# DESIGN OPTIMIZATION AND CHARACTERIZATION OF WHITE LIGHT FOR LED STREET LIGHT APPLICATION

**JOCELYNN KEE XIAO YING**

**UNIVERSITI SAINS MALAYSIA**

**2022**

# DESIGN OPTIMIZATION AND CHARACTERIZATION OF WHITE LIGHT FOR LED STREET LIGHT APPLICATION

**by**

**JOCELYNN KEE XIAO YING**

**Thesis submitted in fulfilment of the requirements for the degree of Master of Science**

**April 2022**

# ACKNOWLEDGEMENT

I would like to thank all the people who contributed in some way to the work described in this thesis. First and foremost, I am so thankful and grateful to Itramas Manufacturing Sdn Bhd for the Master's Degree study sponsorship throughout this 2 years. I would like to acknowledge the Institute of Nano Optoelectronics Research and Technology (INOR) for making it possible for me to study here. I am so thankful to INOR for the high-quality seminars that the department organized. I would like to thank my academic advisor, Dr Lim Way Foong, for accepting me into her group. During my time, she contributed to a great graduate school experience by allowing me intellectual independence in my work, encouraging my participation at conference, engaging me in new ideas, and requiring a high level of work quality in all of my endeavours. Additionally, I would like to thank my Research & Development department colleagues from Itramas Manufacturing Sdn Bhd for their interest and help in my work. I am grateful to all of those with whom I have had the pleasure to work during this and other related projects. Each of my colleagues has provided me extensive personal and professional guidance and taught me a great deal about both scientific research and life in general. Every result described in this thesis was accomplished with the help and support of fellow colleagues. I would sincerely like to thank all my beloved friends who were with me and support me through thick and thin. Nobody has been more important to me in the pursuit of this project than the members of my family. I would like to thank my Dad, my Mom, and my siblings, Jesslynn and Melvynn for their love and guidance in whatever I pursue. They are the ultimate role models.

## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

## LIST OF SYMBOLS

| | |
|---|---|
| °C | Degree Celsius |
| K | Kelvin |
| eV | Electron volt |
| mA | Milliampere |
| mm | Millimeter |
| m/s | Millisecond |
| nm | Nanometer |
| V | Voltage |
| W | Wattage |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| BUG | Backlight Uplight Glare |
| BH | Backlight High |
| BL | Backlight Low |
| BM | Backlight Medium |
| BVH | Backlight Very High |
| CCT | Correlated Color Temperature |
| CFL | Compact Fluorescent Lamp |
| EQE | External Quantum Efficiency |
| FH | Forward High |
| FL | Forward Low |
| FM | Forward Medium |
| FVH | Forward Very High |
| GaN | Gallium Nitride |
| HID | High-Intensity Discharge |
| IDA | International Dark-Sky Association |
| IES | Illuminating Engineer Society |
| IQE | Internal Quantum Efficiency |
| LCS | Luminaire Classification System |
| LES | Light Emitting Surface |
| PC | Polycarbonates |
| PCB | Printed Circuit Board |
| PMMA | Poly(methyl methacrylate) |
| RGB | Red-Green-Blue |
| SDG | Sustainable Development Goals |
| SMD | Surface Mounted Device |
| TIR | Total Internal Reflection |
| TNB | Tenaga Nasional Berhad |
| UH | Uplight High |
| UL | Uplight Low |

# LIST OF APPENDICES

# PENGOPTIMUMAN REKA BENTUK DAN PERNCIRIAN CAHAYA PUTIH UNTUK APLIKASI LAMPU JALAN LED

## ABSTRAK

Matlamat kajian ini adalah untuk menilai kesan bentuk kanta terhadap prestasi cahaya daripada lampu jalan permukaan pemancar cahaya (SMD LED). Faktor lain yang perlu dipertimbangkan adalah pengaruh pelbagai bentuk LES atas SMD LED dan saiz SMD LED pada taburan cahaya. Selain itu, kesan pelbagai suhu warna berkolerasi (CCT) bagi LED juga diselidik. Pencirian optik dilakukan dengan menggunakan Goniophotometer (GO-2000) dan Integrating Sphere (PCE-200A). Perisian DIALux Evo telah digunakan untuk melakukan simulasi. Parameter jalan seperti jarak tiang 35 m dan ketinggian tiang 8 m pada jalan selebar 7 m telah digunakan. Pengujian dan pengukuran tahap pencahayaan adalah berdasarkan spesifikasi Tenaga Nasional Berhad (TNB), di mana lampu jalan mesti mematuhi piawaian lampu jalan ME4A. Hasil dapatan mendapti bahawa kanta E menunjukkan prestasi cahaya yang lebih baik berbanding dengan kanta A, kanta B, kanta C dan kanta D disebabkan oleh bentuk sigi empat tepatnya. Kanta berbentuk segi empat tepat yang lebih kecil dengan klasifikasi jenis II-M mempunyai masalah pencemaran cahaya yang lebih kecil. Perbandingan kajian antara CCT yang berbeza telah dijalankan. Cahaya putih kekuningan adalah suhu warna yang dipilih untuk kajian seterusnya berkenaan bentuk dan saiz SMD LEDs yang berbeza serta warna utama yang digunakan untuk campuran warna. Secara perbandingan, SMD LED bersaiz 3030 yang berbentuk segi empat sama memberikan prestasi cahaya yang lebih baik daripada SMD LED yang lain. Oleh kerana saiznya yang lebih kecil, bilangan SMD LED yang meningkat, serta susunan SMD LED merupakan faktor yang menjurus

kepada taburan cahaya yang besar. Sistem *ColorCalculator* telah digunakan untuk menganggar prestasi fotometri bagi skema campuran warna. Hasil kajian mendapati bahawa campuran cahaya putih kekuningan dengan biru pekat dan hijau sebenar boleh menghasilkan cahaya putih yang mempunyai 4500K CCT.

# DESIGN OPTIMIZATION AND CHARACTERIZATION OF WHITE LIGHT FOR LED STREET LIGHT APPLICATION

## ABSTRACT

The aim of this study was to evaluate the effects of lens type and shape on the light performance from surface mounted device light emitted diode (SMD LED) street light. Another factor considered was the influence of various shapes of the light emitting surface (LES) on the SMD LEDs and size of the SMD LED on light distribution. Besides, the effects of varying correlated colour temperature (CCT) of the LEDs were also investigated. Optical characterization was carried out using the Goniophotometer (GO-2000) and Integrating Sphere (PCE-200A). DIALux Evo software was used to perform the simulation. Road parameters, such as pole distance of 35 m and pole heights of 8 m on a 7 m width road were used. The road requirement was according to the Tenaga Nasional Berhad (TNB), whereby the street lights must comply with ME4A road classification requirements. The findings showed that Lens E demonstrated a better light performance as compared to Lens A, Lens B, Lens C and Lens D, owing to the rectangular shape of Lens E. The smaller shape of the rectangular lens with classification of Type II-M has lesser light pollution problems. A study comparison between the different CCTs was conducted. Warm White was selected for further investigation into the different shape and size of SMD LEDs as well as key colour for colour mixing. In comparison, the 3030 square-shaped LES gave a better light performance as compared to the other SMD LED. Due to its smaller size, the increasing number mounted, as well as the arrangement of the SMD LED, were the factors leading to large light distributions. ColorCalculator System was used to estimate the photometric performance of color mixing schemes. It was

discovered that the mixing of Warm White with Deep Blue and True Green would yield 4500K CCT white light.

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Light is the matter-of-fact, however it is still mysterious to human beings. Each day, human being usually experience the natural light which is produced by the sun and artificial light. Light is the source of each and every form of life. Starting from the history of human raise, it is the most important phenomena of all to make light more efficient. In order to maintain this journey, light emitting diode (LED) was introduced in the early of 1950s. In the early of 1990s, the blue gallium nitride (GaN) based LED has been invented by Shuji Nakamura with a new era. LED becomes more popular in the fields of medical science, engineering, and so on. In the beginning of the LED development, LED is often used for electronic devices and the incandescent bulb was replaced by LED. GaN based LED is the most commonly used LED nowadays for blue and white LED. Phosphor is used to produce white LED. High efficiency LEDs are needed for many applications as it benefits compared to traditional technologies. Surface Mounted Device (SMD) LEDs are the most common LEDs in the market. The LED chip is permanently fused to a printed circuit board, and it is highly popular due to its versatility.

In this research, different types and shapes of lenses were used to examine the corresponding effects towards the light pattern emitted from the SMD LEDs. Thus far, the selected lens for studies in the present work has not been explored previously. Moreover, the optimised lens would be further investigated with SMD LEDs of different forms and size in order to look into the difference in term of the light pattern. Last but not least, a colour mixing using SMD LEDs instead of using red-green-blue (RGB) chips was conducted in order to achieve 4500K colour temperature LEDs.

## 1.2 Problem Statement

The largest problem faced in street lighting is the unreasonable light distribution design and poor penetrability lens. In terms of optical design, the lighting effect is closely correlated with light distribution design. If light distribution is not configured correctly, there will be a poor lighting impact on the residents. Another challenging is the poor heat dissipation design on street light application. For every 10 °C rise in junction temperature of an LED chip, the service life of semiconductor devices is reduced by a factor of ten. The heat dissipation property of LED street lights is very important due to the high brightness requirements of LED street lights and the severe usage environment. If it is not resolved properly, it will cause LEDs to age faster and diminish stability. On top of that, the colour temperature range of outdoor lighting in the lighting market is often within 2800K-3000K, 4000K and 6500K. The colour temperature of 4500K SMD LED is rarely produced by the manufacturer and utilized in outdoor lighting due to its difficulty on achieving 4500K colour temperature of light. The reason of using 4500K light in street lighting is due to the colour temperature that is mimic of daylight. This colour temperature range simulates the natural daylight in mid-morning and afternoon, which are the most productive periods over the course of a day. A moderately high percentage of blue in the spectrum will keep people alert and thus will enhance public safety and well-being as well as producing a better visual comfort. Moreover, the colour mixing of LED is often seen by using RGB LED chips in a single package.

## 1.3 Objectives

The principle objective of this research is to investigate the different approaches on improving light distribution of street lighting applied for roadway. In order to achieve this principal objective, the following aspects are to be achieved:

1. To evaluate the influence of various lens shapes towards the light distribution.

2. To study the characteristics of light distribution using different shapes and sizes of SMD LEDs.

3. To produce 4500K white light using SMD LED via colour mixing technique.

## 1.4 Novelty

The present research is the first study to optimize the components of the street light application by comparing the various types and shapes of lens, studying the different correlated colour temperature of light and also investigating the use of different shapes and size of the SMD LEDs towards the distribution of light for the street light application. In addition, the colour mixing approach using different colours of SMD LEDs instead of mixing chip colours in a single package to achieve 4500K correlated colour temperature (CCT) is a novel concept.

## 1.5 Scope of the Study

In this research, the PCB was successfully designed and fabricated. Various lenses, CCT of SMD LEDs, as well as types of SMD LEDs were prepared and investigated. For the first parameter, the lens was studied and optimized using the parameters, which included (i) the effects of lens types on the light distribution and (ii) effects of lens shapes towards the light distributions. Next, the second parameter studied the effects of different correlated colour temperature (CCT) on the light distribution for street light application. The last parameter was the optimization of SMD LEDs by studying the effects of shape and size of the SMD LEDs towards the light distribution. On the last phase of the research, colour mixing using Warm White as the key colour matrix in combination with different colours to produce white light was studied towards achieving the 4500K CCT of white light.

Optical characterization was performed using Goniophotometer and also the Integrating Sphere. Simulation was performed using DIALux simulation to study the road lighting before analysis of the light performance based on backlight-uplight-glare lighting classification.

## 1.6 Outline of the Thesis

This thesis is organized into five chapters that cover all the aspects of the research. Chapter 1 begins with the introduction to the background of the study. It generally concludes the specific research problem statement, objectives, and scopes of the study. Chapter 2 provides the review for previous research on knowledge sharing and overview of current work. Method and the system used was illustrated in Chapter 3 that describes the research methodology employed in the study as well as providing data collection and data analysis. Chapter 4 presents the empirical results and discusses the findings of the study. Chapter 5 summarizes outcomes of this research with future recommendations.

.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This chapter further explains and discusses about the literature review and background study of this project, which would help to identify the problems that occurred in existing system. This chapter reviews different aspects, which include light innovation, light emitting diode (LED), white light, light properties, light distribution classifications, back-uplight-glare (BUG) rating, and correlated colour temperature (CCT). Outcome of the literature review is crucial to help identifying the best approach to achieve the objectives of this research.

## 2.2 Lighting Innovation

The first commercially viable incandescent bulb, which makes a feature of an electric light with a wire filament heated to a high temperature until it glows, was introduced by Thomas Edison in 1879 (Moran, 2010; Emetere et al., 2021). In order to protect the filament from oxidation, it was encircled by a bulb. Current was supplied to the filament via terminals or wires placed in the glass. A bulb socket offered mechanical support as well as electrical connections (Giridharan, 2010).

Halogen bulbs, which were developed in 1882, were considered a more structured form of incandescent technology since they used halogen gas to improve light life. Halogen lighting has long been preferred for home usage, as well as use in jewellery stores, restaurants, hotels, and other retail and hospitality outlets because of its natural quality and higher efficiency (Sirek and Kane, 2020).

The high-intensity discharge (HID) technologies such as mercury vapour, low and high-pressure sodium, and metal halide emitted light from a tiny discharge tube through an electric arc (Chammam et al., 2017). They are often used in stadiums and other large public venues, as well as highway or street lighting and production or factory settings due to their great light output, durability, and relatively long life. Peter Cooper Hewitt invented the first commercial mercury vapour lamp in 1901 (Baker, 1903).

In 1939, during the New York World's Fair, the fluorescent bulb was first presented to the general public. These lamps, possessing a glass discharge tube, 'fluoresce' emitted light due to a fluorescent coating on the lamp's inside that responded to the presence of mercury gas (Perdahci et al., 2018). For over 50 years, lamps were commonly offered in one-and-a-half-inch-diameter versions operated by magnetic ballasts. In the early 1990s, a smaller, more productive, and longer-lasting fluorescent bulb powered by electronic ballasts appeared on the scene. These lights became a standard in everything from office buildings to high-ceiling industrial uses, schools, and big-box retail outlets due to substantial utility rebates.

Compact fluorescent lamps (CFLs) were later marketed in the 1980s and 1990s, providing the efficiency of fluorescent technology in a compact form. CFLs were popular in general illumination and domestic applications such as downlights, table and floor lamps because they were very efficient yet were available in more consumer-friendly, incandescent-style designs that society was accustomed with (Perdahci et al., 2018).

The light emitting diode (LED) has become the most energy-efficient lighting leading technology for both corporate and commercial use. The LED is an electrical element that extracts light when it is in forward biased conditions. It works on the electroluminescent principle and emits light in the visible spectrum as well as in the infrared and ultraviolet region of the spectrum. LEDs are smaller, consume less energy, and have a longer lifespan.

Nick Holonyak Jr., an employer in General Electric, has developed the first red LED that can emit light in the visible part of the frequency range (Craford, 2013; Holonyak, 2005). In 1972, Holonyak graduate student, M. George Crawford created the first yellow LED and a brighter red LED (Khanna, 2014). Thomas P. Pearsall created high-brightness LEDs for fibre optic application in 1976 (Pearsall, 2017). Shuji Nakamura used gallium nitride to create the first blue LED in 1994 (Nakamura, 2015). Compared to incandescence lamps, LED has faster switching due to the wide palette of applicability. Over the past 150 years, the lighting industry has shown a brilliant evolution in technology, performance, appearance, and purpose, from incandescent and halogen bulbs to fluorescent, high-intensity discharge (HID), compact fluorescent, and now LED.

## 2.3 Street Lighting Innovation

Street lighting is an essential component of road equipment, sidewalks and pathways (Haans and de Kort, 2012; Yoomak and Ngaopitakkul, 2018), which has a sizeable impact on traffic safety and quality of the human environment to provide the sense of security (Murray and Feng, 2016; Ergüzel, 2019; Beccali et al., 2019). The street lighting would allow the road users or pedestrians proceed to safety by increasing apparency of the roadside hazards. The advantages of street lighting installations in terms of road safety, crime prevention, and traffic flow have been exemplified in few studies (Murray and Feng, 2016; Ergüzel, 2019; Beccali et al., 2019; Mansour and Arafa, 2014). In order to ensure a good installation, a road lighting standard is required as a basis for performance metrics such as illuminance or luminance (Fotios and Gibbons, 2018; Hu and Qian, 2013). In addition, the capability of street lighting in improving the day and night time appearance of the environment as well as reduction of glaring effects from other light sources in the visual environment has been reported (Tomczuk, 2013; Kong and Jun, 2020).

The innovation of LED street lighting technology has been built upon years and is growing throughout the world (Haans and de Kort, 2012; Yoomak and Ngaopitakkul, 2018; Dorr et al., 1997; Carli et al., 2018). It is likely to overtake the use of high pressure sodium vapour (HPS) systems due to its higher luminous efficacy, life span in addition to its potential in improving visual quality (Dale et al., 2011; Tähkämö and Halonen, 2015). Even though the LED street lighting technology is more advanced than the HPS system, there remains several disadvantages to the use of LED lights, such as higher cost, unpredictable lifetime, and excess blue and white glare for human eyes (Sędziwy, 2016; Leccese et al.,2017). Hence, it is rather challenging in the LED industry for the enhancement of characteristics and quality of street lighting at considerable cost in the aspects of light efficiency, road surface brightness, illuminance uniformity and glaring effect whilst fulfilling the road lighting standards and requirements (Carli et al., 2017; Marino et al., 2017).

## 2.4 Surface Mounted Device (SMD) LEDs

Lighting quality is critical in affecting the visual performance and comfort of the road users. Specifically, the safety of the road users is dependent on the street lighting performance (Fonseca et al., 2015; Nithya and Hemalatha, 2012; Moreno, 2010). Thus, the optical design of the street lighting becomes very important apart from the mechanical design. The types of LEDs, circuit route, and secondary optic/lens are amongst the few parameters to be taken into consideration in the process of optimising street lighting performance, which can be accessed via average road surface brightness, brightness uniformity, longitudinal brightness uniformity, and threshold increment, commonly known as the glare factor (Murray and Feng, 2016; Ergüzel, 2019; Beccali et al., 2019; Moretti et al., 2016). With the advancement in science and technology, a surface mount device configuration has been developed to replace the traditional LED design. The reason contributing to the emergence of SMD configuration could be associated with the growth of the thin active layer beneath the emitting surface, and the current is applied with a ring electrode. This SMD configuration is better, owing to the ability to reduce heat generation and potentially improve performance of the SMD module as compared to the traditional LED design (Bullough and Skinner, 2019; Khanna, 2014). On top of that, other advantages of SMD LED include low operating conditions, high brightness, and capability to produce saturated colours with high luminous efficiency (Bęczkowski and Munk-Nielsen, 2010). Currently in the lighting industry, there are only two shapes of LES which was round-shaped and square-shaped.

## 2.5 Lens

The matching of secondary lens with the LEDs is a topic of interest, which would assist in the improvement of light distribution pattern suitably for street lighting application. It was reported that the typical light output efficiency of lenses is more than 92% and the acquisition of higher percentage of the efficiency is an indication of having more lights being emitted from the lens surface, rather than being trapped inside the lens. Although lens that could avoid glaring effect, light pollution and provide high uniformity are good optics with perfect light guidance (Lin et al., 2014), it is subjective to determine the quality of light if the road lighting standards are not used as the references. Moreover, the shape of lens is also a subject that would influence the light distribution pattern. W. Prommee and N. Phuangpitak presented four distinct sorts of shapes, including "O" shapes, "I" shapes, oval shapes, and "U" shapes, that produced diverse light patterns on white sheets representing the street (Prommee and Phuangpitak, 2016). It was described that the “O” shaped lens would cast a circle of light on one section of the road while the "I" shape and oval shape lenses provided light across the street area, with the oval lens providing smoother light than the "I" shape lens. On the other hand, the "U" shape lens would provide smooth rectangular light without over lighting. Other study revealed that butterfly lenses when being used on double-cluster LEDs could produce a nice light pattern and have an optical utilisation factor of approximately 43.8%. The light patterns of the butterfly lens, however, were restricted to a road width of 10 m and a spacing length of 30 m (Lo et al., 2012). A cluster of LEDs with total internal reflection (TIR) lenses was covered with a micro lens sheet in ref (Lee et al., 2013), which would regulate light direction solely into the street. However, the luminaire spacing was too close (21.5 m) for 114 watt LED. On top of the above, double freeform surfaces (DFS) lenses were fabricated based on Snell's law (Wu et al., 2015) and the Monte Carlo technique was employed to improve the lens design. The DFS lenses were shown to give better illuminance uniformity than the traditional lens. However, the DFS lenses haven’t been tested on road sides.

Keeping in view with the above-mentioned work, different shapes of lens would affect the lighting performance for street lighting. Furthermore, it is worth mentioning that not all of the light fixtures are created equal. Despite the fact that research efforts have been done on selecting the ideal colour temperature and lumen output for the luminaire, incorrect light distribution type would degrade the lighting performance as the pattern of light emitted by the fixture would rely on the light distribution off the lens. Depending on the application of the street lighting, some types of distribution would be better suited from one to another.

## 2.6 LED Structure and Working Principle

LEDs allow current to flow in only one direction. A p-type semiconductor, an n-type semiconductor, and a depletion layer are the three layers that make up an LED. Both p-type and n-type semiconductors are bordered by the depletion layer, also known as the depletion region (Zhang et al., 2019). The LED structure were shown in Figure 2.1 below.

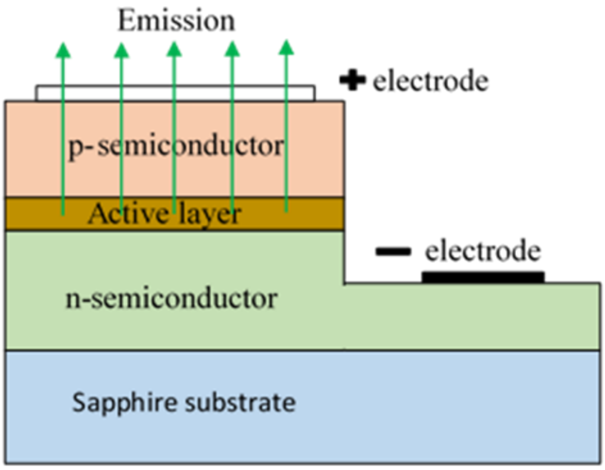



Figure 2.1 LED Structure

In a PN junction, the P side contains excess positive charges, which are also known as holes with the minority of electrons while the N side contains excess negative charges, which are the electrons with the minority of holes. When a forward voltage is applied, the electrons move from the N side towards the P side and holes move towards the N side. Hence, there will be a recombination due to the flow of these charge carriers near the junction. Figure 2.2 below shows the recombination of the diode.

The recombination is the main mechanism that describes carrier activity within an LED. When the electrons jump from one band to another band, the electrons will emit the electromagnetic energy in the form of photons and the photon energy is equal to the forbidden energy gap. As a result, the energy is released in the form of light that is emitted by the LED (Sharma et al., 2015).

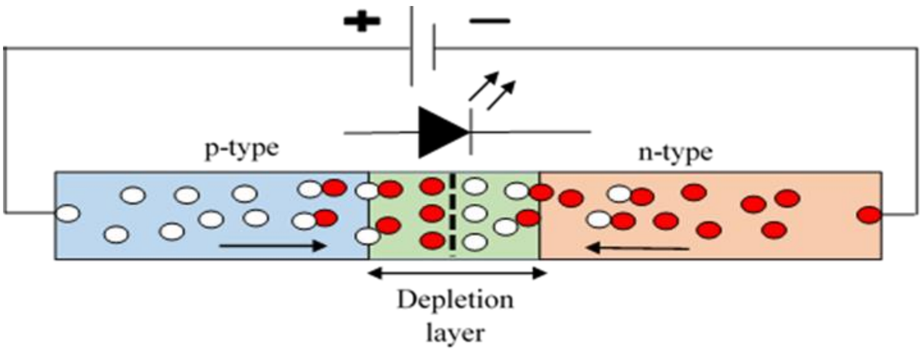
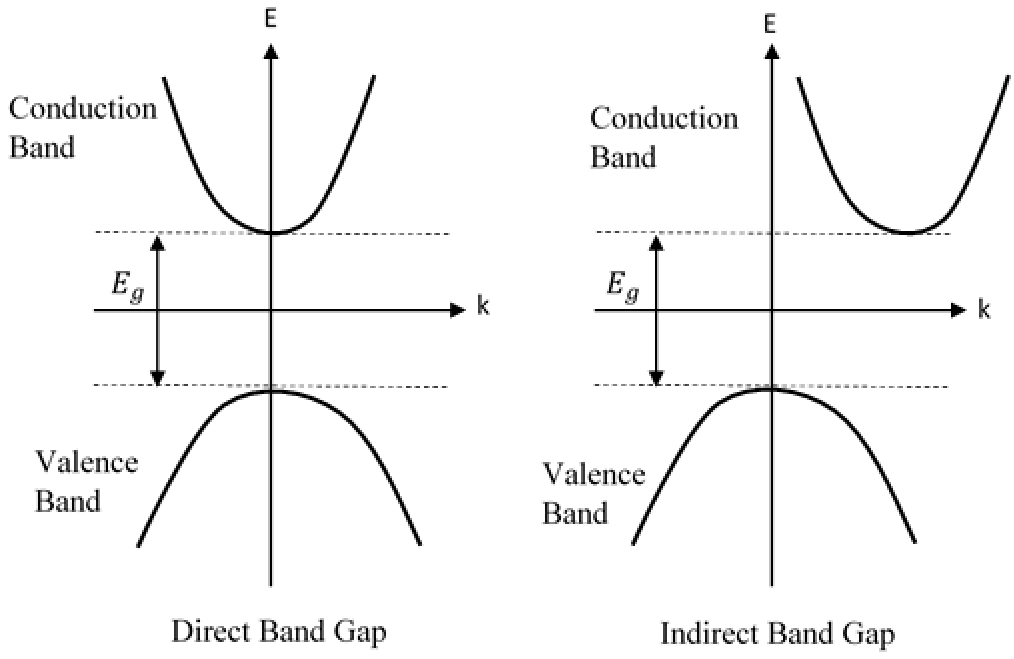



Figure 2.2 PN junction semiconductor diode

## 2.7 Direct and Indirect Band Gap in Semiconductor

A semiconductor's band gap is classified as either direct or indirect in optoelectronics. The minimal-energy state in the conduction band and the maximal-energy state in the valence band are each characterized by a certain crystal momentum (k-vector) in the Brillouin zone (Morrison, 2021). If the momentum of both electrons and holes is the same in both the conduction band and the valence band, the band gap is known as direct band gap. In direct band gap, electron can directly release a photon. The top of the valence band and the bottom of the conduction band occur at the same value of momentum, as shown in the Figure 2.3 below. Meanwhile for indirect band gap, a photon cannot be released out because of the electron must pass through an intermediate state and transfer momentum to the crystal lattice. The valence band's highest energy occurs at a different momentum value than the conduction band's minimum energy (Endres et al., 2016).




(a) (b)

Figure 2.3 (a) Direct Band Gap (b) Indirect Band Gap

As a result, the band gap denotes the smallest energy difference between the top of the valence band and the bottom of the conduction band. Nevertheless, the top of the valence band and the bottom of the conduction band are not always at the same electron momentum value.

## 2.8 Energy Gaps in LEDs

A LED's band gap energy can be determined by measuring the voltage across an LED at the point where the LED barely begins to turn on. This voltage can be converted into unit of eV by multiplying with the charge of an electron. For instance, if the voltage is measured to be 1.8 V, the band gap energy would be 1.8 eV. Since LEDs utilize band-to-band recombination, an electron will drop at the full length of the band gap. In other words, the voltage across the LED corresponds to the band gap energy value. Energy of the emitted photon is defined in Eq (2.1).

$$E = hf = \frac{hc}{\lambda} \tag{2.1}$$

where h is the Planck's constant 4.13 x $10^{-15}$ eVs (in units of eVs), c is the speed of light in vacuum, 2.998 x $10^8$ m/s , f is frequency, and λ is the wavelength of the photon.

The Table 2.1 illustrates the visible light spectrum wavelengths that correlate to different LED colours, as well as the potential semiconductors employed.

Table 2.1 Visible light spectrum wavelengths.

| | LED Colour | Wavelength Range (nm) | Semiconductors Used |
|---|---|---|---|
| | Red | 625-760 | AlGaAs |
| | Orange | 600-625 | GaAsP |
| | Yellow | 577-600 | AlGaInP |
| | Green | 492-577 | GaN |
| | Blue | 455-492 | ZnSe |
| | Violet | 390-455 | InGaN |

## 2.9 LEDs Efficiency

Internal Quantum Efficiency (IQE) of a current-injected semiconductor device is defined as the ratio of the number of electron-hole (e-h) pairs or charge carriers generated to the number of photons absorbed, within the active layers of the LEDs. The internal efficiency is a function of the quality of the material and the structure and composition of the layer, defined in Eq. (2.2).

$$\eta_{int} = \frac{P_{int}/hv}{I/e} \tag{2.2}$$

where $P_{int}$ is the optical power emitted from the active region and I is the injection current.

The light extraction efficiency is defined as the number of photons emitted into free space per second, defined in Eq. (2.3), where P is optical power released into the free space.

$$\eta_{extraction} = \frac{P/hv}{P_{int}/hv} \quad (2.3)$$

External Quantum Efficiency (EQE) is the multiplication of internal efficiency and light extraction efficiency (Eq. (2.4)). It can be also defined as how efficiently the device converts electrons to photons and allows them to escape.

$$\eta_{ext} = \frac{P/hv}{I/e} = \eta_{int}\eta_{extraction} \quad (2.4)$$

The power efficiency (Eq. (2.5)) is defined as

$$\eta_{power} = P/IV \quad (2.5)$$

where IV is the electrical power provided to the LED.

## 2.10 Reflection

Light travels in straight lines (Xu et al., 2019; Padgett, 2014; Gjurchinovski, 2004). When light reflects off a surface, the light rays will change direction from one medium to another. The law of reflection states that the angle of the reflected ray is equal to the angle of the incident ray on reflection from a smooth surface (Ortega and Moura, 2020).

The reflected ray always falls in the plane specified by the incident light and the surface normal (Figure 2.4). The law of reflection can be used to understand the images produced by plane and curved mirrors.

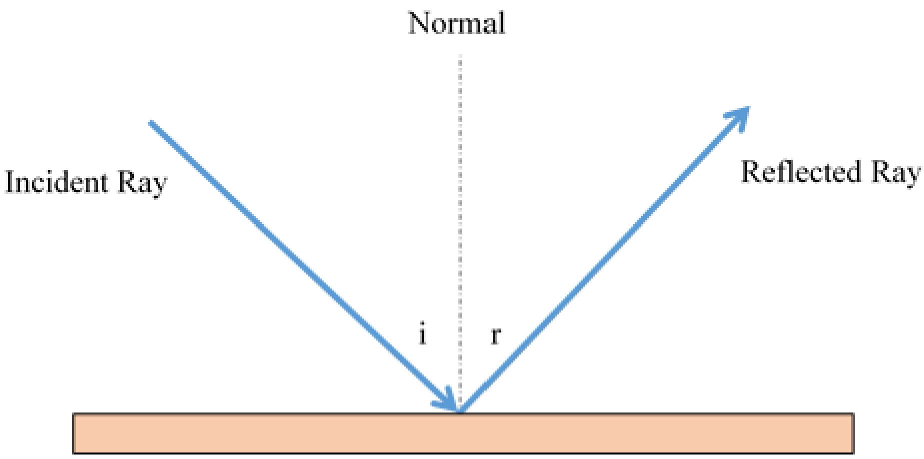



Figure 2.4 Reflection of light

## 2.11 Snell's Law (Refraction)

Refraction of light occurs when the light is travelling from a medium to a different medium such as from air to glass surface as shown in Figure 2.5. When the light encounters different medium, a portion of the light is reflected and a portion is transmitted into the second medium. When the transmitted light moves into the second medium, it is refracted as it changes the direction of travel (Ortega and Moura, 2020). Snell's Law states that the product of sine of angle made by the ray in a medium and the refractive index of that medium is constant. In mathematical terms, the Eq (2.6) is derived as

$$n_i \sin \theta_i = n_r \sin \theta_r, \tag{2.6}$$

where $n_i$ and $n_r$ is the index of refraction of the first and second media respectively.

The index of refraction for any medium is a dimensionless constant equal to the ratio of the speed of light in a vacuum to its speed in that medium.

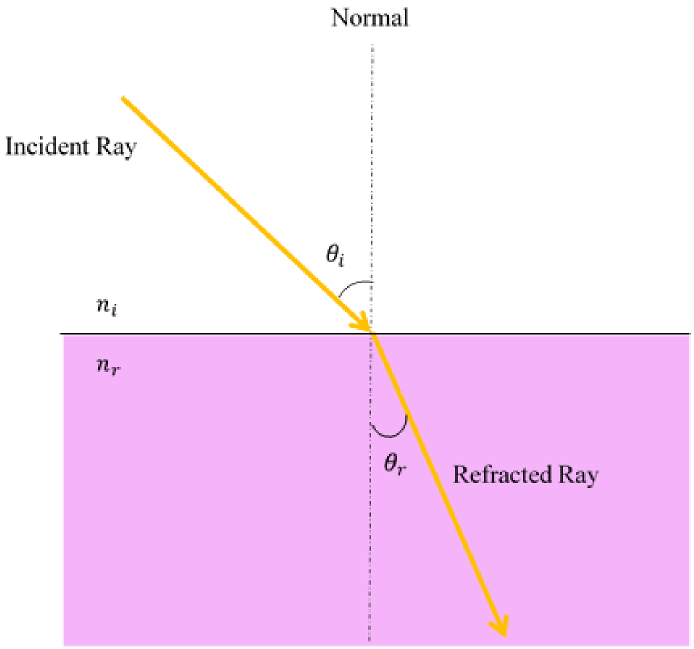



Figure 2.5 Refraction of light

## 2.12 Light Distribution Classifications

A light distribution may be divided into two types: longitudinal light distributions and transverse light distributions. Longitudinal light distributions, also known as lateral light distributions, are classified as short (S), medium (M), and long (L). When the greatest intensity point of a luminaire falls between 1.0 and less than 2.25 mounting heights longitudinally from the luminaire position, the luminaire is said to have a short distribution. The maximum intensity point for a medium light distribution is between 2.25 and less than 3.75 mounting heights from the luminaire position, whereas the maximum intensity point for a long distribution is between 3.75 and less than 6.0 mounting heights from the luminaire position. Figure 2.6 below demonstrate the longitudinal light distributions and transverse light distributions on a road.

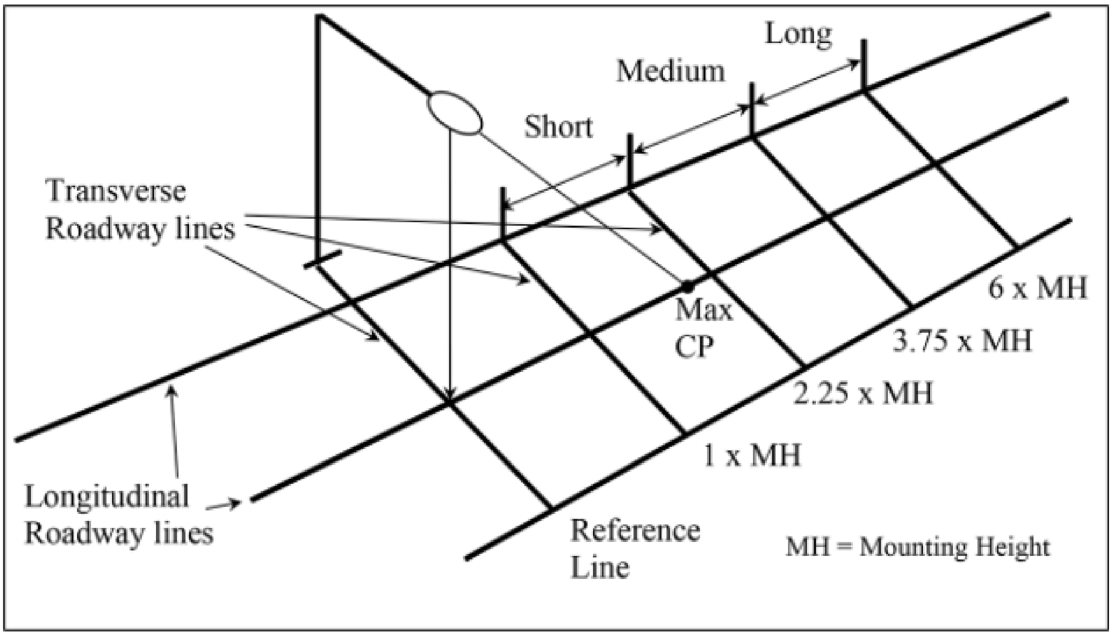



Figure 2.6 Light distribution of streetlight.

Transverse light distributions are classified as Type I, Type II, Type III, Type IV, Type V, and Type VS. When the half-maximum-candlepower isocandela trace falls between 1.0 mounting heights on the house side and 1.0 mounting heights on the street side of the luminaire location, the transverse light distribution is classified as Type I. Type II is defined as the half-maximum-candlepower isocandela trace falling between 1.0 and 1.75 mounting heights on the street side of the luminaire location. Meanwhile, a transverse light distribution is classed as Type III when the half-maximum-candlepower isocandela trace on the street side of the luminaire location falls between 1.75 and 2.75 mounting heights. For Type IV classification is when the half-maximum-candlepower isocandela trace falls beyond 2.75 mounting heights on the street side of the luminaire position. When the light pattern has a circular symmetry of candlepower distribution is classified as Type V while the light pattern has a square shape distribution is classified as Type VS (“LED Distribution Types | EYE Lighting” n.d.).

## 2.13 Backlight-Uplight-Glare (BUG) Lighting Classifications

The BUG lighting classifications system is a valuable tool for measuring the performance of night time luminaires. The Illuminating Engineering Society (IES) and the International Dark Sky Association created the system to evaluate any outdoor light fixture. It was included to the Luminaire Classification System (LCS) for the first time in 2009 to replace the previous system which was mostly focused on street lights (Yoo et al., 2018).

The abbreviation "BUG" stands for Backlight, Uplight, and Glare in the context of these ratings. All three of these are types of stray light that can be emitted by a fixture. Although each has a good usefulness in various circumstances, they are often viewed as "bad" light since they are frequently inaccessible. However, each performs substantially worse for specific activities than others, and the BUG rating assists in quantifying this.

Figure 2.7 below shows the light pollution diagram. The light emitted from behind a fixture is referred to as backlight. This light generally protrudes outside or towards the ground, lighting a region that is not meant to be lit. Backlighting is useful when it comes to boosting the visibility of wristwatches or seeing your smartphone. Manufacturers can redirect light using optics, reflectors, or glare shields to direct more light towards the front.

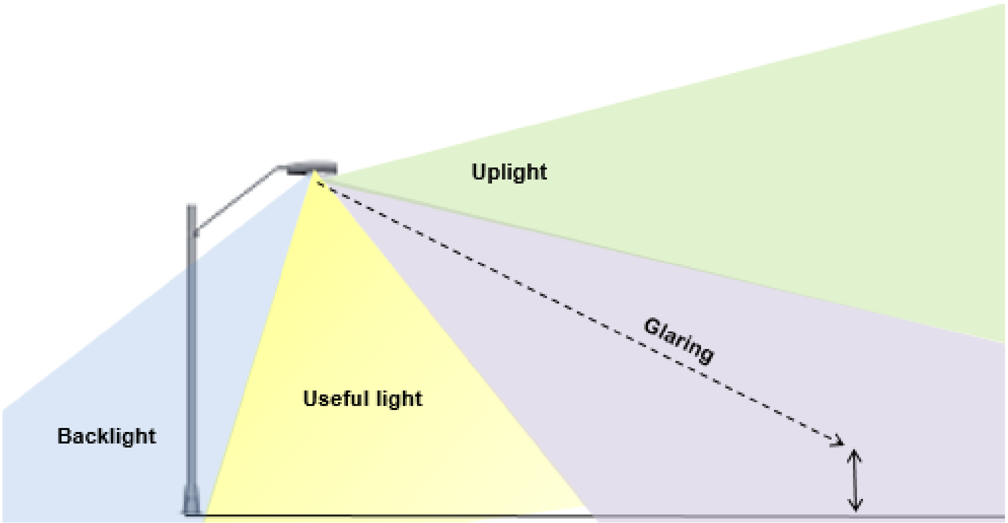



Figure 2.7 The light pollution diagram

The light that radiates upwards from a fixture towards the sky is referred to as uplight, thus the alternative phrase "sky glow." This stray light contributes to the light pollution. Any uplight in outdoor lighting is wasted light since it is not directed toward where people are. Sky glow may be reduced by entirely concealing the fixture and orienting it towards the ground. This will help minimise the energy use and costs. The International Dark-Sky Association (IDA) is especially concerned with minimising the uplight so that more people may enjoy the night sky.

Glare, also known as forward light, is also referred to as "offensive light" since it causes discomfort for the majority of individuals. This reflected or directed light makes it difficult for individuals to see, especially when it beams directly into their eyes. It is extremely risky while driving a car at night. Glare can be decreased by applying less bright lights or by selecting a light with an acceptable distribution pattern for intended usage (Villa et al., 2015).

Figure 2.8 shows the backlight, uplight, and glare zones of a light fixture. These zones are comprised of three main categories which was Forward Light (Forward Very High, Forward High, Forward Medium and Forward Low), Backlight (Backlight Very

High, Backlight High, Backlight Medium and Backlight Low) and Up Light (Uplight High and Uplight Low). The subcategories are used to provide more thorough analysis of light distribution.

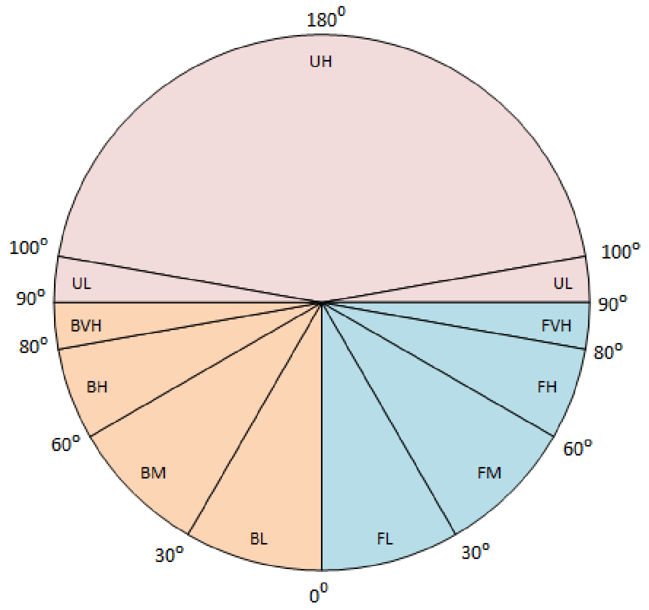



Figure 2.8 A diagram depicting backlight, uplight, and glare zones of a light fixture.

## 2.14 Colour Mixing

The main benefit of LED light sources over the traditional incandescent lamps and fluorescent light tubes is their adjustable spectral design, which allows them to produce white light using various colour mixing schemes. The spectrum design flexibility of white LED light sources will encourage them to be used in innovative applications to enhance the human life quality (Ou et al., 2012). There are two techniques to produce mixed light using LEDs. The first is to use blue LEDs in conjunction with a down conversion phosphor. The second step is to mix red light, blue light and green light in the proper proportions known as RGB method (Steigerwald et al., 2002). RGB LEDs can provide more colour selection in correlated colour temperature (CCT) and colour rendering in lighting applications (Ohno, 2005). As a result, colour mixing using the RGB LEDs is a critical challenge in both display and lighting applications. The RGB LEDs technique enables simple dynamic control of colour spots while also providing outstanding colour rendition and chromaticity stability.

The RGB LEDs have high colour rendering and lighting efficiency to display accurate colour for plate display (Oh et al., 2011; Kari et al., 2011; Chen et al., 2010; Liu et al., 2013). Due to these, LED light sources have narrow band type spectral power distributions that differ from those of traditional light sources. Hashimoto et al. presented the LED light source, specifically consisting of the RGB chips, having significant potential with high sense of contrast (Hashimoto et al., 2007). Furthermore, RGB LEDs have been proven to have sufficiently narrow emission bands for combining them into trichromatic illumination clusters with high saturation of surface colours (Žukauskas et al., 2010). Lee examined the effect of RGB LEDs alignment on colour uniformity and suggested the use of RG-B-RG alignment to increase the colour uniformity of the backlight modules of monitor (Lee et al., 2013). Hsieh et al. demonstrated the light superposition effect analysis in order to accomplish light mixing by combining numerous LED modules (Hsieh, et al., 2013). These modules may be used to create a creative light pattern. These designs performed well in terms of colour mixing and are particularly insensitive to source non-uniformities.

The light mixing using surface mounted device LEDs is to replace the chips in a single package and change the light flux or output power of the chips by restructuring the LED chips or regulating the voltage input to the chips, thereby controlling the proportion of incident lights and achieving the purpose of light mixing. This would enable the development of a light mixing effect with numerous colours based on the colour of the light source (Dong, 2011; Bonenberger et al., 2013; Chen et al., 2014; Wang and Sun, 2009). The RGB LEDs offer several lighting options. However, most

RGB LED colour mixing is done by sealing all three chips in a single package and regulating the mix ratio of these three colours to generate the colour of light. RGB chips may also provide overlapping colours of light and shifting of colours by adjusting the LED array alignment (Dong, 2011; Bonenberger et al., 2013; Chen et al., 2014; Wang and Sun, 2009). As a result, the goal of this research is to offer a novel white light approach by mixing different colours of SMD LEDs instead of using sealed three chips in a single package.

## 2.15 Correlated Colour Temperature (CCT)

A light source's correlated colour temperature (CCT) is defined as the temperature of an ideal black-body radiator that emits light of the same hue as the light source under examination. Light in the range of 2,500 to 10,000K is typically known as “white”, having warm yellowish and cold blue colours at the low and high ends of the CCT spectrum, respectively. Warm colours appear tinged with yellow and generally feel soft and cosy. Warm white ranges from 2800K to 3500K. Cool white are tinted with blue and seem whiter, providing them a more 'honest' and uncompromising light that is more suited to working surroundings than relaxed ones. The Kelvin Temperature scale is used to measure light (Rahm and Johan, 2021).

Due to the technological limits of incandescent, fluorescent, and discharge lamp technology, the available colour temperatures were confined to a finite number of options until the advent of solid-state illumination. A. A. Kruithof, a researcher at Philips Labs, presented the idea that people prefer light of varied CCT under particular illuminance circumstances in 1941 (Davis and Ginthner, 1990; Veitch et al., 2019).

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

There were 4 parameters being studied in this research. Initially, an optimization of lens was carried out by comparing the lens that had the same longitudinal classification (Short “S”) with different lateral light distributions, which were Type I and Type II. Variant shapes of the optimized lens will be then used to study their effect towards the light distributions, followed by studying the different longitudinal classification of the optimized lens. All of the lenses in the first parameter were studied onto the 5050 Warm White SMD LED with Round-Shaped LES for optimisation. Hence, the optimised sample from the first parameter will be utilized in the next experimental designs.

Followed by the second parameter, which was to vary CCT of the samples in order to study the effects of CCT towards the light distributions. In this section, two different colours of light which was Neutral White and Cool White will be used to compare with the Warm White.

Subsequently, the third parameter was to figure out the shape of the LES and the size of the SMD LED. The current market is using SMD LED with a round-shaped and square-shaped LES. In this section, a different shape of LES and a different size of the SMD LED was prepared to compare with the 5050 Warm White Round-Shaped LES. The last parameter was to explore and fact-finding the colour mixing of light.