Design of Optical Fiber Communication System

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ABSTRACT

**Design of Optical Fiber Communication System**

Senior project submitted to the department of (Electrical) Engineering

Important for the design and understanding of optoelectronic integrated devices (OEIDs) is the development of an analytical mathematical model describing the dynamic and static characteristics, or optical and electrical characteristics. This challenge has been taken up by a number of authors whose efforts contribute to this section. Below, in this report, the transient response of the excited photocurrent inside an optoelectronic integrated device (OEID) is analyzed. The device is composed of a heterojunction phototransistor (HPT) and a laser diode (LD). The expressions describing the transient response of the output, the rise time, and the output derivative are derived. The effect of the various device parameters on the transient response is outlined. The results show that the transient response of these types of devices is strongly depend on the optical feedback inside the device and it is found that the device works in two different modes, which are: amplification, for small optical feedback coefficient, switching, for high optical feedback coefficient. This type of model can be exploited as an optical amplifier, optical switching device and other applications.
DEDICATION

To my Father, ................., who, through his financial and moral support was the source of inspiration and the mainstay in my attaining an education, I dedicate this project.
ACKNOWLEDGEMENT

This project was written under the direction and supervision of Prof. Dr. Shaban M. Eladl. We would like to express our sincere appreciation to him for the interest and assistance given to me.
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Chapter 1

Introduction

A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Information is often carried by an electromagnetic carrier wave whose frequency can vary from a few megahertz to several hundred Terahertz. Optical communication systems use high carrier frequencies (~100 THz) in the visible or near-infrared region of the electromagnetic spectrum. They are sometimes called light wave systems to distinguish them from microwave systems, whose carrier frequency is typically smaller by five orders of magnitude (~1 GHz). Fiber-optic communication systems are light wave systems that employ optical fibers for information transmission. Such systems have been deployed worldwide since 1980 and have indeed revolutionized the technology behind telecommunications. Indeed, the light wave technology, together with microelectronics, is believed to be a major factor in the advent of the “information age.” The objective of this book is to describe fiber-optic communication systems in a comprehensive manner. The emphasis is on the fundamental aspects, but the engineering issues are also discussed. The purpose of this introductory chapter is to present the basic concepts and to provide the background material.

1.1 Historical Perspective

The use of light for communication purposes dates back to antiquity if we interpret optical communications in a broad sense [1]. Most civilizations have used mirrors, fire beacons, or smoke signals to convey a single piece of information (such as victory in a war). Essentially the same idea was used up to the end of the eighteenth century through signaling lamps, flags, and other semaphore devices. The idea was extended further, following a suggestion of Claude Chappe in 1792, to transmit mechanically coded messages over long distances (~100 km) by the use of intermediate relay stations [2], acting as regenerators or repeaters in the modern-day language. The first such “optical telegraph” was put in service between Paris and Lille (two French cities about 200 km apart) in July 1794. By 1830, the network had expanded throughout Europe [1]. The role of light in such systems was simply to make the coded signals visible so that they could be intercepted by the relay stations. The optomechanical communication systems of the nineteenth century were inherently slow. In modern-day terminology, the effective bit rate of such systems was less than 1 bit per second (\(B < 1 \text{ b/s}\)).

1.2. OPTICAL COMMUNICATION SYSTEMS

Phase-shift keying (PSK), depending on whether the amplitude, frequency, or phase of the carrier wave is shifted between the two levels of a binary digital signal. The simplest technique consists of
simply changing the signal power between two levels, one of which is set to zero, and is often called on–off keying (OOK) to reflect the on–off nature of the resulting optical signal. Most digital light wave systems employ OOK in combination with PCM.

1.2 Optical Communication Systems

As mentioned earlier, optical communication systems differ in principle from microwave systems only in the frequency range of the carrier wave used to carry the information. The optical carrier frequencies are typically ~200 THz, in contrast with the microwave carrier frequencies (~1 GHz). An increase in the information capacity of optical communication systems by a factor of up to 10,000 is expected simply because of such high carrier frequencies used for light wave systems. This increase can be understood by noting that the bandwidth of the modulated carrier can be up to a few percent of the carrier frequency. Taking, for illustration, 1% as the limiting value, optical communication systems have the potential of carrying information at bit rates ~1 Tb/s. It is this enormous potential bandwidth of optical communication systems that is the driving force behind the worldwide development and deployment of light wave systems. Current state-of-the-art systems operate at bit rates ~10 Gb/s, indicating that there is considerable room for improvement.

Figure 1.1 shows a generic block diagram of an optical communication system. It consists of a transmitter, a communication channel, and a receiver, the three elements common to all communication systems. Optical communication systems can be classified into two broad categories: guided and unguided. As the name implies, in the case of guided light wave systems, the optical beam emitted by the transmitter remains spatially confined. Since all guided optical communication systems currently use optical fibers, the commonly used term for them is fiber-optic communication systems. The term light wave system is also sometimes used for fiber-optic communication systems, although it should generally include both guided and unguided systems.

In the case of unguided optical communication systems, the optical beam emitted by the transmitter spreads in space, similar to the spreading of microwaves. However, unguided optical systems are less suitable for broadcasting applications than microwave systems because optical beams spread mainly in the forward direction (as a result of their short wavelength). Their use generally requires accurate pointing between the transmitter and the receiver. In the case of terrestrial propagation, the signal in unguided systems can deteriorate considerably by scattering within the atmosphere. This problem, of course, disappears in free-space communications above the earth atmosphere (e.g., inter satellite communications). Most terrestrial applications make use of fiber-optic communication systems. This report does not consider unguided optical communication systems.

The application of optical fiber communications is in general possible in any area that requires transfer of information from one place to another. However, fiber-optic communication systems have been developed mostly for telecommunications applications. This is understandable in view of the existing worldwide telephone networks which are used to transmit not only voice signals but also computer data and fax messages. The telecommunication applications can be broadly classified into two categories, long-haul and short-haul, depending on whether the optical signal is transmitted over relatively long or short distances compared with typical intercity distances (~100 km). Long-haul telecommunication systems require high-capacity trunk lines and benefit most by the use of fiber-optic light wave systems. Indeed, the technology behind optical fiber communication is often driven by
long-haul applications. Each successive generation of light wave systems is capable of operating at higher bit rates and over longer distances. Periodic regeneration of the optical signal by using repeaters is still required for most long-haul systems. However, more than an order-of-magnitude increase in both the repeater spacing and the bit rate compared with those of coaxial systems has made the use of light wave systems very attractive for long-haul applications. Furthermore, transmission distances of thousands of kilometers can be realized by using optical amplifiers.

Short-haul telecommunication applications cover intra city and local-loop traffic. Such systems typically operate at low bit rates over distances of less than 10 km. The use of single-channel light wave systems for such applications is not very cost-effective, and multichannel networks with multiple services should be considered. The concept of a broadband integrated-services digital network requires a high-capacity communication system capable of carrying multiple services. The asynchronous transfer mode (ATM) technology also demands high bandwidths.

1.3 Light wave System Components

The generic block diagram of Fig. 1.2 applies to a fiber-optic communication system, the only difference being that the communication channel is an optical fiber cable. The other two components, the optical transmitter and the optical receiver, are designed to meet the needs of such a specific communication channel. In this section we discuss the general issues related to the role of optical fiber as a communication channel and to the design of transmitters and receivers.

1.3.1 Optical Fibers as a Communication Channel

The role of a communication channel is to transport the optical signal from transmitter to receiver without distorting it. Most light wave systems use optical fibers as the communication channel because silica fibers can transmit light with losses as small as 0.2 dB/km. Even then, optical power reduces to only 1% after 100 km. For this reason, fiber losses remain an important design issue and determines the repeater or amplifier spacing of a long-haul light wave system. Another important design issue is fiber dispersion, which leads to broadening of individual optical pulses with propagation. If optical pulses spread significantly outside their allocated bit slot, the transmitted signal is severely degraded. Eventually, it becomes impossible to recover the original signal with high
accuracy. The problem is most severe in the case of multimode fibers, since pulses spread rapidly (typically at a rate of ~10 ns/km) because of different speeds associated with different fiber modes. It is for this reason that most optical communication systems use single-mode fibers. Material dispersion (related to the frequency dependence of the refractive index) still leads to pulse broadening (typically <0.1 ns/km), but it is small enough to be acceptable for most applications and can be reduced further by controlling the spectral width of the optical source.

1.3.2 Optical Transmitters

The role of an optical transmitter is to convert the electrical signal into optical form and to launch the resulting optical signal into the optical fiber. Figure 1.3 shows the block diagram of an optical transmitter. It consists of an optical source, a modulator, and a channel coupler. Semiconductor lasers or light-emitting diodes are used as optical sources because of their compatibility with the optical-fiber communication channel; The optical signal is generated by modulating the optical carrier wave. Although an external modulator is sometimes used, it can be dispensed with in some cases, since the output of a semiconductor optical source can be modulated directly by varying the injection current. Such a scheme simplifies the transmitter design and is generally cost-effective. The coupler is typically a micro lens that focuses the optical signal onto the entrance plane of an optical fiber with the maximum possible efficiency. The launched power is an important design parameter. One can increase the amplifier (or repeater) spacing by increasing it, but the onset of various nonlinear effects limits how much the input power can be increased. The launched power is often expressed in “dBm” units with 1 mW as the reference level. The general definition is (see Appendix A)

\[
power(dBm) = 10 \log_{10} \left( \frac{\text{power}}{1mW} \right).
\]  

(1.3.1)
Thus, 1 mW is 0 dBm, but 1 µW corresponds to −30 dBm. The launched power is rather low (<−10 dBm) for light-emitting diodes but semiconductor lasers can launch powers ∼ 10 dBm. As light-emitting diodes are also limited in their modulation capabilities, most light wave systems use semiconductor lasers as optical sources. The bit rate of optical transmitters is often limited by electronics rather than by the semiconductor laser itself. With proper design, optical transmitters can be made to operate at a bit rate of up to 40 Gb/s.

### 1.3.3 Optical Receivers

An optical receiver converts the optical signal received at the output end of the optical fiber back into the original electrical signal. Figure 1.3 shows the block diagram of an optical receiver. It consists of a coupler, a photo detector, and a demodulator. The coupler focuses the received optical signal onto the photo detector. Semiconductor photodiodes are used as photo detectors because of their compatibility with the whole system; The design of the demodulator depends on the modulation format used by the light wave system. Most light wave systems employ a scheme referred to as “intensity modulation with direct detection” (IM/DD). Demodulation in this case is done by a decision circuit that identifies bits as 1 or 0, depending on the amplitude of the electric signal. The accuracy of the decision circuit depends on the SNR of the electrical signal generated at the photo detector.
Chapter 2

Optical Fibers

The phenomenon of total internal reflection, responsible for guiding of light in optical fibers, has been known since 1854. Although glass fibers were made in the 1920s, their use became practical only in the 1950s, when the use of a cladding layer led to considerable improvement in their guiding characteristics. Before 1970, optical fibers were used mainly for medical imaging over short distances. Their use for communication purposes was considered impractical because of high losses (~1000 dB/km). However, the situation changed drastically in 1970 when, following an earlier suggestion [9], the loss of optical fibers was reduced to below 20 dB/km [10]. Further progress resulted by 1979 in a loss of only 0.2 dB/km near the 1.55-µm spectral region. The availability of low-loss fibers led to a revolution in the field of lightwave technology and started the era of fiber-optic communications. Several books devoted entirely to optical fibers cover numerous advances made in their design and understanding. This chapter focuses on the role of optical fibers as a communication channel in light wave systems. In Section 2.1 we use geometrical optics description to explain the guiding mechanism and introduce the related basic concepts.

2.1 Geometrical-Optics Description

In its simplest form an optical fiber consists of a cylindrical core of silica glass surrounded by a cladding whose refractive index is lower than that of the core. Because of an abrupt index change at the core–cladding interface, such fibers are called step-index fibers. In a different type of fiber, known as graded-index fiber, the refractive index decreases gradually inside the core. Figure 2.1 shows schematically the index profile and the cross section for the two kinds of fibers. Considerable insight in

Properties of optical fibers can be gained by using a ray picture based on geometrical optics. The geometrical-optics description, although approximate, is valid when the core radius ‘a’ is much larger than the light wavelength. When the two become comparable, it is necessary to use the wave propagation theory of Section 2.2.
2.1.1 Step-Index Fibers

Consider the geometry of Fig. 2.2, where a ray making an angle \( \theta \) with the fiber axis is incident at the core center. Because of refraction at the fiber–air interface, the ray bends toward the normal. The angle \( \theta \) of the refracted ray is given by

\[
\sin \theta = n_1 \sin \theta_i \quad (2.1.1)
\]

where \( n_1 \) and \( n_0 \) are the refractive indices of the fiber core and air, respectively. The refracted ray hits the core–cladding interface and is refracted again. However, refraction is possible only for an angle of incidence \( \phi \) such that \( \sin \phi < n_2/n_1 \). For angles larger than a critical angle \( \phi_c \), defined by

\[
\sin \phi_c = n_2/n_1 \quad (2.1.2)
\]

where \( n_2 \) is the cladding index, the ray experiences total internal reflection at the core–cladding interface. Since such reflections occur throughout the fiber length, all rays with \( \phi > \phi_c \) remain confined to the fiber core. This is the basic mechanism behind light confinement in optical fibers.

![Figure 2.2: Light confinement through total internal reflection in step-index fibers. Rays for which \( \phi < \phi_c \) are refracted out of the core.](image)

One can use Eqs. (2.1.1) and (2.1.2) to find the maximum angle that the incident ray should make with the fiber axis to remain confined inside the core. Noting that \( \theta r = \pi/2 - \phi_c \) for such a ray and substituting it in Eq. (2.1.1), we obtain

\[
\theta_0 \sin \theta_0 = n_1 \cos \phi_c = \left( n_1^2 - n_2^2 \right)^{1/2} \quad (2.1.3)
\]

In analogy with lenses, \( n_0 \sin \theta_0 \) is known as the numerical aperture (NA) of the fiber. It represents the light-gathering capacity of an optical fiber. For \( n_1 \approx n_2 \) the NA can be approximated by

\[
NA = n_1 (2\Delta)^{1/2} \quad (2.1.4)
\]

where \( \Delta \) is the fractional index change at the core–cladding interface. Clearly, \( \Delta \) should be made as large as possible in order to couple maximum light into the fiber. However, such fibers are not useful for the purpose of optical communications because of a phenomenon known as multipath dispersion or modal dispersion. Multipath dispersion can be understood by referring to Fig. 2.2, where different rays travel along paths of different lengths. As a result, these rays disperse in time at the output end of the fiber even if they were coincident at the input end and traveled at the same speed inside the fiber. A short pulse (called an impulse) would broaden considerably as a result of different path lengths. One can estimate the extent of pulse broadening simply by considering the shortest and longest ray paths. The shortest path occurs for \( \theta i = 0 \) and is just equal to the fiber length \( L \). The longest path occurs for \( \theta I \) given by Eq. (2.1.3) and has a length \( L/\sin \phi_c \). By taking the velocity of propagation \( v = c/n_1 \), the time delay is given by

\[
\Delta T = n_1/c \left( \frac{L}{\sin \phi_c} - L \right) = L \frac{n_1^2}{c} \Delta \quad (2.1.5)
\]
The time delay between the two rays taking the shortest and longest paths is a measure of broadening experienced by an impulse launched at the fiber input. We can relate $\Delta T$ to the information-carrying capacity of the fiber measured through the bit rate $B$. Although a precise relation between $B$ and $\Delta T$ depends on many details, such as the pulse shape, it is clear intuitively that $\Delta T$ should be less than the allocated bit slot ($TB = 1/B$). Thus, an order-of-magnitude estimate of the bit rate is obtained from the condition $B\Delta T < 1$. By using Eq. (2.1.5) we obtain

$$BL < \frac{n_2^2 c}{n_1^2 \Delta}$$

(2.1.6)

This condition provides a rough estimate of a fundamental limitation of step-index fibers. As an illustration, consider an unclad glass fiber with $n_1 = 1.5$ and $n_2 = 1$. The bit rate–distance product of such a fiber is limited to quite small values since $BL < 0.4$ (Mb/s)-km. Considerable improvement occurs for cladded fibers with a small index step. Most fibers for communication applications are designed with $\Delta < 0.01$. As an example, $BL < 100$ (Mb/s)-km for $\Delta = 2 \times 10^{-5}$. Such fibers can communicate data at a bit rate of 10 Mb/s over distances up to 10 km and may be suitable for some local-area networks.

Two remarks are in order concerning the validity of Eq. (2.1.6). First, it is obtained by considering only rays that pass through the fiber axis after each total internal reflection. Such rays are called meridional rays. In general, the fiber also supports skew rays, which travel at angles oblique to the fiber axis. Skew rays scatter out of the core at bends and irregularities and are not expected to contribute significantly to Eq. (2.1.6). Second, even the oblique meridional rays suffer higher losses than paraxial meridional rays because of scattering. Equation (2.1.6) provides a conservative estimate since all rays are treated equally. The effect of intermodal dispersion can be considerably reduced by using graded-index fibers, which are discussed in the next subsection.

- **2.1.2 Graded-Index Fibers**

The refractive index of the core in graded-index fibers is not constant but decreases gradually from its maximum value $n_1$ at the core center to its minimum value $n_2$ at the core–cladding interface. Most graded-index fibers are designed to have a nearly quadratic decrease and are analyzed by using $\alpha$-profile, given by

$$n(\rho) = \begin{cases} n_1 (1 - \rho/\rho)^\alpha & \rho < a, \\ n_1 (1 - \Delta) = n_2 & \rho \geq a, \end{cases}$$

(2.1.7)

where $a$ is the core radius. The parameter $\alpha$ determines the index profile. A step-index profile is approached in the limit of large $\alpha$. A parabolic-index fiber corresponds to $\alpha = 2$. It is easy to understand qualitatively why intermodal or multipath dispersion is reduced for graded-index fibers. Figure 2.3 shows schematically paths for three different rays. Similar to the case of step-index fibers, the path is longer for more oblique rays. However, the ray velocity changes along the path because of variations in the refractive index. More specifically, the ray propagating along the fiber axis takes the shortest path but travels most slowly as the index is largest along this path. Oblique rays have a large part of their path in a medium of lower refractive index, where they travel faster. It is therefore possible for all rays to arrive together at the fiber output by a suitable choice of the refractive-index profile.
Geometrical optics can be used to show that a parabolic-index profile leads to nondispersive pulse propagation within the paraxial approximation. The trajectory of a paraxial ray is obtained by solving [22]

$$\frac{d^2 \rho}{dz^2} = \frac{1}{\rho} \frac{d n}{d \rho},$$  \hspace{1cm} (2.1.8)

where $\rho$ is the radial distance of the ray from the axis.
Chapter 3

Optical Transmitters

The role of the optical transmitter is to convert an electrical input signal into the corresponding, optical signal and then launch it into the optical fiber serving as communication channel. The major component of optical transmitters is an optical source. Fiber-optic communication systems often use semiconductor optical sources such as light-emitting diodes (LEDs) and semiconductor lasers because of several inherent advantages offered by them. Some of these advantages are compact size, high efficiency, good reliability, right wavelength range, small emissive area compatible with fibercore, dimensions, and possibility of direct modulation at relatively high frequency. Although the operation of semiconductor lasers was demonstrated as early as 1962, their use became practical only after 1970, when semiconductor lasers operating continuously at room temperature became available. Since then, semiconductor lasers have been developed extensively because of their importance for optical communications. They are also known as laser diodes or injection lasers, and their properties have been discussed in several recent books. This chapter is devoted to LEDs and semiconductor lasers and their applications in lightwave systems. After introducing the basic concepts in Section 3.1, LEDs are covered in Section 3.2, while Section 3.3 focuses on semiconductor lasers. We describe single-mode semiconductor lasers in Section 3.4 and discuss their operating characteristics in Section 3.5. The design issues related to optical transmitters are covered in Section 3.6.

3.1 Basic Concepts

Under normal conditions, all materials absorb light rather than emit it. The absorption process can be understood by referring to Fig. 3.1, where the energy levels $E_1$ and $E_2$ correspond to the ground state and the excited state of atoms of the absorbing medium. If the photon energy $h\omega$ of the incident light of frequency $\omega$ is about the same as the energy difference $E_g = E_2-E_1$, the photon is absorbed by the atom, which ends up in the excited state. Incident light is attenuated as a result of many such absorption events occurring inside the medium.
Three fundamental processes occurring between the two energy states of an atom:

(a) absorption; (b) spontaneous emission; and (c) stimulated emission. The excited atoms eventually return to their normal “ground” state and emit light in the process. Light emission can occur through two fundamental processes known as spontaneous emission and stimulated emission. Both are shown schematically in Fig. 3.1. In the case of spontaneous emission, photons are emitted in random directions with no phase relationship among them. Stimulated emission, by contrast, is initiated by an existing photon. The remarkable feature of stimulated emission is that the emitted photon matches the original photon not only in energy (or in frequency), but also in its other characteristics, such as the direction of propagation. All lasers, including semiconductor lasers, emit light through the process of stimulated emission and are said to emit coherent light. In contrast, LEDs emit light through the incoherent process of spontaneous emission.

### 3.1.1 Emission and Absorption Rates

Before discussing the emission and absorption rates in semiconductors, it is instructive to consider a two-level atomic system interacting with an electromagnetic field through transitions shown in Fig. 3.1. If $N_1$ and $N_2$ are the atomic densities in the ground and the excited states, respectively, and $ph(v)$ is the spectral density of the electromagnetic energy, the rates of spontaneous emission, stimulated emission, and absorption can be written as

$$R_{\text{spont}} = AN_2, \quad R_{\text{stim}} = BN_2 \rho_{\text{em}}, \quad R_{\text{abs}} = B'N_1 \rho_{\text{em}}, \quad (3.1.1)$$

where $A$, $B$, and $B'$ are constants. In thermal equilibrium, the atomic densities are distributed according to the Boltzmann statistics

$$N_2/N_1 = \exp(-E_g/k_BT) = \exp(-hv/k_BT), \quad (3.1.2)$$

where $k_B$ is the Boltzmann constant and $T$ is the absolute temperature. Since $N_1$ and $N_2$ do not change with time in thermal equilibrium, the upward and downward transition rates should be equal, or

$$AN_2 + BN_2 \rho_{\text{em}} = B'N_1 \rho_{\text{em}}. \quad (3.1.3)$$

By using Eq. (3.1.2) in Eq. (3.1.3), the spectral density becomes

$$\rho_{\text{em}} = \frac{A/B}{(B'/B) \exp(hv/k_BT) - 1}. \quad (3.1.4)$$
3.1.2 Basic Concepts

In thermal equilibrium, $\rho_{em}$ should be identical with the spectral density of blackbody radiation given by Planck's formula

$$\rho_{em} = \frac{8\pi \hbar^3/c^3}{\exp(\hbar v/k_b T) - 1}. \quad (3.1.5)$$

A comparison of Eqs. (3.1.4) and (3.1.5) provides the relations

$$A = (8\pi \hbar v^3/c^3)B; \quad B' = B. \quad (3.1.6)$$

These relations were first obtained by Einstein. For this reason, A and B are called Einstein's coefficients. Two important conclusions can be drawn from Eqs. (3.1.1)–(3.1.6). First, $R_{sp}$ can exceed both $R_{st}$ and $R_{ab}$ considerably if $kBT > hV$. Thermal sources operate in this regime. Second, for radiation in the visible or near-infrared region ($hV \sim 1$ eV), spontaneous emission always dominates over stimulated emission in thermal equilibrium at room temperature ($kBT \approx 25$ meV) because

$$R_{st} / R_{sp} = [\exp(hv/k_b T) - 1]^{-1} \ll 1. \quad (3.1.7)$$

Thus, all lasers must operate away from thermal equilibrium. This is achieved by pumping lasers with an external energy source. Even for an atomic system pumped externally, stimulated emission may not be the dominant process since it has to compete with the absorption process. $R_{st}$ can exceed $R_{sp}$ only when $N_2 > N_1$. This condition is referred to as population inversion and is never realized for systems in thermal equilibrium [see Eq. (3.1.2)]. Population inversion is a prerequisite for laser operation. In atomic systems, it is achieved by using three- and four-level pumping schemes such that an external energy source raises the atomic population from the ground state to an excited state lying above the energy state $E_2$ in Fig. 3.1.

The emission and absorption rates in semiconductors should take into account the energy bands associated with a semiconductor. Figure 3.2 shows the emission process schematically using the simplest band structure, consisting of parabolic conduction and valence bands in the energy–wave-vector space ($E-k$ diagram). Spontaneous emission can occur only if the energy state $E_2$ is occupied by an electron and the energy state $E_1$ is empty (i.e., occupied by a hole). The occupation probability for electrons in the conduction and valence bands is given by the Fermi–Dirac distributions

$$f_c(E_2) = \{1 + \exp((E_2 - E_{fc})/k_b T)\}^{-1}, \quad (3.1.8)$$

$$f_v(E_1) = \{1 + \exp((E_1 - E_{fv})/k_b T)\}^{-1}, \quad (3.1.9)$$

where $E_{fc}$ and $E_{fv}$ are the Fermi levels. The total spontaneous emission rate at a frequency $\omega$ is obtained by summing over all possible transitions between the two bands such that $E_2 - E_1 = E_{em} = \hbar \omega$, where $\omega = 2\pi \nu$, $\hbar = h/2\pi$, and $E_{em}$ is the energy of the emitted photon. The result is

$$R_{sp} = \int_{E_c}^{E_v} A(E_1, E_2) f_c(E_2) [1 - f_v(E_1)] \rho_{cv} dE_2, \quad (3.1.10)$$
Figure 3.2: Conduction and valence bands of a semiconductor. Electrons in the conduction band and holes in the valence band can recombine and emit a photon through spontaneous emission as well as through stimulated emission. Where $p_{cv}$ is the joint density of states, defined as the number of states per unit volume per unit energy range, and is given by

$$
\rho_{cv} = \frac{(2mr)^{3/2}}{2\pi^2\hbar^3}(\hbar\omega - E_g)^{1/2}. \tag{3.1.11}
$$

In this equation, $E_g$ is the bandgap and $mr$ is the reduced mass, defined as $mr = mcmv/(mc + mv)$, where $mc$ and $mv$ are the effective masses of electrons and holes in the conduction and valence bands, respectively. Since $p_{cv}$ is independent of $E_2$ in Eq. (3.1.10), it can be taken outside the integral. By contrast, $A(E_1, E_2)$ generally depends on $E_2$ and is related to the momentum matrix element in a semiclassical perturbation approach commonly used to calculate it. The stimulated emission and absorption rates can be obtained in a similar manner and are given by

$$
R_{\text{stim}}(\omega) = \int_{E_c} B(E_1, E_2)f_c(E_2)[1 - f_v(E_1)]\rho_{cv}\rho_{em} dE_2, \tag{3.1.12}
$$

$$
R_{\text{abs}}(\omega) = \int_{E_v} B(E_1, E_2)f_v(E_1)[1 - f_c(E_2)]\rho_{cv}\rho_{em} dE_2, \tag{3.1.13}
$$

Where $\rho_{em}$ (infra 3) given by used to calculate it. The stimulated emission and absorption (3.1.1). The population-inversion condition $R_{\text{stim}} > R_{\text{abs}}$ is obtained by comparing Eqs. (3.1.12) and (3.1.13), resulting in $f_c(E_2) > f_v(E_1)$. If we use Eqs. (3.1.8) and (3.1.9), this condition is satisfied when

$$
E_{f_c} - E_{f_v} > E_2 - E_1 > E_g. \tag{3.1.14}
$$
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Since the minimum value of $E_2 - E_1$ equals $E_g$, the separation between the Fermi levels must exceed the bandgap for population inversion to occur. In thermal equilibrium, the two Fermi levels coincide ($E_{fc} = E_{fv}$). They can be separated by pumping energy into the semiconductor from an external energy source. The most convenient way for pumping a semiconductor is to use a forward-biased $p-n$ junction.

3.1.3 $p-n$ Junctions

At the heart of a semiconductor optical source is the $p-n$ junction, formed by bringing a $p$-type and an $n$-type semiconductor into contact. Recall that a semiconductor is made $n$-type or $p$-type by doping it with impurities whose atoms have an excess valence electron or one less electron compared with the semiconductor atoms. In the case of $n$-type semiconductor, the excess electrons occupy the conduction-band states, normally empty in undoped (intrinsic) semiconductors. The Fermi level, lying in the middle of the bandgap for intrinsic semiconductors, moves toward the conduction band as the dopant concentration increases. In a heavily doped $n$-type semiconductor, the Fermi level $E_{fc}$ lies inside the conduction band; such semiconductors are said to be degenerate. Similarly, the Fermi level $E_{fv}$ moves toward the valence band for $p$-type semiconductors and lies inside it under heavy doping. In thermal equilibrium, the Fermi level must be continuous across the $p-n$ junction. This is achieved through diffusion of electrons and holes across the junction. The charged impurities left behind set up an electric field strong enough to prevent further diffusion of electrons and holds under equilibrium conditions. This field is referred to as the built-in electric field. Figure 3.3(a) shows the energy-band diagram of a $p-n$ junction in thermal equilibrium and under forward bias. When a $p-n$ junction is forward biased by applying an external voltage, the built-in electric field is reduced. This reduction results in diffusion of electrons and holes across the junction. An electric current begins to flow as a result of carrier diffusion. The current $I$ increases exponentially with the applied voltage $V$ according to the well-known relation

$$I = I_s \exp \left( \frac{qV}{k_BT} \right) - 1,$$

where $I_s$ is the saturation current and depends on the diffusion coefficients associated with electrons and holes. As seen in Fig. 3.3(a), in a region surrounding the junction (known as the depletion width), electrons and holes are present simultaneously when the $p-n$ junction is forward biased. These electrons and holes can recombine through spontaneous or stimulated emission and generate light in a semiconductor optical source. The $p-n$ junction shown in Fig. 3.3(a) is called the homojunction, since the same semiconductor material is used on both sides of the junction. A problem with the homojunction is that electron–hole recombination occurs over a relatively wide region ($\sim 1-10$ um) determined by the diffusion length of electrons and holes. Since the carriers are not confined to the immediate vicinity of the junction, it is difficult to realize high carrier densities. This carrier-confinement problem can be solved by sandwiching a thin layer between the $p$-type and $n$-type layers such that the bandgap of the sandwiched layer is smaller than the layers surrounding it. The middle layer may or may
not be doped, depending on the device design; its role is to confine the carriers injected inside it under forward bias. The carrier confinement occurs as a result of bandgap discontinuity at the junction between two semiconductors which have the same crystalline structure (the same lattice constant) but different bandgaps. Such junctions are called heterojunctions, and such devices are called double heterostructures. Since the thickness of the sandwiched layer can be controlled externally (typically, ~0.1 μm), high carrier densities can be realized at a given injection current. Figure 3.3(b) shows the energy-band diagram of a double heterostructure with and without forward bias. The use of a heterostructure geometry for semiconductor optical sources is doubly beneficial. As already mentioned, the bandgap difference between the two semiconductors helps to confine electrons and holes to the middle layer, also called the active layer since light is generated inside it as a result of electron–hole recombination. However, the active layer also has a slightly larger refractive index than the surrounding p-type and n-type cladding layers simply because its bandgap is smaller. As a result of the refractive-index difference, the active layer acts as a dielectric waveguide and supports optical modes whose number can be controlled by changing the active-layer thickness (similar to the modes supported by a fiber core). The main point is that a heterostructure confines the generated light to the active layer because of its higher refractive index. Figure 3.4 illustrates schematically the simultaneous confinement of charge carriers and the optical field to the active region through a heterostructure design. It is this feature that has made semiconductor lasers practical for a wide variety of applications.
3.1 Basic Concepts

![Diagram of a double heterostructure design](image)

**Figure 3.4**: Simultaneous confinement of charge carriers and optical field in a double heterostructure design. The active layer has a lower bandgap and a higher refractive index than those of p-type and n-type cladding layers.

### 3.1.4 Nonradiative Recombination

When a p–n junction is forward-biased, electrons and holes are injected into the active region, where they recombine to produce light. In any semiconductor, electrons and holes can also recombine nonradiatively. Nonradiative recombination mechanisms include recombination at traps or defects, surface recombination, and the Auger recombination. The last mechanism is especially important for semiconductor lasers emitting light in the wavelength range 1.3–1.6 μm because of a relatively small bandgap of the active layer. In the Auger recombination process, the energy released during electron–hole recombination is given to another electron or hole as kinetic energy rather than producing light. From the standpoint of device operation, all nonradiative processes are harmful, as they reduce the number of electron–hole pairs that emit light. Their effect is quantified through the *internal quantum efficiency*, defined as

\[
    \eta_{\text{int}} = \frac{R_{\text{tr}}}{R_{\text{tot}}} = \frac{R_{\text{tr}}}{R_{\text{tr}} + R_{\text{nr}}},
\]  

(3.1.16)
where \( R_{rr} \) is the radiative recombination rate, \( R_{nr} \) is the nonradiative recombination rate, and \( R_{tot} = R_{rr} + R_{nr} \) is the total recombination rate. It is customary to introduce the recombination times \( \tau_{rr} \) and \( \tau_{nr} \) using \( R_{rr} = N/\tau_{rr} \) and \( R_{nr} = N/\tau_{nr} \), where \( N \) is the carrier density. The internal quantum efficiency is then given by

\[
\eta_{int} = \frac{\tau_{nr}}{\tau_{rr} + \tau_{nr}}. \tag{3.1.17}
\]

The radiative and nonradiative recombination times vary from semiconductor to semiconductor. In general, \( \tau_{rr} \) and \( \tau_{nr} \) are comparable for direct-bandgap semiconductors, whereas \( \tau_{nr} \) is a small fraction \((\sim 10^{-5})\) of \( \tau_{rr} \) for semiconductors with an indirect bandgap. A semiconductor is said to have a direct bandgap if the conduction-band minimum and the valence-band maximum occur for the same value of the electron wave vector (see Fig. 3.2). The probability of radiative recombination is large in such semiconductors, since it is easy to conserve both energy and momentum during electron–hole recombination. By contrast, indirect-bandgap semiconductors require the assistance of a phonon for conserving momentum during electron–hole recombination. This feature reduces the probability of radiative recombination and increases \( \tau_{rr} \) considerably compared with \( \tau_{nr} \) in such semiconductors. As evident from Eq. (3.1.17), \( \eta_{int} \ll 1 \) under such conditions. Typically \( \eta_{int} \sim 10^{-5} \) for Si and Ge, the two semiconductors commonly used for electronic devices. Both are not suitable for optical sources because of their indirect bandgap. For direct-bandgap semiconductors such as GaAs and InP, \( \eta_{int} \approx 0.5 \) and approaches 1 when stimulated emission dominates.

The radiative recombination rate can be written as \( R_{rr} = R_{spon} + R_{stim} \) when radiative recombination occurs through spontaneous as well as stimulated emission. For LEDs, \( R_{stim} \) is negligible compared with \( R_{spon} \), and \( R_{rr} \) in Eq. (3.1.16) is replaced with \( R_{spon} \). Typically, \( R_{spon} \) and \( R_{nr} \) are comparable in magnitude, resulting in an internal quantum efficiency of about 50%. However, \( \eta_{int} \) approaches 100% for semiconductor lasers as stimulated emission begins to dominate with an increase in the output power. It is useful to define a quantity known as the carrier lifetime \( \tau_c \) such that it represents the total recombination time of charged carriers in the absence of stimulated recombination. It is defined by the relation

\[
R_{spon} + R_{nr} = N/\tau_c. \tag{3.1.18}
\]

where \( N \) is the carrier density. If \( R_{spon} \) and \( R_{nr} \) vary linearly with \( N \), \( \tau_c \) becomes a constant. In practice, both of them increase nonlinearly with \( N \) such that \( R_{spon} + R_{nr} = A_{nr}N + BN^2 + CN^3 \), where \( A_{nr} \) is the nonradiative coefficient due to recombination at defects or traps, \( B \) is the spontaneous radiative recombination coefficient, and \( C \) is the Auger coefficient. The carrier lifetime then becomes \( N \) dependent and is obtained by using \( \tau_c^{-1} = A_{nr} + BN + CN^2 \). In spite of its \( N \) dependence, the concept of carrier lifetime \( \tau_c \) is quite useful in practice.

### 3.1.5 Semiconductor Materials

Almost any semiconductor with a direct bandgap can be used to make a \( p-n \) homojunction capable of emitting light through spontaneous emission. The choice is, however, considerably limited in the case of heterostructure devices because their performance...
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Figure 3.5. Lattice constants and bandgap energies of ternary and quaternary compounds formed by using nine group III–V semiconductors. Shaded area corresponds to possible InGaAsP and AlGaAs structures. Horizontal lines passing through InP and GaAs show the lattice-matched designs. (After Ref Wiley; reprinted with permission.)

depends on the quality of the heterojunction interface between two semiconductors of different bandgaps. To reduce the formation of lattice defects, the lattice constant of the two materials should match to better than 0.1%. Nature does not provide semiconductors whose lattice constants match to such precision. However, they can be fabricated artificially by forming ternary and quaternary compounds in which a fraction of the lattice sites in a naturally occurring binary semiconductor (e.g., GaAs) is replaced by other elements. In the case of GaAs, a ternary compound $\text{Al}_x\text{Ga}_{1-x}\text{As}$ can be made by replacing a fraction $x$ of Ga atoms by Al atoms. The resulting semiconductor has nearly the same lattice constant, but its bandgap increases. The bandgap depends on the fraction $x$ and can be approximated by a simple linear relation

$$E_g(x) = 1.424 + 1.247x \quad (0 < x < 0.45),$$

where $E_g$ is expressed in electron-volt (eV) units. Figure 3.5 shows the interrelationship between the bandgap $E_g$ and the lattice constant $a$ for several ternary and quaternary compounds. Solid dots represent the binary semiconductors, and lines connecting them correspond to ternary compounds. The dashed portion of the line indicates that the resulting ternary compound has an indirect bandgap.
The area of a closed polygon corresponds to quaternary compounds. The bandgap is not necessarily direct for such semiconductors.

The shaded area in Fig. 3.5 represents the ternary and quaternary compounds with a direct bandgap formed by using the elements indium (In), gallium (Ga), arsenic (As), and phosphorus (P). The horizontal line connecting GaAs and AlAs corresponds to the ternary compound Al$_x$Ga$_{1-x}$As, whose bandgap is direct for values of $x$ up to about 0.45 and is given by Eq. (3.1.19). The active and cladding layers are formed such that $x$ is larger for the cladding layers compared with the value of $x$ for the active layer. The wavelength of the emitted light is determined by the bandgap since the photon energy is approximately equal to the bandgap. By using $E_g \approx h\nu = hc/\lambda$, one finds that $\lambda \approx 0.87 \mu m$ for an active layer made of GaAs ($E_g = 1.424$ eV). The wavelength can be reduced to about 0.81 $\mu m$ by using an active layer with $x = 0.1$. Optical sources based on GaAs typically operate in the range 0.81–0.87 $\mu m$ and were used in the first generation of fiber-optic communication systems. As discussed in Chapter 2, it is beneficial to operate lightwave systems in the wavelength range 1.3–1.6 $\mu m$, where both dispersion and loss of optical fibers are considerably reduced compared with the 0.85-$\mu$m region. InP is the base material for semiconductor optical sources emitting light in this wavelength region. As seen in Fig. 3.5 by the horizontal line passing through InP, the bandgap of InP can be reduced considerably by making the quaternary compound In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ while the lattice constant remains matched to InP. The fractions $x$ and $y$ cannot be chosen arbitrarily but are related by $x/y = 0.45$ to ensure matching of the lattice constant. The bandgap of the quaternary compound can be expressed in terms of $y$ only and is well approximated by

$$E_g(y) = 1.35 - 0.72y + 0.12y^2,$$

where $0 \leq y \leq 1$. The smallest bandgap occurs for $y = 1$. The corresponding ternary compound In$_{0.55}$Ga$_{0.45}$As emits light near 1.65 $\mu m$ ($E_g = 0.75$ eV). By a suitable choice of the mixing fractions $x$ and $y$, In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ sources can be designed to operate in the wide wavelength range 1.0–1.65 $\mu m$ that includes the region 1.3–1.6 $\mu m$ important for optical communication systems. The fabrication of semiconductor optical sources requires epitaxial growth of multiple layers on a base substrate (GaAs or InP). The thickness and composition of each layer need to be controlled precisely. Several epitaxial growth techniques can be used for this purpose. The three primary techniques are known as liquid-phase epitaxy (LPE), vapor-phase epitaxy (VPE), and molecular-beam epitaxy (MBE) depending on whether the constituents of various layers are in the liquid form, vapor form, or in the form of a molecular beam. The VPE technique is also called chemical-vapor deposition. A variant of this technique is metal-organic chemical-vapor deposition (MOCVD), in which metal alkalis are used as the mixing compounds. Details of these techniques are available in the literature. Both the MOCVD and MBE techniques provide an ability to control layer thickness to within 1 nm. In some lasers, the thickness of the active layer is small enough that electrons and holes act as if they are confined to a quantum well. Such confinement leads to quantization of the energy bands into subbands. The main consequence is that the joint density of states $p_{cv}$ acquires a staircase-like structure. Such a modification of the density of states affects the gain characteristics considerably and improves.
3.2 Light Emitting Diodes

the laser performance. Such quantum-well lasers have been studied extensively. Often, multiple active layers of thickness 5–10 nm, separated by transparent barrier layers of about 10 nm thickness, are used to improve the device performance. Such lasers are called multiquantum-well (MQW) lasers. Another feature that has improved the performance of MQW lasers is the introduction of intentional, but controlled strain within active layers. The use of thin active layers permits a slight mismatch between lattice constants without introducing defects. The resulting strain changes the band structure and improves the laser performance. Such semiconductor lasers are called strained MQW lasers. The concept of quantum-well lasers has also been extended to make quantum-wire and quantum-dot lasers in which electrons are confined in more than one dimension. However, such devices were at the research stage in 2001. Most semiconductor lasers deployed in lightwave systems use the MQW design.

3.2 Light-Emitting Diodes

A forward-biased p–n junction emits light through spontaneous emission, a phenomenon referred to as electroluminescence. In its simplest form, an LED is a forwardbiased p–n homojunction. Radiative recombination of electron–hole pairs in the depletion region generates light; some of it escapes from the device and can be coupled into an optical fiber. The emitted light is incoherent with a relatively wide spectral width (30–60 nm) and a relatively large angular spread. In this section we discuss the characteristics and the design of LEDs from the standpoint of their application in optical communication systems.

3.2.1 Power–Current Characteristics

It is easy to estimate the internal power generated by spontaneous emission. At a given current $I$ the carrier-injection rate is $I/q$. In the steady state, the rate of electron–hole pairs recombining through radiative and nonradiative processes is equal to the carrierinjection rate $I/q$. Since the internal quantum efficiency $\eta_{\text{int}}$ determines the fraction of electron–hole pairs that recombine through spontaneous emission, the rate of photon generation is simply $\eta_{\text{int}}I/q$. The internal optical power is thus given by

$$P_{\text{int}} = \eta_{\text{int}}(\hbar \omega / q)I,$$

(3.2.1)

where $\hbar \omega$ is the photon energy, assumed to be nearly the same for all photons. If $\eta_{\text{ext}}$ is the fraction of photons escaping from the device, the emitted power is given by

$$P_e = \eta_{\text{ext}}P_{\text{int}} = \eta_{\text{ext}}\eta_{\text{int}}(\hbar \omega / q)I.$$

(3.2.2)

The quantity $\eta_{\text{ext}}$ is called the external quantum efficiency. It can be calculated by taking into account internal absorption and the total internal reflection at the semiconductor–air interface. As seen in Fig. 3.6, only light emitted within a cone of angle $\theta_c$, where $\theta_c = \sin^{-1}(1/n)$ is the critical angle and $n$ is the refractive index of the semiconductor material, escapes from the LED surface. Internal absorption can be avoided by using heterostructure LEDs in which the cladding layers surrounding
Figure 3.6: Total internal reflection at the output facet of an LED. Only light emitted within a cone of angle $\theta_c$ is transmitted, where $\theta_c$ is the critical angle for the semiconductor–air interface.

active layer are transparent to the radiation generated. The external quantum efficiency can then be written as

$$\eta_{\text{ext}} = \frac{1}{4\pi} \int_{0}^{\theta_c} T_f(\theta)(2\pi \sin \theta) d\theta,$$

(3.2.3)

where we have assumed that the radiation is emitted uniformly in all directions over a solid angle of $4\pi$. The Fresnel transmissivity $T_f$ depends on the incidence angle $\theta$. In the case of normal incidence ($\theta = 0$), $T_f(0) = 4n/(n+1)^2$. If we replace for simplicity $T_f(0)$ by $T_f(0)$ in Eq. (3.2.3), $\eta_{\text{ext}}$ is given approximately by

$$\eta_{\text{ext}} = n^{-1}(n + 1)^{-2}.$$

(3.2.4)

By using Eq. (3.2.4) in Eq. (3.2.2) we obtain the power emitted from one facet (see Fig. 3.6). If we use $n = 3.5$ as a typical value, $\eta_{\text{ext}} = 1.4\%$, indicating that only a small fraction of the internal power becomes the useful output power. A further loss in useful power occurs when the emitted light is coupled into an optical fiber. Because of the incoherent nature of the emitted light, an LED acts as a Lambertian source with an angular distribution $S(\theta) = S_0 \cos \theta$, where $S_0$ is the intensity in the direction $\theta = 0$. The coupling efficiency for such a source [20] is $\eta_c = (\text{NA})^2$. Since the numerical aperture (NA) for optical fibers is typically in the range 0.1–0.3, only a few percent of the emitted power is coupled into the fiber. Normally, the launched power for LEDs is 100 $\mu$W or less, even though the internal power can easily exceed 10 mW. A measure of the LED performance is the total quantum efficiency $\eta_{\text{tot}}$, defined as the ratio of the emitted optical power $P_e$ to the applied electrical power, $P_{\text{elec}} = V_0I$, where $V_0$ is the voltage drop across the device. By using Eq. (3.2.2), $\eta_{\text{tot}}$ is given by

$$\eta_{\text{tot}} = \eta_{\text{ext}}\eta_{\text{int}}(\hbar\omega/qV_0).$$

(3.2.5)

Typically, $\hbar\omega \approx qV_0$, and $\eta_{\text{tot}} \approx \eta_{\text{ext}}\eta_{\text{int}}$. The total quantum efficiency $\eta_{\text{tot}}$, also called the power-conversion efficiency or the wall-plug efficiency, is a measure of the overall performance of the device.
3.2 Light Emitting Diodes

Figure 3.7: (a) Power–current curves at several temperatures; (b) spectrum of the emitted light for a typical 1.3-μm LED. The dashed curve shows the theoretically calculated spectrum. (After Ref. AT&T; reprinted with permission.)

Another quantity sometimes used to characterize the LED performance is the responsivity defined as the ratio $R_{\text{LED}} = P_e / I$. From Eq. (3.2.2)

$$R_{\text{LED}} = \eta_{\text{ext}} \eta_{\text{int}} (\hbar \omega / q).$$

A comparison of Eqs. (3.2.5) and (3.2.6) shows that $R_{\text{LED}} = \eta_\text{tot} V_0$. Typical values of $R_{\text{LED}}$ are ~ 0.01 W/A. The responsivity remains constant as long as the linear relation between $P_e$ and $I$ holds. In practice, this linear relationship holds only over a limited current range. Figure 3.7(a) shows the power–current ($P$–$I$) curves at several temperatures for a typical 1.3-μm LED. The responsivity of the device decreases at high currents above 80 mA because of bending of the $P$–$I$ curve. One reason for this decrease is related to the increase in the active-region temperature. The internal quantum efficiency $\eta_{\text{int}}$ is generally temperature dependent because of an increase in the nonradiative recombination rates at high temperatures.
3.2.2 LED Spectrum

As seen in Section 2.3, the spectrum of a light source affects the performance of optical communication systems through fiber dispersion. The LED spectrum is related to the spectrum of spontaneous emission, $R_{\text{spont}}(\omega)$, given in Eq. (3.1.10). In general, $R_{\text{spont}}(\omega)$ is calculated numerically and depends on many material parameters. However, an approximate expression can be obtained if $A(E_1E_2)$ is assumed to be nonzero only over a narrow energy range in the vicinity of the photon energy, and the Fermi functions are approximated by their exponential tails under the assumption of weak injection. The result is

$$R_{\text{spont}}(\omega) = A_0(\hbar\omega - E_g)^{1/2} \exp\left[-(\hbar\omega - E_g)/k_BT\right],$$

(3.2.7)

where $A_0$ is a constant and $E_g$ is the bandgap. It is easy to deduce that $R_{\text{spont}}(\omega)$ peaks when $\hbar\omega = E_g + k_BT/2$ and has a full-width at half-maximum (FWHM) $\nu \approx 1.8k_BT/h$. At room temperature ($T = 300$ K) the FWHM is about 11 THz. In practice, the spectral width is expressed in nanometers by using $\lambda = (c/\nu^2)\nu$ and increases as $\nu^2$ with an increase in the emission wavelength $\lambda$. As a result, $\lambda$ is larger for InGaAsP LEDs emitting at 1.3 $\mu$m by about a factor of 1.7 compared with GaAs LEDs. Figure 3.7(b) shows the output spectrum of a typical 1.3-$\mu$m LED and compares it with the theoretical curve obtained by using Eq. (3.2.7). Because of a large spectral width ($\lambda = 50-60$ nm), the bit rate-distance product is limited considerably by fiber dispersion when LEDs are used in optical communication systems. LEDs are suitable primarily for local-area-network applications with bit rates of 10–100 Mb/s and transmission distances of a few kilometers.

3.2.3 Modulation Response

The modulation response of LEDs depends on carrier dynamics and is limited by the carrier lifetime $\tau_c$ defined by Eq. (3.1.18). It can be determined by using a rate equation for the carrier density $N$. Since electrons and holes are injected in pairs and recombine in pairs, it is enough to consider the rate equation for one type of charge carrier. The rate equation should include all mechanisms through which electrons appear and disappear inside the active region. For LEDs it takes the simple form (since stimulated emission is negligible)

$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_c},$$

(3.2.8)

where the last term includes both radiative and nonradiative recombination processes through the carrier lifetime $\tau_c$. Consider sinusoidal modulation of the injected current in the form (the use of complex notation simplifies the math)

$$I(t) = I_b + I_m \exp(i\omega mt),$$

(3.2.9)

where $I_b$ is the bias current, $I_m$ is the modulation current, and $\omega m$ is the modulation frequency. Since Eq. (3.2.8) is linear, its general solution can be written as

$$N(t) = N_b + N_m \exp(i\omega mt),$$

(3.2.10)

where $N_b = \tau_c I_b / qV$, $V$ is the volume of active region and $N_m$ is given by

$$N_m(\omega m) = \frac{\tau_c I_m / qV}{1 + i\omega m \tau_c}.$$
where \( N_b = |eI_b/qV, \) \( V \) is the volume of active region and \( N_m \) is given by

\[
(\omega_m) = \frac{N_m(\omega_m)}{N_m(0)} - \frac{1}{1 + i\omega_m \tau_c}.
\]
CHAPTER 4

Optical Receivers

The role of an optical receiver is to convert the optical signal back into electrical form and recover the data transmitted through the lightwave system. Its main component is a photodetector that converts light into electricity through the photoelectric effect. The requirements for a photodetector are similar to those of an optical source. It should have high sensitivity, fast response, low noise, low cost, and high reliability. Its size should be compatible with the fiber-core size. These requirements are best met by photodetectors made of semiconductor materials.

4.1 Basic Concepts:

The fundamental mechanism behind the photodetection process is optical absorption.

- 4.1.1 Detector Responsivity

Consider the semiconductor slab shown schematically in Fig. 4.1. If the energy $h\nu$ of incident photons exceeds the bandgap energy, an electron–hole pair is generated each time a photon is absorbed by the semiconductor. Under the influence of an electric field set up by an applied voltage, electrons and holes are swept across the semiconductor, resulting in a flow of electric current. The photocurrent $I_p$ is directly proportional to the incident optical power $P_{\text{in}}$, i.e.,

$$I_p = RP_{\text{in}},$$

where $R$ is the responsivity of the photodetector (in units of A/W). The responsivity $R$ can be expressed in terms of a fundamental quantity $\eta$, called the quantum efficiency and defined as

$$\eta = \frac{\text{electron generation rate}}{\text{photon incidence rate}} = \frac{I_p}{P_{\text{in}}/h\nu} = \frac{h\nu}{q} R, \quad (4.1.2)$$

Figure 4.1: A semiconductor slab used as a photodetector.
where Eq. (4.1.1) was used. The responsivity $R$ is thus given by

$$R = \frac{\eta q}{h\nu} \approx \frac{\eta \lambda}{1.24},$$

(4.1.3)

where $\lambda \equiv c/\nu$ is expressed in micrometers. The responsivity of a photodetector increases with the wavelength $\lambda$ simply because more photons are present for the same optical power. Such a linear dependence on $\lambda$ is not expected to continue forever because eventually the photon energy becomes too small to generate electrons. In semiconductors, this happens for $h\nu < E_g$, where $E_g$ is the bandgap. The quantum efficiency $\eta$ then drops to zero. The dependence of $\eta$ on $\lambda$ enters through the absorption coefficient $\alpha$. If the facets of the semiconductor slab in Fig. 4.1 are assumed to have an antireflection coating, the power transmitted through the slab of width $W$ is $P_{\text{tr}} = \exp(-\alpha W)P_{\text{in}}$. The absorbed power can be written as

$$P_{\text{abs}} = P_{\text{in}} - P_{\text{tr}} = \left[1 - \exp(-\alpha W)\right]P_{\text{in}}.$$  

(4.1.4)

Since each absorbed photon creates an electron–hole pair, the quantum efficiency $\lambda$ is given by

$$\lambda = \frac{P_{\text{abs}}}{P_{\text{in}}} = 1 - \exp(-\alpha W).$$

(4.1.5)

Figure 4.2: Wavelength dependence of the absorption coefficient for several semiconductor materials. As expected, $\eta$ becomes zero when $\alpha = 0$. On the other hand, $\eta$ approaches 1 if $\alpha W >> 1$. Figure 4.2 shows the wavelength dependence of $\alpha$ for several semiconductor materials commonly used to make photodetectors for lightwave systems. The wavelength $\lambda_c$ at which $\alpha$ becomes zero is called the cutoff wavelength, as that material can be used for a photodetector only for $\lambda < \lambda_c$. As seen in Fig. 4.2, indirect-bandgap semiconductors such as Si and Ge can be used to make photodetectors even though the absorption edge is not as sharp as for direct-bandgap materials. Large values of $\alpha$ ($\sim 104$ cm$^{-1}$) can be realized for most semiconductors, and $\lambda$ can approach 100% for $W \sim 10$ $\mu$m. This feature illustrates the efficiency of semiconductors for the purpose of photodetection.
4.1.2 Rise Time and Bandwidth

The bandwidth of a photodetector is determined by the speed with which it responds to variations in the incident optical power. It is useful to introduce the concept of rise time \( T_r \), defined as the time over which the current builds up from 10 to 90% of its final value when the incident optical power is changed abruptly. Clearly, \( T_r \) will depend on the time taken by electrons and holes to travel to the electrical contacts. It also depends on the response time of the electrical circuit used to process the photocurrent. The rise time \( T_r \) of a linear electrical circuit is defined as the time during which the response increases from 10 to 90% of its final output value when the input is changed abruptly (a step function). When the input voltage across an RC circuit changes instantaneously from 0 to \( V_0 \), the output voltage changes as

\[
V_{ou}(t) = V_0 [1 - \exp(-t/RC)]
\]

(4.1.6)

where \( R \) is the resistance and \( C \) is the capacitance of the RC circuit. The rise time is found to be given by

\[
T_r = (\ln 9) RC \approx 2.2 \tau_{RC}
\]

(4.1.7)

where \( \tau_{RC} = RC \) is the time constant of the RC circuit. The rise time of a photodetector can be written by extending Eq.(4.1.7) as

\[
T_r = (\ln 9) (\tau_{tr} + \tau_{RC})
\]

(4.1.8)

where \( \tau_{tr} \) is the transit time and \( \tau_{RC} \) is the time constant of the equivalent RC circuit. The transit time is added to \( \tau_{RC} \) because it takes some time before the carriers are collected after their generation through absorption of photons. The maximum collection time is just equal to the time an electron takes to traverse the absorption region. Clearly, \( \tau_{tr} \) can be reduced by decreasing \( W \). However, as seen from Eq. (4.1.5), the quantum efficiency \( \eta \) begins to decrease significantly for \( \alpha W < 3 \). Thus, there is a trade-off between the bandwidth and the responsivity (speed versus sensitivity) of a photodetector. Often, the RC time constant \( \tau_{RC} \) limits the bandwidth because of electrical parasitics. The numerical values of \( \tau_{tr} \) and \( \tau_{RC} \) depend on the detector design and can vary over a wide range. The bandwidth of a photodetector is defined in a manner analogous to that of a RC circuit and is given by

\[
\Delta f = \frac{1}{2\pi (\tau_{tr} + \tau_{RC})}
\]

(4.1.9)

As an example, when \( \tau_{tr} = \tau_{RC} = 100 \) ps, the bandwidth of the photodetector is below 1 GHz. Clearly, both \( \tau_{tr} \) and \( \tau_{RC} \) should be reduced below 10 ps for photodetectors needed for lightwave systems operating at bit rates of 10 Gb/s or more. Together with the bandwidth and the responsivity, the darkcurrent \( I_d \) of a photodetector is the third important parameter. Here, \( I_d \) is the current generated in a photodetector in the absence of any optical signal and originates from stray light or from thermally generated electron–hole pairs. For a good photodetector, the dark current should be negligible (\( I_d < 10 \) nA).
4.2 Common Photodetectors

The semiconductor slab of Fig. 4.1 is useful for illustrating the basic concepts but such a simple device is rarely used in practice. This section focuses on reverse-biased p–n junctions that are commonly used for making optical receivers. Metal–semiconductor–metal (MSM) photodetectors are also discussed briefly.

- **4.2.1 p–n Photodiodes**

A reverse-biased p–n junction consists of a region, known as the depletion region, that is essentially devoid of free charge carriers and where a large built-in electric field opposes flow of electrons from the n-side to the p-side (and of holes from p to n). When such a p–n junction is illuminated with light on one side, say the p-side (see Fig.4.3), electron–hole pairs are created through absorption. Because of the large built-in electric field, electrons and holes generated inside the depletion region accelerate in opposite directions and drift to the n- and p-sides, respectively. The resulting flow of current is proportional to the incident optical power. Thus a reverse-biased p–n junction acts as a photodetector and is referred to as the p–n photodiode. Figure 4.3(a) shows the structure of a p–n photodiode. As shown in Fig. 4.3(b), optical power decreases exponentially as the incident light is absorbed inside the depletion region. The electron–hole pairs generated inside the depletion region experience a large electric field and drift rapidly toward the p- or n-side, depending on the electric charge [Fig. 4.3(c)]. The resulting current flow constitutes the photodiode response to the incident optical power in accordance with Eq. (4.1.1). The responsivity of a photodiode is quite high ($R \sim 1 \text{ A/W}$) because of a high quantum efficiency. The bandwidth of a p–n photodiode is often limited by the transit time $\tau_{tr}$ in Eq. (4.1.9). If $W$ is the width of the depletion region and $vd$ is the drift velocity, the transit time is given by

$$\tau_{tr} = \frac{W}{vd}. \quad (4.2.1)$$

Typically, $W \sim 10 \mu\text{m}$, $vd \sim 10^5 \text{ m/s}$, and $\tau_{tr} \sim 100 \text{ ps}$. Both $W$ and $vd$ can be optimized to minimize $\tau_{tr}$. The depletion-layer width depends on the acceptor and donor concentrations and can be controlled through them. The velocity $vd$ depends on the applied voltage but attains a maximum value (called the saturation velocity) $\sim 10^5 \text{ m/s}$ that depends on the material used for the photodiode. The RC time constant $\tau_{RC}$ can be...
Figure 4.4: Response of a $p-n$ photodiode to a rectangular optical pulse when both drift and diffusion contribute to the detector current written as

$$\tau_{RC} = (RL + Rs)Cp$$  \hspace{1cm} (4.2.2)$$

where $RL$ is the external load resistance, $Rs$ is the internal series resistance, and $Cp$ is the parasitic capacitance. Typically, $\tau_{RC} \approx 100$ ps, although lower values are possible with a proper design. Indeed, modern $p-n$ photodiodes are capable of operating at bit rates of up to 40 Gb/s. The limiting factor for the bandwidth of $p-n$ photodiodes is the presence of a diffusive component in the photocurrent. The physical origin of the diffusive component is related to the absorption of incident light outside the depletion region. Electrons generated in the $p$-region have to diffuse to the depletion-region boundary before they can drift to the $n$-side; similarly, holes generated in the $n$-region must diffuse to the depletion-region boundary. Diffusion is an inherently slow process; carriers take a nanosecond or longer to diffuse over a distance of about 1 $\mu$m. Figure 4.4 shows how the presence of a diffusive component can distort the temporal response of a photodiode. The diffusion contribution can be reduced by decreasing the widths of the $p$- and $n$-regions and increasing the depletion-region width so that most of the incident optical power is absorbed inside it. This is the approach adopted for $p-i-n$ photodiodes, discussed next.

### 4.2.2 $p-i-n$ Photodiodes

A simple way to increase the depletion-region width is to insert a layer of undoped (or lightly doped) semiconductor material between the $p-n$ junction. Since the middle layer consists of nearly intrinsic material, such a structure is referred to as the $p-i-n$ photodiode. Figure 4.5(a) shows the device structure together with the electric-field distribution under reverse-bias operation. Because of its intrinsic nature, the middle $i$-layer offers a high resistance, and most of
the voltage drop occurs across it. As a result, a large electric field exists in the \( i \)-layer. In essence, the depletion region extends throughout the \( i \)-region, and its width \( W \) can be controlled by changing the middle-layer thickness. The main difference from the \( p-n \) photodiode is that the drift component of the photocurrent dominates over the diffusion component simply because most of the incident power is absorbed inside the \( i \)-region of a \( p-i-n \) photodiode. Since the depletion width \( W \) can be tailored in \( p-i-n \) photodiodes, a natural question is how large \( W \) should be. The optimum value of \( W \) depends on a compromise between speed and sensitivity. The responsivity can be increased by increasing \( W \) so that the quantum efficiency \( \eta \) approaches 100% [see Eq. (4.1.5)]. However, the response time also increases, as it takes longer for carriers to drift across the depletion region. For indirect-bandgap semiconductors such as Si and Ge, typically \( W \) must be in the range 20–50 \( \mu \)m to ensure a reasonable quantum efficiency. The bandwidth of such photodiodes is then limited by a relatively long transit time \( (\tau tr > 200 \text{ ps}) \). By contrast, \( W \) can be as small as 3–5 \( \mu \)m for photodiodes that use direct-bandgap semiconductors, such as InGaAs. The transit time for such photodiodes is \( \tau tr \sim 10 \text{ ps} \). Such values of \( \tau tr \) correspond to a detector bandwidth \( \Delta f \sim 10 \text{ GHz} \) if we use Eq. (4.1.9) with \( \tau tr \_\tau RC \). The performance of \( p-i-n \) photodiodes can be improved considerably by using a double-heterostructure design. Similar to the case of semiconductor lasers, the middle \( i \)-type layer is sandwiched between the \( p \)-type and \( n \)-type layers of a different semiconductor whose bandgap is chosen such that light is absorbed only in the middle \( i \)-layer. A \( p-i-n \) photodiode commonly used for lightwave applications uses InGaAs for the middle layer and InP for the surrounding \( p \)-type and \( n \)-type layers. Figure 4.5(b) shows such an InGaAs \( p-i-n \) photodiode. Since the bandgap of InP is 1.35 eV, InP is transparent for light whose wavelength exceeds 0.92 \( \mu \)m. By contrast, the bandgap of lattice-matched \( In1-xGaxAs \) material with \( x = 0.47 \) is about 0.75 eV a value that corresponds to a cutoff wavelength of 1.65 \( \mu \)m. The middle InGaAs layer thus absorbs strongly in the wavelength region 1.3–1.6 \( \mu \)m. The diffusive component of the detector current is eliminated completely in such a heterostructure photodiode simply because photons are absorbed only inside the depletion region. The front facet is often coated using suitable dielectric layers to minimize reflections. The quantum efficiency \( \eta l \) can be made almost 100% by using an InGaAs layer 4–5 \( \mu \)m thick. InGaAs photodiodes are quite useful for lightwave systems and are often used in practice. Table 4.1 lists the operating characteristics of three common \( p-i-n \) photodiodes. Considerable effort was directed during the 1990s toward developing high-speed \( p-i-n \) photodiodes capable of operating at bit rates exceeding 10 Gb/s. Bandwidths of up to 70 GHz were realized as early as 1986 by using a thin absorption layer (\( < 1 \mu m \)) and by reducing the parasitic capacitance \( C_p \) with a small size, but only at the expense of a lower quantum efficiency and responsivity. By 1995, \( p-i-n \) photodiodes exhibited a bandwidth of 110 GHz for devices designed to

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Si</th>
<th>Ge</th>
<th>InGaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>( \lambda )</td>
<td>( \mu )m</td>
<td>0.4–1.1</td>
<td>0.8–1.8</td>
<td>1.0–1.7</td>
</tr>
<tr>
<td>Responsivity</td>
<td>( R )</td>
<td>A/W</td>
<td>0.4–0.6</td>
<td>0.5–0.7</td>
<td>0.6–0.9</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>( \eta )</td>
<td>%</td>
<td>75–90</td>
<td>50–55</td>
<td>60–70</td>
</tr>
<tr>
<td>Dark current</td>
<td>( I_d )</td>
<td>nA</td>
<td>1–10</td>
<td>50–500</td>
<td>1–20</td>
</tr>
<tr>
<td>Rise time</td>
<td>( T_r )</td>
<td>ns</td>
<td>0.5–1</td>
<td>0.1–0.5</td>
<td>0.02–0.5</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>( \Delta f )</td>
<td>GHz</td>
<td>0.3–0.6</td>
<td>0.5–3</td>
<td>1–10</td>
</tr>
<tr>
<td>Bias voltage</td>
<td>( V_b )</td>
<td>V</td>
<td>50–100</td>
<td>6–10</td>
<td>5–6</td>
</tr>
</tbody>
</table>
Several techniques have been developed to improve the efficiency of high-speed photodiodes. In one approach, a Fabry–Perot (FP) cavity is formed around the $p-i-n$ structure to enhance the quantum efficiency, resulting in a laserlike structure. A FP cavity has a set of longitudinal modes at which the internal optical field is resonantly enhanced through constructive interference. As a result, when the incident wavelength is close to a longitudinal mode, such a photodiode exhibits high sensitivity. The wavelength selectivity can even be used to advantage in wavelength-division multiplexing (WDM) applications. A nearly 100% quantum efficiency was realized in a photodiode in which one mirror of the FP cavity was formed by using the Bragg reflectivity of a stack of AlGaAs/AlAs layers. This approach was extended to InGaAs photodiodes by inserting a 90-nm-thick InGaAs absorbing layer into a microcavity composed of a GaAs/AlAs Bragg mirror and a dielectric mirror. The device exhibited 94% quantum efficiency at the cavity resonance with a bandwidth of 14 nm. By using an air-bridged metal waveguide together with an undercut mesa structure, a bandwidth of 120 GHz has been realized. The use of such a structure within a FP cavity should provide a $p-i-n$ photodiode with a high bandwidth and high efficiency.

Another approach to realize efficient high-speed photodiodes makes use of an optical waveguide into which the optical signal is edge coupled. Such a structure resembles an unpumped semiconductor laser except that various epitaxial layers are optimized differently. In contrast with a semiconductor laser, the waveguide can be made wide to support multiple transverse modes in order to improve the coupling efficiency. Since absorption takes place along the length of the optical waveguide ($\sim 10 \mu$m), the quantum efficiency can be nearly 100% even for an ultrathin absorption layer. The bandwidth of such waveguide photodiodes is limited by $\tau RC$ in Eq. (4.1.9), which can be decreased by controlling the waveguide cross-section-area. Indeed, a 50-GHz bandwidth was realized in 1992 for a waveguide photodiode. The bandwidth of waveguide photodiodes can be increased to 110 GHz by adopting a mushroom-mesa waveguide structure. Such a device is shown schematically in Fig. 4.6. In this structure, the width of the $i$-type absorbing layer was reduced to 1.5 $\mu$m while the $p$- and $n$-type cladding layers were made 6 $\mu$m wide. In this way, both the parasitic capacitance and the internal series resistance were minimized, reducing $\tau RC$ to about 1 ps. The frequency response of such a device at the 1.55-$\mu$m wavelength is also shown in Fig. 4.6. It was measured by using a spectrum analyzer (circles) as well as taking the Fourier transform of the short-pulse response (solid curve). Clearly, waveguide $p-i-n$ photodiodes can provide both a high responsivity and a large bandwidth. Waveguide photodiodes have been used for 40-Gb/s optical receivers and have the potential for operating at bit rates as high as 100 Gb/s. The performance of waveguide photodiodes can be improved further by adopting an electrode structure designed to support traveling electrical waves with matching impedance to avoid reflections. Such photodiodes are called traveling-wave photodetectors.
based implementation of this idea, a bandwidth of 172 GHz with 45% quantum efficiency was realized in a traveling-wave photodetector designed with a 1-μm-wide waveguide. By 2000, such an InP/InGaAs photodetector exhibited a bandwidth of 310 GHz in the 1.55-μm spectral region.

Figure 4.7: Impact-ionization coefficients of several semiconductors as a function of the electric field for electrons (solid line) and holes (dashed line).

- **4.2.3 Avalanche Photodiodes**

All detectors require a certain minimum current to operate reliably. The current requirement translates into a minimum power requirement through $P_{in} = Ip/R$. Detectors with a large responsivity $R$ are preferred since they require less optical power. The responsivity of $p-i-n$ photodiodes is limited by Eq. (4.1.3) and takes its maximum value $R = q/hv$ for $|\gamma| = 1$. Avalanche photodiodes (APDs) can have much larger values of $R$, as they are designed to provide an internal current gain in a way similar to photomultiplier tubes. They are used when the amount of optical power that can be spared for the receiver is limited. The physical phenomenon behind the internal current gain is known as the impact ionization. Under certain conditions, an accelerating electron can acquire sufficient energy to generate a new electron–hole pair. In the band picture the energetic electron gives a part of its kinetic energy to another electron in the valence band that ends up in the conduction band, leaving behind a hole. The net result of impact ionization is that a single primary electron, generated through absorption of a photon, creates many secondary electrons and holes, all of which contribute to the photodiode current. Of course, the primary hole can also generate secondary electron–hole pairs that contribute to the current. The generation rate is governed by two parameters, $\alpha e$ and $\alpha h$, the impact-ionization coefficients of electrons and holes, respectively. Their numerical values depend on the semiconductor material and on the electric field.
Figure 4.8: (a) An APD together with the electric-field distribution inside various layers under reverse bias;
(b) design of a silicon reach-through APD.

that accelerates electrons and holes. Figure 4.7 shows $\alpha_e$ and $\alpha_h$ for several semiconductors. Values $\sim 1 \times 10^4$ cm$^{-1}$ are obtained for electric fields in the range $2-4 \times 10^5$ V/cm. Such large fields can be realized by applying a high voltage ($\sim 100$ V) to the APD. APDs differ in their design from that of $p$–$i$–$n$ photodiodes mainly in one respect: an additional layer is added in which secondary electron–hole pairs are generated through impact ionization. Figure 4.8(a) shows the APD structure together with the variation of electric field in various layers. Under reverse bias, a high electric field exists in the $p$-type layer sandwiched between $I$-type and $n^+$-type layers. This layer is referred to as the multiplication layer, since secondary electron–hole pairs are generated here through impact ionization. The $i$-layer still acts as the depletion region in which most of the incident photons are absorbed and primary electron–hole pairs are generated. Electrons generated in the $i$-region cross the gain region and generate secondary electron–hole pairs responsible for the current gain. The current gain for APDs can be calculated by using the two rate equations governing current flow within the multiplication layer:

$$\frac{d i_e}{d x} = \alpha_i i_e + \alpha_h i_h,$$

(4.2.3)

$$\frac{d i_h}{d x} = \alpha_i i_e + \alpha_h i_h,$$

(4.2.4)

where $i_e$ is the electron current and $i_h$ is the hole current. The minus sign in Eq. (4.2.4) is due to the opposite direction of the hole current. The total current,

$$I = i_e(x) + i_h(x),$$

(4.2.5)

remains constant at every point inside the multiplication region. If we replace $i_h$ in Eq. (4.2.3) by $I - i_e$, we obtain

$$d i_e/d x = (\alpha_e - \alpha_h) i_e + \alpha_h I.$$

(4.2.6)

In general, $\alpha_e$ and $\alpha_h$ are $x$ dependent if the electric field across the gain region is nonuniform. The analysis is considerably simplified if we assume a uniform electric field and treat $\alpha_e$ and $\alpha_h$ as constants. We also assume that $\alpha_e > \alpha_h$. The avalanche process is initiated by electrons that enter the gain region of thickness $d$ at $x = 0$. By using the condition $i_h(d) = 0$ (only electrons cross the boundary to enter the $n$-region), the boundary condition for Eq. (4.2.6) is $i_e(d) = I$. By integrating this equation, the multiplication factor defined as $M = i_e(d)/i_e(0)$ is given by

$$M = \frac{1 - k_A}{\exp[\left(1 - k_A\right) \alpha_e d]} - k_A,$$

(4.2.7)

where $k_A = \alpha_h/\alpha_e$. The APD gain is quite sensitive to the ratio of the impact-ionization coefficients. When $\alpha_h = 0$ so that only electrons participate in the avalanche process, $M = \exp(\alpha e d)$, and the APD gain increases exponentially with $d$. On the other hand, when $\alpha_h = \alpha_e$, so that $kA = 1$ in Eq. (4.2.7), $M = (1 - \alpha e d)^{-1}$. The APD gain then becomes infinite for $\alpha e d = 1$, a condition known as the avalanche breakdown. Although higher APD gain can be realized with a smaller gain region when $\alpha e$ and $\alpha h$ are
comparable, the performance is better in practice for APDs in which either $\alpha_e < \alpha_h$ or $\alpha_h >> \alpha_e$ so that the avalanche process is dominated by only one type of charge carrier. \[\text{where issues related to the receiver noise are considered. Because of the current gain, the responsivity of an APD is enhanced by the multiplication factor } M \text{ and is given by} \]

$$R_{APD} = M \eta q / h \nu,$$  \hspace{1cm} (4.2.8)

where Eq. (4.1.3) was used. It should be mentioned that the avalanche process in APDs is intrinsically noisy and results in a gain factor that fluctuates around an average value. The quantity $M$ in Eq. (4.2.8) refers to the average APD gain. The intrinsic bandwidth of an APD depends on the multiplication factor $M$. This is easily understood by noting that the transit time $\tau_{tr}$ for an APD is no longer given by Eq. (4.2.1) but increases considerably simply because generation and collection of secondary electron–hole pairs take additional time. The APD gain decreases at high frequencies because of such an increase in the transit time and limits the bandwidth. The decrease in $M(\omega)$ can be written as

$$M(\omega) = M_0 \left[ 1 + (\omega \tau_e M_0)^2 \right]^{-1/2},$$  \hspace{1cm} (4.2.9)

where $M_0 = M(0)$ is the low-frequency gain and $\tau_e$ is the effective transit time that depends on the ionization coefficient ratio $kA = \alpha_h / \alpha_e$. For the case $\alpha_h < \alpha_e$, $\tau_e = cA \tau_{tr}$, where $cA$ is a constant ($cA \sim 1$). Assuming that $\tau_{RC} < \tau_e$, the APD bandwidth is given approximately by $\Delta f \approx (2 \pi \tau_e M_0)^{-1}$. This relation shows the trade-off between

The APD gain $M_0$ and the bandwidth $\Delta f$ (speed versus sensitivity). It also shows the advantage of using a semiconductor material for which $kA \ll 1$. Table 4.2 compares the operating characteristics of Si, Ge, and InGaAs APDs. As $kA \ll 1$ for Si, silicon APDs can be designed to provide high performance and are useful for lightwave systems operating near 0.8 $\mu$m at bit rates $\sim$100 Mb/s. A particularly useful design, shown in Fig. 4.8(b), is known as reach-through APD because the depletion layer reaches to the contact layer through the absorption and multiplication regions. It can provide high gain ($M \approx 100$) with low noise and a relatively large bandwidth. For lightwave systems operating in the wavelength range 1.3–1.6 $\mu$m, Ge or InGaAs APDs must be used. The improvement in sensitivity for such APDs is limited to a factor below 10 because of a relatively low APD gain ($M \sim 10$) that must be used to reduce the noise. The performance of InGaAs APDs can be improved through suitable design modifications to the basic APD structure shown in Fig. 4.8. The main reason for a relatively poor performance of InGaAs APDs is related to the comparable numerical values of the impact-ionization coefficients $\alpha_e$ and $\alpha_h$ (see Fig. 4.7). As a result, the bandwidth is considerably reduced, and the noise is also relatively high. Furthermore because of a relatively narrow bandgap, InGaAs undergoes tunneling breakdown at electric fields of about $1 \times 10^5$ V/cm, a value that is below the threshold for avalanche multiplication. This problem can be solved in heterostructure APDs by using

<p>| Table 4.2 Characteristics of common APDs |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Si</th>
<th>Ge</th>
<th>InGaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>$\lambda$</td>
<td>$\mu m$</td>
<td>0.4–1.1</td>
<td>0.8–1.8</td>
<td>1.0–1.7</td>
</tr>
<tr>
<td>Responsivity</td>
<td>$R_{APD}$</td>
<td>A/W</td>
<td>80–130</td>
<td>3–30</td>
<td>5–20</td>
</tr>
<tr>
<td>APD gain</td>
<td>$M$</td>
<td>—</td>
<td>100–500</td>
<td>50–200</td>
<td>10–40</td>
</tr>
<tr>
<td>$k$-factor</td>
<td>$k_A$</td>
<td>—</td>
<td>0.02–0.05</td>
<td>0.7–1.0</td>
<td>0.5–0.7</td>
</tr>
<tr>
<td>Dark current</td>
<td>$I_D$</td>
<td>nA</td>
<td>0.1–1</td>
<td>50–500</td>
<td>1–5</td>
</tr>
<tr>
<td>Rise time</td>
<td>$T_r$</td>
<td>ns</td>
<td>0.1–2</td>
<td>0.5–0.8</td>
<td>0–0.5</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>$\Delta f$</td>
<td>GHz</td>
<td>0.2–1</td>
<td>0.4–0.7</td>
<td>1–10</td>
</tr>
<tr>
<td>Bias voltage</td>
<td>$V_b$</td>
<td>V</td>
<td>200–250</td>
<td>20–40</td>
<td>20–30</td>
</tr>
</tbody>
</table>
an In P layer for the gain region because quite high electric fields (> 5×10^5 V/cm) can exist in InP without tunneling breakdown. Since the absorption region (i-type InGaAs layer) and the multiplication region (n-type InP layer) are separate in such a device, this structure is known as SAM, where SAM stands for separate absorption and multiplication regions. As αh > αe for InP (see Fig. 4.7), the APD is designed such that holes initiate the avalanche process in an n-type InP layer, and kA is defined as kA = αe/αh. Figure 4.9(a) shows a mesa-type SAM APD structure. One problem with the SAM APD is related to the large bandgap difference between InP (Eg = 1.35 eV) and InGaAs (Eg = 0.75 eV). Because of a valence-band step of about 0.4 eV, holes generated in the InGaAs layer are trapped at the heterojunction interface and are considerably slowed before they reach the multiplication region (InP layer). Such an APD has an extremely slow response and a relatively small bandwidth.

Figure 4.9: Design of (a) SAM and (b) SAGM APDs containing separate absorption, multiplication, and grading regions.

The problem can be solved by using another layer between the absorption and multiplication regions whose bandgap is intermediate to those of InP and InGaAs layers. The quaternary material InGaAsP, the same material used for semiconductor lasers, can be tailored to have a bandgap anywhere in the range 0.75–1.35 eV and is ideal for this purpose. It is even possible to grade the composition of InGaAsP over a region of 10–100 nm thickness. Such APDs are called SAGM APDs, where SAGM indicates separate absorption, grading, and multiplication regions. Figure 4.9(b) shows the design of an InGaAsP APD with the SAGM structure. The use of an InGaAsP grading layer improves the bandwidth considerably. As early as 1987, a SAGM APD exhibited a gain–bandwidth product MΔf = 70 GHz for M > 12. This value was increased to 100 GHz in 1991 by using a charge region between the grading and multiplication regions. In such SAGCM APDs, the InP multiplication layer is undoped, while the InP charge layer is heavily n-doped. Holes accelerate in the charge layer because of a strong electric field, but the generation of secondary electron–hole pairs takes place in the undoped InP layer. SAGCM APDs improved considerably during the 1990s. A gain–bandwidth product of 140 GHz was realized in 2000 using a 0.1-μm-thick multiplication layer that required < 20 V across it. Such APDs are quite suitable for making a compact 10-Gb/s APD receiver. A different approach to the design of high-performance APDs makes use of a superlattice structure. The major limitation of InGaAs APDs results from comparable values of αe and αh. A superlattice design offers the possibility of reducing the ratio kA = αh/αe from its standard value of nearly unity. In one scheme, the absorption and multiplication regions alternate and consist of thin layers (~10 nm) of semiconductor materials with different bandgaps. This approach was first demonstrated for GaAs/AlGaAs multiquantum-well (MQW) APDs and resulted in a considerable enhancement of the impact-ionization coefficient for electrons. Its use is less successful for the InGaAs/InP material system. Nonetheless, considerable progress has been made through the so-called staircase APDs, in which the InGaAsP
layer is compositionally graded to form a sawtooth kind of structure in the energy-band diagram that looks like a staircase under reverse bias. Another scheme for making high-speed APDs uses alternate layers of InP and InGaAs for the grading region. However, the ratio of the widths of the InP to InGaAs layers varies from zero near the absorbing region to almost infinity near the multiplication region. Since the effective bandgap of a quantum well depends on the quantum-well width (InGaAs layer thickness), a graded “pseudo-quaternary” compound is formed as a result of variation in the layer thickness. The most successful design for InGaAs APDs uses a superlattice structure for the multiplication region of a SAM APD. A superlattice consists of a periodic structure such that each period is made using two ultrathin (∼10-nm) layers with different bandgaps. In the case of 1.55-μm APDs, alternate layers of InAlGaAs and InAlAs are used, the latter acting as a barrier layer. An InP field-buffer layer often separates the InGaAs absorption region from the superlattice multiplication region. The thickness of this buffer layer is quite critical for the APD performance. For a 52-nm-thick field-buffer layer, the gain–bandwidth product was limited to $M\Delta f = 120$ GHz but increased to 150 GHz when the thickness was reduced to 33.4 nm. These early devices used a mesa structure. During the late 1990s, a planar structure was developed for improving the device reliability. Figure 4.10 shows such a device schematically together with its 3-dB bandwidth measured as a function of $M$. The gain–bandwidth product of 110 GHz is large enough for making APDs operating at 10 Gb/s. Indeed, such an APD receiver was used for a 10-Gb/s lightwave system with excellent performance. The gain–bandwidth limitation of InGaAs APDs results primarily from using the InP material system for the generation of secondary electron–hole pairs. A hybrid approach in which a Si multiplication layer is incorporated next to an InGaAs absorption layer may be useful provided the heterointerface problems can be overcome. In a 1997 experiment, a gain-bandwidth product of more than 300 GHz was realized by using such a hybrid approach. The APD exhibited a 3-dB bandwidth of over 9 GHz for values of $M$ as high as 35 while maintaining a 60% quantum efficiency. Most APDs use an absorbing layer thick enough (about 1 μm) that the quantum efficiency exceeds 50%. The thickness of the absorbing layer affects the transit time $\tau_{tr}$ and the bias voltage $V_b$. In fact, both of them can be reduced significantly by using a thin absorbing layer (∼0.1 μm), resulting in improved APDs provided that a high quantum efficiency can be maintained. Two approaches have been used to meet these somewhat conflicting design requirements. In one design, a FP cavity is formed to enhance the absorption within a thin layer through multiple round trips. An external quantum efficiency of ∼70% and a gain–bandwidth product of 270 GHz were realized in such a 1.55-
μm APD using a 60-nm-thick absorbing layer with a 200-nm-thick multiplication layer. In another approach, an optical waveguide is used into which the incident light is edge coupled. Both of these approaches reduce the bias voltage to near 10 V, maintain high efficiency, and reduce the transit time to \( \sim 1 \) ps. Such APDs are suitable for making 10-Gb/s optical receivers.
CHAPTER 5

Design of Optical Integrated Amplifier

5.1 Introduction

Important for the design and understanding of optoelectronic integrated devices (OEIDs) is the development of an analytical mathematical model describing the dynamic and static characteristics, or optical and electrical characteristics. This challenge has been taken up by a number of authors whose efforts contribute to this section. Below, the formulation of the transient behavior of optoelectronic integrated devices (OEIDs) is presented; this formulation allows the calculation of the frequency response, time response, rise time, and device speed of any OEID. The formulations of the transient behavior of the excited photocurrent inside the optoelectronic integrated devices (OEID) is presented; this formulation allows the calculation of the I-V curve, switching voltage (break over voltage), switching current, optical and electrical feedback of any OEID. Also, theoretical formulation to derive the optical gain of HPT based on solution of the diffusion equation and applying the boundary conditions at the base-collector region is presented, also, theoretical formulations to drive the transient response of OEID composed of HPT and LD based on solution of the rate equations is presented. Finally, a formulation for the relative intensity noise for OEID composed of HPT and LD is presented.

5.2 Excited photocurrent Inside the Device

5.2.1. Transient Behavior

The excited photocurrent inside the Optoelectronic Integrated Device (OEID) has two components; the first is due to the light incident on the Hetrojunction Phototransistor (HPT) from the external source, the second component is due to the light back inside the device from the Laser Diode to the Hetrojunction Phototransistor (HPT). The Block of the device with optical feedback enabling calculation of photocurrent is shown in Fig. 2.2, from the block diagram, the excited photocurrent inside the device can be expressed as:
The ratio of the photons which reach the HPT to those emitted by the LD that is represented by $k_f(\omega)$ is a frequency independent because the delay time for this photons is very small, thus $k_f(\omega) = k_f$.

By using the Laplace method, the frequency response of the excited photocurrent inside the optoelectronic integrated device can thus be expressed as:

$$i(\omega) = \frac{\left( \frac{q}{h\nu} \right) g(\omega) P_m}{1 - k_f(\omega) g(\omega) \eta(\omega)}$$

(5-1)

Fig. 2.2 Block diagram of OEID with optical feedback

When the input light is assumed as a step function in time, the Laplace transform of the photocurrent can be obtained as

$$i(s) = \frac{q g_0 \omega \beta P_m}{h \nu (s + \omega \beta) s(1 - \frac{g_0 \omega \beta \eta_0 w_k k_f}{(s + \omega \beta)(s + \omega_1)})}$$

(5-3)

The output response of the electrical current of the optoelectronic integrated devices can be obtained from the inverse Laplace of Eq. (5-3) as
The output response of the electrical current of the optoelectronic integrated devices can be obtained as

\[ i(t) = L^4 \left( \frac{qg_0\omega_\beta P_w}{h\nu(s + \omega_\beta)s(1 - g_0\omega_\beta\eta_0w_fk_f/(s + \omega_\beta)(s + \omega_\gamma))} \right) \]  

(5-4)

The output response of the electrical current of the optoelectronic integrated devices can be obtained as

\[ i(t) = \left( (q/h\nu)g_0P_m \right) \left\{ \frac{\omega_1\omega_\beta}{\lambda_1\lambda_2} \left( \frac{\omega_\beta(\lambda_1 + \omega_1)}{\lambda_1(\lambda_1 - \lambda_2)} e^{\lambda_1 t} + \frac{\omega_\beta(\lambda_2 + \omega_1)}{\lambda_2(\lambda_2 - \lambda_1)} e^{\lambda_2 t} \right) \right\} \]  

(5-5)

Where \( \lambda_1 \) and \( \lambda_2 \) are the same as described in Eq. (2-5) and Eq. (2-6)

5. 3 Photocurrent Rise Time

By using the approximation where, \( \lambda_1\lambda_2 = \omega_\beta(1 - g_0\eta_0k_f) \) and \( \lambda_2 = -\omega_\beta \). The rise time of the photocurrent inside the optoelectronic integrated devices is defined as the time required for \( i(t) \) to rise to 0.9 of its final value, by solving Eq. (5-5). The rise time can be given as

\[ T_\lambda = \frac{1}{\lambda_1} \ln \left[ \frac{(q/h\nu)g_0P_m - 0.9(1 - k_f g_0\eta_0)}{(q/h\nu)g_0P_m} \right] \]  

(5-6)

Where \( i_* = \frac{(q/h\nu)g_0P_m}{1 - g_0\eta_0k_f} \)  

(5-7)

In the switching mode, the rise time can be obtained by setting \( i_* = i_s \), which can further be simplified as

\[ T_s = \frac{1}{\lambda_1} \ln \left[ \frac{(q/h\nu)g_0P_m + 0.9(k_f g_0\eta_0 - 1)\dot{i}_s}{(q/h\nu)g_0P_m} \right] \]  

(5-8)

5.4 Excited Photocurrent inside the OEID

The device parameters used in the following calculations are the same as those used by Zhu et al. [6], where \( \omega_\beta = 10^8 \text{Hz} \), \( \omega_1 = 10^{10} \text{Hz} \), and \( g_0\eta_0 = 100 \). The input light is assumed as a step function in time. The transient response of the excited photocurrent inside the OEID in the amplification mode is shown in Fig. 2. It can be seen that the photocurrent inside the device approaches a definite and is stable in this mode, while the transient response of the photocurrent inside the device is shown in Fig. 3. In this mode the output photocurrent increases exponentially with time, which corresponds to the jump in the switching mode.
Figure 4 shows the output photocurrent versus the HPT conversion gain at the amplification mode. It can be seen that the photocurrent inside the device increases as the gain of the phototransistor and the optical feedback increase.

The dependence of the rise time of photocurrent inside the OEID on the optical feedback coefficient in the amplification mode is shown in Fig. 5. It is clear that by increasing the optical feedback, there is an increase in the rise time due to the increase of the difference between the output photocurrent at the initial and the final state. The optical feedback is usually weakened in the amplification mode by inserting an absorption layer between the HPT and LD, and thus the rise time in this mode is equal in magnitude as that of the HPT with optical feedback.

![Block diagram of OEID with optical feedback](image-url)
Fig. 2 Transient response of photocurrent inside OEID at different values of \( k_0 \):

- at \( k_0 = 0.001 \)
- at \( k_0 = 0.005 \)
- at \( k_0 = 0.008 \)

Fig. 3. Transient response of the photocurrent in the switching mode:

- at \( k_0 = 0.04 \)
- at \( k_0 = 0.06 \)
- at \( k_0 = 0.08 \)
Fig. 5. Dependence of the Rise Time on optical feedback coefficient in the amplification mode
CAPSTONE DESIGN PROJECT

Project Submission
&
ABET Criterion 3 a-k Assessment Report

Project Title: __________________________________ DATE: / / 14
PROJECT ADVISOR: ______________________________
Team Leader: ______________________________
Team Members: ___________ ______________________________
____________________________
____________________________
____________________________

Design Project Information

Percentage of project Content - Engineering Science %                  ______
Percentage of project Content - Engineering Design %                  __________
Other content %  All fields must be added to 100%                       __________________
Please indicate if this is your initial project declaration
or final project form
☐ Project Initial Start Version
☐ Final Project Submission Version

Do you plan to use this project as your capstone design project? _____________________________

Mechanism for Design Credit
☐ Projects in Engineering Design
☐ Independent studies in Engineering
☐ Engineering Special Topics

Fill in how you fulfill the ABET Engineering Criteria Program Educational Outcomes listed below

Outcome (a),
An ability to apply knowledge of mathematics, science, and engineering fundamentals.
Please list here all subjects (math, science, engineering) that have been applied in your project.
Example: let’s consider a HVAC (Heat Ventilation Air Conditioning) system, then, you would include:

Outcome (b).
An ability to design and conduct experiments, and to critically analyze and interpret data.
In this part, if the project included experimental work for validation and/or verification purposes, please indicate that.
Example: Consider the pervious example (i.e. HVAC system) Validation of Actual Heat Transfer Rates at the site, System.
<table>
<thead>
<tr>
<th>Outcome (c).</th>
<th>An ability to design a system, component or process to meet desired needs within realistic constraints such as economic, Environmental, Social, political, ethical, health and safety, manufacturability, and sustainability.</th>
<th>All projects should include a design component. By design we mean both physical and non physical systems. Example: Designing a HVAC system, or Metal Coating system, Robot Arm would be considered a physical system. The trick here is to be precise in listing what you had actually designed and what you have acquired from the market. On the other hand, if your project had a non-physical nature, such as: designing a quality assurance system, a supply chain, or an ERP (Enterprise Resource Planning) System. Please note that you must be working with real data, i.e. data that has been supplied by a client in the industry. Hence, you must list the overall structure for the designed system, with its inputs, outputs, and constraints.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcome (d).</td>
<td>An ability to function in multidisciplinary teams.</td>
<td>This outcome is achieved automatically by the fact that all projects composed of at least 3 students. However, if the project involved students from other departments, that would be a plus that is worth to be highlighted.</td>
</tr>
<tr>
<td>Outcome (e).</td>
<td>An ability to identify, formulate and solve engineering problems.</td>
<td>In order to meet this specific outcome, it would help if you have a Problem Statement section in your project report. If not, then briefly highlight how the “students” were able to identify, formulate and solve the project’s problem.</td>
</tr>
<tr>
<td>Outcome (f).</td>
<td>An understanding of professional and ethical responsibility.</td>
<td>Here professional and ethical responsibility depends on the project context. Example in the HVAC project it would be not ethical for example to ignore having a ventilation and air conditioning for the rooms of the servants and janitors.</td>
</tr>
<tr>
<td>Outcome (g).</td>
<td>An ability for effective oral and written communication.</td>
<td>Good report and good presentation will fulfill this outcome.</td>
</tr>
<tr>
<td>Outcome (h).</td>
<td>The broad education necessary to understand the impact of engineering solutions in a global economics, environmental and societal context.</td>
<td>This outcome is usually fulfilled by highlighting the economic feasibility of the project, and emphasizing that the project would not harm the environment and does not negatively affect human subjects.</td>
</tr>
<tr>
<td>Outcome (i).</td>
<td>A recognition of the need for, and an ability to engage in life-long learning.</td>
<td>This outcome is fulfilled by suggesting a plan for future studies and what else could be done based on the outcome of the current project.</td>
</tr>
<tr>
<td>Outcome (j).</td>
<td>A knowledge of contemporary issues.</td>
<td>Extensive literature review by the “students” for the current state of the art will fulfill this outcome.</td>
</tr>
<tr>
<td>Outcome (k).</td>
<td>An ability to use the techniques, skills and modern engineering tools necessary for engineering practice.</td>
<td>List all technologies included in the project (hardware and software).</td>
</tr>
</tbody>
</table>
By signing below certify that this work is your own and fulfills the criteria described above

Student Team Signatures

_________________________  __________________________
_________________________  __________________________

Project Advisor Signature __________________________ Date

College Coordinator of Capstone Projects __________________________

Approved By __________________________
1. SUGGESTIONS ON MAKING ORAL CAPSTONE PROJECT PRESENTATIONS

1) Opening: Use a title overhead to open the presentation

2) Organization: An early slide (probably the second one) should give an outline (Agenda) of the presentation. Be sure to include any assumptions made.

   Problem statements are an excellent way to begin the actual presentation (after the outline). However, problem statements should describe the need not the solution. The solution is best presented in the objective of the design. Problem statements are an important part of this process.

3) Slides: Limit the amount of information on a slide and use large print (presentation-sized fonts). Usually, typed material will be too difficult to read from a distance.

   Do not read a list from an overhead word-for-word to the audience. Just summarize the points being presented.

4) General: Limit your discussions as much as possible.

   Be tolerant of questions. Most reviewers do not have intimate knowledge of your project and may even be a different discipline than your own.

   Do not try to cover too much detail, just enough to describe the design process.

   Be prepared before standing up. Sorting through papers, slides or setting up a demo while opening a presentation is too much of a distraction.

   Practice enough so that you do not have to constantly refer to notes. This allows you to judge the time required for your presentation. Stay within the time guidelines provided (less than 20 minutes).

   Include cost analysis information if your project involves construction or manufacturing. These cost estimates should include labor to build or assemble and not just be a summary of the cost of pa

2. PROBLEM STATEMENT

A good problem statement:
• States the specifics of the problem - who, what, when, and where.

• States the effect, but not the cause - what is wrong, not why it is wrong.

• Focuses on the gap between what is and what should be. The gap may be a change or deviation from a norm, standard, or reasonable expectation.

• Includes some measurements of the problem - how often, how much or when.

• Avoids broad categories like moral, productivity, communication and training since these tend to have different meanings for different people.

• Do not state problems as questions, since this implies that the answer to the questions is the solution to the problem.

• States why the problem is important.

3. FINAL ORAL PRESENTATION OUTLINE

• Title
• Agenda and outlines
• General importance of the work
• Specific motivation for the work
• Overall scope of the work
• Specific objectives
• Details of the work
• Results
• Summary
• Conclusions
• Future work
4. The successful oral presentation must provide the members of an audience with the answer to the following questions:

- What is the title of the work?
- What is the name of the presenter and his affiliation?
- Why is the work important?
- What is the presenter’s motivation for the work?
- What related work exists?
- What is unique about the presenter’s approach?
- What is the overall scope of the work?
- What are the specific objectives of the work?
- How was the work performed?
- Did the results meet the objectives?
- What happens next?
Conclusions

The transient response of the excited photocurrent inside an Optoelectronic Integrated Device (OEID) composed of a Hetrojunction Phototransistor (HPT) and Laser Diode (LD) is analyzed. The analytical expressions describing the transient response of the excited photocurrent inside the device are derived; the effect of the various device parameters on the transient response is outlined. The photocurrent inside the device is in the amplification (stable) mode for lower optical feedback, and in the switching (unstable) mode for higher optical feedback. The rise time in both amplification and switching modes have been calculated. In the amplification mode, the rise time increase with increasing the optical feedback inside the device, while in the switching mode, it decreases with increasing the optical feedback inside the device. This type of model can be exploited as optical amplifier, optical switching device and other applications.

References


