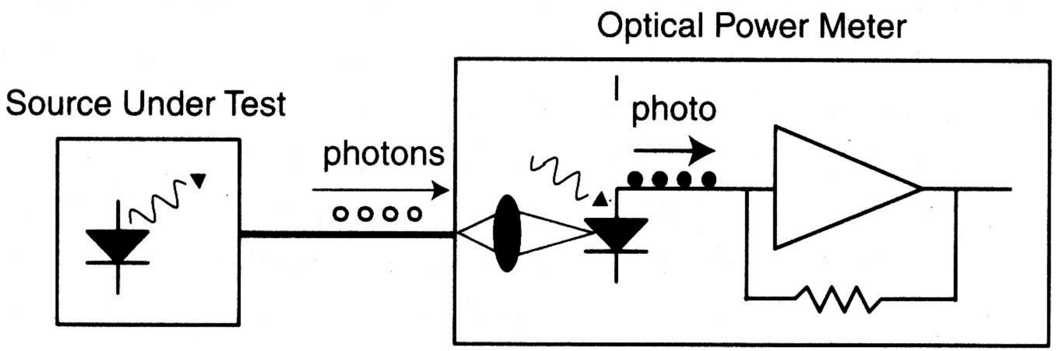
p-i-n photo-detectors

- basic circuits



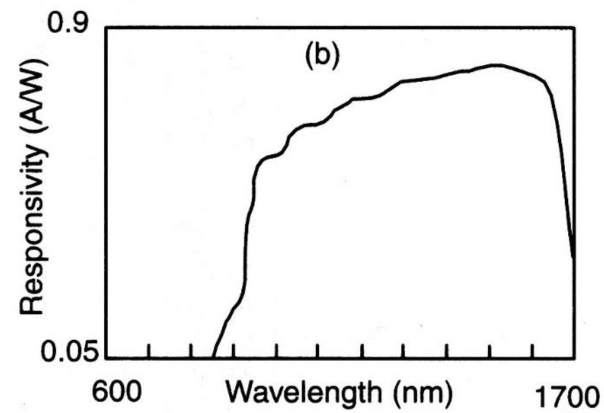


PIN photodiodes



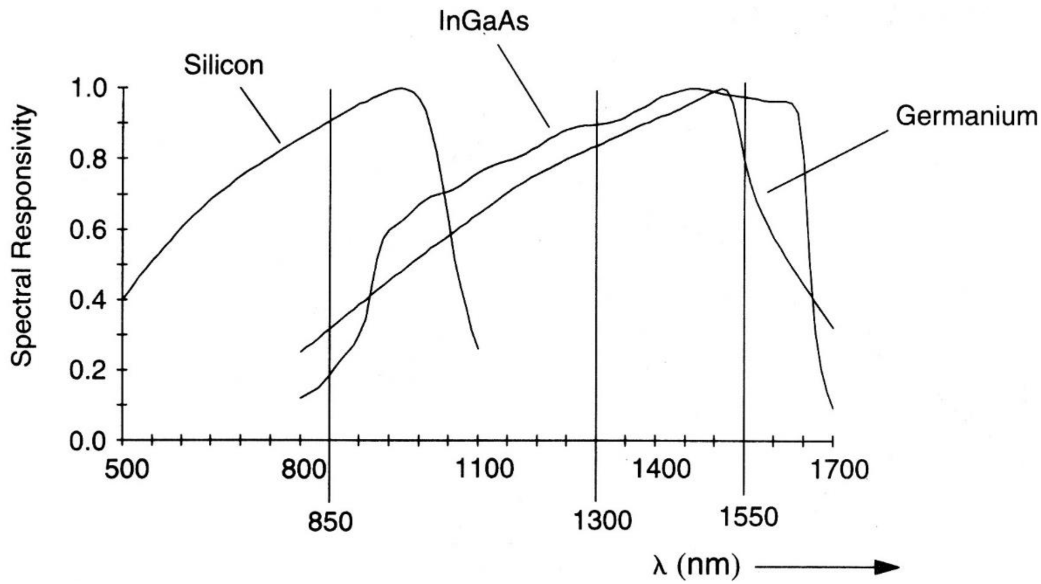
- the responsivity gives the intensity of photo-current per unit of optical power (A/W):

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



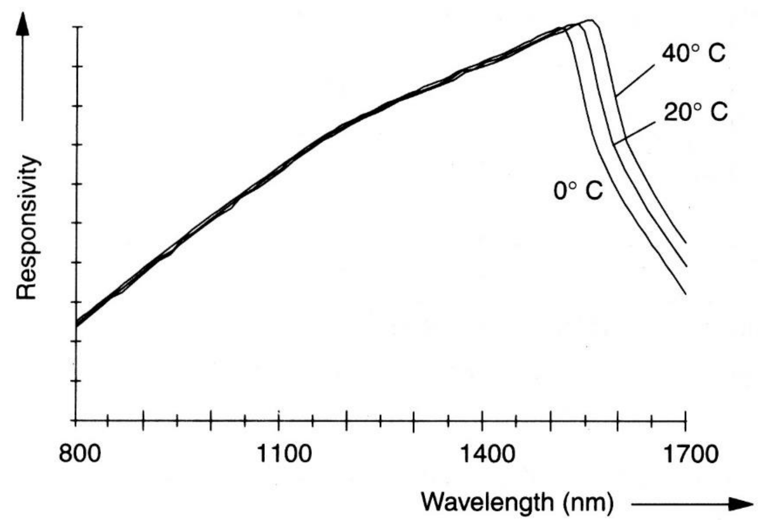
- optical dB vs electrical dB: a change of -3 dB (halving) of the incident optical power induces a halving of the photo-current corresponding to a -6 dB variation of the electrical power at the receiver output

Spectral responsivity of photo-detectors

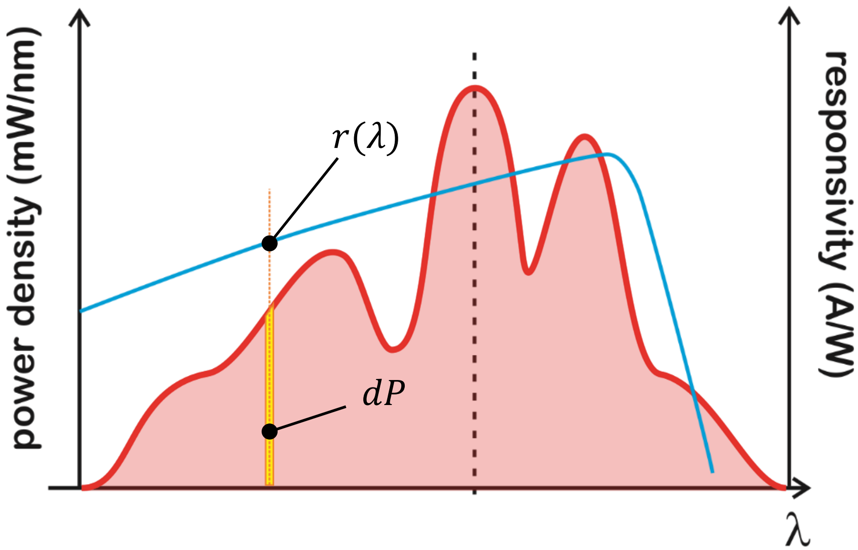


- temperature dependence:

  the cut-off wavelength λ shifts of about 1 nm/K for the InGaAs and germanium diodes



Optical power emitted by a broadband source



- given the source power spectral density

  $p(\lambda)$
- the total emitted optical power is

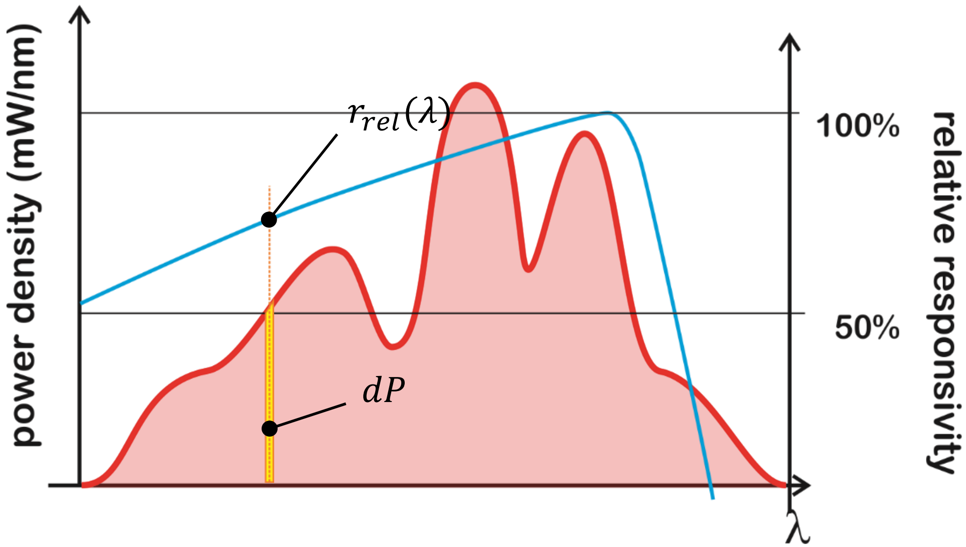
  $$P_{TOT} = \int p(\lambda) d\lambda$$
- given the photo-diode responsivity

  $r(\lambda)$
- the total photo-current is:

  $$I_{TOT} = \int r(\lambda) \cdot dP = \int r(\lambda) \cdot p(\lambda) d\lambda$$

- in case of a broadband light source we cannot directly use a photo-diode to measure the emitted total power

Relative responsivity



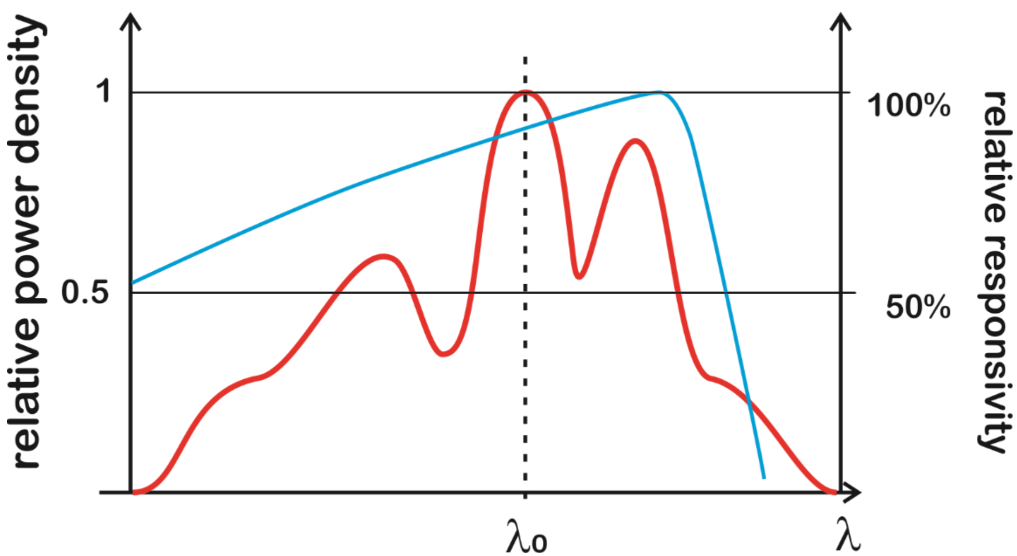
- the responsivity of a photo-diode is usually expressed as:

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

- the total photo-current is:

$$I_{TOT} = \int r(\lambda) \cdot dP = r_{\lambda_0} \cdot \int r_{rel}(\lambda) \cdot p(\lambda) d\lambda$$

Relative power spectral density



- we can express the source power spectral density as:

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

- the total photo-current is:

$$I_{TOT} = \int r(\lambda) \cdot p(\lambda) d\lambda = p_{\lambda_0} \cdot \mathrm{r}_{\lambda_0} \int f(\lambda) \cdot r_{rel}(\lambda) d\lambda$$

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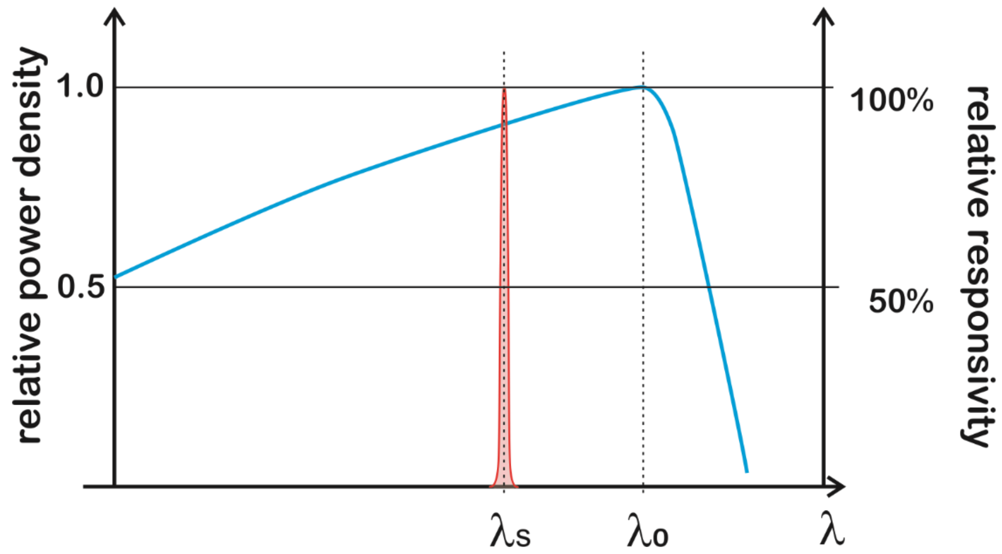
Optical power emitted by a mono-chromatic source

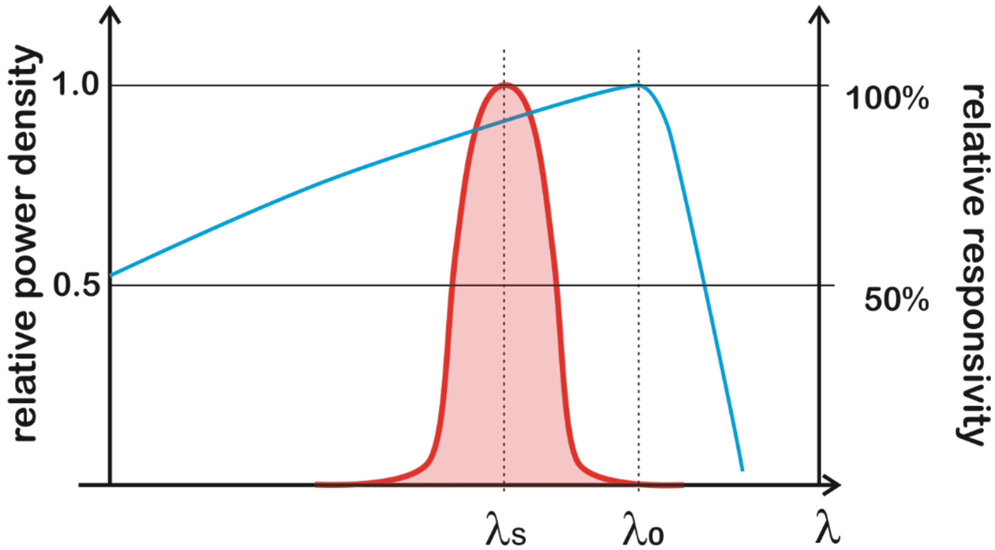


- the emitted optical power is concentrated only on one wavelength, therefore the total photo-current is:

$$I = \int r(\lambda) \cdot p(\lambda) d\lambda = r_{\lambda_0} \cdot r_{rel}(\lambda_s) \cdot p(\lambda_s) \cdot 1 \equiv r_{\lambda_0} \cdot r_{rel}(\lambda_s) \cdot P_{TOT}$$

- by measuring I, we obtain: $P_{TOT} = \dfrac{I}{r_{\lambda_0} \cdot r_{rel}(\lambda_s)}$

Optical power emitted by a LED



$$P_{LED} = \int p_{\lambda_S} \cdot f(\lambda) d\lambda = p_{\lambda_S} \cdot \int f(\lambda) d\lambda$$

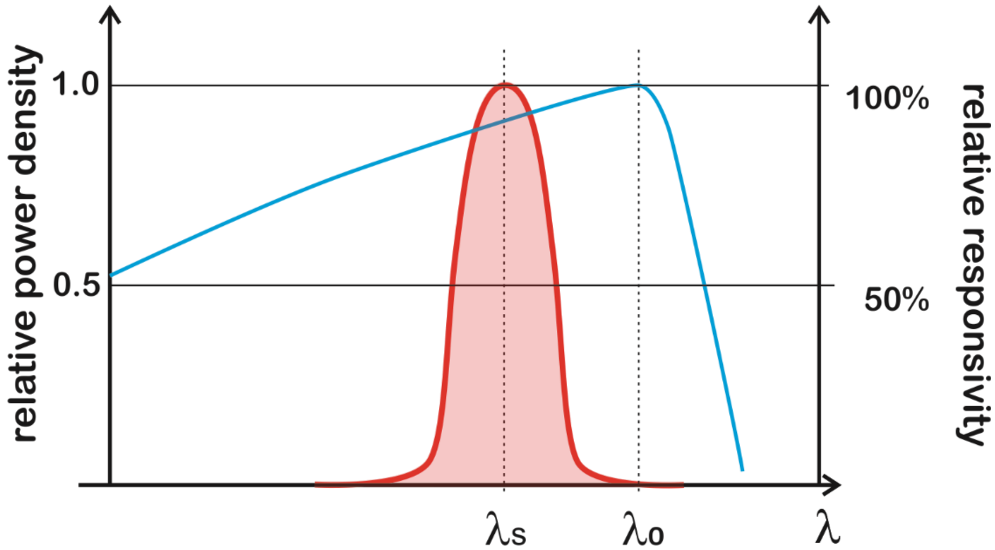
- the emitted optical power is spread over a wavelength range around λ_S, where the responsivity is not constant
- the total photo-current is:

$$I = \int r(\lambda) \cdot p(\lambda) d\lambda = r_{\lambda_0} \cdot p_{\lambda_S} \cdot \int r_{rel}(\lambda) \cdot f(\lambda) d\lambda =$$

$$= r_{\lambda_0} \frac{P_{LED}}{\int f(\lambda) d\lambda} \int r_{rel}(\lambda) \cdot f(\lambda) d\lambda$$

- by measuring I, we obtain: $P_{LED} = \frac{I}{r_{\lambda_0}} \frac{\int f(\lambda) d\lambda}{\int r_{rel}(\lambda) \cdot f(\lambda) d\lambda}$

Optical power emitted by a LED



$$P_{LED} = \int p_{\lambda_S} \cdot f(\lambda) d\lambda = p_{\lambda_S} \cdot \int f(\lambda) d\lambda$$

- $P_{LED} = \dfrac{I}{r_{\lambda_0}} \dfrac{\int f(\lambda) d\lambda}{\int r_{rel}(\lambda) \cdot f(\lambda) d\lambda}$
- **if *a)* the emission spectrum is symmetric and *b)* the responsivity linearly changes with λ, then we can proceed as with a laser source:**

$$P_{LED} = \frac{I}{r_{\lambda_0} \cdot r_{rel}(\lambda_S)} \qquad \textbf{(1)}$$

- **normally we have to apply a correcting factor to the value given by relation (1)**

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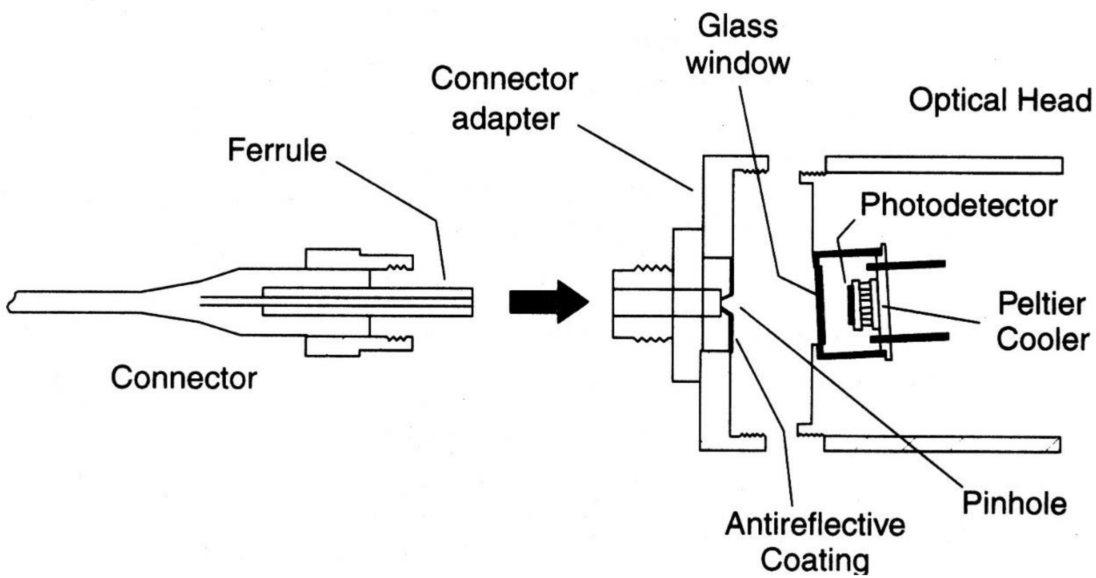
Power meters with photo-detectors



- accurate power measurements only when:
  - an individual correction for each wavelength is applied
  - the temperature is well stabilized
  - the photo-detector has a good spatial homogeneity
  - reflections are minimized
  - a low polarization dependence is guaranteed

Non-linearity of the power meters

- a photo-detector has a typical dynamic of six or more decades
- detector nonlinearities
  - noise effect at the lowest levels of the optical power
  - supra-linearity at the medium power levels
  - saturation at high power levels
- electronic nonlinearities
  - offset of the amplifier at low power levels
  - saturation of the amplifier at high power level
  - ranging discontinuities due to the non-matching amplifier gains

cont.

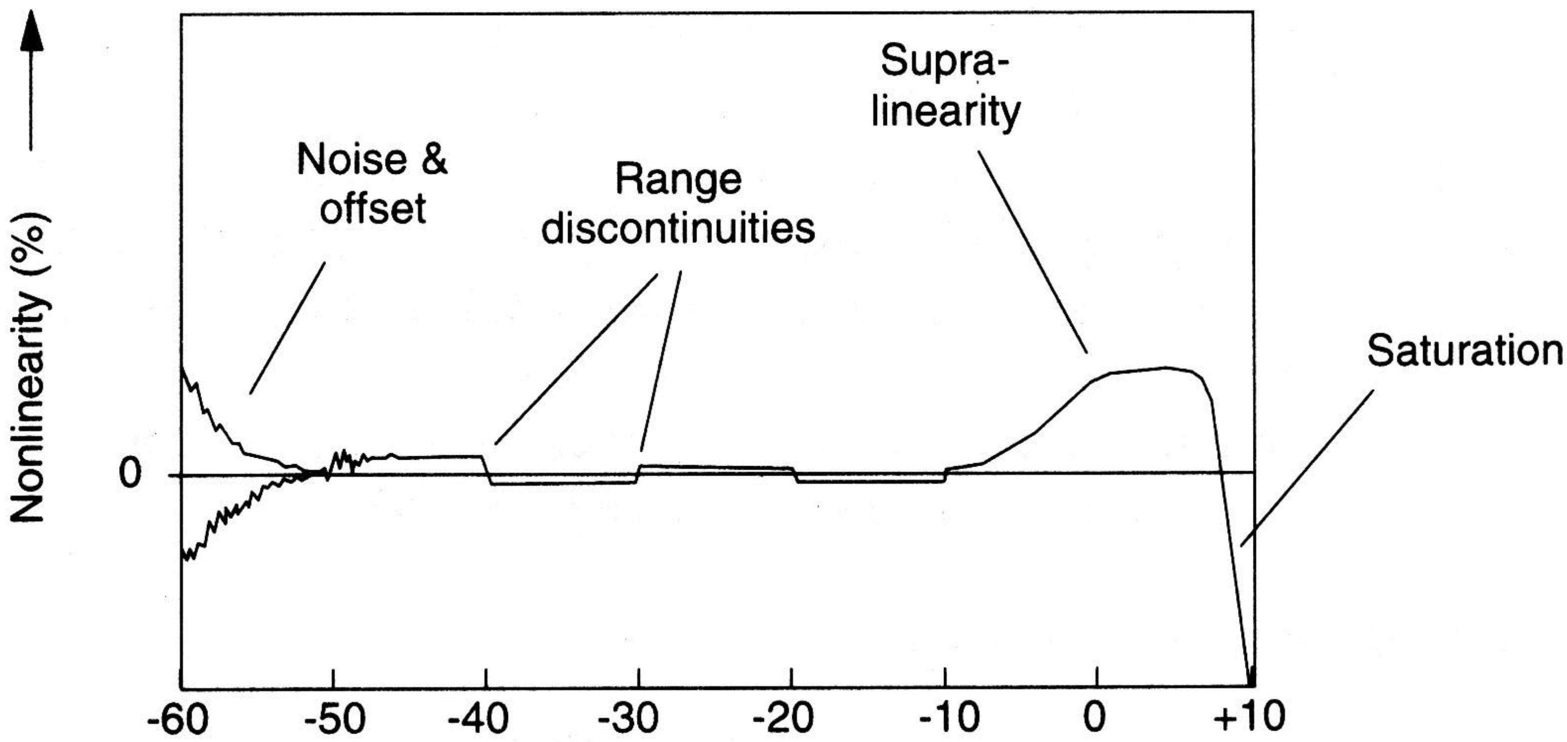

Nonlinearity (%)
0
Noise &
offset
Range
discontinuities
Supra-
linearity
Saturation
-60
-50
-40
-30
-20
-10
0
+10

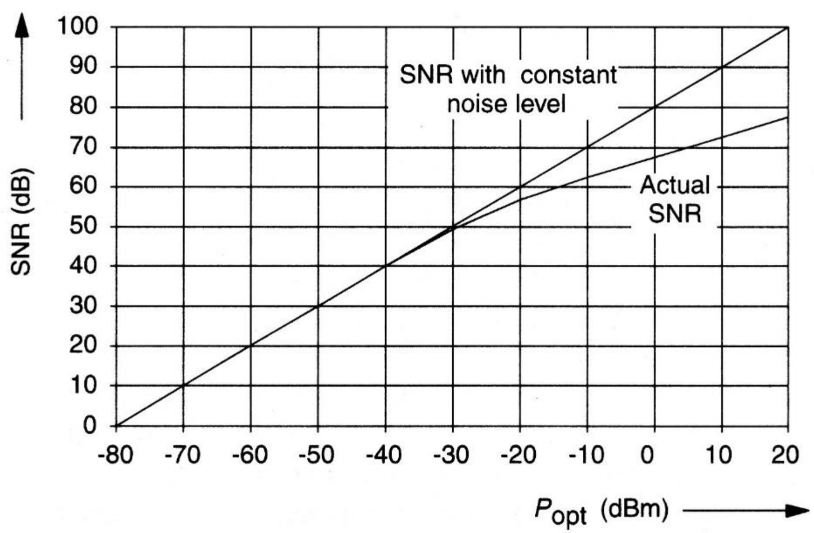
Photo-detector noise

- the current noise can be represented as noise equivalent (optical) power (NEP):

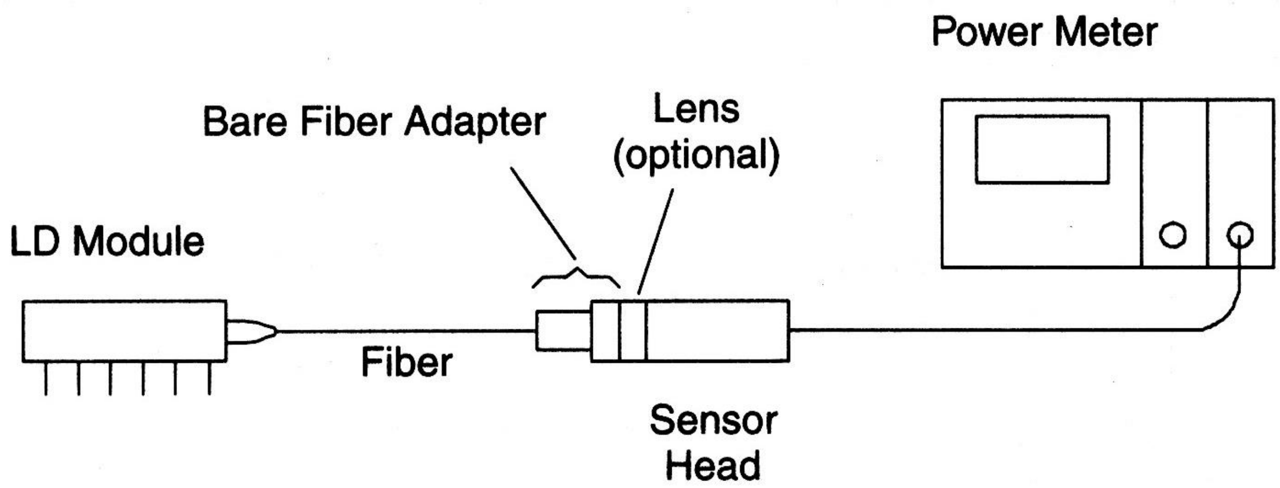
$$NEP = \frac{1}{r}\sqrt{\left[{i_n}^2\right]} = \frac{1}{r}\sqrt{2eB_n\left(2I_{dark} + r\cdot P_{opt}\right)} \qquad \left[\frac{W}{\sqrt{Hz}}\right]$$

where: R is the responsivity, I_{dark} is the dark current, B_n is the noise equivalent bandwidth, and P_{opt} is the incoming optical power

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

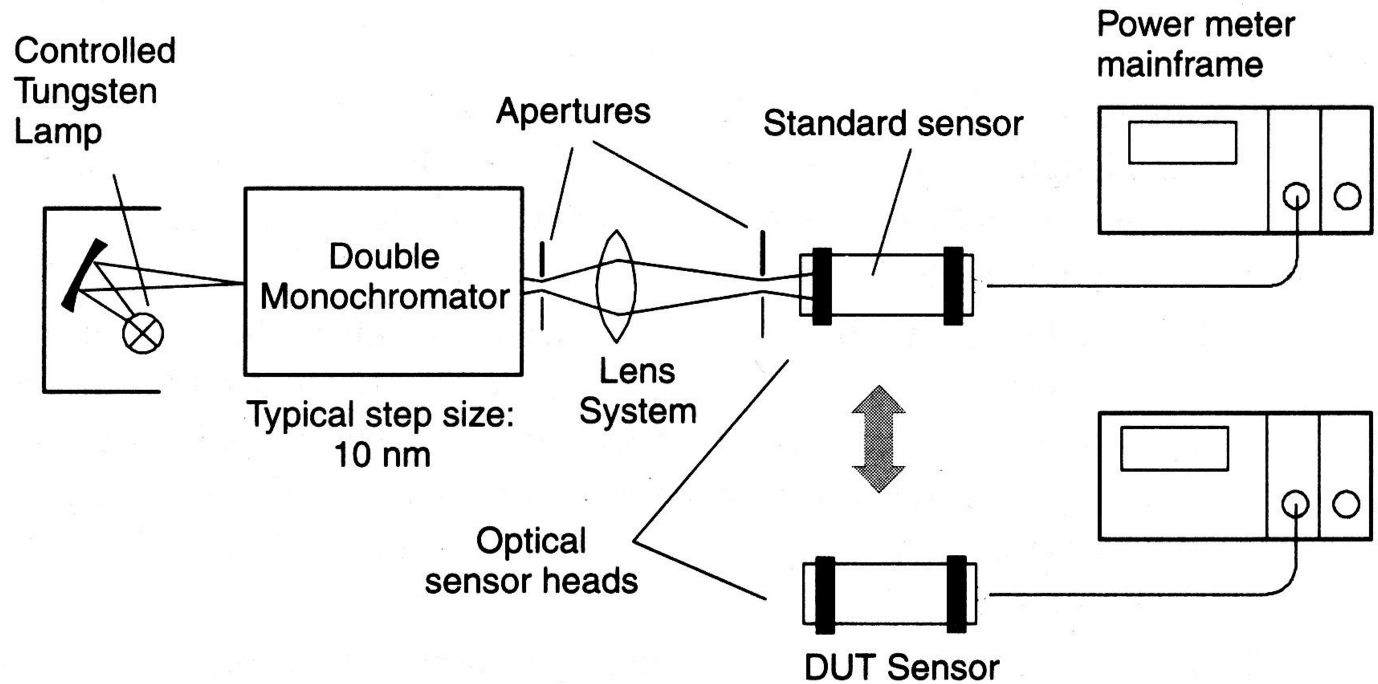


Absolute optical power measurements



- production tests
- for the highest power levels $(> 100\ mW)$ it is necessary to insert an attenuator do avoid the photo-detector damage
- when the light source has a wide emission spectrum, since the detector responsivity is a function of λ, the power meter reading could need a correction

Power meter calibration



- we must have a photo-detector traced to international standard units
- the responsivity curve is constructed point by point

Uncertainty of the optical power measurement

- Fluctuations of the power of the testing laser source: the main cause can be related to the high sensitivity to optical feedback. The inaccuracy can be very high if no caution is used.
- Power meter calibration (see the user manual and the calibration certificate of the instrument): the best instruments declare an accuracy of +/- 2%.
- Systematic errors:
  - short knowledge of the spectral characteristic of the optical source
  - the geometry of the real light beam is different from the specified one