Visible Light Communications

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ABSTRACT

Nowadays, a lot of researchers are working on the development of light-emitting diode (LED) lighting system. The LED lighting system can achieve lower power consumption and has a longer life-time compared to the fluorescent lamp system.

In this project, the characteristic of short transient time in turning the light on/off processes was further investigated. A high-speed wireless communication system, which is embedded in our LED lighting system, was built. The duplex communication system consists of both downlink and uplink media through different frequencies of lights.

Several experiments were conducted in the visible light communication system. In this communication system, off-the-self components were taken part in building the driver circuit and the performance of the system was evaluated, such as, data transmission rate, data transmission distance and the field of view of the transmitter.

Our prototype achieves a transmission data rate of 100 kHz in a direction of 160^{o} field of view with a radius of 1.7 meters. In this paper, transmission of MP3 music was demonstrated by using warm-white LED transmitter. Not limit to this, multiple source signals simultaneously in different frequency bands were transmitted through the RGB LED circuitry, and the signals were recovered successfully. This demonstrates the feasibility studies of our design in signals broadcasting.

Keywords: Wireless Communication by Visible Light

1. INTRODUCTION

Thanks to the rocketed speed of the wireless broadband connection technology, connection to internet through hand held device became possible in the past decades. Among all common wireless LAN technologies currently available, the Wireless Fidelity (Wi-Fi) technology is a faster and less expensive solution thus it is broadly employed in various mobile devices.

Among all wireless communication schemes, transmission using radio waves (RF) or microwaves has dominated. This domination was primarily due to by their availability of high-sensitivity receivers and the ability to provide either broad coverage at low frequencies or line-of-sight propagation at high frequencies. [1] However, RF can support only limited bandwidth because of restricted spectrum availability and interference. [2] As such, visible light in the electromagnetic (EM) wave spectrum was considered to be a potential solution to combat the plight faced by RF.

Visible light communications (VLC) can provide cable free communication at very high bit rates as high as 100Mbps. In addition, it has a major advantage that it causes no interference to RF-based devices. This made wireless communication possible in RF hazardous areas such as hospital and space station. In addition to these two key advantages, safety, simple installation procedures and band licensing-free characteristic also helped increase VLC's potential to be developed as an alternative, or even a new standard to the wireless communication scheme.
This project aimed to investigate the various features as well as the possible configurations of optical wireless communication using visible light LEDs. In which general features and the best configurations of the setup will be investigated. As such multiple color emissions and different configurations of LEDs may be employed.

1.1 Related researches

Researches related to his project are generally divided into 2 categories. The first type is the researches on the visible light communications (VLC) technologies, while the second type is the studies of possible configurations of indoor optical wireless communication set up using white LEDs.

1.1.1 Researches on the visible light communications (VLC) technologies
This type of researches underpinned the project by providing broad fundamental knowledge and current achievements in VLC.

1.1.1.1 Visible Light Communications: recent progress and challenges [3]
Dominic O'Brien, Hoa Le Minha, Lubin Zeng,Grahame Faulkner and Hsi Hsir Chou, Kyungwoo Lee, Daekwang Jung, YunJe Oh, Eun Tae Won

This abstracted white paper from the wireless world research forum (WWRF) stated the key challenges of VC: (1) Improving data rate, (2) Providing an uplink and (3) Compatibility with illumination

(1)Improving data rate
As a common photodiode receiver has sufficient collection area and high enough sensitivity for VLC to fabricate for bandwidths approaching 100MHz, the receiver's performance does not limit VLC channel performance in general. Therefore, the performance of receiver and propagation needs not to be considered unless the bandwidth required is greater than 100MHz. In conclusion, LED limited the VLC channel performance for near and medium term applications. Therefore, mitigating the poor performance of the LED is the most important step in increasing the data-rate.

(2) *Providing an uplink*
Among several possible approaches, adopting a different wavelength uplink is reasonable and relatively easy to implement despite although this may require a transmitter that can track the receiver position within the room.

(3)Compatibility with illumination
The most challenging problem for VLC is compatibility with the commonly used Pulse Width Modulation (PWM) dimming systems, as the channel is not present, during the 'off' periods of the PWM waveform. Approaches that combine modulation with dimming have been proposed [4], but further work is required in this area.

1.1.2 Studies of possible configurations of indoor optical wireless communication set up using white LEDs.
Two important related studies [5][6] that focused on the application of visible light LEDs were found in this category. Both of them employed white LEDs for indoor communication. These studies suggested the possible configuration of the set up of an indoor optical wireless communication using LEDs.

1.1.2.1Fundamental Analysis for Visible-Light Communication System using LED Lights [6]
(IEEE Transactions on Consumer Electronics, Vol. 50, No. 1, FEBRUARY 2004)

(i) Paper Summary
In this paper, Toshihiko Komine and his student member had a fundamental analysis on VLC system using LED lights. In which requirements for optical lighting and optical transmission were discussed and an example of design was set up.

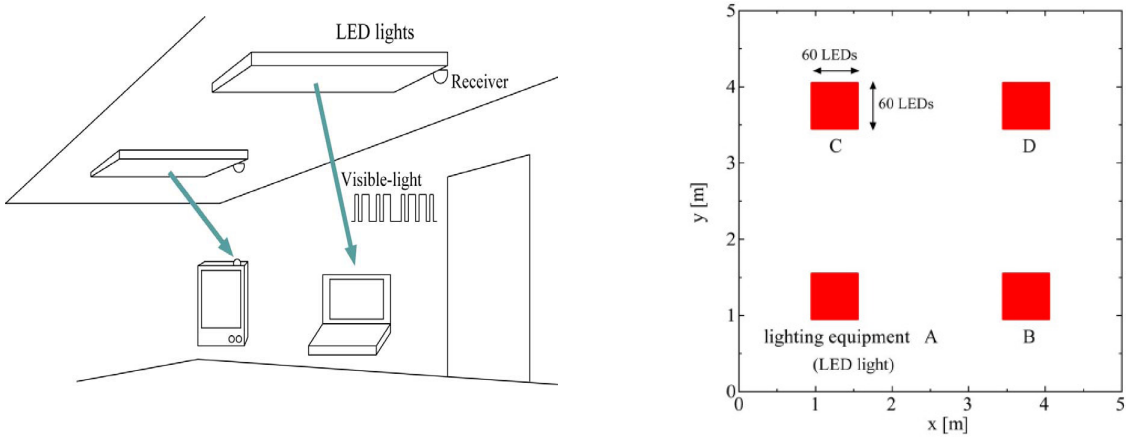


Fig. 1 Optical Wireless Communication Design Setup of [6]

Specification of the Design Setup	
Room Size	5.0 m × 5.0 m × 3.0 m
Distance between LED lights and floor	2.5m
Height of user terminal	0.85 m
No. of LED lamp	4
No. of LED lights in each LED lamp	60 × 60 = 3600
Space between LEDs	1 cm
Semi-angle at half-power of an LED chip	70°
Center luminous intensity of an LED chip	0.73 cd
Transmitted optical power of an LED chip	20.0 mW

Table. 1. Specification of the Design Setup of [6]

FOV		Transmission Rate
With tracking	<30°	300Mbps
	5°	10Gbps
Without tracking	40°-50°	200Mbps
	<40°	**Exist blind area**
Summary of Result		
FOV at a receiver		60°
Detector physical area of photodiode		1.0 cm^2
Gain of an optical filter		1.0
Refractive index of a lens at a photodiode		1.5
O/E Conversion Efficiency		0.53 A/W

Table. 2. Summary of Result

1.1.2.2 Broadband Access over Medium and Low Voltage Power-lines and use of White Light Emitting Diodes for Indoor Communications [5]

(IEEE Communications Society subject matter experts for publication in the IEEE CCNC 2006 proceedings.)

(i) Paper Summary

In this paper, P. Amirshahi and M. Kavehrad not only discussed the potential capacities of emerging powerline communications and white LED indoor communications for broadband access, but also the fundamental analysis of VLC systems using white LEDs. In which they designed a white LED system for lighting and high data rate indoor communications in a model room such that there is no blind spot in the room for data communications.

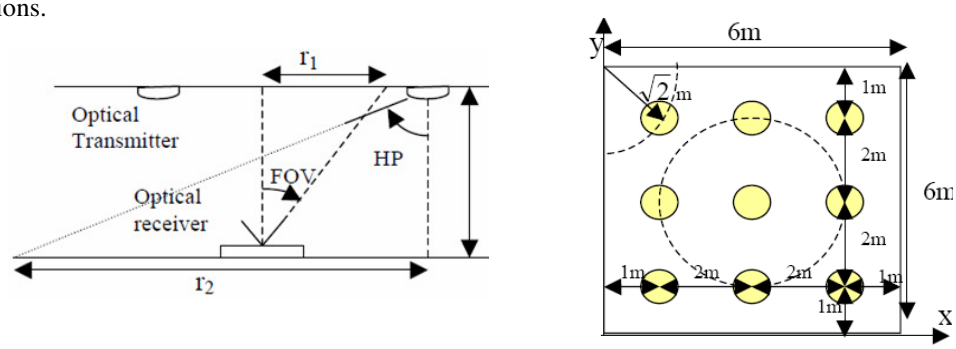


Fig. 2. Optical Wireless Communication Design Setup

Specification of the Design Setup	
No. of LED lamp	9
No. of LED lights in each LED lamp	several
Space between LEDs	2 m
Semi-angle at half-power of an LED chip	70°

Table.3. Specification of the Design Setup of [5]

There are several important findings were in this paper:

1. If the receiver's coverage area radius is greater than √2 meters, receivers at the corners will at least receive one LOS signal from the closest transmitter.
2. The design for the receiver needs a field of view (FOV) equal or greater than 25 degrees.
3. Reflected signals have so much less power at the receiver compared to LOS path signals is confirmed by the equation

$$h(t)=\begin{cases} \dfrac{2\tau_0^2}{t^3 \sin(FOV)} & \tau_0 < t < \dfrac{\tau_0}{\cos(FOV)} \\ 0 & \text{elsewhere} \end{cases} \quad (1)$$

In comparison to the study [6] which is using a simpler set-up, a conclusion can be drawn:

1. With an absence of blind spot in the room, this set up outshone the model shown in a previous research in 2004 by Toshihiko Komine
2. The study found that a wider FOV could certainly provide a larger receiver area yet more complex.
3. A narrower FOV resulted in a smaller delay spread, caused by reflections of the optical signals on the walls**,** in the channel.
4. To attain a higher data rate, impedance matching in the network is necessary.

2. MAIN BODY

2.1 Aim and objectives

2.1.1 Aim

The aim of this project is to build an optical wireless communication (OWC) model featured with high data transmission rate (several MHz), long transmission distance (>1m) and large field of view (FOV). The model will demonstrate how the notion of 2-way communication via visible light works, in which off-the-shelf light-emitting diodes (LEDs) are employed as the light sources. The model will transmit digital signal via direct modulation of the light emission intensity and will be detected by an optical receiver.

In addition to the demonstration purpose, the model enabled investigation into the features of the visible light and IR LED incorporated in the communication model.

2.1.2 Objectives

We believe that the mission of engineering is to provide solutions to both foreseeable and existing problems. In the 21st century, global warming and various environmental crises puzzled the world. Undoubtedly energy saving was a solution to combat the problem of energy shortage on the earth. In recent years people started to pin their faith to eco-friendly products like hybrid cars, [7] biodegradable plastic bags, products made from recycled papers, etc. We believe that the mature visible light or optical wireless communication system will be one of the energy-saving solutions in the future.

Optical wireless communication (OWC) could have a broad range of applications, such as incorporating wireless communication into advertisement boards or traffic controls. [8] As such, energy that consumed to drive the visible light LEDs would drive the wireless signal transmission as well. In that way, wireless communication would not consume extra amount of electricity, thus helping saving energy.

Together with a theoretically higher bandwidth, [9] OWC helped boost the performance of current wireless communication schemes in both transmission speed and energy consumption. Therefore, we undertook this research to build an OWC model incorporating wireless communication and energy-saving lighting and investigate its various features.

2.2 System Block Diagram

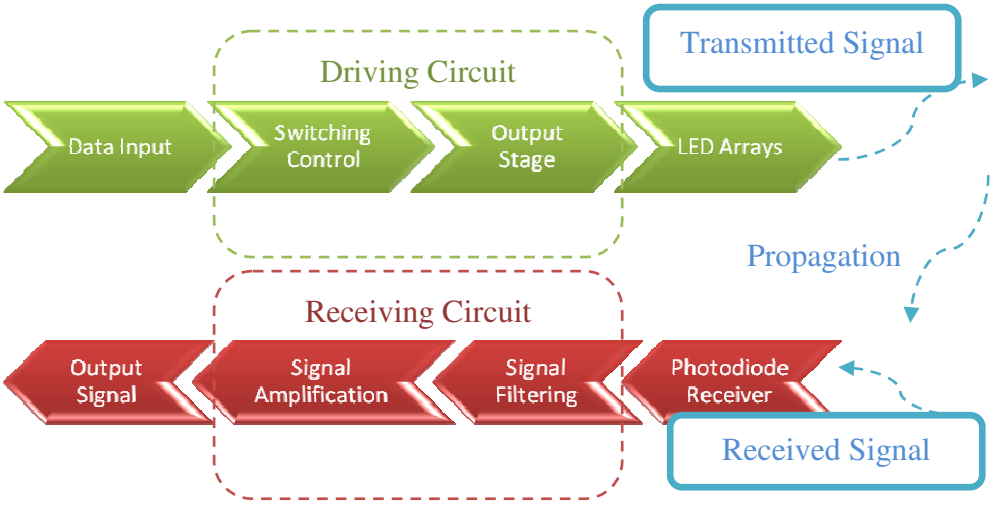


Fig. 3. System Block Diagram of the Wireless Communication System

2.3 Decision about Hardware

Light-emitting Diodes (LED) and Infrared (IR) were used in the "Downlink" and "Uplink" transmitter while a Thorlabs' DET210 silicon detector, which is a visible light photodiode detecting the wavelength ranging from 400nm to 1000nm, and a Newport 818-IR germanium cylindrical detector, which is an IR photodiode detecting the wavelength ranging from 780nm – 1800nm, were used in the downlink and uplink receiver respectively.

There were several reasons on why LED was chosen as the light source instead of using the fluorescent lamp or light bulb. The first reason is that LED has a property of low power consumption (about one tenth of the conventional). A normal incandescent light bulb has a working lifetime of 750 to 1000 hours on average, which is why you have to replace light bulbs quite frequently [1]. However, the typical LED lifetime is several ten thousand hours. Take Luxeon K2 LED as an example, the typical life time of this LED family is 60,000 hours which is longer than that of the incandescent light bulb by 60 times. Thus, the long lifetime of LED was also the reason for choosing it as the light source. What is more, LEDs are fast-switching and the visibility is excellent (many advertising display are using LEDs). It is also predicted that in the very near future, the white LED lamps will replace the conventional incandescent and fluorescent lamps due to their cleaner low power energy, which is ecological to our daily life. It is, therefore, considered as the lighting in the next generation [2].

Infrared (IR) was chosen to be the "Uplink" transmitter. It is because it is not formal to have visible light transmitter on the mobile devices. Let's take computer as an example. Suppose there is a computer under an LED lamp which the wireless communication technology is embedded into it. If visible light transmitter is used in this case, there will be a light source on/next to the computer. It is obvious that the user will not feel comfortable with such configuration. Under these circumstances, LED and IR were used in the downlink and uplink transmitter respectively.

2.4 Driving Circuit Schematic

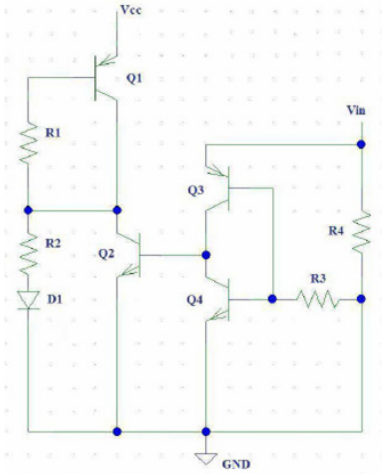


Fig.4. LED Driver Circuit Schematic

2.5 LED Driver Circuit Performance Evaluationc

In order to estimate the performance of the LED Driver Circuit, the circuit is simulated by the use of the software Star-Hspice and the bode-plot was shown below

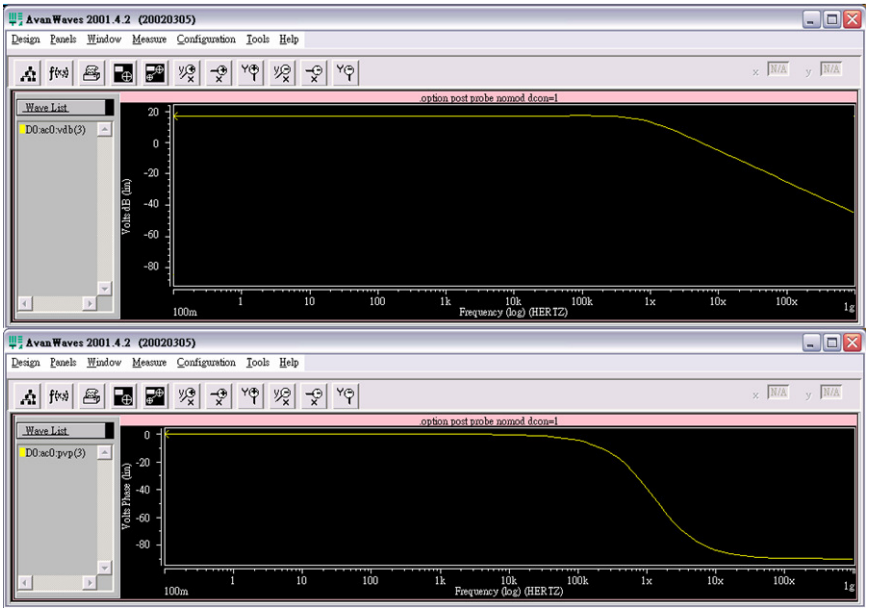


Fig. 5. Bode-plot of the Circuit Schematic in Fig. 4

From the simulation graphs in the previous page, it could be seen that there was a pole at the frequency around 1MHz and the 3-dB bandwidth of this circuit was about 1 MHz. In the experiment, in order to have a long distance data transmission, high brightness LED (LUXEON Rebel Warm-white LED) was chosen as the transmitter. The experimental set-up and the waveform analysis were shown below:

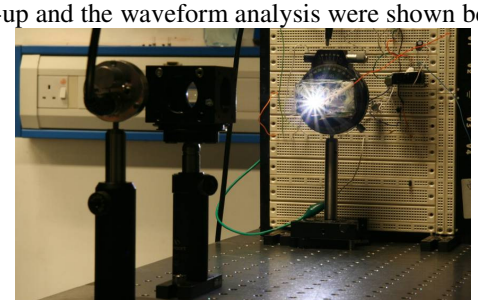


Fig. 6 Experimental set-up in the laboratory

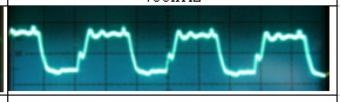
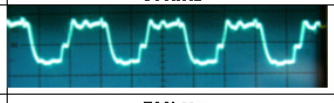
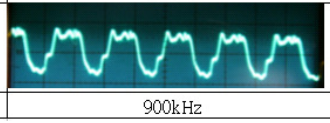
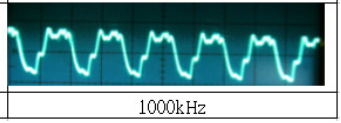
Waveform		
Frequency	100kHz	200kHz
Waveform		
Frequency	300kHz	400kHz
Waveform		
Frequency	500kHz	600kHz
Waveform		
Frequency	700kHz	800kHz
Waveform		
Frequency	900kHz	1000kHz

Fig. 7 Waveforms Captured acorss the HBLED.

From the waveforms showed in Fig. in the previous page, when the input signal frequency was 1MHz square wave, despite the waveform was distorted, the shape could still remain as a square wave. In fact, the results from the waveform analysis were similar to results obtained from the experiment and the Unity Gain Frequency of the circuit was about 5 MHz. Thus, this designed driver circuit could drive the LED at the frequency 1MHz.

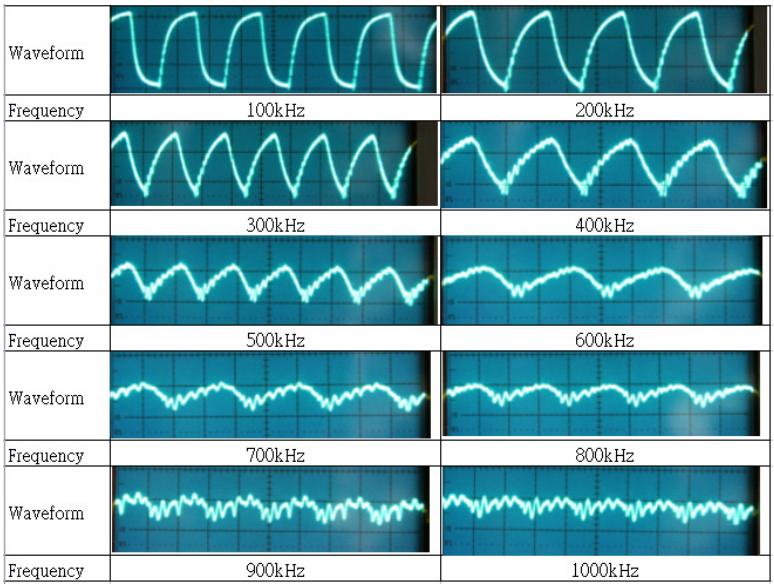


Fig. 8 Waveforms Captured by the Thorlabs' DET210 silicon detector

From the waveform results shown above, it could be seen that the waveform suffer from distortions when the input signal frequency was increasing. Compare with the previous results (the waveform measured across the HBLED), it was observed that the light signal given out by the HBLED did not match with the electrical signal across it. Due to the fact that the photodiode (Thorlabs' DET210 silicon detector) has the response time of 1 ns, it can sense the signal speed in GHz. Thus, photodiode will not be a problem in limiting the speed of the light signal given out by the HBLED. Also, the bandwidth of the oscilloscope used in the laboratory was 25MHz. Under these circumstances, it is concluded that the HBLED could not be switched at a very high frequency. From this experiment, the performance of the HBLED was shown. Although the HBLED could provide a long data transfer distance, it could not be switched at high frequency so that the data transfer rate was quite low. The bandwidth of the HBLED was estimated by the following equation:

$$\text{Bandwidth} = \frac{0.35}{\text{Rise-time}} \qquad (2)$$

The time-base in the waveform at frequency 200 kHz was 2μs /div. The rise time seen from the waveform was about 2.2μs. By the bandwidth calculation equation: From the calculation, the bandwidth of the HBLED was about 160 kHz.

2.6 RGB Light-emitting Diode

In fact, white light could be separated into red, green and blue light which were known as the Primary Color of Light. In the previous experiments, all the white LEDs used were pure white LED. By replacing each white LED with a RGB LED, the technique of Frequency Division Multiplexing (FDM), which is a scheme in which numerous signals are combined for transmission on a single communications line or channel could be achieved.

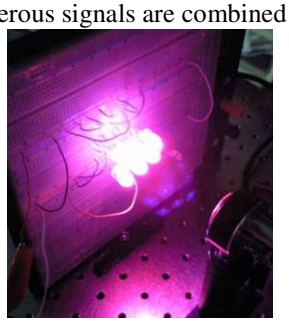


Fig. 9. Red + Blue Signal



Fig. 10. Green + Blue Signal



Fig. 11. Red + Gredn Signal

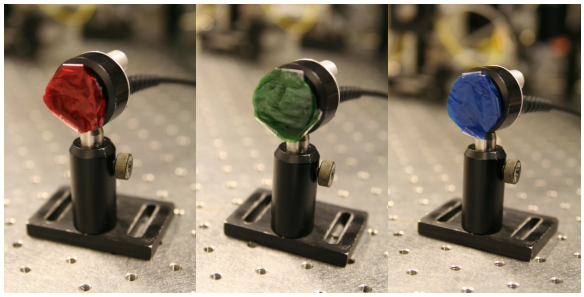


Fig. 12. Different Color Filters are placed in front of the Detector

The experimental results were shown in the following table:

	Signal Separable?		
Signal Color	**Red**	**Green**	**Blue**
Red-Blue	**YES**		**YES**
Green-Blue		**NO**	**NO**
Red-Green	**YES**	**NO**	
Red-Green-Blue	**YES**	**NO**	**NO**

Table. 4.

The results could be explained by the inappropriate cutoff frequency of the filter, which was shown following figure.

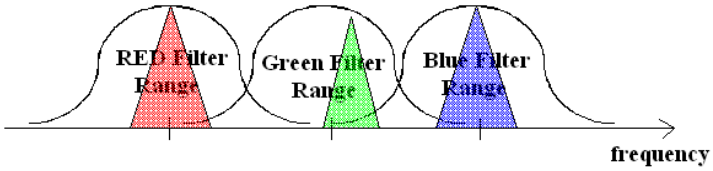


Fig. 13. Filters with inappropriate cutoff frequency

In fact, each signal could be separated by the use of the suitable filter.

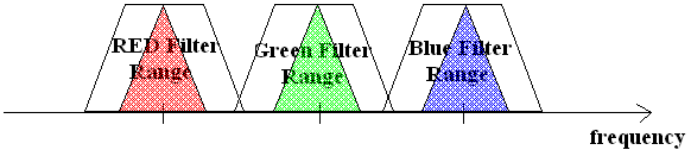


Fig. 14. Filters with appropriate cutoff frequency

2.6 Field of view (FOV) & data transmission distance measurement

In order to obtain the FOV and the data transmission distance, the power distribution was plotted.

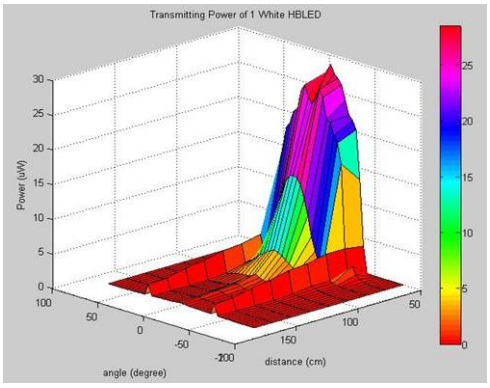


Fig. 15 Power Distribution of 1 HBLED @ I= 0.35A

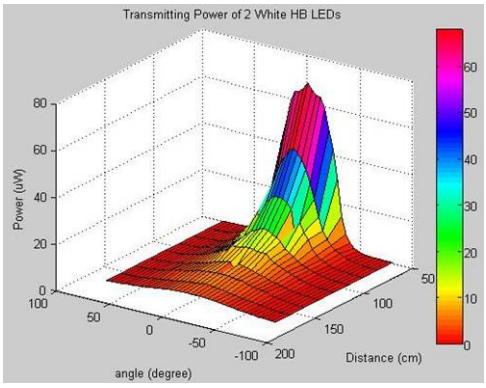


Fig 16 Power Distribution of 2 HBLEDs @ I= 0.5A

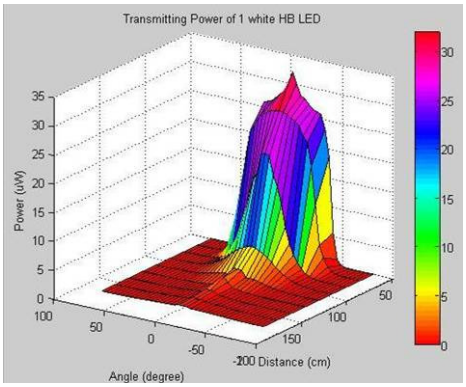


Fig. 17 Power Distribution of 1 HBLED @ I= 0.5A

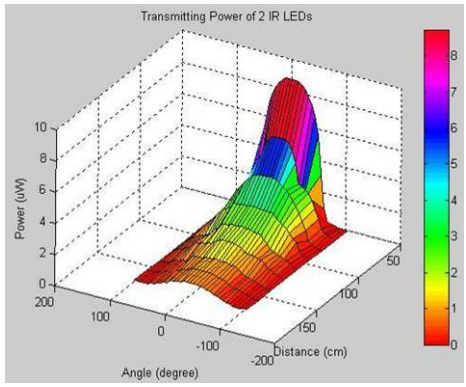


Fig 18 Power Distribution of 2 IRLEDs @ I= 0.35A

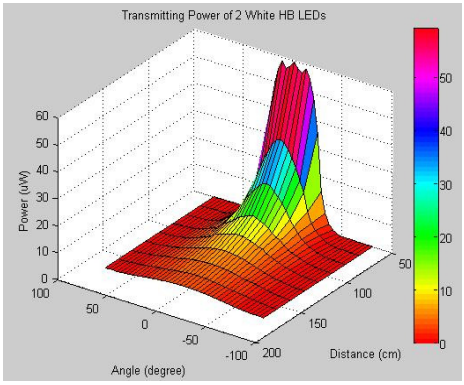


Fig. 19 Power Distribution of 2 HBLED @ I= 0.35A

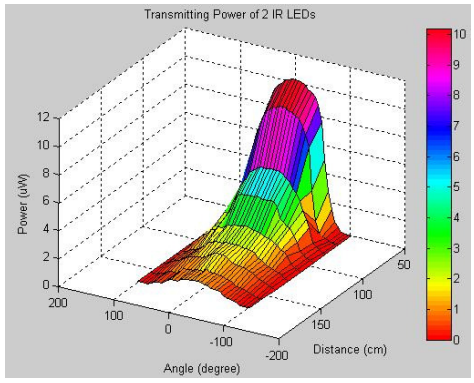


Fig 20 Power Distribution of 2 IRLEDs @ I= 0.5A

From Fig 15 to Fig 20, it could be concluded that the field-of-view of the infrared LED (IRLED), which is about 200^{o}, was larger than that of the HBLED, which was about 160^{o}. Besides, by the observation of the power density shape and comparison of that of different number of LEDs, we could see that transmission distance was a major factor affecting the performance of the visible light signal transmission and the number of LEDs and their positions could increase the receiving intensity. What is more, the data transmission distance achieved was about 170cm.

2.7 Prototype



Fig. 21 Picture of the prototype (overall view)

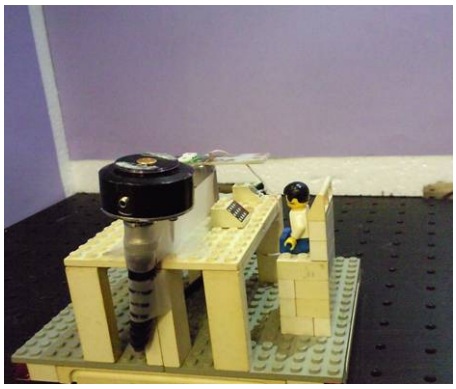


Fig.22 Picture of the prototype (close look of user)

Two white light LED was located on the ceiling of the prototype, which is transmitting the MP3 music. And the Thorlabs' DET210 silicon detector (the large black object on the table of the prototype) was the receiver of the light (music) signal. The received was then passed into the amplifier circuit (loud speaker) and the received music could be heard clearly. Also, when the white LEDs on the ceiling was replaced by the RGB LED, 3 music could be transmitted at the same time. One of the mp3 music was louder when color filter was placed in front of the detector. The black object on the ceiling (between the white light sources in Fig. 21) was the Newport 818-IR germanium cylindrical detector (infrared detector) which is used to receive the signal transmitted by the

infrared LEDs (the small white objects next to the silicon detector in Fig. 22) on the table of the prototype.

2.8 Commercial value

2.8.1 Cost reduction

- Low implementation cost – by simple installation procedures and fixture of LEDs
- Low maintenance cost – by low power consumption and long life-time of LEDs

2.8.2 Social responsibility

- Visible light communication system is safe for human as it is a harmless frequency. Unlike WIFI or other radio frequency, visible light cannot pass through human body. The concerns of cell mutation could be minimized.

2.8.3 Feasibility of the technology of visible light communication

- Global Positioning System (GPS) is a famous positioning system nowadays. However, due to the blockage of the buildings, blind spots will exists. Besides, there would be some errors in detecting the actual position although several satellites were used as the references. In fact, the visible light communication system could be installed into the street lamps. The blind spots problem in GPS could be tackled. Also, the errors in detecting the actual position could be reduced.
- LED commercial displays can be seen everywhere such as the advertising displays. The visible light communication could also be applied into it, i.e. besides displaying the information; the displays could also be used as the wireless communication transmitters.

3. CONCLUSIONS

To conclude, several tasks had been achieved in the project.

- 1MHz LED Driver Circuit
- 170cm Data transmission Distance
- 160^{o} Field of View
- Music Transmission by using different transmitter
- 100kHz Data Transmission rate (Using HBLED)

This project would certainly be further developed in near future. The mp3 music transmission was in real-time. If there was a micro processor connected to the detector, the music file could be saved by implementing some programming for the microprocessor. Also, encoding and decoding could be used in the transmitter part and receiver part to reduce the error in transmission. In addition, the data transmission rate could be enhanced by using fast switching LED. The driving speed of the circuit could also be enhanced if fast switching transistors were used. Finally, the wireless communication technology could be embedded into the visible light source which is the ultimate goal of the project.

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