Design of Wireless Communication Link using Transreceiver System

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Abstract

Modern optical wireless communication (OWC) was an offshoot of the development of laser technologies in the 1960s. The main aim then was to develop communication between satellites and submarines beneath the surface of the sea. In the communication world, optical wireless communication (OWC) is the only area that remains to be comprehensively researched. It uses light beams propagated through the atmosphere or space to carry information. The reflection of sunlight by mirrors is another early method of OWC. Naturally, modern communication systems exhibit much higher data rates with better quality of service (QoS) compared to these ancient methods. In this paper we present the idea of OWC link design, which is organized as follows Section I deals with introduction, section II deals with transmitter Design, and section III deals with Receiver Design, section IV concludes the paper.

Keywords

OFC, FSO, LED, LD Optical wireless link.

I. Introduction

In the generalized free-space optical (FSO) link the information, prior to transmission from the source to the receiver, exists in electrical form. The transmitter, which consists of two parts; an interface circuit and a source drive circuit, converts the input signal to an optical signal suitable for transmission. The drive circuit of the transmitter transforms the electrical signal to an optical signal by varying the current flow through the light source. This optical light source can be of two types a light emitting diode (LED) or a laser diode (LD). The information signal modulates the field generated by the optical source. The modulated optical field then propagates through a free-space path before arriving at the receiver. Here, a photo detector converts the optical signal back into an electrical form. The receiver consists of two parts the optical detector and the signal conditioning circuit. The optical detector receives the optical signal, and the signal-conditioning circuit regulates the detector output so that the receiver output matches the original input at the transmitter. A good receiver amplifies and processes the optical signal without introducing noise or signal distortion. Noise effects and limitations of the signal-conditioning circuit introduce distortion in the receiver's electrical output signal. The optical detector used at the receiver can be either a semiconductor positive-intrinsic-negative (PIN) diode or an avalanche photodiode (APD) [1].

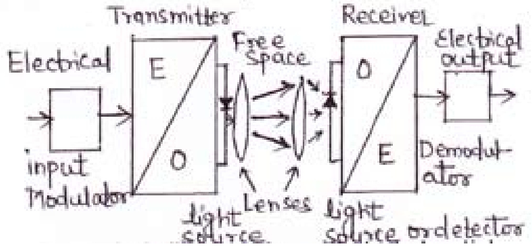


Fig. 1: Block diagram of an optical wireless link showing the front end of an optical transmitter and receiver.

II. Transmitter Design

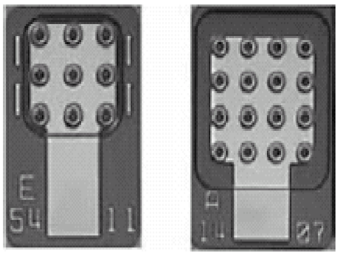
The development of optical fiber transmitter systems has spawned semiconductor lasers with broad bandwidths and high launch powers, features that should be equally attractive to optical wireless applications. Unfortunately, one of the most important restrictions to optical wireless transmitters is precisely the optical power level emitted by the source, which, when exceeding specific levels, is potentially dangerous to the human eye. This situation must be taken into account, particularly for indoor free-space optic applications where lasers pose a particular safety hazard to unaware bystanders, which may walk through the path of a wireless IR link. The creation of eye safety standards is justified by the large number of people who may be exposed to the IR radiation of an optical wireless system not just during system operation, but also during system development, installation, and maintenance. The optical transmitter front end consists of a driver circuit along with a light source. The general structure of the optical transmitter may consist of a lens, an LD or an LED, a driver IC, a Peltier element for cooling, and a modulator block. All these components can be assembled into a mini-sized package, as illustrated in Fig. 2. For outdoor use, this module package generally presents a special casing to protect it from the rain and from direct exposure to sunlight.

An Optical Source to transmit light in an optical wireless communication link, a suitable light source is needed at the end of the transmitter circuit. The appropriate light source, which as discussed above can be a light emitting diode (LED) or a laser diode (LD), is chosen depending on the specific application of the system. These optical sources are often considered the active component in an optical communication system. Their basic principle of operation is discussed in detail in a number of reference books [2-4]. The output properties and the characteristics of the optical source used for the transmitter are important parameters to consider when designing and evaluating an optical wireless communication system. It is important, for example, that the light source launches its energy at angles that optimize the transmitted beam. It is also important that the frequency response of the light source exceeds the frequency of the input signal. Furthermore, the light source should have a long lifetime, present a sufficiently high intensity, and be reasonably monochromatic. Both LEDs and LDs provide good brightness, small size, low drive voltage, and are able to emit a signal at a desired wavelength or range of wavelengths. The selection of one over another depends on the characteristic of the particular application in which they are to be used. When deciding whether to choose an LED or an LD as the light source in a particular transmitter system, one of the main features to consider is their optical power versus current characteristics. This is particularly important because the characteristics of these devices differ considerably (as illustrated in Fig. 3). It can be seen in the Fig. that, near the origin, the LED response is linear, although it becomes nonlinear for larger power values. The laser response, on the other hand, is linear above the threshold. Sometimes, mode-hopping creates a slightly nonlinear response above the threshold in a multimode laser. Single-mode lasers exhibit a linear response above the threshold. The linearity of the source is particularly important for analog systems. The power supplied by both devices is similar (about 10 to 20 mW) [3], but LDs are much more sensitive to temperature variations than LEDs. This is illustrated in Fig. 3, where it can be observed that, as the temperature increases, the laser diode's gain decreases (for example, a laser that at 30 °C requires 70 mA to output 2 mW of optical power may require in excess of 130 mA at 80 °C). This implies that more current is required before oscillation.

Another important feature that must be taken into account when deciding whether to use an LD or an LED for a specific application is the speed of the device. LDs, for example, are much faster than LEDs due to the fact that the rise time of an LED is determined by the natural spontaneous-emission lifetime of the material, whereas the rise time of the laser diode depends on the stimulated emission lifetime. Because an LED emits spontaneous radiation, the speed of modulation is limited by the spontaneous recombination time of the carriers. LEDs have a large capacitance, which means that their modulation bandwidths are not very large (a few hundred megahertz). Biasing the diode with a forward current can reduce the capacitance, resulting in an increase of the modulation speed. In the case of a laser above the threshold, the electrons remain in the conduction band for a very short time due to the stimulated recombination; therefore, very fast modulation is possible (up to 10 GHz). Fig. 4 shows this characteristic. The spectral emission of an LD remains more stable with temperature than that of an LED. Fig. 5 shows the spectral shift due to temperature variation in a typical LD. Changes in the output power of the LD with temperature can be prevented by stabilizing the heat sink temperature with a Peltier element and a control circuit. This generally requires more complicated electronic circuits than the ones used for LEDs. Laser diodes are semiconductor junction devices that contain etched or cleaved substrates, to act as reflecting facets for field reinforcements over the junctions. They therefore combine the properties of an LED and a cavity reflector, producing an external light radiation that is higher in power (10 to 50 mW) and has a better focused beam than that of a simple LED. LED radiation, on the other hand, is projected outward in all directions, depending on its aperture. The ways in which light is emitted by the source can influence its apparent brightness. First-generation optical communication sources were designed to operate between 800 and 900 nm. This is because, originally, the properties of the semiconductor materials used lend themselves to emission at these wavelengths. An LED is formed from semiconductor junctions that interact when subjected to an external current, which results in radiated light energy. The choice of junction material determines the emitted wavelength. These materials must emit light at a suitable wavelength if they are to be utilized in conjunction with commonly available detectors, whose spectral response is in the range 0.8 to 1.7μm. Ideally, to achieve emission at a desired specific wavelength, they must allow band gap variation, which can be achieved through appropriate doping and fabrication. Semiconductor optical sources are typically formed from compounds of gallium arsenide (GaAs) and produce light as presented in Table 1 [3].

Most optical transmission technology is designed to operate at a wavelength of 850 nm. However, the latest technology includes 1.55-μm devices [5, 7], which are attractive due to the fact that, up to certain power levels, they do not harm the human eye as the cornea filters incoming light and allows only wavelengths ranging from 0.4 to 1.4 μm into the retina. Thus, transmissions at 1.55 μm do not pass through the corneal filter, and cannot harm the sensitive retina. This means that, at these wavelengths, the emitted power is allowed to reach values up to 10 mW [8] when the source is used as the transmitter of a wireless IR link.

IR sources pose a potential safety hazard if operated incorrectly. For this reason, safety standards have been established to classify optical sources according to their total emitted power [9]. LEDs, for example, do not produce a concentrated light beam. They are large-area devices that cannot be focused by the retina. LDs, on the other hand, are collimated sources whose energy can be focused by the retina. This means that a much lower launch power can be used in order to be considered Class 1 (eye safe). This favors the use of LEDs for indoor applications. The penalty, however, is bandwidth. Whereas the speed of LDs extends to gigabits per second (Gbps), the speed of LEDs is limited typically to 10 Mbps, perhaps extending to 50 Mbps for some specialty devices [8]. Unlike indoor optical wireless systems, the design of an outdoor wireless link or line-of-sight terrestrial system must deal with propagation effects due to atmospheric phenomena (which attenuate the transmitted signal) and with high levels of atmospheric turbulence across the path. In outdoor environments, the properties of LDs such as narrow spectra, high power launch capability, and higher access speed make these devices the favorite optical source for long-distance and outdoor directed-LOS links. However, recent developments in vertical cavity surface emitting lasers (VCSEL), which offer a safer peak wavelength at 1.55 μm [10], is changing this situation. VCSELs are becoming an increasingly attractive option for outdoor and even indoor applications due to their well-controlled, narrow beam properties, high modulation bandwidth, high-speed operation, excellent reliability, low power consumption, and the possibility of having array arrangements. The most commonly developed VCSELs today are the selective oxide-confined ones. In these devices, the operation current is increased to obtain an optical output power that results in a multiple cone-shaped far-field pattern (FFP). A high-power VCSEL can be obtained by increasing the size of the current confinement aperture; however, this method raises concerns regarding device characteristics such as low-frequency performance and a large dip at the center of the FFP [11]. Simultaneously driven VCSEL arrays have been developed by [12] to overcome these issues. Fig. 6 illustrate the microscopic top views of two VCSEL arrays (3×3 and 4×4). These devices consist of several high-speed VCSELs placed 50 μm apart and integrated on a single chip. The epitaxial layers of these VCSELs consist of AlxGa1-xAs semiconductors grown by metalorganic chemical vapor deposition. The development and use of effective VCSEL arrays in optical wireless applications is a topic of increasing interest and ongoing research [13].



Simultaneously Driven 3 x 3 VCSEL Array

Simultaneously Driven 4 x 4 VCSEL Array

Fig. 2 Microscopic top views of the simultaneously driven 3×3 and 4×4 VCSEL arrays.

III. Receiver Design

Optical wireless links operate with limited transmitter power due to eye safety considerations; and in relatively high noise environments due to ambient illumination, the performance of the optical receiver has a significant impact on the overall system performance. To reduce the shot noise introduced in the detector by ambient light, an optical filter is required, while the preamplifier needs to allow for shot-noise limited operation. In addition, due to link budget considerations, the receiver must have a large collection area, can be achieved through the use of an optical concentrator (that offers effective noiseless gain). Furthermore, as indoor and outdoor optical transceivers are intended for mass computer and peripheral markets, the receiver design is extremely cost sensitive, which makes sophisticated optical systems unattractive. The design of an optical receiver depends on the modulation format used by the transmitter. Optical wireless receiver systems are very similar to fiber-based receiver systems. They consist essentially of a photo detector and a preamplifier, with possibly additional signal processing circuitry. Therefore, it is necessary to consider the properties of the photo detector in the context of the associated circuitry combined in the receiver because it is essential that the detector performs efficiently with the following amplifying and signal processing stages. This chapter discusses some of the key issues related to the specification and design of optical wireless receivers.

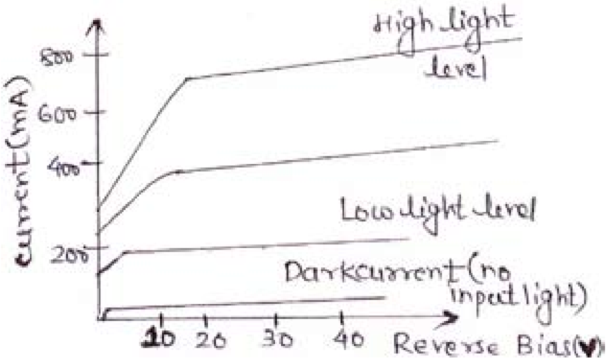


Fig. 3: Current-voltage (CV) characteristics of a typical photodiode.

A. Photo detection in Reverse-Biased Diodes

Before embarking on the analysis of receiver design, it is necessary to understand the operation of the semiconductor photodiodes found in most optical fiber and wireless systems. The photodiode is similar in structure to the PN junction diode, except that its junctions can be exposed to external light. This forms a third optical “terminal” that produces a current flow that is fed to the next stage of the circuit for further amplification. Fig. 7 shows the current output characteristic of a typical PN photodiode. A detailed analysis of these devices can be found in [2-4]. The front of the photodiode wafer is usually heavily doped with an opposite dopant type using ion implantation in such a way as to produce a diffusion of majority carriers across the interface of the p and n regions. This zone is important to the photodiode’s performance (efficiency) because it converts photons into electron-hole pairs. When light or photons of energy impinge on the front surface of the photodiode, they penetrate into it and are absorbed by the semiconductor. If the energy of the photons is larger than the energy of the band gap of the semiconductor material, an absorbed photon excites an electron from the valance band to the conduction band and leaves a hole in the valance band. That is, it generates an electron-hole pair. When an electron-hole pair is created inside the depletion region, these electrons and holes rapidly drift in opposite directions because of the built-in electron field. This produces the photocurrent flowing in the external circuitry. The band gap and the corresponding typical operating wavelengths for several popular semiconductor materials .The InxGa1-xAsyP1-y material is commonly called indium-gallium arsenide- phosphide, and it is particularly attractive because its band gap can be varied by the crystal composition.

The diode shunt resistance Rj in a reverse biased junction is usually very large (>106 Ω) compared to the load impedance Rl and can therefore be neglected. The resistance Rs represents ohmic losses in the bulk p and n regions adjacent to the junction, and Cd represents the dynamic photodiode capacitance. One of the most important considerations when choosing optical detectors is their frequency response, that is, their ability to respond to variations in the incident intensity such as the one created by high-frequency modulation. The three main mechanisms limiting the frequency response of photodiodes are:

1. The finite diffusion time carriers produced in the p and n regions. This effect can be minimized by the proper choice of length in the depletion layer.
2. The shunting effect of the signal current by the junction capacitance Cd. This effect places an upper limit on the cut-off frequency of the photodiode.
3. The finite transit time of the carriers drifting across the depletion layer. For this reason, the photodiodes operated with a reverse-bias, which gives a larger field causing a faster drift. Note that with regard to the junction capacitance, reducing the diode area and the doping level may reduce Cd. Increasing the reverse bias voltage as the depletion region is made wider increases the associated bandwidth, which is the opposite of what occurs in terms of transit time. There is, consequently, a trade-off between transit time and junction capacitance. Because the photodiode’s quantum efficiency is also improved by lengthening the depletion region, there is a similar trade-off between quantum efficiency and transit time. A well-designed photodiode can have both high quantum efficiency and a wide bandwidth. A wider depletion region can be achieved by another type of the semiconductor PN photodiode — a PIN photodiode — which has a layer of intrinsic semiconductor material sandwiched between the p and n layers. The depletion region in this structure is almost entirely contained in the intrinsic region and it is wider than the depletion region obtained by a PN photodiode, thus giving the extra advantage mentioned above. The photo detector is an integral part of the optical front end of a wireless IR receiver because it converts an optical signal into an electrical signal. It is important for the receiver to detect low-level optical signals without introducing many errors. Also, as in digital systems, noise gives rise to bit errors, and it is important that the signal - to- noise ratio (SNR) is sufficiently large to yield an acceptable bit error rate (BER). Therefore, when considering signal attenuation along a wireless link, the system performance is determined by the detector. Thus, improvements in the detector characteristics and performance allow wider or longer optical wireless coverage. The role the detector plays demands that it satisfies very stringent requirements of performance and compatibility. The following criteria define some of the most important performance and compatibility requirements for optical wireless detectors, which, as can be observed, are similar to the requirements for optical sources:

1. High sensitivity at the operating wavelength.
2. High fidelity: to reproduce the received signal waveform with accuracy (for analog transmission, the response of the photo detector must be linear, with regard to the optical signal, over a wide range).
3. Large detection area: to offer a large collection aperture and increased effective detection field-of-view (FOV).
4. Large electrical response to the received optical signal: the photo detector should be able to produce an electrical signal as high as possible for a given amount of optical power.
5. Short response time: present systems can operate at speeds of up to several GHz; thus, it is not unreasonable to suppose that future systems will operate at even higher speeds.
6. Minimum noise: dark currents, leakage currents, and shunt conductance must be low. In addition, the gain mechanism within either the detector or the associated circuitry must present low noise.
7. Other considerations: low cost, small size, and high stability and reliability. Four types of photo detectors are available for the design of optical receivers:

(1) Avalanche photodiodes (APDs),
(2) Photoconductors,
(3) metal-semi conductor metal photodiodes (MSM PDs), and (4) PIN photodiodes (PIN PDs).

The first three types have internal gain, whereas the PIN photodiode does not have any internal gain, which is compensated by a larger bandwidth. Because of their compliance with the requirements mentioned above, APDs and PIN PDs are two of the most popular detectors for optical receiver systems. This is explained by the fact that despite the simplicity of photo detectors and their gain, they have a low-gain band width product that makes them unsuitable for practical optical wireless systems. MSM PDs, on the other hand, present gain and bandwidth advantages when compared to other photo detectors. They can also be monolithically integrated with a preamplifier. More details about the preferred photo detectors used for wireless IR communication receivers are presented below:

1. PIN PD

This structure offers a wider depletion region that allows operation at longer wavelengths. It also allows light to penetrate more deeply into the semiconductor material. In both device types (horizontally or vertically illuminated detectors), a depleted In GaAs layer of around 3 to 5μm is used to provide high quantum efficiency (up to 90 percent). Considerable effort was directed during the 1990s toward developing high-speed PIN photo detectors capable of operating at bit rates exceeding 100 Gbps. A bandwidth of up to 40 GHz was demonstrated by at a responsivity of 0.55 A/W (external quantum efficiency of 44 percent); and in the year 2000, such an InP/InGaAs photo detector exhibited a bandwidth of 310 GHz in the 1.55-μm spectral region. Several techniques have been developed to improve the efficiency of high-speed photodiodes. In one approach, nearly 100-percent quantum efficiency was realized in a photodiode in which one mirror of the Fabry-Perot cavity was formed using the Bragg reflectivity of a stack of AlGaAs/AlAs layers. Using an air-bridged metal waveguide together with an undercut mesa structure, Tan et al. demonstrated a bandwidth of 120 GHz. However, the bandwidth of current commercially available package detectors is usually up to 20 GHz due to limitations of the packaging.

2. APD

This photo detector achieves internal gain through a more sophisticated structure that creates an extremely high electric field region. At low gain, the transit time and RC effects dominate, giving a definitive response time and hence constant bandwidth for the device. At high gain, the avalanche build-up time dominates and therefore the device bandwidth decreases proportionately with an increase in gain. Such APD operation is distinguished by a constant-gain bandwidth. Often, an asymmetric pulse shape is obtained from the APD, which results from a relatively fast rise time as the electrons are collected; and from a fall time dictated by the transit time of the holes traveling at a slower speed. Hence, although the use of suitable materials and structures give rise times of between 150 and 200 picoseconds, fall times of 1 nanosecond or more are quite common, which limits the overall response of the device. An APD employing a mesa structure has achieved a high gain band width product at 120 GHz. Other researchers such as have developed an asymmetric waveguide APD. This asymmetric waveguide structure is effective for achieving robustness under high input power operation and high quantum efficiencies. Quantum efficiencies of 94 percent for 1.55 mm and 90 percent for 1.31 mm wavelengths have been demonstrated. A gain-bandwidth product of 110 GHz is large enough to produce excellent performance of an APD operating at 10 Gbps. Higher gain-bandwidth products have also been demonstrated. Otani et al., for example, demonstrated a gain-bandwidth product of more than 300 GHz using a hybrid approach that exhibited a bandwidth of up to 10 GHz and APD gain of up to 35 while maintaining 60 percent quantum efficiency. Table 2 summarizes some typical values for PIN and APD detectors. The values given are typical for commonly used devices and do not necessarily represent fundamental limits to the performance. In many cases, it is possible to improve the performance in one specific area (bandwidth) at the cost of sacrificing the performance in others (that is, sensitivity quantum efficiency).

IV. Conclusion

The main advantages of OWC are:

1) There are no licensing requirements or tariffs for its utilization;
2) There are no radiofrequency (RF) radiation hazards;
3) There is no need to dig up roads, etc.
4) It has a large bandwidth, which enables very high data rates;
5) It is small, light, and compact; and
6) It has low power consumption.

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