5.3.1 Surface-Emitting LEDs

In **SLEDs** shown in Figure 5.4, the size of the primary active region is limited to a small circular area of **20 μm** to **50 μm** in diameter. The active region is the portion of the **LED** where photons are emitted. The primary active region is below the surface of the semiconductor substrate perpendicular to the axis of the fiber. A well is etched into the substrate **to make direct coupling between the emitted light and the optical fiber by allowing the optical fiber to come into close contact with the emitting surface.** In addition, the **epoxy resin** that binds the optical fiber to the **SLED reduces** the **refractive index mismatch and increasing coupling efficiency**.

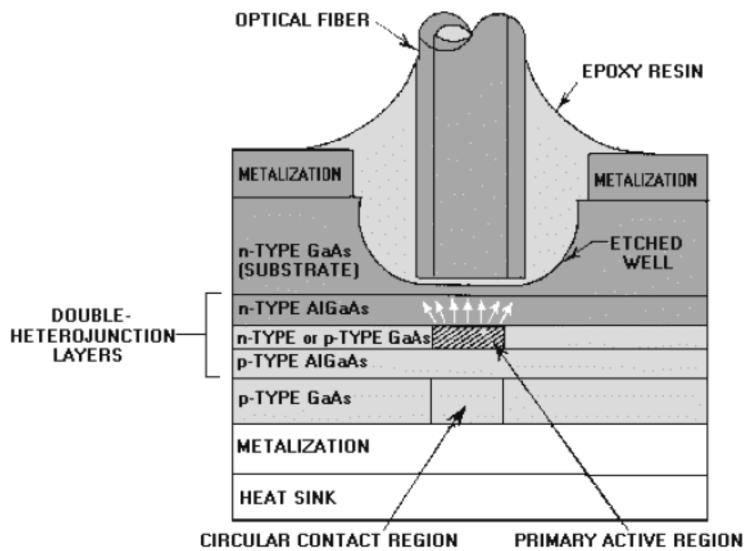

Figure 5.4: Schematic of **SLED** structure

5.3.2 Edge-Emitting LEDs

The demand for optical sources for **longer distance**, **higher bandwidth** systems operating at **longer wavelengths** led to the development of edge-emitting **LEDs**. Figure 5.5 shows a typical **ELED** structure. It shows the different layers of semiconductor material used in the **ELED**. The primary active region of the **ELED** is a **narrow stripe**, which lies below the surface of the semiconductor substrate. The semiconductor substrate is cut or polished so that the stripe runs between the front and the back of the device. The polished or cut surfaces at each end of the stripe are called facets.

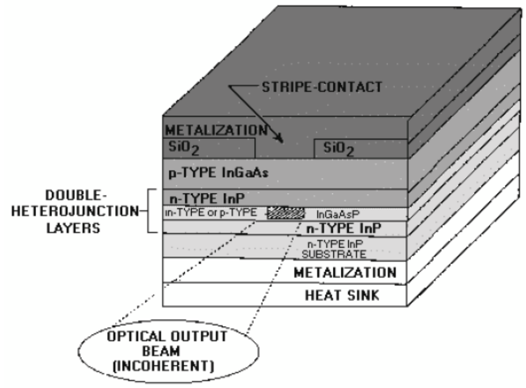

Figure 5.5 Schematic of **ELED** structure.

In an **ELED** the rear facet is highly reflective and the front facet is antireflection-coated. The rear facet reflects the light propagating toward the rear end-face back toward the front facet. By coating the front facet with antireflection material, the front facet reduces optical feedback and allows light emission. **ELEDs** emit light only through the front facet and emits the light in a narrow emission angle, **allowing for better source-to-fiber coupling**. They couple more power into smaller **NA** fibers than **SLEDs**. **ELEDs** can couple enough power into single mode fibers for some applications and emit power over a narrower spectral range than **SLEDs**. **However, ELEDs typically are more sensitive to temperature fluctuations than SLEDs**.

5.4 Laser Diodes

A laser is a device that produces optical radiation by the process of stimulated emission. It is necessary to contain photons produced by stimulated emission within the laser active region. **Figure 5.6** shows an optical cavity formed to contain the emitted photons by placing one reflecting mirror at each end of an amplifying medium. One mirror is made partially reflecting so that some radiation can escape from the cavity for coupling to an optical fiber.

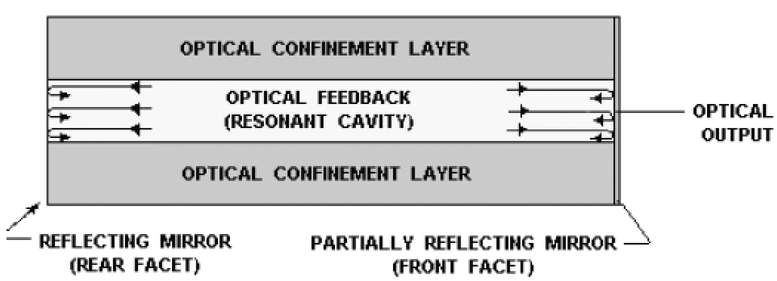

Figure 5.6: Optical cavity for producing lasing.

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Only a portion of the optical radiation is amplified. For a particular laser structure, there are only certain wavelengths that will be amplified by that laser. Amplification occurs when selected wavelengths, also called laser modes, reflect back and forth through the cavity. For lasing to occur, the optical gain of the selected modes must exceed the optical loss during one round-trip through the cavity. This process is referred to as optical feedback. **The lasing threshold is the lowest drive current level at which the output of the laser results primarily from stimulated emission rather than spontaneous emission.**

Figure 5.7 illustrates the transition from spontaneous emission to stimulated emission by plotting the relative optical output power and input drive current of a semiconductor laser diode. The lowest current at which stimulated emission exceeds spontaneous emission is the threshold current. Before the threshold current is reached, the optical output power increases only slightly with small increases in drive current. However, after the threshold current is reached, the optical output power increases significantly with small changes in drive currents.

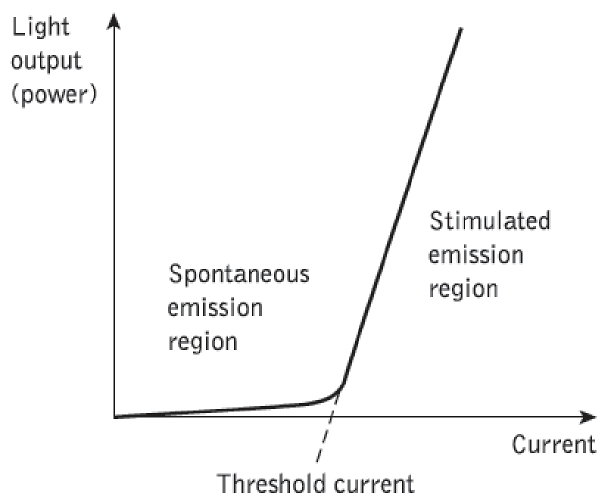

Figure 5.7: The optical output power as a function of input drive current of a semiconductor laser diode.

5.4.1 Distributed feedback lasers

Distributed feedback (DFB) lasers were developed during the 1980s and are used for WDM lightwave systems. **DFB is laser diode has a grating structure in the cavity that produces multiple reflections throughout the cavity**.

This leads to narrower linewidth than are produced by Fabry-Perot lasers. The structure which is employed is the distributed **Bragg diffraction grating** which provides periodic variation in refractive index in the laser heterostructure along the direction of wave propagation so that feedback of optical energy is obtained through Bragg reflection rather than by the usual cleaved mirrors. Hence the corrugated grating structure shown in Figure 5.8 (a) determines the wavelength of the longitudinal mode emission instead of the Fabry–Pérot gain curve shown in Figure 5.8 (b). When the **period of the corrugation (grating space)** is equal to $\mathbf{l\lambda_B/2n_e}$ where **l** is the integer order of the grating, $\boldsymbol{\lambda_B}$ is the Bragg wavelength and $\mathbf{n_e}$ is the effective refractive index of the waveguide, **then only the mode near the Bragg wavelength $\boldsymbol{\lambda_B}$ is reflected constructively** (i.e. Bragg reflection). Therefore, as may be observed in Figure 5.8 (a), this particular mode, will lase while the other modes exhibiting higher losses are suppressed from oscillation.

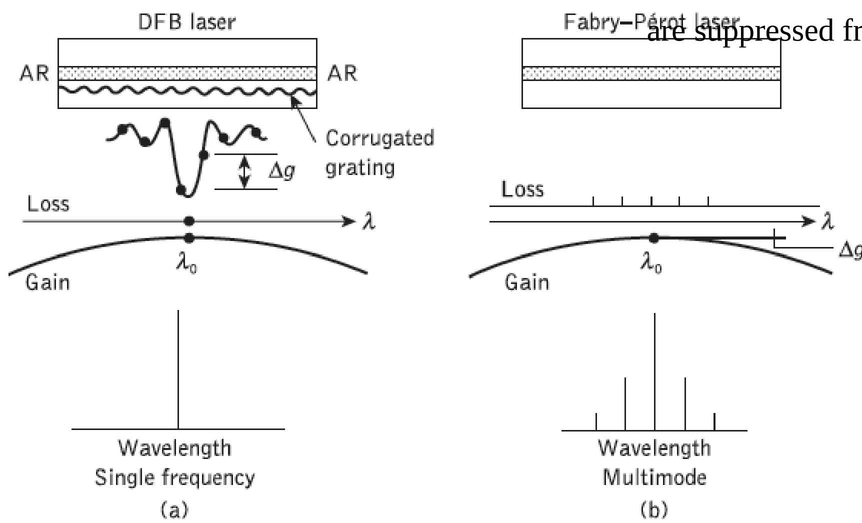

Figure 5.8: Illustrated the single-frequency operation of (a) the distributed feedback (DFB) laser (b) the Fabry–Pérot laser.

5.4.2 Vertical cavity surface-emitting laser

The vertical cavity surface-emitting laser (VCSEL, pronounced 'vixel') **emits a coherent optical signal perpendicular to the device substrate**. In comparison with edge-emitting lasers, the VCSEL structure is somewhat different, since a short vertical cavity is formed by the surfaces of epitaxial layers and the optical output is taken from one of the mirror surfaces.

Figure 5.9 illustrates the structure of a typical VCSEL where a Fabry–Pérot cavity consisting of multiquantum well (MQW) material is sandwiched between two mirrors each formed by the multilayered distributed Bragg reflector DBR mirror. The top surface DBR mirror comprising p-type material has a low facet reflectivity as compared with the n-type DBR mirror at the bottom of the device. **The number of Bragg gratings determines the amount of facet reflectivity and it generally requires between 10 and 30 Bragg grating periods to develop satisfactory facet reflectivity for the top or bottom DBR mirrors where the particular grating number depends upon the specific semiconductor material composition.**

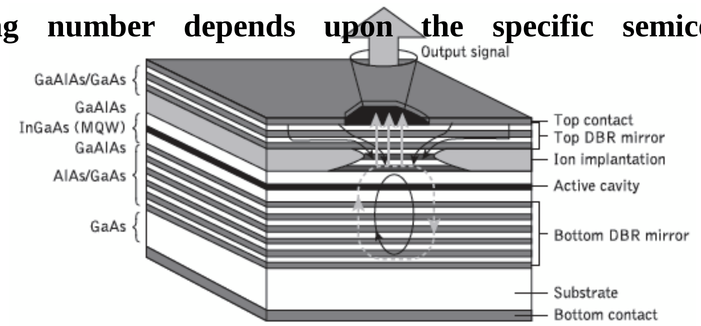

Figure 5.9: Structure of a vertical cavity surface-emitting laser.

5.5 Glass fiber lasers

The basic structure of a glass fiber laser is shown in **Figure 5.10**. An optical fiber, the core of which is doped with rare earth ions, is positioned between two mirrors adjacent to its end faces which form the laser cavity. Light from a pumping laser source is launched through one mirror into the fiber core which is a waveguiding resonant structure forming a Fabry–Pérot cavity. The optical output from the device is coupled through the mirror on the other fiber end face. Thus the fiber laser is effectively an optical wavelength converter in which the photons at the pumping wavelength are absorbed to produce the required population inversion and stimulated emission; this provides a lasing output at a wavelength which is characterized by the dopant in the fiber.

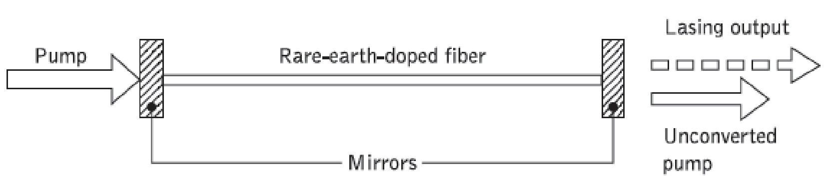

Figure 5.10: Schematic diagram showing the structure of a fiber laser

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In summary, there are two semiconductor sources are used in optical communication, namely, LED and LD. Each source has its own advantages and disadvantages as listed in Table 5-3.

Table 5-3: The advantages and disadvantages of LED and LD

Characteristic	LED	Laser
Output power	Lower	Higher
Spectral width	Wider	Narrower
Numerical aperture	Larger	Smaller
Speed	Slower	Faster
Cost	Less	More
Ease of operation	Easier	More difficult

5.6 Source Fiber Coupling

The design objective for any transmitter is to couple as much light as possible into the optical fiber. In practice, the coupling efficiency depends on the type of optical source (LED versus laser) as well as on the type of fiber (multimode versus single mode). The coupling can be very inefficient when light from an LED is coupled into a single-mode fiber. The coupling efficiency for an LED change with the numerical aperture, and can become < 1% in the case of SMF. In contrast, the coupling efficiency for an edge emitting laser is typically 40-50% and can exceed 80% for VCSELs because of their circular spot size. A small piece of fiber (known as a pigtail) is included with the transmitter so that the coupling efficiency can be maximized during packaging; a splice or connector is used to join the pigtail with the fiber cable.

Optical power produced by optical sources can range from microwatts (μW) for LEDs to tens of milliwatts (mW) for semiconductor LDs. However, it is not possible to effectively couple all the available optical power into the optical fiber for transmission. The amount of optical power coupled into the fiber depends on the following factors:

1. The angles over which the light is emitted.
2. The size of the source's light-emitting area relative to the fiber core size.
3. The alignment of the source and fiber.
4. The coupling characteristics of the fiber (such as the NA and the refractive index profile).

Two approaches have been used for source-fiber coupling. In one approach, known as **direct or butt** coupling, the fiber is **brought close to the source and held in place with epoxy**. In the other, known as **lens coupling**, a lens is used to maximize the coupling efficiency. Each approach has its own merits, and the choice generally depends on the design objectives.

5.6.1 Butt Coupling

The coupled power (P_c) into a multimode step index fiber may be estimated from the relationship:

$$P_c = \pi(1 - r) A R_D (NA)^2$$

Where r is the Fresnel reflection coefficient of the fiber surface, A **is the smaller** of the fiber core cross-section **or** the emission area of the source and R_D is the radiance of the source W sr^{-1} cm^{-2} (watt per steradian per square centimeter).

Example 5.1:

A surface emitting LED which has an emission area diameter of 50 μm is butt jointed to an 80 μm core step index fiber with a numerical aperture of 0.15. The device has a radiance of 30 W sr^{-1} cm^{-2} at a constant operating drive current. Estimate the optical coupled power into the fiber if it is assumed that the Fresnel reflection coefficient at the index matched fiber surface is 0.01.

Solution: The optical power coupled into the fiber Pc is given by:

$$P_c = \pi(1 - r) A R_D (NA)^2$$

In this case A represents the emission area of the source.

Hence:

$$A = \pi(25 \times 10^{-4})^2 = 1.96 \times 10^{-5}\ cm^2$$

Thus:

$$Pc = \pi(1 - 0.01)1.96 \times 10^{-5} \times 30 \times (0.15)^2$$

$$= 41.1\ \mu W$$

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5.6.2 Lens Coupling to Fiber

It is apparent that much of the light emitted from **LEDs** is not coupled into the generally narrow acceptance angle of the fiber. Even with the etched well surface emitter, where the low-**NA** fiber is butted directly into the emitting aperture of the device, coupling efficiencies are poor (***of the order of 1 to 2%***). However, it has been found that greater coupling efficiency may be obtained if lenses are used to collimate the emission from the LED, particularly when the fiber core diameter is significantly larger than the width of the emission region. There are several lens coupling configurations which include **spherically polished structures**, **spherical-ended or tapered fiber coupling**, **truncated spherical microlenses**, graded index (**GRIN) rod lenses** and **integral lens structures**.

A GaAs/AlGaAs spherical-ended fiber-coupled **LED** is illustrated in Figure 5.11. It consists of a planar surface-emitting structure with the spherical-ended fiber attached to the cap by epoxy resin. An emitting diameter of **35** μm was fabricated into the device and the light was coupled into fibers with core diameters of **75** and 110 μm. The geometry of the situation is such that it is essential that the active diameter of the device be substantially less (factor of 2) than the fiber core diameter if increased coupling efficiency is to be obtained. In this case good performance was obtained with coupling efficiencies around 6%.

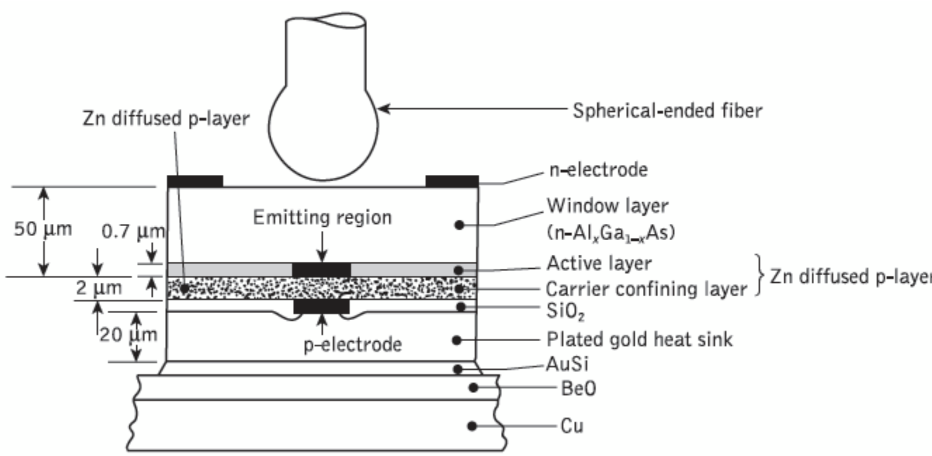

Figure 5.11: Schematic illustration of the structure of a spherical-ended fiber-coupled AlGaAs LED.

Another common lens coupling technique employs a truncated spherical microlens. This configuration is shown in Figure 5.12 for an etched well **InGaAsP/InP** surface emitter operating at a wavelength of 1.3 μm. Again, a requirement for efficient coupling is that the emission region diameter is much smaller than the core diameter of the fiber. In this case the best results were obtained with a 14 μm active diameter and an 85 μm core diameter for a step index fiber with a numerical aperture of 0.16.

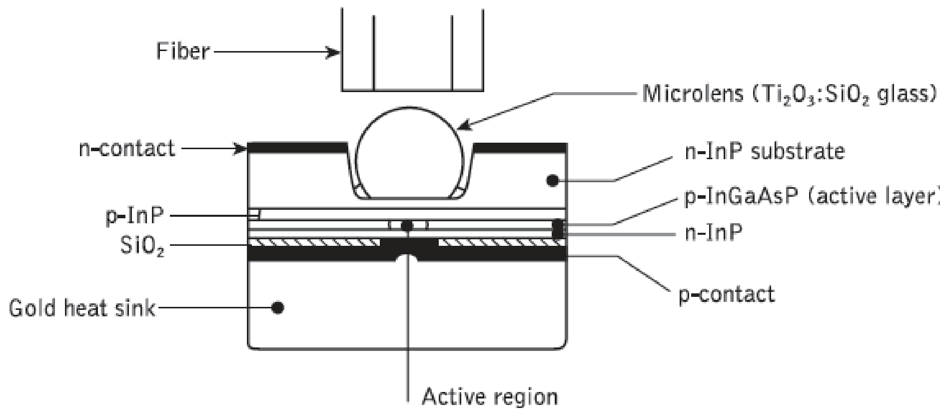

Figure 5.12: The use of a truncated spherical microlens for coupling the emission from an InGaAsP surface-emitting LED to the fiber

An example of the former technique is illustrated in Figure 5.13 (a) in which a hemispherical lens is epoxied onto the fiber end and positioned adjacent to the ELED emission region. The coupling efficiency has been increased by a factor of three to four times using this strategy. Alternatively, a truncated spherical lens glued onto the emitting facet of a superradiant ELED has given a coupling gain of a factor of five or 7 dB.

Tapered fiber lenses have been extensively used to couple power from ELEDs into SMF. Butt coupling of optical power from LEDs into SMF is substantially reduced in comparison with that obtained into multimode fiber. It ranges from between 0.5 and 2 μW for a standard SLED up to around 10 to 12 μW for an ELED. The small core diameter of single-mode fiber does not allow significant lens coupling gain to be achieved with SLEDs. For edge emitters, however, a coupling gain of around 5 dB may be realized using tapered fiber. An alternative strategy to improve the coupling efficiency from an ELED into SMF is depicted in Figure 5.13(b).

In this case a tapered graded index (GRIN) rod lens was positioned between the high-power ELED and the fiber. A coupling efficiency defined as the ratio of the coupled power to the total emitted power of around 15% was obtained. The coupling efficiency can also be improved when microlenses with micrometer dimensions integrate with the specific optical components (i.e. the LED or optical fiber). Using such microlenses the coupling of a SLED to fiber provided increased output power by a factor of 1.6. Moreover, in comparison with a typical flat-end or arc-lensed fiber, the microlensed fiber gave an improvement in coupling efficiency of 40% and 18%, respectively.

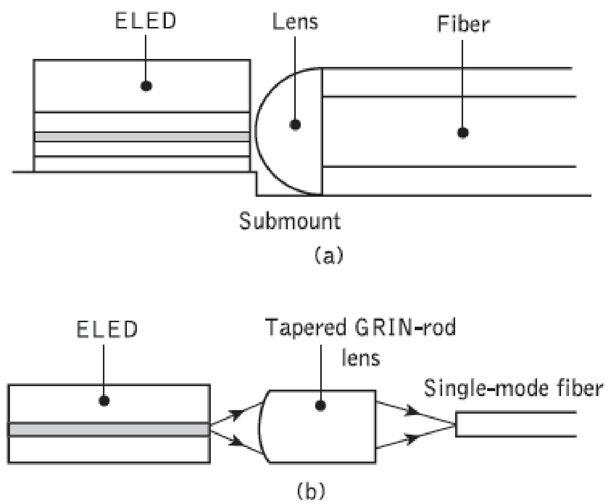

Figure 5.13: Lens coupling with edge-emitting LEDs: (a) lens-ended fiber coupling; (b) tapered (plano-convex) GRIN-rod lens coupling to single-mode fiber

However, the overall power conversion efficiency η_{oc} which is defined **as the ratio of the optical power coupled into the fiber P_c to the electric power applied at the terminals of the device P** and is therefore given by:

$$\eta_{oc} = \frac{P_c}{P} \quad \textbf{(Equation 5.1)}$$

Example 5.2

A lens-coupled surface-emitting LED launches 190 μW of optical power into a multimode step index fiber when a forward current of 25 mA is flowing through the device. Determine the overall power conversion efficiency when the corresponding forward voltage across the diode is 1.5 V.

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Solution: The overall power conversion efficiency may be obtained from (Equation 5.1) where:

$$\eta_{oc} = \frac{P_c}{P} = \frac{190 \times 10^{-6}}{25 \times 10^{-3} \times 1.5} = 5.1 \times 10^{-3}$$

Hence the overall power conversion efficiency is 0.5%.

5.7 Modulation Bandwidth

The modulation bandwidth in optical communications may be defined in either **electrical or optical terms**. However, it is often more useful when considering the associated electrical circuitry in an optical fiber communication system to use the electrical definition **where the electrical signal power has dropped to half its constant value due to the modulated portion of the optical signal**. This **corresponds to the electrical 3 dB point or the frequency at which the output electrical power is reduced by 3 dB with respect to the input electric power**. As optical sources operate down to d.c. level, we only consider the high-frequency 3 dB point, the **modulation bandwidth being the frequency range between zero and this high-frequency 3 dB point.**
Alternatively, if the 3 dB bandwidth of the modulated optical carrier (optical bandwidth) is considered, we obtain an increased value for the modulation bandwidth. The reason for this inflated modulation bandwidth is illustrated in Example 5.3 and Figure 5.14.

Example 5.3

Compare the electrical and optical bandwidths for an optical fiber communication system and develop a relationship between them.

Solution: In order to obtain a simple relationship between the two bandwidths it is necessary to compare the electric current through the system. Current rather than voltage (which is generally used in electrical systems) is compared as both the optical source and optical detector may be considered to have a linear relationship between light and current.

Electrical bandwidth: The ratio of the electric output power to the electrical input power in decibels $\mathbf{RE_{dB}}$ is given by:

$$RE_{dB} = 10\log_{10}\frac{\text{Electric power out (at the detector)}}{\text{Electric power in (at the source)}} = 10\log_{10}\left[\frac{I_o^2 / R_o}{I_i^2 / R_i}\right]$$

$$= 10\log_{10}\left[\frac{I_o}{I_i}\right]^2$$

The electrical 3 dB points occur when the ratio of electric powers shown above is 1/2. Hence it follows that this must occur when:

$$\left[\frac{I_o}{I_i}\right]^2 = \frac{1}{2} \quad or \quad \frac{I_o}{I_i} = \frac{1}{\sqrt{2}} = 0.707$$

Thus, in the electrical region the bandwidth may be defined by **the frequency when the output current, has dropped to 1/√2 or 0.707 of the input current to the system**.

Optical bandwidth: The ratio of the optical output power to the optical input power in decibels RO_{dB} is given by:

$$RO_{dB} = 10\log_{10}\frac{\text{Optical power out (at the detector)}}{\text{Optical power in (at the source)}} = 10\log_{10}\frac{I_o}{I_i}$$

(Due to the linear light/current relationships of the source and detector). Hence the optical 3 dB points occur when the ratio of the currents is equal to 1/2, and:

$$\frac{I_o}{I_i} = \frac{1}{2}$$

Therefore, in the optical regime the bandwidth is defined by **the frequencies at which the output current, has dropped to 1/2 or 0.5 of the input current to the system**.

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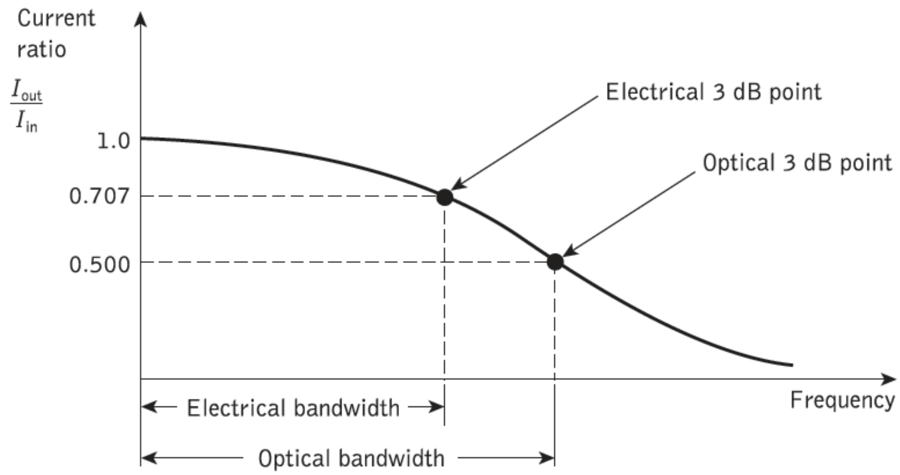

Figure 5.14: The frequency response of an optical fiber system showing the electrical and optical bandwidths.

where it may be7.25 The comparison between the two bandwidths is illustrated in Figure noted that the optical bandwidth is significantly greater than the electrical bandwidth. The difference between them (in frequency terms) depends on the shape of the frequency response for the system. However, if the system response is assumed to be Gaussian, then the optical .greater than the electrical bandwidth2 √bandwidth is a factor of

The speed at which an LED can be directly current modulated is fundamentally limited by the recombination lifetime of the carriers, where the optical output power Pe(ω) of the device (with constant peak current) and angular modulation frequency ω is given by:

$$\frac{P_e(\omega)}{P_{dc}} = \frac{1}{[1+(\omega\tau_i)^2]^{1/2}}$$

is the injected (minority) carrier lifetime in the recombination region and P_{dc} is the τ_i where .d.c. optical output power for the same drive current

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Example 5.4

The minority carrier recombination lifetime for an LED is 5 ns. When a constant d.c. drive current is applied to the device the optical output power is 300 μW. Determine the optical output power when the device is modulated with an rms drive current corresponding to the d.c. drive current at frequencies of (a) 20 MHz; (b) 100 MHz. It may be assumed that parasitic capacitance is negligible. Further, determine the 3 dB optical bandwidth for the device and estimate the 3 dB electrical bandwidth assuming a Gaussian response.

Solution: (a) the optical output power at 20 MHz is:

$$P_e(20\ \text{MHz}) = \frac{P_{dc}}{[1+(\omega\tau_i)^2]^{1/2}}$$

$$= \frac{300 \times 10^{-6}}{[1+(2\pi \times 20 \times 10^{6} \times 5 \times 10^{-9})^2]^{1/2}} = \frac{300 \times 10^{-6}}{[1.39]^{1/2}}$$

= 254.2 μW

(b) the optical output power at 100 MHz is:

$$P_e(100\ \text{MHz}) = \frac{P_{dc}}{[1+(\omega\tau_i)^2]^{1/2}}$$

$$= \frac{300 \times 10^{-6}}{[1+(2\pi \times 100 \times 10^{6} \times 5 \times 10^{-9})^2]^{1/2}} = \frac{300 \times 10^{-6}}{[10.78]^{1/2}}$$

= 90.9μW

To determine the optical 3 dB bandwidth, the high-frequency 3 dB point occurs when $P_e(\omega)/P_{dc} = 1/2$

5.8 PROBLEMS

Q1. Briefly outline the general requirements for a source in optical fiber communications.

Q2. What are the three main parts of a fiber optic transmitter?

Q3. The amount of optical power coupled into an optical fiber depends on what four factors?

Q4. What are the basic **LED** types used in fiber optic communication systems?

Q5. Briefly outlines the advantages and drawbacks of the LED in comparison with the injection laser for use as a source in optical fiber communications.

Q6. Describe the relationship between the electrical and optical modulation bandwidths for an optical fiber communication system. Estimate the 3 dB optical bandwidth corresponding to a 3 dB electrical bandwidth of 50 MHz. A Gaussian frequency response may be assumed. Ans. (70.7 MHz)

htiw retemaid eroc mμ50 Estimate the coupling optical power into a step index fiber of **.7Q**
W60 fo ecnaidar a dna mμ75 from a SLED with an emission area diameter of 0.18 an NA of
$^{1-}$sr cm^{-2}. The Fresnel reflection at the index-matched semiconductor–fiber interface may be considered negligible.

Ans. (0.26 mW)

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