

Design and Evaluation of Inorganic and Organic Light-Emitting Diode Displays for
Signage Application

by

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Abstract

High brightness inorganic LEDs have been utilized effectively for signage application using the edgelighting technique. In this thesis, the inorganic LED-based edgelit signage using transparent acrylic has been evaluated. We determine that the edgelighting technique, although superior in efficiency to other available techniques, suffers from intrinsic limitations, particularly in terms of illumination uniformity. The illumination uniformity can be improved by external means such as a diamond grating. In order to quantitatively establish this, the illumination uniformity of the LED-based signage with and without the diamond grating is examined. The results show a considerable improvement in the illumination uniformity when a diamond grating is used. However, the high cost of the diamond grating and the transparent acrylic amplify the overall cost of signage using LEDs. Therefore, a distributed light source, which can eliminate the use of the diamond grating, is determined to be more suitable for signage application. Organic Light-Emitting diode (OLED), which is a distributed light source, emerges as a possible contender.

The second part of our research focuses on the application of OLEDs for signage. We examine two OLED modules from different manufacturers for our evaluation. The first module is a prototype module obtained from the National Research Council (NRC) and the second module is a commercially available OLED from RiT Display Corporation. We present novel design techniques that can be used to implement signage based on OLEDs. A prototype tiled OLED display using commercially available OLEDs is designed and tested. Our investigation suggests that good light uniformity in signage panels can be achieved using OLED modules in the form of tiles. This proves that OLEDs are superior to conventional light-emitting diodes as light sources for signage in terms of illumination uniformity.

However, we determine that the currently available OLEDs have a lower light-conversion efficiency in addition to higher costs when compared with conventional LEDs. Though the individual OLEDs cost more than LEDs, signage panels based on OLEDs can be made cheaper by avoiding the use of acrylic sheet and diamond grating.

Moreover, the light weight of OLEDs and the fact that OLEDs are diffused sources (rather than point sources like LEDs) add an additional advantage. Also, OLEDs have the potential to be built inexpensively on flexible substrates by using the roll-to-roll technique. This makes OLEDs superior to conventional LEDs in large-area signage applications.

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Dedication

Dedicated to my family

List of Abbreviations

AMOLED	Active Matrix Organic Light Emitting Diode
CFL	Compact Fluorescent Lamp
CIE	Commission Internationale de l'Eclairage
CMOS	Complimentary Metal Oxide Semiconductor
EEPROM	Electrically Erasable Programmable Read Only Memory
EL	Electro-Luminescence
FOLED	Flexible Organic Light-Emitting Diode
HIL	Hole Injection Layer
HOMO	Highest Occupied Molecular Orbital
HTL	Hole Transport Layer
IESNA	Illuminating Engineering Society of North America
ITO	Indium –Tin Oxide
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
LUMO	Lowest Unoccupied Molecular Orbital
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
NRC	National Research Council
OLED	Organic Light-Emitting Diode
OMBD	Organic Molecular Beam Deposition

PDA	Personal Digital Assistant
PHOLED	Phosphorescent Organic Light-Emitting Diode
PLED	Polymer organic Light-Emitting Diode
PMOLED	Passive Matrix Organic Light Emitting Diode
RGB	Red Green Blue
SMOLED	Small-Molecule Organic Light-Emitting Diode
SOLED	Stacked Organic Light-Emitting Diode
SSL	Solid-State Lighting
TOLED	Transparent Organic Light-Emitting Diode

Chapter 1

Introduction

Lighting technology has undergone rapid advancements since the discovery of incandescent lamps. An incandescent lamp emits light when a large amount of current passes through its filament, which acts as a resistor. Almost 95 percent of the electrical energy is lost as heat in this process [1]. Hence, in order to reduce energy consumption and to save electricity, alternative sources of lighting have been considered. Solid-state lighting (SSL) technology is a possible contender in this regard, promising higher energy savings at a lower cost [2].

SSL using light-emitting diodes (LEDs) has progressed quickly with the light output doubling every 18-24 months for the past 34 years (Haitz law) [3]. Initially, these LEDs based on inorganic material, were used as status indicators due to their low efficiency. In recent years, high-power LEDs with 50 percent greater efficiencies than the indicator LEDs have been demonstrated and are available commercially [3]. These LEDs have demonstrated efficiencies better than the incandescent lamps and are available in numerous colors. They have been proven to possess long lifetimes, low operating voltages and are very robust. These advantages associated with LEDs have encouraged the industry to use them for signage application. Signage comprises of a group of signs, their design and usage.

The interest in solid-state lighting sources has further been fueled by the development of light-emitting diodes based on organic materials. These diodes are known as organic light-emitting diodes (OLEDs). The novel OLED technology has validated its potential in microdisplays such as the cell-phone display and the personal digital assistant (PDA) screens and has invoked considerable interest in the flat panel display market [4]. It has successfully challenged its counterpart, the liquid crystal display, in this application.

However, its potential application in large displays for signage has not been ascertained. The primary focus of this thesis is to compare and evaluate the state-of-the-art inorganic and organic light-emitting technology for application in large displays for *signage*. We also intend to present novel design techniques, which can be utilized for designing OLED-based signage.

The inorganic LEDs would be referred to as the conventional LEDs or LEDs and organic LEDs will be referred to as OLEDs for the rest of this thesis.

1.1 Motivation

The prime motivation for this thesis comes from the necessity of achieving uniform light intensity over the surface of signage panels. Illumination of signs during nighttime is very essential to convey necessary information. Signage such as the highway signs, if not properly illuminated may lead to life-threatening consequences. A non-uniform sign causes stress on the viewer's eyes and hence, is considered inappropriate for public usage. Various kinds of signage techniques are available which are being used contemporarily. One of the recent techniques that is being used is the LED-based signage. LEDs are point sources that can be used for element-lit applications for lighting signage (such as alphanumeric signs). However, this technique consumes more power and cannot be used for large displays. So, edgelighting, which is a fairly new and more efficient technique, is regarded more suitable for large signs. Signs using edgelighting, however, suffer from very bright and dark areas. This is mainly due to the fact that LEDs are point sources and cannot spread out light like the distributed sources. The illuminance uniformity of a sign can be improved by using external means such as diamond gratings. However, this amplifies the cost of the signage, making it infeasible to be used for mass manufacturing. The inherent disability of the point source, the conventional LED, for a distributed area application such as signage is primarily responsible for the non-uniformity. Hence, we look for other potential sources that can replace conventional LEDs for signage application.

A recent upcoming light-emitting device: the Organic light-emitting diode emerges as a potential candidate. The performance of OLEDs in the microdisplay and flat panel display industry prompts us to view it as a light source for signage. The potential and

characteristics of OLEDs as a diffuse light source make it specifically favorable to be used in signage.

1.2 Introduction to Signage

Signage is used to convey information, in the form of a display, to the viewer. It may be in the form of an exit sign, a stop sign, an arrow sign (used for highways), or an address sign, which we come across in our daily lives. Its main objective is to provide information in an easily readable and distinct manner without stressing the eyes of the viewer [5, 6]. While, painted boards are usually used for signage during daytime, signs, which are meant to be used for daytime as well as nighttime, are generally *illuminated*. Electric signage has attracted a lot of attention in the lighting industry due to its new and upcoming uses. Roadway signs are a special case of signage, which are of much concern. The legend or the information content in the signage will be termed as the signage pattern throughout the length of this thesis.

The prime parameters for evaluation of an electric signage are the signage uniformity, signage cost, efficiency and the environmental effects that the signage may have. The efficiency of the sign can be calculated as the ratio of light output to the input power of the sign. For electric signage, the focus is to reduce energy consumption and utilize more energy-efficient sources of signage. Signage manufacturers also aim to manufacture signage that is environmentally safe and friendly. The mass manufacture, operation and disposal of signs should not have any harmful effects on the environment.

This thesis aims to address the issue of signage uniformity and hence, the importance of uniform light intensity for signage has been described in detail in the following subsection. Also, the cost of signs is an important parameter for the design of signage displays, hence, we look at it in detail furthermore.

1.2.1 Signage Uniformity

Although there are no specific brightness uniformity standards for signage, it is essential to determine a criterion to compare uniformity. For this purpose Illuminating Engineering Society of North America (IESNA), which is a recognized technical authority on illumination, has provided some recommended practices and guidelines in [6]. Roadway

signs have been considered an important case due to their significance when the overall road traffic increases or when the ambient brightness increases and also when the weather conditions are adverse. The reason for no specific brightness standards could be the varying geographical locations in which signage is employed. However, it is essential to determine uniformity ratio of the sign to evaluate its useful life. Uniformity ratio can be defined as the ratio of the highest sign face luminance to the lowest sign face luminance. A uniformity ratio of 1 is considered to be the best for signs. Uniformity ratio of 1.3 to 1.5 is considered to be satisfactory. These values are based on the guidelines from IESNA for building fascia signs [6].

A sign with an increase in non-uniformity with time would no longer be considered suitable [7]. Hence, it is essential for signage manufacturers to develop uniform signs to ensure a longer useful life.

Studies have reported the perception of uniformity by human beings [7]. For a larger viewing distance the acceptability of non-uniformity is greater. However, as the number of non-uniformities increase, the acceptability of a sign decreases. Also, it has been observed that for higher background luminance non-uniformities are more noticeable. For signage such as the highway signs, improper illumination and large non-uniformities could prove hazardous. Hence, uniformity of sign is essential to increase the acceptability of a sign and also increase its useful life.

1.2.2 Economic Considerations

The economical considerations should also be kept in mind for manufacturing signage. Signage has practically become a necessity for conveying information. Hence, a higher cost would restrict the users employing quality signage. It is sometimes possible to improve the illumination uniformity of the sign by external means, which may increase the overall cost of signage. Hence, it is ideal to reduce the cost by limiting the use of additional components.

1.3 Light Sources for Signage

Currently, there are five different techniques that are being used for illuminating signage, namely incandescent bulbs, compact fluorescent lamps, tritium gas signs, photoluminescent signs and LED-based signs. The features of these light sources have been described furthermore.

1.3.1 Incandescent Bulbs

The tungsten-filament incandescent lamp is the most commonly used light-source. It emits light due to the thermal excitation of atoms when the tungsten filament is heated to incandescence within a glass enclosure [8]. These lamps are simple to use and can be directly coupled to the power supply. A 75W incandescent bulb has an efficacy of approximately 13 lumen/watt [9]. Due to their very low efficiency, these sources are not considered appropriate for signage. Also, they are very sensitive to vibrations and shock, which leads to frequent replacement and an increase in their maintenance costs.

1.3.2 Compact Fluorescent Lamps (CFLs)

These are electric-discharge sources composed of fluorescent material, which is activated by the application of a low-pressure mercury arc [10]. These lamps are available in the form of glass-tubes that are attached to the back of the signs. Although they are more efficient than the incandescent lamps, these signs lack uniformity and suffer from very bright and dark areas. In addition, the material used for manufacturing them is highly toxic and difficult to dispose. This can be considered a limiting factor for their usage.

1.3.3 Tritium Gas Signs

Illuminated signs filled with tritium gas are also used for signage. They possess a long life and do not consume any power [10]. However, tritium is a radioactive substance and its disposal can lead to environmental pollution, hence is a cause of concern to the general public.

1.3.4 Photoluminescent Signs

Photoluminescent signs emit visible light after activation with optical radiation. Photoluminescent signs are made up of non-radioactive pigments that store energy from normal light. These signs require more maintenance and have lower luminance values than the other signs. They do not need any external wiring but do require external illumination. Also, a progressive decrease in illumination is observed when the stored energy is used-up [10,11].

1.3.5 LED-Based Signs

Conventional LEDs are mainly used in three different ways for signage, namely the element lit signs, the edgelit signs and the cavity lit signs. The element lit signs are used for alphanumeric or graphic applications [10], where the LEDs elements can be lighted up individually to form a pattern. In cavity-lit signs, series of LEDs are placed along the top and bottom edge of the sign inside a cavity. In the case of edgelit signs, one or more series of LEDs are placed on the sides behind a transparent acrylic material. These LEDs backlight the display. Edgelighting represents a very recent application of LEDs. Both engraved and non-engraved signs are being manufactured using this technology. Engraved signs possess a pattern engraved on the acrylic sheet and are mostly used for advertising boards and address signs. These signs have to be manufactured separately for specific applications. Non-engraved signs on the other hand, are more generic and can be used for a broader class of signs from roadway to advertising signs. The signage pattern can be easily changed for these signs. Edgelighting technique is used to backlight a display. In this work, we concentrate on signage based on non-engraved LED-edgelighting technology, which can be used for roadway signage. Table 1-1 gives a comparison of the technologies currently used for signage in exit signs [10]. Exit signs are the most common form of signage available.

Table 1-1: A comparison of the technologies available for signage in exit signs as per the data in [10].

Signage sources	Average Lifetime (years)	Power Consumption (Watts)	Illumination quality	Disadvantages
Incandescent lamps	0.1-1	30-50	Highly non-uniform	Heated display
CFLs	1-2	12-20	Non-uniform	Toxic material used
Tritium gas	10-20	0	Uniform	Radioactive hazard
Photoluminescent signs	10	0 (Charging required)	Uniform	Low luminance
LED- based signs	15-25	1-10	Uniform	Medium luminance

1.4 Components of an Electronic Signage System

Electronically illuminated signage systems can be designed in different ways depending upon the application they are used for. Display systems for signage may be composed of the following sub-components, namely:

- Light sources
- Driver circuits
- Signage Panels, including the pattern required to be depicted.

The interfacing of these components and their individual performance has a great bearing on the operation of a signage system. However, the main focus of this thesis is to evaluate the *light sources* employed for signage.

1.5 Evaluation Parameters for Light Sources

Measurement and evaluation of light sources is vital prior to using them for signage applications. This allows for a comparison of their characteristics and helps the user to determine the most suitable light source for a particular application.

Light sources used for signage can be characterized on the basis of the following three sets of properties:

- Optical

- Electrical, and
- Physical

In the following sub-sections, we describe the parameters that relate to the above properties.

1.5.1 Optical Properties

A light source can be characterized in terms of its optical properties or radiometric properties [12].

Radiometry is the science of measurement of electromagnetic energy radiated in any part of the electromagnetic spectrum, both visible and otherwise. For optical measurements in signage, we focus on the part of the electromagnetic energy visible to the human eye. These measurements are termed as *Photometric measurements*.

The effectiveness of radiated power on vision is evaluated in photometric units. The photometric units are related mathematically to the radiometric units. In photometry, we measure the response of the human eye to certain wavelengths and intensities of light. The human eye is composed of rods and cones which act as receptors to light. Rods are more efficient at low light levels (scotopic vision) such as at nighttime and cones are more sensitive to higher light levels (photopic vision). Hence, the response of human eye varies with the surrounding light conditions. We, hereby, define the photometric terms that are fundamental for the evaluation of light sources for signage.

Luminous flux is the amount of light that falls on a unit area at a unit distance from a source of one candela. The unit of luminous flux is *lumens*. An ideal blackbody radiator with a projected area of $1/60 \text{ cm}^2$ at 2042 K^1 , the freezing point of platinum, emits a total luminous flux of $4\pi \text{ lm}$ [12].

Luminous intensity is the luminous flux of the light source in a certain direction. Its unit is *lumen/steradian (lm/sr)* or *candela (cd)*.

¹ 2042 K refers to the temperature in kelvins to which the black body is heated in this case.

Illumination is the luminous flux delivered to a unit surface area. The unit of illuminance is *lux* (lm/m^2). The visual effect of this quantity is characterized by photometric brightness. Photometric brightness is different from “brightness” as a psychological perception and is independent of the angle of measurement. Illuminance is usually used to characterize distributed area light sources

Luminous efficacy is the ratio of emitted luminous flux in lumens to the power used in watts. Its unit is *lumen/watt*. It is one of the standard parameters, which is used for comparing light sources.

1.5.2 Electrical properties

The electrical properties of interest for a signage system are the total power consumption and the efficiency of the display. The current-voltage curves or the I-V curves help to characterize and determine a technique to use the device for a particular application. If the device is a current-controlled device then the I-V curve determines the change in voltage due to a change in the current. These properties are important to determine the energy savings associated with a particular type of device. The power efficiency of a light-emitting device is the ratio of the light energy output obtained from the display to the electrical power applied.

1.5.3 Physical Properties

The physical properties of light sources are also important for their application in signage. Signage panels are employed outdoors and are affected by changes in the environmental conditions. Hence, it is desirable to have light sources that can endure varying range of temperatures and humidity.

Another important feature of the light source depends on the area that can be covered and the packaging requirements of the signage. The size of the source must be suitable to fit on the panel. The weight of the source is also important because bulky light sources would require more robust fixtures. These properties are important in evaluating a light source as well as the signage display and would be examined later in this thesis.

1.6 Evaluation Parameters for Driver Circuits

The systems used for driving the light sources also play an important role in evaluation of a display for signage. Solid-state lighting sources are very advantageous as they can be easily driven with the help of integrated circuits laid on printed circuit boards. However, if the driver circuits are not optimized for power then it may lead to higher energy losses instead of energy savings and the purpose of using SSL may not be served. Both voltage and current dependent sources can be used for driving SSL sources. Current-dependent light sources require a constant current supply for a stable operation and uniform light output. In the following chapters of this thesis, we describe the basic driving techniques for LEDs and OLEDs. The most important evaluation parameter for a driver circuit would be the power consumption.

1.7 Back Panels for Signage

Panels form the backbone of signage. They are thin sheets on top of which a signage pattern is positioned. The main function of back panels is to provide support to the signage. The choice of panels depends on the choice of light source employed. Robust back panels are required for light sources that are bulky and occupy a large space. Panels used for signage may be made of different types of material. It would be noticeable that some of the light sources would not require the use of panels for signage.

The back panels, if used, are supposed to be light, easy to handle and maintain, to save the cost of maintenance and installation. They should possess a good lifetime and should be resistant to the changes in the environment such as very high and low temperatures and precipitation. This would enable their usage in different geographical regions. In addition, it is ideal if the panels can be reused and disposed off easily. Also, they should be able to bear the weight of the light source they are intended to be used with.

1.8 Overview and Contribution of the Thesis

This thesis studies the physics, structure and characteristics of inorganic and organic light-emitting diodes for the specific application of signage. Inorganic light-emitting diode has already been used for commercial signage application. But organic light-

emitting diode, which is a novel light source, has not been utilized for this purpose. Some of the contributions of this thesis can be enumerated as:

- The detailed quantitative evaluation of the already existing edgelit signage based on inorganic LEDs with the help of opto-electrical measurements. This includes the standardization of the sign and the analysis of its design.
- Initial investigation of the characteristics of organic light-emitting diodes through experimentation and measurements with prototype OLEDs that are available as research samples.
- New design techniques for using organic light-emitting diodes for signage application along with the implementation methodology for the most feasible technique.
- Implementation of a tiled OLED display and development of a prototype using commercially available OLEDs.
- Characterization of commercially available OLEDs with the help of opto-electrical measurements
- Evaluation of OLED displays for signage application
- Comparison of inorganic LEDs and OLEDs as light-emitting devices and as light sources for signage.

The thesis is divided into six chapters. The first chapter introduces the reader to the main purpose of signage and the various components in signage.

In Chapter 2, solid state-light sources have been explained. The state of the art inorganic light-emitting diode technology is described. It explains the device characteristics and operation. Also, this chapter gives an introduction to the OLEDs, their types and operation.

Chapter 3 describes about the measurements that we obtained for single light-emitting diodes as well as prototype OLEDs. The light-emitting diodes were available commercially from different manufacturers and the OLEDs were obtained from the National Research Council of Canada.

Chapter 4 describes inorganic LED-based displays that utilize edgelighting for illuminating signage. Here, a detailed quantitative and qualitative assessment of the

displays is made with the help of photometric and electrical measurements along with the design of the display.

Chapter 5 looks at commercially available OLEDs. This chapter also presents new design methodologies for implementation of OLED-based displays and analyzes a commercially available module for evaluation. It also analyzes the design techniques and uses the most feasible technique for final implementation and test.

Chapter 6 summarizes the results of the thesis along with its contributions. The chapter also gives an idea for future research.

Chapter 2

Solid-State Light Sources

There has been a rising concern on the expenditure of energy for lighting in the recent years. The prime motivation to utilize solid-state lighting in place of the conventional lighting technologies has been the energy savings associated with SSL. The signage industry has not remained isolated in this regard. Rated at \$2 billion each year [7], light source manufacturers have shown tremendous interest in signage industry, which has led to the development of novel techniques for energy reduction in signage application.

In this chapter we describe the operation and characteristics of solid-state light sources, namely, the conventional light-emitting diodes and the organic light-emitting diodes, which have stimulated tremendous interest in the solid-state lighting industry. Our main focus for this thesis is on the application of light sources for signage.

2.1 Conventional Light-Emitting Diodes

Light emitting diode technology, based on inorganic materials, has undergone immense improvements in the last 40 years. The development of LEDs began in the 1960s, when the silicon technology reached a very mature stage of development. The earliest practical light-emitting diode was demonstrated in 1962 and was based on GaAs phosphide [13]. Early LEDs emitted red light and demonstrated an efficiency of less than 0.2 lm/W, which was approximately 1/100th of the efficiency of an incandescent lamp. This low efficiency was due to the low quantum and external extraction efficiency. It was increased around 1 lm/W by the addition of nitrogen to the material [14]. Further improvements in 1980s led to the usage of AlGaAs material [15] that enabled the LEDs to challenge incandescent lamps for automobile and traffic light applications.

The vast improvement in the efficiency and structure of LEDs has widened the range of applications of this technology. The application of LEDs in the different markets is the result of the new advances made towards obtaining diverse wavelengths and high efficiencies from these devices.

2.1.1 Principle of Operation

Light-emitting diodes are based on the principle of electroluminescence, converting the electrical energy input to an electromagnetic energy output. The electromagnetic radiation emitted by these devices can be in the ultra-violet, visible or the infrared range. The range of wavelengths emitted by a semiconductor is dependent on the bandgap of the material. In inorganic light-emitting diodes, light-emission takes place when a device is kept under the influence of an electric field and a current passes through it.

LEDs are semiconductor based. Semiconductors possess conductivities between those of the insulators and the conductors. When these materials are doped with p-type (acceptor) or n-type (donor) impurity atoms, the conductivity of the semiconductor increases. The p-type and n-type semiconductors when grown on a common substrate form a semiconductor diode. The p-type material consists of holes as the majority charge carriers and n-type material consists of electrons. When an external electric field or a forward bias is applied to the junction, electrons are injected into the p-doped region and the holes into the n-doped region.

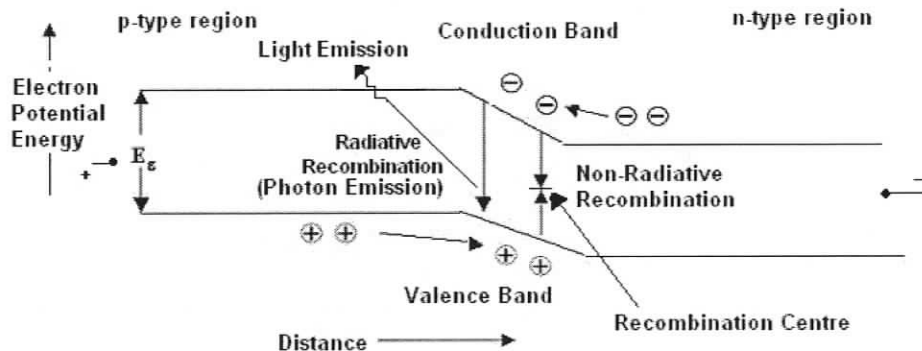


Figure 2-1: Recombination in light-emitting diodes

The injected electrons recombine with the holes and release energy. In terms of band gap energy picture, when an electron transitions from the conduction band to the valence band, the annihilation of an electron-hole pair takes place and this is termed as recombination [16]. The process is illustrated in Figure 2-1[13]. When energy is released in the form of photons, the resulting recombination is termed as radiative recombination, otherwise a non-radiative recombination.

The simplest LED consists of a p-n junction consisting of either a direct band gap material or an indirect band gap material. In direct bandgap semiconductors, the conduction band minimum is directly above the valence band maximum in the momentum-energy diagram (Figure 2-2 (a)) and the exchange in electron and hole momenta is zero. Hence the recombination is direct [13,16]. Direct gap semiconductors favor radiative recombination. GaAs is one of such semiconductors that emits red light.

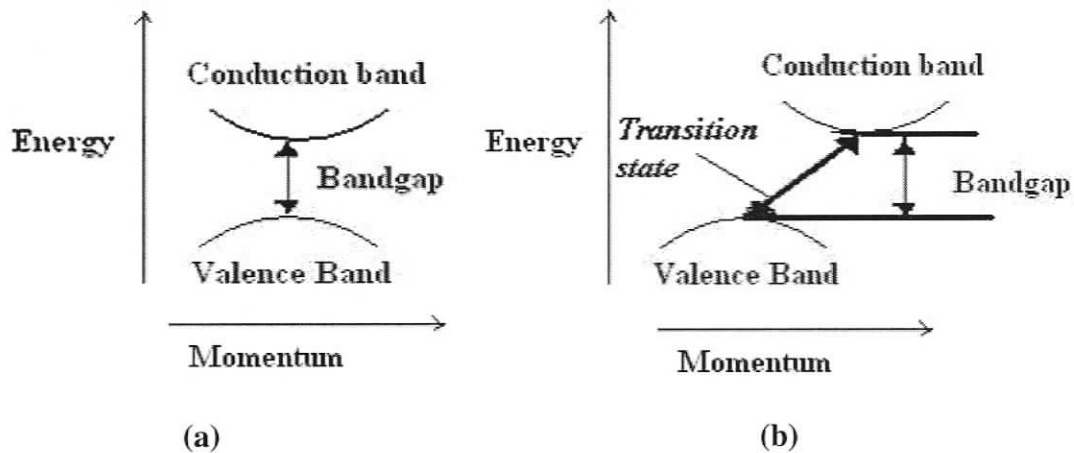


Figure 2-2 : Energy momentum diagram of the (a) Direct band gap semiconductors and (b) Indirect band gap semiconductors

On the other hand, in indirect band gap semiconductors, the minimum energy of conduction band is shifted from the maximum in the valence band as represented in Figure 2-2 (b). The net momentum exchange is not zero. Hence, recombination cannot occur, as the momentum cannot be conserved. So, electron transition occurs via intermediate energy states in the forbidden gap region. The interaction produces a particle called the phonon along with the emitted photon, which conserves momentum. These semiconductors possess longer recombination time and low quantum efficiencies.

Semiconductor layers are doped on top of the substrate in a LED. The n-type layer is laid at the bottom and the light is emitted from the p-type layer on top of it. The epitomical layers and the substrate layers can be of different materials. However, the lattices of these layers should be perfectly matched. For instance, AlGaAs alloys can be grown on GaAs substrates through the lattice matching capabilities. The junction in an LED may be formed of the same semiconductor material. LEDs possessing such junctions are termed as homojunction LEDs. When semiconductors with two different band gaps are used, the LEDs are called as heterojunction LEDs. Homojunction LEDs suffer from many limitations such as the reabsorption of the emitted electrons. Hence, double heterostructure devices have been introduced to minimize reabsorption of electrons [17]. Normally, the spectral output of an LED depends on the materials used for designing the junction. Red, blue and green LEDs are made from different kinds of semiconductor materials. As white light can be obtained from a combination of red (R), green (G) and blue (B) light, white colored LEDs are usually obtained by layering RGB materials and mixing the light emitted through them.

LED lamps are available as conventional lead type LEDs and as surface mount devices. A LED lamp consists of the LED chip encapsulated in a plastic lens. The latter can be transparent or semi-transparent. The encapsulation, which may be colored, improves the light quality emitted through the LED. It also protects the LED chip from aberrations. The leads for the electrodes are usually taken out from the chip to make external connections. If the chip of the LEDs is placed sideways, side-emitting LEDs can be formed. Such devices are useful in coupling the light into a light-pipe for optical communication applications.

If radiative recombination allows the emission of light in the visible spectrum, then the human eye can detect it. The response of a human eye is dependent on the wavelength of the light falling on it. The eye responds to wavelengths from 400-700 nm [12] with a maximum sensitivity to the greenish yellow color at 555 nm (see Figure 2-3). As indicated by the figure, the response of human eye varies with low-light (scotopic) and bright light (photopic) conditions. The relative spectral efficiency is measured with respect to the wavelength.

The minimum wavelength, which can be sensed by a human eye, is 380 nm in scotopic (dark or low-light) conditions as shown in Figure 2-3. This corresponds to energy of approximately 3.2 eV. The data for Figure 2-3 has been obtained from [12].

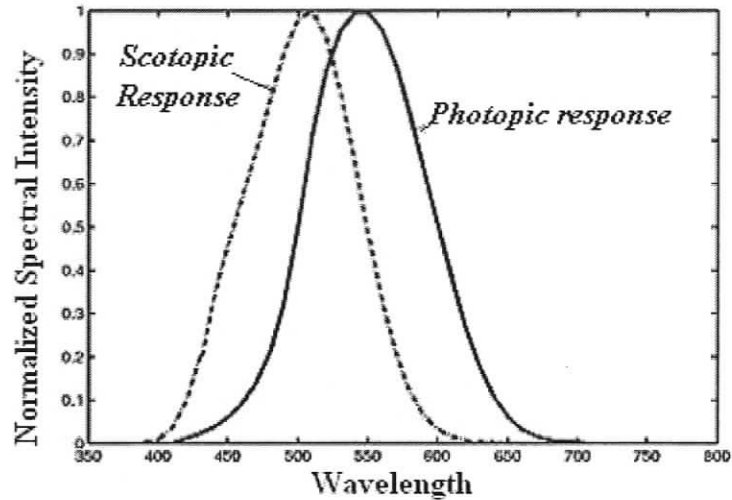


Figure 2-3: Response of human eye to different colors in scotopic (---) and photopic conditions(—)

Similarly the lowest energy corresponding to the highest wavelength (700 nm) is 1.8eV. Hence, the band gap of the semiconductors to be used should be larger than this energy so that the emitted light is in the visible spectrum. Such a band gap can be attained with the semiconductors that are made up of alloys or compounds of different materials such as the $\text{GaAs}_{1-y}\text{P}_y$ which a popular material for making LEDs.

Inorganic light-emitting diodes have progressed significantly during the last decade and have given way to research and development in the field of organic light-emitting diodes (OLEDs).

2.2 Organic Light-Emitting Diodes

Organic LEDs are still in their budding stages and have not reached a very mature stage of development. Organic LEDs work on the principle of electroluminescence (EL) similar to the conventional LEDs. Light emission is due to recombination of carriers in an electric field. Electroluminescent devices built with inorganic materials are already in use in many civilian and military applications [18]. EL in organic materials was first

discovered in the 1960s when an anthracene crystal emitted light on application of a very large voltage. External quantum efficiencies of 1-8 percent were reported with a theoretical efficiency of about 40 percent [19]. The reported efficiency was not sufficient for practical applications.

It was in 1987 when Tang and VanSlyke vitalized the OLED industry by demonstrating a green electroluminescent device based on organic materials [20]. They used a *small molecule* based double-layered structure made by vapor deposition of tris(8-hydroxyquinoline)aluminum (Alq_3) with a metallic cathode on a conductive substrate. The luminous efficiency was reported to be 1.5 lumen/watt at a driving voltage less than 10 volts. This was followed by the demonstration of *conjugate polymer* based single-layered organic light-emitting device by a research group [21] in Cambridge University. The device was prepared by the spin coating process using polyphenylenevinilene (PPV) as the emitter. These devices were reported to possess better processing capability due to their polymer base.

2.2.1 Physics of the Device

A conventional LED consists of a p-n junction. When an electric field is applied to the junction with energy greater than the barrier potential, the minority charge carriers move under its influence, recombine and generate light. Although, the working of an OLED is analogous to an inorganic LED, the physics are markedly different [22]. OLEDs possess an electron injecting layer (the cathode) and a hole injecting layer (the anode), instead of the p-layer and n-layer in a conventional LED.

Organic LEDs are made up of carbon and its compounds. These materials possess a very large band gap and resemble insulators. An OLED is formed when a thin film of an organic material is sandwiched between an anode and a cathode. This film is very amorphous and highly disordered. The conduction mechanism of this device may be understood using the molecular energy levels (see Figure 2-4), namely: the lowest unoccupied molecular orbital (LUMO) and the highest occupied molecular orbital (HOMO). V is the applied voltage in the Figure 2-4.

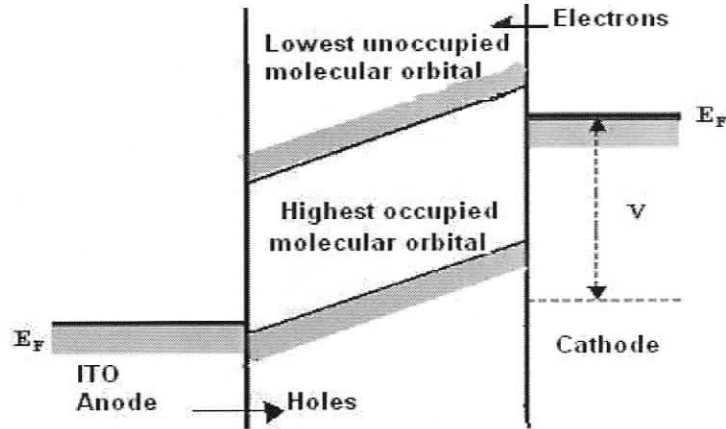


Figure 2-4: Molecular energy level structure for an OLED

The anode of the device is made up of a material with a high work function such as Indium-tin oxide (ITO) and the cathode is made with a different low work function material. This enables thermionic injection of charges. The device possesses a barrier potential, which is reduced by the application of forward bias, and the electrons and the holes are injected from the electrodes separately. The mutual attraction between these positive and negative charges results in the formation of excitons¹. Excitons exist either in singlet or triplet state. A singlet state represents an anti-symmetric spin state while the triplet state represents a symmetric spin state. When the exciton relaxes from the singlet state to the ground state, light is emitted due to *fluorescence*. In the triplet state, *phosphorescence* is the main cause of light emission.

2.2.2 OLED Structure

The simplest OLED consists of a single layer of the organic material laid between two electrodes. However, the device first demonstrated by researchers at Kodak [20] was a double-layered device. The addition of another layer enhances the injection of the charge carriers in the emitting layer. This layer allows monopolar transport, blocking the injected electrons to make the recombination process more effective. A recombination results in the formation of excitons, whose relaxation causes the emission of light.

¹Exciton is a neutral excited state of an insulator or semiconductor. It refers to a bound state of an electron and hole

With the progress made in this area, multilayered heterostructures have also been developed [23]. These additional layers separate the transport region from the emitting region and enhance device efficiency. The layers also broaden the color spectrum of the light emitted. Figure 2-5 depicts such a structure.

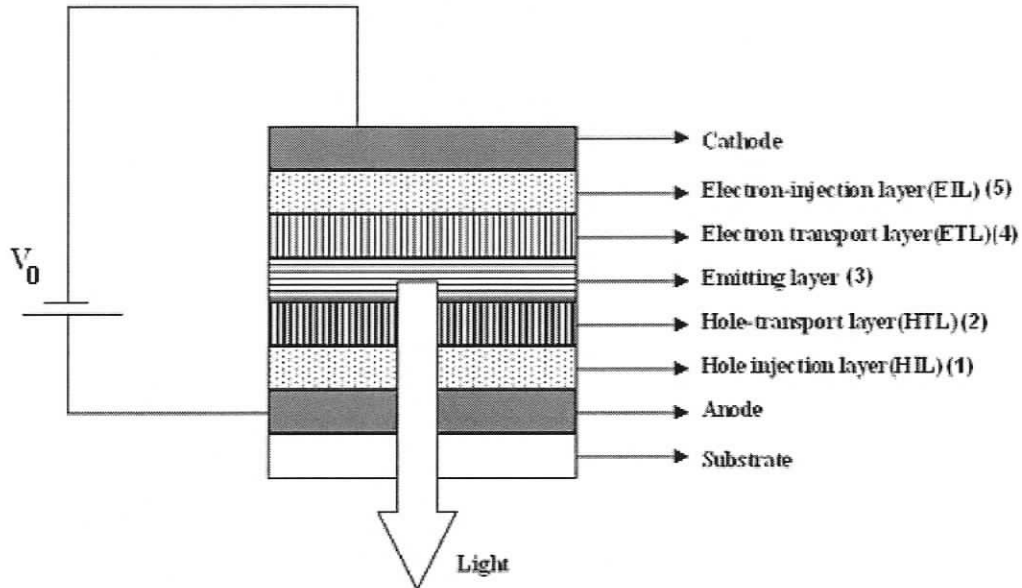


Figure 2-5: *Multilayered bottom-emitting OLED*

The *substrate* of an OLED is a material on which the device is deposited. It can be a rigid substance such as glass or a flexible material like plastic. For some specific cases such as the bottom emitting OLED (where light comes out from the bottom of the device), the substrate is made transparent. The choice of the material used as a substrate has a great bearing on the efficiency and degradation of the device. A rigid material is less prone to the effect of moisture and air than a flexible material. OLEDs that are built on flexible structures are known as flexible OLEDs (FOLEDs) [24]. FOLEDs are ultra-thin and lightweight. The flexibility of these devices broadens the spectrum of application of OLEDs.

The following explains the device operation using Figure 2-5.

Holes are injected from the anode to the hole injection layer (HIL) (1). The function of this layer is to control and enhance the injection of holes to the hole transport layer (HTL) (2). The HTL transports the holes to the emission region (3).

The emitting layer is the most significant layer in an OLED. The charge carriers recombine in this layer to form excitons which eventually lead to light emission.

The electron transport layer (4) performs the same function as hole transport layer except that it transports electrons from the electron injection layer (5) to the emitting layer.

Multilayered OLED devices require less power due to the effective transport of holes and electrons. Figure 2-5 depicts a multilayered, bottom-emitting device. Light is emitted through the transparent anode in these devices. Due to the emission of light from the bottom part of the OLED, it is almost impossible to integrate the drivers with it for high-resolution applications. Thus, top-emitting architectures with an optically clear cathode have been favored. These OLEDs with transparent cathodes are termed as Transparent OLEDs (TOLEDs) [25]. Vertically stacked red, green and blue pixels form a stacked OLED (SOLED) structure, which uses transparent OLEDs. This structure generates a full-colored OLED module, which is spectroscopically tunable.

2.2.3 Types of OLEDs

There are two broad ways for classifying organic LEDs. OLEDs can be classified on the basis of the emissive material used and on the basis of the mechanism used for addressing them.

On the basis of the **emissive material used**, OLED devices can be classified as:

1. Small-molecule OLEDs (SMOLEDs)
2. Polymer OLEDs (PLEDs)
3. Phosphorescent OLEDs (PHOLEDs)

Based on the technique used for **addressing**, OLEDs are classified into two types:

1. Passive matrix organic light emitting devices (PMOLEDs)
2. Active matrix organic light emitting devices (AMOLEDs)

In the following subsections, we give a brief explanation of these devices. Active matrix OLEDs are used for high-resolution applications and as signage is not a high resolution application, we do not concentrate on them for this thesis.

2.2.3.1 Small Molecule OLEDs (SMOLEDs)

Small molecule OLEDs are devices made with a low-molecular weight material as the emissive layer. The emission color of the device is dependent on the emissive material used. These devices are processed in ultra-high vacuum systems known as organic molecular beam deposition (OMBD) systems. These OLEDs have been shown to be very suitable for microdisplays [27] because of their higher operational lifetimes than the polymer and phosphorescent OLEDs.

2.2.3.2 Polymer OLEDs (PLEDs)

Polymer OLEDs are devices using organic polymers as the emissive material. These devices are processed by the spin-coating technique, which is much simpler than the vacuum deposition technique used for SMOLEDs. During the deposition, the solvent evaporates and the polymer molecules readily form an amorphous film [26]. The molecular weight is easily controlled and color tuning is possible. However, this technique leads to a greater wastage of materials. However, if there is any reduction in pixel pitch, it is more difficult to lay down the top electrode [27]. PPV has been regarded as the first generation material for OLEDs and poly-fluorine as the second-generation material for the manufacture of these devices.

2.2.3.3 Phosphorescent OLEDs (PHOLEDs)

A breakthrough in OLED efficiency was achieved with the discovery of phosphorescent OLEDs (PHOLEDs) by a research group [28] at Princeton University. PHOLEDs are formed with the addition of phosphorescent dyes to organic material. Light emission in these OLEDs may result from both singlet and triplet states due to phosphorescence, which is not common in the other OLEDs. Hence, they exhibit higher efficiency and possess the potential to achieve 100 percent internal quantum efficiency. Also, they can be driven by low voltages. There is a possibility of obtaining a more efficient, tunable white light source using phosphorescent dyes.

2.2.3.4 Passive Matrix OLEDs (PMOLEDs)

Passive multiplexing is the simplest way to address the pixels in an organic LED display. Passive matrix OLED displays were the first ones to enter the OLED market due to their uncomplicated structure. In PMOLEDs, the drivers are attached to each row and column and the pixel is lighted up by selecting the required row and column as in Figure 2-6 [29]. The display is scanned line by line over a period of time. Current passes through the selected pixels and varying the current changes the brightness of the display. Passive matrix displays can be voltage or current controlled.

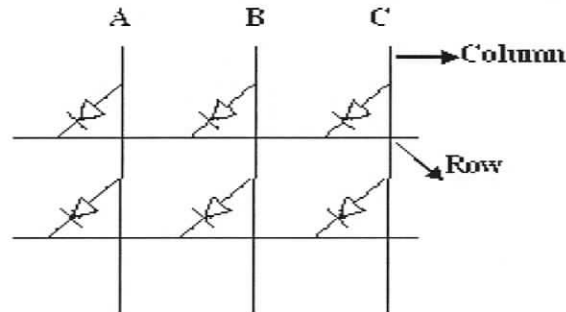


Figure 2-6: *Passive matrix OLED structure*

PMOLEDs can be driven by the anode to cathode voltage difference. In order to use this voltage driving method, it is necessary to do the required gamma correction [30]. Gamma correction is the adjustment of the levels of the signal voltage to counteract the non-linear effects in the display output. To obtain uniform picture quality or a uniform luminance the input current to each pixel should be the same and the pixel characteristics should be identical. But that is hard to achieve due to the differences in the characterization of each pixel. A small change in voltage results in a relatively large change of luminance and a high gray scale image is hence difficult to obtain through the voltage-driving method.

The current-driving method for OLEDs is, therefore, more helpful in obtaining a uniform picture quality. However, low gray levels are difficult to obtain with a current driven OLED as the driving current is not sufficient to charge up the data line voltage in order to achieve low gray levels. To eliminate this problem, pre-charging is performed. A pre-charging circuit is essential to be used with the current controlled PMOLEDs. Passive matrix OLED devices are contemporarily used in low-cost and low information content

applications. Due to the fact that they are operated on a higher current, PMOLEDs possess a shorter lifetime than AMOLEDs.

As signage is a low-information content application, hence, passive matrix OLEDs are more useful.

2.3 Summary

The structure and working of the inorganic and organic light-emitting diodes were discussed in this chapter. It also described the different types of OLEDs and their principle of operation based on already available literature. This chapter intended to familiarize the reader with the device behavior before using it for any application.

Chapter 3

Evaluation of Light-Emitting Devices

3.1 Evaluation of Conventional Light-Emitting diodes

Conventional light-emitting diodes have been studied extensively and have been commercially used for many applications. In this section we look at the commercially available lead-type LEDs, their efficiency and characteristics.

In incandescent lamps the majority of power is lost in the form of heat and so the efficiencies are very low. In LEDs, the overall efficiency is based on the internal quantum efficiency and the light extraction efficiency. The value of internal quantum efficiency has been enhanced to high values and there have been many improvements in the light extraction efficiency as well [31].

We took measurements with a commercially available Nichia NSPW500BS white LED as shown in Table 3-1 with various values of input current in order to determine the current status of LEDs. The I-V characteristics of this device can be obtained from the device datasheet. However, the L-I characteristics had to be measured due to the unavailability of luminance ratings in candela, which is a standard unit for measurement of LEDs. This also shed light on the measurement techniques commonly employed for LEDs.

Table 3-1: *Variation of luminous intensity with input current*

Current (mA)	Luminous Intensity (cd)
5	1.220
13.5	4.30
41.1	10.25
60.7	14.64
116.3	18.63

The absolute light output was noted in terms of candela. The efficiency of this LED could be calculated with the help of the data in Table 3-1.

The average current is 47.32 mA and the average light output is 9.8 cd. So, the efficiency will be 20.7 cd/A. Figure 3-2 depicts the luminance-current characteristics of this LED. The luminance intensity is proportional to the current through the LED. These values were matched with the manufacturers datasheet and the values were found to be similar as shown in Figure 3-1. The manufacturer quotes the luminous intensity as a relative value with arbitrary units, but we have obtained the absolute values in millicandelas (mcd). The curves are not perfectly linear. Datasheet for NSPW500BS is given in Appendix C.

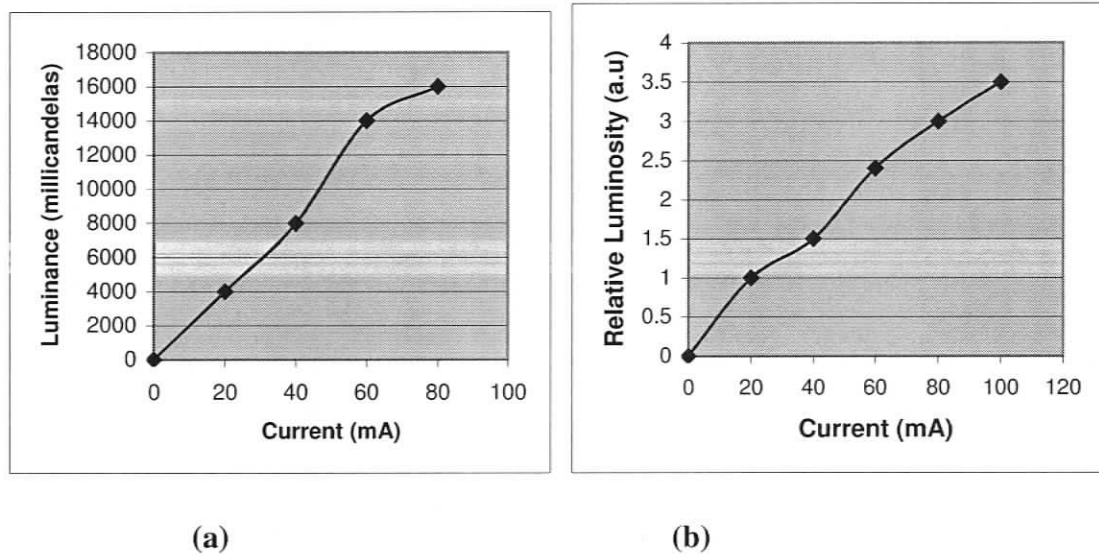


Figure 3-1: Current vs. Luminous intensity for the Nichia white LED (a) based on our measurements and (b) based on manufacturer's datasheet.

It should be noted that light output is measured in candelas for point sources such as inorganic light-emitting diodes. These values can be measured using instruments such as integrating spheres that measure the light output in all directions.

Conventional inorganic LEDs are available in different colors with different specifications. In order to select the type of LED for signage application, we did a preliminary study of the efficacy of LEDs available from different manufacturers. In

order to determine the light output of the LED for different currents, measurements were made with the most commonly used LEDs.

This data would be useful in comparing the L-I curves of the commercially available LEDs and would influence the choice of LEDs used for signage application. Radiometer IL-1400A along with the LED probe from International light Inc. was used for the measurement. The luminance was proportional to current (Figure 3-2).

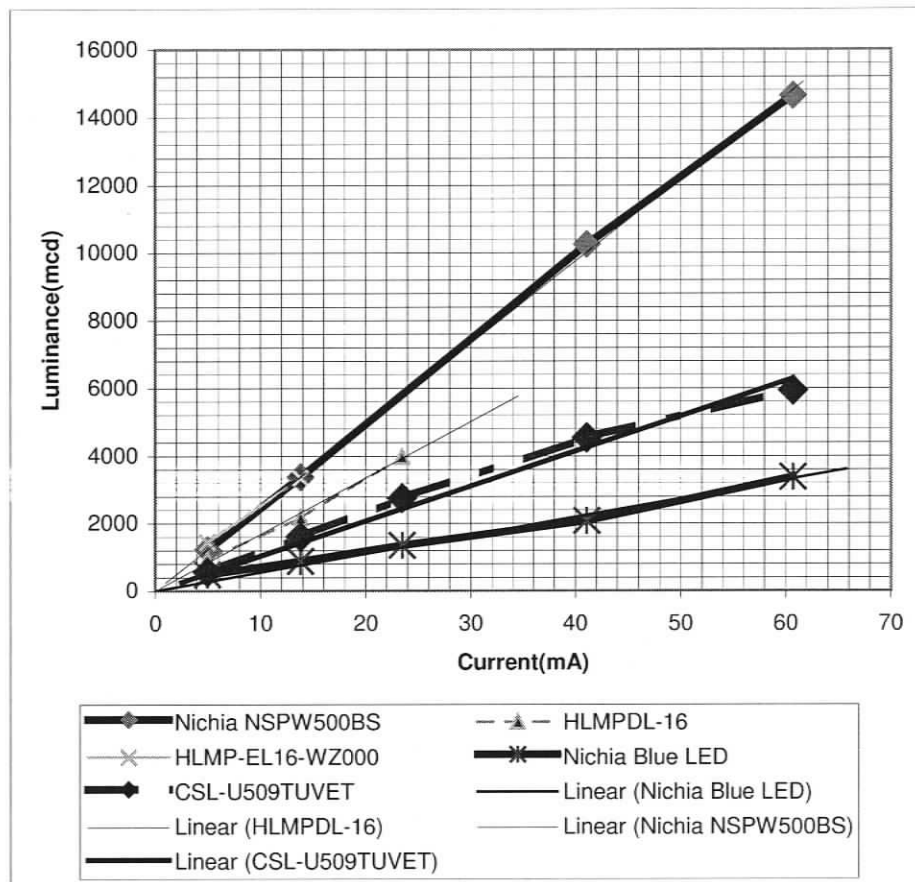


Figure 3-2: L-I characteristics for commercially available LEDs compared with linear curves.

According to the data obtained with these LEDs, we could determine that the efficacy of Nichia NSPW500BS was higher than the other commercially available LEDs. Hence, it was more suitable for signage application.

LEDs possess a better efficiency than the incandescent lamps. The efficiency of commercially available white LEDs is 20.7 cd/A according to our measurements. Inorganic LEDs are available easily from various manufacturers in various colors.

3.2 Evaluation of Prototype Organic Light-Emitting Diodes

OLED devices are developed in many research laboratories. These devices are available as prototypes. Prototypes serve as preliminary samples used for evaluation. For a preliminary study, the National Research Council (NRC) based in Ottawa sent us a prototype sample for analysis. These samples had been fabricated at NRC and had not been characterized before. The samples were small-molecule based and emitted green light. These samples could provide an initial idea about the features of OLEDs and hence, were very crucial for our investigation. In this section, we will report and discuss the characteristics of these OLEDs.

3.2.1 Construction of the OLED panel

The prototype OLEDs were available as an eight-segment display that could be used for alphanumeric applications. The OLEDs were laid down on glass substrate without any encapsulation. Figure 3-3 shows the layout and the physical appearance of the OLED samples.

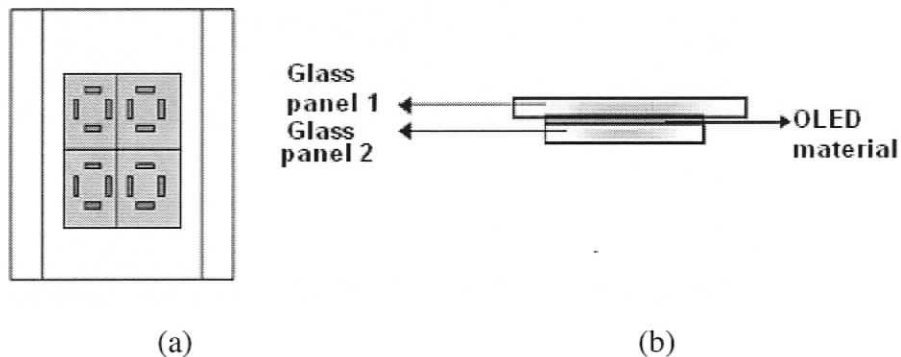


Figure 3-3: *a. Top-view of the OLED sample b. Side-view showing the layout*

The panel consisted of two glass slabs with the OLED layer sandwiched between them.

The dimensions of the sample are:

Length of the display: 5cm

Width of the display: 5cm

Height of the display: approximately. 1.9mm

Length of each segment: 5mm

Width of each segment: 1mm

Area of each segment: 0.05 cm²

The sample is composed of two eight-segment displays, which can be lit up independently.

3.2.2 Testing

The samples were not encapsulated, and the pin-outs were not clearly observable. The electrical connections on the glass panel were determined with the help of a digital multimeter. The connections were found to be on both the sides of the glass panel. A thin insulator strip separated these connections. Each of the segments was connected to these connections and could be powered up independently. These samples were not configured for use as a passive matrix or an active matrix display. Hence, they could be turned ON by supplying direct power through a voltage source. So, no external driver circuitry was required.

3.2.3 Electrical Characteristics

As the dimensions of all of the segments were equal, we assumed that the I-V characteristics for each of the segment would be the same. However, in order to be sure of our assumption we measured the values of the two OLED segments in the display – one vertical and one horizontal. We numbered these segments as segment A and segment B. In order to perform these measurements, a stable fixture was built and we connected the wires to the display. As the display panel was made of glass, the connection made via the conventional soldering method was liable to damage the sample due to excessive heat (temperature of a soldering iron reaches near 200 deg C). Therefore, we used a conducting silver epoxy paste to connect the wires. This silver paste was ideal to be used as a cold solder and required around 6-7 hours in practice to cure.

Figure 3-4 depicts the set-up used to perform the measurements.

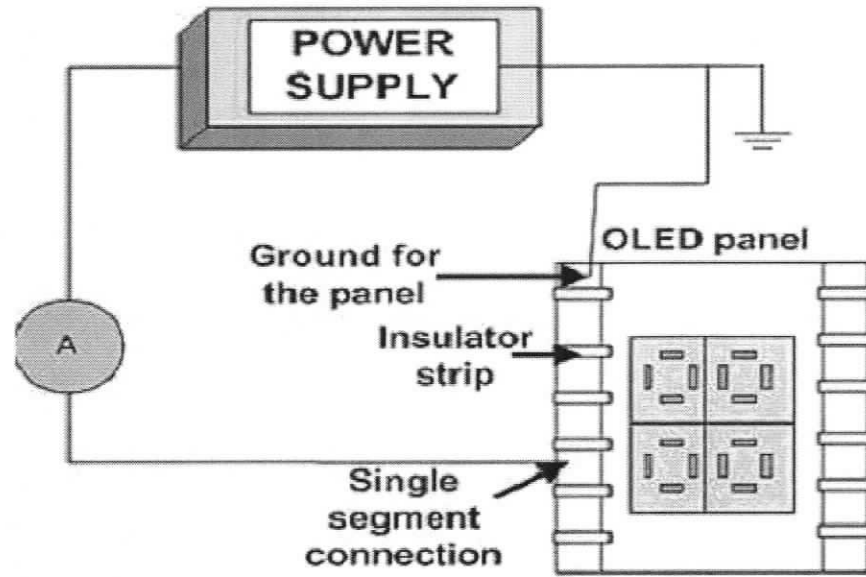


Figure 3-4: Set-up for the measurement of the I-V characteristics

The input voltage value was limited to 5.2 V because the maximum safe voltage level for this device was unknown and a higher value of voltage probably would impede its operation and burn it out. Table 3-2 shows the voltage and current measurements and Figure 3-5 depicts the corresponding I-V characteristics for segment A, which were measured using an accurate digital multimeter.

Table 3-2: The I-V measurements for segment A

Voltage (Volts)	Current (mA)
0	0
2.8	0.001
3	0.05
3.2	0.017
3.4	0.0295
3.6	0.049
3.8	0.1
4	0.1345
4.2	0.221
4.4	0.322
4.6	0.427
4.8	0.553
5	0.78
5.2	1.04

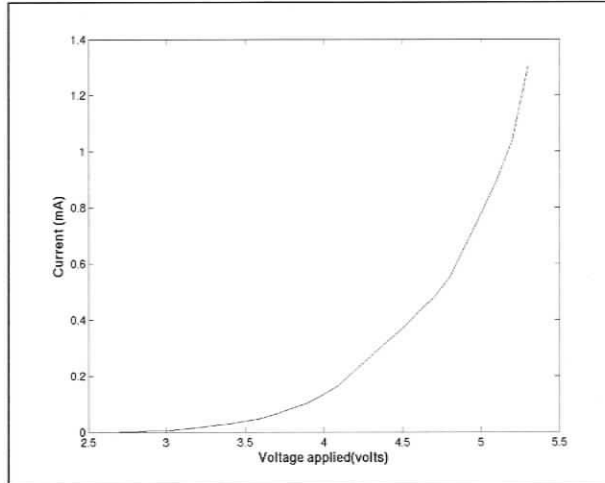


Figure 3-5: *The I-V Characteristics of segment A under forward bias.*

Table 3-3 and Figure 3-6 depict the voltage and current measurements and the I-V curve of segment B respectively.

Table 3-3: *Voltage and current values for segment B under forward bias*

Voltage (Volts)	Current (mA)
0	0
2.8	0.001
3	0.005
3.2	0.016
3.4	0.034
3.6	0.0585
3.8	0.086
4	0.1465
4.2	0.222
4.4	0.327
4.6	0.4705
4.8	0.6035
5	0.875
5.2	1.218

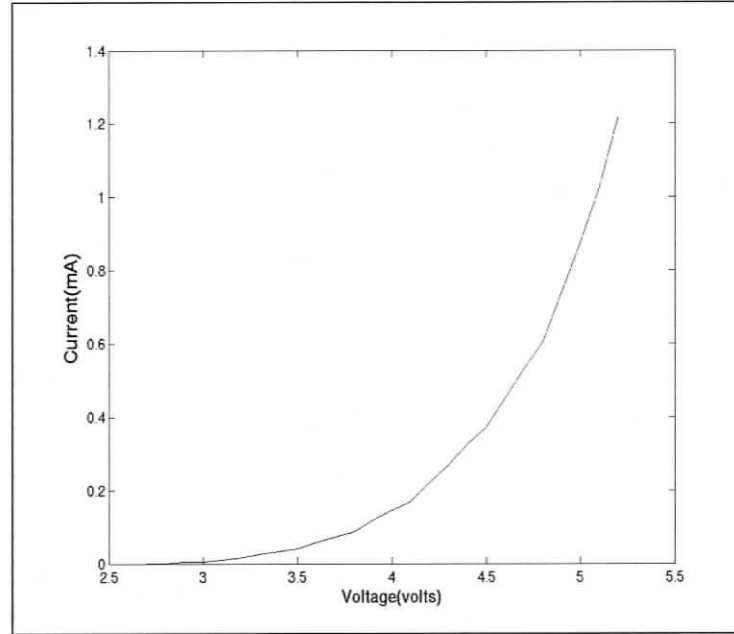


Figure 3-6: *The I-V Characteristics for segment B under forward bias*

The ideal diode equation [32] in the forward bias condition is given by equation 3-1.

$$I_F = I_0(\exp(qV_F / \eta k_B T) - 1) \quad (3-1)$$

where q is electronic charge, I_F is the forward current, I_0 is the saturation current, V_F is the forward voltage, k_B is the Boltzmann's constant, η is the ideality factor and T is the absolute temperature.

Equation 3-1 could be simplified by taking the natural log on both sides

So

$$\ln I_F = \ln I_0 + \frac{qV_F}{\eta k_B T} \quad (3-2)$$

By using equation 3-2 we could calculate the saturation current I_0 and the ideality factor η associated with the prototype OLED device based on the I-V measurements.

Table 3-4 depicts the values of saturation current I_0 and ideality factor η for each of the segments.

Table 3-4: Reverse saturation current (I_0) and ideality factor (η) for segments A and B.

Parameters	Segment A	Segment B
I_0 (picoamperes)	1	1
η	7.55	7.69

The high values of ideality factor η indicate an unusual behavior, which is not seen in conventional p-n junction diodes. These high values have been reported in different types of organic and inorganic light emitting diodes as in [33], [34].

3.2.4 Optical Characteristics

Like other light emitting devices, OLEDs are also characterized by their luminance/illuminance. Luminance is the amount of visible light leaving a point on a surface in a given direction while illuminance refers to the light incident on a surface due to reflection, transmission, and/or emission. Luminance is the luminous intensity per unit-projected area on any surface, as measured from a specific direction. In the case of conventional LEDs, which are essentially point sources, the luminous intensity is measured in *candelas*. However for a surface emitter like the organic LED, the best way to measure the brightness is in terms of *lux or candelas/m²*. This is because in this way we could measure the illuminance output from the emitter.

In order to perform this measurement we needed a device that could detect and measure light. Such devices are known as *photodetectors*. The size of the photodetector was a major consideration for this measurement.

The photodetector should be able to cover the whole area of the segment without any losses. Various types of photodetectors were available. However the most suitable one was determined on the basis of the area covered.

A calibrated **S-370 optometer** from UDT instruments along with **Agilent 6612C system DC power supply** were used for the measurements. The features of the Agilent power supply were helpful in setting-up the display to be used with current-control or voltage-

control. A circular photometric head was already attached to the optometer and the measurements were made. The display was green in color.

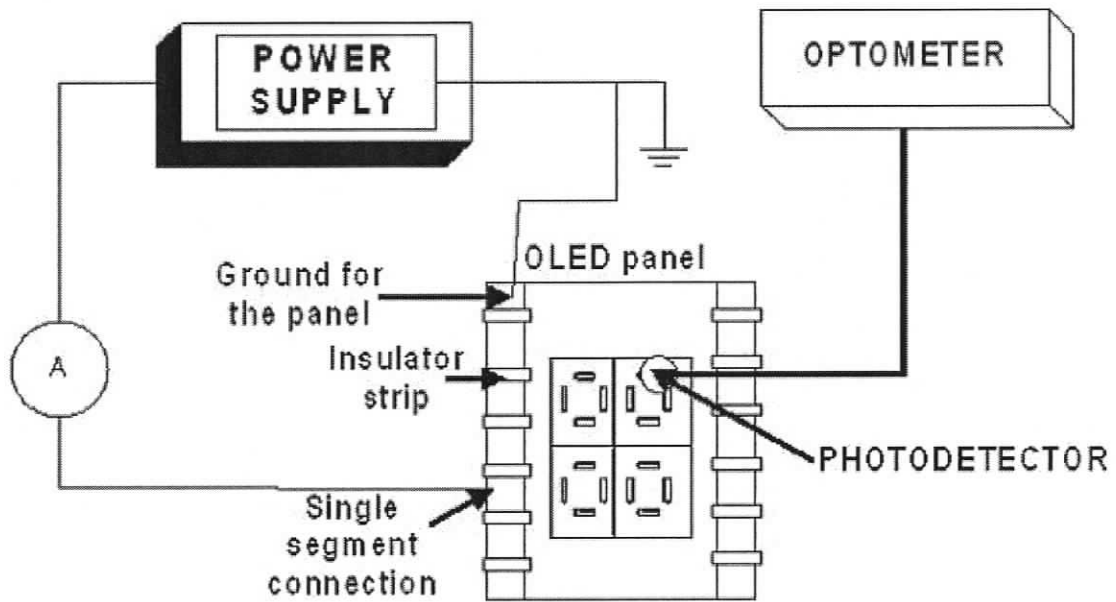


Figure 3-7: Set-up for the measurement of L-I characteristics

The measurements were performed in a dark room and any unwanted light was avoided. The light output was noted in scotopic¹ conditions and was taken in consideration while recording the measured data. Any offsets in the measurement instruments were also noted. The measurements were done at various current levels and corresponding illuminance (in lux) for recorded.

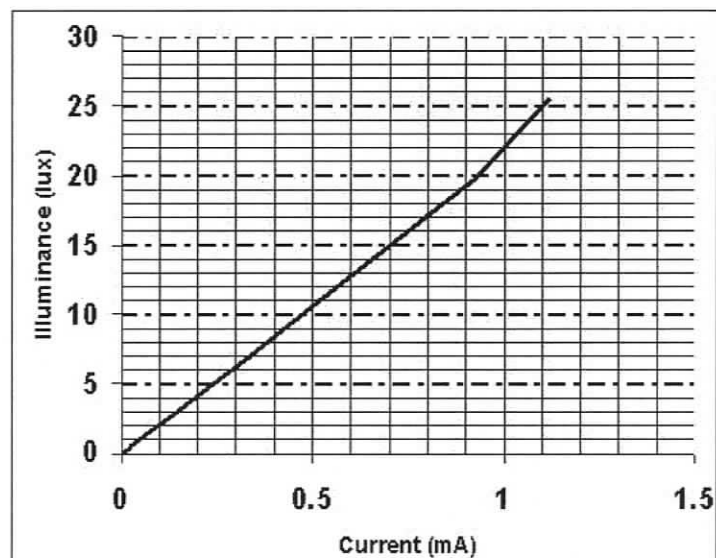
The current and illuminance values for segment A are given in Table 3-5.

¹Scotopic implies low light conditions such as nighttime

Table 3-5: *Current and luminance values for Segment A*

Current (mA)	Luminance (lux)
0	0.004
0.001	0.075
0.02	0.365
0.028	0.532
0.039	0.758
0.052	1.027
0.068	1.36
0.142	2.9
0.175	3.6
0.261	5.44
0.313	6.54
0.442	9.32
0.6	12.74
0.8	17.1
0.917	19.6
1.119	25.48

The illuminance-current characteristics obtained from segment A are shown in Figure 3-8.

**Figure 3-8:** *The illuminance-current characteristics for Segment A*

Similarly, current and luminance values for segment B are shown in Table 3-6.

Table 3-6: *Current and Luminance values for Segment B*

Current (mA)	Luminance (lux)
0.002	0.03805
0.007	0.1181
0.024	0.421
0.0345	0.639
0.0445	0.862
0.0745	1.511
0.0945	1.933
0.118	2.441
0.146	3.04
0.18	3.786
0.21	4.6
0.262	5.55
0.3115	6.65
0.438	9.46
0.515	11.11
0.604	13.07
0.808	17.53
1.065	23.01

The illuminance-current curve for segment B is shown in Figure 3-9.

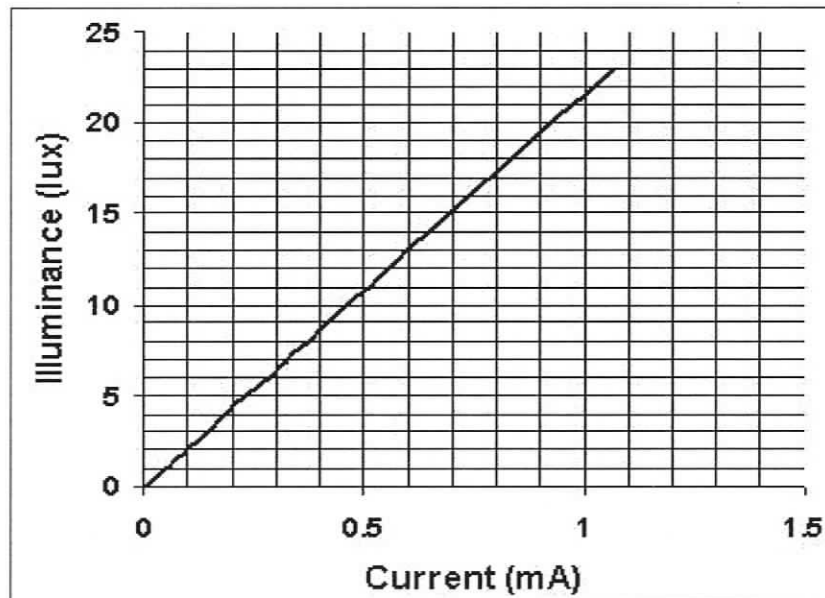


Figure 3-9: *The illuminance-current characteristics for Segment B.*

3.3 Results and Discussion

This chapter presented numerous initial results with commercially available LEDs and prototype OLED module. The commercially available LEDs were analyzed with the help of their L-I characteristics and the OLEDs on the basis of their illuminance-current characteristics. On the basis of our measurements we determined that Nichia's NSPW500BS was be the most suitable LED for signage application due to its higher efficacy.

We also analyzed the OLED research sample from National Research Council, which had not been analyzed before. Analysis of the data recorded and the graphs obtained from the segments in the module proved that the segments performed in a similar manner. The total luminance from the OLED display, when all segments were lit up, could be estimated by multiplying the luminance from one segment by 16. The luminous efficacy of the device was 0.02 lm/watt. Due to the unavailability of an optical detector with a greater surface area, the luminance from the whole display could not be measured. Also it was observed that if the voltage level was increased beyond 5.2-5.4 volts the current value increased drastically. The I-V curves obtained clearly indicated the conventional diode-like behavior. The current dependence of light output was also undoubtedly visible. This device was useful to understand the basic properties of a simple OLED. However, the extremely low luminous efficacy of the device did give rise to some predicaments about its application for signage. It was also observed that the device developed small bubbles after a period of time when lighted up, which were indicative of its degradation. The lack of appropriate encapsulation for this display would have indubitably caused an effect on its properties.

This device suffered from some intrinsic limitations and hence it was difficult to conclude if OLEDs could be used for signage using this device. However, the analysis OLED module helped us to determine if OLED modules were capable to achieve high luminance for signage application. It could be seen that it was possible to obtain 23-lux output when the module was operated at about 1mA. This motivated us to investigate further. Also, this sample was indicative of the fact that the external environment could affect OLED devices. Hence in order to investigate the application of OLEDs for

signage, we had to procure samples with proper encapsulation. In addition, other available modules had to be procured and analyzed for a vivid and detailed investigation. This is discussed in the following chapters.

3.4 Summary

In this chapter we looked at commercially available LEDs obtained from Nichia Corporation and prototype OLEDs obtained from the National Research Council of Canada. This chapter served to provide preliminary data on LEDs and OLEDs. The data was analyzed specifically keeping in view the specific application of signage. The data obtained from conventional LEDs will be used in the following chapter to design signage based on LEDs.

Chapter 4

Design and evaluation of Conventional LED-based Signs

The development in LED technology has facilitated its use in many new applications. Being one of the most efficient sources of lighting available today, inorganic LEDs have been employed for signage commercially. These LEDs are compatible with integrated circuits, hence can be driven easily and are prove advantageous to signage manufacturers.

Displays for signage application using LEDs are commercially available in different designs and types. Inorganic LEDs are commercially available in various colors and specifications so it is possible to construct displays in various colors. However, this evaluation is limited to the displays available for generic use for the edgelighting technology.

4.1 Signage Standardization and Design

For this evaluation, a backlit display that utilized the edgelighting technique was selected. These signs consisted of high brightness LEDs placed on the edges of an acrylic panel or sheet. The signage manufacturers often obtain the acrylic panel as a separate component. It consists of a base panel and a transparent panel on top of it. The acrylic base panel obtained for this evaluation was white with a smooth transparent surface exclusive of any engravings or customized wave-guides.

The acrylic was cut in a rectangular or square shape depending upon the sign to be displayed. The size of the acrylic panel was standardized to (600mm x 600mm) size for this work on the basis of the commercial usage. The signs with an approximate area of (600 mm x 600 mm) were easily available for evaluation. These were termed as the 600 mm series signs. Although, these signs had slightly different areas still they were considered useful for evaluation due to their similar construction and set-up.

Figure 4-1 shows the set-up for the 600 mm backlit-edgelit sign.

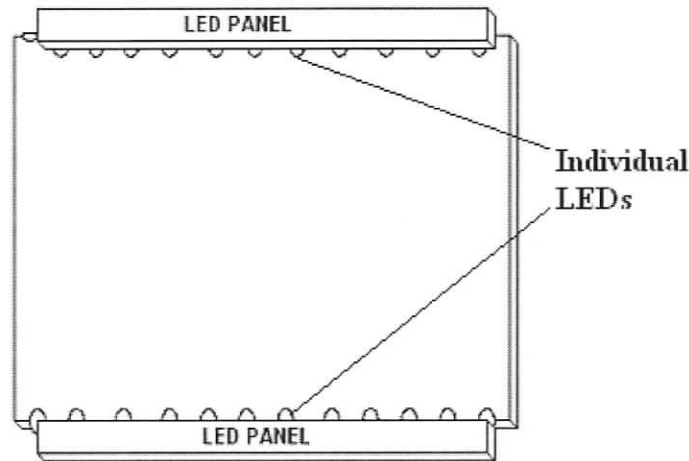


Figure 4-1: *Set-up for a commercial LED based backlit sign using edgelighting*

It must be noted that this was a type of generic display, which could be used for any signage pattern. Any signage pattern could be placed on the top of this acrylic panel for representation.

4.2 Display Design with Grating

The standard sign was basic and did not have any engravings. Modified signs with specialized diamond gratings were also commercially available for evaluation. This signage design was included in this evaluation to get a distinct idea of the usage of LEDs as sources and to study the different methods, which are commercially popular for this application.

Diamond gratings were available in the form of circular plastic sheets with small pyramidal reflectors (Figure 4-2). The diamond gratings had a diameter of 600 mm. These could be simply glued on the top of the acrylic sheet base. Diamond gratings were known to help in the dispersal and spreading of the light. Hence, they were mostly used for large area display lighting. A sample sign with a circular diamond grating in the center was also analyzed. Figure 4-2 depicts a sign with a diamond grating.

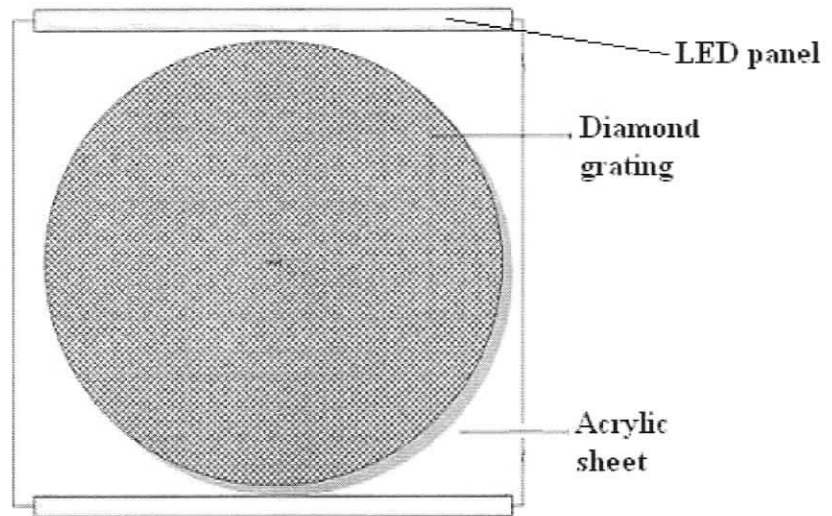


Figure 4-2: *Display panel with a diamond grating on top*

The primary reason to use a diamond grating with the signage panel was to diffuse light in all directions. Plastic diamond gratings are very well known to distribute light due to the pyramidal reflectors on the surface. The evaluations of signs with a diamond grating would throw light on how we could try to change the light-distribution in a display using external means. The cost of the diamond grating was about \$500 for a 600 mm diameter.

4.3 Signage Patterns

Usually the 600 mm series signs were the standard signs with an acrylic base on top of which the pattern was to be placed. The pattern structure was dependent on the information required to be conveyed. Patterns for stop sign, arrow sign or any highway sign were easy to obtain. They were plastic sheets with a painted legend or pattern on top. The pattern employed for our evaluation was an arrow sign, which is a commonly used signage in North America.

Figure 4-3 depicts the arrow sign pattern, which was placed on top of the display for comparison

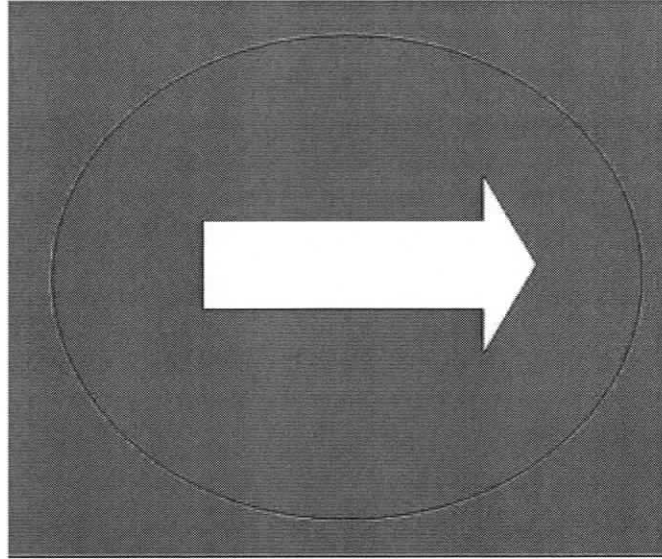


Figure 4-3: *A Sign shown with a display pattern on the top surface*

4.4 Driver Circuit

LEDs could be driven directly from a DC power supply. However, this technique was usually used for systems that required less number of LEDs. In the 600mm series signs, 48 LEDs were used from the same bin (from Nichia Corporation). Nichia's NSPW500BS model for LEDs was chosen for this design due to its higher efficacy as determined in Chapter 3. 12 LEDs were connected together in series and then the strings were wired in parallel. In order to optimize the power consumption of the display, pulse width modulation technique was employed to drive the LEDs. LED drivers could be constructed by the standard CMOS technology or by hardwiring the required components together. It was easier to control LED displays using a microcontroller.

We looked into the existing LED driver circuit that had been used for the standard 600mm series sign. This circuit had been so designed to operate in conjunction with a photovoltaic cell. The basic circuit could be divided into the following three sub-circuits:

- Charge system stage
- Microcontroller IC stage
- Output stage

The charge system stage consisted of a charge-transfer touch sensor, a general-purpose n-p-n transistor and several hexfet power MOSFETs. The microcontroller section consisted of an infrared detector, which enabled the device to be controlled remotely. A touch sensor was also present along with a CMOS serial EEPROM (electrically erasable programmable read-only memory), which stored the data and the program to control the LEDs. A microcontroller chip was also used that could be programmed according to the type of application. The output stage was a gain stage with current mode switching circuits to switch the current power-rectifiers and power MOSFETs. Diodes providing high over-voltage protection through a damping action were also used.

4.5 Electrical Measurements

A signage display could be evaluated on the basis of its power consumption. However, it was difficult to isolate the optical characteristics of the display from its electrical characteristics. The reason was that the brightness of the LEDs was dependent on the current supplied. So the light output had to be standardized in order to measure the power dissipation and calculate the efficiency.

The light output was standardized to 20 lux for the 600 mm series signs on the basis of industrial usage. It was determined that the display consumed about 330-500 mW and gave an average light output of 20 lux.

4.6 Optical Measurements

A detailed evaluation of the display required measurement of its visual quality. The display was for a distributed area application, so photometric measurements were used. In this way the light falling on a surface was perceived the way it would have been visible to the viewer (human eye). A photometer (S-370 optometer from UDT Instruments) was used for the measurements. This photometer measured all values in lux. The display was powered up with a programmable Agilent 6612C System DC power supply.

As the size of the photodetector was much smaller than the display, so the total luminance could not be estimated in a single measurement. The measurement was therefore made at various specific points on the display panel one at a time. However, the current and voltage to the display were kept constant in order to avoid any changes in

measurement. Also, any large changes in environmental conditions were also avoided. The measurement points were evenly distributed across the display. The method of measuring illuminance with the help of spatial measurements is considered as a standard for measuring the light output from a flat panel display.

Figure 4-4 shows the position of the points on the display. The measurement could be averaged out to get the total luminance from the display. The display quality could be judged on the basis of its illuminance distribution. So, it was more advantageous to make measurements on the specific points rather than measuring the light output from the whole display.

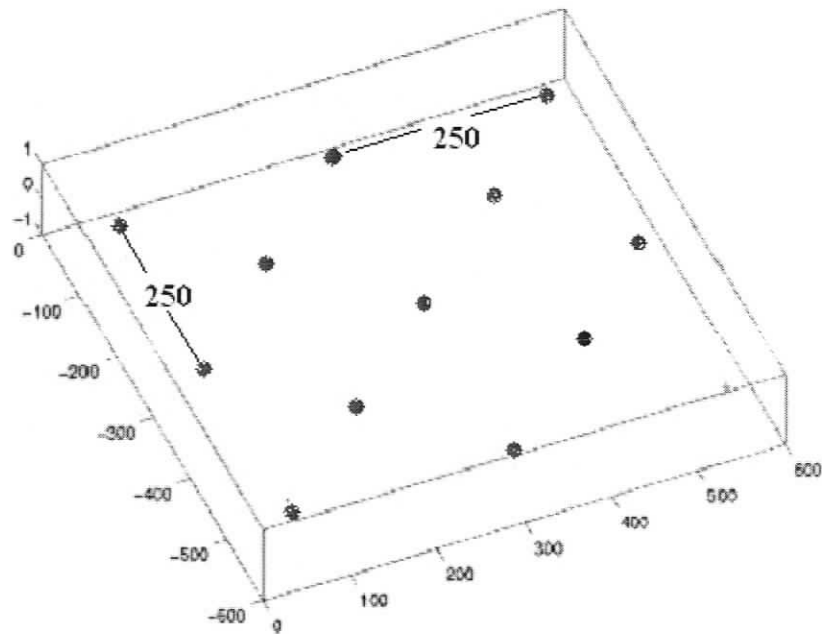


Figure 4-4: Strategic points chosen to measure the illumination uniformity on top of the display panel

The standard 600mm series sign was powered up with a simple driver circuit using different voltages and currents. Brightness of the display was controlled by varying the input current.

The first set of measurements was carried out with a generic 600 mm sign without an external diffuser (diamond grating) or a legend/pattern on top. This sign is referred to as sample A for the entire length of the thesis. The voltages applied were $V = 11.55V$ and $I = 29.1mA$ (Table 4-1) and at $V = 11.59V$ and $I = 31.1mA$ (Table 4-2).

Different voltages and current were used in order to note the luminance changes and to get an average output of 20 lux from the display.

Table 4-1: *Illuminance values for $V = 11.595V$ and $I = 29.1mA$ for sample A*

Position #	X Coordinate (mm)	Y Coordinate (mm)	Illuminance Value (lux)
1	60	-60	17.95
2	310	-60	19.48
3	555	-60	18.78
4	185	-180	21.15
5	445	-180	16.52
6	60	-302.5	15.66
7	310	-302.5	25.94
8	555	-302.5	13.90
9	185	-420	15.05
10	445	-420	15.33
11	60	-545	17.00
12	310	-545	17.33
13	555	-545	18.02

Table 4-2: *Illuminance values for $V = 11.59V$ and $I = 31.1mA$ for sample A*

Position #	X Coordinate (mm)	Y Coordinate (mm)	Illuminance Value (Lux)
1	60	-60	19.27
2	310	-60	21.22
3	555	-60	20.06
4	185	-180	21.69
5	445	-180	17.88
6	60	-302.5	17.20
7	310	-302.5	27.22
8	555	-302.5	15.37
9	185	-420	15.73
10	445	-420	16.43
11	60	-545	17.94
12	310	-545	19.39
13	555	-545	19.50

The illuminance measurements were taken with the various samples and the surface plot for the standard 600 mm display was generated. This plot indicated the distribution of light over the surface of the panel without any diamond grating or any pattern on the top of the display. It was observed that some LEDs were brighter than the others after the display was lit up.

Figure 4-5 depicts such a surface plot.

The uniformity ratio [6] for this sign could be calculated using equation 4-1.

$$\text{Uniformity Ratio} = \text{Highest sign face luminance} / \text{Lowest sign face luminance} \quad (4-1)$$

The uniformity ratio in this case was calculated from the measurements as 1.87.

This is greater than the allowable values of 1.3 to 1.5 as recommended by IESNA [6].

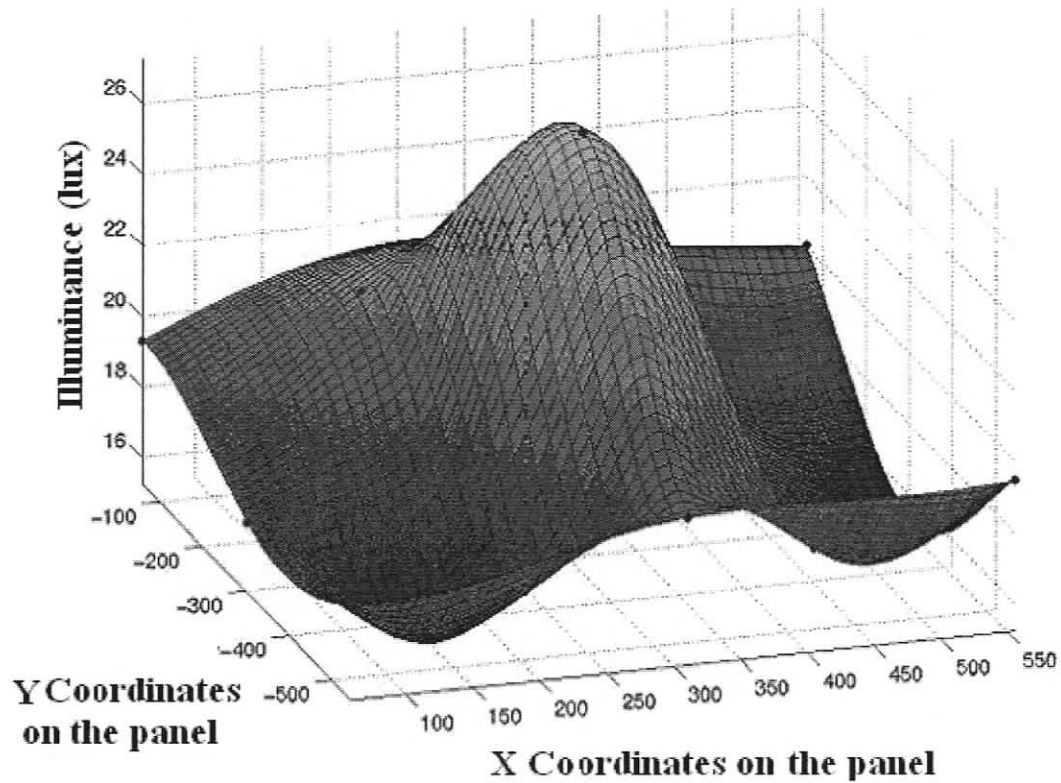


Figure 4-5: *Illuminance distribution in a generic LED backlit display using edgelighting showing extreme variation in illuminance*

In addition to the standard 600mm sign, a sign with a diamond grating was also evaluated. Circular diamond gratings were placed in the center of the acrylic surface. Photometric measurements were taken and a surface plot was generated as shown in Figure 4-6.

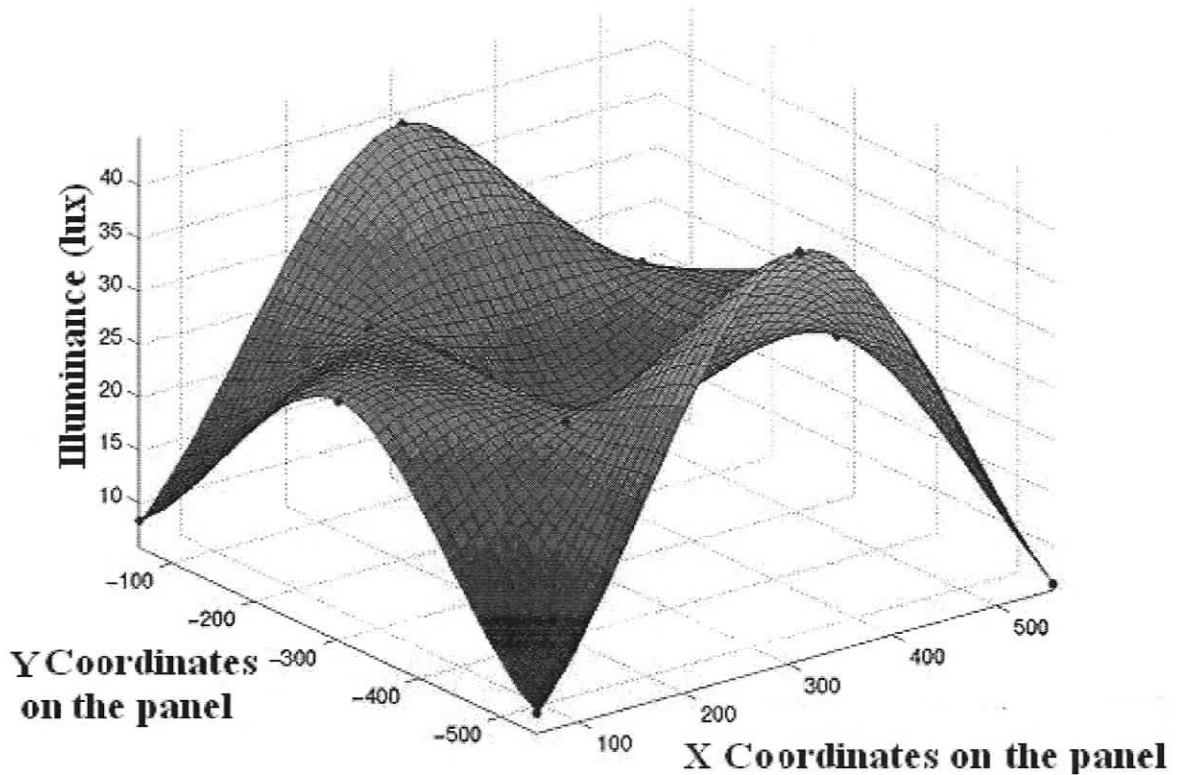


Figure 4-6: *Surface plot of the display with diamond grating showing more uniform illuminance*

The average lux value with the diamond grating was 22.6 lux and the measurement points, which were equidistant from the light-source, indicated similar illuminance. This was not seen in the generic display.

The standard deviation was calculated for the measurement values at different points on the display for the generic display as well as the display with a diamond grating. Equation 4-2 gives the formula used for calculating the standard deviation [34].

$$S = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n}} \quad (4-2)$$

where n = number of samples, x_i is the i^{th} value and \bar{x} is the average value. On the basis of this equation, the standard deviation calculated for points on the surface for a generic sign was 3.12 lux and for equidistant points on the sign with a diamond grating was 1.1 lux (see Table 4-3). The illumination uniformity ratio was also 1.1.

Table 4-3 : *Standard deviation for the sign with and without diamond grating*

Signage Type	Standard Deviation
Without Diamond Grating	3.12
With Diamond Grating	1.1

Hence, it was clearly observable that the areas covered with the diamond grating were more uniform. In order to compare the change in illuminance after putting together the final display pattern, the measurements were made with the pattern placed on top of the display. The pattern was a plastic sheet which had an arrow painted on it. The pattern size was matched to occupy the same as the size as the panel. Figure 4-7 shows the surface plot of the display illuminance for such a pattern. The overall cost of the display along with the acrylic panel and the pattern was about \$1000. The cost of diamond grating was not included in this. According to the bill of materials the cost of the acrylic sheet was about 50% of the overall cost of the generic display without the diamond grating.

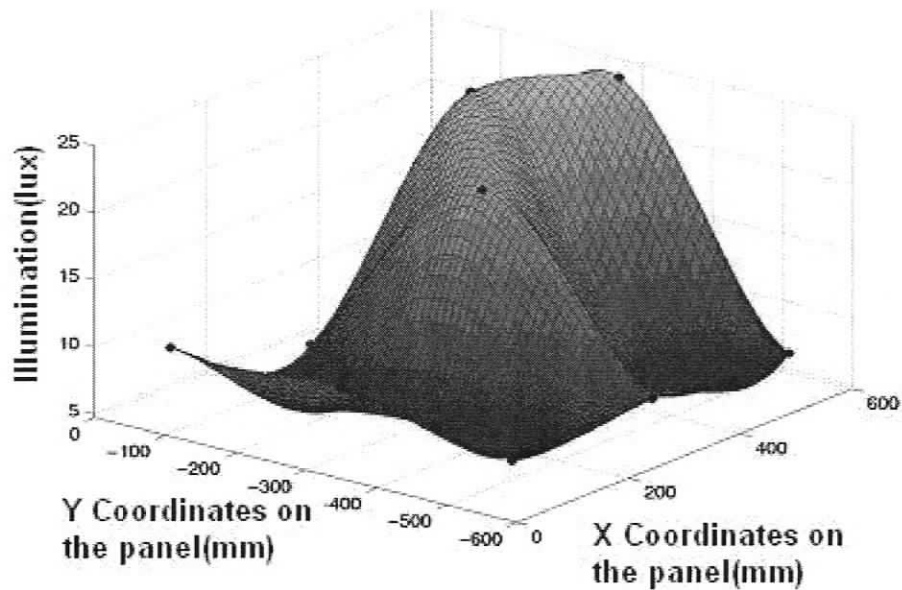


Figure 4-7: *Surface plot for a display with an arrow pattern on the top surface*

All the measurements were taken in a dark room with black curtains in matte cloth to avoid any unwanted light from the other sources or from the reflection from the walls in the room.

The standard deviation for the points positioned in the arrow with identical colors was also measured. It was clearly visible that the illuminance values with the pattern even in the identically colored areas were different. The standard deviation was measured for the points inside the white arrow (refer to figure 4-3) and it was calculated to be 11.32.

4.6.1 Spectral Measurements

Spectral measurements form an integral part of the optical evaluation of the light source. With the help of spectral measurements it is possible to deduce the purity of the white light source. The spectrum of light emitted from the LED was determined using the MAS-40 mini array spectrometer and the Specwinlight software. These measurements would aid in determining the dominant and peak wavelength in the light emitted by the LEDs. The measurements have been made spatially so as to determine the net spectral response of the display along with the transparent acrylic and the white base. The measurements were made with a generic display without a diamond grating and without a

pattern. Table 4-4 depicts the spectral values obtained with the generic LED edgelit display.

Table 4-4: *Spectral Measurements with the generic, edgelit, LED-based sign*

No.	Photometric value (lux)	Radiometric value (W/cm ²)	Dominant WL (nm)	Chromaticity x	Chromaticity y	Integration time (ms)	Max Counts (Counts)
1	2.416	6.555E-07	570.7	0.4429	0.5386	1000	200
2	3.062	8.024E-07	571.1	0.446	0.5359	1000	241
3	3.062	8.132E-07	571.1	0.4459	0.536	1000	241
4	2.598	6.954E-07	570.8	0.4439	0.5376	1000	211
5	2.65	7.075E-07	569.9	0.4325	0.5337	1000	208
6	3.54	9.19E-07	569.9	0.4327	0.5339	1000	263
7	3.143	8.565E-07	569.8	0.4319	0.5346	1000	239
8	3.143	8.408E-07	569.8	0.432	0.5344	1000	239
9	3.151	8.78E-07	569.8	0.4317	0.5346	1000	240
10	3.092	8.235E-07	570.6	0.4418	0.5387	1000	240

The measurements were made at lower current levels and hence the photometric value is low. The radiometric values indicate the light output per unit area from the display irrespective of the perception of human eye. It gives the output power emitted in watts per unit area. The average value of dominant wavelength is 570.35 nm, which indicates the dominance of yellow color in the display. The average value of x and y chromaticity coordinates is (0.43,0.53). These coordinates can be plotted in the CIE chromaticity diagram as shown Figure 4-8.

CIE is a French abbreviation for Commission Internationale de l'Eclairage or the International Commission on illumination. It is an international organization that lays down standards and promotes information exchange in the field of lighting. CIE standards have been recognized worldwide and have been used to standardize light sources¹. Figure 4-8 is called the CIE 1931 chromaticity diagram [12]. It is located within a color triangle with the vertices representing pure red, pure green and pure blue primary colors. The x coordinate in the CIE diagram represents the contribution from the hypothetical red sensor and y the fraction of the total response from the hypothetical green sensor.

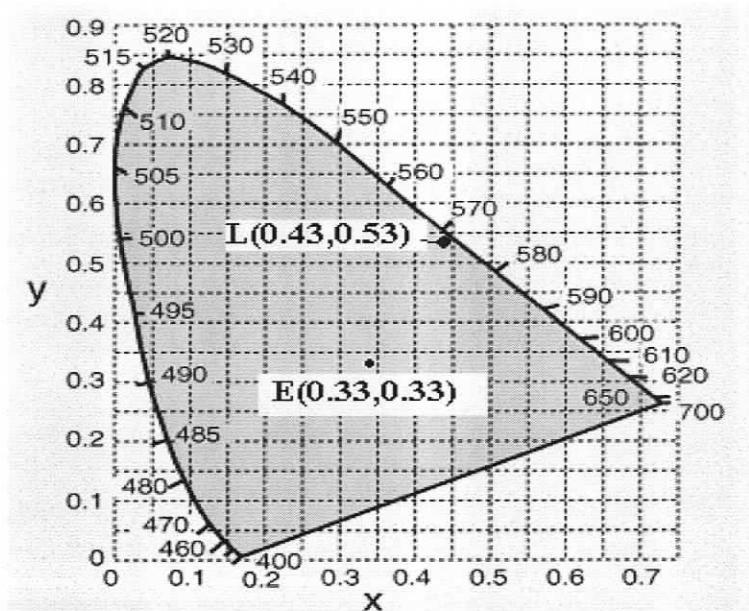


Figure 4-8: CIE chromaticity diagram with the LED display chromaticity coordinates (represented by point L (0.43,0.53)) and the achromic point (represented by point E (0.33,0.33))

The spectral response for the LED edgelit display, there is a clear dominance of yellow color. The color matches a low-pressure sodium lamp. Also the distance between the achromic point (E) and the LED chromaticity point (L) is large. This points out to the impurity of the color emitted from the display. For signage application, it would be ideal to have a light source emitting pure white light and the current display was not very close to the white light of the spectrum.

4.7 Results and Discussion

In this chapter, new measurements were performed and numerical data with the commercially available signage displays using edgelighting was presented. Measurements with 600 mm series edgelit LED-signage has not been seen anywhere in previous literature. Also, the techniques, which have been employed to increase uniformity in signage, were evaluated. Detailed measurements were made and numerical data was presented. This chapter was useful in quantitatively analyzing the commercially available edgelit signs. Some of the results and contributions from this chapter are explained further.

The LED-based displays were easily available commercially and were already accepted in the market. The standardization of signs was necessary to evaluate this technology. The standard size used for the signs was 600 mm x 600 mm. It was evident that the design of these signs was not complicated. The driver circuit was very simple, with surface mount components and was easy to maintain.

The photometric measurements from the standard 600 mm display sign clearly depicted areas of very high and very low illuminance (refer to Figure 4-5, Figure 4-6 and Figure 4-7 for details). The fact that not all of the LEDs were giving the same light output, pointed out that either the type of LEDs used was different or the driver circuitry was not perfectly optimized.

Although the LEDs were used from the same voltage bin, but there could be minor differences in the performance of these LEDs due to material discrepancies. As the light output of an LED is dependent upon the input current, so if there were any variation in the current value then the LEDs would have different outputs. This was the most convincing reason for the non-uniform light output from the LEDs.

The light distribution for the standard display was highly non-uniform and edgelighting with these point sources was intermittent in nature. The uniformity ratio obtained with the generic sign was 1.87. This was much greater than the allowable range of 1.3-1.5. These facts re-established the need for improvement. The displays with the diamond grating were certainly superior but were not fully capable of eliminating the non-uniformity in the display. Also, the use of diamond grating increased the cost of the display by \$500, which was an appreciable amount in comparison to the overall cost of the display without diamond grating (\$1000). Hence, the economical reasons also discouraged the use of diamond grating to improve the illuminance uniformity of a display. The acrylic panel also contributed \$500 to the overall cost of the display.

The effect of placing the pattern on the top of the display was measured. The surface plot depicted a sharp change in the illuminance. The darker portion on the pattern blocked essentially all the light and a large amount of light was wasted. The spectral measurements suggested that the spectral response of the display was shifted towards the yellow color in the spectrum. Hence, the light emitted was not purely white with the

transparent acrylic and the white base. This could be possible due to the color of the LED as well as the color of the base and the acrylic. The properties of the white base could change the spectral output of the display. So, it would be highly desirable if a light source emitting light closer to the achromic point were used.

The efficacy of these signs was about 18 lumen/Watt, which perfectly measured up to the existing techniques of signage such as the florescent lamp etc.

The photometric measurements strongly suggested that LEDs being point sources possessed limitations when used in large area displays. On the basis of the measurements it was evident that these signs could perform well for small size panels but if the display panel size was increased, it could lead to a darkened center. Also, if the display size was increased, it would imply a large diamond grating with a higher cost for making the display more uniform.

Hence, it was reasonable to look at distributed light sources such as organic LEDs large area signage application.

Chapter 5

Design and Implementation of OLED-based signs

5.1 Design of OLED-Based Panels

In this section we present novel design techniques that could be used for implementation of OLEDs as light sources for signage application. Various designs would be presented and the benefits as well as disadvantages of each design would be examined. One of the designs would be chosen for a detailed evaluation.

5.1.1 Using Edgelighting Technique

The advantages of edgelighting technique used to backlight a sign were well known due to the already existing conventional-LED based signage. OLEDs could be used to light the back of a panel using edgelighting similar to the inorganic LEDs. Small OLED modules in the form of long strips could be placed on the edges of the display panel for edgelighting (Figure 5-1). However, using edgelighting OLEDs would produce a light, which is continuous and not intermittent (like conventional LEDs).

Also, a similar kind of diamond grating placed on the panel could spread out the light more evenly. The diamond grating would reflect the light out from the backplane and would avoid any absorption of light by the acrylic material. The advantage of using the edgelit-backlit technique is that the light intensity would be uniform on all sides of the panel. Even if a long continuous strip of OLEDs was not used, small sized OLED modules could be tiled side-by-side on all the four edges of the display. This would make maintenance easy. If one of the OLED deteriorated then it could be replaced easily.

The design of these displays would be simple and they could be connected serially or in parallel along the edges of the panel.

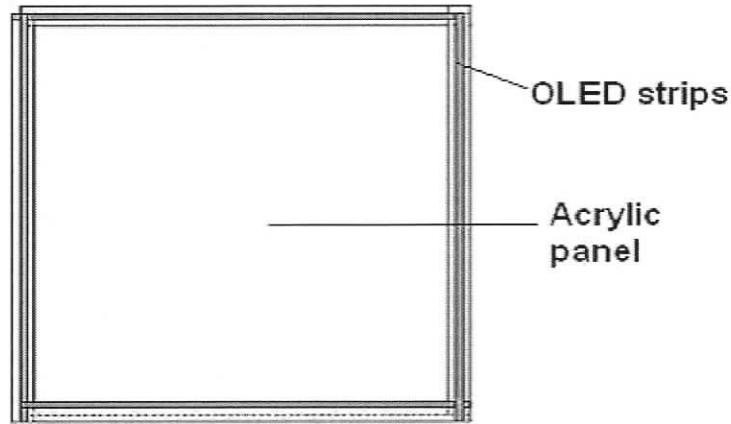


Figure 5-1: *Backlit OLED panel design using edgelighting*

However, it was visible that the limitations of this technique would be similar to the conventional LED-based edgelighting. Larger displays would appear darker in the center and hence the uniformity of the displays would be lost if the display size is increased. The use of diamond grating could be more effective than the conventional LED displays due to non-intermittent light through the edges.

5.1.2 Using a Reflective Coating as a Diffuser

If the OLEDs are placed in different positions on the display such as in Figure 5-2.

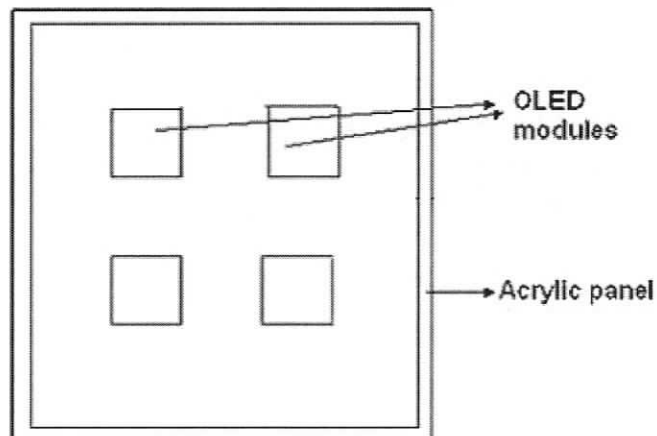


Figure 5.2: *Use of a reflective coating as a diffuser*

If a partially reflective coating is laid on the top surface of the panel, then the coating will act as a diffuser. It will allow the light to scatter in all directions, which may lead to a uniform display.

In order to determine the uniformity of the display using this design we simulated a sign assuming arbitrary values of OLED illuminance and calculating relative or normalized values. We assumed that four OLEDs placed as in Figure 5-2 were used. It was also assumed that the illuminance of the light-source is inversely proportional to the square of distance between the light-source and the points of measurement.

Figure 5-3 depicts the results of the simulation.

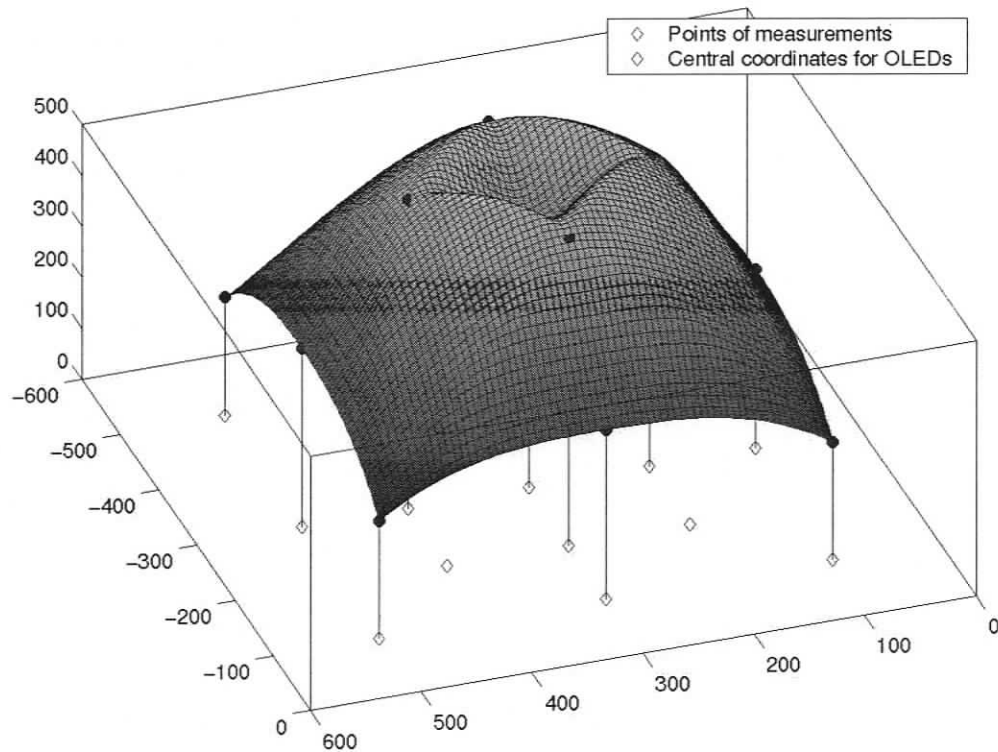


Figure 5-3: *OLED signage with a partially reflective coating that acts as a diffuser.*

It was clearly visible from the simulation that this design would not yield a uniform display due to the progressive decrease in illuminance in the areas, which do not have OLEDs on the surface.

5.1.3 Using Two Reflective Coatings

OLED signs based on the backlighting technique could use a reflective coating to spread the light as desired. Small sized OLEDs placed in different positions on the display panel could be designed as shown in Figure 5-4. A sheet of transparent plastic with a partially reflective coating could be placed on the top of the panel, which would prevent the light from escaping completely. Instead it could reflect at least 50 percent of the light back to the panel. If the portion of the panel where the OLED modules were not placed was covered with a mirror-like coating then light could easily spread on the panel.

If the small sized OLEDs are operated at a higher current level such that the illuminance value is high then this technique could be used.

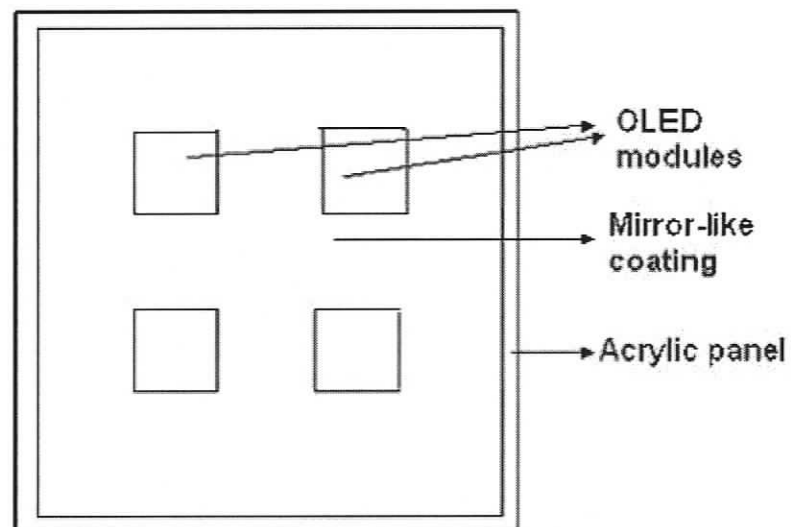


Figure 5-4: *Backlighting using reflective coating*

The reflectivity of the coating on top of the panel could be calculated with the help of Figure 5-5.

Using equation 5-3 the value of r can be determined as ,

$$r = \frac{a}{2b} + 0.5 \quad (5-4)$$

For example if 1 m^2 of OLED emits a light of 20 lumen then in order to obtain 5 lumens light output the area required to be covered with OLEDs would be 0.25 m^2 . For a sign of area 1 m^2 , if we substitute the value of $a = 0.25 \text{ m}^2$ and $b = 0.75 \text{ m}^2$ then the reflectivity would be

$$r = \frac{0.25}{(0.75) \times 2} + 0.5 = 0.66 \quad (5-5)$$

Hence the value of the reflectivity could be determined. As the reflectivity of a material is a specific characteristic for each material; suitable material for the coating could be selected. Based on the area ratio (a/b) the reflectivity can be determined using Table 5-1.

Table 5-1: *Determination of reflectivity for a specific area ratio*

Area Ratio	Reflectivity
0.5	0.75
0.75	0.66
0.25	0.625

There was a possibility of attaining a uniform final light output through this technique. However, economically it could cost more to get a partially reflective coating sheet. Also, the complexity of the sign would be more in this case as the net output would not only be dependent on the size and illuminance of the OLED but also on the quality of the partially and fully reflective coating.

5.1.4 Completely Tiled OLED Display

A signage could be backlit using small OLED modules tiled on top of the acrylic panel as shown in Figure 5-6.

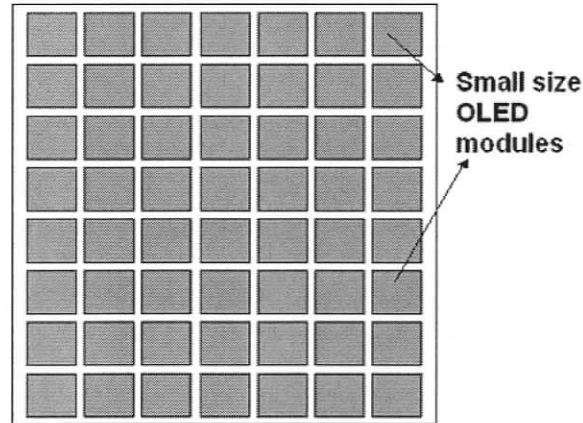


Figure 5-6: *Tiled OLED display*

As the whole signage area would be covered with OLED panels, it would be easier to achieve uniformity by passing the same amount of current through each OLED module and tuning them to same color. If one of the OLED modules failed during operation then it would be very simple to replace it. However, this design might require a more complex driver circuitry and the tiles would have to be programmed separately. The signage pattern, in this case could be laid on top of the display similar to the conventional LED-based displays.

5.1.5 Single Large OLED Display

Using a single large (600mm sign size) OLED could be another option for signage application. A single display driver was a requirement for this kind of signage display. This display could be a fully programmable module with any sign driven by any electronic pattern generator as shown in Figure 5-7.

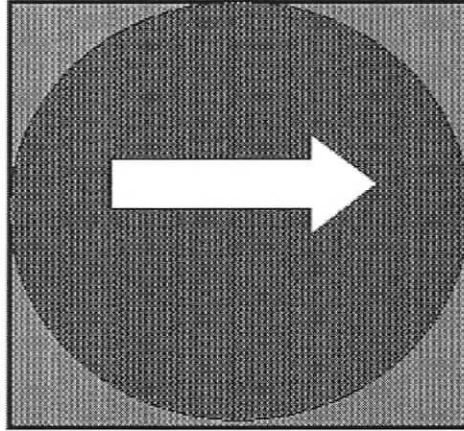


Figure 5-7: Large OLED display with the pattern programmed to it.

There were several advantages associated with this design. The OLED in this case could be programmed easily to depict any pattern and could be used without the use of any acrylic sheet. If the OLED module were encapsulated, then no protective sheet would be essential. This would eliminate some of the cost associated with a signage panel. In addition, the display would possess all the properties such as a good contrast ratio, a wide viewing angle etc. associated with an organic light-emitting device irrespective of the backing material.

The disadvantages of this design were the cost of developing large OLED modules and their maintenance. Pixel degradation in a small part would imply the replacement of the complete panel.

5.2 Illuminance Standardization

The comparison of the Organic LED displays and the conventional LED displays could only be made if the devices were normalized. In this case we normalized the displays on the basis of the *light output*.

The required average illuminance from a 600mm sign display = 20 lux = 20 lumen/ m²

Area of the panel = (0.6 x 0.6) m²

Net luminous flux from the display = 20 x 0.6 x 0.6 = 7.2 lumen

Therefore, **7.2 lumen** would be the target output for the display.

5.3 OLED Procurement

Different kinds of OLED modules were available commercially. The choice of the OLED module could have a great bearing on its performance. So, this choice was made carefully, keeping in mind the requirements of the specific application for signage.

Signage is a very low-resolution application. Large display signs are usually viewed from a distance and so the number of pixels and the display resolution is not of larger concern. Hence, it was evident that a *passive matrix OLED display* would be adequate.

In addition, small-molecule OLEDs under mass-production were available commercially in different sizes in full-color unlike polymer OLEDs. Polymer OLEDs were only available as monochrome microdisplays or research samples having large areas. So, small-molecule based OLEDs were used.

The signage display could have a pattern in different colors on the top, so full-colored or white-colored OLED modules were chosen.

Various small-sized OLED modules were available commercially which could be used for feasibility determination. In our study we selected the OLED modules based on their data sheets. The following OLEDs were chosen for initial feasibility determination.

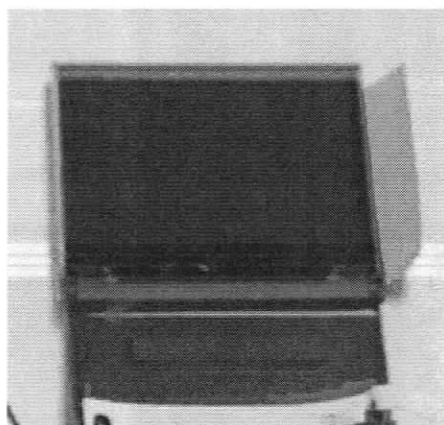
- OL-6416 module from LC Design
- RGS25128064GH000 from RiT displays
- RGC10096064FW005 from RiT displays

On the basis of our requirements, RGC10096064FW005, 65K color OLED modules were found to be suitable and were purchased from RiT Display Corporation. Due to the lack of a large-sized OLED and the economic disadvantages associated, the tiled design was adopted as the best choice.

The specifications given for the display are shown in Table 5-2. Figure 5-8 shows the picture RiT OLED module with the display OFF.

Table 5-2: *Specifications of the RiT display module*

Specification name	Specific value	Unit
Dot Matrix	96 (W) x (RxGxB) x 64(H)	dot
Active area	20.135 x 13.42	mm
Panel size	26.66 x 20.38	mm
Panel thickness	1.65 +/-0.1	mm
Display color	65K	

**Figure 5-8:** *The 65K colored OLED module*

5.4 Display Set-Up

These displays were small-molecule based and used the passive mode of addressing. The OLED module had a single chip driver (SSD1332) from Solomon Systech. The driver chip used a constant current driving mode with a pulsed operation. Pulsed operation was shown to increase the lifetime of OLED [36]. The display driver consisted of a CPU, a memory, brightness control circuits and row and column drivers. It was attached to the OLED on the PCB board. The use of this OLED module required the design of a power-driver circuit and a microcontroller to program the module. The block diagram of the display set-up is depicted in Figure 5-9.

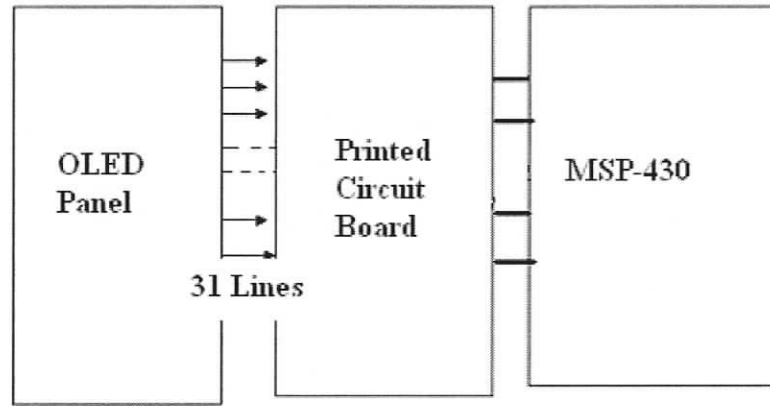


Figure 5-9 : *The block diagram of the display set-up for the OLED module*

5.5 OLED Power-Driver Design

An additional driver circuit built on a printed circuit board (PCB) was designed and constructed to supply the required voltage levels needed in the module. This chip PCB was designed using Protel 99 software. The PCB had a double layer and only surface mount components were used. The size of the PCB was made such that it fitted directly behind the display. This provided the desirable aesthetics for the display, as the surface mount components were not visible.

A 1" x 1" printed circuit board was constructed. All the components were chosen to be well within the range of maximum voltage allowed for the display. The maximum voltage range was defined to be 25V on the basis of the various voltages given to the circuit. Figure 5-10 depicts the schematic of the PCB. The schematic of the PCB consists of the OLED panel along with resistive and capacitive components for the power supply. The schematic clearly describes the design of the power driver. This helps us in determining the complexity of the driver circuitry. It was important to determine this for signage application as the more complex the circuitry, the higher would be the cost of manufacture.

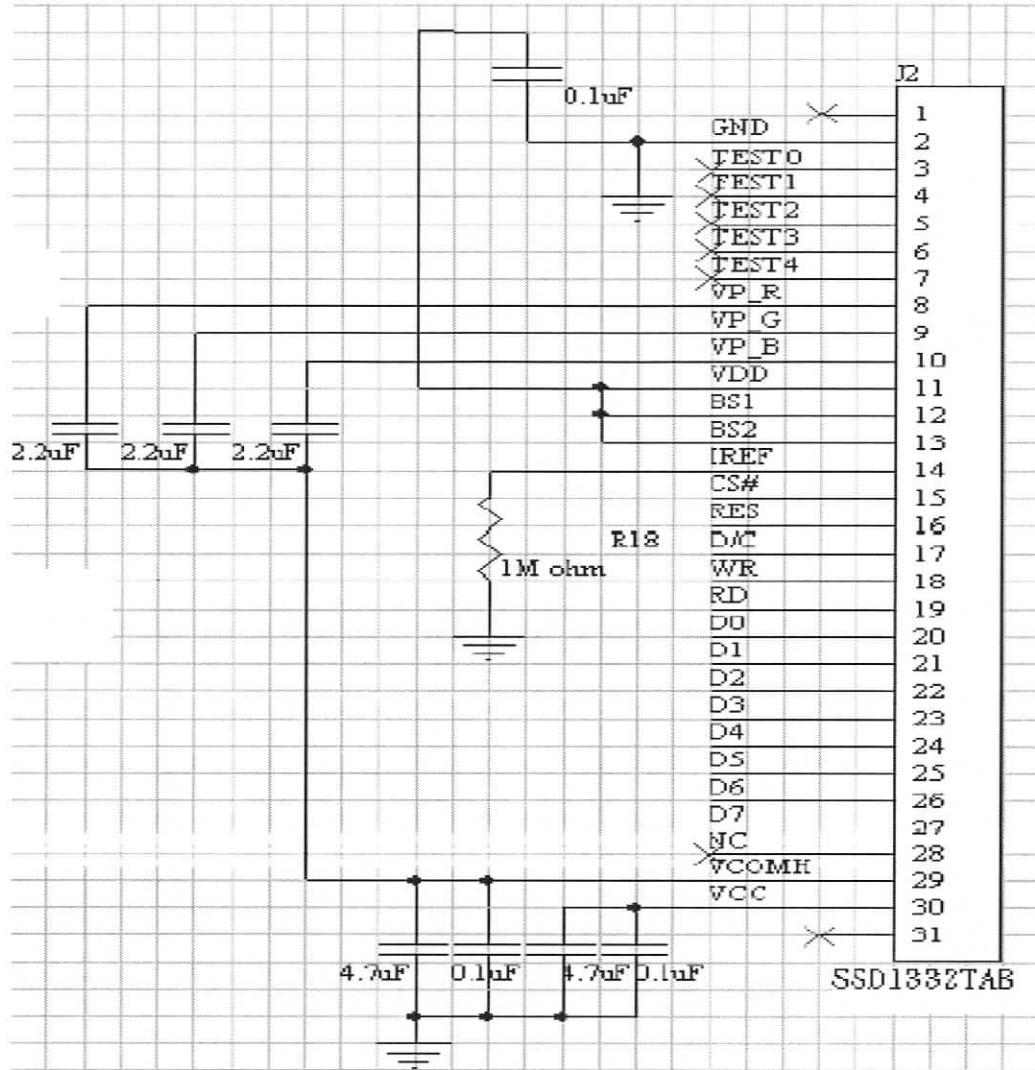


Figure 5-10: Schematic of the OLED driver PCB

The OLED module had a 31-pin connection. The connections were made using the application sheet provided by the manufacturer. In Figure 5-10, V_{cc} referred to the voltage supplied to the display and V_{dd} was the voltage supplied to the driver circuit. Color tuning was controlled using the voltages supplied to the red, green and blue voltage pin coming out of the driver. The PCB was populated in-house.

Figure 5-11 shows the PCB layout. The PCB layout was so designed such that it could be positioned behind the display panel without affecting the aesthetics. Also, surface mount components were used instead of through hole to lessen the heat generated. The traces in

the PCB were made according to the approximate current that could flow. Higher the current, wider would be the trace for that net.

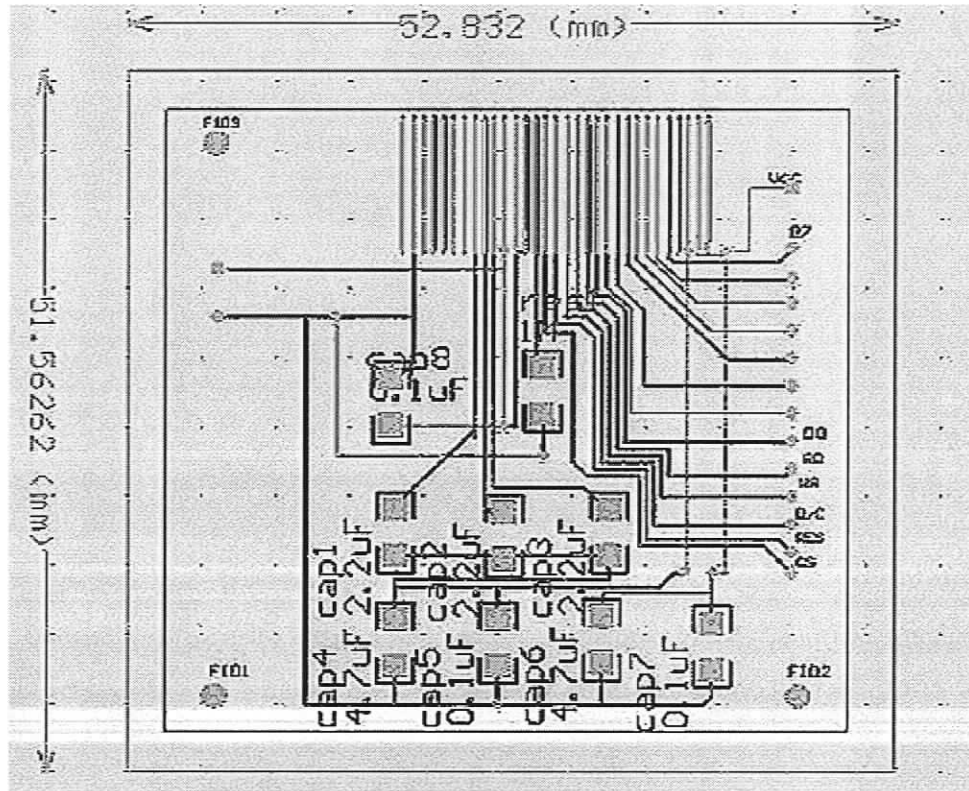
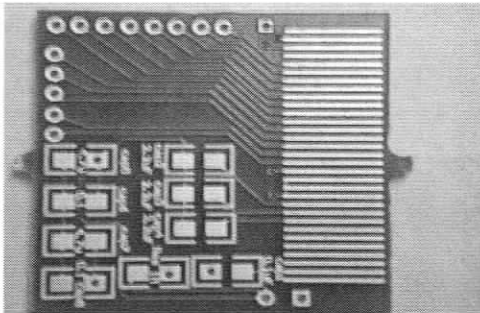
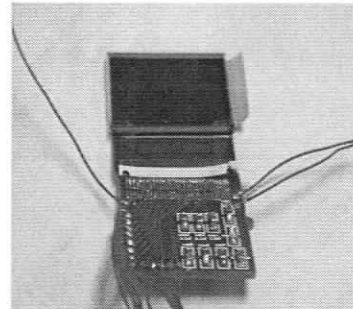


Figure 5-11: *Layout of the OLED driver PCB*

Figure 5-12(a) shows the picture of the unpopulated board and Figure 5-12(b) depicts the populated board attached to the display panel. The unpopulated board depicts the simplicity of the driver circuit and the populated PCB indicates the first prototype constructed.



(a)



(b)

Figure 5-12: (a) *The unpopulated PCB* (b) *The populated PCB with the OLED*

The devices were first tested by directly powering them up using the Agilent 6621C System DC power supply.

5.6 Display Software

In order to enable a stable operation, OLEDs required an additional microcontroller to turn the display ON and to tune to different colors. The driver chip attached to the module had to be programmed and continuously connected to the microcontroller as it had a random access-memory (RAM), and its contents could be erased if the display was disconnected from the power supply. Carmanah Technologies Inc. had been using the MSP-430, a low power microcontroller for the LED systems. This controller worked very well in supplying the different inputs to the conventional LED-based systems. Based on the previous experience of Carmanah Technologies Inc. with these microcontrollers, MSP-430 was chosen for this project. MSP-430 provided a user-friendly environment with the option of using C language for programming. The evaluation kit for the MSP 430 with the F149 microcontroller IC was used. Figure 5-13 shows the architecture of the MSP-430 F149, which is available from the datasheet [35].

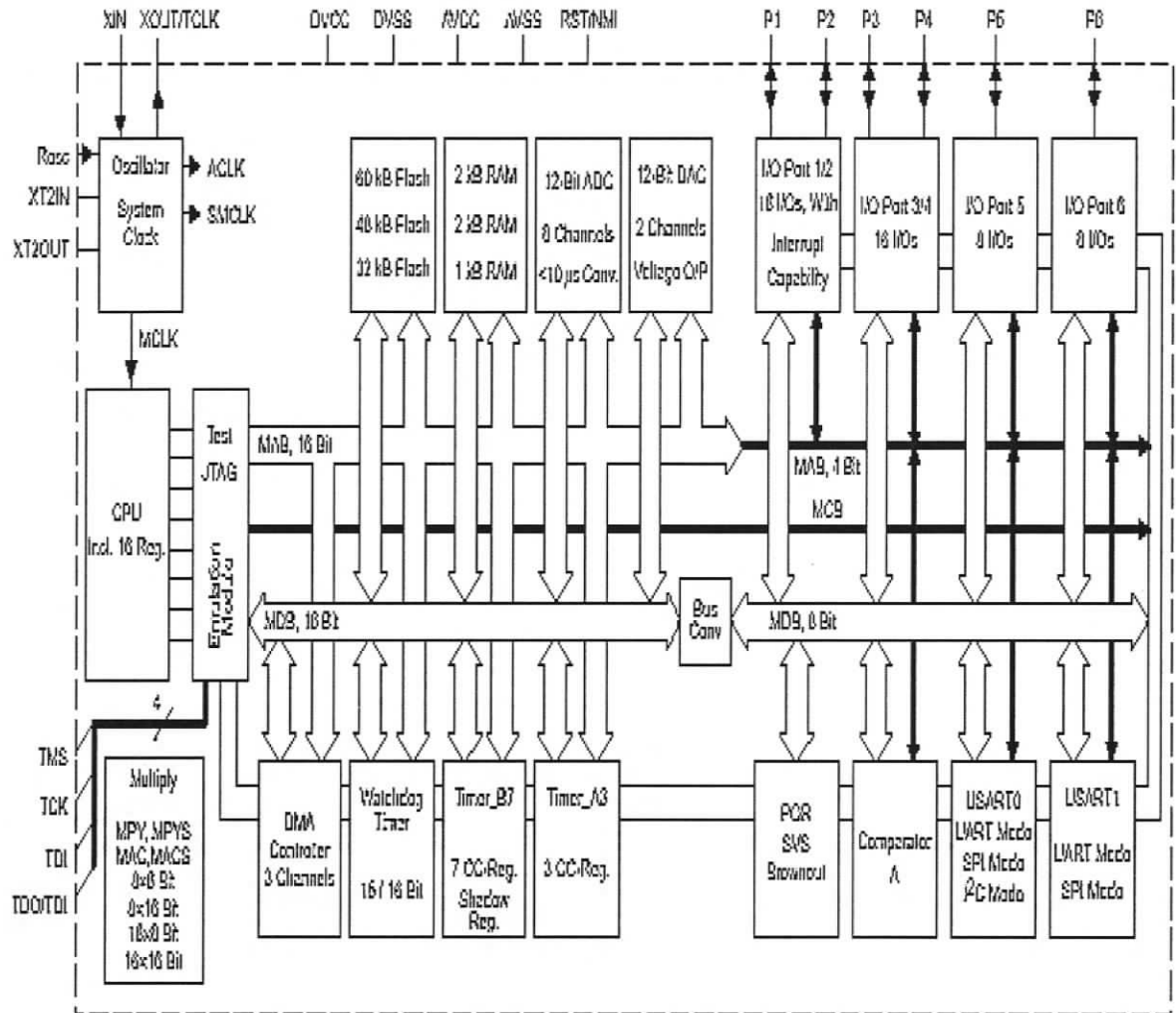


Figure 5-13: MSP-430F149 structure (Courtesy: Texas Instruments)

The lines from the digital I/O ports-1 and 2 of this microcontroller, were used to input data and commands to the OLED driver SSD-1332. A program giving instructions to the OLED driver chip through the PCB was written in the C language (see Appendix A). The program was first simulated and then written to the microcontroller.

The RiT OLED module was bonded to the populated PCB and the commands and data instructions were coded in.

5.7 OLED Evaluation

The illuminance-current characteristics and the I–V characteristics were not available from the manufacturer of this commercial OLED module. Hence, detailed measurements were performed.

The measurement and evaluation of the OLEDs could be done with the help of the commercially available OLEDs. The optical measurements primarily concentrated on the photometric measurement of the display. The photometric measurement determined the light output as perceived by the human eye and hence it was crucial for analysis.

The OLED module was encapsulated and was assumed to be unaffected by changes in temperature and humidity. In any event the extreme changes in the environmental conditions were completely avoided. The OLED being a distributed source was composed of pixels. The lifetime of the OLEDs depended upon the individual pixels. The individual pixels were made of the same material hence promised uniform light output for a long time.

5.7.1 Measurement of Electrical Characteristics

We determined the electrical characteristics of OLEDs in terms of their current and voltage. The I-V curves provided the electrical performance of the diodes. The threshold voltage for the OLEDs was 7 volts. As the display consisted of a driver and a display screen itself, two power supplies were required. A circuit to step down the power supply to two different levels could also be constructed. But that would require additional circuits, which could occupy more area. In our set-up, two different supplies were used. Voltage V_{dd} (2.5 V) was connected to the display driver and the V_{cc} (13 -18 V) was used to drive the display screen.

Agilent 6612C power supplies were employed for this purpose.

The duty cycle of the display was 1/60. This gave the fraction of time during which the device was driven. There was no flicker observed at this frequency in the OLED screen.

The I-V curve for the display is depicted in Figure 5-14. These characteristics were not available from the manufacturer.

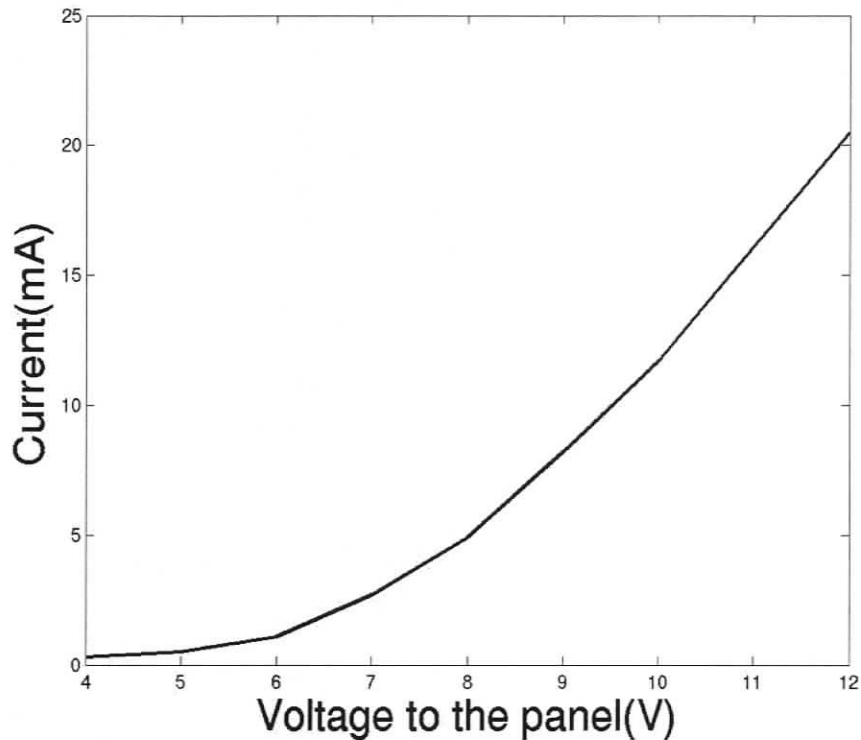


Figure 5-14: *The I-V curve for the commercially available OLED module.*

5.7.2 Measurement of Optical Characteristics

The optical characteristics of the OLED could be measured in terms of the luminous intensity or in terms of illuminance. This value showed the amount of light falling on a surface. Illuminance values in lux were chosen as a standard unit of reference. The Agilent supply 6612C and the S-370 photometer were used for making the measurement. This enabled us to compare the light output from the LED-based display with the OLED display.

The measurements were performed in a dark room (scotopic conditions) to avoid unwanted light. The walls of the dark room were black and the OLED was placed in an area surrounded by black curtains made up of matte cloth to avoid reflection. The temperature of the surroundings was kept to be the same throughout the measurements.

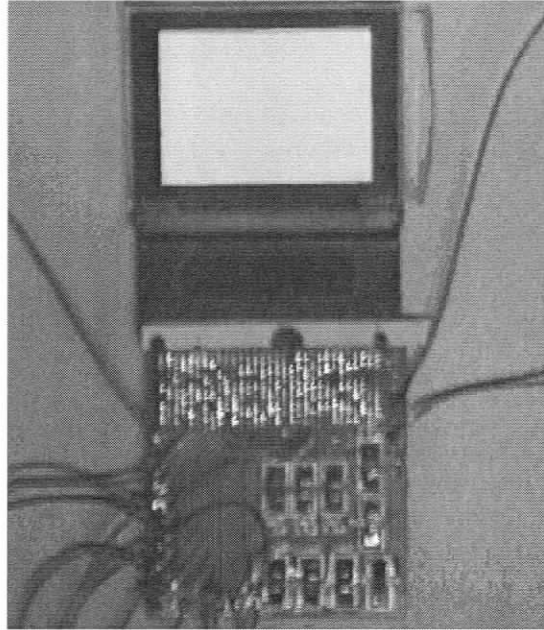


Figure 5-15: A lit-up commercially available OLED module

Figure 5-15 displays the OLED module when lighted up. Figure 5-16 shows the illuminance-current curve of this module.

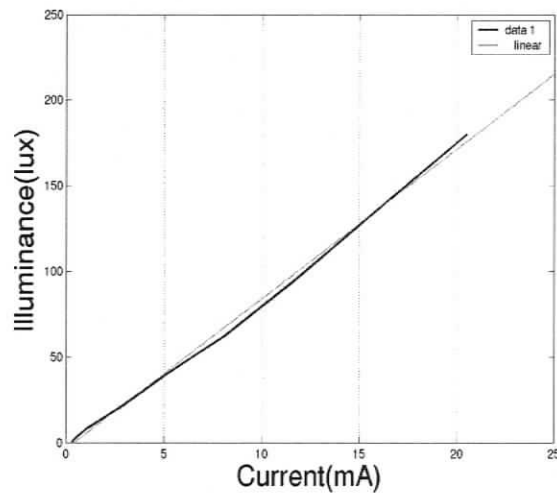


Figure 5-16: Illuminance-current curve for the commercial OLED module

5.7.2.1 Spectral Measurement

The most accurate method for measuring color is by using a Spectroradiometer. The spectrum of light emitted from the OLED was determined using the MAS-40 mini array spectrometer and the Specwinlight software. These measurements were important to

determine the spectral response of the OLED i.e. how the light output would be perceived by the human eye. Table 5-3 specifies the data obtained for the OLED module with the spectrometer with a number of iterations (counts). The photometric values from the display were also measured simultaneously. The photometric values signify the illuminance in lux from the display. In addition, the radiometric values, which are output power measurements, irrespective of the human eye response were obtained along with. The table presents all the measurements integrated over a period of time. The dominant wavelength of 493 nm denotes the dominance of bluish-green color. The measurements were integrated over a time period of 25 ms.

Table 5-3: Spectral measurement data for the commercially available OLED module

Number	Photometric value(lux)	Radiometric value (W/cm ²)	Dominant WL (nm)	Chromaticity x	Chromaticity y	Integration time (ms)	MaxCounts (Counts)
1	36.45	0.0000143	493.6	0.2474	0.3458	25	114
2	29.19	1.081E-05	493.3	0.2432	0.3448	25	99
3	22.55	9.696E-06	494.1	0.2419	0.3505	25	86
4	32.58	1.497E-05	494	0.2442	0.349	25	108
5	30.07	1.174E-05	493.6	0.2425	0.347	25	104
6	32.03	1.397E-05	493.9	0.2429	0.3484	25	106
7	34.14	1.251E-05	494.8	0.2421	0.3554	25	111
8	30.09	1.518E-05	493.5	0.2444	0.3458	25	101
9	37.29	1.523E-05	493.8	0.2427	0.3483	25	119
10	33.81	1.455E-05	492.5	0.241	0.3389	25	112
11	29.79	1.229E-05	494.4	0.2432	0.3521	25	100
12	36.3	1.127E-05	495.3	0.2405	0.3589	25	116

Figure 5-17 (a) depicts the CIE diagram along with the values obtained for the OLED (point O). CIE diagram for the generic edgelit LED based sign is also depicted for comparison (see Figure 5-17 (b)).

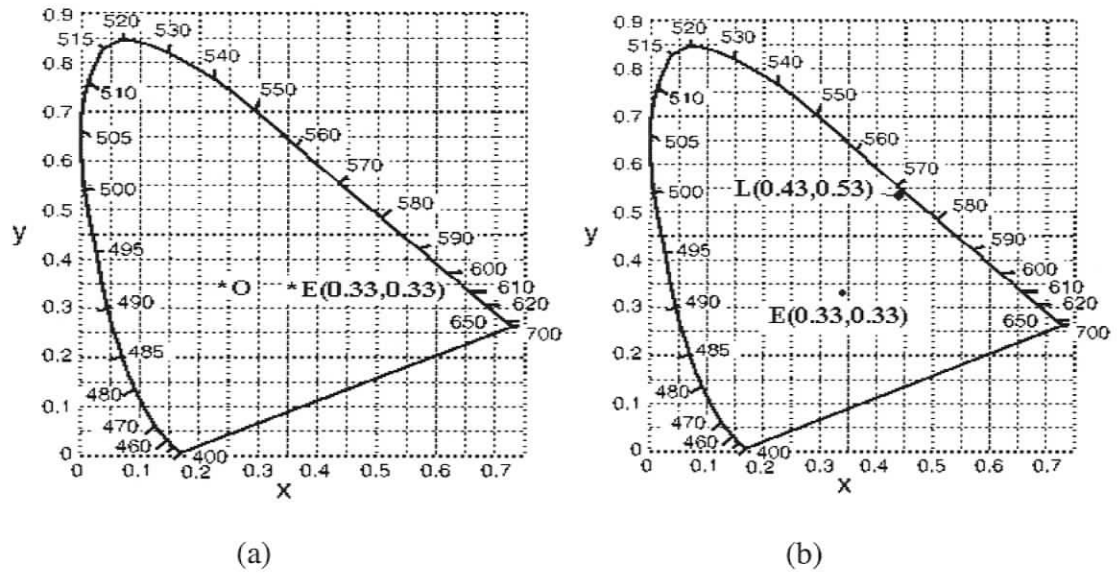


Figure 5-17: CIE chromaticity diagram along with the (a) OLED color coordinates from the commercially available OLED and (b) LED color coordinates obtained from the edgelit LED based generic sign.

Figure 5-17 indicates color purity of both white OLED display and white LED display. It is visible that the OLED (POINT O) is closer to the achromatic point for pure white light. The LED color purity (point L) is less than the OLED and the display is shifted towards the yellow color. Hence, it can be inferred that OLEDs would be more suitable as white light sources than the conventional LEDs. Our comparison is however limited by the number of samples that we analyzed.

The three primary colors are red, green and blue and most of the colors could be obtained by mixing these primary colors. The color rendition index of our OLED was 55.06 and which was an acceptable value for white color. The dominant wavelength was 493nm showing the dominance of bluish-green color. These measurements were important to determine the purity of white color. If the white color for the display was beyond the standards of CIE then the display could not be deemed “white”. The display was tuned at complete red, green and blue settings and the luminance was noted.

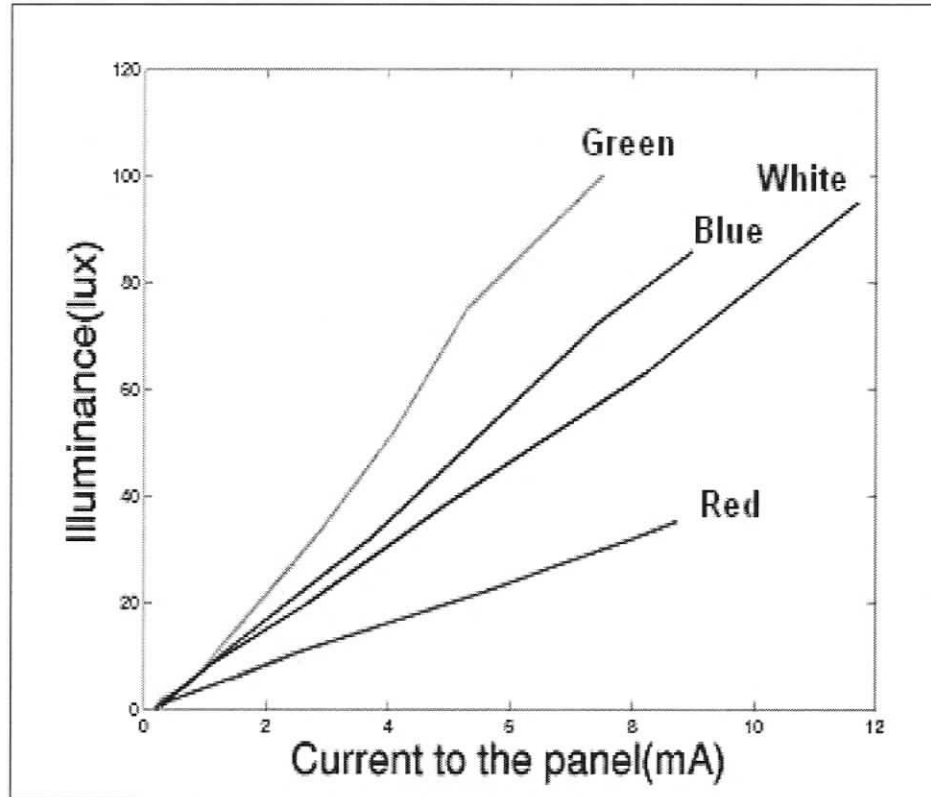


Figure 5-18: *Measured Illuminance– current characteristics for the RGB and white colors*

Figure 5-18 depicts the luminance value observed for an entirely red display, an entirely green display, an entirely blue display and a white display. The measurements were taken by programming the OLED with the help of MSP-430. Figure 5-18 clearly indicates a linear response of the OLED to different current levels. A comparison of the different illuminance values can be made using this figure. The fact that the green colored OLED has higher illuminance at lower current level could be due to the sensitivity of human eye to the green color. By the same rationale, red would have a lower illuminance due to eye's less sensitivity towards red wavelength. The illuminance value obtained by tuning the display to white color is more critical for a backlighting signage application and would aid us in determine the efficacy of the white light-emitting OLED.

5.8 Tiled OLED Display

In this design, the OLEDs had to be programmed in such a way that the system would not appear to be tiled but appears like a single OLED. Also, it was necessary to tune it to a single white color and lay the pattern on the top of the display. It was possible for us to connect all the four OLEDs next to each other, as tiles. However, the MSP 430 microprocessor could not support all of them simultaneously. Hence, we lighted a two of them at a time. It was observed that the photometric output for each of the pair was similar. The variation for two white displays can be seen in Figure 5-19.

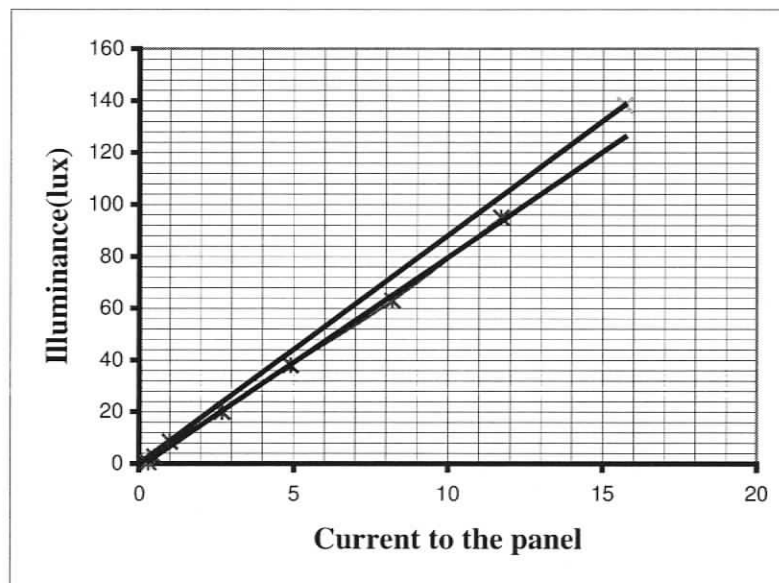


Figure 5-19: Variation in illumination values for two samples tuned to white color
The display design for four OLEDs is depicted in Figure 5-20.

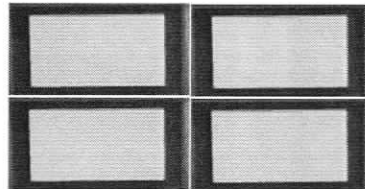


Figure 5-20: Tiled-OLED display

Each of the OLED modules measured showed a uniform value of illuminance and almost similar I-V characteristics. This implied that it was possible to attain uniformity with the

OLED display. The scaled simulation for a tiled OLED display is shown in Figure 5-21

(a)

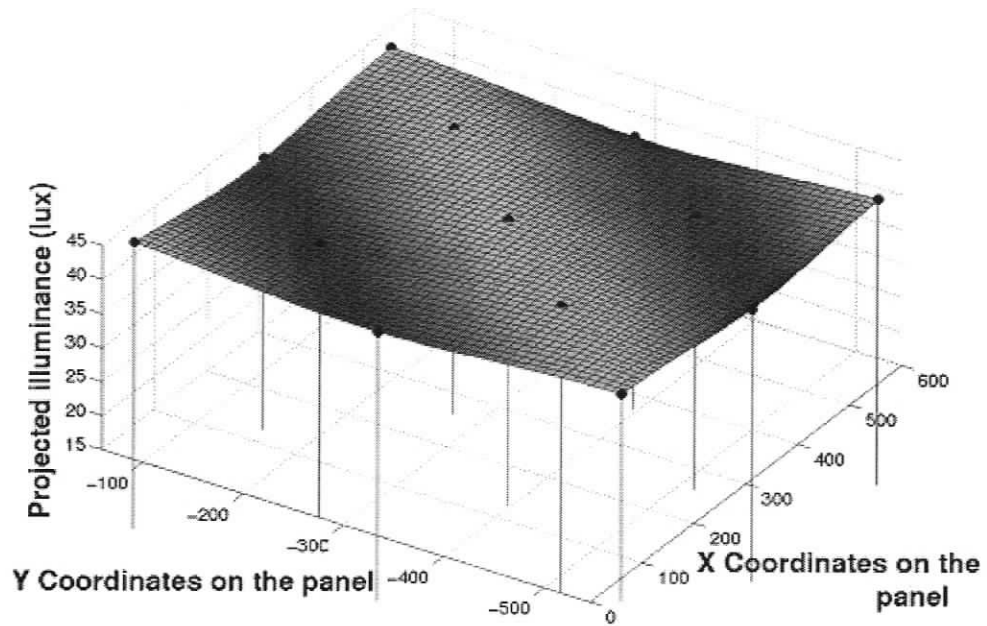


Figure 5-21 (a): Simulation of a 600mm tiled display using the illuminance values obtained with the OLED module

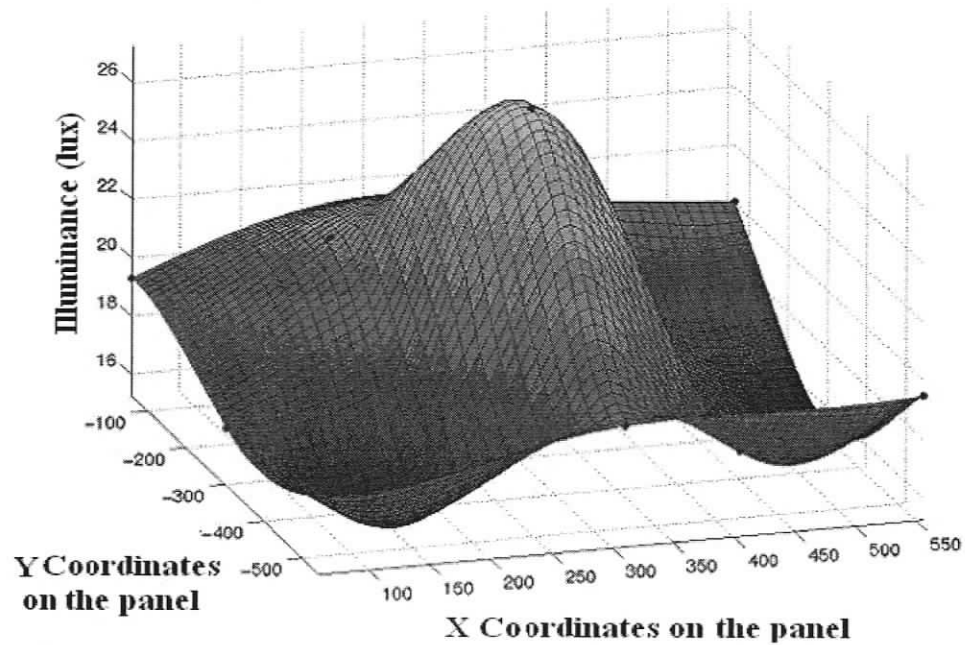


Figure 5-21 (b): Illuminance distribution for a generic edgelit LED display

The standard deviation that could be obtained for the tiled OLED display was close to 1. The standard deviation was calculated to be 1.03 lux. Figure 5-21 (b) depicts the illuminance values obtained with a generic edgelit conventional LED-based display. It is clear that much better uniformity can be obtained with tiled OLED sign as compared to the edgelit LED sign. Table 5-4 depicts the comparison of uniformity ratios for the LED and OLED signs.

Table 5-4 : *Uniformity ratio and standard deviation for a tiled OLED sign and an edgelit LED sign*

<i>Parameter</i>	<i>Edgelit LED based generic sign</i>	<i>Edgelit sign with a diamond grating</i>	<i>Tiled OLED sign</i>
<i>Uniformity Ratio</i>	1.87	1.13	1.05
<i>Standard deviation (lux)</i>	3.12	1.1	1.03

According to Table 5-4, it can be seen that the tiled OLED display possesses a greater uniformity than the edgelit signage with or without the diamond grating. Also, the cost of the diamond grating is much higher which discourages the signage manufacturer to use it. This result is a major contribution of this thesis. The uniformity ratio obtained with OLEDs satisfies the guidelines of IESNA [6].

Also, the economic considerations are also met with this design as it eliminates the use of both the diamond grating as well as the acrylic panel, which accounts for about 2/3 of the cost of the edgelit LED signage.

A comparison of efficacy was also done. The power consumption of this tiled display was extended for a 600mm sign. This display was scaled to a 600mm sign with 20" diagonal. The illuminance-current characteristics were measured and the values were scaled proportionally. The power consumption was determined to be about 20W for a 20-lux output for a standard size. The display would have good uniformity if the same kind of devices with the same inputs were used.

The other way by which the display could be standardized is by the maximum ratings. No maximum ratings were available for this display. However, the typical current value for operation is 15mA. We were able to operate the display at 20mA without causing any

damage to the display. Hence, considering 20mA as the maximum rating for current. The corresponding illuminance output would be around 222.2 lux. Considering this as the maximum illuminance output for the current OLED module, the area, which is required to generate a net light output of 7.2 lumen, can be estimated.

For a light output of 222.2 lumens the area required is 1 m^2 . Hence the area required for obtaining 7.2 lumen output will be approximately 0.032 m^2 which is about 10 times lesser than the standard display size of 600mm by 600mm.

5.9 Results and Discussion

In this chapter, we presented novel design techniques for the implementation of OLEDs as light-sources for signage. The contribution of this chapter is the evaluation of the various design techniques and implementation of the tiled OLED design with a commercially available module. The results obtained for the commercially available OLED module were compared with the edgelit LED-based signage measurements. We now summarize the various results obtained.

Different designs techniques, which could be used to implement signage displays using OLEDs, were presented. Edgelighting using small sized OLED modules, although had the potential to produce a more uniform display, was not considered very suitable due to the limitations similar to what is found in inorganic LED-based signage. Also, the use of edgelighting technique would require additional diamond grating to achieve uniformity. Hence, this technique was ruled out.

Signs with one partially reflective coating could also be designed. Our simulation, however, suggested a non-uniform display with a single reflective coating. Hence, an improvement over this technique was suggested using one partially reflective coating on the top surface and a mirror like coating on the base of the panel. Although these designs were better than edgelighting, still the cost of reflective coatings could increase the overall cost of the display. Also, this design was not very suitable for mass-production due to its complexity.

A single large-sized OLED could also be used to commercially construct signs. The main advantages of a single large display would be the simplicity of driver circuitry, a wide viewing angle, possibility of a programmable display and a higher resolution.

However, a single OLED would require a higher maintenance. If a part of the signage lost its uniformity then it could lead to the replacement of the whole display, hence a higher maintenance cost.

The best possible design, the tiled OLED design, was chosen to be evaluated using small-sized OLEDs. The OLED modules, available commercially from RiT Display Corporation, were successfully evaluated. The commercially available OLED module possessed the characteristic I-V curve for diodes. The spectral characteristics of the OLED showed a dominance of blue color. The chromaticity coordinates of the OLED-based display and the edgelit LED-based sign were compared. It was seen that the light emitted from the OLED display was spectroscopically closer to the achromic point (pure white light), than the light emitted from the edgelit LED-based display.

The illuminance was proportional to current for red, green, blue and white colors. This measurement was a photometric measurement in which the response of human eye was a vital component. The receptor cells for color are most sensitive to a frequency of 500-580 nm. This is clearly a green colored light. The measurements with the three red, green and blue colors reinstated the sensitivity of human eye to various colors: green being the most.

The linearity in the illuminance-current curve indicated the current dependence of illuminance. The values were similar for different OLED modules, which suggested that a uniform display was possible using the OLED technology.

A tiled OLED design was constructed with the help of a power driver circuitry. A microcontroller was used to control the OLED modules. The data obtained from the tiled OLED-based sign and the generic edgelit LED-based sign was compared. The OLED-based display depicted a fair amount of improvement in illuminance uniformity in comparison with the generic edgelit LED-based sign. The uniformity ratio obtained with the OLED was much better than the edgelit LED-based display. The illumination uniformity ratio for a tiled OLED sign was 1.03 and for an edgelit LED-based sign was 1.87. The illumination uniformity ratio obtained with the OLED-based displays was close to IESNA's ideal illuminance uniformity ratio of 1. The illuminance distribution of points on the panel depicted a marked difference in uniformity. The standard deviation in the case of edgelit LED-based signs was 3.12 lux and with OLEDs was 1.05 lux. Therefore,

it could be seen that OLED-based signage was superior to the edgelit LED-based signage in terms of illumination uniformity. OLED-based signage also reduces the cost by eliminating the diamond grating and the acrylic panel. The demonstration of improvement in illuminance uniformity using OLEDs without using any external means is an important contribution of this thesis.

It was also observed that OLEDs required a complicated driver circuitry. However, it was possible to design compact circuits, which were extremely light and were useful in maintaining the aesthetics of the display. The development in the Si technology enabled the use of highly sophisticated and programmable drivers for addressable display applications. These drivers controlled by microcontrollers provided a good control over the display settings.

The power consumption was approximated to *20 W for a uniform 20-lux output*. This implied an efficacy of 0.35 lm/W at 40 cd/m² for this signage. In addition, if the commercially available module is used at full power then the display size would have to be decreased by 10 times in order to achieve the net output of 7.2 lumen. The power dissipation of this device could be decreased if a white-light generator OLED was used. The OLED module used here was a full colored emitter in which light was obtained after mixing of red, green and blue colors, hence more power was consumed to maintain the intensity of these colors to obtain white light. OLED modules doped with dyes and dopants to obtain a blue OLED could also be used to generate white color.

It was interesting to note that the need for both a diamond grating and acrylic was eliminated if a single, large OLED module or a tiled OLED display was used. This could lead to a reduction in the overall cost of the signage system. The condition of uniformity of signage was satisfied using the tiled OLED design. The potentially lower cost of OLEDs, if processed by the roll-to-roll technique also could have an important impact in the reducing the overall cost of signage.

Chapter 6

Conclusion and Future Work

6.1 Summary of Contributions

This thesis examined two solid-state light sources, namely the conventional LEDs and the OLEDs, for application in signage. In summary, the first part of the thesis focused on the evaluation of edgelit signage that is based on conventional LEDs, while the latter part investigated the application of OLEDs for signage.

The contributions of the thesis are outlined as under:

- This thesis provided a detailed quantitative analysis of signage based on LED edgelighting technology. Novel opto-electrical measurements were presented and analyzed. This has not been reported previously in other literature.
- An analysis of the prototype OLED modules, which were available as research samples from the National Research Council of Canada, was also performed. These samples had not been characterized previously. Hence, the investigation done in the thesis was the first analysis of these samples.
- New design techniques for implementation of OLEDs as light-sources for signage were introduced. Signage with reflective coatings and a tiled OLED display were described in detail.
- An important contribution of the thesis was the implementation of a tiled OLED display and development of a prototype signage display using commercially available OLEDs. The tiled display was characterized with the help of opto-electrical measurements
- The main contribution of the thesis is a detailed comparison of LED-based and OLED-based signage. This was done with the help of measurement data obtained from the LED and OLED signage displays. Uniformity ratios and standard deviations

for the display were calculated. The thesis demonstrated a novel technique for usage of OLEDs for signage and validated the technique with the help of measurements and analysis. It was shown that OLED based signage was better than LED based signage in terms of illumination uniformity.

6.2 Comparison of LED- and OLED-Based Signage

Illuminance uniformity is an important aspect in evaluating signage. This is because non-uniformities reduce the useful life of the sign and also stress the eyes of the viewer. Different types of light-sources can be used for signage. Among these, conventional LEDs and OLEDs offer several advantages, and hence have the potential to replace the other light sources.

Conventional LEDs, which are based on inorganic materials, have undergone a lot of research and development and have reached a mature stage proving effective for lighting applications, signage being one of them. Our research, based on the measurements using white LEDs from Nichia Corporation, suggests that conventional LEDs possess a higher efficacy than other light sources available for signage. The average efficacy was determined to be 20.7 cd/A. In addition, conventional LEDs have the advantages of low maintenance cost, long lifetime, and robust design. Therefore, they have been successfully used for signage.

The most efficient technique of using LEDs for signage is edgelifting. This is because edgelifting employs fewer light-sources when compared to the element-lit design. This shows that the method for designing signs has a great bearing on the sign's performance. We evaluated the conventional LED-based edgelif signs on the basis of their opto-electrical measurements. The spectral characteristics of the sign showed a dominance of yellow color. The illumination uniformity of the sign was examined in detail. For the 600 mm generic signs, an illuminance uniformity ratio of 1.87 was obtained. This ratio does not comply with the guidelines issued by Illuminating Engineering Society of North America (IESNA). Hence, there is a need for improvement in the illumination uniformity. This improvement can be achieved by using external diffusers such as the diamond grating. Even with the use of the diamond grating, it was not possible to achieve a uniformity of 100% with conventional LEDs according to our

measurements. Moreover, the use of the diamond grating and acrylic panel amounted to about 2/3 of the overall cost of the sign. Therefore, though the use of the diamond grating improved the illumination uniformity, it is not cost-efficient for mass production.

On the other hand, despite the fact that OLEDs are currently in the budding stage of development, they can be used for signage application. The OLED module obtained from the National Research Council (NRC) of Canada, was useful in providing information on the basic characteristics of the device. The availability of this prototype sample was the starting point of our research. Although the sample possessed low efficacy (0.02 lm/W), we were able to characterize it and determine if a reasonable light output was obtainable. The sample also familiarized us with the behavior of OLEDs and the effect of environmental factors in the absence of encapsulation. It was observed that the measurements from the two segments in these OLEDs were identical. Hence, it was possible to obtain uniform light output from the segments.

In order to establish the applicability of OLEDs for signage, we examined a commercially available OLED module from RiT Display Corporation. The use of a commercially available OLED module was critical for our assessment, as it establishes the feasibility of OLED-based signs for mass production. The OLEDs from RiT Display Corporation were particularly suitable for our evaluation due to their passive-matrix design and their ability to be tuned to different colors (65 K colors).

OLED signage could be designed using various techniques such as edgelighting and the tiled display technique. The tiled display technique was found to be more suitable for our evaluation. We evaluated the light intensity and the spectral characteristics for a tiled OLED display. The spectral characteristics determined the dominant wavelength of the OLED to be 483 nm suggesting the dominance of blue color. We also compared the spectral characteristics of the OLED with those of the LED and determined that the chromaticity coordinates for OLEDs were closer to the achromic point (pure white light) than the chromaticity coordinates for LEDs.

Our evaluation, based on the opto-electrical measurements, suggested that OLEDs, undoubtedly, promise better illumination uniformity for large signs when compared to the conventional LEDs. An illumination uniformity ratio close to 1 was achieved for OLEDs, which is highly desirable for signage application. This ratio was

achieved without the use of diamond gratings or any other external means. This implies a potential reduction in the cost of the display. The major difference between the conventional LED and the OLED is that the conventional LED is a point source whereas the OLED is a diffused light source. This characteristic of the OLED makes it an ideal choice for a distributed-area application such as signage.

As per our evaluation, the commercially available OLED possesses a luminous efficacy of 0.35 lm/W. However, in order to compete effectively with conventional LEDs in terms of luminous efficacy, OLEDs need to attain an efficacy of at least 18 lm/W. Thus, although the luminous efficacy of OLEDs is lower than that of LEDs at this time, in terms of illumination uniformity, the OLED signs prove to be superior to the edgelit LED signs.

Finally, from a system's perspective, it can be seen that the high energy consumption and the high initial cost of OLED can be traded off in exchange for a better illumination quality. The use of OLEDs also eliminates the need for a diamond grating and an acrylic panel, resulting in a reduction in the cost of the sign. The cost can be further reduced if OLEDs are manufactured by the roll-to-roll technique. It is also possible to design flexible signage using OLEDs, which will introduce a new paradigm in signage. Also, energy-efficient displays using OLEDs can be designed, which could be a possible extension of this work as described in the following section.

A comparison between the LEDs and OLEDs is given in Table 6-1. The data quoted in this table is based on our measurements.

Table 6-1: Comparison of LEDs and OLEDs

Parameters	Conventional LED	Organic LED
Source Type	Emissive point source	Emissive diffused source
Luminous Efficacy	High (18 lm/W)	Potentially high. Research samples have reported an efficacy of 6 lm/W. Calculated efficacy = 0.35 lm/W
Viewing Angle	Not wide, 20° for Nichia LEDs	Very wide, greater than 160°.
Color Rendition Index	Varies with temperature Reported value is 70 at 25°C	High – Measured value of 55.3 at most temperatures.
Applications	Traffic lights, as status indicator in displays, Backlighting LCDs, Optical communication, Edgelit signage.	Microdisplays, replacing fluorescent lamps in the long run, flat panel displays, potential application in general illumination and signage, electronic paper, flexible signage
Signage design	Element-lit, Cavity lit and edgelit design	Backlit or element lit signage, with reflective coating or tiled design
Uniformity for signage	Uniformity Ratio = 1.87 without diamond grating	Uniformity ratio = 1.1 without acrylic and diamond grating
Standard deviation in illuminance values for signage	3.12 lux for a generic sign	1.03 lux for a tiled OLED display
Power Consumption	500 mW for a 600 mm edgelit sign	20W for a 600 mm tiled sign
Design and Maintenance	Ease of design, operation and maintenance	Ease of design operation with passive-matrix OLEDs, programmable with microcontrollers such as MSP-430
Economical Considerations	High fabrication costs and high cost for edgelighting application due to diamond grating. Cost of edgelit 600 mm sign with acrylic panel and diamond grating is \$1500.	Potentially low fabrication costs if roll-to-roll technology is used. Cost of a 600 mm tiled OLED display is 10 times more than edgelit LED display at this time.

6.3 Future Work

New sources of lighting, which promise more energy savings with superior light quality, are being designed using SSL, and alternative sources of energy, are also being considered. Energy sources based on sun's energy are possible alternatives, which have

been undergoing investigation for almost 150 years. Photovoltaic powered lighting systems have been in use for many years for buildings and indoor lighting. Photovoltaic systems are available as standalone, utility and hybrid systems for different applications. They have been used for lighting in remote and rural areas. They are considered to be useful not only in far-fetched places which do not have enough power supply from the grid but are suitable for big cities as well which suffer from frequent power outages. The purpose of these cells is to convert sunlight into electrical energy, which can be stored for later use. Due to the unavailability of electricity in many remote, rural areas of the world, there is a need to other energy sources such as solar cells for providing energy for signage.

OLEDs can be used in the form of a tiled display as well as a single sheet of OLEDs and LEDs using edgelighting. SSL-based signage can be made “intelligent” or self-regulating. If the SSL source based display responds in correspondence to the ambient light levels, then it could lead to higher energy savings. The major component required to make the signage “intelligent” is a photosensor. Photosensors have been employed since the last two decades as a controlling device in fluorescent lighting. Photosensor consist of a photocell that converts the incoming optical signal into an electrical signal and the optics along with it. If a large display is constructed, a photosensor can be added to the circuitry to sense ambient light levels. The photosensor output could be provided as a feedback to the microcontroller and different light levels can be set at varying ambient light conditions. In this way, the application of a photosensor with an SSL based signage would imply higher energy savings over time.

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Appendices

Appendix A

C code for the Program

```

//*****

// MSP-FET430P140 :OLED DRIVER SOFTWARE WRITTEN FOR SSD1332 driver and Rit
full color displays
// Steps before the program
// Power up Vdd =max 3.5 typical 2.5V
// Ground the Gnd port in the PCB
// Connect Vcc but DO NOT power it up until #####
// Connect P1.0 -> CS# (Chip Select: Low enable)
// Connect P1.1 -> RES(RESET:Low enable: should be maintained high for most of the program
except for resetting)
// Connect P1.2 -> D/C(Data and command control: high for data enable; low for command
enable)
// Connect P1.3-> WR(Write: Low enable:Enable to input data/commands)
// Connect P1.4-> RD (Read should be kept high)
// Connect P.2.0 tO P.2.7 ->D0-D7(Data bus)
//*****
*****

// Software written in original for 8080 and 6800 series microprocessors by Rit displays
// modified for use with MSP430 by Pratibha Sharma on
// 4.43p.m, June 24, 2004
//last modified : 4:04p.m on June 29,2004
//*****
*****

#include <msp430x14x.h>

#define COMMANDPORT P1OUT
#define DATAPORT P2OUT
#define CS 0x01           //Chip select :low enable
#define RES 0x02         // Reset :Low enable
#define DATA 0x04       //D/C input low->command,high->data
#define WR 0x08          //Write:low enable
#define RD 0x10          //Read:Low enable

void write_red_data(void);
void write_green_data(void);
void write_blue_data(void);
void write_white_data(void);
void init_reg(void)

```

```

{
COMMANDPORT &=~ RES;
}
void writecommand(int i)
{
    COMMANDPORT &= ~CS;           //Chip selected
    COMMANDPORT |=RES;           //Reset Disable
    COMMANDPORT &= ~DATA;        // Command input for D/C
    COMMANDPORT &= ~WR;          //Write enable
    COMMANDPORT |= RD;           //Read Disable
    DATAPORT = i;                //Port#2 output
    COMMANDPORT |=CS;
}
void writedata(int i)
{
    COMMANDPORT &= ~CS;           //Chip selected
    COMMANDPORT |=RES;           //Reset disable
    COMMANDPORT |= DATA;        //Data input for D/C
    COMMANDPORT &= ~WR;          //Write enabled
    DATAPORT = i;                //Port#2 output
    COMMANDPORT &= ~RD;          //Read enabled
}

void main(void)
{
    WDTCTL = WDTPW + WDTHOLD;     // Stop watchdog timer

    P1DIR |= 0xFF; //Configured as digital output
    P2DIR |= 0xFF; //Configured as digital output

    init_reg();
    writecommand(0xAE); //Display off #####STOP HERE :Power-up Vcc wait for 100ms till
VCC is stable
    writecommand(0xA8); //64 row setting
    writecommand(0x3F);
    writecommand(0xA1); //Display start line
    writecommand(0x00);
    writecommand(0xA2); //Display offset
    writecommand(0x00);
    writecommand(0xA0); // Display remap
    writecommand(0x60);
    writecommand(0x87); //Master current control
    writecommand(0x0B);
    writecommand(0x81); //Color blue contrast control
    writecommand(0x00);
    writecommand(0x82); //Color green contrast control
    writecommand(0x00);
    writecommand(0x83); //Color red contrast control
    writecommand(0x0A);
    writecommand(0xA5); //Normal display

```

```

writecommand(0xB1);//Set Phase length
writecommand(0x11);
writecommand(0xB2);//Row period setting
writecommand(0x7F); //
writecommand(0xD1);//Display RAM speed-up
writecommand(0xFF);
writecommand(0xA9);//Enable OSC
writecommand(0x03);
writecommand(0xAF);//DISPLAY ON!
write_red_data();
write_green_data();
write_blue_data();
write_white_data();
}

```

```

void write_red_data(void)
{int i;
writecommand(0x15);//Column address counter
writecommand(0x00);
writecommand(0x5F);
writecommand(0x75);//Row address counter
writecommand(0x00);
writecommand(0x3F);
for(i=0;i<6144;i++)
{
writedata(0xF8);//red
writedata(0x00);
}
}

```

```

void write_green_data(void)
{int i;
writecommand(0x15);//Column address counter
writecommand(0x00);
writecommand(0x5F);
writecommand(0x75);//Row address counter
writecommand(0x00);
writecommand(0x3F);
for(i=0;i<6144;i++)
{
writedata(0x07);//Green
writedata(0xE0);
}
}

```

```

void write_blue_data(void)
{int i;
writecommand(0x15);//Column address counter
writecommand(0x00);
writecommand(0x5F);

```

```
writecommand(0x75);//Row address counter
writecommand(0x00);
writecommand(0x3F);
for(i=0;i<6144;i++)
{
writedata(0x00);//blue
writedata(0x1F);

}
}

void write_white_data(void)
{int i;
writecommand(0x15);//Column address counter
writecommand(0x00);
writecommand(0x5F);
writecommand(0x75);//Row address counter
writecommand(0x00);
writecommand(0x3F);
for(i=0;i<6144;i++)
{
writedata(0xFF);//white
writedata(0xFF);
}
}
```

Appendix B

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COMPANY: UNIVERSITY OF VICTORIA

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Dear Sir/Madam,

I am a M.ASc candidate at the University of Victoria, BC, Canada. I wanted to seek permission to use the MSP-430 block diagram given in the data sheets for my thesis work.

If I can get this permission, I would request you to kindly reply by facsimile.

Thanks a lot!

Regards

Pratibha

Appendix C

Datasheet for NSPW500BS.

SPECIFICATIONS FOR NICHIA WHITE LED

MODEL : NSPW500BS

NICHIA CORPORATION

1.SPECIFICATIONS

(1) Absolute Maximum Ratings

(Ta=25°C)

Item	Symbol	Absolute Maximum Rating	Unit
Forward Current	IF	30	mA
Pulse Forward Current	IFP	100	mA
Reverse Voltage	VR	5	V
Power Dissipation	PD	120	mW
Operating Temperature	Topr	-30 ~ + 85	°C
Storage Temperature	Tstg	-40 ~ +100	°C
Soldering Temperature	Tsld	265°C for 10sec.	

IFP Conditions : Pulse Width \leq 10msec. and Duty \leq 1/10

(2) Initial Electrical/Optical Characteristics

(Ta=25°C)

Item	Symbol	Condition	Min.	Typ.	Max.	Unit	
Forward Voltage	VF	IF=20[mA]	-	3.6	4.0	V	
Reverse Current	IR	VR= 5[V]	-	-	50	μ A	
Luminous Intensity	Rank S	Iv	IF=20[mA]	7800	9200	11000	mcd
	Rank R	Iv	IF=20[mA]	5520	6400	7800	mcd
	Rank Q	Iv	IF=20[mA]	3900	4600	5520	mcd

* Measurement Uncertainty of the Luminous Intensity : \pm 10%

Color Ranks

(IF=20mA, Ta=25°C)

	Rank a0			
x	0.280	0.264	0.283	0.296
y	0.248	0.267	0.305	0.276

	Rank b1			
x	0.287	0.283	0.330	0.330
y	0.295	0.305	0.360	0.339

	Rank b2			
x	0.296	0.287	0.330	0.330
y	0.276	0.295	0.339	0.318

	Rank c0			
x	0.330	0.330	0.361	0.356
y	0.318	0.360	0.385	0.351

* Measurement Uncertainty of the Color Coordinates : \pm 0.01

* One delivery will include up to two consecutive color ranks and three luminous intensity ranks of the products.

The quantity-ratio of the ranks is decided by Nichia.

2.TYPICAL INITIAL OPTICAL/ELECTRICAL CHARACTERISTICS

Please refer to figure's page.

3.OUTLINE DIMENSIONS AND MATERIALS

Please refer to figure's page.

Material as follows ;

Resin(Mold) : Epoxy Resin (over YAG Phosphor)

Leadframe : Ag plating Copper Alloy

4.PACKAGING

- The LEDs are packed in cardboard boxes after packaging in anti-electrostatic bags. According to the total delivery amount, cardboard boxes will be used to protect the LEDs from mechanical shocks during transportation. Please refer to figure's page. The label on the minimum packing unit bag shows;
Part Number, Lot Number, Ranking, Quantity
- The boxes are not water resistant and therefore must be kept away from water and moisture.

5.LOT NUMBER

The first six digits number shows **lot number**.

The lot number is composed of the following characters;

○□×××× - △■

○ - Year (1 for 2001, 2 for 2002)

□ - Month (1 for Jan., 9 for Sep., A for Oct., B for Nov.)

×××× - Nichia's Product Number

△ - Ranking by Color Coordinates

■ - Ranking by Luminous Intensity

6.RELIABILITY

(1) TEST ITEMS AND RESULTS

Test Item	Standard Test Method	Test Conditions	Note	Number of Damaged
Resistance to Soldering Heat	JEITA ED-4701 300 302	Tsld=260 ± 5°C, 10sec. 3mm from the base of the epoxy bulb	1 time	0/100
Solderability	JEITA ED-4701 300 303	Tsld=235 ± 5°C, 5sec. (using flux)	1 time over 95%	0/100
Thermal Shock	JEITA ED-4701 300 307	0°C ~ 100°C 15sec. 15sec.	100 cycles	0/100
Temperature Cycle	JEITA ED-4701 100 105	-40°C ~ 25°C ~ 100°C ~ 25°C 30min. 5min. 30min. 5min.	100 cycles	0/100
Moisture Resistance Cyclic	JEITA ED-4701 200 203	25°C ~ 65°C ~ -10°C 90%RH 24hrs./1cycle	10 cycles	0/100
Terminal Strength (bending test)	JEITA ED-4701 400 401	Load 5N (0.5kgf) 0° ~ 90° ~ 0° bend 2 times	No noticeable damage	0/100
Terminal Strength (pull test)	JEITA ED-4701 400 401	Load 10N (1kgf) 10 ± 1 sec.	No noticeable damage	0/100
High Temperature Storage	JEITA ED-4701 200 201	Ta=100°C	1000hrs.	0/100
Temperature Humidity Storage	JEITA ED-4701 100 103	Ta=60°C, RH=90%	1000hrs.	0/100
Low Temperature Storage	JEITA ED-4701 200 202	Ta=-40°C	1000hrs.	0/100
Steady State Operating Life		Ta=25°C, If=30mA	1000hrs.	0/100
Steady State Operating Life of High Humidity Heat		60°C, RH=90%, If=20mA	500hrs.	0/100
Steady State Operating Life of Low Temperature		Ta=-30°C, If=20mA	1000hrs.	0/100

(2) CRITERIA FOR JUDGING THE DAMAGE

Item	Symbol	Test Conditions	Criteria for Judgement	
			Min.	Max.
Forward Voltage	V _F	I _F =20mA	-	U.S.L.*) × 1.1
Reverse Current	I _R	V _R =5V	-	U.S.L.*) × 2.0
Luminous Intensity	I _V	I _F =20mA	L.S.L.**)	× 0.7

*) U.S.L. : Upper Standard Level

**) L.S.L. : Lower Standard Level

7.CAUTIONS

White LEDs are devices which are materialized by combining Blue LEDs and special phosphors. Consequently, the color of White LEDs is changed a little by an operating current. Care should be taken after due consideration when using LEDs.

(1) Lead Forming

- When forming leads, the leads should be bent at a point at least 3mm from the base of the epoxy bulb. Do not use the base of the leadframe as a fulcrum during lead forming.
- Lead forming should be done before soldering.
- Do not apply any bending stress to the base of the lead. The stress to the base may damage the characteristics or it may break the LEDs.
- When mounting the LEDs onto a printed circuit board, the holes on the circuit board should be exactly aligned with the leads of the LEDs. If the LEDs are mounted with stress at the leads, it causes deterioration of the epoxy resin and this will degrade the LEDs.

(2) Storage

- The LEDs should be stored at 30°C or less and 70%RH or less after being shipped from Nichia and the storage life limits are 3 months. If the LEDs are stored for 3 months or more, they can be stored for a year in a sealed container with a nitrogen atmosphere and moisture absorbent material.
- Nichia LED leadframes are comprised of a silver plated copper alloy. The silver surface may be affected by environments which contain corrosive gases and so on. Please avoid conditions which may cause the LED to corrode, tarnish or discolor. This corrosion or discoloration may cause difficulty during soldering operations. It is recommended that the LEDs be used as soon as possible.
- Please avoid rapid transitions in ambient temperature, especially, in high humidity environments where condensation can occur.

(3) Static Electricity

- Static electricity or surge voltage damages the LEDs.
It is recommended that a wrist band or an anti-electrostatic glove be used when handling the LEDs.
- All devices, equipment and machinery must be properly grounded. It is recommended that measures be taken against surge voltage to the equipment that mounts the LEDs.
- When inspecting the final products in which LEDs were assembled, it is recommended to check whether the assembled LEDs are damaged by static electricity or not. It is easy to find static-damaged LEDs by a light-on test or a VF test at a lower current (below 1mA is recommended).
- Damaged LEDs will show some unusual characteristics such as the leak current remarkably increases, the forward voltage becomes lower, or the LEDs do not light at the low current.

Criteria : (VF > 2.0V at IF=0.5mA)

(4) Soldering Conditions

- Nichia LED leadframes are comprised of a silver plated copper alloy. This substance has a low thermal coefficient (easily conducts heat). Careful attention should be paid during soldering.
- Solder the LED no closer than 3mm from the base of the epoxy bulb. Soldering beyond the base of the tie bar is recommended.
- Recommended soldering conditions

Dip Soldering		Soldering	
Pre-Heat	100°C Max.	Temperature	300°C Max.
Pre-Heat Time	60 seconds Max.	Soldering Time	3 seconds Max.
Solder Bath	260°C Max.	Position	No closer than 3 mm from the base of the epoxy bulb.
Temperature			
Dipping Time	10 seconds Max.		
Dipping Position	No lower than 3 mm from the base of the epoxy bulb.		

- Do not apply any stress to the lead particularly when heated.
- The LEDs must not be repositioned after soldering.
- After soldering the LEDs, the epoxy bulb should be protected from mechanical shock or vibration until the LEDs return to room temperature.
- Direct soldering onto a PC board should be avoided. Mechanical stress to the resin may be caused from warping of the PC board or from the clinching and cutting of the leadframes. When it is absolutely necessary, the LEDs may be mounted in this fashion but the User will assume responsibility for any problems. Direct soldering should only be done after testing has confirmed that no damage, such as wire bond failure or resin deterioration, will occur. Nichia's LEDs should not be soldered directly to double sided PC boards because the heat will deteriorate the epoxy resin.
- When it is necessary to clamp the LEDs to prevent soldering failure, it is important to minimize the mechanical stress on the LEDs.
- Cut the LED leadframes at room temperature. Cutting the leadframes at high temperatures may cause failure of the LEDs.

(5) Heat Generation

- Thermal design of the end product is of paramount importance. Please consider the heat generation of the LED when making the system design. The coefficient of temperature increase per input electric power is affected by the thermal resistance of the circuit board and density of LED placement on the board, as well as other components. It is necessary to avoid intense heat generation and operate within the maximum ratings given in this specification.
- The operating current should be decided after considering the ambient maximum temperature of LEDs.

(6) Cleaning

- It is recommended that isopropyl alcohol be used as a solvent for cleaning the LEDs. When using other solvents, it should be confirmed beforehand whether the solvents will dissolve the resin or not. Freon solvents should not be used to clean the LEDs because of worldwide regulations.
- Do not clean the LEDs by the ultrasonic. When it is absolutely necessary, the influence of ultrasonic cleaning on the LEDs depends on factors such as ultrasonic power and the assembled condition. Before cleaning, a pre-test should be done to confirm whether any damage to the LEDs will occur.

(7) Safety Guideline for Human Eyes

- In 1993, the International Electric Committee (IEC) issued a standard concerning laser product safety (IEC 825-1). Since then, this standard has been applied for diffused light sources (LEDs) as well as lasers. In 1998 IEC 60825-1 Edition 1.1 evaluated the magnitude of the light source. In 2001 IEC 60825-1 Amendment 2 converted the laser class into 7 classes for end products. Components are excluded from this system. Products which contain visible LEDs are now classified as class 1. Products containing UV LEDs are class 1M. Products containing LEDs can be classified as class 2 in cases where viewing angles are narrow, optical manipulation intensifies the light, and/or the energy emitted is high. For these systems it is recommended to avoid long term exposure. It is also recommended to follow the IEC regulations regarding safety and labeling of products.

(8) Others

- Care must be taken to ensure that the reverse voltage will not exceed the absolute maximum rating when using the LEDs with matrix drive.
- The LEDs described in this brochure are intended to be used for ordinary electronic equipment (such as office equipment, communications equipment, measurement instruments and household appliances). Consult Nichia's sales staff in advance for information on the applications in which exceptional quality and reliability are required, particularly when the failure or malfunction of the LEDs may directly jeopardize life or health (such as for airplanes, aerospace, submersible repeaters, nuclear reactor control systems, automobiles, traffic control equipment, life support systems and safety devices).
- User shall not reverse engineer by disassembling or analysis of the LEDs without having prior written consent from Nichia. When defective LEDs are found, the User shall inform Nichia directly before disassembling or analysis.
- The formal specifications must be exchanged and signed by both parties before large volume purchase begins.
- The appearance and specifications of the product may be modified for improvement without notice.

ICI Chromaticity Diagram

