Sources I: Semiconductor Lasers and Light Emitting Diodes

Three Main Components of a Laser

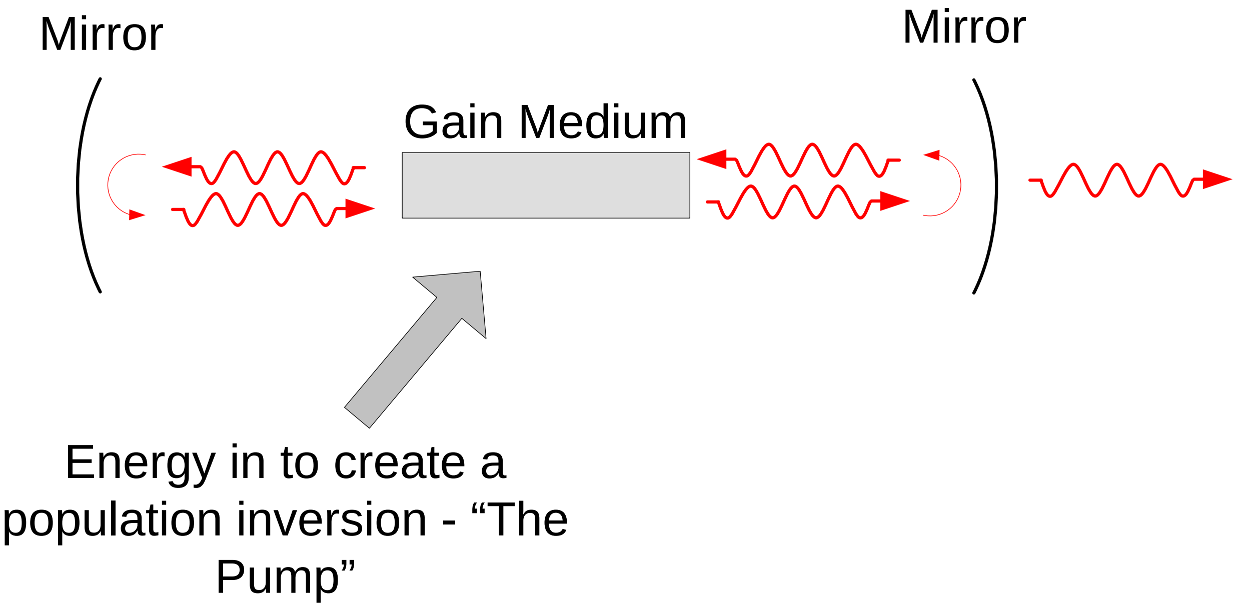


Figure 1. Lasers have a gain medium, a pump, and mirrors.

Active Gain Medium

Every laser has a gain medium that emits and amplifies light (Figure 1). The laser is almost always named after the gain medium. For example, a gas laser with a combination of helium and neon lasers as the active medium is called a helium-neon laser.

Pump

The active gain medium must be supplied energy to produce a population inversion so that medium can amplify light. Energy may be supplied in a variety of forms including optical, electrical, or chemical. We call the device that delivers energy to the gain medium (e.g. a flashlamp) the pump.

Mirrors

In lasers, mirrors form a “resonator” or “cavity” that is used to circulate light so that the light passes multiple times through the gain medium, experiencing amplification on each pass. The mirrors are essential for some of the most important properties of a laser such as monochromaticity and directionality. One of the mirrors, the “output coupler” must be partially transmissive in order to allow circulating laser light to escape.

Basic Condition for Lasing

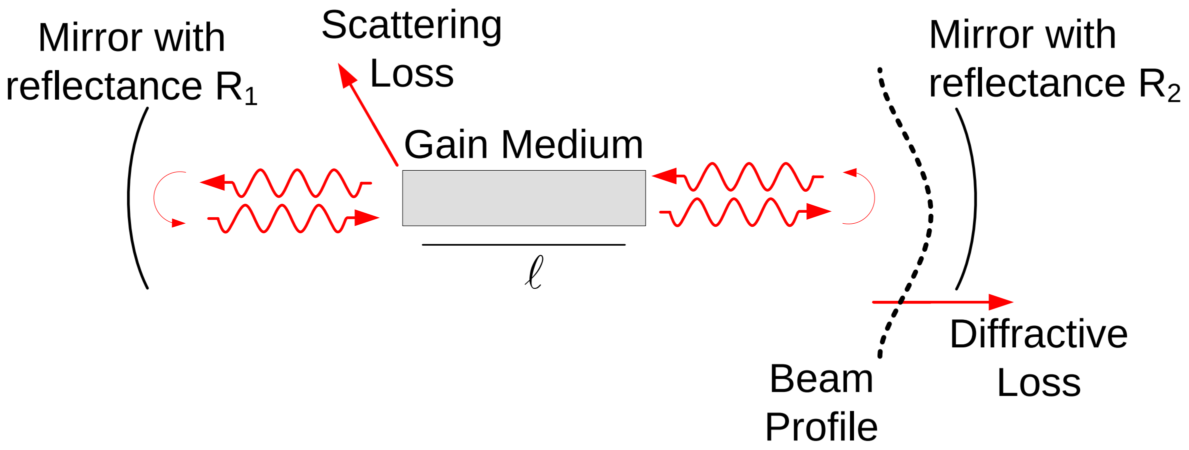


Figure 2. Gain and loss mechanisms for a laser.

Lasing occurs when the gain the gain medium balances optical loss in the laser resonator. For a laser with discrete components, such as the laser pictured in Figure 2, loss mechanisms include scattering at surfaces, optical loss at the mirrors, which are never 100% reflective, and leakage of the circulating beam out of the resonator when the beam profile extends beyond the edges of a mirror. The quantitative condition for lasing and the balance between gain and loss is

$$G\left(2\ell\right)R_1R_2(1-L_i)^2 = 1,$$

where $G\left(2\ell\right)$ is the optical gain after two passes through the gain medium (i.e. $P_{final} = G\left(2\ell\right)P_{initial}$), R1 is the reflectance of the rear mirror, R2 is the reflectance of the front mirror, and L_i is the additional optical loss after a single (one way) pass of the resonator.

It is common to define a gain coefficient g with

$$G\left(z\right) \equiv e^{gz}.$$

The gain coefficient has units of inverse length and is a property of a material medium that, like the absorption coefficient, is independent of the dimensions of the medium. In terms of g, the basic balance condition for lasing is

$$e^{2g\ell}R_1R_2(1-L_i)^2 = 1$$

Loss for a Semiconductor Laser

As pictured in Figure 3, the gain medium for the most common types of semiconductor lasers extends the entire length of the optical resonator. The mirrors (i.e. reflectors) that circulate light in the semiconductor are the surfaces (or “facets”) of the semiconductor. An uncoated semiconductor surface reflects approximately 30 % of incident light. Dielectric coatings are added to the semiconductor surfaces to increase or decrease reflectance.

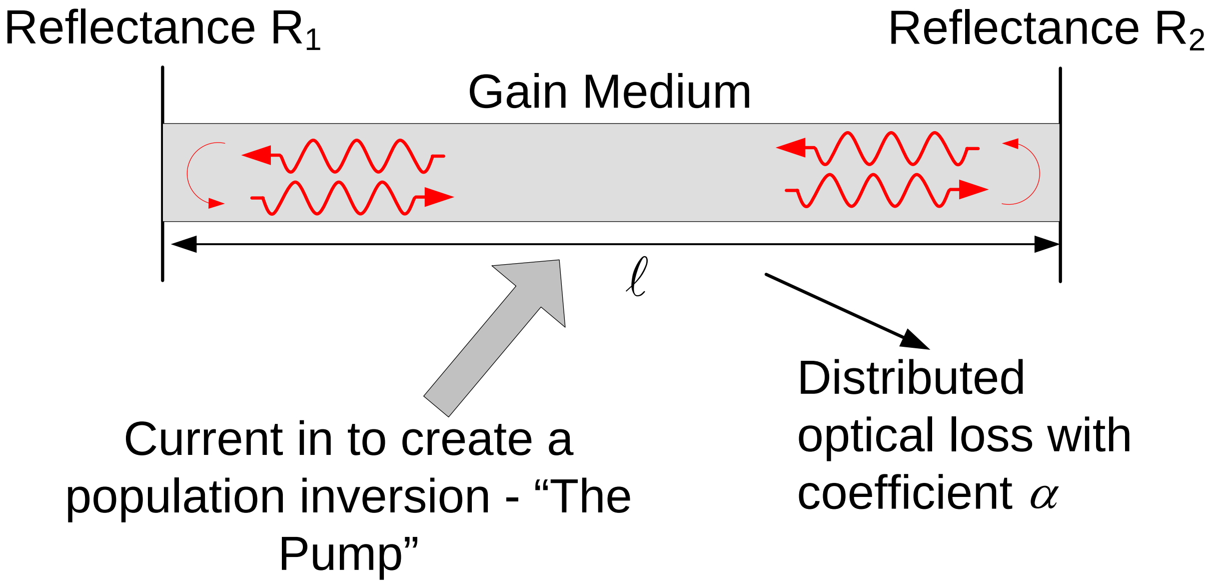


Figure 3. Electrical current is the pump source for most semiconductor lasers. Optical loss is distributed throughout the gain medium.

Most semiconductor lasers are pumped with electrical current. Furthermore, there are significant contributions to optical loss inside the gain medium. These losses are distributed throughout the medium and characterized with an optical loss coefficient α, which, like the gain coefficient, has units of inverse length.

Basic Condition for Lasing for a Semiconductor Laser

The balance equation for a semiconductor laser of the type pictured in Figure 3 is

$$e^{2g\Gamma\ell} R_1 R_2 e^{-2\alpha\ell} = 1,$$

which can also be written

$$e^{2(g\Gamma-\alpha)\ell}R_1R_2=1$$

where Γ is called the “confinement factor”. The confinement factor is a number that varies between zero and one and is included to take into account the imperfect overlap between the circulating optical beam and the gain medium. The quantity is considered in more detail in the following section.

The Optical Confinement Factor

Care must be taken when writing the balance equation for semiconductor lasers because it is almost always true that there is light circulating in the laser that does not overlap the gain region, as pictured in the side view of a semiconductor laser in Figure 4.

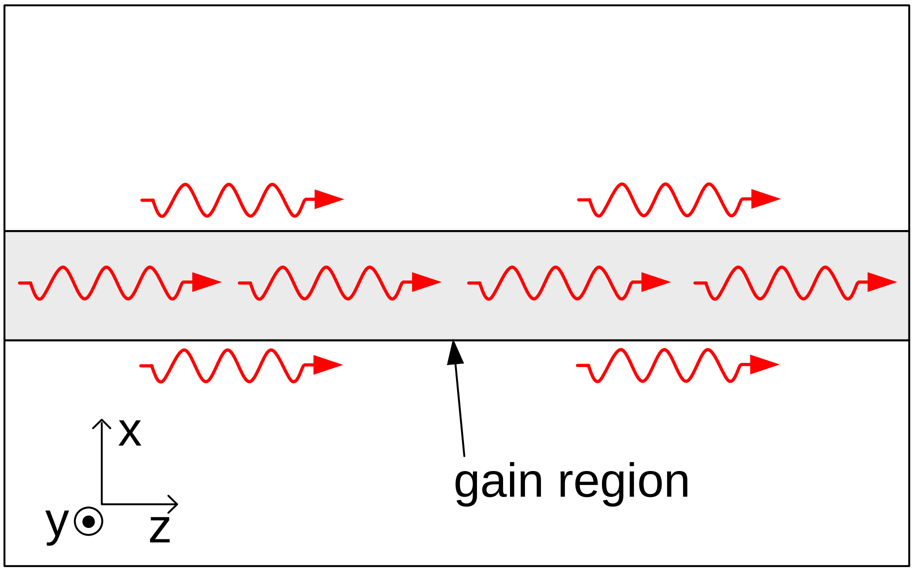


Figure 4. Semiconductor lasers contain light outside of the gain region.

The perspective of Figure 5 is of an observer looking down the length of a semiconductor laser. The red ellipses indicate the profile of the optical beam in the laser with each ellipse being a curve of constant electric field strength.

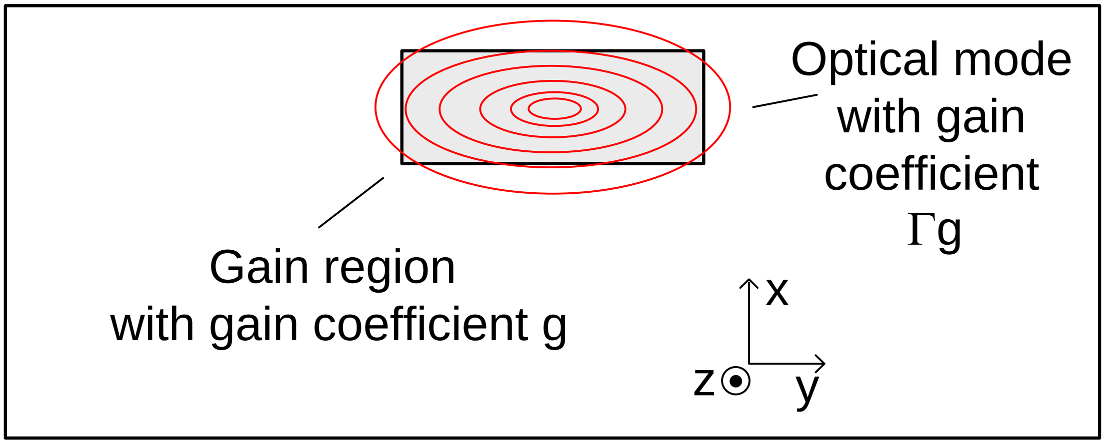


Figure 5. The overlap of an optical beam with the gain region defines the confinement factor.

Intuitively we would surmise that the greater the overlap of the optical beam with the gain region, the greater the optical gain experienced by the beam. We can make this thought somewhat more quantitative by defining the optical confinement factor for the beam/gain region:

$$\Gamma \equiv \frac{\displaystyle\int_{\substack{\text{cross section}\\ \text{of gain region}}} \left|E^{+}\right|^{2} dA}{\displaystyle\int_{\text{Entire plane}} \left|E^{+}\right|^{2} dA},$$

where E^{+} is the electric field for circulating light traveling in the positive z direction, the integral in the numerator is over a cross section of the gain region in the x-y plane, and the integral in the denominator is over the entire x-y plane.

It is also common to introduce an effective gain coefficient for light in the laser, called the modal gain coefficient, which is related to the gain coefficient in the gain region by the expression

$$g_m = \Gamma g\,.$$

In terms of the modal gain coefficient, the laser balance equation is

$$e^{2(g_m-\alpha)\ell}R_1R_2 = 1$$

Using the Balance Equation

Problem

A semiconductor laser has a length of 250 μm. We find that by injecting current into the laser that we can create a gain coefficient of 250 cm^{-1} in the gain region. The optical confinement factor is 0.3. The gain region has imperfections that contribute a distributed optical loss α = 40 cm^{-1}. The front mirror of the laser is uncoated. What must be the reflectance of the back surface to achieve lasing?

Solution

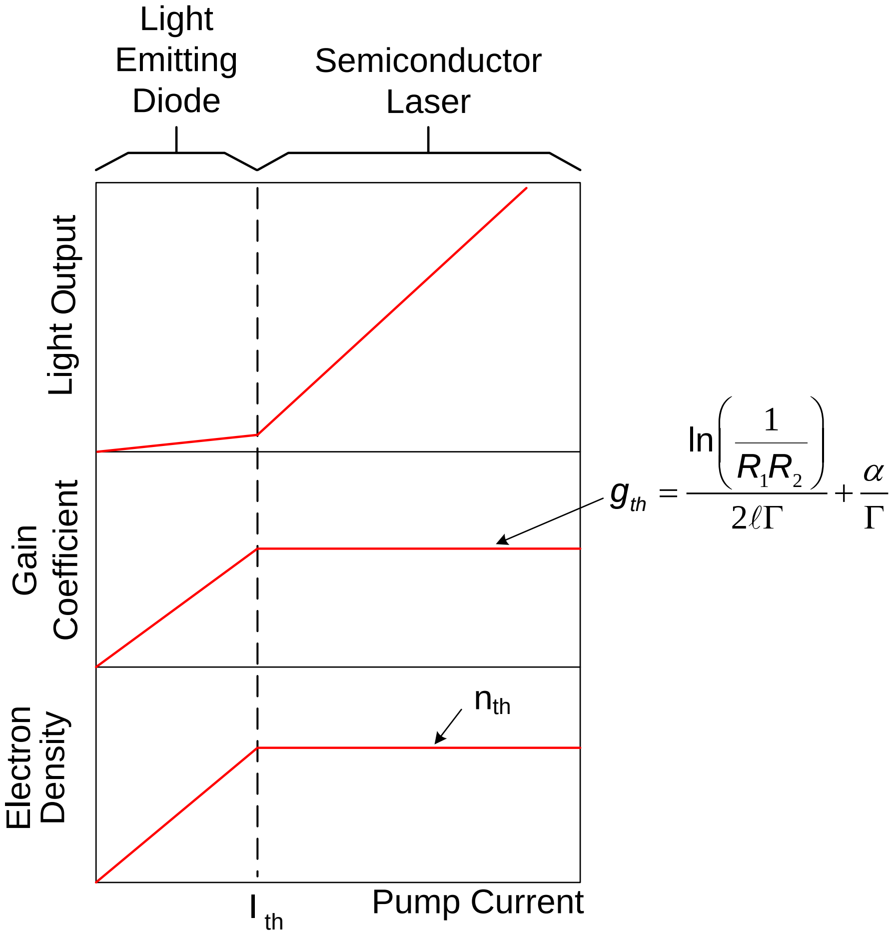
For lasing to occur, gain must balance loss. From the balance equation we find

$$R_1 = \frac{1}{R_2}e^{-2(g_m-\alpha)\ell} = \frac{1}{R_2}e^{-2(g\Gamma-\alpha)\ell}\,.$$

$$= \frac{1}{0.3}e^{-2(250\cdot 0.3-40)250\times10^{-4}} = 58\%$$

Output Power

In this section we consider the effects of increasing the pumping current for a semiconductor laser from zero to a value greater than what is required for lasing. The results are illustrated In Figure 6. Initially, the electron density in the active region, the gain coefficient, and the light output increase roughly linearly with current. The light output is relatively low and due primarily to spontaneous emission. In this regime, the device is operating as a light emitting diode.



$$g_{th} = \frac{\ln\left(\frac{1}{R_1 R_2}\right)}{2\ell\Gamma} + \frac{\alpha}{\Gamma}$$

Figure 6. Above threshold the electron density n and gain coefficient g are clamped at values determined by the gain-loss balance equation while light output increases linearly.

When the pump current reaches a threshold value the gain-loss balance condition for lasing is met. Above this value for current, additional energy from the electrical pump goes into increasing output from the laser, primarily by stimulated emission. The electron density and gain coefficient are clamped at the threshold values. This last result may seem counterintuitive, but consider the following argument. If n and g were to increase beyond their threshold values, then gain would exceed loss. In this case, the light circulating in the laser would increase upon each round trip – and the optical power of the laser would continue to increase without limit. The curves in Figure 6 represent steady state values, and a condition for steady state operation of the laser is that gain just balances loss.

The Phase Condition for Lasing and the Laser Spectrum

For lasing to occur, circulating light must add constructively to itself after a round trip in the resonator. We will make this statement quantitative with the aid of Figure 7.

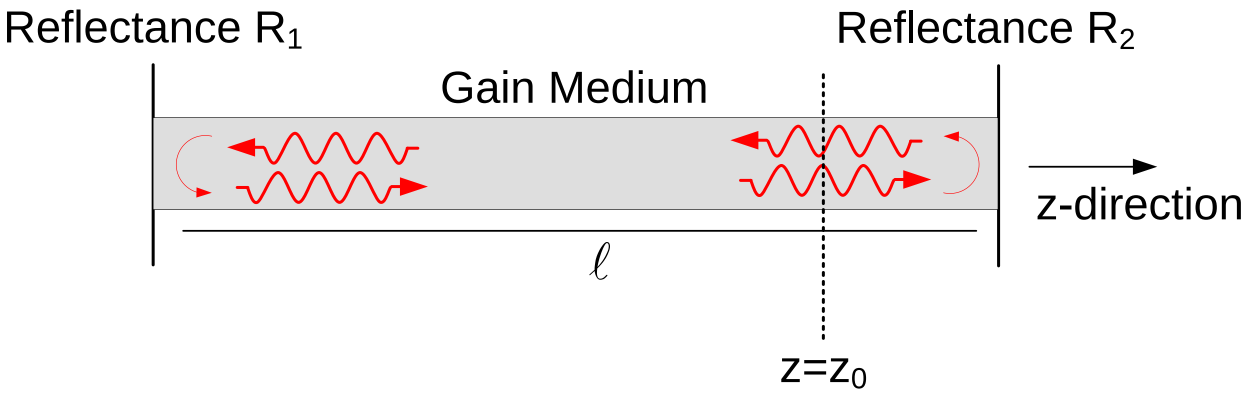


Figure 7. To establish a phase condition for lasing we examine the phase of the circulating light at the plane $z = z_0$.

The electric field propagating in the forward direction in the laser is

$$E = E\left(x,y\right)e^{j\left(\frac{2\pi n_{eff}}{\lambda_0}z-\omega t\right)},$$

where E(x,y) is the transverse beam profile and $\frac{2\pi n_{eff}}{\lambda_0}z-\omega t$ is the phase of the wave. Because the light propagates in both the gain region and the surrounding semiconductor, the phase of the wave is determined by an effective refractive index n_{eff} that can be thought of as weighted average of the material index over the beam profile.

At the point z = z_0 and time t_0 the electric field is

$$E\left(z=z_0,t_0\right) = E\left(x,y\right)e^{j\left(\frac{2\pi n_{eff}}{\lambda_0}z_0-\omega t_0\right)},$$

and after one round trip in the cavity the field is

$$E\left(z=z_0+2\ell,t_0+\Delta t\right) = E\left(x,y\right)e^{j\left(\frac{2\pi n_{eff}}{\lambda_0}(z_0+2\ell)-\omega(t_0+\Delta t)\right)}.$$

In order for the beam to add constructively to itself we must have

$$e^{j\left(\frac{2\pi n_{eff}}{\lambda_0}(z_0+2\ell)-\omega(t_0+\Delta t)\right)} = e^{j\left(\frac{2\pi n_{eff}}{\lambda_0}(z_0)-\omega(t_0+\Delta t)\right)},$$

and this gives the phase condition

$$\frac{2\pi n_{eff}}{\lambda_0}2\ell = p2\pi$$

where p is a positive integer. The phase condition can be rearranged to give the discrete set of wavelengths at which a laser can operate:

$$\lambda_{0,p} = \frac{2n_{eff}\ell}{p}, \quad p = 1, 2, 3 \ \cdots .$$

We call a circulating light beam with one of these wavelengths a longitudinal mode for the laser. A semiconductor laser will often operate in several of longitudinal modes simultaneously as illustrated in Figure 8. The frequencies for the longitudinal modes are

$$\nu_p = \frac{c}{2n_{eff}\ell} p .$$

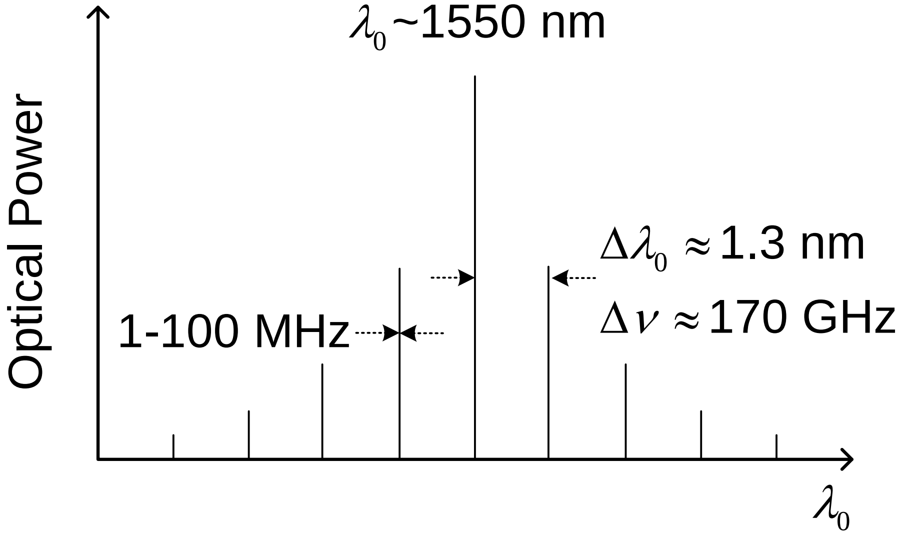


Figure 8. A semiconductor laser can operate in several longitudinal modes.

The resonant frequencies are uniformly spaced:

$$\Delta\nu = \nu_p - \nu_{p-1} = \frac{c}{2n_{eff}\ell} \text{ (independent of p).}$$

For a 250 μm long semiconductor laser and an effective index of 3.5, the spacing of longitudinal modes is about 170 GHz. The wavelength spacing of the longitudinal modes varies slowly, and if the laser operates at approximately 1550 nm, the longitudinal modes are separated by about 1.3 nm. The spectral width of the individual modes is of the order of one to 100 megahertz.

Types of Semiconductor Lasers

Buried Heterostructure Lasers

One of the most commonly used semiconductor lasers for optical fiber communications is the buried heterostructure laser. Figure 9 shows the cross section of a typical buried heterostructure device. An intrinsic (undoped) gain region is sandwiched between p and n-type layers, forming a forward biased diode during laser operation. A p-type InGaAsP layer is used to make a low resistance contact to the upper metal electrode.

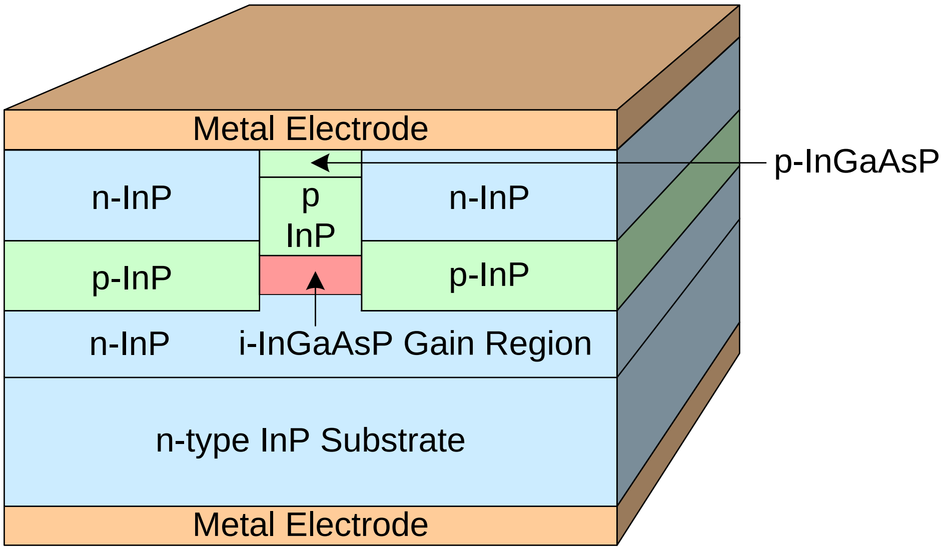


Figure 9. A buried heterostructure semiconductor laser.

Figure 10 shows the flow of current injected into the diode when applying a positive voltage to the upper electrode or a negative voltage to the lower electrode. The n-InP and p-InP layers just below the top electrode on either side of the gain region are reversed biased and current blocking – concentrating the current flow through the gain region. The gain region fills with electrons in the conduction band and holes in the valence band, creating a population inversion and optical gain.

Layers have been removed in the schematic of Figure 11 to provide a better view of the gain region. This region is formed from InGaAsP, or a similar material, and has a refractive index that is larger than the surrounding InP. Light tends to be confined to materials of larger refractive index so the gain region is an optical waveguide in which the laser light circulates from one end to the other.

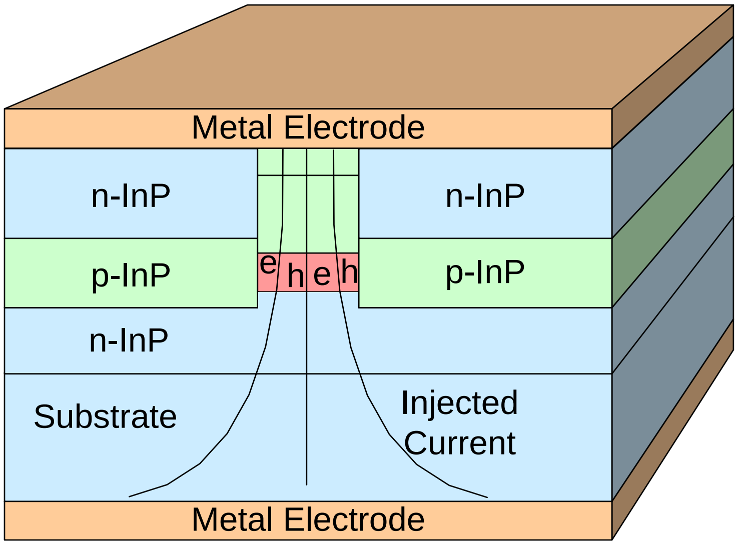


Figure 10. Current flow in a buried heterostructure semiconductor laser.

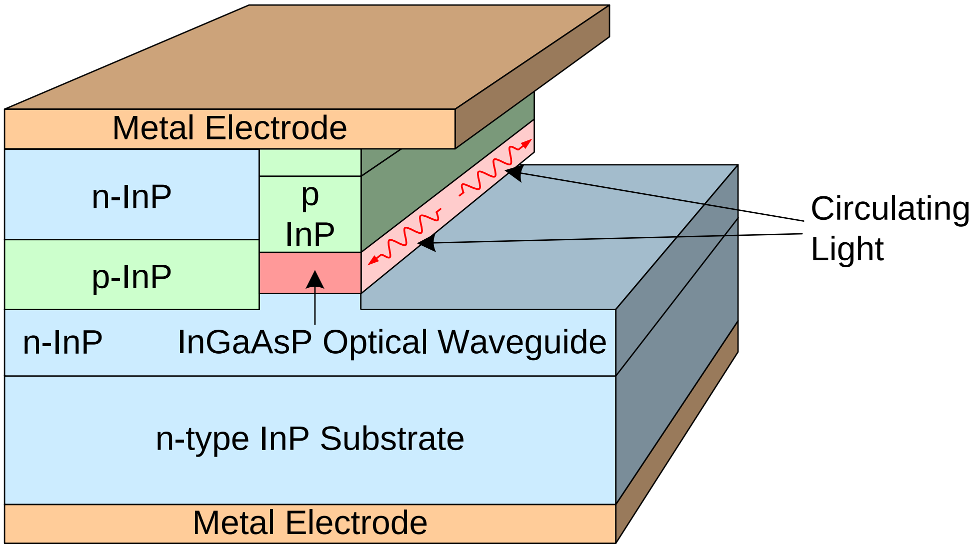


Figure 11. The InGaAsP gain region has a high refractive index than the surrounding material and forms the core of an optical waveguide that confines light that circulates from end to end.

Distributed Feedback Lasers

The semiconductor laser pictured in Figures 9-11 is called a “Fabry-Perot” type because light circulates between two planar reflectors separated by a medium that has a uniform refractive index along an axis perpendicular to the reflectors. A drawback of the Fabry-Perot structure is that it can lase in multiple longitudinal modes so that the output spectrum may span 10 nm or more. The wideband spectral output can lead to pulse spreading and signal degradation in optical communication links. For this reason, it is desirable to modify the Fabry-Perot structure so that the laser operates in a single longitudinal mode.

The basic idea for modifying the frequency spectrum of a semiconductor laser is to introduce a frequency selective element in the resonator as pictured in Figure 12. The selective element may or may not overlap the gain medium but it must overlap the circulating optical beam.

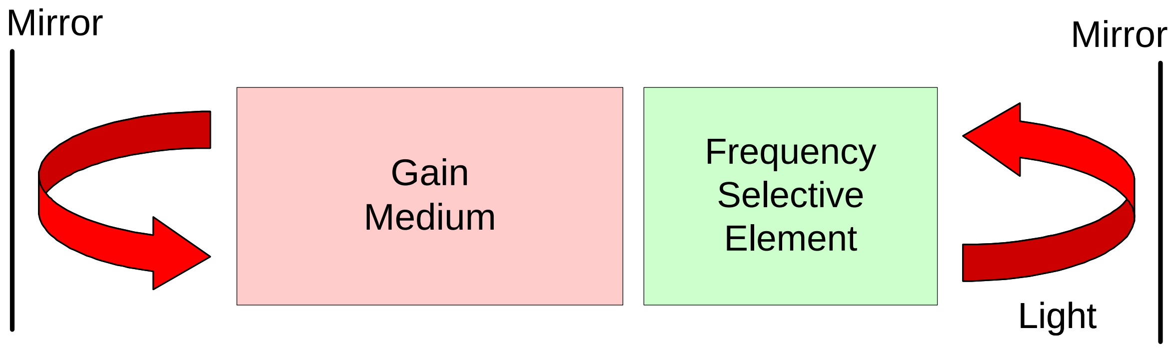


Figure 11. A frequency selective element is introduced into a semiconductor laser to narrow the output spectrum.

A widely used frequency selective element for semiconductor lasers is a periodic modulation to the refractive index of the laser material. The idea is illustrated in Figure 13. The drawing at the top left of Figure 13 is for a semiconductor structure that is similar to the Fabry-Perot structure of Figures 9-11. Thin layers of n and p-type InGaAsP have been added to either side of the intrinsic InGaAsP active region. The purpose of these additional layers can be understood with the aid of the cross section of the laser that is pictured in Figure 13. The InP below the gain region has been etched to form a corrugation at the surface. InGaAsP is deposited on top of the corrugation. There is a periodic modulation along the length of this “grating” because InP and InGaAsP have different refractive indices. The grating is the frequency selective unit that is used to narrow that laser’s spectral output.

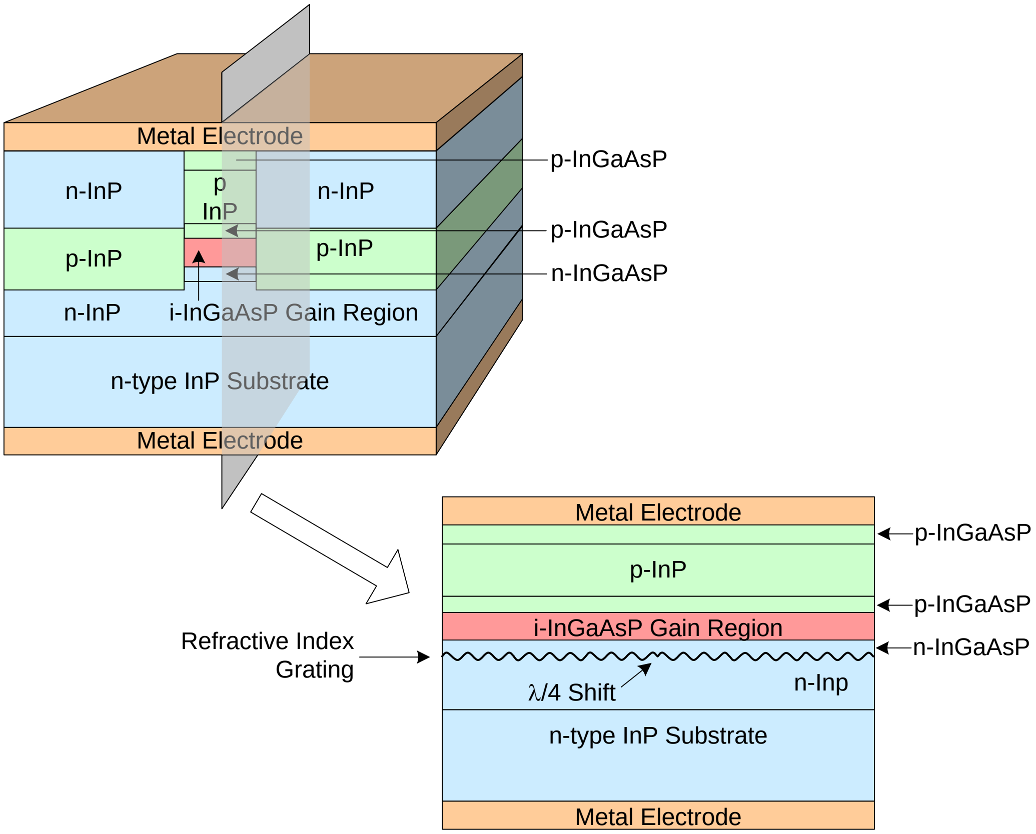


Figure 13. A cross section of a distributed feedback (DFB) semiconductor laser.

The grating is produced in the added n-InGaAsP, instead of the active region, in order to maintain high crystalline quality in the active region. Nevertheless, the circulating optical beam extends beyond the active region and overlaps the grating. The circulating light is continuously reflected back onto itself and the phase condition for constructive interference is

$$\frac{\lambda_0}{n_{eff}} = \Lambda,$$

where Λ is the period of the refractive index grating. With a uniform grating, the phase condition allows the laser to operate in two modes that see very slightly different effective refractive indices. In order to ensure laser operation in a single longitudinal mode and the narrowest possible output spectrum, a $\Lambda/4$ shift is added to the grating as indicated in the cross section of Figure 13.

Distributed Bragg Reflector Lasers

In a distributed Bragg reflector (DBR) laser, the gain medium is physically separated from the frequency selective element. The selective element is a stack of quarter wavelength layers of alternating refractive index with a very narrow reflectance band that serves as the rear mirror of the laser. The laser operates in the one longitudinal mode of the gain region that is reflected by the Bragg stack.

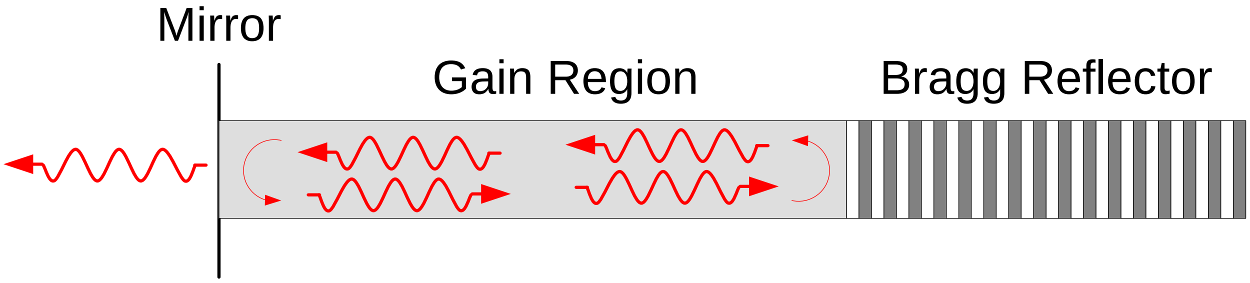


Figure 14. A single mode distributed Bragg reflector laser.

The separate Bragg reflector used in a DBR laser is a somewhat less selective element that the grating that is integrated into the gain region of a DFB laser. For this reason, DFB lasers are the preferred choice for optical communication links when frequency stability is a primary consideration. However, the use of a separate Bragg reflector allows more flexibility in the design of a semiconductor laser, and the DBR laser is the basis for a tunable laser described in the next section.

Tunable Distributed Bragg Reflector Lasers

A tunable distributed Bragg reflector laser (Figure 15) has electrodes for injecting current into each of three segments - a gain region, a Bragg reflector, and a phase control region. The current to the gain region supplies the pump power that allows for lasing. The current to the Bragg reflector adjusts the center wavelength of the reflector, and thus wavelength at which the laser can operate.

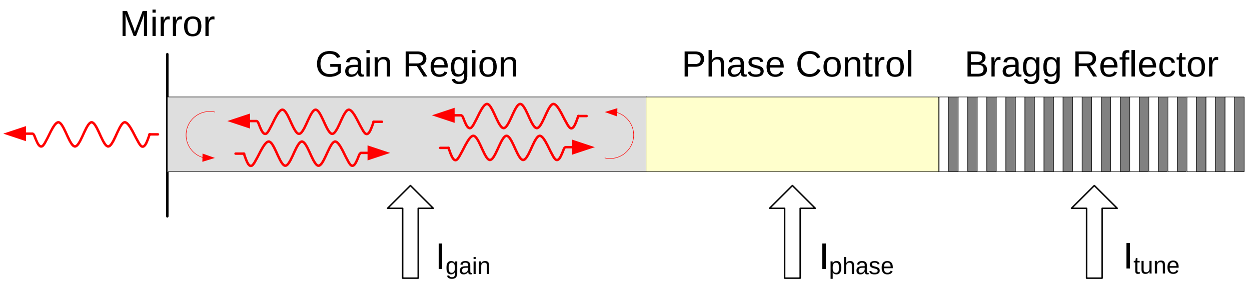


Figure 15. A tunable distributed Bragg reflector laser.

The physical mechanism that adjusts the wavelength of the Bragg reflector is a carrier density dependent refractive index. The tuning current injects charge into the Bragg reflector that decreases the refractive index of the layers by an amount

$$\Delta n_r(\lambda_0) = -\frac{q^2\lambda_0^2}{8\pi^2 n_r(\lambda_0)\varepsilon_0 c^2}\left(\frac{n}{m_e} - p\frac{m_{lh}^{1/2}+m_{hh}^{1/2}}{m_{lh}^{3/2}+m_{hh}^{3/2}}\right),$$

where q is the electronic charge, λ_0 is the optical wavelength, $n_r(\lambda_0)$ is the refractive index at λ_0, n and p are the density of injected electrons and holes respectively, and m_e, m_{lh}, and m_{hh} are the effective masses for electrons, light-holes and heavy-holes respectively. The center wavelength of the reflector is four times the optical thickness of the Bragg layers, so an increase in charge carrier density in the layers decreases the center wavelength.

The way in which the tuning current and the phase control work together can be made clear with the aid of Figure 16. Current to the Bragg reflector sets the position of the high reflectance band that determines the lasing wavelength. However, lasing can only take place if there is a longitudinal mode that coincides with this wavelength. The phase current modifies the optical path length of the laser resonator and thus the location of the longitudinal modes. For proper operation of the tunable laser, the phase current is adjusted to position a longitudinal mode at the Bragg reflectance maximum.

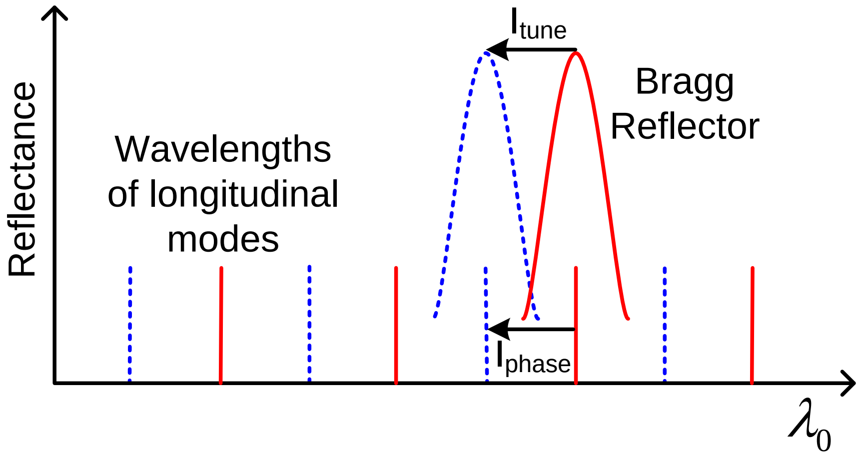


Figure 16. The phase current positions a longitudinal mode in the high reflectance band of the Bragg reflector.

Vertical Cavity Surface Emitting Lasers (VCSELs)

The structure of a surface emitting laser is pictured in Figure 17. This particular structure is for a semiconductor laser known as a vertical cavity surface emitting laser or VCSEL (pronounced “vick sell”).

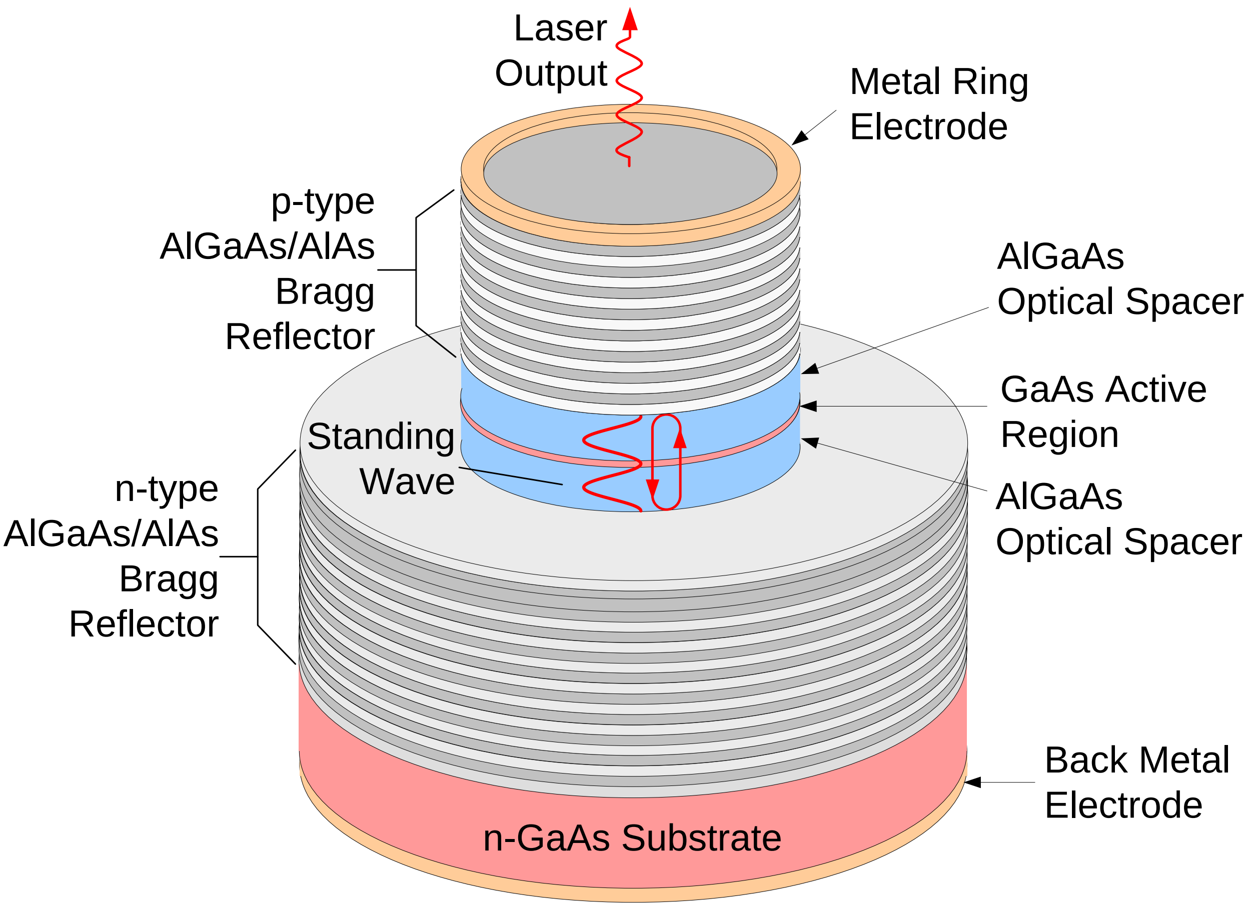


Figure 17. A GaAs surface emitting laser.

The gain region of the VCSEL is a layer of GaAs. The mirrors for the laser are distributed Bragg reflectors formed by depositing stacks of quarter wavelength layers of AlGaAs (high index) and AlAs (low index) material. The stacks are doped p and n-type to form a p-n junction for electrical pumping of the laser. Light circulates between the two Bragg stacks to be amplified by the GaAs gain region. Optical spacers are used to adjust the optical thickness of the region between the Bragg stacks to an integer number of wavelengths. This ensures that the circulating light forms a standing wave pattern with an intensity maximum at the gain region and maximizes the interaction of the light with the gain region.

Because of the very short resonator length, VCSELs operate in a single longitudinal mode. As can be seen in Figure 18, the short resonator produces widely spaced longitudinal modes separated by approximately 100 nm. Only one of these modes can experience high gain.

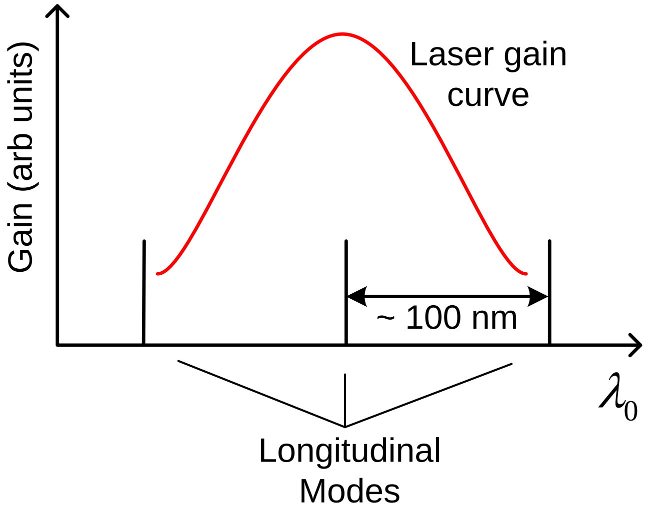


Figure 18. Only one longitudinal mode falls under a VCSEL gain curve.

In addition to high spectral purity, other advantages for VCSELs include a circular optical output profile that couples well to optical fibers and low manufacturing costs. On the other hand, the small gain volume limits the output power of VCSELs to values on the order of one mW. Furthermore, VCSELs are most easily constructed for lasing at wavelengths near 1 μm, where optical absorption in optical fibers is relatively high. For these reasons, VCSELs are most frequency used for data transmission in local area networks with short fiber spans.

Light Emitting Diodes

The simplest and least expensive light source for optical transmitters is a light emitting diode or LED. A surface emitting LED is pictured in Figure 19.

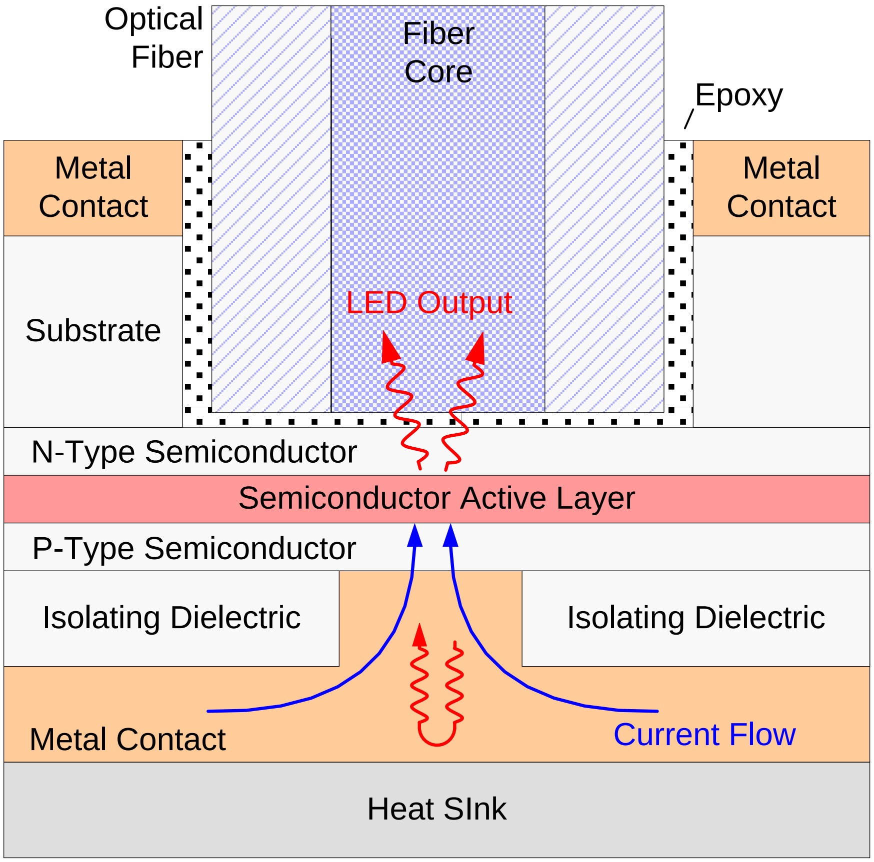


Figure 19. A light emitting diode (LED).

Electrical current is injected into an optically active semiconductor layer by forward biasing a p-n junction. The electrically excited active region emits optically incoherent light generated primarily from spontaneous emission. Light is emitted in all directions but downward emitted light is reflected upwards off a metal electrode. Light that leaves the surface of the LED can be coupled into the core of an optical fiber.

LED emission is relatively broadband, and this limits both the data rate and length of optical data links. For this reason, LED’s are most often used for optical transmitters when the data rate is 200 Mbits/sec or less, and for applications such as local area networks where fiber spans are short.