Chapter 6

Light Sources

- Optic beams generated by light sources carry the information.
- Laser diodes and light-emitting diodes are the most common sources. Their small size is **compatible** with the small diameters of fibers, and their solid structure and low power requirements are compatible with modern solid state electronics.
- In the majority of systems, information is put onto the beam by modulating the source input current.
- External modulation is possible but will not be stressed because it is less important.
- Our study of LEDs and laser diodes includes:
  - operating principles,
  - transfer characteristics, and
  - modulation.
- We plan to obtain a good idea of the differences between the two sources and what situations call for one or the other.

6.1 LIGHT-EMITTING DIODES

- A light-emitting diode is a ***pn* junction** semiconductor that emits light when forward biased.

> FORWARD BIAS.—An external voltage applied to a PN junction is call BIAS. If, for example, a battery is used to supply bias to a PN junction and is connected so that its voltage opposes the junction field, it will reduce the junction barrier and, therefore, aid current flow through the junction. This type of bias is known as forward bias, and it causes the junction to offer only minimum resistance to the flow of current

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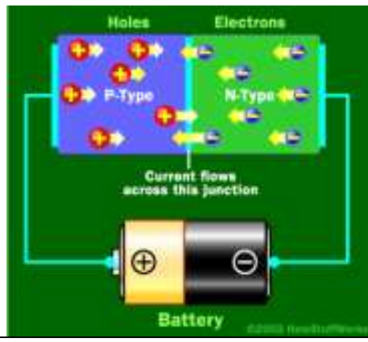
<td>
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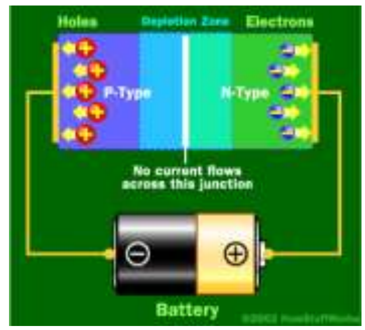
<td>
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<td>Forward-Biased: Positive end of the battery meets the positive end (the anode) of the diode, causing current flow.</td>
<td>Reverse-Biased: Negative end of the battery meets the negative end (the cathode) of the diode, no current flow occurs.</td>
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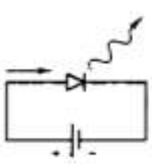
http://ffden-2.phys.uaf.edu/212_fall2003.web.dir/Marvin_Casanova/physics.htm

http://www.upscale.utoronto.ca/PVB/Harrison/BohrModel/Flash/BohrModel.html

http://www.learnerstv.com/animation/animation.php?ani=110&cat=physics

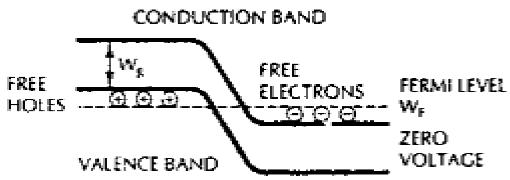
http://www.yteach.com/page.php/resources/view_all?id=p5_LDR_diode_light_LED_bias_colourdepended_resistor_t

- Band theory provides a simple explanation of semiconductor emitter (and detector) operation. Two allowed bands of energies are shown in the figure, separated by a forbidden region (**a bandgap**) whose width has energy W_g.
- In the upper-energy level, called the *conduction band,* electrons not bound to individual atoms are free to move. In the lower level, the *valence band,* unbound holes are free to move. Holes have positive charge.
- They exist at locations where an electron has been taken away from a neutral atom, leaving the atom with a net positive charge.
- A free electron can recombine with a hole, returning the atom to its neutral state.
- Energy is released when this occurs. An *n* type semiconductor has a number of free electrons, as pictured in Fig. 6-1. A *p* type semiconductor has a number of free holes.



CIRCUIT

pn junction



Forward voltage

zero voltage

Figure 6-1 Light-emitting diode. The circled plus and minus signs on the energy-band diagram designate free holes and free electrons, respectively. Electron energy is plotted vertically in the energy-band diagrams.

- When a *p* type and an *n* type material are brought together without any applied voltage, the Fermi levels (W_F) of the *p* and *n* materials align, producing the energy barrier shown on the figure.
- The materials for which this figure was drawn were heavily doped, a condition necessary to provide the many **electrons** and **holes** needed in the emission process.
- Free electrons in the *n* region do not have enough energy to climb over the barrier and move into the *p* region. Similarly, holes lack sufficient energy to surmount the barrier.
- The potential energy of holes, being opposite to that of electrons, increases in the downward direction in the diagram. With zero voltage applied to the diode, there is no charge movement because of the energy barrier.
- A forward voltage *V* separates the Fermi levels of the two materials. The applied voltage decreases the barrier by raising the potential energy of the *n* side and lowering that of the *p* side.
- If the energy supplied *(eV)* is about the same as the gap energy (W_g), **free electrons** and **free holes** will have sufficient energy to move into the junction region as shown on the bottom figure.
- When a free electron meets a free hole in the junction, the electron can fall to the valence band and **recombine** with the hole.
- The energy lost in the transition is converted to optic energy in the form of a **photon**.
- **In its simplest terms, radiation from an LED is caused by the recombination of holes and electrons that are injected into the junction by a forward bias voltage.**
- Different materials and alloys have different bandgap energies.
- Common emitter materials, operating wavelengths, and approximate bandgap energies are shown in Table 6-1.

- Silicon is not listed. Its holes and electrons do not recombine directly, making it an inefficient emitter.
- The operating wavelength can be chosen for the GaInP, AlGaAs, InGaAs, and InGaAsP devices by varying the proportions of the constituent atoms.
- The red emitting material, GaInP, is included for operation with plastic fibers that have a relative attenuation minimum in this region. The other materials are used with glass fibers.

TABLE 6-1. Light-Emitting Semiconductors

Material	Wavelength Range (/mm)	Bandgap Energy (eV)
GaInP *	0.64-0.68	1.82-1.94
GaAs	0.9	1.4
AlGaAs	0.8-0.9	1.4-1.55
InGaAs	1.0-1.3	0.95-1.24
InGaAsP	0.9-1.7	0.73-1.35

- Figure 6-1 illustrates a *homojunction,* a *pn* junction formed with a single semiconductor.
- A **homojunction LED** does not confine its emitted radiation very well. Photons radiate from the **edges of the junction** and from its large planar surface. This makes coupling to a small fiber very **inefficient.**
- **Two reasons** for this behavior can be identified.
    1. charge carriers exist over a large area, causing recombination and emission over an extensive region.
    2. after the photons are created they **diverge over unrestricted paths.**
- These problems are solved by the **heterojunction LED**, shown in Fig. 6-2. A *heterojunction* is a junction formed by **dissimilar semiconductors**.

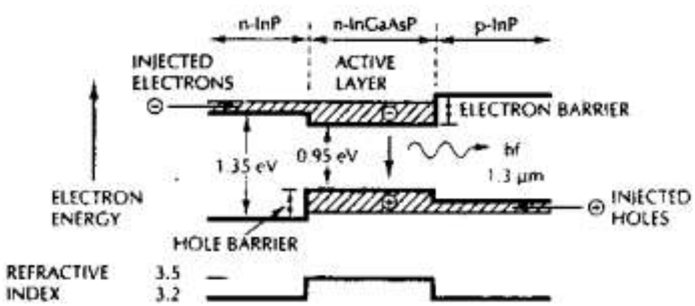


Figure 6-2 Double-heterojunction emitter. The crosshatched regions represent the energy levels of the free charges. The junction on the right forms an energy barrier that prohibits electrons from crossing into the *p* region; the junction on the left prohibits holes from crossing into the InP *n* region. Recombination occurs only in the active InGaAsP layer. This LED emits at wavelengths around 1.3 µm.

- The LED pictured in Fig. 6-2 actually contains two heterojunctions and is thus a ***double-heterojunction*** emitter.
- The two materials have different bandgap energies and different refractive indices. The changes in bandgap energies create potential barriers for both holes and electrons.
- The free charges can meet and re-combine only in the **narrow**, well-defined active layer.
- Because the active region has a higher refractive index than the materials on either side, an optic waveguide is formed.
- This is precisely the dielectric slab waveguide studied in Chapter 4. Critical-angle reflections keep some of the photons in the active region, creating a small area of high intensity.
- The confined emission improves the **coupling efficiency**, particularly for small fibers. Power can be coupled to a fiber from the planar surface of an emitting layer or from its edge. The most efficient surface coupler is the **Burrus, or *etched-well*,** construction, shown in Fig. 6-3.

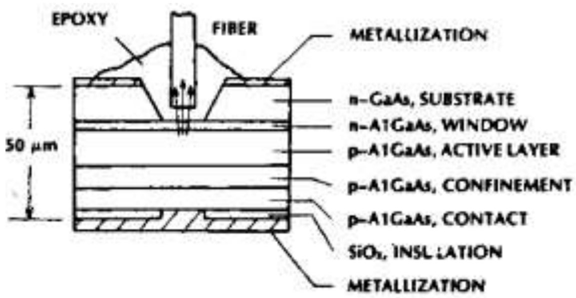
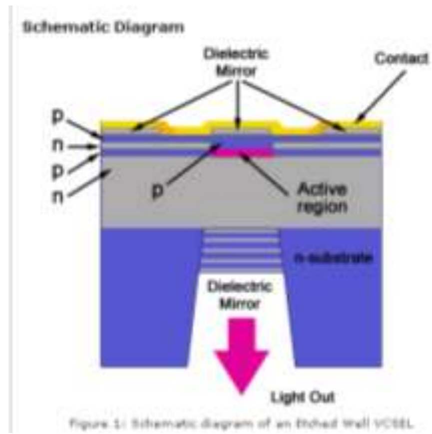
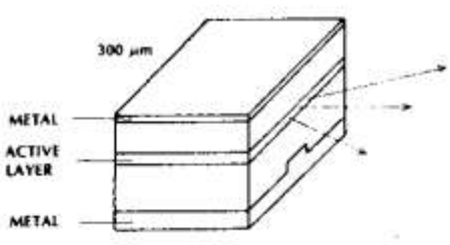


Figure 

6.3

Etched-well, surface-emitting LED.



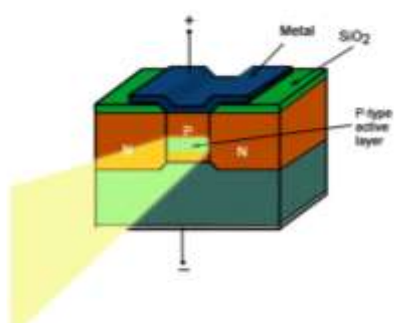


Fig 6.4 Edge –Emitting diode

6-2 LIGHT-EMITTING DIODE OPERATING CHARACTERISTICS

The **rise time** t_r of a source is the time it takes for the output to change from 10% to 90% of its final value when the input is a step in current. Rise time is illustrated in Fig. 6-9.

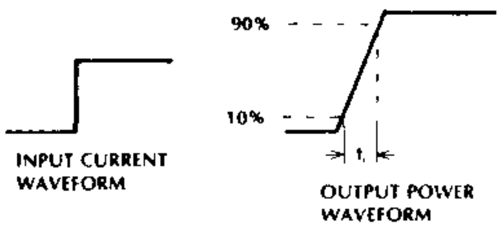


Fig 6.9 Rise time of an optic source

- As we know, the optic spectrum of the source directly influences material and waveguide dispersion. Pulse spreading due to these causes increases linearly with source spectral width.
- LEDs operating in the region 0.8 to 0.9 µm generally have widths of 20-50 nm, and LEDs emitting in the longer-wavelength region have widths of 50-100 nm.
- The increased **spectral width** of a longer-wavelength emitter is compensated by the markedly reduced material dispersion *M* (shown in Fig. 3-8) in this region.
- **Coupling efficiency** depends heavily on the radiation pattern of an emitter. Surface emitters radiate in what is called a *Lambertian* pattern.
- Edge emitters having speeds above 500 Mbps have been developed for use with single-mode fibers.
- Light-emitting diodes are very **reliable** and long lasting if operated within the power, voltage, current, and temperature limits specified by the manufacturer. As times goes on, LED output power diminishes. The **lifetime** is the time it takes for the power to reduce to half its initial value. Lifetimes of 10^5 hours (about 11 years) and more are common for good LEDs.
- Temperatures between -65° and 125°C can be tolerated during operation by some of the diodes, although the output power decreases as the junction temperature rises.
- A representative decrease is 0.012 dB/°C. Over the 190° range between -65° and 125°C, this represents a 59% change in power.
- The output power can be maintained at a constant level by increasing the drive current as the temperature increases. Of course, allowing for this type of compensation complicates the transmitter circuitry.

TABLE 6-2. Typical **Characteristics** of Diode Light Sources

Property	
Spectral width (nm)	20-100
Rise time (ns)	2-250
Modulation bandwidth (MHz)	<300
Coupling efficiency	Very low
Compatible fiber	Multimode SI[b] Multimode GRIN[C]
Temperature sensitivity	Low
Circuit complexity	Simple
Lifetime (hours)	10^5
Costs	Low
Primary use	Moderate paths Moderate data rates

- **Light emitters come in a variety of packages**. In some cases it is up to the purchaser to use skill and ingenuity to efficiently couple the source to the fiber transmission line. In others, the source is packaged in a form that makes coupling simple.
- We will look at a few of the packaging possibilities.

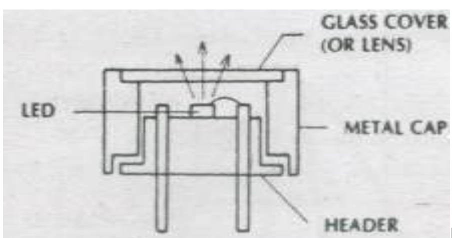
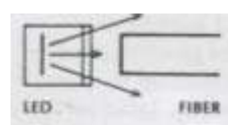
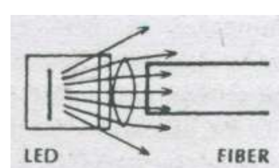


Figure 6-12 LED mounted on a header.

Electrical Leads

- LEDs can be mounted on standard headers, such as the TO-18 (sketched in Fig. 6-12).
- The header is covered by a metal cap having a clear glass top through which the light can pass.

• As illustrated in Fig. 6-13(a), the radiated beam expands quickly. In addition to the loss of rays beyond the acceptance angle, some of the rays miss the fiber completely.	 without lens
• An **external lens** can be added to the system to reduce the ray angles, but the lens will not reduce the beam diameter (see Fig. 6-13(b)).	 With a lens
Fig 6.13 Source-to-fiber coupling of a glass covered LED	

- Part of the light is still lost. The efficiency is improved if the ` in Fig. 6-12 is removed (in some designs the metal cap is removable) and the fiber attached directly on, or just above, the emitting diode.
- Most of the light will now be intercepted by the fiber core. Attaching the fiber in this manner is a chore that most users wish to avoid.

- Diodes can be purchased with a short length of **fiber already attached**. This is the *pigtailed* construction. The manufacturer has epoxied the pigtail close to the emitter.
- The **pigtail** can be spliced onto the desired transmission fiber. Alternatively, a connector can be attached to the pigtail, allowing quick connection to the rest of the system.
- A problem arises when the pigtail and the transmission fiber are not identical. If their core diameters or numerical apertures differ, then there will be a loss in power when they are connected. Losses of this type are evaluated in Chapter 8.
- Another package is illustrated in Fig. 6-14. In this device a very small lens (a *microlens)* is placed directly on the emitter.

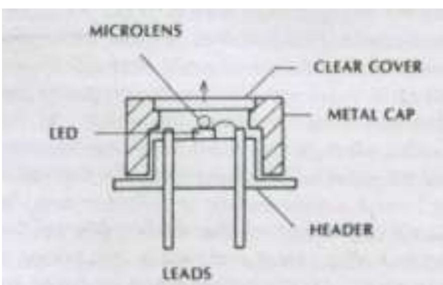


Fig 6.14 Microlensed LED

- This differs from the design in which the lens is away from the LED because in this case, the beam does not enlarge much before collimation.
- This construction is efficient for fiber core diameters as small as 50 µm and numerical apertures above 0.1.

6-3 LASER PRINCIPLES

- We do not have to be experts on lasers to use them in communications systems. On the other hand, a knowledge of laser principles helps to explain laser peculiarities and limitations.
- The more we know about a device, the less likely we are to make an error using it.
- Although the semiconductor laser diode is the most common laser for fiber communications, several other lasers will be mentioned:
    1. the gas laser (operating in the visible region of the spectrum),
    2. the bulk Nd:YAG (neodymium yttrixim-aluminum-garnet) laser, which operates in the infrared,
    3. the fiber laser.

The **gas laser**, principally the red-emitting helium-neon laser, is used for testing fibers and other fiber optics devices:

- In a simple test a HeNe laser beam is coupled to a bare fiber to detect a break or crack.
- If no light emerges from the fiber, then a break has obviously occurred.
- Small disturbances, such as air bubbles or slight fractures, can be located visually by the localized scattering of light around them.
- As another example, the numerical aperture of a fiber can be conveniently measured by using the HeNe laser, because the NA is independent of the wavelength.

The **Nd: YAG laser** is a solid-state device.

- Its principal operating wavelength is 1.06 µm, but it can also be designed to emit near 1.35 µm. Its 1.06 µm operating wavelength is in a region of lower fiber attenuation and lower material dispersion than the commonly utilized 0.8 to 0.9 µm.
- In addition, its spectral width is around 0.1 nm, much narrower than the linewidth of LD.
- This means that the Nd:YAG laser would greatly increase the bandwidth of a system that was limited by material and waveguide dispersion rather than by modal distortion.
- This conclusion becomes apparent when looking at Fig. 5-26 for a single-mode fiber at 1.06 µm.
- The 0.1-nm linewidth produces so little pulse spreading that it does not even appear on the graph.

A few of the **characteristics that all lasers possess**, and which are important in their utilization, follow:

1. *Pumping threshold.* The power input to a laser must be above a threshold level before the device will emit. This is unlike an LED, which radiates even at very low levels of input current.
2. *Output spectrum.* The laser output power is not at a single frequency but is spread over a range of frequencies. Usually the power does not vary smoothly over this range but is a series of peaks and valleys.
3. *Radiation pattern.* The range of angles over which a laser emits light depends on the size of the emitting area and on the modes of oscillation within the laser.

It is easier to explain these effects for a gas laser than for a laser diode. For this reason the **HeNe laser** will be analyzed in the rest of this section. We will then apply the results to the LD by analogy.

A HeNe laser is drawn in Fig. 6-16, and a partial energy-level diagram for the helium-neon mixture appears in Fig. 6-17.

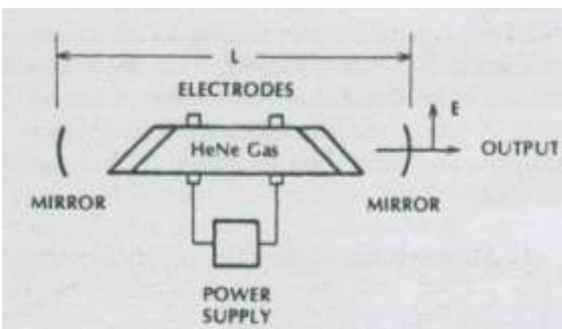


Fig 6.16 Helium Neon Laser

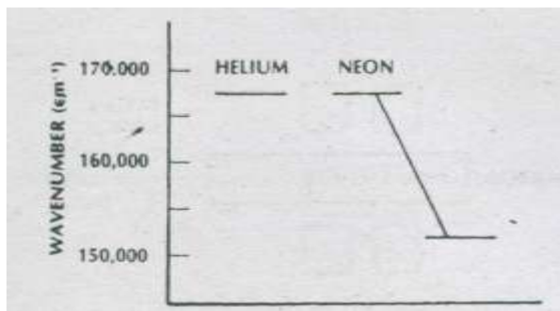


Fig 6.17 Helium-neon allowed energy states

Many more levels exist, but those shown illustrate the principles of laser action. The levels represent the allowed energy states of electrons in the atom. In simplest terms, each state corresponds to a different orbit and to different spin and angular momentum of an electron.

6-4 LASER DIODES

- Laser diodes and light-emitting diodes have quite similar constructions.
- The structure of an AlGaAs laser diode is illustrated in Fig. 6-19 and should be compared with the LED in Fig. 6-3.
- The energy-band diagram is similar to that shown in Fig. 6-2 with the appropriate change of bandgap energy values.
- Most laser diodes are **edge emitters**. When forward biased, charges are injected into the active layer where recombination takes place, causing the spontaneous emission of photons. Some of the injected charges are stimulated to emit by other photons.

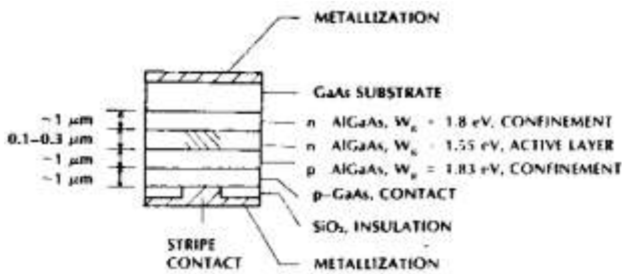


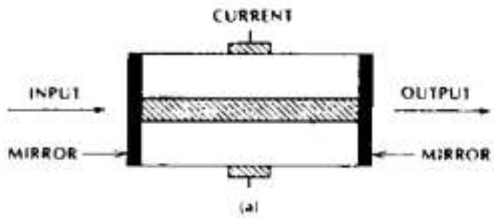
Fig 6.19 Double- heterojunction stripe contact ALGaAs laser diode. The emitting edge is shown crosshatched in the active layer.

- If the current density is sufficiently high, then a large number of injected charges are available for stimulated recombination. The optic gain will be large.
- The threshold current is reached when the gain is large enough to offset the diode losses. At this point, laser oscillation occurs.
- The threshold current must be small to prevent **overheating** of the semiconductor, particularly when operating continuously or at high peak power.
- A low threshold is achieved by confining the injected charges and the light wave to the active layer by heterojunctions, as explained in Section 6-1.
- The heterojunctions provide confinement in the vertical direction in Fig. 6-19. The confinement of charges in the lateral direction is assured by the stripe contact.
- The charges are injected over the small width of the stripe (about 10-20 µm). They spread only slightly as they move into the recombination layer.
- The output wavelength, determined by the bandgap energy of 1.55 eV in the active region, is 0.8 µm for the LD in Fig. 6-19.

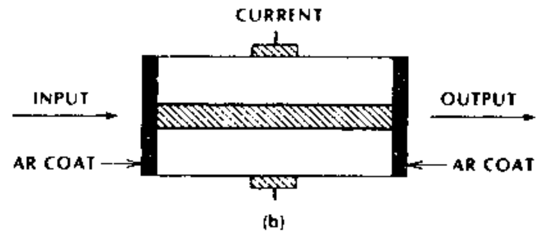
6-7 OPTICAL AMPLIFIERS

- We have indicated that fiber systems are ultimately **limited by either bandwidth or attenuation.**
- In either case, for digital systems a **regenerator** can be inserted in the path to reshape and amplify the pulses.

- This is done by **detecting** the optical signal (which converts it to electrical form), determining the presence of ones and zeroes and reconstructing the original optical signal (now at full power and with the pulse-spreading distortion removed) by modulating a light source.
- Regenerators have successfully been used to extend fiber paths from practical point-to-point limits of a few hundred kilometers to total lengths of thousands of kilometers. For example, **transatlantic** fiber cables cover over 5000 km and require about a **hundred regenerators**.
- While regenerators are invaluable, they are **expensive to construct,** expensive to install, and expensive to maintain.
- If analog modulation is used, then the situation becomes **worse** for fiber communications.
- Regeneration is impossible because we do not know what the signal is supposed to look like. (In a digital system we know the data stream consists of only zeroes and ones, allowing us to reconstruct each bit.
- In an analog system the choices of waveshapes are limitless.) Conversion of an optical analog signal to electrical form for amplification and retransmission is expensive and (probably) noisy.
- The preceding discussion leads us to search for an **all-optical amplifier** i.e. one that amplifies the signal without the intermediate conversion to electrical form.
- Optical amplifiers will not solve the problem of reconstructing signal waveshapes, but they will allow extension of power-limited links.
- In other words, bandwidth-limited systems will not be helped but power-limited ones will.
- Because fibers can operate with little bandlimiting near the zero-dispersion point of conventional or dispersion-shifted fibers, bandwidth is less of a problem than attenuation.
- In addition, if the data stream consists of soliton pulses, then no pulse spreading occurs and bandwidth is no longer limited. (We discussed soliton propagation in Section 3-2.)
- In the late 1980s several successful amplifiers were developed. Two of them are the **semiconductor amplifier** and the **erbium-doped fiber amplifier.**



Fabry-Perot amplifier



Traveling-wave amplifier

Fig 6.34 Semiconductor laser amplifiers

6.8 FIBER LASER

- Laser diodes and light-emitting diodes **do not couple** the light they generate **efficiently** into fibers. The problem arises because of the **different geometries** of semiconductor sources and optical fibers.
- The emitting region of the edge-emitting laser diode is rectangular and nonsymmetric and the fiber is circularly symmetric.
- In addition, the radiation pattern of the source does not match the acceptance pattern of the fiber, and the emission pattern of a laser diode does not match the single-mode pattern of a single-mode fiber.
- Coupling would be more efficient if the laser were constructed in the form of a fiber itself.
- As described in the previous section, fiber amplifiers are available. Because a laser consists of an amplifier with feedback, it is clear that a fiber laser is also possible.
- One fiber laser structure is shown in Fig, 6-37. The pump source is a laser diode whose output passes into the doped active fiber through the mirror M_1.
- Although this mirror is highly reflective at the laser wavelength λ_L, it is highly transmissive at the pump wavelength λ_P.
- At the other end of the fiber is a mirror which is partially transmissive at the laser wavelength λ_L.
- The structure shown is similar to the helium-neon laser and the laser diode, consisting of a pump, an amplifying section, and feedback in the form of a Fabry-Perot resonator.
- Structures other than the Fabry-Perot have also been developed for fiber lasers.[1!]
- Candidates for the active amplifying fiber are erbium-doped silica (in the 1.55-µm region) and Nd:YAG-doped silica (in the 1.35-µm region).
- By choosing the core diameter small enough, the fiber laser can be constructed to operate in a single-transverse mode, just as does a conventional single-mode fiber.
- Coupling to a single-mode fiber for transmission is now simple and efficient.

- The two fibers are simply spliced together. It should be recognized, however, that modulation is best done externally if a fiber laser is the light source.
- While this may be a disadvantage at low modulation rates, at very high rates it may be preferred.

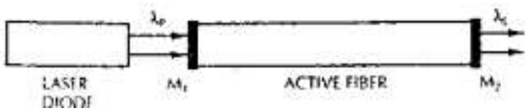


Figure 6-37 Fabry-Perot fiber laser. Mirror M transmits the pump wavelength A_P and reflects the laser wavelength X_4, while mirror M_2 is partially transmitting at wavelength A_t.

6.9 VERTICAL-CAVITY SURFACE-EMITTING LASER DIODE*S*

- A newer type of laser diode is the *vertical-cavity surface-emitting laser* (VCSEL).[13]
- As indicated by the drawing in Fig. 6-38, this diode emits from its surface rather than from its side. This structure has **several unique characteristics**.
- One is that the beam pattern is circular, the same shape as the fiber. This improves the coupling efficiency.
- Because of the geometry, monolithic two-dimensional laser diode arrays can be formed. Such arrays can be useful in fiber optic network interconnects and possibly in other communications applications.
- VCSELs operating in the visible spectrum show promise as sources for plastic-fiber systems.

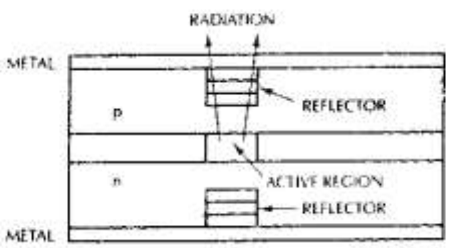


Figure 6-38 Vertical-cavity surface-emitting laser diode. The reflectors are made from a stack of dielectrics whose index of refraction alternates between high and low values, resulting in a high reflection. The upper reflector is partially transmissive at the laser output wavelength.

TABLE 6-2. Typical Characteristics of Diode Light Sources

Property	LED	Laser Diode	Single-Mode Laser Diode
Spectral width (nm)	20-100	1-5	<0.2
Rise time (ns)	2-250	0.1-1	0.05-1
Modulation bandwidth (MHz)	<300	2000	6000
Coupling efficiency[8]	Very low	Moderate	High
Compatible fiber	Multimode SI[b] Multimode GRIN[C]	Multimode GRIN Single-mode	Single-mode
Temperature sensitivity	Low	High	High
Circuit complexity	Simple	Complex	Complex
Lifetime (hours)	10^5	10^4-$I0^5$	10^4-10^5
Costs	Low	High	Highest
Primary use	Moderate paths Moderate data rates	Long paths High data rates	Very long paths Very high rates

[a] Coupling efficiency can be improved with lenses.
[b] First-window system.
[c] Second-window system.

Assignment ch 6
Discuss types of light sources with operational characteristics.
What is LED? How it works.
Discuss light emitters packages.