Introduction

Main bands in the optical frequency spectrum, these are:

- Infra-red: the band of light wavelengths that are too long to seen by the human eye
- Visible: the band of light wavelengths that the human eye responds to
- Ultraviolet-band: the band of light wavelengths that are too short for the human eye to see

x-rays:

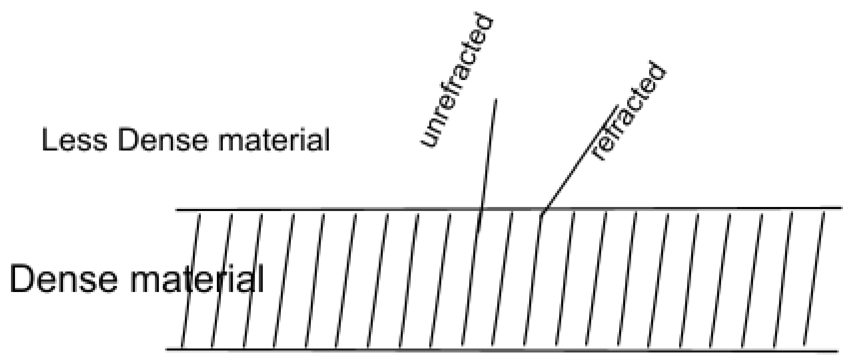
violet indigo blue green yellow orange red

300 nm 900 nm

ultraviolet	light	Infra red

EM optoelectronic spectrum:

In free space electromagnetic waves travels at approximate $3x10^8$ m/s. However, **their velocity is lower when they travel through denser materials**. When traveling from a material to another which is less dense than the ray to be refracted (or bent) away from the normal as shown in fig below



Refracted ray

Refractive index:

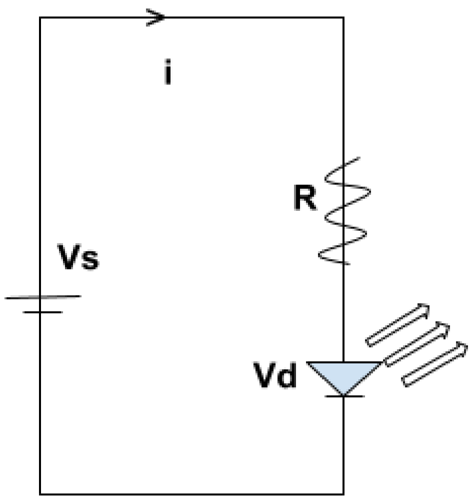
The amount of bending or refraction at the interface between 2 materials of different densities depends on the refractive index of the two materials. this index is the ratio of the velocity of propagation of the light ray in free space to the velocity of propagation of a light ray in the material, as given by $n = \frac{c}{V}$

Reflective index for popular medium:

- air n=1.003
- water n=1.33
- glass fiber n=1.5 to 1.9
- gallium arsenide n=2 to 2.42
- silicon n=3.4

Light emitting diode (LED) /Injection laser diode(ILD):

For converting electrical energy to light energy, fig below shows a simple bias circuit for this purpose



$$i = \frac{V_s - V_d}{R}$$

R is used to limit the current in the LED

Normally a current of 10 mA is necessary to produce a good intensity of light.

For a GaAs diode the ON voltage is around 2v, for GaAs diode, with an ON bias current of 10 mA and 5v source, the limiting resistor value would be R=300 Ω

The wavelength of the light emitted depends upon the type of semiconductor used **GaAs emits a wavelength in the infra-red range**.

Although the basic **GaAs** emits infra-red it can be doped with other materials to provide a wider range of wavelengths.

Gallium phosphide GaP emits green light and it can radiate red light depending on the doping.

GaAsP can emit **yellow** light

Injection laser diode (ILD):

A laser (light amplification of simulation emission of radiation) diode emits light at a single wavelength known as monochromatic light. It is a **more focused ray**, has **o/p radiation greater** than an LED, it has **higher bit rates** (it can be turned ON or OFF faster).

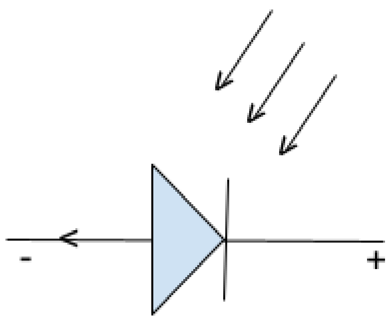
The main disadvantages of ILD are that they are more **expensive**, have a **shorter lifetime** and are more **temperature dependent**.

Photodiodes:

Photodiodes and phototransistors **convert light energy (photons) into electrical energy**. Their operation is based on the fact that the number of free electrons generated in a semiconductor material is proportional to the intensity of incident light,

A photodiode must be **reverse biased**, the reverse biased current varies as the amount of light on the diode junction. A basic biasing circuit for photodiodes is shown in the fig below.

The amount of current is normally extremely small, possibly just a few hundred micro amperes.



The photodiodes use the reverse of the physical process in the LED. When a photon of sufficient energy enters a semiconductor material, it may be absorbed by that material. Photon absorption results in the freeing of an electron from a chemical band, resulting in a hole-electron pair. Both the hole and the electron are free carriers, and can move within the semiconductor in the presence of an electrical field.

The minimum energy that the photon must have to create a hole-electron pair is the semiconductor band gap Eg. If the photon has more energy than this, the hole and electron will convert the **excess** energy to kinetic energy. **A photon must have at least 2 Eg of energy before it can create a second pair**.

A photodiode is characterized by the window in which it can be used. the cutoff energy has a corresponding cutoff λ;

- Si: has cutoff length of **1100 nm**, can only be used in the **short wavelength** window.
- For long wavelength **(1200-1600)** nm the Ⅲ **-** Ⅴ materials is used (Ge is suitable for some applications).

Silicon photodiodes have a number of **advantages** :

- **Si wafers** are commercially available up to s in compared to 4th for Ⅲ-Ⅴ materials such as GaAs.
- Si photodiodes can easily integrate with transistors on an **IC**, making it possible to fully integrate the receiver.
  (A fully IC produces the lowest overall cost and improves reliability)

Example:Si has a band gap energy of **1.12 eV**, what is the minimum energy of photons that can be absorbed by a photodiode?
what is the max λ of the photons?
sol:
Emin=Eg=1.12 ev
λmax occurs at Emin

$$\lambda_{max} = \frac{h\,c}{E_g} = \frac{1.240\ ev\ \mu m}{1.12\ ev} = 1.11\ \mu m$$

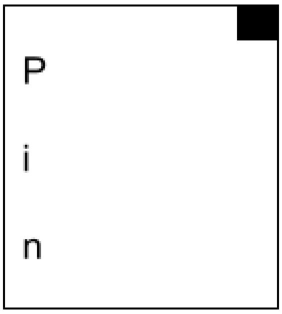
h: planck's constant = 6.626x$10^{-34}\,J$

1 ev=1.6x$10^{-19}\,J$

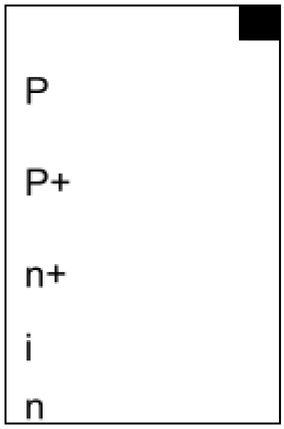
Types of photodiodes:

There are 2 types of photodiode structures, the PIN and APD. The PIN structure is similar to the basic P-N junction diode, except that an **intrinsic layer** is sandwiched between the P and N materials, the Advanced photodiode (APD) structure is more complex, having several P and N layers.

fig shows the basic structure of 2 types of photodiodes, the PIN photodiode is named for the structure of P-I-N layers. In both the PIN and APD photodiode structures, the intrinsic layer is relatively thick (on the order of s-i μm), **enhancing photon capture**.



PIN



APD

The probability of a photon being captured within a region of semiconductor material depends on:

- the photon energy
- the semiconductor material properties
- the thickness of the absorbing layer, with a greater thickness absorbing more light.

Photodiodes are operated in the reverse bias region. since the signal current is in the order of **10 nA to 100µA**. A forward current of 1mA or more would totally swamp this signal current, making it impossible to separate the signal from the noise.

When no light shines on the photodiodes, only the leakage current of the junction flows, this is referred to as the **"dark current"** (in the order of 1-10 nA). Photocurrent caused by the optical signal adds to the leakage current. In an APD photodiode, the dark current increases with the bias,

In **avalanche** breakdown, both holes and electrons may collide, the gain M is the ratio of the average number of carriers leaving the avalanche region to the number that enters, the gain will vary as a function of:

- bias voltage
- temperature
- optical wavelength
- semiconductor material

The practical gain on the order of 5-50

An APD achieves gain only when the bias exceeds the first breakdown voltage, below the avalanche breakdown voltage M=1, for most practical devices, V_{br} **is between 25 and 200v**.

Switching speed is determined by the physics of the avalanche region. Rise Time is very fast when the gain is high (since a single photon can result in a large o/p current)

APD can not be used on a 5v oriented circuit board.

On most local area network links, the **PIN is the preferred device because it can be operated from a standard board power supply (5-15v).**

APD devices,while providing **5-10 db more sensitivity** and **half the rise time**, where the increased repeater spacing provides cost saving to overcome the costs associated with special power supplies.

for either type of photodiode structure, the amount of the photo current I_p generated by a photodiode is given by

$$I_p = MRP$$

P is the **optical power** at certain wavelength, M is the **gain**, R is the **responsivity**, and it's a function of both semiconductor material and optical wavelength λ

R range between 0.2 to 0.5 A/W or μA/μW

Example:

A silicon PIN diode has a responsivity of 0.58 A/W at 830 nm. optical power of 800 nm falls on the diode (at 830 nm) what is the resulting photo current?

sol:

since a PIN diode has no internal gain, ∴ $M = 1$

I_p = the photo current = MRP

= 1(0.58 A/W)(800nW)

= 464 nano Amper

Example:

A silicon APD diode has a low-bias responsivity of 0.58 A/W at 830 nm and is operated with a gain of 5, optical power of 800 nW at 830 nm falls on the diode. What is the resulting photo current?

sol:

I_p = the photo current = MRP

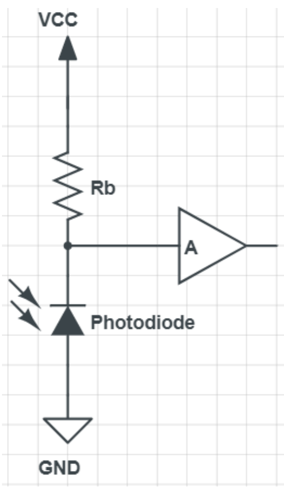
=5(0.58 A/W)(800 nW)

=2320 nano Amper

The responsivity R exhibits a strong dependence on the optical wavelength. In particular, the responsivity drops to zero above the cutoff wavelength.

Receiver Modules

Receivers convert optical inputs back into electrical inputs. A photodiode converts the optical signal to a current signal. Because the received optical signal and resulting electrical current have small amplitudes, the receiver will usually contain one or more amplification stages. The receiver may also contain filters or equalizers to improve signal quality. A digital receiver converts the amplified signal into a digital signal level.



A receiver is generally designed to be used with a particular transmitter. For example, a TTL transmitter is generally paired with a TTL receiver.
A receiver consists of a photodiode, bias resistor and low noise preamplifier as shown in the following figure.

It may also contain additional amplification and filters or equalizers. These components may be on a single IC, a hybrid, or a printed circuit board.

Also the receiver has a **clock** (for timing). This hole framing information and decreases BER.

Clock recovery in fiber optics systems is important, since the clock is not transmitted separately from the data.
Other support functions may include decoding, error detection, error recovery and detection of the link failures (i.e. loss of optical signal or loss of modulation).

A receiver must have:

- High sensitivity.
- High bandwidth (or fast rise time).
- Low noise.
- High gain.
- Large output signal with low bias complexity.
- High reliability and low cost.

Amplifiers

The first amplifier (pre - amp) in a receiver must have very low input noise to avoid swamping the small signal current provided by the photodiode.

The photodiode, its bias resistor, and the pre-amp should be designed as a unit. Interactions between these components will determine receiver bandwidth and SNR and sensitivity (minimum desirable signal).

Amplifiers can be divided into 4 groups based on the input transistor as follow:

- The transistor (FET or BJT).
- Configuration (high impedance or transimpedance).

All 4 types are used in receiver design depending on the desired characteristics.
The quantum unit is the sensitivity (minimum detectable power).
Amplifier groups:

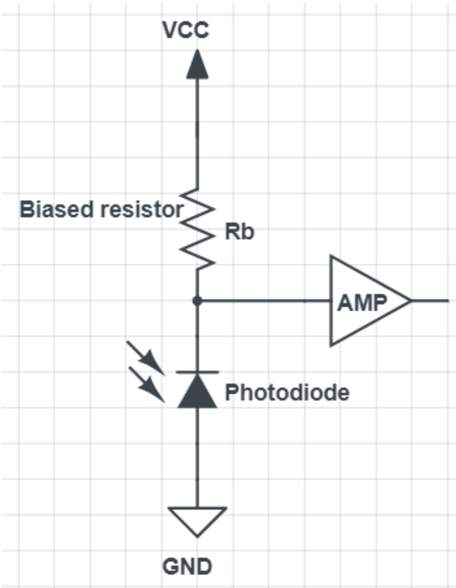
- PIN + BJT
- PIN + FET
- APD + FET
- APD + BJT

The APD provides greater sensitivity at all data rates.

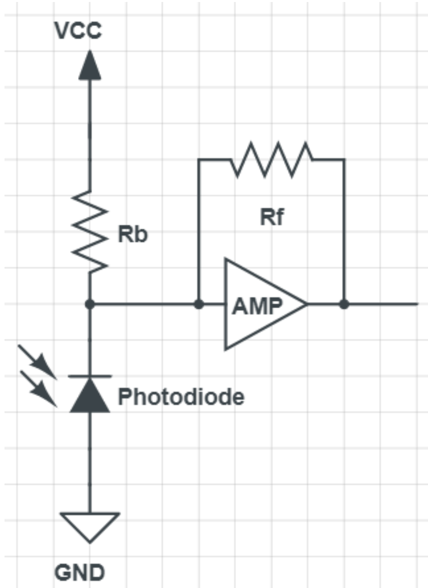
FET amp provides improved sensitivity at lower data rate.
A bipolar amp at higher

The choice of amp type will therefore be influenced by the desired operating range.

The pre-amp high impedance and transimpedance pre-amp are shown in figure below. It is a DC coupled amplifier stage.



High impedance pre-amp



Transimpedance pre-amp

- **Advantages of the high impedance pre-amp:**
  - Higher sensitivity at low frequency.
  - Higher gain.
- **Disadvantages of the high impedance pre-amp:**
  - Low bandwidth.
  - Low dynamic range.
  - Integrates the signal.
- **Advantages of transimpedance pre-amp:**
  - High bandwidth.
  - Wide dynamic range.
  - High sensitivity at high frequency.
  - Low output impedance.
  - Controllable gain (R_f).
  - Stable gain.
- **Disadvantages of transimpedance pre-amp:**
  - More components.

If the information is bandwidth limited, it is desirable to AC couple the photodiode and the pre-amp. This eliminates low frequency noise.

AC-coupled receivers are more commonly used than DC-coupled receivers. Reducing the noise improves sensitivity and improves the receivers performance (Figure 2).

Receiver Bandwidth:

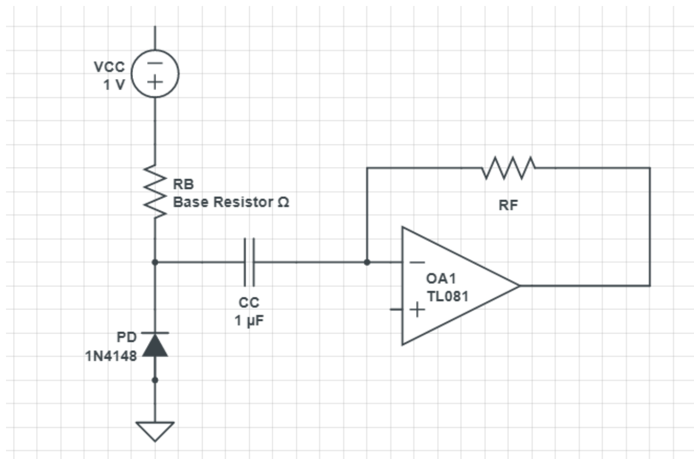
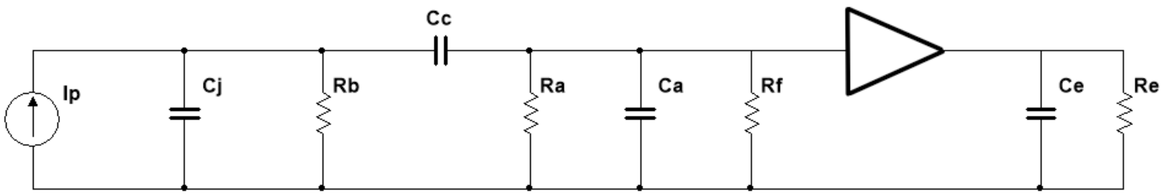


Fig 2 AC coupled transimpedance pre-amplifier

The receiver bandwidth is determined by the photodiode, the coupling capacitor (if any), the pre-amp, and any following filter or equalizer. Figure below shows the AC equivalent circuit for an AC-coupled receiver.



The input of an AC-equivalent circuit is the AC phota current I_p. There are 2 parasitic capacitors Ca and Cj for the photodiode and the pre amp. input respectively. The parasitic resistor Ra is the input resistance of the pre-amp, the receiver has a cut off frequency ad then lower of the filter and pre-amp AC input bandwidth

Typical value of:

1. C_a is around 1 - 100 pf
2. C_j is around 10 - 1000 pf
3. Ra is around 10 M ohm for FET input pre-amp and around 10K ohm for bipolar i/p pre-amp

The parasitic capacitors can be ignored in determining low cutoff frequency.

In analyzing that high frequency cutoff, the coupling capacitor can generally be ignored. Care must be taken to minimize the wiring capacitance and amplify with high BW, high input impedance and low input capacitance. Photodiode rise time is significant for high speed.

Example: A receiver has a bias resistor of 10 $K\Omega$ and a photodiode capacitance of 4 pf. It is DC Coupled to a high-impedance. preamp.with an input impedance of 10 M ohm and input capacitance of 8pf . The o/p filler has a frequency cut off of 10 Mhz Determine the receiver bandwidth

Solution :

for the DC coupled to a high impedance pre-amp . The o/p stage capacitance $C = C_a + C$

C = 4 + 8 = 12 pf

The i/p stage resistance $R = R_b // R_a$

$R = 10K\Omega // 10M\Omega = 9.99\ K\Omega$

$F_{RC} = \frac{1}{2\pi RC}$

F_{RC} = 1.33 M Hz

The receiver bandwidth is the lower of two frequencies (The frequency cutoff) . the filter which is 10 MHz and the receiver bandwidth due RC time is constant which is 1.33 MHz

The receiver cutoff frequency with lower of F_{max} = Min(1.33 MHz , 10 MHz) = 1.33 MHz

Example:A receiver has a bias resistor of 10 KΩ and a photodiode Capacitance of 4 pf It is DC coupled.A transimpedance pre-amp-with an input impedance of 10 MΩ , input capacitance of 8pf and 10 KΩ feedback resistor. Determine the receiver bandwidth. If the o/p filter has a cutoff frequency 10MHz

Solution:

The input stage capacitance is

$C = C_a + C$

C = 4 + 8 = 12 pf

The i/p stage resistance

$R = 10K\Omega // 10M\Omega // 10K\Omega = 5\ K\Omega$

F_{RC} = the receiver bandwidth due to the time constant

$F_{RC} = \frac{1}{2\,\pi\,RC}$

$F_{RC} = \frac{1}{2\,\pi\,(5K\Omega * 12\,pf)}$

F_{RC} = 2.65 MHz

The receiver cutoff frequency is The Lower of the two frequencies Min (2.65 MHz ,10 MHz) = 2.65 MHZ
It’s clear that BW or the receiver cutoff frequency is larger when we use transimpedance pre-amp then if we use high impedance pre-amp.

Filtering or equalization is used after the amplifier for a number of reasons, the fiber optic link particulate the transmitter and receiver introduce non-linearity into the information transfer function.
Non-linearities cause information transmitted at one frequency to appear at harmonies of that frequency and so cause signals at different frequencies w_1 and w_2, and to become coupled at frequencies $\mathbf{w_1 + w_2}$ and $\mathbf{w_1 - w_2}$ and others. These effects are referred to as harmonic and intermodulation distortion respectively.

Selective filtering of the output can remove harmonic and intermodulation-signs that are not in the same band as the original information. This filtering can also remove low and high frequency noise.

Receiver Noise Performance

The receiver is the major contributor to noise in fiber optic links. The transmitter generally provides high SNR and the transmission media does not couple in (EM) noise.
At the receiver the noise amplitude is a significant fraction of the signal amplitude; and more attenuation must be given.

Circuit design and component selection

There are three major sources of noise at the receive fluctuations in:

1. The optical input
2. The photodiode
3. The amplifier input (including the base resistor)

Next notes includes:

- Calculation of noise in optical systems
- Losses in fibers and attenuation

- Optical fiber characteristics

Receiver Noise Performance

There are 3 sources of noise at the receiver:

1. The amplifier electronics (including the bias resistor)
2. The optical input
3. The photodiode

Noise from the optical input maybe because the input optical is not continuous being composed of discrete photons, then the noise results in a fundamental quantum limit on the noise, photon quantum noise not a problem for a fiber optical data link since it is served down from the other major noise sources.

A quantum process such as photon arrival, current flow, cross junction or avalanche gain will result in noise. In certain time (1-ns for example) an observable will see a different number of electronics.

The distribution of all observations follows a classic poisson distribution.

The probability of observing n items (electrons) in an interval is:

$$P_n = (N^n * e^{-N}) / n!$$

Where P_n is probability of observing n items (electrons) in an interval, N is the average.

The probability of observing bet n a and b number is given by:

$$\sum_a^b P_n$$

Example: An avalanche photodiode is biased to rare a gain of N = 3.5 for one incident carrier into the avalanche region

a) What is the probability of exactly 3.5 collisions occurring?
b) What is the probability of 2 or fewer collisions occurring?

Solution :

a) Since the number of actual collision isn't an integer then $P_n = 0$
b) $P_n = (3.5^0 * e^{-3.5})/0! + (3.5^1 * e^{-3.5})/1! + (3.5^2 * e^{-3.5})/2!$
   $Pn = 0.32$

The photodiode contribute noise through the current (both dark and photo current) and through fluctuation in the analchae process current, considering of flow of discrete electrons, will diculate them to an offer to an " shot noise ", similarly The available mechanism consist of a discrete number of collision for each photogenerated carrier.
The mean square current noise associated with the photodiode is :

$$< i_{n_p}^{2} > \ = \ 2qB(I_p + I_{dp})\, M^{2+x} + \ 2qB(I_{ds})$$

where I_p is the photocurrent

I_{dp} and I_{ds} are the photo leakage current term

M the avalanche gain

x is the characteristic of the photodiode

B is the receiver noise bandwidth

B is a feedback resistor that contributes thermal (Johnson) noise due to the random motion of electrons.
The thermal noise associated with a resistor is :

$$< Inr>^{2} \ = \ (4 \ * \ k \ * \ T \ * \ B)/R$$

k is boltzmann constant $1.38 \ * \ 10^{-23}$ J/k
T is the temperature with kelvin
B is the receiver noise bandwidth
R is the resistor value

Resistor noise appears as a current source in parallel with the resistor
Dark current contribute to noise will depend on bias and an temperature
leakage current increases rapidly with temperature , also increases with increasing bias , particularly for IIIV compound semiconductor.

The amplifier noise arises from shot noise of the i/p transistor and the thermal noise of the feedback resistor.
The amplifier is characterized by voltage and current noise power spectral density, en and in . The noise of amplifier coming by:

$$< inp^{2} > \ = \ 2B[In^{2} + \ (en/R)^{2}]$$

Example :

A PIN photodiode has dark current 2 nA and a photo current 50 nA
It is connected to a 10 k ohm bias resistor, The input stage bandwidth is 50 MHZ . Compare the photodiode and thermal noise contribution at room temperature (300 k).

Solution:

a) $< i_{n_p}^{2} > \; = \; 2qB(I_p + I_{dp})\, M^{2+x} + 2qB(I_{ds})$

$= \; 2 * \; (1.6 * 10^{-19}) \; * \; (50 * 10^{6}) \; * (50 \; * 10^{-9} \; + \; 2 * 10^{-9})\,(1) \; + \; 0$

$= \; 0.832 \; * 10^{-18} A^{2}$

b) $< Inr>^{2} \; = \; (4 * k * T * B)/R$

$= \; (4 \; * 1.38 \; * 10^{-23} \; * \; 300 \; * 50 * 10^{6})/10 * 10^{3}$

$= 82.8 \; * \; 10^{-18} A^{2}$

In this case the resistor contributes the majority of the noise current.

Example:

A photodiode and bias resistor of the previous example are connected to a high impedance amplifier have noise spectral density of en = $10\, nv/Hz^{0.5}$ and in $6\, PA/HZ^{0.5}$ compare the amplifier noise to the thermal noise

Solution:

from before, $<I_{nr}^{2}> = 82.8 * 10^{-18}\, n^{2}$

$$< I_{na}^{2} > \; = \; 2B\,(I_{n}^{2} + (\frac{en}{R})^{2})$$

$$= \; 2\,(50 \; * \; 10^{6}\, Hz)(36 * 10^{-24}\, A^{2}/Hz \; + \; (\frac{10*10^{-9}\, V/Hz^{\frac{1}{2}}}{10kn})^{2}) \; = \; 3.7 \; * \; 20^{-15}\, A^{2}$$

In this case, the amplifier dominates the total noise current.
The total noise current is given by the sum of the 3 noise power.
the SNR is given by:

$$SNR \; = \; \frac{(m\, I_p)^{2}}{<I_{np}^{2}> + <I_{nr}^{2}> + <I_{na}^{2}>}$$

where m is the modulation index $(\frac{\Delta I}{I_p} \; = \; \frac{\Delta P_0}{P_{dc}})$

and Ip is the average amplitude of the (modulated) current the max value of m is 0.5

Environmental Effects:

PIN photodiodes are relatively insensitive in temperature and bias voltage; the same cannot be said for APDs.

The avalanche mechanism is sensitive to many things including temperature, bias voltage, and optical wavelength.

For the APDs: -

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- M varies with temperature and bias for a silicon APD.
- Gain increases with decreasing λ.
- Gain increases with increasing bias voltage, approaching infinity at the breakdown voltage (the second breakdown voltage increases with increasing temperature)
- Note: an APD must be biased so that it does not reach breakdown over the entire operating temperature range and life.

Receiver noise increases with increased temperature due to the increased thermal noise and increased leakage current.

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The pre-amp gain may change with temperature, the increase in leakage current can be significant, particularly for semiconductors having smaller bandgap (those used in the shorter wavelength window)

The variation of the resistors and capacitor values with temperatures (this effect is less critical in digital links and the small shift can be tolerated. However, in analog links, the tolerance in the components and the thermal coefficients must be determined)

هام في ال digital
هام في ال analog

Notes:

مقاومة الكربون
الضوضاء عالية بها
ولذلك يستخدم ال
metal film او مواد
اخري

1. Large excess noise is commonly seen in carbon resistors. The metal film or other low-noise resistors are used.
2. Dust particles are comparable in size to the fiber diameter and to source and photodiode size; dust particles can block so much light the SNR decreases or the BER increases drastically.

Receiver layout notes there are 2 effects in the board layout.

ال fiber عازل، ولكن الوصلات معدنية فيها تتفاعل مع الموجات الكهرومغناطيسية

1. The receiver should be in a metal package to eliminate pickup electromagnetic signal through the metal wiring between components and so the connecting wires should be as short as possible to eliminate on-board crosstalk.
2. The ground bounce: the ground voltage changes due to the changes relative to the power supply voltage, and each changes relative to the true earth ground, due to the current flowing in the wire between the power supply and the devices on the board.

Also, for a digital board, ground bounce may be as high as O.S.V or more. This O.S.V charge in the bias across the photodiode will generate a change in current; many produce spurious data.

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For highest sensitivity and lowest noise performance, analog and digital grounds should be routed separately all the way back to the power supply, However, it may be possible to join the two grounds at the edge of the board.

Summary:

A receiver consists of:

- A photodiode, a pre-amp and other support circuits.
- The key features of a receiver are the sensitivity and B.W.
- The photodiode may be a simple PIN structure or APD with internal gain.
- A PIN can be repeated from standard board power supplies.

- An APD requires a stable high voltage supply. (The first breakdown of the APD occurs between 25 and 200V depending on the device).

A/W
MA/MW

- Responsivity of a photodiode mainly depends on the material.
- Si is a good material for short window and several III-V compounds are suitable for long- λ window.
- The B.W of a receiver is primarily determined by the RC time of constant of the amplifier i/p node and the post amplifier or equalizer.
- B.W is sensitive to the layout parasitic particularly wiring capacitance at the pre-amp i/p.
- Noise originates in the photodiode, the resistors, and the pre-amp transistors.
- Noise increases with temperature and the APD gain.
- Noise can be reduced through careful board layout.

Optical fiber characteristics

Fiber profiles:

A fiber is constructed of a core surrounded by a cladding. The core and cladding are both made from glass with only a small difference in doping. To achieve guided propagation. The core index of refraction must be higher than the cladding.

The ruler diameter is normally 125 µm, to fit standard fiber optic connectors. Also other outer diameters are available; the symbol n1 is used for the core index. and n2 for cladding index.

$$\Delta n=\frac{n1-n2}{n1}=\frac{NA^2}{2n1^2}$$

$$n_1\Delta=n_1-n_2$$

$$n_2=n_1-n_1\Delta = n_1(1-\Delta)$$

$$NA=\sqrt{(n1^2-n2^2)}=n1\sqrt{2\Delta}$$

For typical fibers, Δn on the order of 0.01 (usually between 0.005 and 0.02).

only n1 and NA are given on data sheets.

EX: a fiber has a core index of 1.448 and NA of 0.21 find the index difference and the cladding index .

Sol:

$$\Delta = \frac{NA^2}{2n1^2} = \frac{(0.2)^2}{2(1.448)^2} = 0.0105$$

n2=n1(1-Δ)=1.448(1-0.0105)=1.433

Types of fiber optic cables

There are 2 basics ways of classifying fiber optic cables:

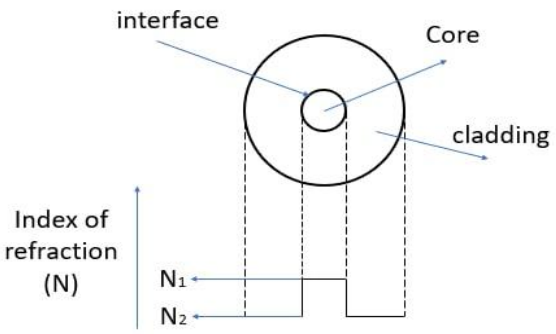
•First way is an indirection of how the index of refraction varies across the cross-section of the cable.

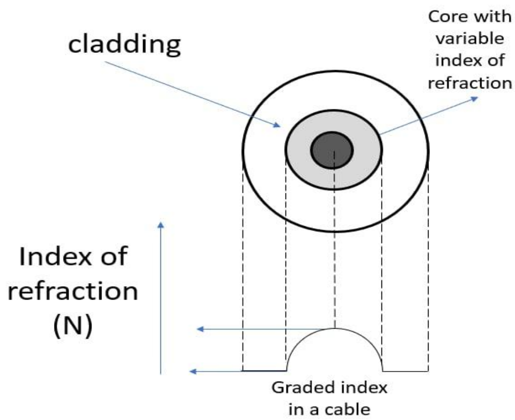
•The 2nd way of classification is by mode.

Mode refers to the various paths that the light Rays can take in passing through the fiber.

Usually 2 methods of classification are combined to define the type of cable.

1- Step index





There are 3 fiber profiles in commercial use. Step-index, graded-index and single mode. Each fiber has advantages and disadvantages.

- Step-index fiber is easy to couple to, but has low B.W (band width).
- Graded-index fiber is easy to couple to, and has a medium B.W (band width). And the most expensive.
- Single-mode fiber, with less than 10 μm core diameter is very difficult to couple to, but has high B.W (band width) and moderate. Mode: refers the number of paths for the light ray in the cable

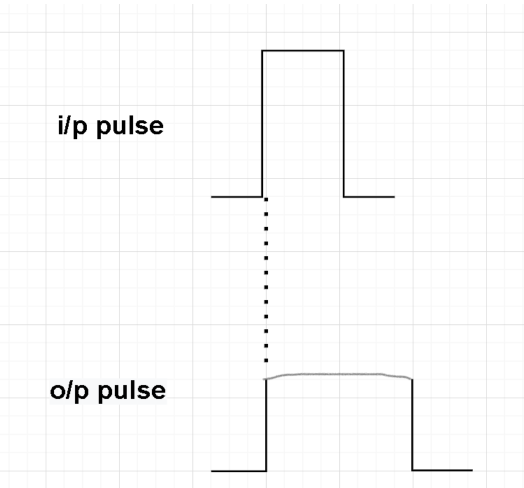
There are 2 classifications : (I) Single mode
(2) multi mode

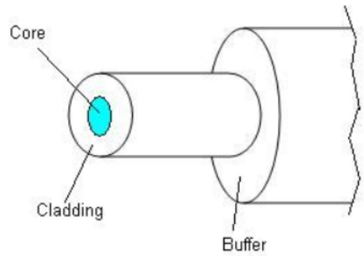
Each type of fiber-optic cable is classified by one of These methods. Of rating the index or mode.
In practice there are 3 commonly used types of fiber optic Cables These are:

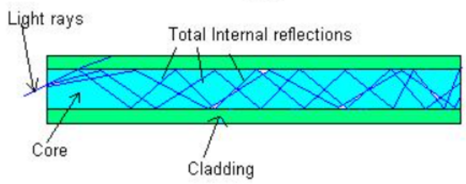
- Multimode step index (most common and widely used).
- Single mode step index.
- Multimode graded index.

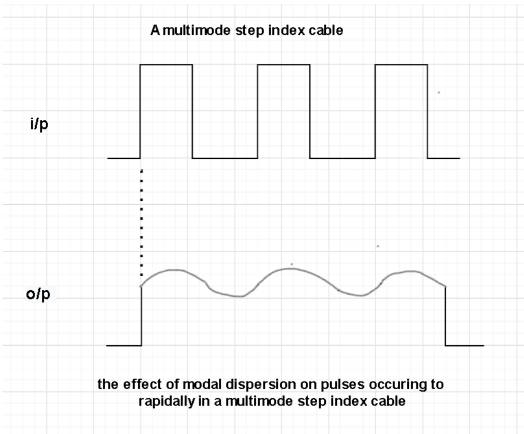
A multimode step index: widely used type , easiest to mode (least expensive) used for Medium distances at relatively low pulse frequencies.

Its large size, typical core diameter 30 -1000 µm. The problem with this type is at stretches the light- pulses. due to the different arrival time of the various light rays This stretches the pulse. The stretching of the pulse is referred to as a modal dispersion.
Because the pulse has been stretched, the i/p pulses cannot occur at a rate faster than the o/p pulse duration permits. Otherwise, the pulses will essentially merge.









Single-mode step-index cable:

Here the core is so small that the total number of paths through the fiber core is minimized and modal dispersion is essentially eliminated. No pulse stretching occurs (core sizes are 2: 15 μm).

Here the pulses repetition rate can be high and the max num of information can be carried.

Used for very long distances and max information content.

Disadvantages:

- Difficult to mode
- expensive
- Difficult to splice and interconnect
- Used with laser i/p source for long-distance

Multimode graded index:

Because of the varying of n across the core light rays near the edge, takes a longer path but travel faster since the index of refraction is lower.

All the modes or lightpaths tend to arrive at one point simultaneously then the modal dispersion is low. It can be used at high pulse rates.

It’s much wider in diameter core (50: 100 μm) range than its easier to splice and interconnect, and cheaper. A less intense light source may be used.

Attenuation:

Attenuation is the loss of optical signal strength down on the length of the fiber.

Attenuation is the highest in the 850 nm window. For long-haul communication, fiber is selected that fiber it’s the lowest attenuation. The optical coupling loss decreases as the num of fibers increases.

Once the power has been coupled into a fiber, the optical signal will interact with the fiber. There are 2 major interaction effects: Attenuation and dispersion.

- Attenuation decreases the optical power.
- Dispersion decreases the available bandwidth.

Both effects degrade link performance. The longer the link, the greater the degradation.

Attenuation is caused by 2 physical effects: absorption and scattering.

- absorption removes the photon in interaction with atoms and molecules.
- Scattering redirects the light out of the core.

Absorption occurs when the energy of the photon is equal to a difference between two electrons' energies.

Scattering losses occur when the photon sees a variation in the core’s index of refraction. Photons can be scattered out of the fiber from small density variations in the glass. Density variations may be caused by incomplete molecular bonds. Or by variations in molecular spacing.

A major cause of the absorption is the presence of OH radicals, which results from the presence of the water. OH radicals enter the fiber during manufacturing or in humidity in the operating environment. The main OH absorption peak is at 13400 nm, with a secondary peak at 950 nm.

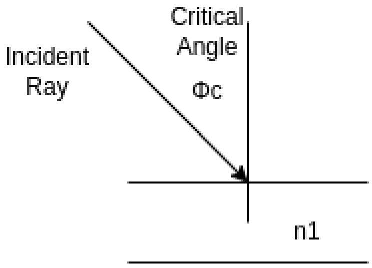
Dispersion
Dispersion is generally divided into two categories:

1- Modal Dispersion: it is a pulse spreading caused by the time delay between lower order mode or the rays propagating straight into the fiber close to the axis and the higher order modes propagating at steeper angles. It causes B.W limitations. It is not a problem for single mode.

2- Chromatic Dispersion: is a pulse spreading due to the fact the different λ of light propagates at slightly different velocities through the fiber.

All light sources whether laser or LED emits more wavelengths at different (lamda) propagates at different velocities.

Chromatic dispersion is expressed in time/length (nsec or psec per km).



$\phi_c = sin^{-1}(n2/n1)$

In order for a ray to propagate {VV} the cable, it must stride the core-cladding interface at an angle greater than the critical angle.

$N_\theta = sin\phi_0 max$

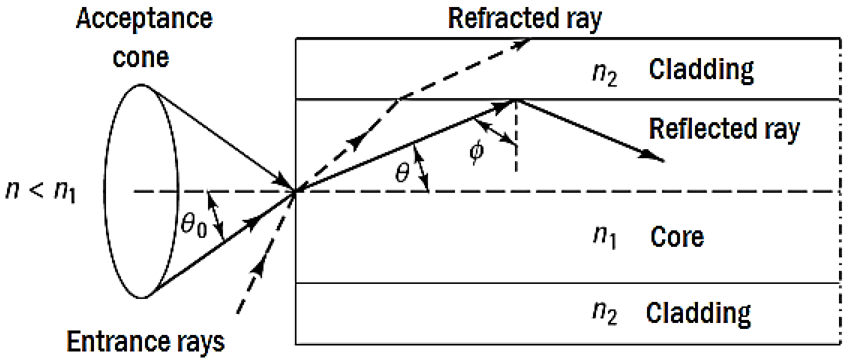
Acceptance angle = $sin^{-1}\sqrt[2]{n^2core - n^2cledge}$

NA = $\sqrt[2]{n^2core - n^2cledge}$.

Index difference Δ and NA related by:

Δ = $(n_1 - n_2)/(n_1)$ = $(N_A^2)/(2n_1^2)$

NA = $n_1 * \sqrt[2]{2\Delta}$


Acceptance
cone
Refracted ray
n_2 Cladding
Reflected ray
$n < n_1$
θ_0
θ
ϕ
n_1 Core
n_2 Cladding
Entrance rays

Losses

- Bending losses
- connection losses

splices and connectors lyres and characteristic
optical fiber use λ just above the red visible
typical transmission λ are :

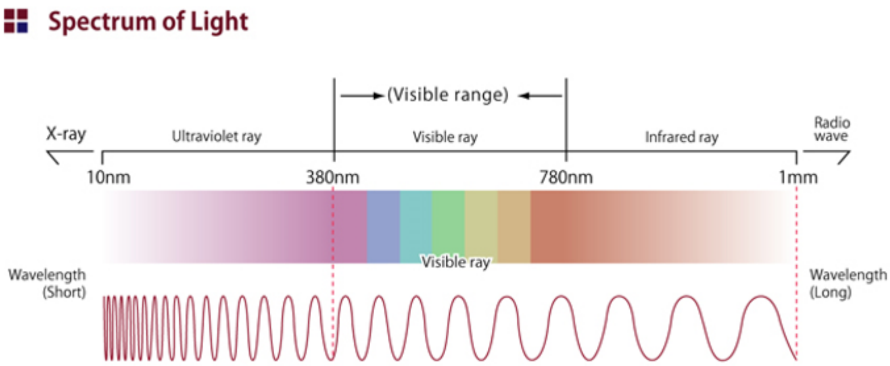
- 850 nm used with leds or 1310 multimode
- 1310 & 1550 nm used with laser diode single mode (loss minimum at 1550 nm)

هذه ال λ مسجل بها ال best fiber operator كل منهم تسمى operating window

best match the transmission properties of the available light sources with the transmission qualities of optical fiber

Sheet 1

- $E = \frac{hc}{\lambda}$ (Joule)
- $E = \frac{1240}{\lambda}$ ($E \Rightarrow$ e.v , $\lambda \Rightarrow$ nm)
- $\lambda = \frac{C}{f}$
- $P = \frac{h}{\lambda}$ (Momentum kg.m / s)
- $Pw = E.R$ (Power watt)
- $h = 6.62 * 10^{-34}$ $m^2.kg / s$
- $e = 1.6 * 10^{-19}$ Coulombs
- $C = 3 * 10^8$ m/s

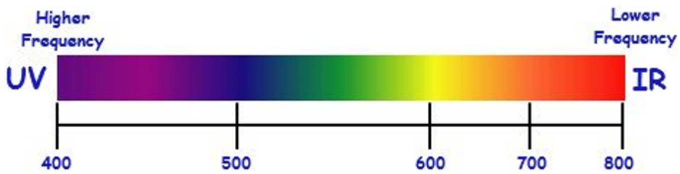


Sheet 2

- $E = \Phi + K.E$
- $E = \Phi + ev_0$
- $K.E = \frac{1}{2}mv^2$
- Electron mass $m = 9.1*10^{-31}$ kg
- To remove an electron : $\mathbf{E \geq E_c}$

  $\mathbf{f \geq f_c}$

  $\boldsymbol{\lambda \leq \lambda_c}$



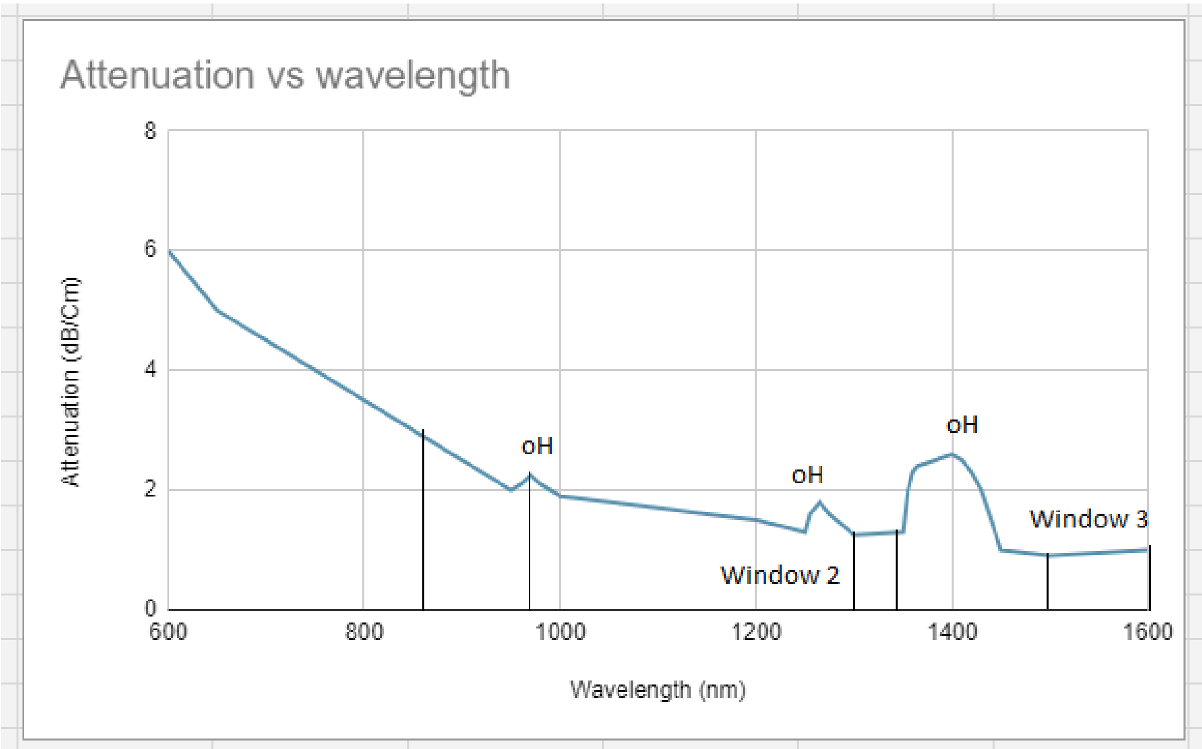
- Violet 400 - 420nm
- Indigo 420 - 440nm
- Blue 440 - 490nm
- Green 490 - 570nm
- Yellow 570 - 585nm
- Orange 585 - 620nm
- Red 620 - 780nm

Because it is impossible to provide 0% humidity over the entire life of fiber, optical communication systems are designed near 1300nm or 1350nm. But not near 1400nm.

The attenuation for a particular fiber may be specified in one or more windows, Centrally a fiber should be used only in iRose windows for which specifications are given.

The alternation will vary with:

1. The quality of the glass materials
2. Impurity types and concentration
3. Optical wavelength
4. Fiber care diameter



The output power Po at the end of fiber links depends on the coupled power Pc, the attenuation per unit length α, and length L.

Ex: A fiber to a coupled power of 0.16 mW, an attenuation of 6dB/Km, and a length of 2Km. What is output power?

Solution

$$P_o = P_c 10^{-(\frac{\alpha L}{10})} = [0.16\, mW]\alpha .\ 10^{\frac{[-6\, dB/Km * 2\, Km]}{10}}$$

$$P_o = 10\ \mu WoH = -\ 20\, dBm$$

Notes:

$$P(dBm) = 10\, log P(mW)$$

$$P(mw) = 10^{P(dBm)/10}$$

Example: A fiber has a coupled power of -8dbm, an attenuation of 6db/Km, and a length of 2km. what is the o/p power.
<u>solution</u>:

$$P_o = P_c - \alpha L$$

$$P_o = (-8\,dbm) - (6\,dB/km)(2km)$$

$$P_o = -20\,dBm$$

$$P(m\,watt) = 10^{\frac{-20\,dbm}{10}} = 10^{-2} m\,watt$$

$$= \frac{1}{100} * 1000\,\mu\,watt = 10\,\mu\,watt$$

Hint: the amount of attenuation, of course varies with:

- The type of cable
- the size

Glass has less attenuation than plastic.
Wider core has less attenuation than the narrower core.

The attenuation is directly proportional to the length of the cable. It's obvious that the longer the light has to travel, the greater the loss due to absorption, scattering and dispersion.

Attenuation expressed in dB/unit length

dB = 10 log$\frac{po}{pi}$

Then 3dB represents half power(50%) appears at the o/p

- The higher the disciple figure, the greater the attenuation and loss

loss(dB)	power o/p (%)
1	79
2	63
3	50
4	40
5	31
6	25
7	20
8	14
9	12
10	10
20	1
30	0.1
40	0.01
50	0.001