Chapter 1

Optoelectronics and Channel Modelling for Indoor Infrared Links

This document is a summary of Chapter 2 of the following work :

> Steve Hranilovic, *Modulation and Constrained Coding Techniques for Wireless Infrared Communication Channels*, M.A.Sc. Thesis, 1999, University of Toronto.

The full thesis is available by mailing the author at `steve@comm.utoronto.ca`.

In order to proceed with the design of a high-speed wireless optical link, a basic knowledge of the channel characteristics is required. This document presents a high-level overview of the characteristics and constraints of wireless optical links. The basic channel characteristics are further illuminated by an overview of the device physics governing opto-electronic devices. On the basis of device behaviour, a comparison between popular devices is used to justify the design choices. Various noise sources present in the free space optical link are also discussed to determine which are dominant.

1.1 The Wireless Optical Channel

Wireless optical channels differ in several key ways from conventional communications channels treated extensively in literature. This section presents introductory remarks on the channel characteristics and structure.

1.1.1 Basic Channel Structure

In a wireless optical channel, information is transmitted by sending a time varying optical signal between the transmitter and receiver. The information sent on this channel is not contained in the amplitude, phase or frequency of the transmitted optical waveform, but rather in the *intensity* of the transmitted signal. Present day optoelectronics cannot operate directly on the frequency or phase of the 10^{14} Hz range optical signal. Instead, only the intensity, defined as the power per area in $\mathrm{W/m^2}$, can be modulated or detected by the optoelectronics.

On a conceptual level, the operation of optoelectronic devices can be seen as performing a conversion between the optical domain, where the signal is a time varying intensity, and the electrical domain, where the information is sent as a current signal. In ideal devices, the conversion between the two signal domains is governed by a linear proportionality constant. The operation of some popular optoelectronic components is described in more detail in Sections 1.2.1 and 1.2.2.

The operation of a wireless optical channel is outlined in Figure 1.1. The transmit electronics convert an input data stream into a time varying current, $i_{tx}(t)$. This current is used to drive a light emitting device to produce the output optical radiation. The electrical characteristics of the light emitter can be modelled as a diode, as shown in the figure. The electrical current signal is converted to an optical intensity signal, $x(t)$, by the light emitter. The intensity signal $x(t)$ ideally is proportional to the magnitude of the electrical signal current, $i_{tx}(t)$.

This optical radiation propagates through free-space until it reaches the light detector at the receive side of the link. The light detector is often termed a square law device since its operation is modelled as squaring the amplitude of the incoming electromagnetic signal and integrating over time to find the intensity. The output of the light detector is a current signal, $i_{rx}(t)$, proportional to the intensity of the received optical signal. The electrical operation of this device is most often modelled as a reverse biased diode, as shown

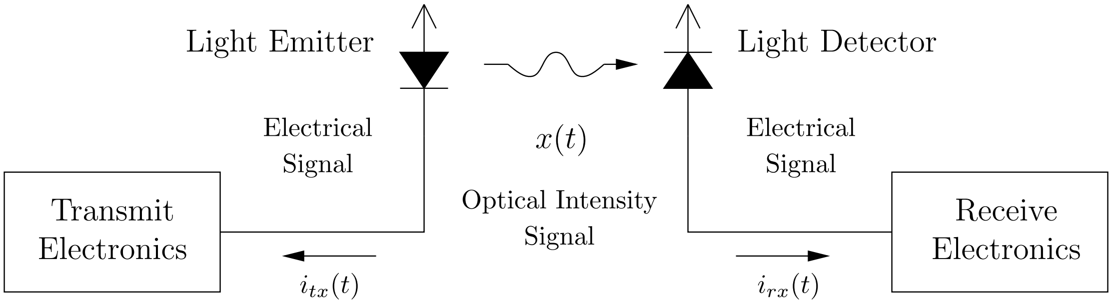


Figure 1.1: Basic channel structure of a wireless optical link.

in Figure 1.1. This received electrical current signal is amplified and the digital information detected.

The fact that the optical channel is an intensity modulated one, adds constraints on the class of signals which may be transmitted. The information bearing intensity signal must remain positive for all time since the transmitted power can physically never be negative. Thus, the physics of the link imposes the fundamental constraint that the transmitted signals remain non-negative for all time.

1.1.2 Eye Safety

Safety considerations must be taken into account when designing a wireless optical link. Since the energy is propagated in a free-space channel, the impact of this radiation on eye safety must be considered.

The International Electrotechnical Commission (IEC) is the standards body which classifies exposure limits of optical sources. Table 1.1 includes a list of the primary classes under which an optical radiator can fall. Class 1 operation is most desirable for a wireless optical system since emissions from products are safe under all circumstances. Under these conditions, no warning labels need to be applied and the device can be used without special safety precautions. This is important since these optical links are destined to be inexpensive, portable and convenient for the user. Longer distance free-space links often operate in class 3B mode, and are used for high data rate transmission over moderate distances (40 m in [1]). The safety of these systems is maintained by locating optical beams on rooftops or on towers to prevent inadvertent interruption [2].

The critical parameter which determines whether a source falls into a given class

	Interpretation
Class 1	Safe under reasonably foreseeable conditions of operation.
Class 2	Eye protection afforded by aversion responses including blink reflex (for visible sources only λ=400–700 nm).
Class 3A	Safe for viewing with unaided eye. Direct intra-beam viewing with optical aids may be hazardous.
Class 3B	Direct intra-beam viewing is always hazardous. Viewing diffuse reflections is normally safe.

Table 1.1: Interpretation of IEC safety classification for optical sources [3].

depends on the application. The allowable exposure limit (AEL) depends on the wavelength of the optical source, the geometry of the emitter and the intensity of the source. For high frequency modulated sources, the average transmitted power of modulation scheme used sets the AEL for a given geometry and wavelength. At modulation frequencies greater than about 24 kHz, the AEL can be calculated based on average output power of the source [4].

The choice of which optical wavelength to use for the wireless optical link also impacts the AEL. Table 1.2 presents the limits for the average transmitted optical power for the IEC classes listed in Table 1.1 at four different wavelengths. The allowable average optical power is calculated assuming that the source is a point emitter, in which the radiation is emitted from a small aperture and diverges slowly as is the case in laser diodes. Wavelengths in the 650 nm range are visible red light emitters. These are seldom used due to the high background ambient light noise present in the channel. Infrared wavelengths are typically used in optical networks. The wavelengths λ=880 nm, 1310 nm and 1550 nm correspond to the loss minima in typical silica fibre systems, at which wavelengths optoelectronics are commercially available [5]. The trend apparent in Table 1.2 is that for class 1 operation the allowable average optical power increases as does the optical wavelength. This would suggest that the "far" infrared wavelengths above 1 μm are best suited to wireless optical links due to their higher optical power budget for class 1 operation. The difficulty in using this band is the prohibitive cost associated with these far infrared devices. Photodiodes for far infrared bands are made from exotic III-V semiconductor compounds while photodiodes for the 880 nm band are manufactured in low cost silicon technologies. As a result, the 880 nm "near" infrared optical band is typically used for wireless optical links, and is assumed as the optical wavelength in the balance of this work.

The power levels listed in Table 1.2 are pessimistic when applied to light sources

	650 nm visible	880 nm infrared	1310 nm infrared	1550 nm infrared
Class 1	< 0.2 mW	< 0.5 mW	< 8.8 mW	< 10 mW
Class 2	0.2–1 mW	n/a	n/a	n/a
Class 3A	1–5 mW	0.5–2.5 mW	8.8–45 mW	10–50 mW
Class 3B	5–500 mW	2.5–500 mW	45–500 mW	50–500 mW

Table 1.2: Point source safety classification based on allowable average optical power output for a variety of optical wavelengths [2, 3].

which emit less concentrated beams of light, such as light emitting diodes. For a diode with λ=880 nm, a diameter of 1 mm and emitting light through cone of angle 30°, the allowable average power for class 1 operation is 28 mW [4]. However, the allowed average optical power for class 1 operation still increases with wavelength. Section 1.2.1 discusses the tradeoff between the use of lasers or light emitting diodes as light emitters.

Eye safety considerations limit the average optical power which can be transmitted. This is another fundamental limit on the performance of free-space optical links. Therefore, the constraint on any modulation scheme constructed for wireless optical links is that the *average* optical power is limited.

1.1.3 Channel Propagation Properties

As is the case in radio frequency transmission systems, multipath propagation effects are important for wireless optical networks. The power launched from the transmitter may take many reflected and refracted paths before arriving at the receiver. In radio systems, the sum of the transmitted signal and its images at the receive antenna cause spectral nulls in the transmission characteristic. These nulls are located at frequencies where the phase shift between the paths causes destructive interference at the receiver. This effect is known as *multipath fading* [6].

Unlike radio systems, multipath fading is not a major impairment in wireless optical transmission. The “antenna” in a wireless optical system is the light detector which typically has an active radiation collection area of approximately 1 cm^2. The relative size of this antenna with respect to the wavelength of the infrared light is immense, on the order of $10^4\lambda$. The multipath propagation of light produces fades in the amplitude of the received electromagnetic signal at spacings on the order of half a wavelength apart. As mentioned earlier, the light detector is a square law device which integrates the square of the amplitude of the electromagnetic radiation impinging on it. The large size of the detector with respect to the wavelength of the light provides a degree of inherent spatial diversity in the receiver which mitigates the impact of multipath fading [7].

Although multipath fading is not a major impediment to wireless optical links, temporal dispersion of the received signal due to multipath propagation remains a problem. This dispersion is often modelled as a linear time invariant system since the channel properties change slowly over many symbol periods. The impact of multipath dispersion is most noticeable in diffuse infrared communication systems. In short distance line-of-sight (LOS) links, multipath dispersion is seldom an issue. Indeed, channel models proposed for LOS links assume the LOS path dominates and model the channel as a linear attenuation and delay. Thus, for the short range optical links considered in this work, multipath effects are not significant [8, 9, 10].

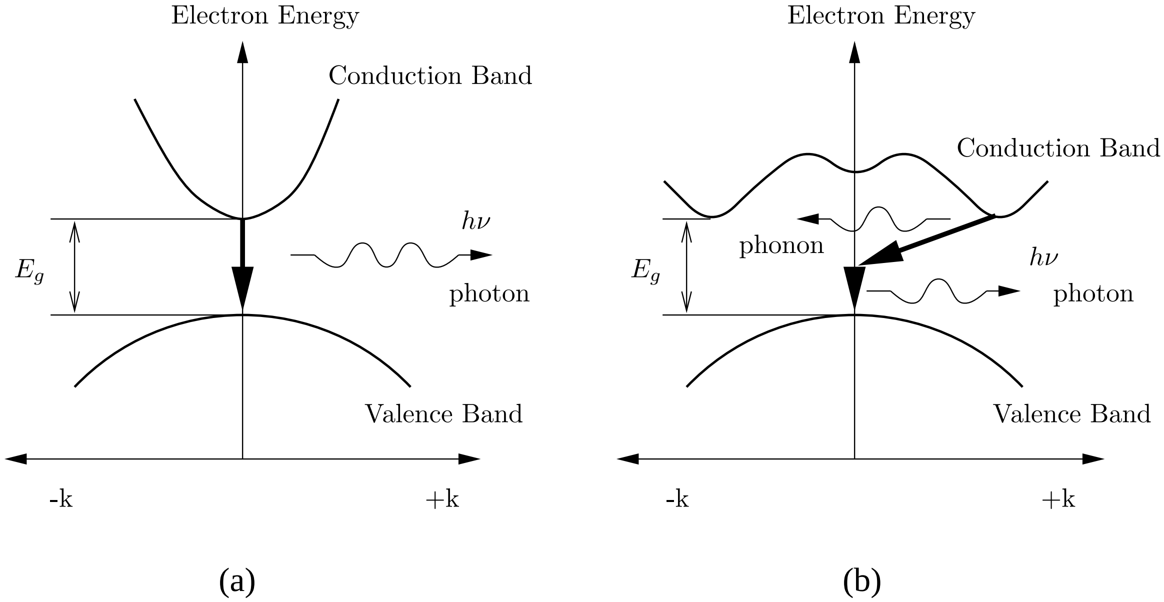
1.2 Optoelectronic Components

The basic channel characteristics can be investigated more fully by considering the operation of the optoelectronic devices alone. Device physics provides significant insight into the operation of these optoelectronic devices. This section presents an overview of the basic device physics governing the operation of certain optoelectronic devices, emphasising their benefits and disadvantages for wireless optical applications.

1.2.1 Light Emitting Devices

Solid state light emitting devices are essentially diodes operating in forward bias which output an optical intensity approximately linearly related to the drive current. This output optical intensity is due to the fact that a large proportion of the injected minority carriers recombine giving up their energy as emitted photons.

To ensure a high probability of recombination events causing photon emission, light emitting devices are constructed of materials known as *direct band gap* semiconductors. In this type of crystal, the extrema of the conduction and valence bands coincide at the same value of wave vector. As a result, recombination events can take place across the band gap while conserving momentum, represented by the wave vector (as seen in Figure 1.2)[11]. A majority of photons emitted by this process have energy $E_{photon} = E_g = h\nu$, where E_g is the band gap energy, h is Planck's constant and ν is the photon frequency in hertz. This



(a) (b)

Figure 1.2: An example of a one dimensional variation of band edges with wave number (k) for (a) direct band gap material, (b) indirect band gap material [13].

equation can be re-written in terms of the wavelength of the emitted photon as

$$\lambda = \frac{1240}{E_g} \tag{1.1}$$

where λ is the wavelength of the photon in nm and E_g is the band gap of the material in electron-Volts. Commercial direct band gap materials are typically compound semiconductors of group III and group V elements. Examples of these types of crystals include: GaAs, InP, InGaAsP and AlGaAs (for Al content less than ≈ 0.45) [12].

Elemental semiconducting crystals silicon and germanium are *indirect band gap* materials. In these types of materials, the extrema of conduction and valence bands do not coincide at the same value of wave vector k, as shown in Figure 1.2. Recombination events cannot occur without a variation in the momentum of the interacting particles. The required change in momentum is supplied by collisions with the lattice. The lattice interaction is modelled as the transfer of phonon particles which represent the quantisation of the crystalline lattice vibrations. Recombination is also possible due to lattice defects or due to impurities in the lattice which produce energy states within the band gap [12, 14]. Due to the need for a change in momentum for carriers to cross the band gap, recombination events in indirect band gap materials are less likely to occur. Furthermore, when recombination does take place, most of the energy of recombination process is lost to the lattice as heat and little is left for photon generation. As a result, indirect band gap materials produce highly inefficient light emitting devices [13].

The structure of light emitting devices fabricated in direct band gap III-V compounds greatly varies the properties of the emitted optical intensity signal. The two most popular solid-state light emitting devices are light emitting diodes (LEDs) and laser diodes (LDs).

Light Emitting Diodes

As was mentioned in Section 1.1.2, the use of the $780 - 950$ nm optical band is preferable due to the availability of low cost optoelectronic components. The direct band gap, compound semiconductor GaAs has a band gap of approximately 1.43 eV which corresponds to a wavelength of approximately 880 nm following (1.1).

Most modern LEDs in the band of interest are constructed from GaAs and AlGaAs as double heterostructure devices. This type of structure is formed by depositing two wide band gap materials on either side of a lower band gap material, and doping the materials appropriately to give diode action. An example of an AlGaAs/GaAs/AlGaAs double heterostructure LED is illustrated in Figure 1.3. Under forward bias conditions, the band diagram forms a potential well in the low band gap material (GaAs) into which carriers are injected. This region is known as the *active region* where recombination of the injected carriers takes place. The recombination process in the active region occurs randomly and as a result the photons are generated incoherently (i.e., the phase relationship between emitted photons is random in time). This type of radiation is termed *spontaneous emission* [12].

The advantages of using a double heterostructure stem from the fact that the injected carriers are confined to a well defined region. This confinement results in large concentration of injected carriers in the active region. This in turn reduces the radiative recombination time constant, improving the frequency response of the device. Another advantage of this carrier confinement is that the generated photons are also confined to a well defined area. Since the adjoining regions have a larger band gap than the active region, the losses of due to absorption in these regions is minimised [11].

Using the structure for the LED in Figure 1.3, it is possible to derive an expression for the output optical power of the device as a function of the drive current in the following

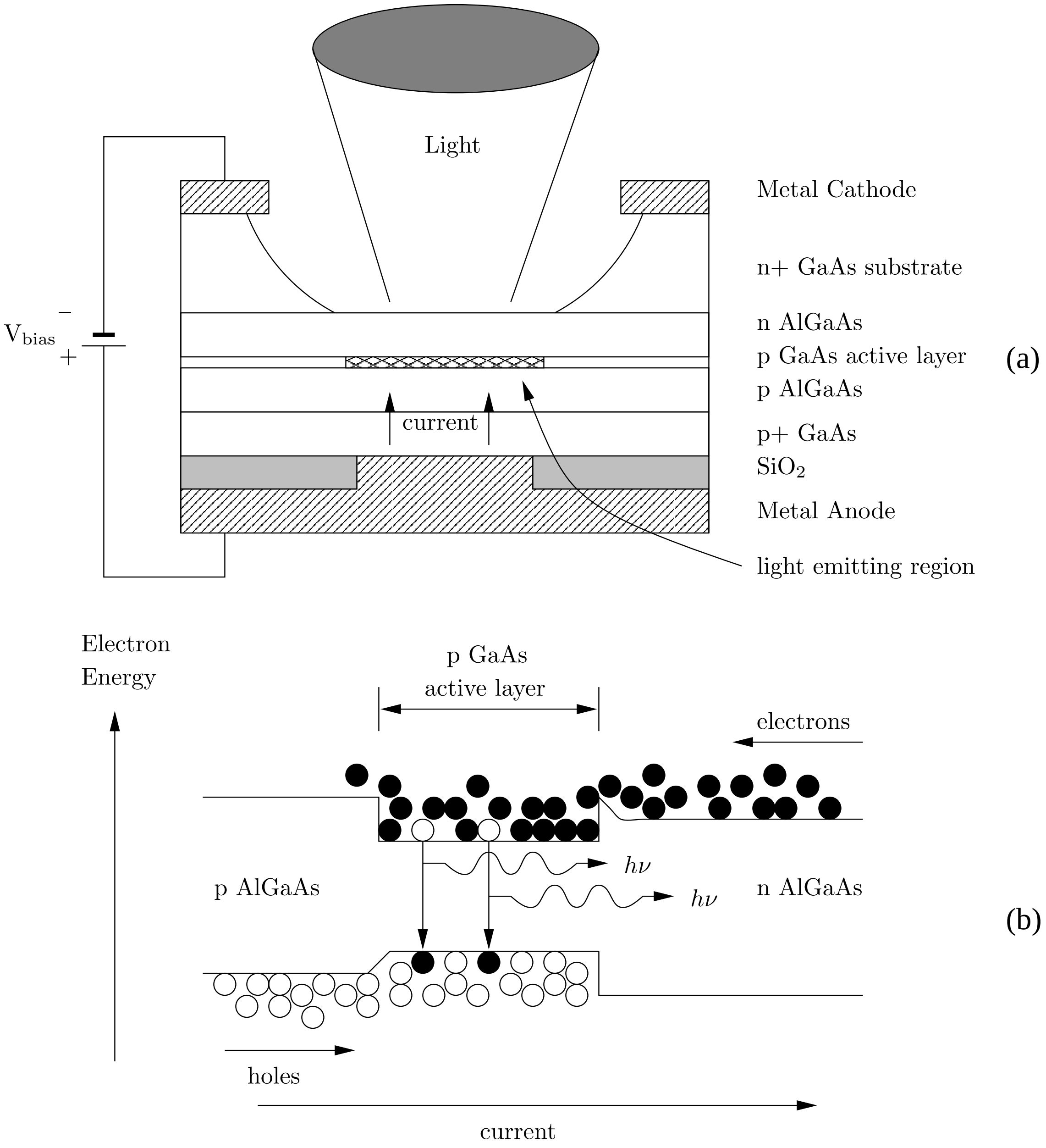


Figure 1.3: An example of an AlGaAs/GaAs/AlGaAs double heterostructure LED (a) construction and (b) band diagram under forward bias [12, 11].

form :

$$P_{vol} = h\nu \frac{J}{qd} B\tau_n \left(p_o + n_o + \frac{\tau_n J}{qd} \right), \tag{1.2}$$

where P_{vol} is the output power per unit device volume, J is the the current density applied, $h\nu$ is the photonic energy, d is the thickness of the active region, B is the radiative recombination coefficient, τ_n is electron lifetime in the active region and p_o, n_o are carrier concentrations at thermal equilibrium in the active region [12].

Equation 1.2 shows that for low levels of injected current, $p_o > \tau_n J/qd$ and P_i is approximately proportional to the current density. As the applied current density increases (by increasing drive current) the optical output of the device exhibits more non-linear components. The choice of active region thickness, d, is a critical design parameter for source linearity. By increasing the thickness of the active region, the device has a wider range of input currents over which the behaviour is linear. However, an increase in the active region thickness reduces the confinement of carriers. This, in turn, limits the frequency response of the device as mentioned above. Thus, there is a trade-off between the linearity and frequency response of LEDs.

Another important characteristic of the LED is the performance of the device due to self-heating. As the drive current flows through the device, heat is generated due to the Ohmic resistance of the regions as well as the inefficiency of the device. This increase in temperature degrades the internal quantum efficiency of the device by reducing the confinement of carriers in the active region since a large majority have enough energy to surmount the barrier. This non-linear drop in the output intensity as a function of input current can be seen in Figure 1.4. The impact of self-heating on linearity can be improved by operating the device in pulsed operation and by the use of compensation circuitry [15, 16, 17]. Prolonged operation under high temperature environments reduces output optical intensity at a given current and can lead to device failure [18, 5].

The central wavelength of the output photons is approximately equal to the result given in (1.1). The typical width of the output spectrum is approximately 40 nm around the centre wavelength of 880 nm. This variation is due to the temperature effects as well as the energy distributions of holes and electrons in the active region [12].

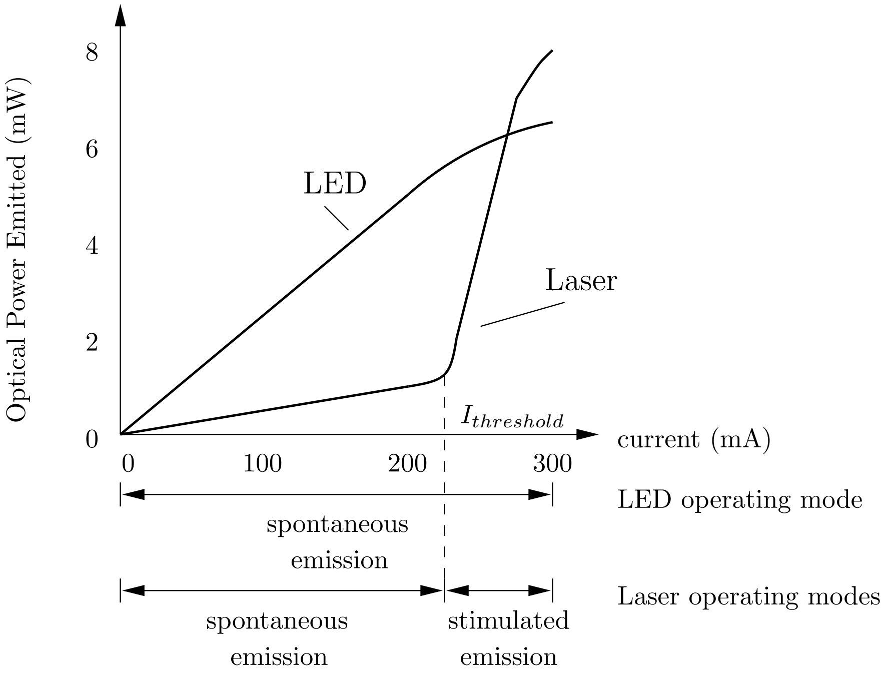


Figure 1.4: An example of an optical intensity versus drive current for LED and LD [18]

Laser Diodes

Laser diodes (LDs) are a more recent technology which has grown from underlying LED fabrication techniques. LDs still depend on the transition of carriers over the band gap to produce radiant photons, however, modifications to the device structure allow such devices to efficiently produce coherent light over a narrow optical bandwidth.

As mentioned above, LEDs undergo spontaneous emission of photons when carriers traverse the band gap in a random manner. LDs exhibit a second form of photon generation process : *stimulated emission.* In this process, photons of energy E_g are incident on the active region of the device. In the active region, an excess of electrons is maintained such that in this region the probability of an electron being in the conduction band is greater than it being in the valence band. This state is called population inversion and is created by the confinement of carriers in the active region and the carrier pumping of the forward biased junction. The incident photon induces recombination processes to take place. The emitted photons in this process have the same energy, frequency, and phase as the incident photon. The output light from this reaction is said to be *coherent* [12, 13, 19].

In order for this process to be sustainable, the double heterostructure is modified to provide optical feedback. This optical feedback occurs essentially by placing a reflective surface to send generated photons back through the active region to re-initiate the recombination process. There are many techniques to provide this optical feedback, each with their merits and disadvantages. A Fabry-Perot laser achieves photon confinement by having internal reflection inside the active region. This is accomplished by adjusting the refractive-index of surrounding materials. The ends of the device have mirrored facets which are cleaved from the bulk material. One facet provides nearly total reflection while the other allows some transmission to free-space [12].

The operation of this optical feedback structure is analogous to microwave resonators which confine electromagnetic energy by high conductivity metal. These structures resonate at fixed set of modes depending on the physical construction of the cavity. As a result, due to the structure of the resonant cavity LDs emit their energy over a very narrow spectral width. Also, the resonant nature of the device allows for the emission of relatively high power levels.

Unlike LEDs which emit a light intensity approximately proportional to the drive current, lasers are threshold devices. As shown in Figure 1.4, at low drive currents spontaneous emission dominates and the device behaves essentially as a low intensity LED. After the current surpasses the threshold level, $I_{threshold}$, stimulated emission dominates and the device exhibits a high optical efficiency as indicated by the large slope in the figure. In the stimulated emission region, the device exhibits an approximately linear variation of optical intensity versus drive current.

Comparison

The chief advantage of LDs over LEDs is in the speed of operation. Under conditions of stimulated emission, the recombination time constant is approximately one to two orders of magnitude shorter than during spontaneous recombination [11]. This allows LDs to operate at pulse rates in the gigahertz range, while LEDs are limited to megahertz range operation.

The variation of optical characteristics over temperature and age are more pronounced in LDs than in LEDs. As is the case with LEDs, the general trend is to have lower radiated power as temperature increases. However, a marked difference in LDs is that

Characteristic	LED	LD
Optical Spectral Width	25–100 nm	0.1 to 5 nm
Modulation Bandwidth	Tens of kHz to Hundreds of MHz	Tens of kHz to Tens of GHz
Special Circuitry Required	None	Threshold and Temperature Compensation Circuitry
Eye Safety	Considered Eye Safe	Must be rendered eye safe
Reliability	High	Moderate
Cost	Low	Moderate to High

Table 1.3: Comparison of LEDs versus LDs for wireless optical links (based on [4, 5])

the threshold current as well as the slope of the characteristic can change drastically as a function of temperature or age of the device. For commercial applications of these devices, such as laser printers, copiers or optical drives, additional circuitry is required to stabilize operating characteristics over the life of the device [20, 21].

For LDs the linearity of the optical output power as a function of drive current above $I_{threshold}$ also degrades with device aging. Abrupt slope changes, known as *kinks*, are evident in the characteristic due to defects in the junction region as well as due to device degradation in time [18]. LEDs do not suffer from kinks over their lifetimes. Few manufactures quote linearity performance of their devices over their operating lifetimes.

LDs are more difficult to construct and as a result can be more expensive than LEDs. The use of inexpensive optical components is a key factor determining the implementation of a wireless IR link.

An important limitation for the use of LDs for wireless optical applications is the fact that it is difficult to render laser output eye safe. Due to the coherency and high intensity of the emitted radiation, the output light must be diffused. This requires the use of filters which reduce the efficiency of the device and increase system cost. LEDs are not optical point sources, as are LDs, and can launch greater radiated power while maintaining eye safety limits [4, 2].

As a result of these issues, LEDs were chosen as the light emitting devices for the target application. The strengths and weakness of LDs and LEDs for wireless applications are summarised in Table 1.3.

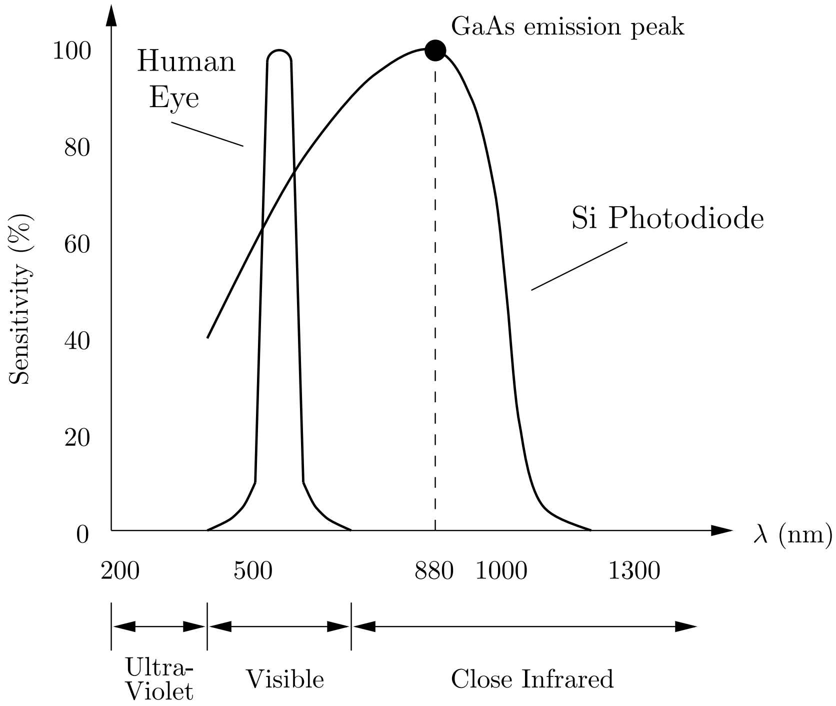


Figure 1.5: Relative sensitivity curve for a silicon photodiode [14]. Note that the position of the GaAs emission line is located near the peak in sensitivity of the photodiode.

1.2.2 Photodetectors

Photodetectors are solid-state devices which perform the inverse operation of light emitting devices : they convert the incident radiant light into an electrical current. Photodetectors are essentially reverse biased diodes on which the radiant optical energy is incident, and are also referred to as *photodiodes*. The incident photons, if they have sufficient energy, generate free electron-hole pairs. The drift or diffusion of these carriers to the contacts of the device constitutes the detected photocurrent.

Inexpensive photodetectors can be constructed of silicon (Si) for the 780–950 nm optical band. The photonic energy at the 880 nm emission peak of GaAs is approximately $E_g = 1.43$ eV, by rearranging (1.1). Since the band gap of silicon is approximately 1.15 eV, these photons have enough energy to promote electrons to the conduction band, and hence are able to create free electron-hole pairs. Figure 1.5 shows that the sensitivity of a silicon photodiode is maximum in the optical band of interest.

The basic steady-state operation of a solid-state photodiode can be modelled by the expression,

$$I_p = q\eta_i \frac{P_p}{h\nu}, \tag{1.3}$$

where I_p is the average photocurrent generated, η_i is the internal quantum efficiency of the device, P_p is the incident optical power and $h\nu$ is the photonic energy. The internal quantum efficiency of the device, η_i, is the probability of an incident photon generating an electron-hole pair. Typical values of η_i range from 0.7 to 0.9. This value is less than 1 due to current leakage in the device, absorption of light in adjacent regions and due to device defects [5].

Equation (1.3) can be re-arranged to yield the *responsivity* of the photodiode in the following manner,

$$R = \frac{I_p}{P_p} = \frac{q\eta_i}{h\nu} \tag{1.4}$$

The units of responsivity (R) are in amperes per watt, and it represents the optoelectronic conversion factor from optical to electrical domain. Responsivity is a key parameter in photodiode models, and is taken at the central optical frequency of operation.

Two popular examples of photodiodes currently in use include p-i-n photodiodes and avalanche photodiodes.

p-i-n Photodiodes

As the name implies, p-i-n photodiodes are constructed by placing a relatively large region of intrinsic semiconducting material between p+ and n+ doped regions (Figure 1.6). Once placed in reverse bias, an electric field extends through most of the intrinsic region. Incident photons first arrive upon an anti-reflective coating which improves the coupling of energy from the environment into the device. The photons then proceed into the p+ layer of the diode. The thickness of the p+ layer is made much thinner than the absorption depth of the material so that a majority of the incident photons arrive in the intrinsic region. The incident light is absorbed in the intrinsic region, producing free carriers. Due to the high electric field in this region ($\mathcal{E}$), these carriers are swept up, and collected across the junction at a saturation velocity on the order of 10^7 cm/s. This generation and transport of carriers through the device is the origin of the photocurrent.

Although carrier transit time is an important factor limiting the frequency response of photodiodes for fibre applications, the main limiting factor for wireless applications is the junction capacitance of the device. In wireless applications, devices must be made with

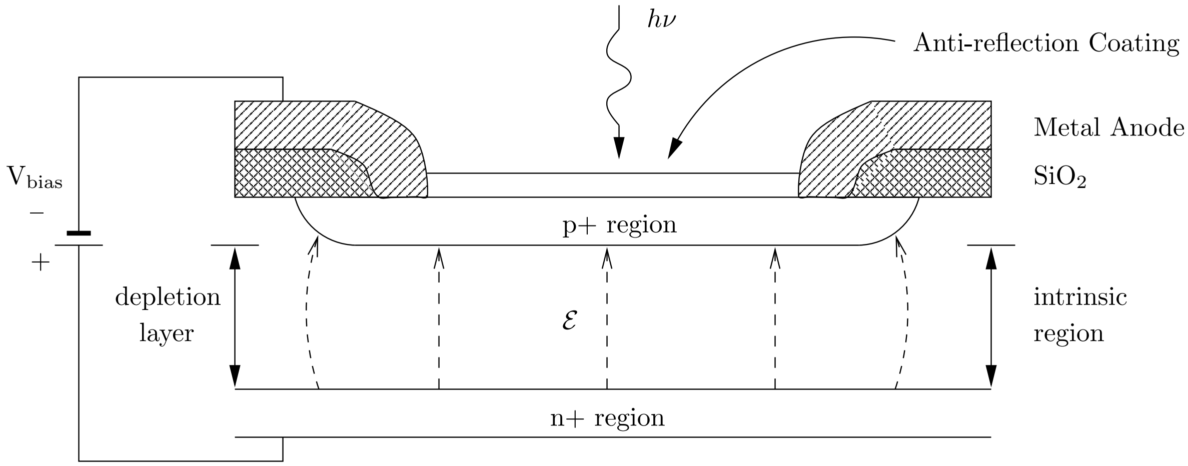


Figure 1.6: Structure of a simple silicon p-i-n photodiode [22].

relatively large areas so as to be able to collect as much radiant optical power as possible. As a result, the capacitance of the device can be relatively large. Additionally, the junction capacitance is increased due to the fact that low reverse bias voltages must be used. This is due to the fact that these devices are destined for applications in portable devices where power consumption and hence voltage rails are minimised. Typical values for this junction depletion capacitance at a reverse bias of 3.3 V range from 2 pF for expensive devices used in some fibre applications to 20 pF for very low speed, and cost devices. Careful design of receiver structures is necessary so as not to unduly reduce system bandwidth or increase noise [23].

The relationship between generated photocurrent and incident optical power for p-i-n photodiodes in (1.3) has been shown to be linear over six to eight decades of input level [24, 14]. Second order effects appear when the device is operated at high frequencies as a result of variations in transport of carriers through the high-field region. These effects become prevalent at frequencies above approximately 5 GHz and do not limit the linearity of links at lower frequencies of operation [25]. Since the frequency of operation is limited due to junction capacitance, the non-linearities due to charge transport in the device are negligible. The p-i-n photodiode behaves in a linear fashion over a wide range for the proposed application.

Avalanche Photodiodes

The basic construction of avalanche photodiodes (APDs) is very similar to that of a p-i-n photodiode. The difference is that for every photon which is absorbed by the intrinsic layer, more than on electron-hole pair may be generated. As a result, APDs have a photocurrent gain of greater than unity, while p-i-n photodiodes are fixed at unit gain.

The process by which this gain arrives is known as *avalanche multiplication* of the generated carriers. A high intensity electric field is established in the depletion region. This field accelerates the generated carriers so that collisions with the lattice generate more carriers. The newly generated carriers are also accelerated by the field, repeating the impact generation of carriers. The photocurrent gain possible with this type of arrangement is of the order 10^2 to 10^4 [24, 22]. In wired fibre networks, the amplifying effect of APDs improves the sensitivity of the receiver allowing for longer distances between repeaters in the transmission network [11].

The disadvantage of this scheme is that the avalanche process generates excess shot noise due to the current flowing in the device. This excess noise can degrade the operation of free space links since a majority of the noise present in the system is due to high intensity ambient light. These noise sources are discussed in more detail in Section 1.3.

The avalanche gain is a strong non-linear function of bias voltage and temperature. The primary use of these devices is in digital systems due to their poor linearity. Additional circuitry is required to stabilize the operation of these devices. As a result of the overhead required to use these devices, the system reliability is also degraded [5].

Comparison

APDs provide a gain in the generated photocurrent while p-i-n diodes generate at most one electron-hole pair per photon. It is not clear that this gain produces an improvement in the signal-to-noise ratio (SNR) in every case. Indeed, for the case of a free space optical link operating in ambient light, APDs can actually provide a decrease in SNR [7], as described in Section 1.3.

Due to the non-linear dependence of avalanche gain on the supply voltage and temperature, APDs exhibit non-linear behaviour throughout their operating regime. The addition of extra circuitry to improve this situation increases cost and lowers system reliability. Additional circuitry is also necessary to generate the high bias voltages necessary for

Characteristic	p-i-n Photodiode	Avalanche Photodiode
Modulation Bandwidth (ignoring circuit)	Tens of MHz to Tens of GHz	Hundreds of MHz to Tens of GHz
Photocurrent Gain	1	$10^2 – 10^4$
Special Circuitry Required	None	High Bias Voltages and Temperature Compensation Circuitry
Linearity	High	Low – suited to digital applications
Cost	Low	Moderate to High

Table 1.4: Comparison of p-i-n photodiodes versus avalanche photodiodes for wireless optical links (based on [5, 24])

high field APDs. Typical supply voltages range from 30 V for InGaAs APDs to 300 V for silicon APDs. Since these devices are destined for portable devices with limited supplies, APDs are not appropriate for this application.

p-i-n diodes are available at relatively low cost and at a variety of wavelengths. They have nearly linear optoelectronic characteristics over many decades of input level. p-i-n photodiodes can be biased from lower supplies with the penalty of increasing junction capacitance.

Due to the issues discussed in the preceding section, a p-i-n photodiode was chosen as the photodetector in this application. The characteristics of both p-i-n photodiodes as well as APDs are summarised in Table 1.4.

1.3 Noise

Along with specifications regarding the frequency and distortion performance, the noise sources of a wireless optical link are critical factors in determining performance. The determination of noise sources at the input of the receiver is necessary since this is the location where the incoming signal contains the least power.

As was justified in Section 1.2.2, p-i-n photodiodes are commonly used as photodetectors for wireless infrared links. The two primary sources of noise at the receiver front end are due to noise from the receive electronics and shot noise from the received DC photocurrent.

As is the case with all electronics, noise is generated due to the random motion of carriers in resistive and active devices. A major source of noise is thermal noise due to resistive elements in the pre-amplifier. If a low resistance is used in the front end to improve the frequency response, an excessive amount of thermal noise is added to the photocurrent signal. Transimpedance pre-amplifiers provide a low impedance front end through negative feedback and represent a compromise between these constraints [23]. Thermal noise is generated independently of the received signal and can be modelled as having a Gaussian distribution. This noise is shaped by a transfer function dependent on the topology of the pre-amplifier once the noise power is referred to the input of the amplifier. As a result, the noise due to the circuit follows a Gaussian distribution, but it is generally non-white [4].

Photogenerated shot noise is a major noise source in the wireless optical link. This noise is fundamentally due to the discrete nature of energy and charge in the photodiode. Carrier pairs are generated randomly in the space charge region due to the incident photons. Furthermore, carriers traverse the potential barrier of the p-n junction in a random fashion dependent on their energy. The probabilistic generation and transport of carriers due to quantum effects in the photodiode gives rise to shot noise in the photocurrent. This random process can be modelled as a having Poisson distribution with a white power spectral density [23, 26].

Using these two sources of noise, the signal-to-noise ratio for a wireless optical link can be approximated in a simple example (based on [27]). The input signal to the receiver is a time varying optical intensity signal. Let the transmitted intensity signal, $x(t)$, be a fixed sinusoid of the form

$$x(t) = P_t(1 + m \sin \omega t)$$

where P_t is the average transmitted power and m is the amplitude of the sinusoid. To ensure transmission of this signal requires $|m| < 1$, since negative intensity values are not possible as discussed in Section 1.1.

This intensity signal is attenuated as it propagates through free-space to the receive side. The received signal also consists of ambient, background light that is present in the channel and detected by the photodiode. This ambient light consists of incandescent light, natural light and other illumination in the environment. The received intensity, $r(t)$, can be written as

$$r(t) = P_r(1 + m \sin \omega t) + P_{amb},$$

where P_r is the average power at the receive side and P_{amb} is the power of the ambient light incident on the photodiode. The photodiode converts this incident optical intensity into a photocurrent in accordance with the responsivity relationship in (1.4). The signal and DC quantities of the photocurrent can be isolated in the following form :

$$i_{photo}(t) = R \cdot r(t) = R(P_r + P_{amb}) + (RP_r m \sin \omega t).$$

The electrical signal power at the receive side is contained entirely in the time varying component and can be written as

$$P_{signal} = \frac{1}{2} m^2 (RP_r)^2.$$

The noise power due to the pre-amplifier and due to shot noise is uncorrelated, and so the total noise power is simply the sum of the individual noise source powers. If the noise power due to the circuit is $\overline{i_{circ}^2}$, the total noise power takes the form

$$P_{noise} = \overline{i_{circ}^2} + \overline{i_{shot}^2} = \overline{i_{circ}^2} + 2qR(P_r + P_{amb})B_{eff},$$

where q is the electronic charge and B_{eff} is the equivalent noise bandwidth of the system. Combining the results, an estimate of the signal-to-noise ratio of the system can be formed as

$$\mathrm{SNR}_{\mathrm{link}} = \frac{P_{signal}}{P_{noise}} = \frac{1}{2} \cdot \frac{m^2 (RP_r)^2}{\overline{i_{circ}^2} + 2qR(P_r + P_{amb})B_{eff}}. \tag{1.5}$$

The dominant source of noise in a wireless optical channel is due to the ambient background light. To reduce the impact of ambient light, optical low-pass filtering can be used to attenuate visible and higher frequency light sources with little added cost [8]. In some links, this ambient light may be as much as 25 dB greater than the signal power, even after optical filtering [7]. The high ambient light levels cause the ambient light shot noise component to dominate the circuit noise, allowing (1.5) to be simplified to

$$\mathrm{SNR}_{\mathrm{link}} \approx \frac{m^2 (RP_r)^2}{4qRP_{amb}B_{eff}}.$$

Using this assumption, the resulting noise of the channel is signal independent, white shot noise following a Poisson distribution. This high intensity shot noise is the result of the summation of many independent, Poisson distributed random variables. In the limit, as the number of random variables summed approaches infinity, the cumulative distribution function approaches a Gaussian distribution by the central limit theorem. Thus, the dominant noise source can be modelled as being white, signal independent and having a Gaussian distribution [28, 26, 4].

This situation is in contrast to optical fibres where the ambient light is essentially zero, and circuit noise is the dominant noise factor [27, 28]. The use of an APD is advantageous in fibre applications as long as the circuit noise is much greater than the added shot noise of the APD. In this manner, APDs can provide a gain to the signal portion of the received power while keeping the noise power essentially constant. The net effect is to allow for wider repeater spacing in a fibre network, reducing system cost [11].

Emissions from fluorescent lighting create a noise source unique to wireless optical channels. Fluorescent lamps have strong emissions at the spectral lines of argon in the 780–950 nm near infrared band. Although economical narrow band optical filters have been used for some time in such links [8], significant energies are still detected by the photodiode. The detected output of fluorescent lamps is nearly deterministic and periodic with components at multiples of the ballast drive frequency. Most fluorescent ballasts drive the lamps at the line frequency of 50–60 Hz, with harmonics up to tens of kilohertz. Modern ballasts modulate the lamp at higher frequencies to improve power efficiency and reduce unit size. Typical modulation rates are 22 kHz and 45 kHz. The harmonics generated by these sources, and detected by the photodiode extend into the hundreds of kilohertz and can present an impediment to wireless optical data transmission. The impact of periodic interference from high frequency modulated fluorescent light sources has only recently been investigated for wireless optical links [29, 4, 7].

1.4 Summary of Characteristics and Conclusions

LEDs and p-i-n diodes are economical and practical optoelectronic components for implementing wireless optical links. They remain reliable over a long lifetime, and require no additional support circuitry to guarantee operation. The disadvantages of these devices over other optoelectronic components is their slower frequency response as well as lower efficiency.

The noise corrupting the input signal is due to high intensity shot noise due to ambient light impinging on the photodiode. This noise can be modelled as signal independent, additive, white Gaussian noise. Low pass interference is also present due to the modulation of ballasts in fluorescent lighting fixtures. The impact of this low pass interferer depends heavily on system architecture and on the modulation scheme used.

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