Course: TCET 4102 Fiber-optic communications

Module 6-1: Light sources - LEDs

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Module 6-1: Light sources – light emitting diodes (LEDs)

- Fiber-optic cables – review
- Fiber connectorization – review
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- Light sources: light emitting diodes (LEDs) and laser diodes (LDs)
- Light radiation by semiconductor – energy-band model and p-n junction model
- LED principle of operation
- LED light power
- LED spectral bandwidth (width)
- LED modulation bandwidth
- Reading the LED data sheet


Notes:
- The figure numbers in these modules are the same as in the textbook. New figures are not numbered.
- Always see examples in the textbook.

Key words
- Light sources
- Light emitting diodes (LEDs)
- Laser diodes (LDs)
- Semiconductor
- Energy-band model
- Energy gap
- p-n junction model
- Electron-hole recombination
- Forward (driving) current
- Quantum efficiency
- Spectral bandwidth (width)
- Modulation bandwidth
- Rise time and fall time
- Power-bandwidth product
Fiber-optic cables - review

• Now that we know how an optical fiber works, it’s time to discuss how to work with it. A bare fiber -- a core with its cladding surrounded by a coating -- is still very sensitive to the adverse environment regardless of how perfect the coating is. Thus, in practice, you will find a fiber only in some protective enclosure, which is called fiber-optic cable.

• Ready fiber cable is installed within a building in urban areas, outdoors in rural areas, or under the sea. The place of installation may change a fiber’s characteristics dramatically.
Figure 7.7: Basic structure of a fiber-optic cable.
Figure 7.7 Cross sections of loose and tight buffer designs:

a) Loose buffer. b) Tight buffer.
Figure 7.10  Buried and aerial installation of a fiber-optic cable:
  a) Buried installation using conduit and innerducts.
  b) Aerial installation.
Connectorization - review

• There are two types of connections in fiber-optic communications technology: permanent, providing by splicing, and temporary, providing by using connectors.

Splicing
• Splicing is the permanent connection of two pieces of optical fiber. Two types of splicing -- mechanical and fusion -- are in use today. Splices are of two types: midspan (the connecting of two cables) and pigtail. (A pigtail assembly consists of a fiber that has been factory-installed into a connector at one end, with the other end free for splicing to a cable.) The quality of splicing is measured by the insertion and reflection losses introduced by the splice.
• Splicing is a very common mass procedure. To establish a fiber-optic network, an installer, depending on the scale of the network, has to make thousands--or even hundreds of thousands--of splices. Thus, any efforts to make splicing more cost-effective and improve the quality of the splices will significantly increase the efficiency of fiber-optic communications technology.
Figure 8.2: Extrinsic connection losses caused by misalignment:

a) Lateral misalignment.  b) Angular misalignment.

c) End separation.
Figure 8.3  Lateral and angular misalignments caused by tolerances of fiber geometry:
   a) Non-concentricity. b) Fiber curl.
Figure 8.4  Reflection loss.
Figure 8.5  Connection loss caused by bad cleaving:
   a) Non-flat ends. b) Large cleave angle.
Figure 8.6  Schematic of a mechanical splice:
   a) Splicing device. b) V-groove element.
**Fusion splicing**

Fusion connects two fiber ends by melting them. This is like welding metallic wires, and it is usually accomplished by use of an electric arc. A schematic of fusion splicing is shown in Fig. 8.7a.

Fusion splicing connects fibers without a gap; therefore, no reflection loss is introduced. Insertion loss, also minimal, is in the range of 0.01 dB to 0.15 dB.

**Figure 8.7** Schematic of fusion splicing:

a) Regular fusion splicing. b) Fusion splicing of erbium fiber.
Figure 8.9  Schematics of fusion-splicer systems:
  a) Profile alignment system (PAS).
  b) Power alignment technology (PAT), the new generarion of local injection and detection (LID) systems.
  (Adapted from [24].)
Figure 8.11  Typical structure of a connector:
a) Fiber-optic cable prepared for termination. b) Connector.
Connectors - major characteristics

- **Insertion loss**
  - For regular connectors, the average insertion loss today is about 0.25 dB. This figure can vary from 0.1 dB (ideal) to 1 dB. The maximum insertion loss is about 0.5 dB, varying approximately from 0.3 dB to 1.5 dB.

- **Return loss (reflectance or back reflection)**
  - As you can see from Fig. 8.12a, to improve physical contact, one must reduce the contact area because the quality of a smaller area can be controlled more effectively. The polishing process has been so improved that manufacturers have been able to reduce the return loss of PC connectors from -40 dB, which it was just a few years ago, to -55 dB today, simultaneously holding average insertion loss to an acceptable 0.2 dB level. Some manufacturers do additional polishing to achieve an even better performance. So today we have what are called ultra-polishing connectors (UPC) or enhanced ultra-polishing connectors (EUPC), whose back reflections are about -60 dB. Return loss can be reduced even more by polishing the ferrule endface at an angle of 80 with respect to the center line of the hole. Such connectors are designated angled physical contact (APC), or angled polishing connectors. Average return loss at the -75 dB level is common for APC connectors but any achievement comes with a price. This endface tends to increase the insertion loss, but today manufacturers manage to keep the insertion loss of APC connectors between 0.2 dB and 0.5 dB, which is the same as for PC connectors.

- **Repeatability (Durability)**
  - A connector is used for temporary connection, so it should be able to hold its characteristics after many connect-disconnect operations, called matings. Thus, repeatability, or durability, is one important connector characteristic. It shows that insertion loss increases after a certain number of cycles, or matings. Typically, this increase is < 0.2 dB for 500 matings.
  - A clean ferrule endface, immune to scratches and other microdamage, can hold up during many matings. Just remember, it is the installer’s responsibility to keep a connector clean from dirt and dust.
Figure 8.12

Ferrule endfaces used for decreasing return loss:

a) Ferrule endfaces for improvement of physical contact.
b) Angled physical contact (APC). c) APC in large scale.
Light sources

Detailed block diagram of a fiber-optic communications system: The function of a light source is to convert electrical information signal into optical information signal.
Light sources - semiconductors

Introduction

- A transmitter consists of a light source, coupling optics, and electronics. Only miniature semiconductor light sources -- light emitting diodes, LEDs, and laser diodes, LDs -- are used in fiber-optic communications technology. LEDs and LDs are the heart and soul of transmitters. This is why we'll concentrate on their principle of operation and key features. Though LEDs practically disappear from the current scene of optical communications, we will study them as examples of semiconductor light sources. Progress in fiber-optic communications technology cannot be achieved without progress in both light sources and photodetectors has accompanied the progress made in optical fiber. At the same time, integrated electronics became part and parcel of transmitter/receiver specifications.

- LEDs have been around for more than thirty years. They have found application in nearly every consumer electronic device: TV sets, VCRs, telephones, car electronics, and many others. They were used in fiber-optics communications, mostly because of their small size and long life. However, their low intensity, poor beam focus, low modulation bandwidth, and incoherent radiation -- in comparison with laser diodes, that is -- and appearance inexpensive laser diodes, VCSELs, result in their retirement form the mainstream of optical communications.

Light radiation by a semiconductor

- **Energy band diagram**

- First, you'll recall that all materials consist of atoms, which are nuclei surrounded by electrons rotating at stationary orbits. Each orbit corresponds to a certain energy value; thus, these atoms may possess only discrete energy values. We represent this idea through an energy-level diagram.

- Semiconductors are solid-state materials consisting of tightly packed atoms. Atoms, in turn, are bonded by interatomic forces into a lattice structure. Each atom includes many electrons, but a material’s properties are determined by its outermost electrons.

- The important fact is that in semiconductors (and in solids in general) the possible energy levels of an electron are still discrete, but they are so close to one another that we depict them as an energy band rather than a set of separate levels. We think of an energy band as a wide, continuous region of energy, but if you had a magic magnifier to look at this band closely, you would see the discrete energy levels that make up the band. Fig. 9.1a shows this. It should be noted that the vertical axis in Fig. 9.1 represents an electron’s energy, while the horizontal axis serves merely as a visual aid.
In semiconductors we distinguish two energy bands: valence (lower, meaning less energy) and conduction (upper, meaning higher energy). They are separated by an energy gap, $E_g$, where no energy levels (that is, no electrons) are allowed. In other words, electrons can be either at the valence band or at the conduction band but cannot be in between -- at the energy gap.

An energy band consists of allowed, or possible, energy levels, which means the electrons may occupy them.

Figure 9.1  Energy bands of an intrinsic semiconductor (adapted from [1]):

a) General representation.

b) For finite temperature and/or $E_{g_{inf}} = 0$. 
When the absolute temperature is zero and no external electric field is applied, all electrons are concentrated at the valence band and there are no electrons at the conduction band. This is because none of the electrons possess enough extra energy to jump over the energy gap. But when some external energy—either through temperature or by an external electric field—is provided to the electrons at the valence band, some of them acquire enough energy to leap over the energy gap and occupy energy levels at the conduction band. We say these electrons are “excited.” These “excited” electrons leave holes (positive charge carriers) at the valence band, as Fig. 9.1b shows.

- **Light radiation -- energy bands**
  - Recall again how light is radiated: When an excited electron falls from an upper energy level to a lower one, it releases a quantum of energy called a photon. The relationship showing the difference between the energy levels—the photon’s energy, $E_p$, and the wavelength (frequency) of radiated light, $\lambda$—is given by: $\Delta E$ (the difference in the energy levels) = $E_p = hf = hc/\lambda$.
  - The same idea holds for semiconductors. If an excited electron falls from a conduction band to a valence band, it releases a photon whose energy, $E_p$, is equal to or greater than the energy gap $E_g$. Since not just one but many energy levels at the conduction and valence bands can participate in the radiation process, many close wavelengths, $\lambda_i$, can be radiated. This is why we said that $E_p \geq E_g$, which has another form: $\lambda_i \leq hc/E_g$. (If you measure $E_g$ in electron volts, eV, and $\lambda$ in nanometers, nm, then $\lambda_i \leq 1248/E_g$.) The result of this multi-wavelength radiation is a wide spectral width, $\Delta \lambda$, of light emitted by the semiconductor. This explanation is depicted in Fig. 9.2.
  - Thus, to make a semiconductor radiate, it is necessary to excite a significant number of electrons at the conduction band. This can be done by providing external energy to the material. The most suitable form of this external energy is electric current flowing through a semiconductor.
Discuss the concept of spectral width!

**Figure 9.2** Light radiation by a semiconductor-energy bonds.

a) Radiation process.

b) Spectral width of radiated light.
Light sources - semiconductors

- **Light radiation -- the p-n junction**

- There n-type of semiconductors, where a majority of charge carriers are electrons (negative charge carriers) or p-type, where a majority charge carriers are holes (positive charge carriers). When an n-type semiconductor is brought into physical contact with a p type, a p-n junction is created. At the boundary of the junction, electrons from the n side diffuse to the p side and recombine with holes and, at the same time, holes from the p side diffuse to the n side and recombine with electrons. Thus, a finite width zone, called the *depletion region*, forms. Here, there are no mobile electrons or holes. Since positive ions at the n side and negative ions at the p side within the depletion region are left without electrons or holes, these ions create an internal electric field called a *contact potential*. We characterize this field by *depletion voltage*, $V_D$. Fig. 9.3a illustrates this explanation.

- The most important point to keep in mind is this: *An electron-hole recombination releases a quantum of energy--a photon*. In other words, to make a semiconductor radiate, it is necessary to sustain electron-hole recombinations. But the depletion voltage prevents electrons and holes from penetrating into a depletion region; therefore, external energy must be supplied to overcome this voltage barrier. This external voltage, called *forward biasing*, $V$, is shown in Fig. 9.3b. Obviously, $V$ must be greater than $V_D$.

- To achieve permanent light radiation, the following dynamic process must occur: Mobile electrons from the n side, attracted by the positive terminal of V, enter the depletion region. Simultaneously, mobile holes from the p side, attracted by the negative terminal of V, enter the same depletion region. Electron-hole recombinations within a depletion region produce light. Electric charges return through a biasing circuit.

- (Note: In semiconductors, electrons are much more mobile than holes. This is why, when a dynamic process is described, it is customary to refer to electrons entering the active region and ignore the movement of the holes. But holes are present even though they aren’t mentioned explicitly, and, again, only the electron-hole recombination produces light.)
Figure 9.3  Light radiation by a semiconductor - p-n junction:
   a) Depletion region and depletion voltage, \( V_d \).
   b) Light radiation as the result of electron-hole recombinations.
LED: principle of operation

A light-emitting diode, LED, is a semiconductor diode made by creation of a junction of $n$-type and $p$-type materials. Thus, the principle of an LED’s action works precisely the same way that we described the creation of permanent light radiation: The forward-biasing voltage, $V$, causes electrons and holes to enter the depletion region and recombine (Fig. 9.3b). Alternatively, we can say that the external energy provided by $V$ excites electrons at the conduction band. From there, they fall at the valence band and recombine (Fig 9.2a). Whatever point of view you prefer, the net result is light radiation by a semiconductor diode.

This idea is displayed by the circuit of an LED (Fig. 9.4a). If you are familiar with a semiconductor forward-biased diode, you will immediately recognize this circuit.

The forward current injects electrons into the depletion region, where they recombine with holes in radiative and nonradiative manners. Thus, nonradiative recombinations take excited electrons from useful, radiative recombinations and decrease the efficiency of the process. We characterize this by the internal quantum efficiency, $\eta_{\text{int}}$, which shows what fraction of the total number of excited (injected) electrons produces photons.

Now you are able to sketch the input-output characteristic of an LED: power of radiated light as a function of forward current. It is evident that the greater the forward current, the greater the number of electrons that will be excited at the conduction band and the greater the number of photons (light) that will be emitted. An input-output characteristic is shown qualitatively in Fig. 9.4b.
The above reasoning can be quantified as follows: Light power is energy per second, that is, the number of photons times the energy of an individual photon, $E_p$. The number of photons is equal to the number of excited (injected) electrons, $N$, times the internal quantum efficiency, $\eta_{\text{int}}$. Thus,

$$P = \frac{N \eta_{\text{int}} E_p}{t} \quad (9.1)$$

On the other hand, the number of electrons times the electron charge per second constitutes current:

$$I = \frac{N e}{t} \quad (9.2)$$

and $N = \frac{I t}{e}$. Hence, the radiated light power is:

$$P = \left(\frac{I t}{e}\right) \left(\eta_{\text{int}} E_p\right)/t = \left[\frac{\eta_{\text{int}} E_p}{e}\right] I \quad (9.3)$$

Here, $E_p$ is measured in joules. If you measure $E_p$ in electron volts and $I$ in mA, then

$$P \text{ (mW)} = \left[\eta_{\text{int}} E_p(eV)\right] I \text{ (mA)}. \quad (9.3a)$$

In sum, an LED’s light power is proportional to the forward current, as Fig 9.4b shows.
First page of specifications sheet of IF-E97 LED (see the lab manual). Discussion of all parameters given in table “Characteristics” follows.

Pay attention to specification “$T_A = 25^\circ C.$” As any semiconductor device, an LED changes its parameters when ambient temperature changes.
Light sources - LEDs
Reading the data sheet

Input-output characteristic of various LEDs. The slope of such a graph is the measure of LED’s efficiency; in other words, this slope shows how efficiently an LED converts current into light.

Output and coupled power
An LED, couples only a fraction of its output power into a fiber. In the simplest approach, we can relate these powers by using formula, \( P_0 = \frac{P_{in}}{(NA)^2} \).

The values of coupled power are given in the table of specifications and shown in the graph “Coupled Power vs. Forward Current”. Coupled power, obviously, depends on the type of fiber and on the LED’s package.

LED output and coupled power depends on wavelength. See data sheets of the LEDs in your lab manual.
**Light sources – LEDs**

**Reading the data sheet**

- **Coupling light from LED into a fiber**
  - It is quite evident that we are interested in having as powerful an input light signal as possible because, given fiber attenuation, a more powerful signal travels a greater distance. It would seem that to accomplish that, we would need a more powerful light source, but this is not the whole truth. *The key to the distance a signal travels is not just the power radiated by the source but the power coupled into an optical fiber because this is the real input signal being transmitted.* With inefficient coupling, you may lose most of the light power radiated by your LED, thus making the quality of the LED absolutely unimportant from the transmission standpoint.
  - If you approximate the radiation pattern of a LED by a Lambertian model, then light power (Pin) coupled into a step-index fiber with a numerical aperture (NA) can be calculated by the following formula:
    - Pin = P0(NA)^2
      - (9.5)
    - where P0 is determined by Formula 9.4.
  - LED radiates light as a Lambertian source if its power distribution is described by the following formula:
    - P = P0cosθ
      - (9.4)
    - where θ is the angle between the direction of observation and the line orthogonal to the radiating surface; thus, P = P0 when θ = 0°. Half of the power of the Lambertian source is concentrated in a 120° cone.
Wavelength and spectral width

Radiated wavelength, often referred to as a peak wavelength, $\lambda_p$, is determined by an energy gap, $E_g$. Manufacturers usually specify minimum, maximum and typical values of $\lambda_p$. Peak wavelength, $\lambda_p$, shifts to the longer wavelengths with increasing current and temperature but it stays within a specified range.

- A spectral width, $\Delta\lambda$, is measured as full width at half maximum, FWHM, as data sheets show in the graph “Spectral Width.” (See the lab manual.) For LEDs used in our experiments the spectral width varies from 20 to 65 nm.

- You will recall that spectral width is the critical parameter that determines the chromatic dispersion -- and, hence, bandwidth -- of an optical fiber. Chromatic dispersion is proportional to both spectral width and distance; therefore, these LEDs can be used only for narrow-bandwidth, short-distance applications.
Light sources – LEDs

Reading the data sheet

- Excerpts from data sheet of IF-E97 (super-bright red LED) is shown here. Observe typical input-output characteristic (Figure 1) and graphical presentation of the LED’s spectral width (Figure 2).

Observe nonlinearity (saturation) in the graph “Coupled power versus forward current” (Figure 1). Compare spectral width shown in Figure 2 with that given in optical specifications.
Light sources – LEDs

Reading the data sheet

- Capacitance, $C$, specified in the data sheet, is inherent in an LED. There are two sources of $C$: (a) charge capacitance associated with the $p$-$n$ junction and (b) diffusion capacitance, associated with carrier lifetime at the active region. An LED’s capacitance limits its practical modulation ability and, thus, restricts its bandwidth.

- Rise/fall time, $t_{\text{r}}$, is defined as 10 to 90 percent of the maximum value of the pulse, as Fig. 9.9b shows. For an LED, this characteristic shows how an output light pulse follows the input electrical-modulating pulse. (See Fig. 9.9c.) An ideal step pulse is shown as a double-dotted line in Fig. 9.9b. This enables you to visualize the pulse distortion caused by the rise/fall time.

- Rise/fall time is essentially determined by an LED’s capacitance, $C$, and the total recombination lifetime, $\tau$.

- Modulation bandwidth, $BW$, is the range of modulating frequencies within which detected electric power declines at -3 dB. In electronics, the general relationship between bandwidth and rise time is given by the well-known formula

$$BW = \frac{0.35}{t_{\text{r}}} \quad (9.9)$$

This formula stems from the exponential response of an RC circuit to a step-input pulse.

Figure 9.9: Characteristics of an LED:

a) Typical graph of forward voltage vs. current.
b) Rise, $t$, and fall, $t_f$, time. c) Modulation of an LED.
Light sources – LEDs

Reading the data sheet

The textbook presents another important formula regarding an LED’s bandwidth:

- \( BW = \frac{1}{\tau} \)  
  \( (9.11) \)
- where \( \tau \) is lifetime of the charge carriers.
- This yields a very important principle: An LED’s modulation bandwidth is limited by the recombination lifetime of the charge carriers. The physics governing this result is as follows: Suppose you excite an electron at the conduction band. It takes \( \tau \) ns for this electron to fall to the valence band and recombine. During this interval you cannot change its status, so that if you turn off the forward current, you must wait \( \tau \) ns until radiation will actually cease. This \( \tau \) ns interval is necessary to allow a charge carrier to reach its destination. In other words, you cannot stop an excited electron that is on its way from the conduction band to the valence band. Thus, lifetime \( \tau \) puts a fundamental limit on the modulation bandwidth of an LED.
  
  (You can repeat this reasoning using a \( p-n \) junction model: While an electron is moving through an active region, you cannot stop it; that is, you cannot change its status until this electron recombines.)
- This is why LEDs are restricted by bandwidth in the range of hundreds of MHZ. Such restrictions determine their applications in local area and other low-bandwidth networks.

Power-bandwidth product is another important characteristic of an LED. It appears that the product of an LED’s output optical power and its modulation bandwidth is constant:

- \( BW \times P = \text{constant} \)  
  \( (9.12) \)
- In other words, you can increase an LED’s bandwidth but only at the expense of its output power. Alternatively, you can increase output power but then bandwidth decreases.
In LEDs, an information-containing electrical signal pumps electrons at the conduction band; they then fall to the valence band and radiate light. This is how an electrical signal is converted into an optical signal. Thus, on/off electrical pulses are converted into on/off optical flashes, which are transmitted down the optical fiber.

Since an LED is a semiconductor diode, a radiating mechanism can be explained in terms of the p-n junction model. When an external electrical signal is applied, electrons and holes enter the depletion region and recombine, resulting in the release of a quanta of energy, that is, photons. In other words, electron-hole recombinations produce light. Again, this light radiation occurs if, and only if the LED is forward-biased, a phenomenon that forces electrons and holes to penetrate in active region and recombine.

An LED radiates light at a wavelength not less than that dictated by the energy gap. The spectral width of this light is rather wide (on the order of tens of nanometers) because electron transitions from many levels of the conduction and valence bands contribute to this light. The power of the radiated light is proportional to the forward current, as an LED’s principle of operation suggests.

An LED radiates rather dispersed light, which makes coupling this light into an optical fiber a problem. Special coupling techniques, including lens-coupling, improve coupling efficiency. There are two types of LEDs: surface-emitting (SLED) and edge-emitting (ELED). The latter type radiates less divergent light, which, along with good coupling technique, allows the manufacturer to even couple an ELED with a singlemode fiber. At 100 mA of forward current, an SLED couples into an MM fiber at about 50 μW and an ELED couples into an SM fiber at about 10 μW.