CHAPTER 14
Optoelectronics

14.1 What is Optoelectronics?

The area where photons deal with matter - specifically semiconductors is called optoelectronics. It includes the way photons interact with electrons. When photons are absorbed producing a change in some property in a semiconductor, the device is called photodetector. When electrons are caused to emit photons, the device is called a source. The information carried by electrons may then be changed into information carried by light photons in a process called optical modulation, whereas the information carried by photons may be extracted into information carried by electrons (electric current) in a process called light detection. Between the source and the receiver, there is a medium that carries light, or in which light waves carrying the information propagate. This propagation can be in air or open space. This is called unguided propagation. Alternatively, this propagation may be confined in special conduits, called optical fibers. The optical system, thus, consists of the source with its modulating circuits (collectively called transmitter), the detector and demodulating circuits (collectively called receiver), and the optical medium. Optical communication is finding a vast area of both analog and digital applications in modern times.

We will confine our attention here to the basic analog applications, and defer the digital applications for another book (Digital Communication Electronics). For sources, we will concentrate on light emitting diodes (LEDs) and semiconductor lasers, whereas for detectors we will focus on photoconductors and photodiodes.

14.2 Generation and Recombination:

In a semiconductor, in thermal equilibrium, two converse processes act at the same time. Electrons and holes are generated at a rate g_o, due to thermal excitation. At the same time, electrons and holes recombine at a rate R_o proportional to the product of their concentrations (mass action law), such that

$$R_0 = g_0 = rn_0\ p_0, \qquad (14-1)$$

where r is a constant (cm^3/s) depending on the characteristics of the material. Eqn. (14.1) expresses the principle of detailed balance. It must be remembered that the process of generation of electron hole pairs - generally speaking - entails the absorption of photons. The process of recombination involves the emission of photons, or generally energy.

Now, let additional electron-hole pairs be generated at a steady state rate of g_s (pairs per unit volume per unit time) by means of an external (nonthermal) source. Thus, $n = n_o + \Delta n$ and $p = p_o + \Delta p$, where Δn and Δp are steady state excess carrier concentrations. We shall assume that $\Delta n = \Delta p$, since, an excess hole is associated with an excess electron.

$$g_0 + g_S = r(n_0 + \Delta n)(p_o + \Delta p) \quad (14-2)$$

$$= rn_o p_o + r(n_o + p_o)\Delta n + r\Delta n^2 \quad (14-3)$$

Using eqn. (14-1) and neglecting second order terms, eqn. (14-3) becomes

$$g_S = \Delta n / \tau , \quad (14-4)$$

where τ is called excess carrier lifetime, and is given by

$$\tau = \frac{1}{r(n_0 + p_0)} \quad (14-5)$$

In transients, we may write the deviation excess carrier as δn and is given by:

$$\frac{d\,\delta n}{dt} = g_S - \frac{\delta n}{\tau} \quad (14-6)$$

In steady state, $\frac{d\,\delta n}{dt} = 0$. Thus,

$$\delta n = \Delta n = g_S \tau \quad (14-7)$$

When the external source is removed, eqn. (14-6) becomes

$$\frac{d\,\delta n}{dt} = -\frac{\delta n}{\tau}, \quad (14-8)$$

whose solution is given by

$$\delta n = \delta n(t_o) e^{-(t-t_o)/\tau} \quad (14-9)$$

The source g_s may be a light beam, in which case g_s expresses the rate of photons absorbed (or the rate of electron-hole pairs generated) per unit volume per unit time. Alternatively, g_s may express the rate of injection of electron-hole pairs per unit volume per unit time. This constitutes current due to injection, which amounts to the process of supplying minority carriers at a rate at which these carriers are disappearing, due to the process of recombination. This analysis may be used to obtain the I-V characteristic of a pn diode and is called charge control model.

It must be noted here that not all recombination processes give out photons. They must always, though, release out energy. But this released energy may be either direct (radiative) or indirect (nonradiative). Nonradiative recombination gives out energy to the lattice as heat, i.e., in vibration. They are said to give out phonons. Thus, the excess carrier lifetime may be split as:

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}, \qquad (14-10)$$

where τ_r denotes radiative recombination lifetime, and τ_{nr} denotes the nonradiative recombination lifetime.

We define the internal efficiency η_i as

$$\eta_i = \frac{r_r}{r} = \frac{\tau}{\tau_r} = \frac{\tau_{nr}}{\tau_r + \tau_{nr}}, \qquad (14-11)$$

where r in eqn. (14-1) is split into

$$r = r_r + r_{nr} \qquad (14-12)$$

14.3 Injection:

In a pn junction in thermal equilibrium, some holes diffuse from the hole - rich p region to the n region, leaving behind a layer of acceptor ions. Similarly, some electrons in the n region diffuse to the p region, leaving behind a layer of donor ions. Thus, a depletion region is formed in this double layer. An electric field exists in this depletion region, an internal potential barrier is built up, opposing further diffusion. The steady state carrier distribution in thermal equilibrium (Fig. 14.1a) shows that outside the depletion region, the thermal equilibrium carrier concentrations prevail. Under forward bias, the external voltage effectively lowers the potential barrier, encouraging further diffusion. Some electrons are injected into the p region and some holes into the n region forming exponentially decaying distributions.

$$\Delta p_n(x) = \Delta p_n(x_n) e^{-(x-x_n)/L_p} \qquad (14-13)$$

$$\Delta n_p(x) = \Delta n_p(-x_p) e^{-(x+x_p)/L_n} \qquad (14-14)$$

However, to maintain charge neutrality outside the depletion region, majority carriers accumulate around the injected carriers, a process called neutralization. This means that the majority charges will redistribute to maintain charge neutrality in the bulk as much as possible. We must note, however, that this is an idealistic assumption, since there is need for a drift current in the bulk, which requires a small electric field to drive it. So, the condition of charge neutrality can be compromised into a negligibly small electric field. Now, the current may be viewed as the rate of pumping-in enough minority carriers on both sides of the junction, to maintain the excess carrier distribution in a steady state, by replenishing carriers lost in the process of recombination between the injected carriers and the majority carriers engulfing them. Once again, recombination is between a pair of carriers, one from the injected distribution (minority) and one from the neutralizing distribution (majority).

One decaying majority carrier will be replaced by another thermally generated one. The generated majority will exit the pn structure at the metal contact as a drift current. It is to be noted that the static charges at the metal surfaces account for charge neutrality and electric field requirements.

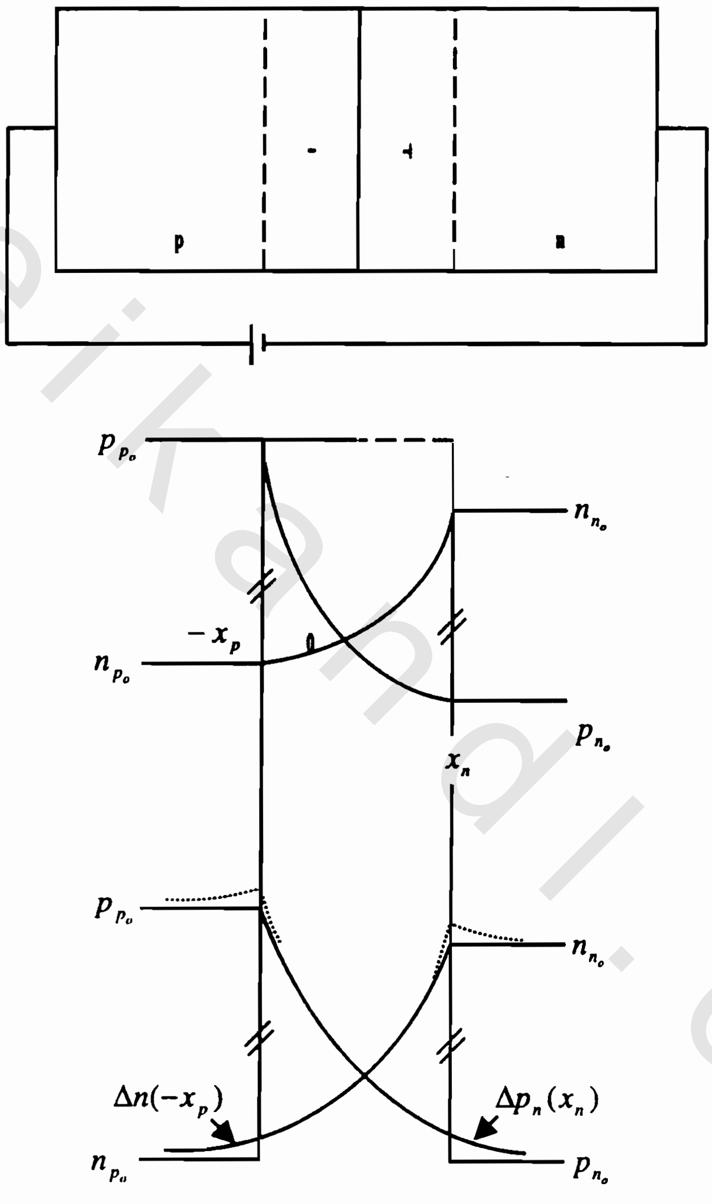


Fig. 14.1 Carrier distribution in a pn junction
a) in thermal equilibrium b) under forward bias

14.4 Light Emitting Diodes:

A light emitting diode (LED) is a forward biased pn junction in which injected carriers emit radiation upon recombination. We may think of electron motion in a forward biased pn junction as an electron moving from the n side to the p side in the conduction band, then falling down to the valence band (by act of recombination), then continuing into the valence band to the positive side of the battery (Fig. 14.2). The downfall of the electron emits energy. It could be a photon for radiative recombination, or a phonon (crystal heating) in nonradiative recombination.

The motion of electrons in the valence band can also be represented by an equivalent hole motion. Conduction band electrons may recombine with majority holes in the p side, or with the diffusing holes into the n region. In both cases, we have injection electroluminescence. LEDs are used as solid state lamps and sources of light for optical communication. Under steady state conditions, in a forward biased pn junction, the injection rate R_{inj} must be equal to the rate of recombination Δ_n / τ , where τ is given by

$$\tau = \frac{1}{r(n_0 + p_0)} \qquad (14-15)$$

We assume that the pn junction is heavily doped, so that all recombination takes place in the n region, and that $\Delta n = \Delta p$ due to the charge neutrality condition

$$R_{inj} = \frac{\Delta n}{\tau} = r\Delta n(n_0 + p_0) \qquad (14-16)$$

Only radiative recombination generates photons. Using eqns. (14.11), and (14.16), the total flux ϕ (photons/second) due to the injection of $R_{inj}\, vol$ (where vol is the volume) carriers per second is given by

$$\phi = \eta_i R_{inj} vol = \eta_i \frac{vol\,\Delta n}{\tau} = \frac{vol\,\Delta n}{\tau_r}, \qquad (14-17)$$

An injected dc current I supports the recombination rate $\Delta n / \tau$.
Thus,

$$R_{inj} = \frac{I}{e}\frac{1}{vol} = \frac{\Delta n}{\tau} \qquad (14-18)$$

$$\Delta n = \frac{(I/e)\tau}{vol} \qquad (14-19)$$

Thus, the internal quantum efficiency η_i is simply the ratio of the generated photon flux to the injected electron flux. Each photon has energy $h\nu$. Thus, the output power P_o is given by:

$$P_0 = h\nu\,\phi = \eta_{ex}\,h\nu\,\frac{I}{e}, \qquad (14-21)$$

From eqns. (14.17) and (14.19),

$$\phi = \eta_i\,\frac{I}{e} \quad , \qquad (14-20)$$

where η_{ex} is the external quantum efficiency:

$$\eta_{ex} = \eta_e \eta_i, \qquad (14-22)$$

where η_e is the overall transmission efficiency measuring photons which may be extracted from the LED structure.

Another measure of performance is the overall quantum efficiency η or power conversion efficiency. It is the ratio of the emitted optical power P_o to the applied electrical power:

$$\eta = \frac{P_0}{IV} = \eta_{ex}\,\frac{h\nu}{eV} \quad , \qquad (14-23)$$

where V is the voltage drop across the device.

For $h\nu \sim eV$ -as is the case for commonly encountered LEDs - then $\eta \simeq \eta_{ex}$.

We may also define responsivily $\mathcal{R}$ as the ratio of the emitted optical power P_o to the injected current:

$$\mathcal{R} = \frac{P_0}{I} = \frac{h\nu\,\phi}{I} = \eta_{ex}\,\frac{h\nu}{e} \qquad (14-24)$$

$$\mathcal{R} = \eta_{ex}\,\frac{1.24}{\lambda_0(\mu m)}, \qquad (14-25)$$

where λ_o is the wavelength of the emitted light. For example, if $\lambda_0 = 1.24\mu m$, then $\mathcal{R} = \eta_{ex}$ W/A. If η_{ex} were unity, the maximum optical power that could be produced by an injection current of 1mA would be 1mW.

From eqn. (14.21), the LED output power P_o is proportional to the injected current I. In practice, this linearity is limited to a restricted range, where responsivity is constant. For large drive currents, saturation causes the proportionality to fail, and the responsivity is then no longer constant.

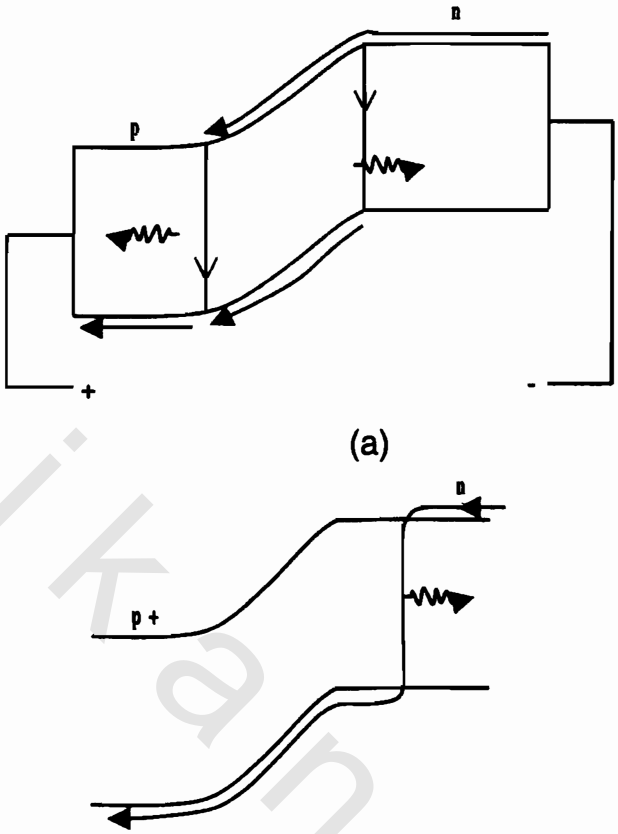


Fig. 14.2 Electron flow in a forward biased pn junction
a) pn junction b) p^+n junction

Ex. 14.1:

The curve shown relates the optical power to the drive current. What is the responsivity? Then show how this responsivity varies if the drive current varies sinusoidally. Find the highest frequency at which a LED can be effectively modulated.

Solution:

The responsivity is the slope of the curve which is 25 μW/mA, for I <75mA. For larger I, the responsivity ceases to be a linear function of I, causing saturation. For further increase in I, the responsivity declines due to the increasing ohmic loss.

When the current is sinusoidal in the form $i = I_1 + I_2 \cos \omega t$, where I_2 is sufficiently small, so that the emitted power varies linearly with the injected current, the emitted optical power varies as $P_o = P_1 + P_2 \cos(\omega t + \theta)$.
The associated transfer function is defined as

$$H_2(\omega) = \frac{P_2}{I_2} e^{j\theta} = \frac{H_2}{1 + j\omega\tau}, \qquad (14-26)$$

which is characteristic of an RC circuit, τ is the rise time and the bandwidth $BW = 1/2\pi\tau$. A larger BW is attained by decreasing τ.

Since $\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$, reducing τ_{nr} results in the reduction of $\eta_i = \frac{\tau}{\tau_r}$. It is then desirable to maximize the internal quantum efficiency-bandwidth product $\eta_i BW = 1/2\pi\tau_r$, rather than maximizing BW alone. This requires a reduction of only the radiative lifetime τ_r without a reduction of τ_{nr}. Typical rise times range from 1 to 50ns corresponding to bandwidth as large as hundreds of MHz.

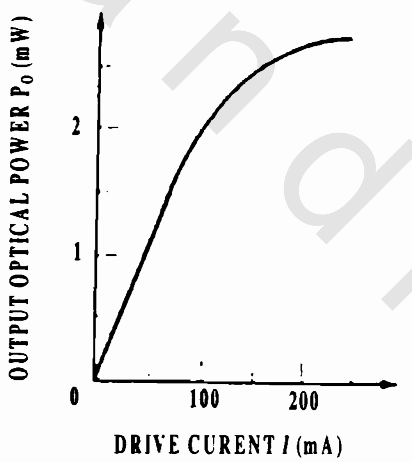


Fig. 14.3 Optical power as a function of the drive current

14.5 Laser:

The word LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. The laser is a source of highly directional monochromatic coherent light. The light from a laser may be a continuous beam of low or medium power, or it can be a short burst of intense light up to millions of watts. When we have two electronic levels E_1 and E_2 with $E_2 > E_1$, the process of emission of radiation from E_2 to E_1 is called spontaneous radiation, and its rate is proportional to the population of E_2 (electrons in E_2). We expect this process of decay or relaxation to be exponential, emptying electrons in the excited state to the ground state with a mean decay time called spontaneous lifetime. Let us visualize an electron in E_2 waiting to drop spontaneously to E_1 with the emission of a photon of energy $h\nu_{12} = E_2 - E_1$.

Now, we assume that this electron in the upper state is immersed in an intensive field of photons, each having energy $h\nu_{12} = E_2 - E_1$ and in phase with the other photons. The electron is induced to drop in energy from E_2 to E_1, contributing a photon whose wave is in phase with the radiation field. If this process continues, and other electrons are stimulated to emit photons, a large radiation field can build up. This radiation will be monochromatic, i.e., each photon has $h\nu = E_2 - E_1$, and will be coherent, since the released photons will be reinforcing each other.

If we assume the instantaneous populations of E_1 and E_2 to be n_1 and n_2, respectively, then, from Boltzman distribution at thermal equilibrium

$$\frac{n_2}{n_1} = e^{-(E_2 - E_1)/kT} = e^{-h\nu_{12}/kT} \qquad (14-27)$$

We note that $n_2 << n_1$ at equilibrium, i.e., most electrons are in the lower (ground) state. If the atoms exist in a radiation field of photons with energy density of the field $\rho(\nu_{12})$, then stimulated emission can occur along with absorption and spontaneous emission.

The rate of stimulated emission is proportional to the instantaneous population in E_2 and to the density of the stimulating field $\rho(\nu_{12})$. Thus, the rate of stimulated emission is $B_{21}n_2\rho(\nu_{12})$, where B_{21} is a proportionality constant. The rate of absorption of photons by electrons in E_1 is, similarly, $B_{12}n_2\rho(\nu_{12})$, where B_{12} is a proportionality constant for absorption. Finally, the rate of spontaneous emission is proportional only to the population of the upper level, i.e. $A_{21}n_1$ where A_{21} is a proportionality constant for spontaneous emission. We note that spontaneous emission does not require energy density.

For steady state, the rate of absorption is equal to the total rate of emission (spontaneous and stimulated):

$$B_{12}n_1\rho(\nu_{12}) = A_{21}n_2 + B_{12}n_1\rho(\nu_{12}) \qquad (14-28)$$

The coefficients B_{21}, B_{12} and A_{21} are called Einstein's coefficients. At thermal equilibrium, the ratio of stimulated to spontaneous rates is very small, and the contribution of stimulated emission is negligible.

$$\frac{\text{stimulated emission rate}}{\text{spontaneous emission rate}} = \frac{B_{21}}{A_{21}}\rho(\nu_{12}) \qquad (14-29)$$

In order to enhance stimulated emission over spontaneous emission, we must have a very large field energy density $\rho(\nu_{12})$. In the laser, an optical resonant cavity is used in which the photon density can build up to a large value through multiple internal reflections at certain frequencies. Also, to obtain more stimulated emission than absorption, we must have $n_2 > n_1$

$$\frac{\text{stimulated emission rate}}{\text{absorption rate}} = \frac{B_{21}n_2}{B_{12}n_1} \qquad (14-30)$$

Thus, if we want stimulated emission to dominate over absorption of photons, we must find a way of maintaining more electrons in the upper level than in the lower level. This is called population inversion, and it is a nonequilibrium state. It is equivalent to having a negative temperature according to eqn. (14-27). Thus, the two conditions for "lasing" or "laser action" are: having a population inversion and a resonant cavity.

The first working laser was built in 1960 by Maiman, using a ruby crystal. Ruby crystals are available in rods (several inches long). The crystal is cut and polished, so that the ends are flat and parallel. The ends are coated with a highly reflective material, thus, producing a resonant cavity. One of the ends is made, however, partially transmitting, to allow a fraction of light to leak out and form the laser output.

In a resonant cavity, light of a particular frequency can be reflected back and forth within the cavity in a reinforcing (coherent) manner if an integral number of half wavelengths fit between the end mirrors. The length of the cavity for stimulated emission must be

$$L = \frac{m\lambda}{2}, \qquad (14-31)$$

where m is an integer and λ is the photon wavelength in the material (Fig.14.3).

In ruby, there are 3 levels in concern. E_1 is the ground state, E_2 is called a metastable state. E_3 is another metastable state, called the pumping level (actually a broad band of levels). Excitation occurs by raising electrons in E_1 to E_3. This is called optical pumping, and it is caused by noncoherent flash lamp. The excited levels are unstable, and electrons decay quickly to level E_2, giving up the energy difference $E_3 - E_2$ as heat. Because the lifetime in E_2 is long (metastable state), electrons are excited from E_1 to E_3, and then passed on to E_2 at a rate faster than the decay rate from E_2 back to E_1, i.e., E_2 can be made more populated than E_1. The laser does not operate continuously during optical pumping, but instead, emits a series of very short spikes (Fig.10.5). When the flash lamp intensity becomes large enough to create population inversion (threshold pumping level), stimulated emission from the metastable level to the ground level occurs, resulting in laser output. Once the stimulated emission begins, however, the metastable level is depopulated very quickly. Thus, the laser output consists of an intense spike lasting from a few nanoseconds to microseconds. After the stimulated emission spike, population inversion builds up again, and a second spike results. This process continues as long as the flash lamp intensity is above the threshold pumping level. Thus, the metastable level never receives a highly inverted population of electrons. Whenever the population of E_2 reaches the minimum required for stimulated emission, these electrons are depleted quickly in one of the spikes. To prevent this, we must, somehow, keep the coherent photon field in the ruby rod from building up - and thus, prevent stimulated emission, until after a large population inversion is obtained. This can be done by temporarily interrupting the action of the resonant cavity by a process called Q - switching. In this case, the back reflector of the optical cavity is provided by an external mirror which can be rotated at high speeds, while the front surface is partially reflecting. As the mirror is tilted, there is no build up of photons by multiple reflections, and no laser action can occur.

Thus, during a flash from the Xenon lamp, a very large inverted population builds up, as long as the mirror is off axis (Fig.14.6). When the mirror returns to the perpendicular position, stimulated emission can occur, and the large population inversion gives way to an intense laser pulse. This is called a giant laser or a Q - switched laser. By saving the population inversion for one giant pulse, a large amount of energy is released in a very short time. (1J in a pulse width of 100 ns or power 10 MW), (Fig. 14.7).

Instead of using a mechanical mirror, a device called Kerr cell is used. A transverse electric field is used to control the transmission of light longitudinally through the material in the laser path. By controlling the polarization of light transmitted through the cell, the Q of the laser cavity can be reduced, until the cell is pulsed on by the applied electric field.

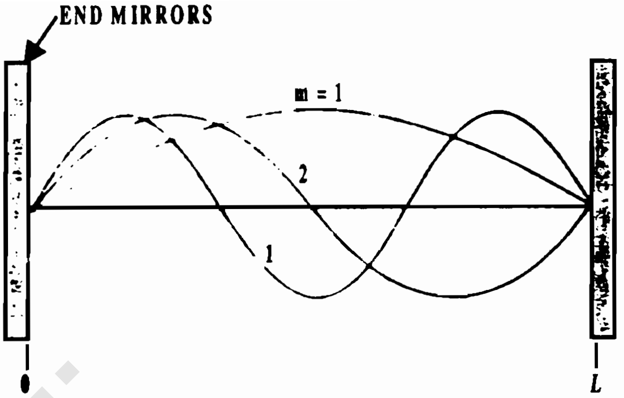


Fig. 14.4 Resonant modes in a laser cavity

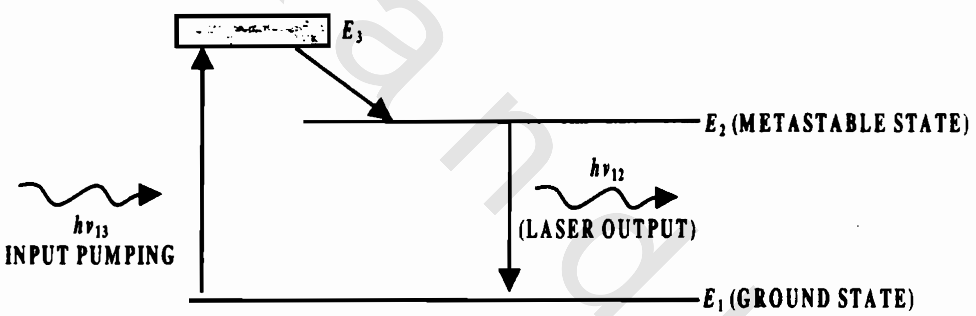


Fig. 14.5 A 3- level laser system

One disadvantage of a 3-level laser system is that no significant stimulated emission occurs, until at least half the ground state electrons have been excited to the metastable state, i.e., population inversion exists only when the metastable state is more density populated than the ground state. Thus, the threshold for optical pumping is high.

Laser systems of better performance include a 4 – level laser, in which the terminal state is another excited state of less population than the ground state, reducing the lasing limit, and hence, the threshold. Even that system is inefficient, since large amount of energy is required for pumping and is wasted. Many laser applications require a steady long-term output of light (continuous wave or CW operation). In gas lasers, electric discharge can be used to excite atoms, since energy may be transferred to the atoms of the gas by electron impact and collisions between atoms.

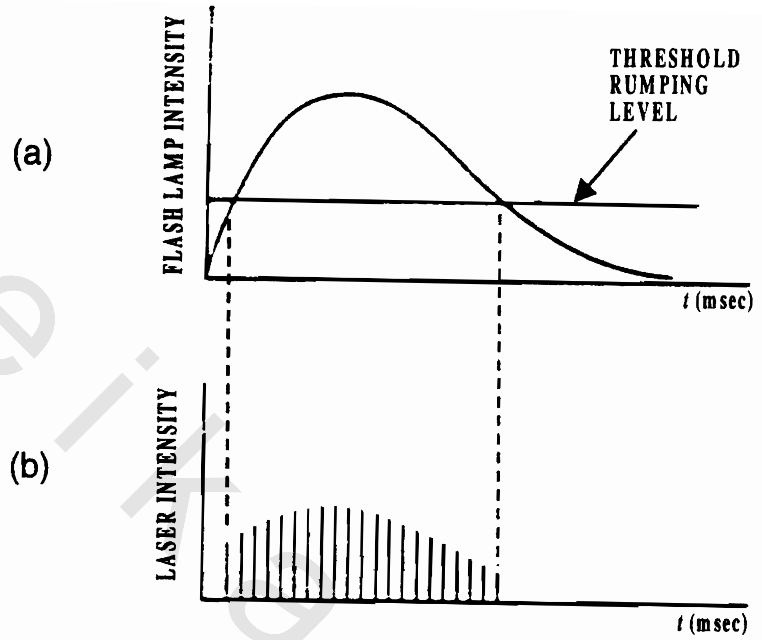


Fig. 14.6 Laser spikes in the output of ruby laser
a) variation of flash lamp intensity
b) spikes while intensity is above threshold

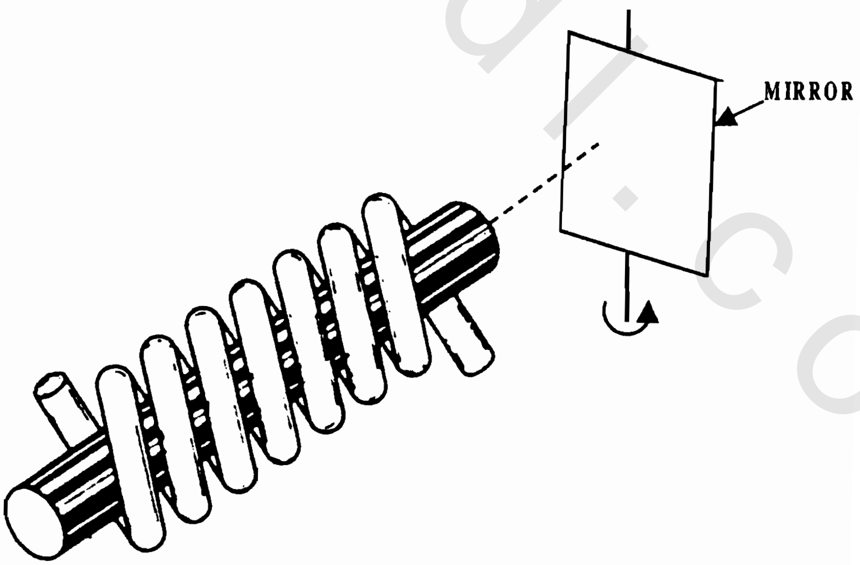


Fig. 14.7 Q - switched laser

The resulting mixture of electrons and gas ions (plasma) is a source of spectral emission, which is continuous as long as power is supplied. The most commonly used gas laser system employs a mixture of helium and neon gases. There is a resonant energy transfer between colliding He and Ne atoms. The lasing action takes place in the Ne atoms, usually around 0.63 μm. This arrangement is capable of CW operation through electric discharge.

14.6 Semiconductor Laser:

We have discussed the case of LED, where incoherent light is emitted from a pn junction through spontaneous emission due to the recombination of electrons and holes injected across the junction. We discuss now semiconductor (or junction) lasers. Semiconductor (Junction) lasers are remarkably small. They are portable and have high efficiency. The laser output can easily be modulated by controlling the junction current. It can operate as CW or pulsed mode, but it is generally of low power ratings.

In a pn junction formed between degenerate (heavily doped) materials under bias, the bands appear as in (Fig.14.8). If the bias (and the current) is large enough, electrons and holes are injected into and across the transition region in considerable amounts (heavy doping).The region around the junction cannot be considered anymore depleted of carriers. This region contains large concentrations of electrons in the conduction band and holes in the valence band. A condition of population inversion results, and the region - where this condition prevails - is called inversion (active) region. Since forward biasing is a nonequilibrium state, relations obtained under thermal equilibrium no longer apply.

The concentration of electrons in the inversion region – even several diffusion lengths into the p material - exceeds values at thermal equilibrium. The same comment applies to holes injected into the n material. Carrier concentrations in such cases may best be described in terms of quasi-Fermi levels for electrons and holes in steady state. Thus,

$$n = N_c\, e^{-(E_c - F_n)/kT} = n_i\, e^{(F_n - E_i)/kT} \qquad (14-32)$$

$$p = N_v\, e^{-(F_p - E_v)/kT} = n_i\, e^{(E_i - F_p)/kT} \qquad (14-33)$$

where N_c and N_v are the effective density of states at CB and VB edges, respectively, and F_n, F_p are quasi-Fermi levels for electrons and holes, respectively. E_i is the intrinsic Fermi level midway in the band gap, n_i is the intrinsic concentration, k is Boltzmann constant and T is temperature in degrees Kelvin. F_n in the neutral region is essentially the same as the equilibrium Fermi level E_{Fn}, since the electron concentration on the n side is equal to its equilibrium value n_0. Thus, due to heavy injection of electrons across the junction, the electron concentration begins at a high value near the junction and decays exponentially to its equilibrium values n_{p_o} deep into the p material. Therefore, F_n drops from E_{Fn} to E_{Fp} within the inversion region. (Fig.14.9). The separation of F_n and F_p at any point is a measure of the departure from equilibrium. In the inversion region, for the case of heavy doping, where Fermi level lies within the CB and VB, F_n and F_p are separated by an energy difference greater than the band gap (Fig. 14.10).

Population inversion exists for transitions between a level in the CB (from E_c to F_n) to any level in the VB (from F_p to E_v). Thus, for any given transition energy $h\nu$ in a semiconductor, population inversion exists when

$$(F_n - F_p) > h\nu \qquad (14-34)$$

The minimum requirement for population inversion occurs for photons with $h\nu = E_c - E_v = E_g$. Thus, we require

$$F_n - F_p > E_g \qquad (14-35)$$

since F_n and F_p lie within their respective bands (Fig.14.9). Stimulated emission can dominate over a range of transitions from $h\nu = F_n - F_P$ to $h\nu = E_g$. The dominant transitions for laser action are determined by the resonant cavity and the a strong radiation occurs near $h\nu = E_g$.

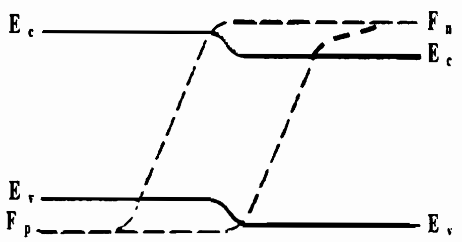


Fig. 14.8 Quasi Fermi levels in a degenerate (heavily doped) pn junction under forward bias

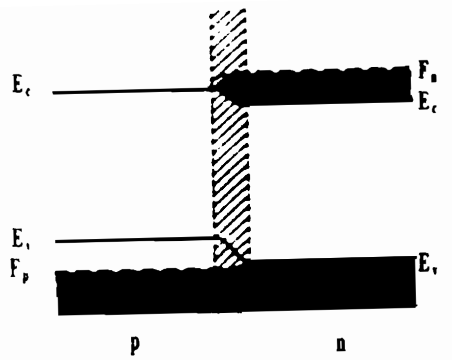


Fig. 14.9 Band diagram of a pn junction laser under injection in heavy forward bias. The cross hatched region is the inversion region formed near the junction

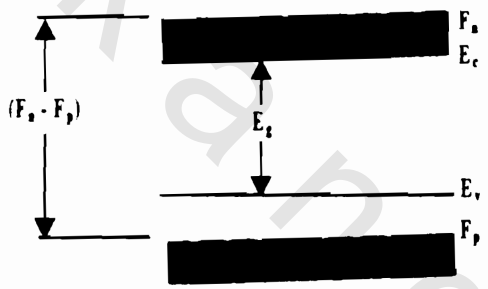


Fig.14.10 A simplified band diagram in the inversion region

The lasing action may be increased by increasing the bias current and the bias voltage. We note that there is a range for $h\nu$ (from E_g to $F_n - F_p$). These are the outside limits of the laser spectra. Fig. 14.11 shows the effect of increasing the forward voltage on F_n and F_p. Fig. 14.12 illustrates a typical plot of emission intensity versus photon energy for a semiconductor laser. At low current levels (Fig. 14.12a), a spontaneous emission spectrum containing energies with range $E_g < h\nu < F_n - F_p$ is obtained. As the current is increased to the point when significant population inversion exists, stimulated emission occurs at frequencies corresponding to the cavity modes (Fig. 14.12b). These modes correspond to successive numbers of integral λ/2 fitted within the cavity (eqn. 14-31). At a higher current level, a dominant mode will prevail (Fig. 14.12c). This very intense mode represents the main laser output which is almost a monochromatic radiation superimposed on a relatively weak radiation background (due to spontaneous emission).

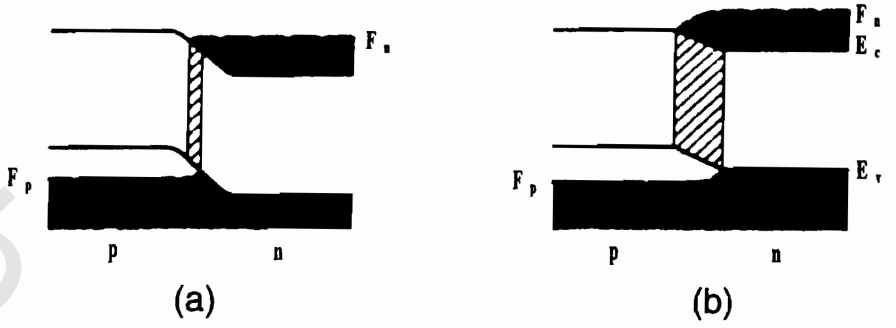


Fig.14.11 Increase of inversion region width with increasing bias current
a) small forward voltage b) large forward voltage

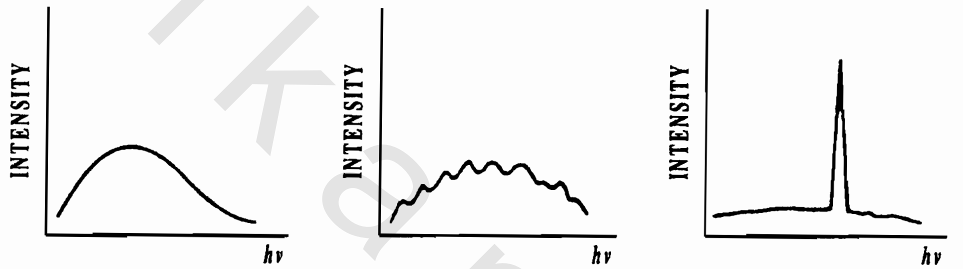


Fig.14.12 Illustrative semiconductor laser emission spectra
a) below threshold b) at threshold c) dominant mode above threshold

14.7 Photoconductors:

We have discussed solid state light sources, namely, LED and semiconductor laser. We want now to discuss photodetectors. A photodetector is a transducer which converts an optical signal to an electrical signal. Hence, the information embedded in the optical signal may be retrieved. The ability to use a semiconductor as a detector depends on using a property in the semiconductor which changes with light. Hence, by measuring the change in this property, the optical signal may be "detected".

We will discuss here two types of photodetectors, namely, photoconductor and photodiode. In a photoconductor, conductivity σ_o at thermal equilibrium may be expressed as

$$\sigma_0 = q\mu_n n_0 + q\mu_p p_0 \qquad (14-36)$$

Due to light, extra generation of electron - hole pairs results, such that - according to eqn. (14-16) - we have

$$\frac{d\,\delta n}{dt} = g_\phi - \frac{\delta\, n}{\tau}, \qquad (14-37)$$

Where g_ϕ is the rate of electron-hole pair generation due to light (or the rate of absorption of photons) per unit volume. At steady state, the excess electron concentration $\delta n = \Delta n = \Delta p$, $\Delta n = \Delta p$, such that

$$\Delta n = \Delta p = g_\phi \tau \qquad (14-38)$$

Hence, conductivity may now be expressed as $\sigma = \sigma_0 + \Delta\sigma_\phi$, where $\Delta\sigma_\phi$ is the photoconductivity, and is given by

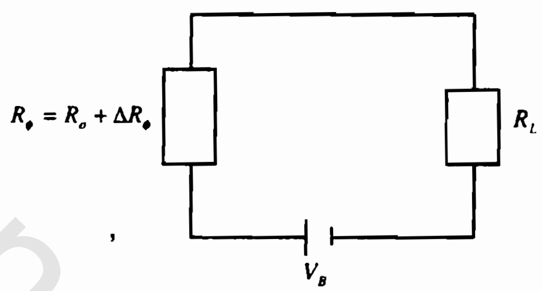
$$\Delta\sigma_\phi = q(\mu_n + \mu_P) g_\phi \tau \qquad (14-39)$$

Ex. 14.2:

Obtain the small signal equivalent circuit for a photoconductor at low frequency.

Solution:

The circuit shows two resistors R_ϕ and R_L. R_ϕ is the light-dependent resistor and R_L is the load resistor



The current i is given by

$$i = \frac{V_B}{R_\phi + R_L} = \frac{V_B}{(R_0 + \Delta R_\phi) + R_L} ,$$

where R_o is the dark resistance.

Hence,

$$i = \frac{V_B}{R_o + R_L} \frac{1}{1 + \frac{\Delta R_\phi}{R_0 + R_L}} = I_0 \frac{1}{1 + \frac{\Delta R_\phi}{R_0 + R_L}} , \qquad (14-40)$$

$$I_0 = \frac{V_B}{R_o + R_L} , \qquad (14-41)$$

where I_o is the bias current. Thus, for small signal, $\frac{\Delta R_\phi}{R_0 + R_L} << 1$,

$$i = I_0 + \Delta i_\phi = I_0 \left(1 - \frac{\Delta R_\phi}{R_0 + R_L}\right) \qquad (14-42)$$

$$\Delta i_\phi = -\frac{I_0 \Delta R_\phi}{R_0 + R_L} \qquad (14-43)$$

Thus, we obtain the small signal equivalent circuit at low frequency in the form of a voltage sources $I_o \Delta R_\phi$ and an internal resistor R_0.

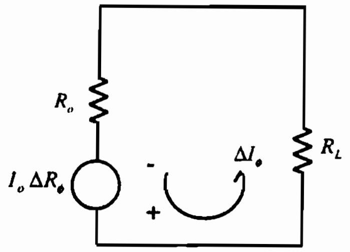


Fig. 14.13 Small signal equivalent circuit of a photoconductor at low frequency

14.8 Photodiodes:

Junction diodes may be used as photodetectors. They are called photodiodes. They are characterized by high sensitivity and high speed of response. We may describe the total current in a photodiode by the relation

$$I = I_s(e^{V/V_T} - 1) - I_\phi \qquad (14-44)$$

$$= qA\left(\frac{L_P}{\tau_P} p_n + \frac{L_n}{\tau_n} n_P\right)(e^{V/V_T} - 1) - I_\phi, \qquad (14-45)$$

$$I_\phi = qAg_\phi(L_P + L_n + W), \qquad (14-46)$$

where L_n, L_p are the diffusion lengths for electrons and holes, respectively, W is the width of the transition region and V_T is kT/q. From eqn. (14-44), we see that the IV characteristic of a photodiode is that of a regular diode but shifted by $-I_\phi$ (Fig. 14.14).

An open circuit voltage V_{OC} results in a photodiode when $I = 0$. From eqn. (14-44),

$$V_{oc} = V_T \, ln\frac{I_\phi + I_s}{I_s} \qquad (14-47)$$

This is called photovoltaic voltage of a photodiode.

A photodiode may be further developed into a p-i-n photodiode. It is a pn junction with an intrinsic (lightly doped) layer sandwiched between the p and n layers. This structure (Fig. 14.15) serves to extend the width of the depletion region, hence, increase the width of the region available for capturing light. Also, increasing the width of the depletion layer reduces the junction capacitance, and thereby, the RC time constant (see prob. 14-12), and this increases the bandwidth. In most optical detection applications, the detector speed of respose is critical. For example, if the photodiode is to respond to a series of light pulses (1ns apart), the photogenerated minority carriers must diffuse to the junction and be swept across the other side in a time much less than 1ns. The carrier diffusion step is the most time consuming. Therefore, it is desirable to have the width of the depletion region W be large enough, within the lightly doped side of both $p-i$ and $n-i$ junctions, so that most of the photons are absorbed within W rather than in the neutral p and n regions. When an electron-hole pair is created in the depletion region, the electric field sweeps the electron to the n side and the hole to the p side. Since this carrier drift occurs in a very short time the response of the photodiode can be quite fast. In a $p-i-n$ diode, the field under reverse bias appears almost entirely across the i region.

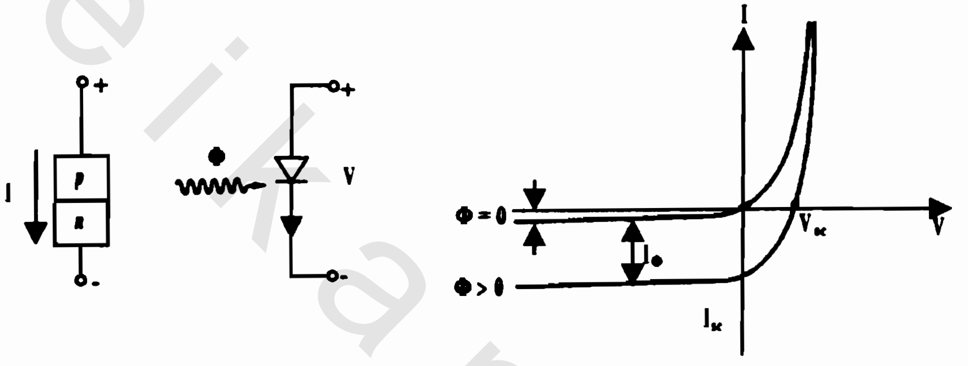


Fig. 14.14 Photodiode and its I-V characteristic

As the carrier lifetime within the i region is made long - compared with the drift time - most of the photogenerated carriers will be collected by the n and p regions before recombination. We must note that W must not be too wide, or the drift time would be too long, reducing the speed of response. If this reverse biased diode is operated in its avalanche (breakdown) mode, then it is called (breakdown) avalanche photodiode. It is most suitable for the detection of low-level optical signals.

14.9 Fiber optics:

The transmission of optical signals from source to detector may be either guided or unguided. Guided transmission implies that the optical signal is contained in a light pipe, (a waveguide for optical frequencies). The basic structure of an optical fiber is an outer layer of pure fused silica surrounding a core of glass with a higher index of refraction. Such a step index fiber contains (or traps) the light beam in the central core with little loss at the surface. The light is transmitted along the length of the fiber by internal reflections at the step of the refractive index.

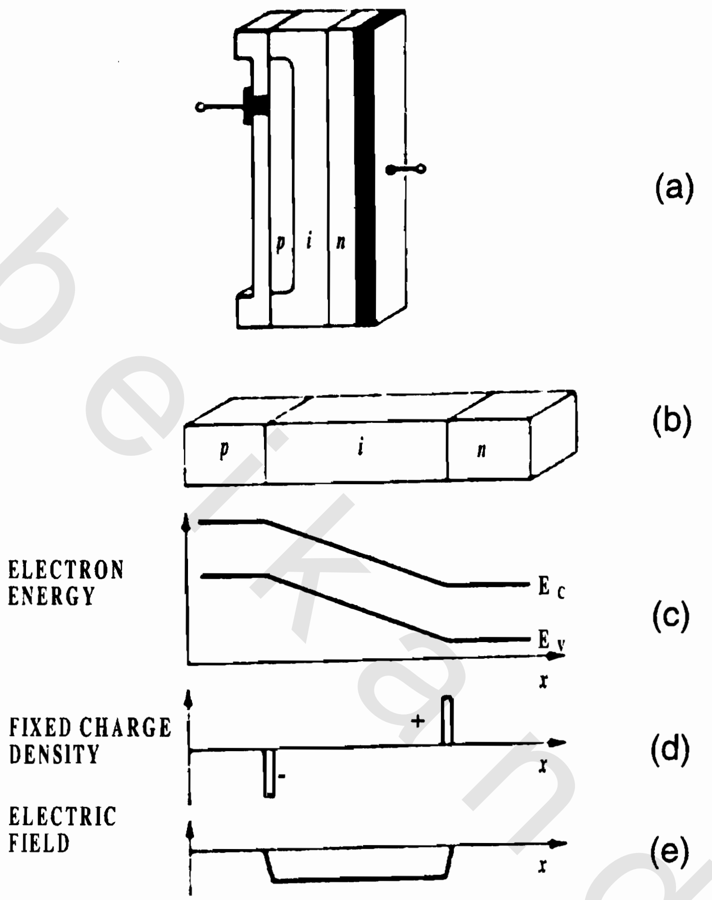


Fig. 14.15 ***p-i-n*** **diode**
a) structure b) simplified model
c) energy diagram d) fixed charge density (symmetric case)
e) electric field distribution (symmetric case)

To gain basic insight into optical waveguides, we use a simple structure of two parallel infinite planar mirrors separated by a distance d. The mirrors are assumed ideal. A ray of light making an angle θ with the mirror (in $y-z$ plane) reflects, and bounces back and forth between the mirrors without loss of energy. The ray is, thus, guided along the z axis. We now associate with the ray a transverse electromagnetic (TEM) wave. The electric field is parallel to the mirror. Each reflection is accomplished by a π phase shift (to maintain zero electric field at the surface of the mirror). At each point within the waveguide, we have TEM waves traveling in the upward direction at an angle θ, and others traveling in the downward direction at an angle $-\theta$. All waves are polarized in the x direction.

We now impose the self-consistency condition by requiring that as the wave reflects twice it reproduces itself (Fig.14.16), so that we have only two distinct plane waves. Fields that satisfy this condition are called eigenmodes (fields that maintain the same transverse distribution and polarization at all distances along the waveguide axis.

The phase shift encountered by the original wave in traveling from A to B must be equal to (or different by an integer multiple of 2π) from that encountered when the wave reflects and travels from A to C and reflects again. Accounting for a phase shift of π at each reflection, we have

$$2\pi \frac{\overline{AC}}{\lambda} - 2\pi - 2\pi \frac{\overline{AB}}{\lambda} = 2\pi q, \quad q = 0,1,2 \qquad (14-48)$$

But

$$\overline{AC} - \overline{AB} = 2d \sin\theta\,, \qquad (14-49)$$

where d is the distance between the mirrors (prob 14.14).
Thus,

$$\frac{2\pi}{\lambda}(2d\sin\theta) = 2\pi(q+1) = 2\pi m\,,\ m = 1,2,.... \qquad (14-50)$$

The self-consistency condition is satisfied only for certain bounce angles:

$$\sin\theta_m = m(\lambda / 2d)\,, \qquad (14-51)$$

Each integer m corresponds to a bounce angle θ_m, and the corresponding field is called the m^{th} mode. The $m=1$ mode has the smallest angle $\theta_1 = \sin^{-1}(\lambda/2d)$. Modes with larger m are composed of plane wave components, which are more oblique.

Now consider a planar dielectric waveguide, which is a slab of dielectric material of width d and refractive index n_1, surrounded by media of lower refractive indices. The inner medium is called the core, and the outer medium is called the cladding of refractive index n_2. All materials are assumed lossless (Fig. 14.17).

Light rays making angles θ with the z axis - in the yz plane -undergo multiple reflections at the slab boundaries, provided that θ is smaller than $\theta_{\max}$, which is the complement of $\psi_{\min}$, where $\psi_{\min}$ is the critical angle at the n_1/n_2 interface for grazing condition, i.e.,

$$\psi_{\min} = \sin^{-1}\frac{n_2}{n_1}.$$

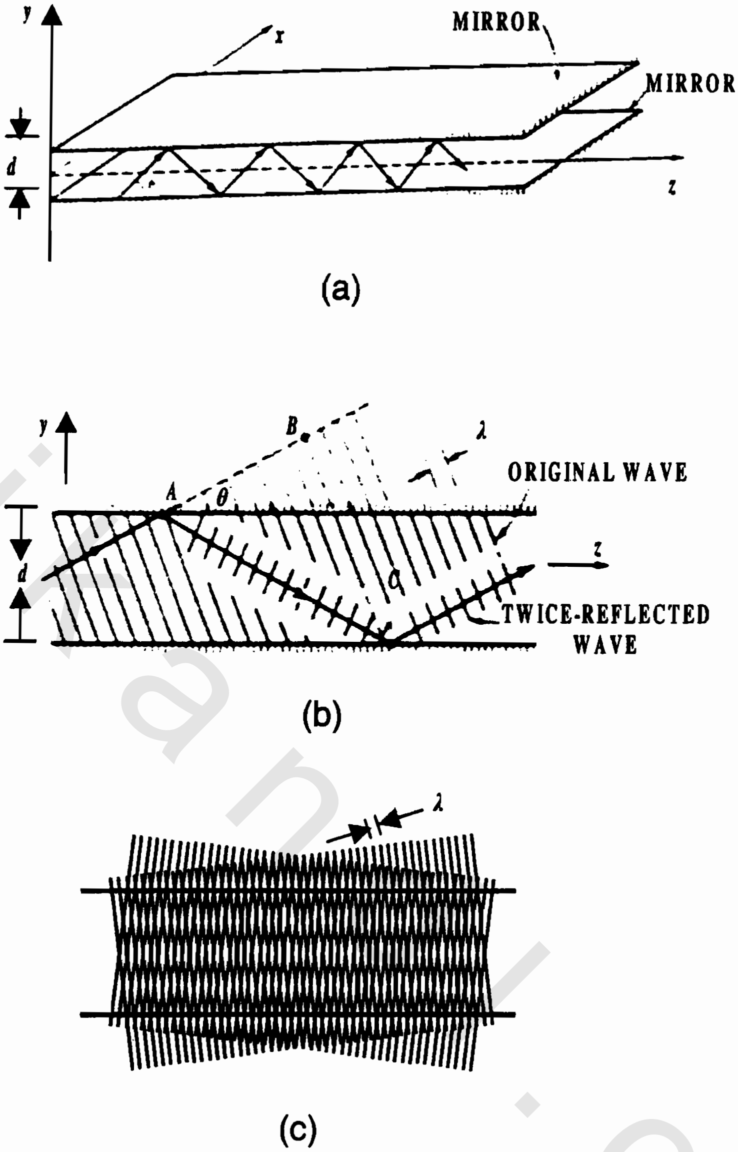


Fig. 14.16 Planar mirror waveguide
a) structure
b) conditions for self-consistency
c) standing wave pattern

Thus

$$\theta_{max} = \frac{\pi}{2} - \psi_{min}$$

$$\theta_{max} = \frac{\pi}{2} - \sin^{-1}\frac{n_2}{n_1} = \cos^{-1}\frac{n_2}{n_1} \qquad (14-52)$$

Rays making larger angles refract and lose portion of their power at each reflection. A phase shift φ_r is introduced at each reflection instead of π. Thus, eqn. (14.50) is modified to

$$\frac{2\pi}{\lambda}(2d\sin\theta) - 2\varphi_r = 2\pi m \qquad (14-53)$$

The reflection phase shift φ_r is a function of θ, and also depends on the polarization of the incident wave. In the TE case,

$$\tan\frac{\varphi_r}{2} = \left(\frac{\sin^2\theta_{max}}{\sin^2\theta} - 1\right)^{1/2}, \qquad (14-54)$$

where φ_r varies from π to 0, as θ varies from 0 to θ_{max}. We may rewrite eqn. (14-53) as

$$\tan\left(\frac{\pi d\sin\theta}{\lambda} - m\frac{\pi}{2}\right) = \left(\frac{\sin^2\theta_{max}}{\sin^2\theta} - 1)^{1/2}\right) \qquad (14-55)$$

This is a transcendental equation in one variable $\sin\theta$. Its solution yields the bounce angles θ_m of the modes (Fig. 14.18).

To determine the number of TE modes supported by the dielectric waveguide, we examine Fig. 14.18. The abscissa is divided into equal intervals of width $(\lambda/2d)$, each of which contains a mode marked by a filled circle for the intersection of RHS and LHS of eqn. (14-55). This extends over angles for which $\sin\theta \le \sin\theta_{max}$. The number of TE modes is, therefore, the smallest integer greater than $\frac{\sin\theta_{max}}{(\lambda/2d)}$, so that

$$M \hat{=} \frac{\sin\theta_{max}}{(\lambda/2d)} \qquad (14-56)$$

The symbol $\hat{=}$ denotes that $\frac{\sin\theta_{max}}{(\lambda/2d)}$ is increased to the nearest integer.

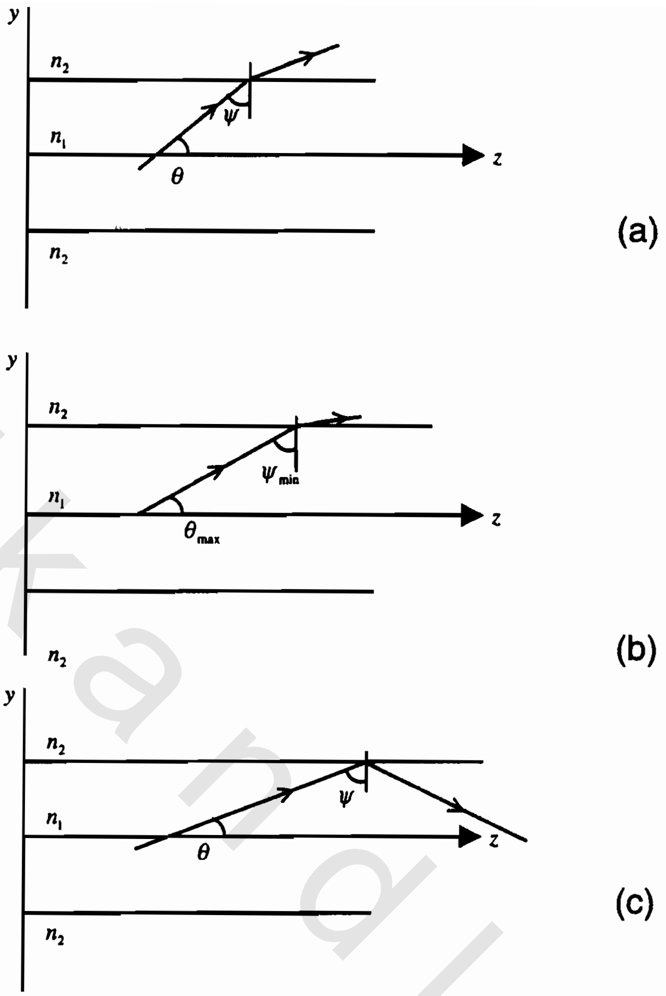


Fig. 14.17 Planar dielectric waveguide

a) leaky ray $\theta > \theta_{max}$, $\psi < \psi_{min}$ b) grazing condition $\theta = \theta_{max}$, $\psi = \psi_{min}$

c) total reflection $\theta < \theta_{max}$, $\psi > \psi_{min}$

Substituting $\cos\theta_{max} = \dfrac{n_2}{n_1}$ into eqn. (14-56),

$$M \hat{=} 2\frac{d}{\lambda} NA \quad (14-57)$$

$$NA = (n_1^2 - n_2^2)^{1/2} \quad (14-58)$$

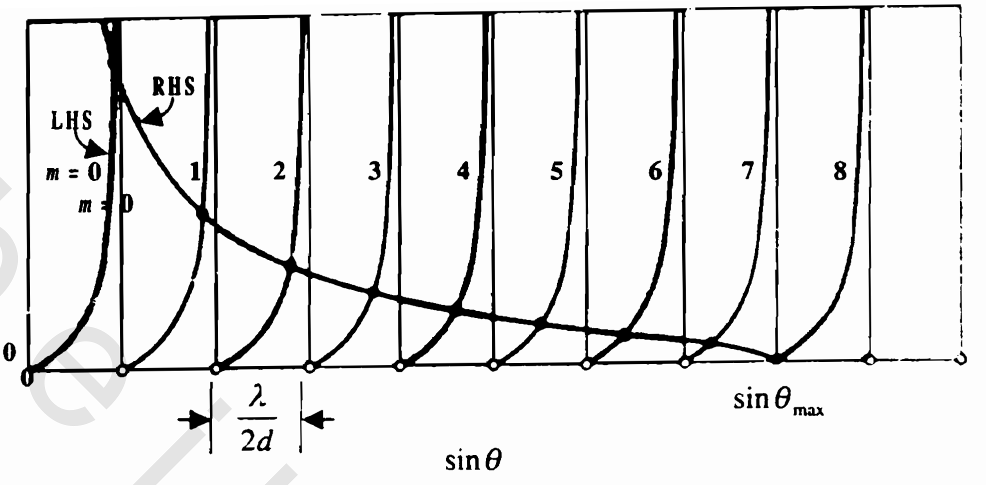


Fig. 14.18 Solution for $\sin\theta_m$ in planar dielectric waveguide

NA is called the numeral aperture of the waveguide. It is the sine of the angle of acceptance of rays from air into the slab, (see Ex. 14.3). Using eqns. (14-56) and (14-57), when $\lambda/2d > \sin\theta_{max}$, or $(2d/\lambda_0)NA < 1$, only one mode is allowed, and the waveguide is then a single mode waveguide (the slab is thin or λ is long).

In a circular optical fiber, the analysis is more complex, and the number of modes is approximately given by

$$M \cong 0.5\left(\frac{\pi dNA}{\lambda}\right), \qquad (14-59)$$

where d is the diameter of the core. As the diameter of the core is reduced, fewer modes propagate. When eventually the diameter is close to the wavelength of light, then only a single mode propagates.

Ex. 14.3:

Find the maximum launch angle $\hat{\theta}_1$ for the fiber structure shown

Solution:

At the air / glass interface,

$$\sin\hat{\theta}_1 = n_1 \sin\hat{\theta}_2 = n_1 \sin\theta_{max} \qquad (14-60)$$

At the glass / dielectric interface,

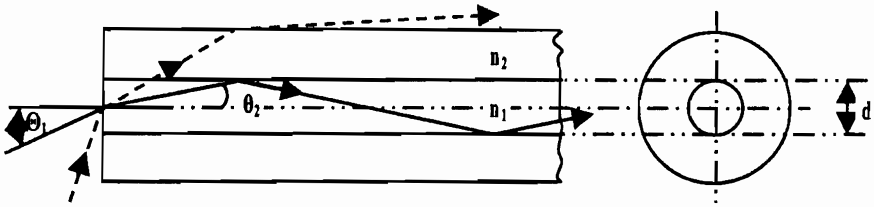


Fig. 14.18 Numerical aperture calculation

$$n_1 \sin\left(\frac{\pi}{2} - \hat{\theta}_2\right) = n_2 \sin\frac{\pi}{2} = n_2 \qquad (14-61)$$

or

$$n_1 \cos\hat{\theta}_2 = n_2 \qquad (14-62)$$

$$\cos\hat{\theta}_2 = n_2 / n_1, \qquad (14-63)$$

where $\hat{\theta}_2$ is the complement of the critical angle at the n_1/n_2 interface. From eqns. (14-60) and (14-63),

$$\sin\hat{\theta}_1 = n_1\sqrt{1-\cos^2\hat{\theta}_2}$$
$$= n_1\sqrt{1-(n_2/n_1)^2}$$
$$= \sqrt{n_1^2 - n_2^2} \quad , \quad n_1 > n_2$$
$$= NA$$

In other words, the numerical aperture is the sine of the maximum launch angle of the ray for total internal reflection in the optical waveguide, or

$$NA = \sqrt{n_1^2 - n_2^2} = \sin\hat{\theta}_1 \qquad (14-64)$$

As long as the launch angle remains below $\sin^{-1}(NA)$, the ray is confined in the optical waveguide (Fig. 14.20).

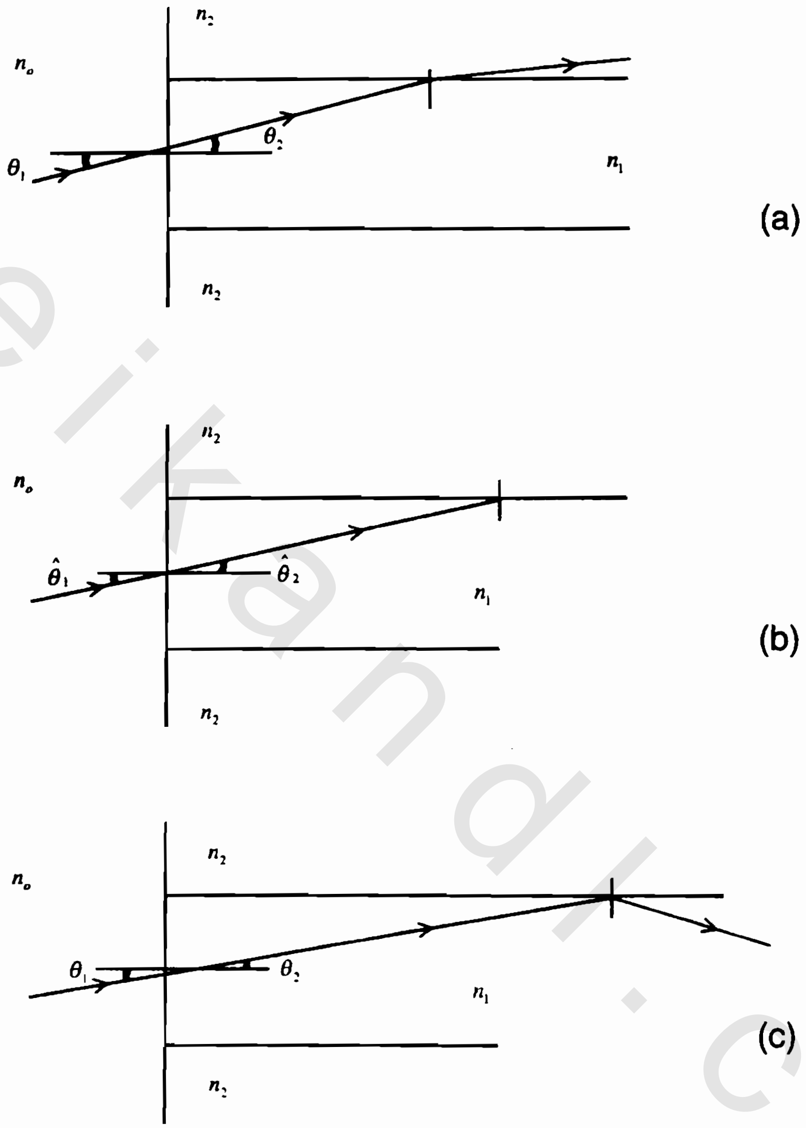


Fig. 14.20 Launching a ray in an optical waveguide

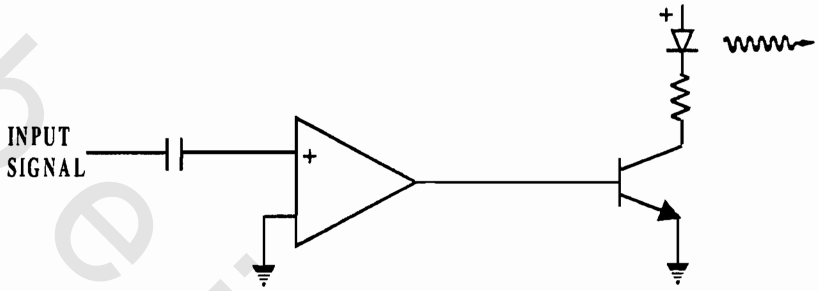
a) general incidence – leaky ray b) critical (grazing) condition

b) working condition, $\theta_1 < \hat{\theta}_1$

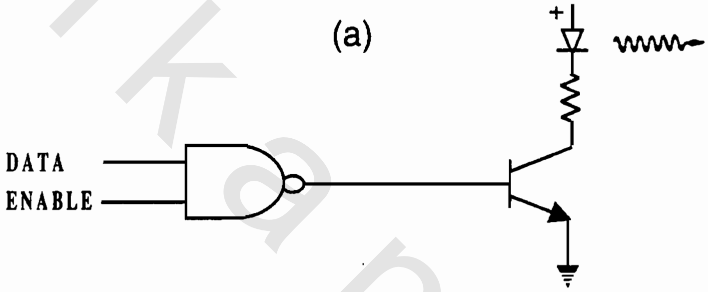
Problems:

1- Starting from eqn. (14.6), derive eqn. (14.26). Then, sketch the LED resposivity as a function of modulating frequency.

2- Analyze the LED modulating circuits shown



(a)



(b)

3- Show that population inversion cannot be obtained in a two- level system.

4- Write down the rate equations governing the population in both 3-level and 4-level laser systems. Discuss the best conditions for lasing.

5- From Einstein's coefficients. obtain the photon density at thermal equilibrium. What can you conclude?

6- Show how eqn. (14-31) may be derived, and explain its physical significance.

7- If the index of refraction n depends on wavelength in eqn. (14-31), find the rate of change of m with respect to λ, and hence, find an expression for the separation in wavelength between successive modes.

8- Obtain the small signal equivalent circuit of a photoconductor at high frequency.

9- If the optical signal is in the form of a square wave, obtain the output.
   a) for low frequency
   b) for high frequency
   What do you conclude?

10- Discuss the pros and cons for increasing τ on the responsivity, the speed of response and the bandwidth of a photoconductor.
11- Verify eqns. (14-44) to (14-46).
12- Obtain the low and high frequency equivalent circuits of a photodiode.
13- Show how a photodiode may be used as a solar cell. Obtain the I-V characteristic of a solar cell.
14- Verify eqn. (14-50).

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