Photodiode

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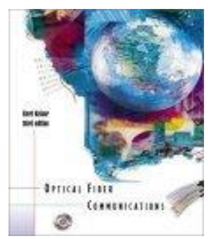
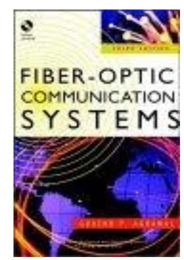
Outline

- Photo-diode
- Quantum Efficiency and Responsivity
- Noises in Photodiode
  - Shot Noise, Thermal Noise, Gain Noise
- Receiver Performance
  - Signal-to-Noise Ratio
  - Bit-Error-Rate
- Receiver sensitivity

Ref: [Keiser Ch6 and Ch7.1, 7.2, 7.4, 7.5]  [Agrawal Ch4] 

Performance requirement

- high sensitivity (at 1.3 and 1.55 μm for telecommunication)
- high conversion efficiency ($P \rightarrow I$)
- fast response (multi-GHz)
- high fidelity (linearity, dynamic range)
- low noise (low dark current, leakage current)
- temperature stability
- cost

Types of common Photo-detectors

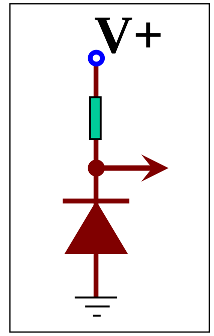
- p-n diode
- P-I-N diode
- avalanche photo-diode (APD)
- Schottky-barrier diode (Metal-Semiconductor-Metal)
- photo conductor
- photo transistor
- photomultiplier

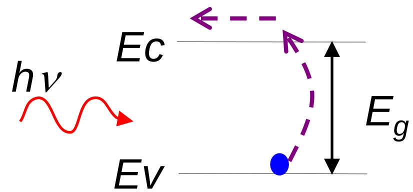
used in optical receiver for optical communication

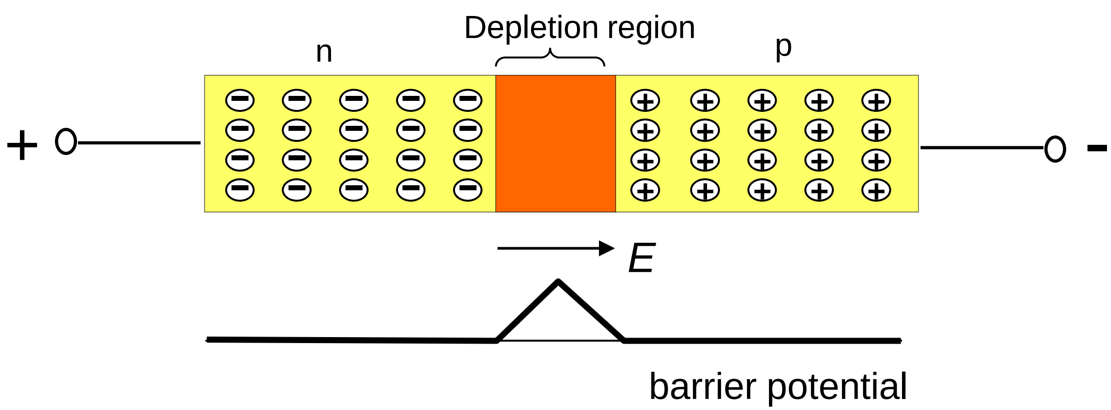
P-N Diode

- P-N junction operates with reversed-biased voltage
- When an incident photon has energy > *bandgap energy*, an electron-hole pair (*photocarrier*) can be generated.
- The carriers are separated by the electric field in the depletion region and are collected by the reverse-biased junction.

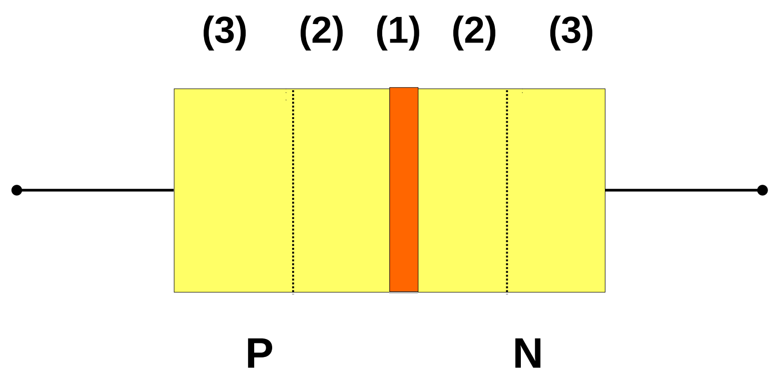
→ photo-current I_{photo} is generated.







P-N Diode



Region (1) : depletion region; electrons & holes swept by E (electric field)
-- create *drift current* (fast)

Region (2) : hole and electrons diffuse randomly towards depletion region -
-- create *diffusion current* (slow)

Region (3) : far away from depletion region (useless if photocarriers are generated here)

➔ Diode response is fastest if electron/hole pairs are generated mainly in the depletion region.

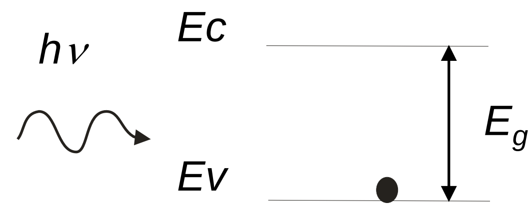
Cutoff wavelength

cutoff wavelength **:** λ_c

If the incident photon's energy ($h\nu$) is < *Eg,* the photon cannot be absorbed.

Q: So what is the <u>shortest</u> photon wavelength such that no photon absorption occurs in a material with bandgap energy *Eg*?

$$\boxed{\lambda_c = \frac{hc}{E_g} \quad \text{or} \quad \lambda_c(\text{in } \mu m) = \frac{1.24}{E_g(\text{in } eV)}}$$



λ_c : Si:1.06 μm, GaAs 0.87 μm, and Ge:1.6 μm.

Note: Two-photon or three-photon absorption are possible, but with very low probability. (e.g. check out the two-photon absorption (TPA) at http://en.wikipedia.org/wiki/Two-photon_absorption)

The photo-current

The current generated by a photodiode is given by

$$I = I_{photo} + I_{dark}$$

$$I_{photo} = P_{rec}(1 - R_e)(1 - e^{-\alpha_s w})\frac{q}{h\nu}$$

where

I_{photo}: photo-current

I_{dark}: dark current (current that exists even without light)

P_{rec}: received optical power

R_e : facet reflection

α_s: absorption coefficient

w : absorption depth

q : electron charge (=1.6×10^{-19} coulomb (C))

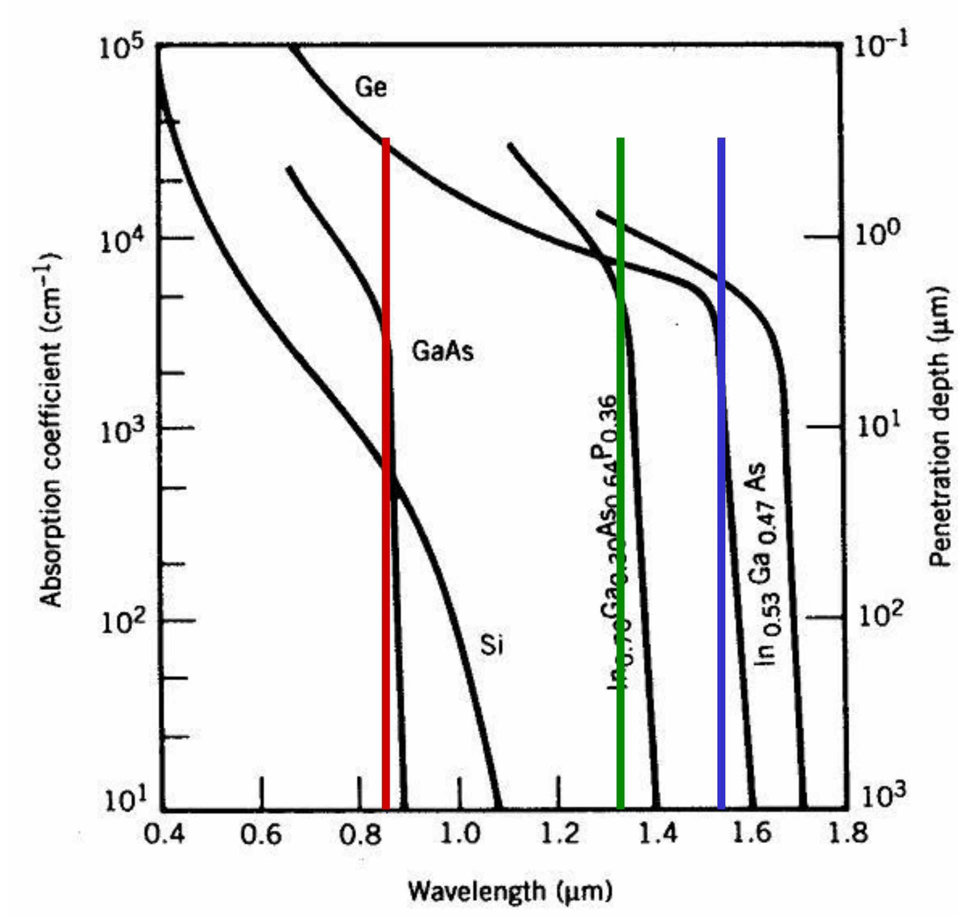
h : Planck's constant (=6.625×10^{-34} J·s)

ν : optical frequency

The absorption coefficient

- ❑ $\alpha \sim 10^4$ /cm
- 1.55 $\mu\mu$ - In $_{0.53}$ Ga $_{0.47}$ As(III – ς), Ge(IV)
- 1.3 $\mu\mu$) - In $_{0.7}$ Ga $_{0.3}$ As $_{0.64}$ P $_{0.36}$ (III-V)
- 0.85 $\mu\mu$ - Si or GaAs

- Note the sharp cut-off wavelength for direct bandgap material



Q: Can Si be used for 1550nm optical signal detection?

Quantum Efficiency and Responsivity

Photo-current: $I_p = P_{rec}(1-R_e)\left(1-e^{-\alpha_s w}\right)\dfrac{q}{h\nu}$ P_{rec}: receive optical power

Define *Quantum efficiency* : $\boxed{\eta = (1-R_e)\left(1-e^{-\alpha_s w}\right)}$ $\eta = \dfrac{I_p/q}{P_{rec}/(h\nu)}$

and *Responsivity*: $\boxed{R_o = \dfrac{\eta q}{h\nu}}$ Unit: A/W

Thus, photo-current: $\boxed{I_p = P_{rec}R_o}$

Note: $\boldsymbol{R_o}$ is wavelength-dependent. Below λ_c, $\boldsymbol{R_o}$ increases as λ increases.

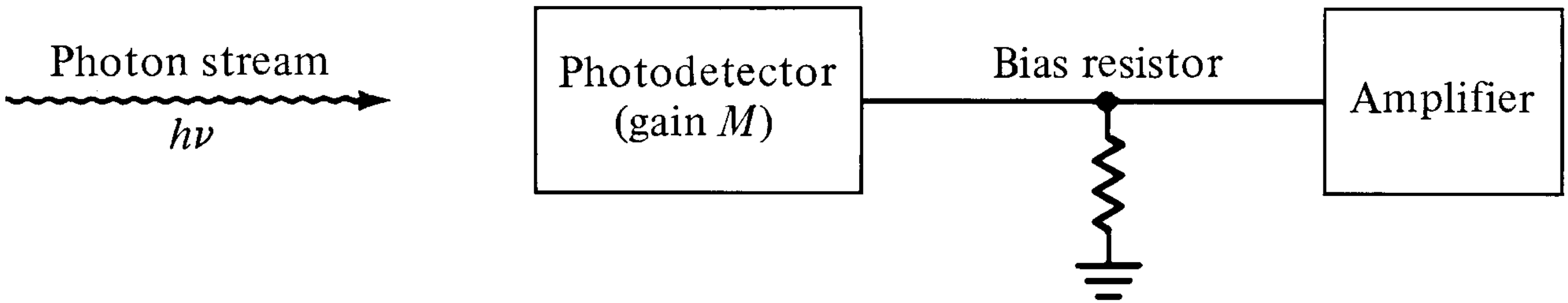
Example: An InGaAs detector has an energy bandgap=0.73eV and η=60% for 1.3 μm optical signal.

The responsivity is:

R_o=0.6(1.609×10^{-19}) λ /(6.6256×10^{-34} · 3×10^{8})= 0.63 (A/W).

The cutoff wavelength is: 1.24/E_g=1.70 μm.

Noise in Photodetectors



- Photon detection quantum noise (Poisson fluctuation)

- Bulk dark current
- Surface leakage current
- Statistical gain fluctuation (for avalanche photodiodes)

- Thermal noise

- Amplifier noise

Noise in Photodetectors – shot noise

Shot Noise

- Photon arrival is discrete and random in nature (Poisson distributed)

  Probability of receiving n photons in time interval τ is $\boxed{p(n)=\frac{\bar{n}^{n}\exp(-\bar{n})}{n!}}$
  where $\bar{n}$ is the mean value of n.

- For a certain quantum efficiency η at the photodetector, the mean number of photoelectron generated ($\bar{m}$) is $\bar{m}=\eta\bar{n}$

- Mean photocurrent generated is $\bar{i}_p=\left(\frac{q}{\tau}\right)\bar{m}$; Variance: $\sigma_i^2=\left(\frac{q}{\tau}\right)^2\sigma_m^2$

  Since both n and m are Poisson distributed, $\sigma_m^2=\bar{m}$ q: electron charge

  Thus, $\sigma_i^2=\left(\frac{q}{\tau}\right)^2\bar{m}=\left(\frac{q}{\tau}\right)\left(\frac{q}{\tau}\bar{m}\right)=\left(\frac{q}{\tau}\right)\bar{i}_p=2q\bar{i}_pB$ since $B=\frac{1}{2\tau}$

  (B: bandwidth)

Shot noise $\boxed{\sigma_i^2=2q\bar{i}_pB}$

In the presence of dark current i_D of the PN junction $\Rightarrow$ $\boxed{\sigma_i^2=2q(\bar{i}_p+i_D)B}$

Noise in Photodetectors – thermal noise

Thermal Noise

- also called *Johnson noise* or *Nyquist noise*
- at a given temperature, electrons move randomly in any conductor
- random thermal motion of electrons in a resistor $\Rightarrow$ current fluctuation
  Even with no applied voltage bias, thermal noise still exists.

- *Thermal noise* $$\boxed{\sigma_T^2 = \frac{4k_B TB}{R_{eq}}}$$

where k_B is the Boltzmann constant (1.38×10^{-23} J/K), T is the operating temperature in Kelvin scale, and R_{eq} is the equivalent receiver resistance.

- In the presence of FET preamplifier, $$\boxed{\sigma_T^2 = \frac{4k_B TF_t B}{R_{eq}}}$$

where F_t is the amplifier noise figure
(F_t represents the factor by which thermal noise is enhanced by various resistors used in the preamplifier)

*Noise in Photodetectors – APD Gain noise

- The impact ionization process is random $\rightarrow$ generation of multiplied photoelectrons is also random $\rightarrow$ additional contribution to shot noise
- multiplication factor, M, is also a random variable
- Shot noise in APD:

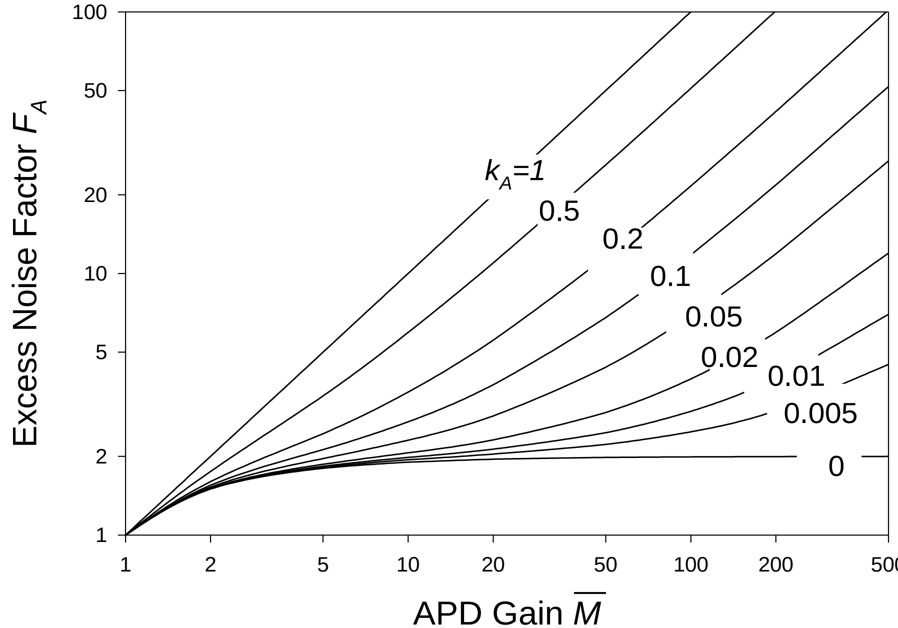
$$\boxed{\sigma_i^2 = 2q\left(\bar{i}_p + i_D\right)\overline{M}^2 F_A B}$$

where F_A is the excess noise factor of APD with

$$\boxed{F_A = k_A \overline{M} + (1 - k_A)(2 - 1/\overline{M})}$$

(assume k_A << 1)

- If k_A=0, F_A is at most 2 and nearly independent of APD gain $\overline{M}$ at high $\overline{M}$



e.g. For Si APD with k_A=~0.1, $\overline{M}$=100 → F_A=11.8
→ mean detected photocurrent increases 100 times.
→ noise increases by a factor of 11.8.

Signal-to-Noise Ratio (SNR)

- SNR is an important parameter to evaluate the performance of a photodetector

$$SNR = \frac{\overbrace{\left(\overline{M}\cdot\overline{i}_p\right)^2}^{\text{Signal}}}{\underbrace{2q\left(\overline{i}_p+i_D\right)F_A\overline{M}^2 B}_{\text{Shot/Gain noise}} + 2qi_L B + \underbrace{4k_BTBF_t/R_{eq}}_{\text{Thermal noise}}} = \frac{\left(\overline{M}R_o\overline{P}_{rec}\right)^2}{2q\left(R_o\overline{P}_{rec}+i_D\right)F_A\overline{M}^2 B + 2qi_L B + 4k_BTBF_t/R_{eq}}$$

where i_p is the mean generated photocurrent,
i_D is the dark current,
i_L is the surface dark/leakage current,
$\overline{M}$ is the mean APD gain,
F_A is the excess noise factor of the APD,
R_o is the responsivity,
$\overline{P}_{rec}$ is the mean received optical power,
B is the receiver bandwidth,
F_t is the noise figure of the FET preamplifier,
R_{eq} is the equivalent receiver circuit resistance,
T is the operating temperature (in Kelvin scale),
k_B is the Boltzmann constant (1.38×10^{-23} J/K),
q is the electric charge (1.609×10^{-19} C)

*For *P-I-N* photodiode, $\overline{M}$=1, F_A=1
*If no FET preamplifier is used, F_t=1

Signal-to-Noise Ratio (SNR)

Example: For an InGaAs P-I-N diode with the following parameters: incident power 300nW @1300 nm, I_D=4 nA, η=0.65, R_L=1000 Ω and negligible leakage current.
If the receiver has bandwidth 20MHz, the signal and noises are

$$I_p = R_o P = (\eta q / h\nu) P = 0.205\ \mu\text{A}$$

$$\sigma_s^2 = 2\, q\, I_p\, \overline{M^2}\, B\, F_A = 1.32\times10^{-18}\ \text{A}^2$$

$$\sigma_D^2 = 2\, q\, I_D\, \overline{M^2}\, B\, F_A = 2.57\times10^{-20}\ \text{A}^2$$

$$\sigma_{th}^2 = 4\, k_B T B / R_L = 3.31\times10^{-16}\ \text{A}^2 \text{ at } T = 27^o\text{C}$$

Example: For a P-I-N photodiode with a load resistance of 1 kΩ without FET preamplifier. The quantum efficiency at 1550 nm is 0.8 and the receiver bandwidth is 500-MHz. The operating temperature is 27^{o}C.

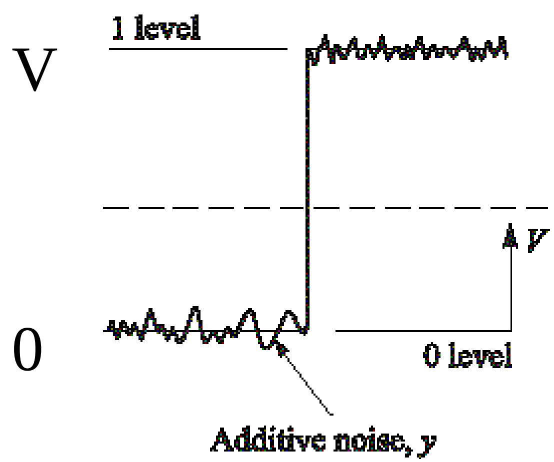
Responsivity $R_o = \dfrac{\eta q \lambda}{hc} = 1.0$

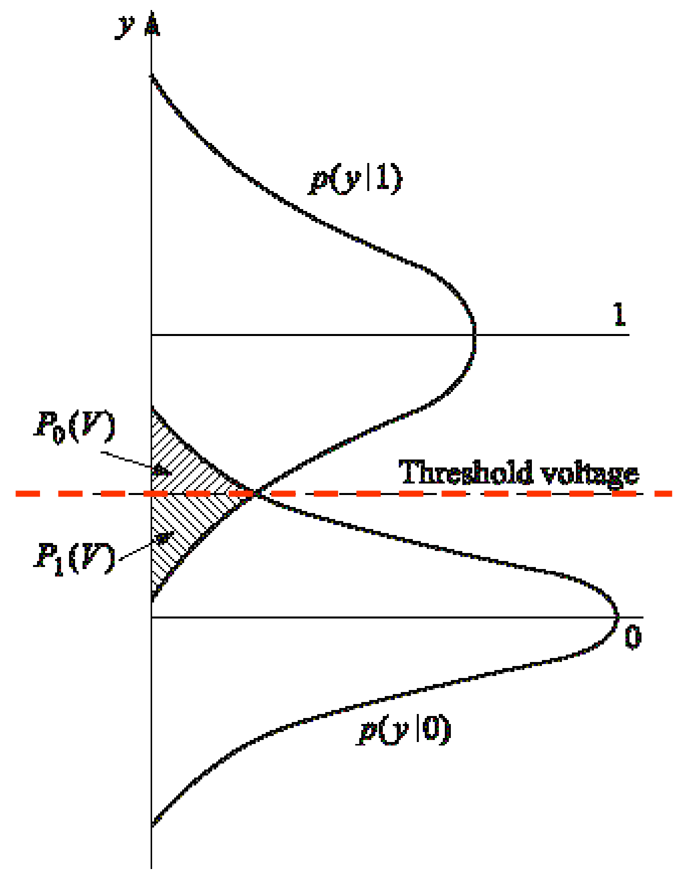
If the detected power is -30dBm, i.e. $\overline{P}_{rec}$= 1 μW, and with B=500MHz, R_{eq}=1 kΩ, T=300K, and R_o=1.0

Use $SNR = \dfrac{\left(R_o \overline{P_{rec}}\right)^2}{2qR_o \overline{P_{rec}} B + 4k_B TB / R_{eq}}$ $\Rightarrow$ SNR = 118.47 =20.74 dB

Bit-Error-Rate (BER)

Probability of detection error: $\boxed{Pe = P(1)\ \ P(0\,|\,1) + P(0)\ \ P(1\,|\,0)}$





Receiver sensitivity

Receiver sensitivity **:**

the required minimum average (for “1” bit and “0” bit) *incident optical power or energy to achieve <u>a desired BER</u> (typical value=10^{-9}) at <u>a specific bit-rate</u>.*

Q: 1. What would happen if the desired BER is smaller?

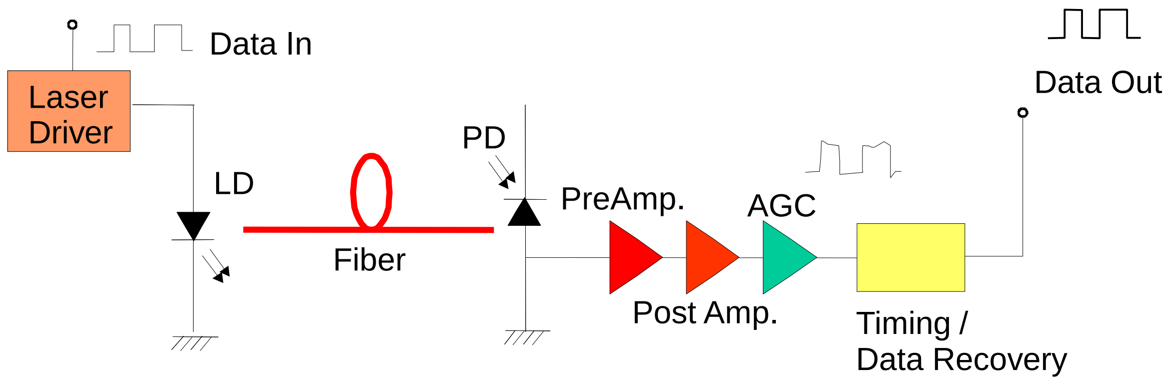
2. What would happen if the bit-rate is higher?

Typical value (@1550nm and @BER=10^{-9}) of receiver sensitivity

for 2.5 Gbit/s : ~ -24dBm for for PIN and -32dBm for APD receivers.

for 10 Gbit/s : ~ -21dBm for PIN and -27dBm for APD

Typical optical communication link



Components	Functions
Detectors (Photodiode PD)	Convert *photon* to electron
Preamplifier	1^{st} amplification brings voltage level from μV to mV (incoming signal ~ -30 dBm, 1A/W)
Postamplifier	2^{nd} amplification brings mV to a usable range of a few V
Automatic Gain Control (AGC)	For better dynamic range: control the gain to have about same power entering time/data extraction circuit
Timing and Data Recovery	Retrieval of data and timing (for digital communcation)

Q: Why two Amps are used and what is the function of timing/data recovery?

Receiver Data Sheet

LUMENTUM 10G XFP ROSA (receiver optical sub-assemly)

Specifications

Parameter	Symbol	Conditions	Minimum	Typical	Maximum
TIA supply voltage	V_{cc}		3.15 V	3.30 V	3.45 V
TIA supply current	I_{cc}	V_{cc}=3.3 V	—	28 mA	41mA
Wavelength	λ		1260 nm	—	1565 nm
Photodiode responsivity	R	Measured at 1310 nm	0.75 A/W	—	—
Single ended output impedance	Z_{out}		40 Ω	50 Ω	60 Ω
Power consumption	P_e		—	100 mW	—
RSSI offset current (no light)[1]	Id_{RSSI}		3.5 μA	10 μA	16 μA
RSSI gain internal bias	A_{RSSI}		0.48 A/A	0.50 A/A	0.52 A/A
Data rate	B		9.95 G	—	11.35 G
RF bandwidth (–3 dB)	BW	Small signal bandwidth	7 GHz	—	—
Low frequency cut-off (–3 dB)	f_c, low		—	30 KHz	100 KHz
Sensitivity average power	Sens_Avg	10.709 G, NRZ, PRBS 2^{31}–1 1550 nm, ExtRatio>10 dB, BER=10^{-12}	—	–19.5 dBm	—
Stressed sensitivity OMA XFP-SR1 XFP-IR2	 SRS_10GbaseL SRS_10GbaseE	 IEEE802.3ae, 10GBase-L stress IEEE802.3ae, 10GBase-E stress	 - -	 –16 dBm –16 dBm	 - -
Overload	P_{max}	10.709 G, NRZ, PRBS 2^{31}–1, 1260 – 1355 nm, Ext Ratio=13.0 dB, BER=10^{-12}	1.5 dBm	-	-
Optical return loss XFP-SR1 XFP-IR2	ORL	 1290 – 1330 nm 1530 – 1565 nm	 - -	 - -	 –14 dB –28 dB
Transimpedance (single-ended)	Z_T		5000 Ω	7000 Ω	10000 Ω
Maximum differential output voltage	V_{out}, D, Max		240 mV_{PP}	280 mV_{PP}	350 mV_{PP}
TIA input referred RMS noise		10 GHz bandwidth	-	0.9 μA	1.6 μA

Optical Receiver Products

- Oclaro (was called Bookham):

  http://www.oclaro.com/products/#title

- LUMENTUM (former JDSU):

  10G ROSA

  https://www.lumentum.com/sites/default/files/technical-library-items/rxpmgrtl097-ds-oc-ae.pdf

  100G 10km Optical Receiver

  https://www.lumentum.com/sites/default/files/technical-library-items/jc2-10lx4aa1-ds-oc-ae.pdf