Optical Amplifiers

…Continued

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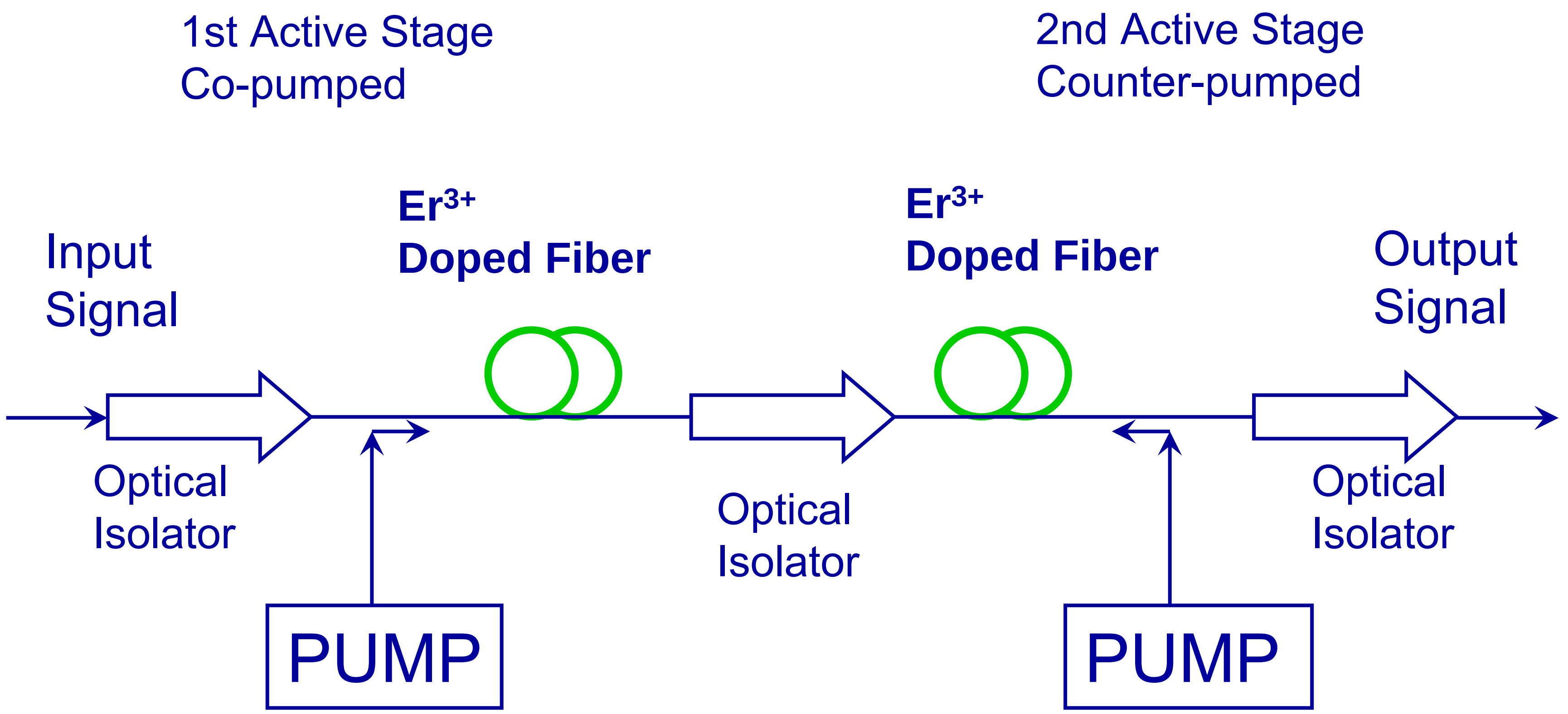
EDFA – Multi Stage Designs



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EDFA – Multi Stage Designs

- 1st stage gives high gain, low noise
- 2nd stage give high output power
- Combined both, we get a high gain and high power output signal with low noise.
- Also multiple pumps give failure recovery benefits.
- Optical isolator/filter can be placed in between to flatten the gain or remove pump signal.

EDFA - Advantages

- EDFAs have high pump power utilization (>50%)
- Directly and simultaneously amplify a wide wavelength band (> 80 nm) in the 1550 nm region, with a relatively flat gain.
- Flatness can be improved by gain-flattening optical filters
- Gain in access of 50 dB
- Low noise figure
- Transparent to optical modulation formats
- Suitable for long haul applications

Demerit

- EDFAs are not small and cannot be integrated with other semiconductor devices

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Raman Amplifiers

- Raman gain spectrum is fairly broad and the peak of the gain is centered about 13 THz below the frequency of the pump signal used.
- Unlike EDFAs, we can use the Raman effect to provide gain at any wavelength.
- Raman amplification can potentially open up other bands for WDM, such as the 1310 nm window, or the so-called S-band lying just below 1528 nm.
- Also, we can use multiple pumps at different wavelengths and different powers simultaneously to tailor the overall Raman gain shape.
- Another major concern with Raman amplifiers is crosstalk between the WDM signals due to Raman amplification.

Semiconductor Optical Amplifiers

- They are not a good as EDFAs for use as amplifiers.
- Used for other applications: in switches and wavelength converter devices.
- First, the populations are not those of ions in various energy states but of carriers-electrons or holes.
- Semiconductor consists of two bands of electron energy levels: a band of low mobility levels called the valence band and a band of high mobility levels called the conduction band.
- At thermal equilibrium, there is only a very small concentration of electrons in the conduction band of the material,

Semiconductor Optical Amplifiers

- Population inversion condition, the electron concentration in the conduction band is much higher.
- Population inversion in an SOA is achieved by forward-biasing a pn-junction.
- Nevertheless, EDFAs are widely preferred to SOAs for several reasons.
- Main reason is that SOAs introduce severe crosstalk when they are used in WDM systems.
- Gains and output powers achievable with EDFAs are higher.
- Coupling losses and the polarization-dependent losses are also lower with EDFAs since the amplifier is also a fiber. Due to the higher input coupling loss, SOAs have higher noise figures relative to EDFAs.

Semiconductor Optical Amplifiers

- Finally, the SOA requires very high-quality antireflective coatings on its facets (reflectivity of less than 10^{-4}) which is not easy to achieve.
- Higher values of reflectivity create ripples in the gain spectrum and cause gain variations due to temperature fluctuations.

Crosstalk in SOAs

- Consider an SOA to which is input the sum of two optical signals at different wavelengths.
- Assume that both wavelength are within the bandwidth of the SOA.
- Presence of one signal will deplete the minority carrier concentration by the stimulated emission process so that the population inversion seen by the other signal is reduced.
- Thus the other signal will not be amplified to the same extent and, if the minority carrier concentrations are not very large, may even be absorbed.

Crosstalk in SOAs

- Thus, for WDM networks, the gain seen by the signal in one channel varies with the presence or absence of signals in the other channels.
- This phenomenon is called crosstalk, and it has a detrimental effect on the system performance.
- This crosstalk phenomenon depends on the spontaneous emission lifetime from the high-energy to the low-energy state.
- The spontaneous emission lifetime in an EDFA is about 10ms.
- Therefore lifetime is large enough compared to the rate of fluctuations of power in the input signals.
- Elecrtons cannot make the transition from the high-energy state to the lower-energy state in response to these fluctuations.
- Thus there is no crosstalk whatsoever in EDFAs.

Crosstalk in SOAs

- In the case of SOAs, this lifetime is on the order of nanoseconds.
- Thus the electrons can easily respond to fluctuations in power of signals modulated at gigabit/second rates, resulting in a major system impairment due to crosstalk.
- Thus crosstalk is introduced only if the modulation rates of the input signals are less than a few kilohertz, which is not usually the case.
- EDFAs are better suited for use in WDM systems than SOAs.
- Crosstalk effect is not without its uses.

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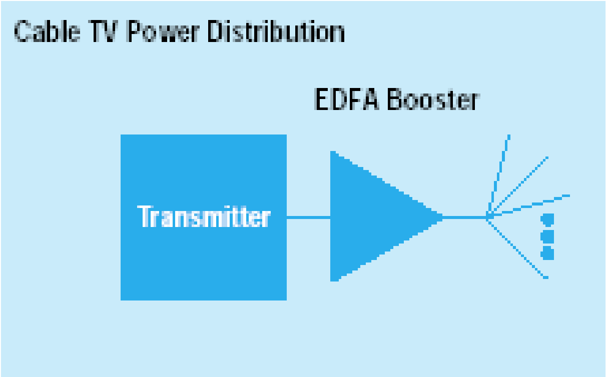
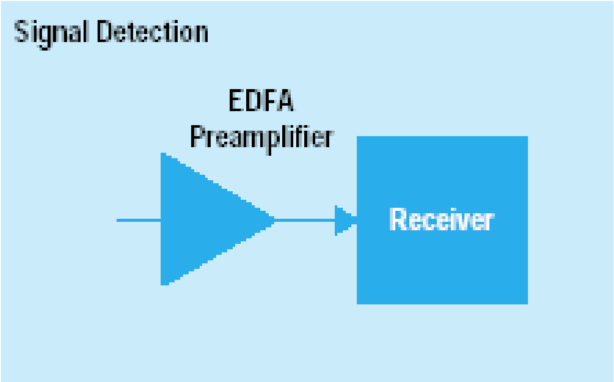
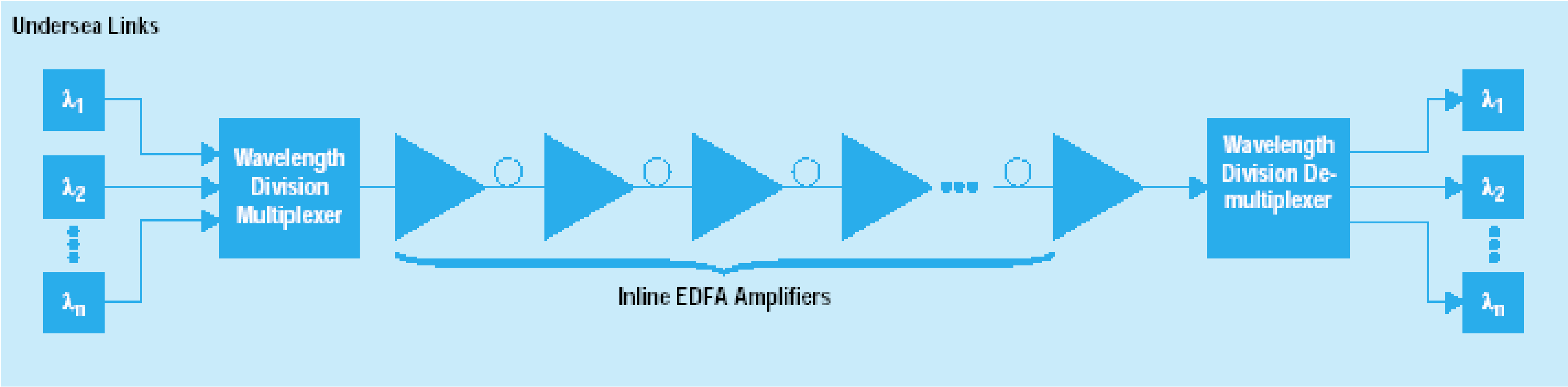
EDFA - Applications

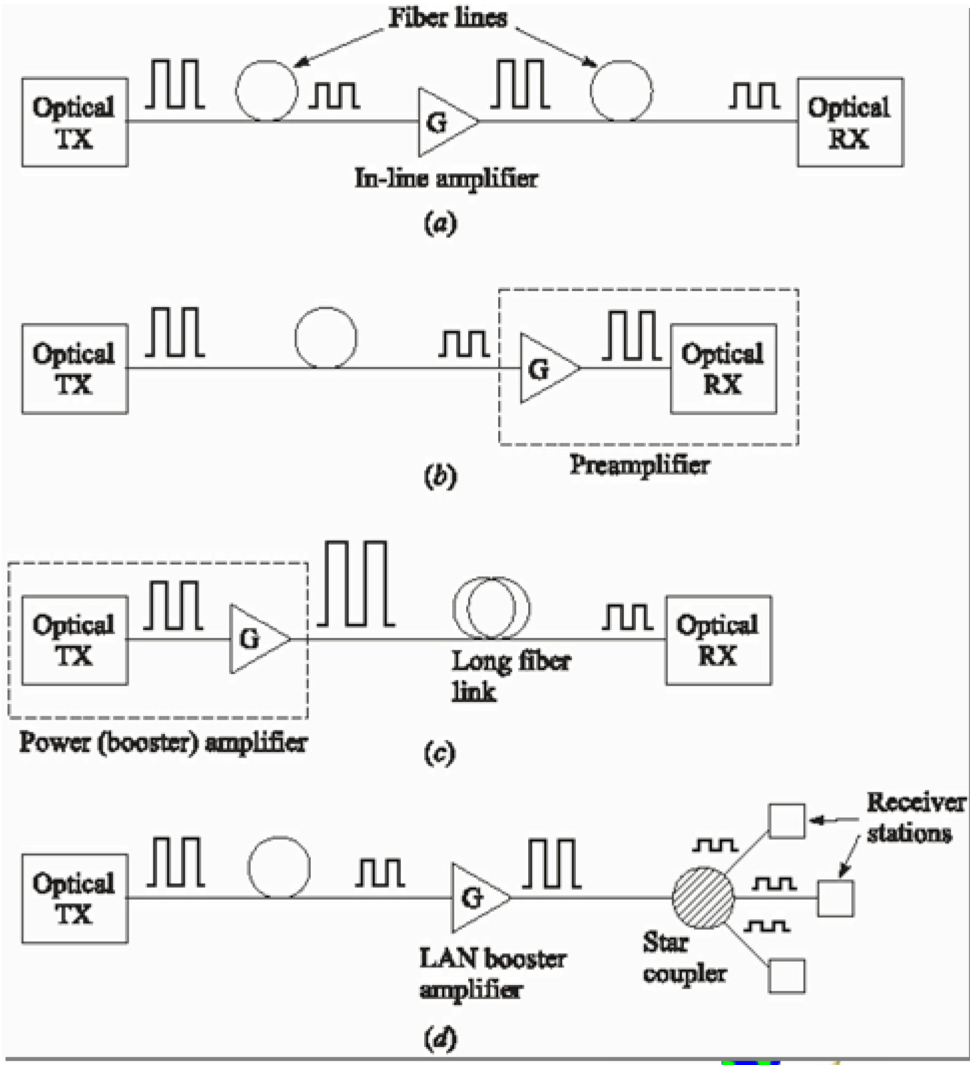






Optical Amplifiers - Applications

- In line amplifier
  - -30-70 km
  - -To increase transmission link
- Pre-amplifier
  - - Low noise
  - -To improve receiver sensitivity
- Booster amplifier
  - - 17 dBm
  - - TV
- LAN booster amplifier

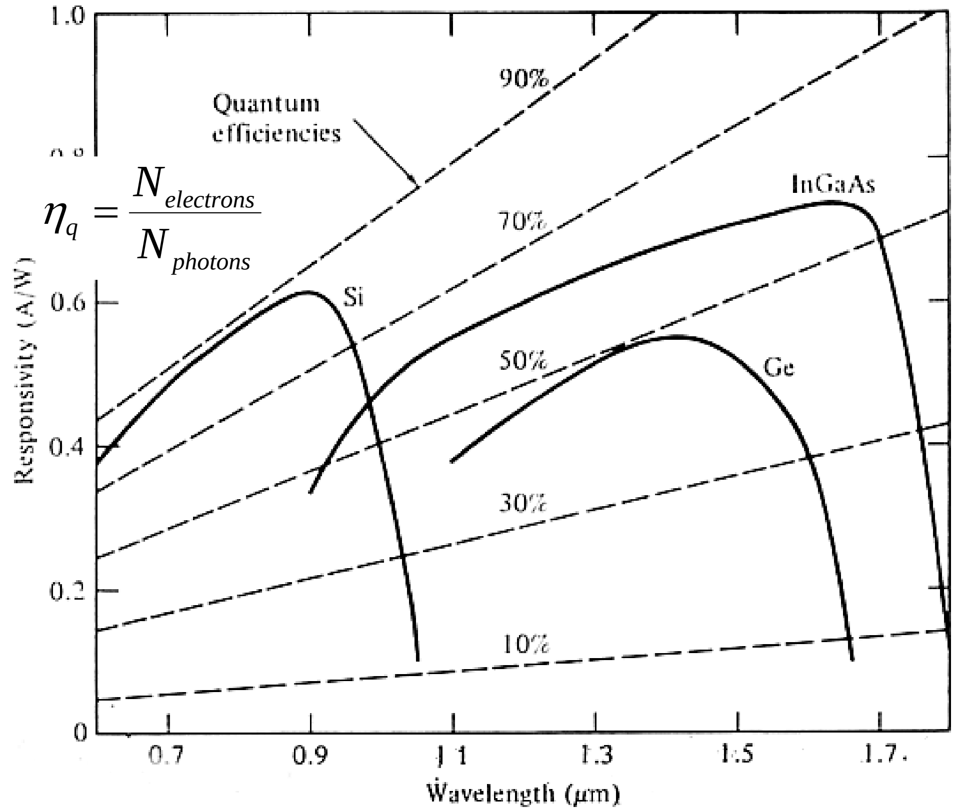


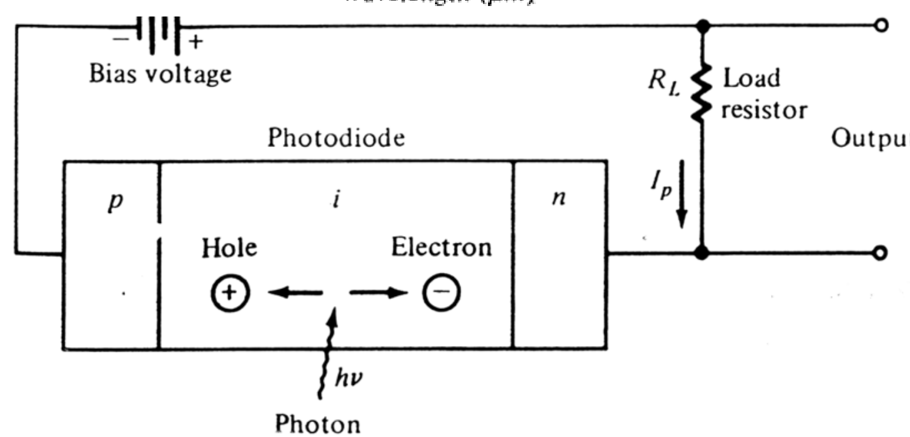
Optical Photodetectors

Optical photodetectors (PDs)

- PDs convert photons to electrons
- Two photodiode types
  - PIN
  - APD
- For a photodiode it is reqd that it is
  - sensitive at the used λ
  - small noise
  - long life span
  - small rise-time (large BW, small capacitance)
  - low temperature sensitivity
  - quality/price ratio

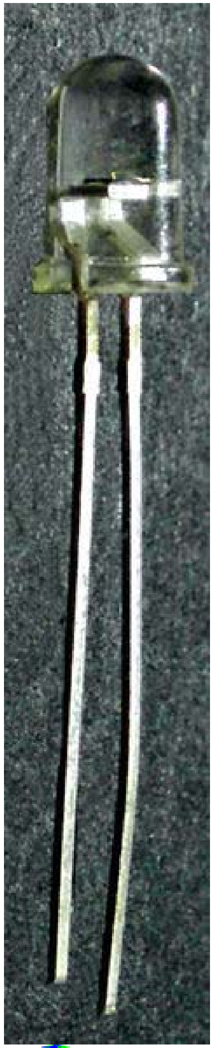
$$\eta_q = \frac{N_{electrons}}{N_{photons}}$$





PhotoDetectors

- Basic principle of photodetection
- Photodetectors made up of S.C materials
- Photons incident on S.C absorbed by electrons in valence band
- These electrons acquire higher energy and are excited into the conduction band, leaving behind a hole in the valence band.
- When an external voltage is applied to the semiconductor, these electron-hole pairs give rise to an electrical current, termed the photocurrent.
- Principle of quantum mechanics is that each electron can absorb only one photon to transit between energy levels.



Photodetection Principle

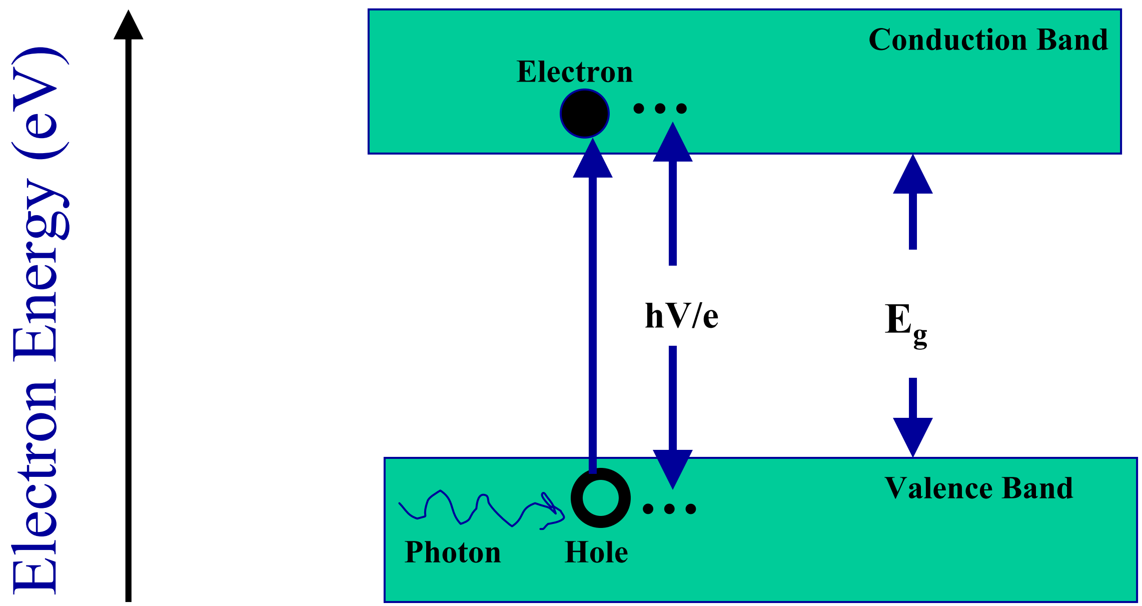


Fig: 3.62
The basic principle of photodetection using a semiconductor. Incident photons are absorbed by electrons in the valence band, creating a free or mobile electron-hole pair. Electron-hole pair gives rise to a photocurrent when an external voltage is applied.

Materials commonly used to produce photodiodes:

MaterialWavelength	**range (nm)**
Silicon	190–1100
Germanium	800–1700
Indium gallium arsenide	800–2600
lead sulfide	<1000-3500

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PhotoDetectors

- Energy of the incident photon must be at least equal to the band gap energy in order for a photocurrent to be generated.
- This gives us the following constraint on the frequency f_c or the wavelength λ at which a semiconductor material with band gap E_g can be used as a photodetector

$$hf_c = hc/\lambda \geq eE_g$$

- The Largest value of λ for which this equation is satisfied is called the cutoff wavelength and is denoted by λ_{cutoff}
- We see from the table 3.2 that the well-known semiconductors silicon (Si) and gallium arsenide (GaAs) cannot be used in the 1.3 and 1.55 μm bands.

PhotoDetectors

- Although germanium (Ge) can be used in both these bands, it has some disadvantages that reduce its effectiveness for this purpose.
- New compounds indium gallium arsenide phosphide (InGaAsP) are commonly used to make photodetectors in the 1.3 and 1.55 μm bands.
- Silicon photodetectors are widely used in the 0.8 μm bands.
- Fraction of the energy of the optical signal that is absorbed and gives rise to a photocurrent is called the efficiency η of the photodetector.
- For transmission at high bit rates over long distances, optical energy is scarce, and thus it is important to design the photodetector to achieve an efficiency η as close to 1 as possible.
- The power absorbed by a semiconductor slab of thickness L μm can be written as

$$P_{abs} = (1 - e^{-\alpha L})\, P_{in}$$

Also,

$$\eta = P_{abs} / P_{in} = 1 - e^{-\alpha L}$$

PhotoDetectors

- Where P_{in} is the incident optical signal power, and α is the absorption coefficient of the material.
- ά depends on the wavelength and is zero for wavelengths $\lambda > \lambda_{cutoff}$
- Typical values of α are on the order of 10^4 /cm, so to achieve an efficiency ή > 0.99, a slab of thickness on the order of 10μm is needed.
- Area of the photodetector is usually chosen to be sufficently large so that all the incident optical power can be captured by it.
- Photodectectors have very wide operating bandwidth since a photodetector at some wavelength can also serve as a photodetector at all smaller wavelengths.
- Thus a photodetector designed for the 1.55μm band can also be used in the 1.3μm band.

Band gap Energies and Cutoff wavelengths

Table 3.2

Material	E_g (eV)	λ_{cutoff} (μm)
Si	1.17	1.06
Ge	0.775	1.6
GaAs	1.424	0.87
InP	1.35	0.92
$In_{0.55}Ga_{0.45}As$	0.75	1.65
$In_{1-0.45y}Ga_{0.45y}As_yP_{1-y}$	0.75-1.35	1.65-0.92

PhotoDetectors

- Photodetectors are commonly characterized by their responsivity R.
- If a Photodetector produces an average current of I_p amperes when the incident optical power is P_{in} watts, then the responsivity is

  $$\mathbf{R = I_P/P_{in}\ A/W}$$

- Since an incident optical power P_{in} corresponds to an incidence of P_{in}/hf_c photons/s on the average, and a fraction η of these incident photons are absorbed and generate an electron in the external circuit, we can write

  $$\mathbf{R = e\eta/hfc\ A/W.}$$

- Responsivity is commonly expressed in terms of λ; thus

  $$R = e\eta\lambda / hc = \eta\lambda/1.24\ A/W$$

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PhotoDetectors

- Since η can be made quite close to 1 in practice, the responsivities achieved are on the order of 1 A/W in the 1.3μm band 1.2 A/W in the 1.55μm band.
- Using slab of semiconductor does not give high efficiencies.
- A photodetector is called a photodiode when a reverse bias voltage is applied to a semiconductor instead of using homogenous slab of it.
- Depletion region in a pn-junction creates a built-in electric field.

PIN Photodiodes

- To improve the efficiency of the photodetector, a very lightly doped intrinsic semiconductor is introduced between the p-type and n-type semiconductors.
- Such photodiodes are called pin photodiodes, where the I in PIN is for Intrinsic.
- Width of the p-type and n-type semiconductors is small compared to the intrinsic region so that much of the light absorption takes place in this region.
- This increases the efficiency and thus the responsivities of the photodiode.
- From table 3.2, we see that the cutoff wavelength for InP is 0.92 μm, and that for In GaAs is 1.65 μm.
- Thus the p-type and n-type regions are transparent in the 1.3-1.6μm range.

PIN Photodiodes

- PIN diode is a variation on standard pn-diode
  - An intrinsic (pure) layer of semiconductor is fabricated between the p and n-types
  - Depletion layer widens
  - Internal electric field is maintained over a wider layer
  - Because very few electrons and holes are in this region
    - Its resistivity is low
    - Only a small reverse bias is needed to increase the depletion region
    - Stretches almost entire way between the terminals
- Very fast response times
  - A few nanoseconds or less

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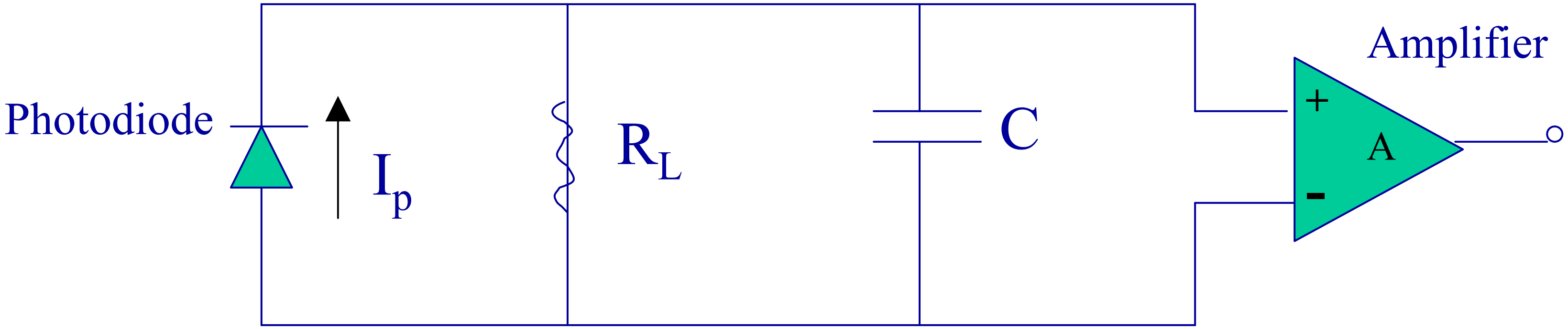
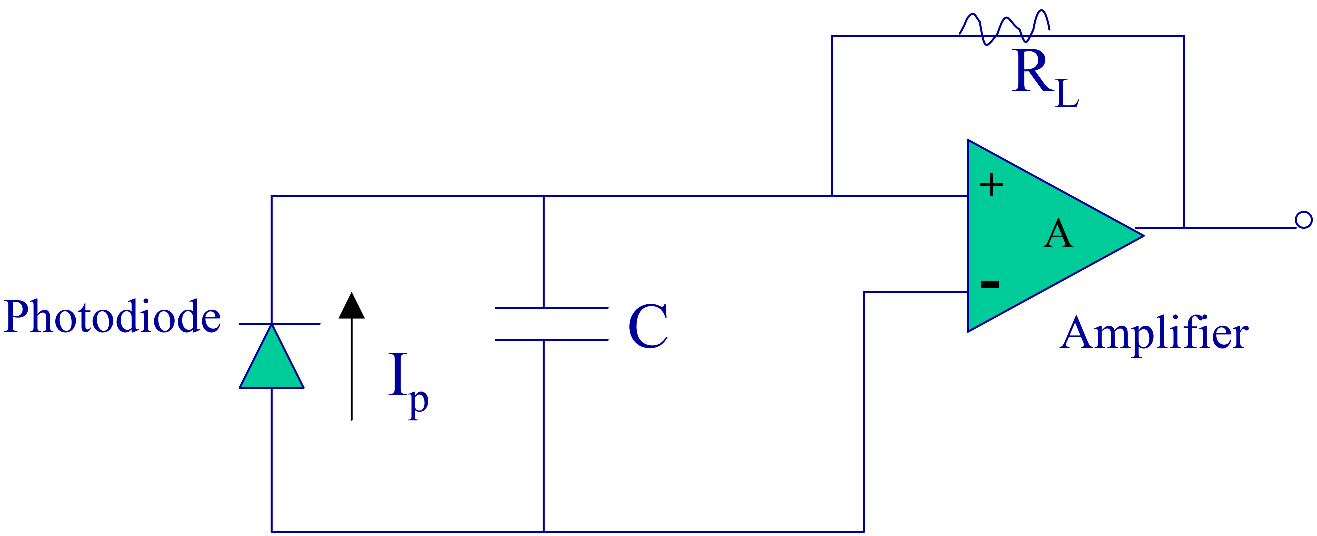
Front-End Amplifiers

- Two Front-End amplifier types:
  - High-impedance Amplifier
  - Trans-impedance Amplifier
- Thermal noise current that arises due to the random motion of electrons and contaminates the photocurrent is inversely proportional to the load resistance.
- Thus, to minimized the thermal noise, we must make $\mathbf{R_L}$ large.
- Thus there is a trade-off between the bandwidth of the photodiode and its noise performance.
- Thus the transimpedance front end is chosen over the high-impedance one for most optical communication systems.

Front-End Amplifiers



High-impedance Front End Amplifier Circuit



Trans-impedance Front End Amplifier Circuit

Front-End Amplifiers

- There is another consideration in the choice of a front-end amplifier: dynamic range. This is the difference between the largest and smallest signal levels that the front-end amplifier can handle.
- However, dynamic range of the receivers is very important consideration in the case of networks where the received signal level can vary by a few orders of magnitude, depending on the location of the source in the network.
- Transimpedance amplifier has significantly higher dynamic range than the high-impedance one, and this is another factor in favor of choosing the transimpedance amplifier.

PinFET

- A field-effect transistor (FET) has very high input impendence and for this reason is often used as the amplifier in the front end.
- A pin photodiode and an FET are often integrated on the same semiconductor substrate, and the combined device is called pinFET.