A study on Ultraviolet Optical wireless communication employing WDM

A Thesis Submitted to the Department of Computer Science and Communication Engineering, the Graduate School of Fundamental Science and Engineering of Waseda University in Partial Fulfillment of the Requirements for the Degree of Master of Engineering

February 1st, 2019

Tokyo, Japan

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Research Guidance: Research on Wireless Access

Acknowledgement

IN THE NAME OF ALLAH, THE MOST GRACIOUS AND THE MOST MERCIFUL. All praise to Allah Almighty, who is the creator of all creatures for giving me opportunities of studying and peace be upon Mohammad the Prophet who conveyed the message of Allah Almighty very perfect and honestly.

I would like to express my deep gratitude and appreciation to my supervisor, Professor Shigeru Shimamoto for his continuous support, kind guidance and patience during this research period. He was always available to give valuable advices, which truly helped me to complete this research. I would like to appreciate cooperation of all members in Shimamoto laboratory specially to Dr. Jiang Liu, Dr. Zhenni Pan and Ms. Megumi Saito for their support, technical discussions and useful comments which helped me to formulate this research work.

It's my honor and privilege that I have been granted a JICA scholarship under PEACE program. My special thanks go to JICA for their financial support, JICA/JICE coordinators for organizing, support and guidance, specifically to Ms. Kumiko Asano for her long-term coordination and support and Ms. Kyoko Watanabe for her support and coordination in my final semester.

I would like to express my profound gratitude and sincere appreciations to my Grandfather, Father, Mother, wife, brothers, sister and all friends who have always been supportive in all ups and downs of my life.

Finally, I would like to thank and appreciate staff members of Waseda University, specially student's administration, health and library departments for their support and kind guidance during my research period.

Patmal, Mohammad Hamed

March 2019

Abstract

We have demonstrated a wavelength division multiplexing (WDM) of ultraviolet (UV) and visible light communication (VLC) system based on UV band-A LED (365 nm) and VLC blue LED (470 nm) experimentally with 64 Mbps, employing several orders of quadrature amplitude modulation (QAM).

Path loss of UV-band-A is much lower compared to other UV-bands. We had firstly performed an experiment to measure UV-band-A path loss. We have compared our experimental results with a simulation-based measurement for several distances. The result of our experiment clears that our UV transmitter path loss perform better than a condition which is near to ideal situation.

Secondly, we conducted an experiment for environmental noise measurement at receiver side for both of our system detectors. Both LEDs are considered to have same conditions. As the result of experiment total noise voltage level for UV receiver was 14 mV, while it was 53.6 mV for blue-light receiver, approximately four-fold of the UV receiver. This higher noise level directly affected VLC detector in SNR measurement level to be in lower compared to UV receiver.

We have measured the BER for several data rate of the UV-WDM communication system from 34 to 75 Mbps for an FEC threshold level of 3.8 x 10-3. To improve BER performance we used VDFE nonlinear equalizer here to compensate nonlinearity of LEDs spectral characteristics. We achieved that for 4QAM when applying lower data rates such as 34 Mbps to 56 Mbps, its BER is much lower, but when we increase it to 64 Mbps its BER level is crossing the FEC threshold level. Therefore, we can have 56 Mbps data rate by using 4QAM. When we applied 16-QAM scheme, system BER performance improved and we achieved data rate of 64 Mbps under FEC threshold level for our system.

We used diffused LOS link to measure our system performance not in a directed LOS link, but in configurations to have direction angles between Tx and Rx. We measured BER of our UV communication system with various angles between transmitter and receiver for FEC threshold level. We have put our receiver in points with different angles but same distance of 1.5 m from transmitter. The result of experiment shows that for 4QAM we can achieve 34 Mbps with BER below FEC up to 10 degrees of angle, while for 16QAM we can achieve 64 Mbps with BER below threshold level of FEC up to 10 degrees of angle.

To improve further system performance, we should consider higher nonlinear terms for equalizer. To the best of our knowledge, this is the highest data rate ever reported in UV communications systems and it is the first time studying WDM for UV communication system.
***Keywords*—** UV, WDM, Volterra DFE equalizer

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List of Acronyms

ACGIH American Conference of Governmental Industrial Hygienists

APD Avalanche Photodiode

ATM Automated Teller Machine

BER Bit Error Rate

DC Direct Current

DSL Digital Subscriber Line

EA Electrical Amplifier

FEC Forward Error Correction

FOV Field of View

FSK Frequency Shift Keying

FSO Free Space Optics

FTTH Fiber-To-The-Home

FTTP Fiber-To-The-Premises

FWHM Full Width Half Maximum

IM/DD Intensity Modulation Direct Detection

IR Infrared

ISI Inter Symbol Interference

Laser Light Amplification by Stimulated Emitted Radiation

LEDs Light Emitting Diodes

LDs Laser Diodes

LOS Line of Sight

LP Low Pressure

MCPCB Metal-Core Printed Circuit Board

MIMO Multiple Input Multiple Output

MP Medium Pressure

NLOS Non-Line-of Sight

OFDM Orthogonal Frequency Division Multiplexing

OOK On-Off-Keying

OSC Oscilloscope

OWC Optical Wireless Communication

PMTs Photomultiplier Tubes

PPM Pulse-Position Modulation

QAM Quadrature Amplitude Modulation

RF Radio Frequency

RX Receiver

SISO Single Input Single Output

SNR Signal to Noise Ratio

SLDs Super Luminescent Diodes

3D Three-Dimensional

TLV Threshold Limit Values

TX Transmitter

UAV Unmanned Aerial Vehicle

UV Ultraviolet

UVC UV Communications

VDFE Volterra Decision Feedback Equalizer

VLC Visible Light Communication

WDM Wavelength Division Multiplexing

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Chapter 1

Introduction

1.1 Background

In human history people were sending their letters by themselves to far distances taking days or even months. In battle fields people were using fire or loud sounds to communicate between each other. When Radio frequency (RF) communications has been developed, people were able to send their letters and even talk to people living in other side of the earth at same time. RF communications brought evolution to the life of people, but due to some limitations RF communications became challenging and very congested environment. In near future a huge number of elements and devices will be connected to internet as from physically and virtually to transfer data. Those challenges of RF communications are due to its limited bandwidth which causes lower data rate, propagation challenges, larger size with high weight and high-power of transmitting antennas. Optical wireless communication (OWC) is considered as better alternative to RF communication as it has huge unlicensed bandwidth, no interference to RF, very secure, low cost of devices, low weight and size of devices and potential for high data rate due to this huge bandwidth [3]. OWC can be categorized into three major types as visible light communication (VLC), infrared (IR) communication and ultraviolet (UV) communication. Figure 1 shows the electromagnetic spectrum from RF to gamma rays, we can see that RF bandwidth is from Hz to GHz while OWC bandwidth is more than 1000 Tb (1 Tb = 1000GHz).

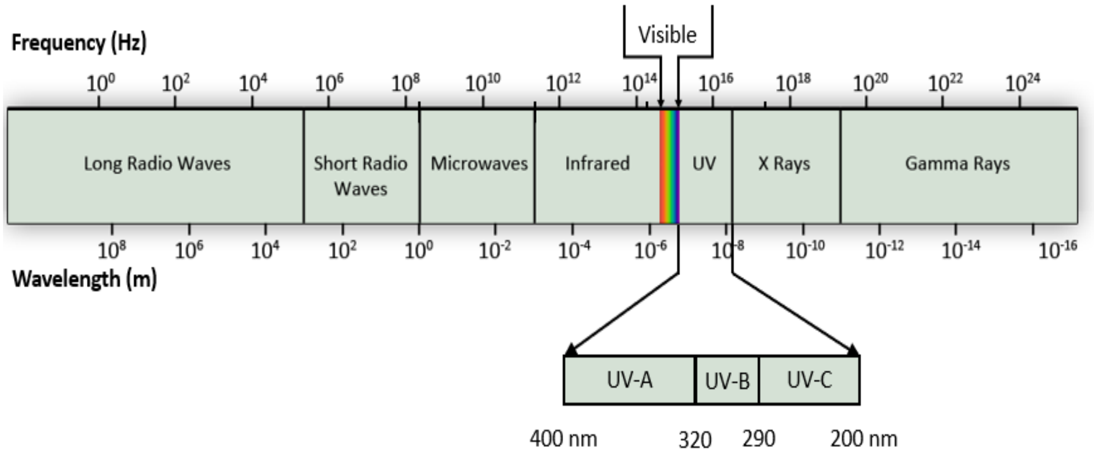


Figure 1 Ultraviolet (UV) in electromagnetic spectrum

Each of VLC, IR and UV waves has specific properties with their own extensions in some part while limitations in other part of applications. This paper focuses UV communication system for short range using wavelength division multiplexing (WDM) for UV-band-A with VLC blue light and achieves high data rate speed. UV communications are applicable to civilian and military environments. It can be used for short range data communications, air craft landing in a foggy weather, detecting missiles path, under water communications and many other places.

Table 1 shows access technologies to the last mile connection. Digital subscriber line (DSL) technology can support high speed internet access but it has limited bandwidth and the installation with cables slows down its deployment. As we have discussed about RF spectrum that it is limited compare to OWC, beside that it is congested and has lower data rates. Fiber optics have very high speed and new technology but still everyone is not able to connect with internet through this technology.

Table 1 Access Technologies for the last mile link [13]

xDSL	■ Copper based (limited bandwidth)—phone and data combine ■ Availability, quality and data rate depend on proximity to service provider's C.O.
RF	■ Spectrum congestion (license needed to reduce interference) ■ Security worries (encryption?) ■ Lower bandwidth than optical bandwidth ■ At higher frequencies atmospheric conditions attenuation (rain)/absorption (oxygen gas) limits link to ~1km Frequency bands: 7, 18, 23, 35, 60, 66 GHz
Cable	■ Shared network resulting in quality and security issues ■ Low data rate during peak times
FTTH	■ 100 Mb/s, but costly ■ Right of way required—time consuming
Satellite	■ Expensive ■ Limited bandwidth
OWC	

Fiber to the homes (FTTH) or fiber to the premises (FTTP), is connection of everyone home or office to optical fiber central point. According to [10], there are some problems we would face with fiber optics such as (i) need more physical space for their equipments, (ii) it would operate in customers environments, so cooling/heating variation could affect its performance, (iii) for some places it would not be practical to install fiber optics. Satellite communication system can offer up to high data rates of speed, but this speed is varying by place and its installation is very expensive.

1.2. Problem statement

VLC and IR are not applicable when there is a blockage or an obstacle for Line of sight (LOS) link, UV communication systems has unique channel properties that can be used in such environments to establish communication link [1]. UV waves have strong scattering effects, which gives UV communications a high potential for establishing a communication link when a direct LOS path or an alternative path is not available. The UV waves are scattering through air particles such as molecules, aerosols, haze, fog, and others [2].

Meanwhile recently, UV communication system devices technologies have been developed and available to commercial which caused extension and emerging in application demands for UV communication systems. As shown in Figure 1, total UV wavelength band is divided into three sub-bands as UV-band-A (320 to 400 nm), UV-band-B (290 to 320 nm), and UV-band-C (200 to 290 nm), every sub-band has its specific properties, that can limit or extend their applications. Solar lights radiate UV lights to earth, but some of those radiations are filtered by ozone layer [1], UV-band-C are called a deep UV or solar blind region, since solar radiations in this band are mostly blocked by ozone layer, therefore it has very low background noises. But beside that UV-band-C has higher propagation losses. UV-band-A has very lower propagation losses compared to UV-band-C, while it has ambient lighting noises [11]. The critical challenge for UV communication system is inter symbol interference (ISI) and environmental noises that lowers the data rate. To compensate the ISI and environmental noises several techniques of signal processing can be applied.

Reported speeds in UV communication systems is very low and we will explore it in more details in 1.3. Related works. This paper experimentally explores UV-WDM with VLC using UV-band-A LED and VLC-blue LED in short range communication system. To mitigate noises and LED nonlinearity we used Volterra decision feedback equalizer, and therefore we were able to achieve higher data rate and lower bit error rate (BER).

1.3. Thesis Organization

- ✓ **Chapter 1 (Introduction)**

  This chapter talks about the background information centered on thesis title and its problem statement and thesis organization.

- ✓ **Chapter 2 (Related works)**

  This chapter presents literature review on UV communication systems

- ✓ **Chapter 3 (UV Sources and Detectors)**

This chapter introduces current technologies of ultraviolet devices, mainly UV sources and detectors

- ✓ **Chapter 4 (UV Communications)**

  This chapter talks about characteristics of UV communications systems including UV link configurations (LOS, NLOS, tracked), UV safety and UV application

- ✓ **Chapter 5 (Proposed system)**

  This chapter presents our proposed UV communication system including experimental details and setup

- ✓ **Chapter 6 (Results and discussions)**

  This chapter gives experimental and simulation results, and discussing achieved results

- ✓ **Chapter 7 (Conclusions and future path)**

  This chapter talks about total achievement of research and its contributions with giving future directions

1.4. Related works

UV communication system is explored in various environments, such as indoor scenarios, outdoor scenarios, short range data communications, long distance Non-LOS communication links. The reported explorations, approximately all are focusing on UV in solar blind region, since it has lower environmental noises and previously UV devices were mostly manufactured for this region. Currently there is a trend of research in UV-band-A for its much lower propagation losses and availability of devices in this band for commercial uses.

If we divide all UV communication systems according to the light source devices in two categories as LED and non-LED based systems. Non-LED based UVC systems use flash tubes, lamps and lasers as light sources and the reported speed for this category is from kbps to few Mbps with few km distance [3], while LED based UV communication systems use LEDs as light source and the reported speed for this part is from tens of kbps to hundreds of kbps with tens of meter distance range [3].

In [9], using UV channel properties to improve potential of UV radiations for the help of aircraft landing in a foggy weather condition, signal was modulated as pulse position modulation (PPM) then it is transmitted by a 265-nm mercury-xenon lamp as UV runway light source with channel length of 1.6 km, the data rate of this system is reported as 1.2 Mbps. Aircraft landing in bad weather condition as in [9] is considered in [8], the signal is modulated by PPM, then transmitted by solar blind UV source 253-nm mercury-argon lamp as runway light with channel length of 0.5 km, for UV photon counting the Monte Carlo and semi-empirical techniques are used and data rate of this system is measure as 10 kbps with using of three types of sensors.

For short range communications in [7], voice signal in daylight is transmitted by solar blind 254-nm low- pressure mercury as light source, then is modulated by frequency shift keying (FSK) with channel length of 6 m, solar blind filters are used with photomultiplier tube PMT the communication system is established, and data rate of this system is reported as 1.2 kbps. In [6], free space optics (FSO) in solar blind region 265-nm LED array is used for light source under on-off keying (OOK)/PPM modulation with channel length of 100 m, and its potential is investigated for subsea FSO the data rate of this system is reported as 2.4 kbps. An experimental study has been conducted in [5] using single input single output (SISO) and then multiple input multiple output (2x2 MIMO) scheme for solar blind UV 265 nm LED array as light source under intensity modulation direct detection (IM/DD), the data rate is increased to 250 kbps as twice of SISO with channel length of 30 m.

Recently an experimental investigation is report using UV-band-B near solar blind region with 294-nm LED as light source for this communication link. Signal is modulation by quadrature amplitude modulation (QAM) with orthogonal frequency division multiplexing (OFDM) scheme for a diffuse LOS link and a very short distance of 8 cm, the data rate of this system is reported as 71 Mbps using 8-QAM-OFDM [12].

Chapter 2

UV Sources and Detectors

2.1. UV Light Sources

A combination of natural and artificial UV sources are around us. According to black-body-radiation, every very hot object radiates UV light. Sun radiates a combination of wavelengths ranges to space from IR to UV. The composition of solar radiation is approximately 50 % in IR range, 40 % in VLC and about 10 % in UV wavelength range [4]. The Figure 2 shows sunlight spectrum in a clear weather condition and on surface with 60 degrees zenith angle for solar.

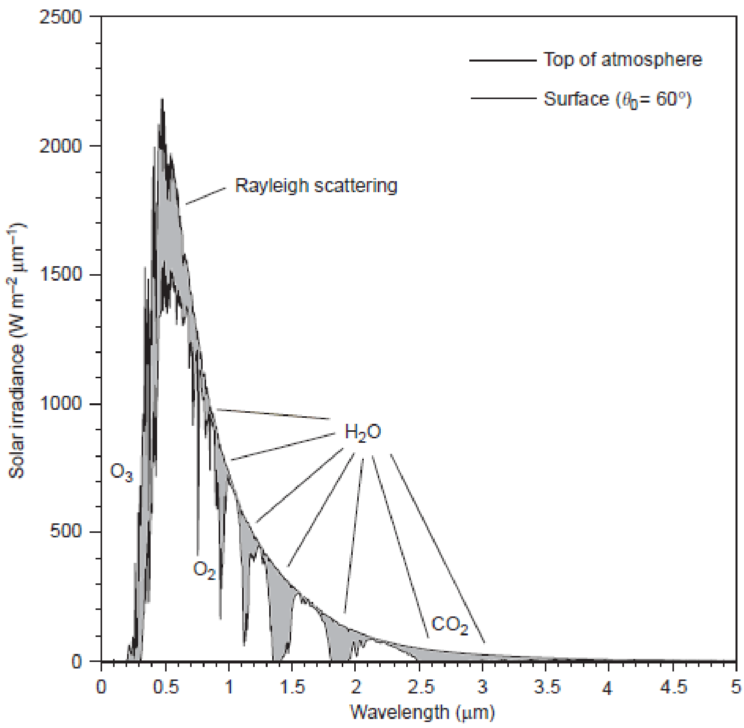


Figure 2 Sunlight spectrum at top of atmosphere in clear weather, absorption and scattering are shown dark [4]

Giving very large amount of heating to the temperature of incandescent to an object will cause emission of UV radiations, as we mentioned earlier for sunlight. In artificial UV radiations are generated through discharging of some type of gas, mostly vaporized mercury [12]. The mostly used sources are LEDs and laser diodes (LDs). There are several artificial UV sources to be used for its communication system. Each of the UV source will have its unique properties with some extensions and some limitations in applications we will go briefly to them as in following pages.

2.1.1. UV LED

UV-LED is a semiconductor element, that is composed of p-n junction. It radiates UV lighting when it is driven electrical biased. This is called LED electronic excitation. When a forward bias voltage is connected to p-n junction of LED, then it is excited. This condition causes electrons in their chemical layers to be unstable, it means the electrons jump from one level to another. By coming back of those excited electrons to their stable states, they release energy in the format of photons. The energy band gap of LED *p-n* junction determines whether it radiates in wavelength of UV, VLC or IR. This band gap energy of LED depends on LED manufacturing semiconductor materials. Table 2 shows commonly used materials for manufacturing of LED and the peak wavelength or wavelength range of its radiation.

Table 2 common led materials and Their optical radiation Wavelengths [13]

LED Material/Substrate	Peak Wavelength or Range (nm)
AlGaN/GaN	230–350
InGaN/GaN	360–525
ZnTe/ZnSe	459
SiC	470
GaP	470
$GaAs_{0.15}P_{0.85}$	589
AlGaInP/GaAs	625–700
$GaAs_{0.35}P_{0.65}$/GaAs	632
$GaAs_{0.6}P_{0.4}$/GaAs	650
GaAsP/GaAs	700
$Ga_{1-x}Al_xAs$/GaAs	650–900
GaAs	910–1020
InGaAsP/InP	600–1600

The process of electrical to optical conversion is very efficient in LED, it releases very little heat compared to UV-Lamps.

Generally, LEDs are used for indoor environments. It would be possible to use LEDs array for shorter UV communication links (less than one kilometer) instead of LDs.

Since UV wavelength is categorized into three groups from (200 to 400) nm, the higher wavelengths near to upper limit of this range will have higher output optical power compared to the lower wavelengths. LEDs are used for digital printing and UV curing application environments and many other areas, while can be used for data communication as well. UV curing is suitable beside digital-printing to 3D-printing, coating and decoration. UV-LED application are depicted in Figure. 3

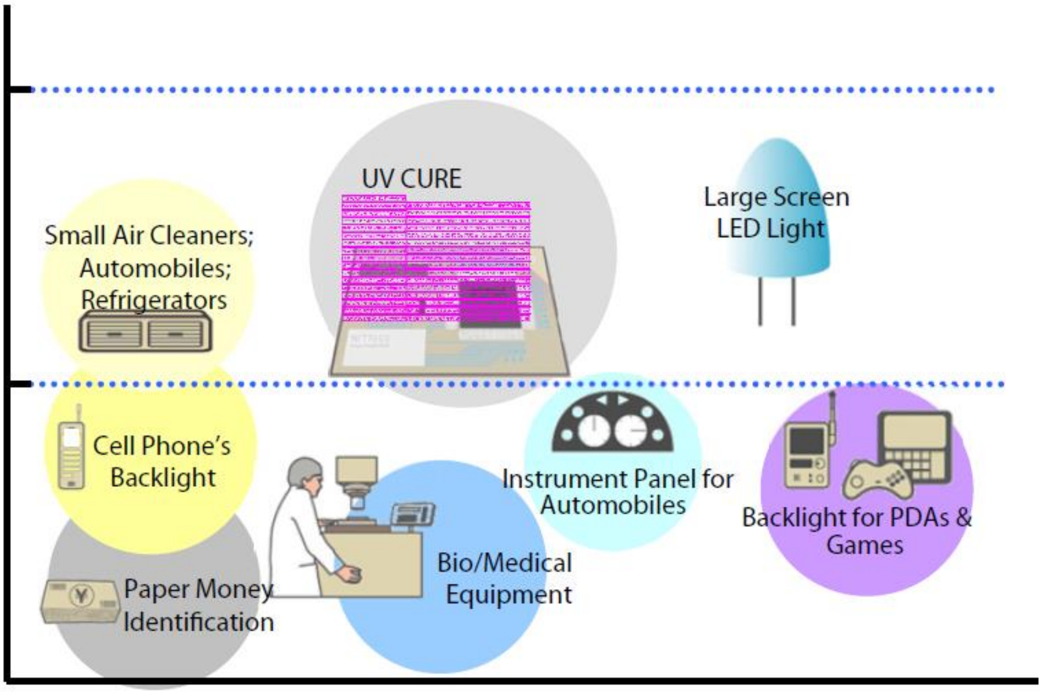


Figure 3 UV-LED application areas [14]

The external quantum efficiency of UV-LED specially between (350 to 400) nm has been vastly improved, since crystal developments has been empowered, chip processing and packaging technologies have been developed [14].

The external quantum efficiency of UV-LEDs is plotted in Figure 4. The plot of quantum efficiency for UV-LEDs shows that by increasing the wavelength its quantum efficiency is increasing as well. According to [14], increase and decrease of external quantum efficiency is due to three possible causes and related to crystal improvement.

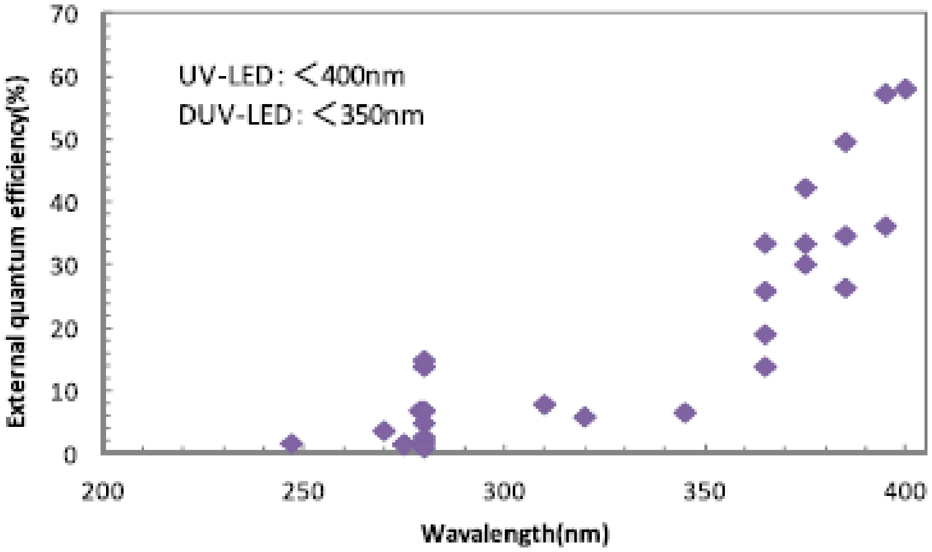


Figure 4 External quantum efficiency of UV-LEDs [14]

Several types of UV-LEDs are commercially available, including low power, high power, mounted, unmounted, single LED or LED arrays. Some of commercially available LEDs are shown in Figure 5.

(a) (b) (c) (d)

Figure 5 Several UV-LEDs (a)UV-LEDs for counterfeit detection [a] (b) High power ball lens UV-LED [b] (c) Mounted high-power LEDs with heat sink [b] (d) 100W high power UV LED array [c]

Note: a - www.sparkfun.com, b - www.thorlabs.com, c - www.made-in-china.com

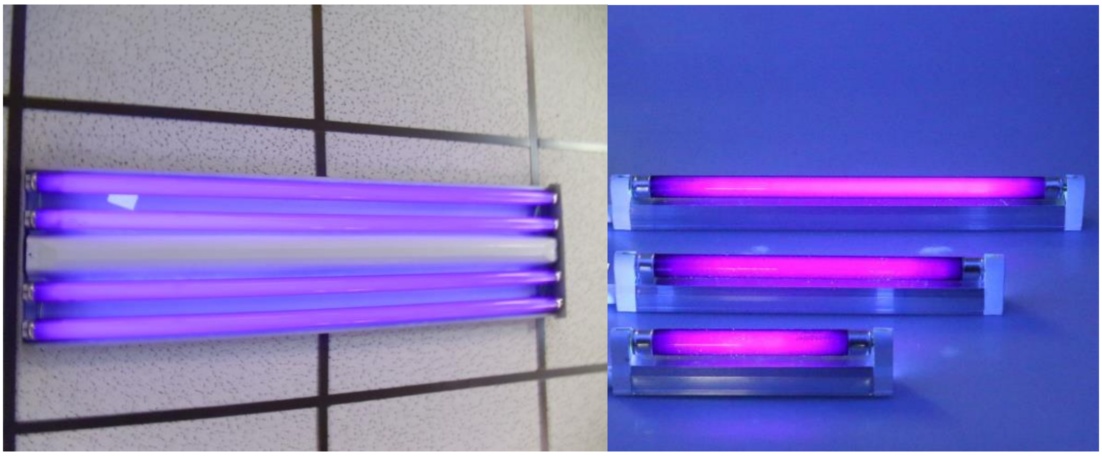
2.1.2. Black light UV-lamp

Generally, UV-lamps are in low cost and can generate high power. The field of view (FOV) of transmitter has sufficiently great angle. UV-lamps are suitable to be used for networking systems.

Black lights are UV-lights wavelengths are in range of (320 – 400) nm or UV-band-A region. Some stuff will glow when a black light is turned on. These objects to glow contain phosphors in their combinations. There are many such stuffs like quinine water, laundry detergent, teeth, and fingernails. These phosphors will convert UV light to visible light by fluorescing molecules [15]. It is because when UV photon is absorbing by a fluorescing molecule, it receives energy which will cause sudden movement of electron from one energy level to a higher one. When this electron comes to its first energy level, in this case photon as kind of energy is released with wavelength of visible light, and this cause the object to glow [16].

Black light lamps commonly radiate light energy in UV region, meanwhile they radiate a little visible light energy as well. The small portion of light that black light radiates is in blue visible range [16]. There is another lamp that is black-light-blue-lamp, it radiates the same way as black-light-lamp does, but this lamp has additional filters for visible light that compensate the blue light's radiations. Black-light-blue-lamp has a black-blue color, it does not have blue color as black-light-lamp has.

Black-light-lamps are very inefficient due to inside layers for filters. Only 0.1% of input power is radiated as its output useful power [12]. Black light is mostly used for validating of oil painting, antiques, and used for safeguarding to counterfeiting of banknotes. It can be used to detect fungal infections and diagnosing some skin diseases.



(a) (b)

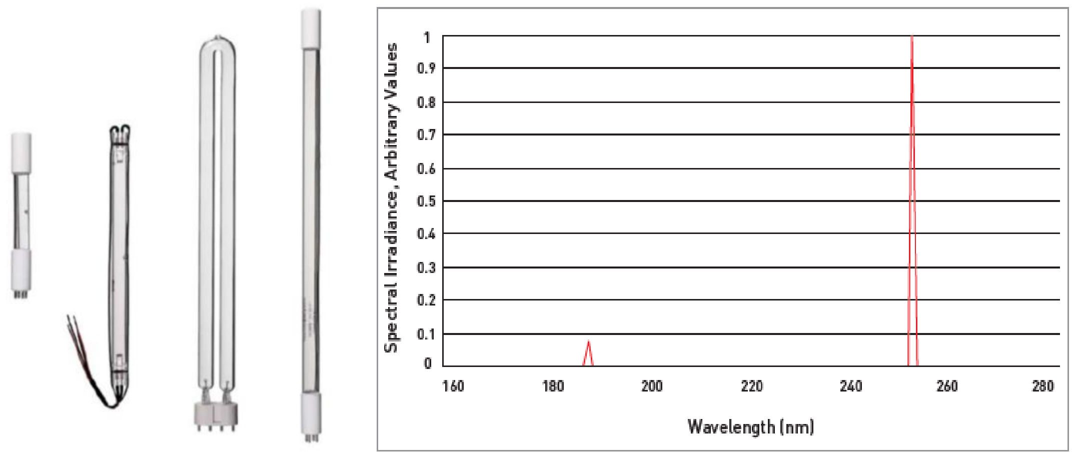
Figure 6 Black light lamps (a) Black light fluorescent tubes. (www.wikipedia.org) (b) Black light blue lamps (www.aliexpress.com)

2.1.2. Low pressure UV-lamp

UV low pressure (LP) lamps contains an arc tube from a transparent glass of UV or a quartz glass, it is filled with noble gases with low amount of mercury at low pressure in range of millibar. When a current is driven between its electrodes at two sides of the lamp, then plasma starts radiates UV lighting emission [17].

LP lamps are known as germicidal lamps. It is used for disinfection of bacteria, fungi, viruses and microorganisms, while it can be used both in free space or in water. UV LP lamps has efficiency of 40% that converts electrical energy to optical UV output, this means that when we give 100 W input to it, it gives 40 W output optical power. This lamp radiates UV radiations in UV-band-C in two specific wavelengths at 254 nm and 185 nm. Commonly UV low pressure lamps are designed as linear, U-form, spiral and other forms [18].

The Figure 7(a) shows LP UV lamps in linear and U-shapes. UV LP lamps are also called monochromatic UV lamps, they are producing in specific wavelengths. Its spectrum is shown in Figure 7 (b).

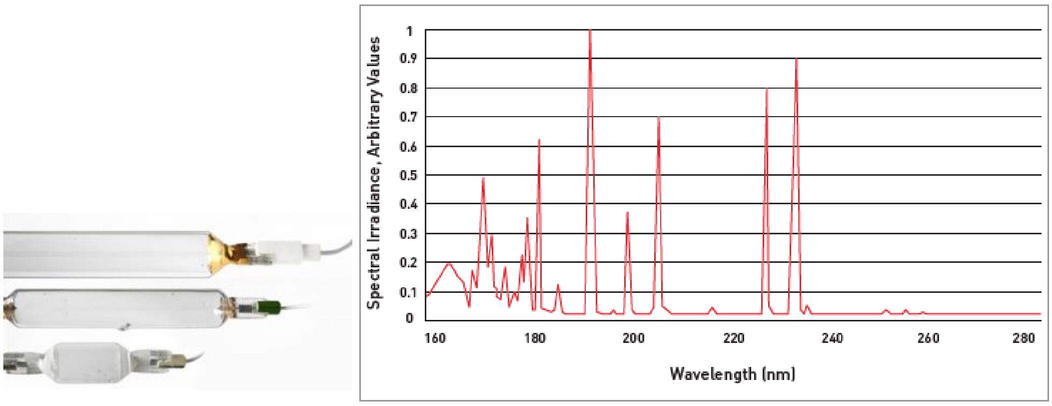


(a) (b)

Figure 7 (a) UV low-pressure (LP) lamps (www.heraeus.com) (b) UV low pressure lamp spectrum [19]

2.1.3. Medium pressure UV-lamps

Medium pressure (MP) UV-lamps are emitting light in in various wavelengths, not as low pressure to be monochromatic, these lamps are called polychromatic UV-lamps as well. MP lamps normally work between 800 °C to 900 °C. These lamps have much higher power in kilowatts compared to low-pressure lamps, but efficiency of these medium-pressure lamps is lower compared to low-pressure lamps. That is 11 to 12 % of electrical energy given as input to them will be converted to UV output power. These lamps have spectral range of radiation between 220 nm to 280 nm. When medium-pressure lamps are operating it radiates some wavelengths outside of (220 – 280) nm as well, since they have high power density and this characteristic is causing to degrade output power efficiency. They are commonly used for UV-curing, drying, disinfection and oxidation. Medium-pressure lamps and their spectral characteristics are drawn in Figure 8 for more details.



(a) (b)

Figure 8 (a) UV Medium-pressure lamps (MP) (Jelosil UV-Technology) (b) UV medium-pressure lamps spectrum [19]

2.1.4. Comparison of UV LEDs and UV lamps

As UV-LEDs and UV-lamps are discussed earlier, here we will talk about the features of both in a comparison method. Totally UV-LEDs are better from UV-lamps due to some aspects as: its high efficiency of converting to energy, long lasting, optical output stability, much easier to absorb and disperse heat generated from LED diode to heat sink, due to wide spectrum has potential for high speed, lower physical size [20], [21]. In Figure 9 you can see some comparison of UV-LED with UV-lamps.

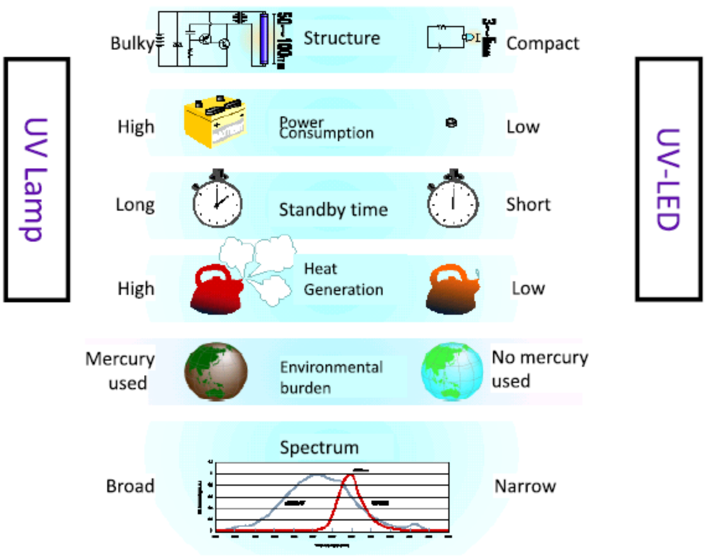


Figure 9 Comparing UV-LED features versus UV lamp [14]

Since UV-LEDs have perfect potential for several application areas, UV-LEDs that radiates lighting power of few milliwatts have already used for banknote identification in ATMs (automated teller machine) instead of UV-lamps.

2.1.5. UV-Lasers

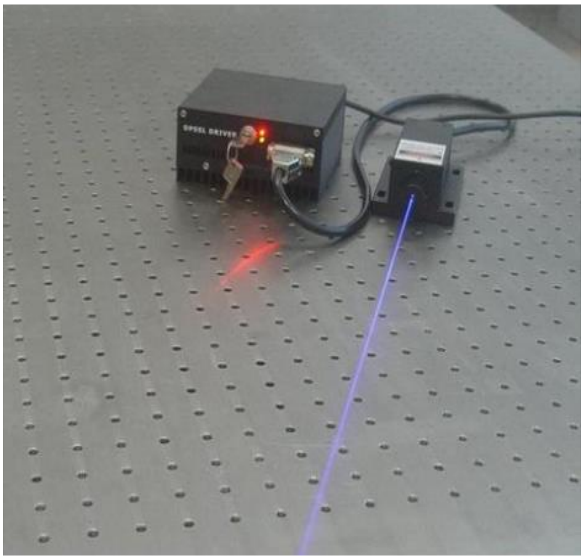
Acronym for laser is light amplification by stimulated emitted radiation (LASER), as from name it amplifies its generated light which are monochromatic, coherent and greatly collimated. Lasers can have all UV wavelength ranges. We have described this under UV-LEDs that When electrons are excited and move to other band, by coming back of excited electrons to their stable states, they release energy in the format of photons. The released energy is related to the energy difference of conduction band and valence band, where electron and hole are located respectively. The energy of band gap determines in which wavelength the LD would radiate. This band gap energy of LD is depended on LD manufacturing semiconductor materials. Table 3 shows LDs commonly used with their semiconductor materials and related wavelength range or peak wavelength of their operation.

Table 3 laser diode materials and Their corresponding radiation Wavelengths [13]

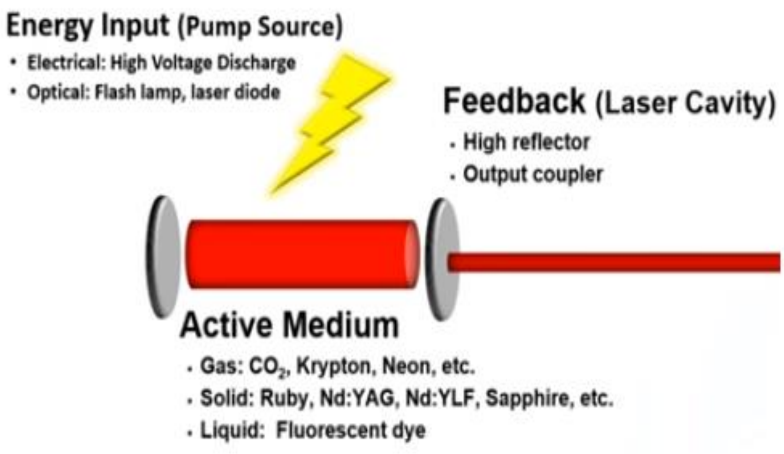
Laser Material/Substrate	Wavelength
AlGaN	350–400 nm
GaAlN	375–440 nm
ZnSSe	447–480 nm
ZnCdSe	490–525 nm
AlGaInP/GaAs	620–680 nm
$Ga_{0.5}In_{0.5}P$/GaAs	670–680 nm
GaAlAs/GaAs	750–900 nm
GaAs/GaAs	904 nm
InGaAs/GaAs	915–1050 nm
InGaAsP/InP	1100–1650 nm
InGaAsSb	2000–5000 nm
PbCdS	2700–4200 nm
Quantum cascade	3–50 µm
PbSSe	4.2–8 µm
PbSnTe	6.5–30 µm
PbSnSe	8–30 µm

Every laser radiates very pure wavelength (monochromatic) compared to lamps or other sources of light. Other light sources have high divergence of light, but lasers have very low divergence. Laser uses high input power and its light can travel for very long distances.

Very common laser is laser diode (LD) [22], [23] and super luminescent diodes (SLDs) [24]. Lasers can be categorized by their excitation medium as solid lasers, gas lasers, liquid lasers or semiconductor lasers. Beside active medium lasers can be divided with according to some parameters such as: gain medium of the laser, laser input power, its efficiency or its applications. Solid state lasers use excited solid active medium instead of gas, liquid. Its solid active medium contains glass or crystalline. Semiconductor lasers excites their active gain medium electrically or some optically.



(a)



(b)

Figure 10 (a) 261 nm Solid State UV-Laser (www.hjoptronicsinc.com) (b) Lasers working principles (www.photomachining.com)

Previously mercury lamp was commonly used as UV source, that produces high optical output power, while it needs high input power, low modulation rate with short life cycle and very susceptible to temperature.

2.1.6. LED and LDs comparison

For selection of optical sources some important features need to be considered as modulation bandwidth, input and output power characteristics, spectral measurements and purity of spectrum. LEDs compared to lasers have extended spectral range, whereas lasers have improved pure radiated wavelength.

Table 3.2 shows comparison of LEDs and laser diodes (LDs) for different important characteristics such as optical output power, optical spectral width, modulation bandwidth, safety and many others. The mentioned characteristics are generally compared between LDs and LEDs. Some LEDs and LDs could more unique characteristics according to their manufacturing materials, wavelengths and purposes of applications. Due to these specific characteristics, their application areas could be assigned for each of them.

Table 4 A comparison of an LED and a semiconductor laser diode [13]

Characteristics	LED	LD
Optical output power	Low power	High power
Optical spectral width	25–100 nm	0.01–5 nm
Modulation bandwidth	Tens of kHz to hundreds of MHz	Tens of kHz to tens of GHz
E/O conversion efficiency	10–20%	30–70%
Eye safety	Considered eye safe	Must be rendered eye safe
Directionality	Beam is broader and spreading	Beam is directional and is highly collimated
Reliability	High	Moderate
Coherence	Noncoherent	Coherent
Temperature dependence	Little temperature dependence	Very temperature dependent
Drive and control circuitry	Simple to use and control	Threshold and temperature compensation circuitry
Cost	Low	Moderate to high
Harmonic distortions	High	Less
Receiving filter	Wide—increase noise floor	Narrow—lower noise floor

2.2. UV Light Detectors

In OWC system light detector is very important operator, it is commonly called photodetector as well. Each photodetector has active area(aperture), it collects light photons and covert it to electrical voltage or current signal. There are three popular photodetectors commonly used: PIN photodiode, avalanche photodiode (APD) and photomultiplier tube (PMT). The photodetector has its range of wavelength at which responses the receiving light, this range of wavelength depends on the materials photodetectors.

3.2.1. PIN photodetectors

PIN photodetector is composed of very little *n*-doped intrinsic semiconductors region between *p*-and *n-type* semiconductor materials [25]. PIN photodiodes are without internal gain but are having larger bandwidth. An enough large reverse bias voltage across photodiode is needed for its operation as shown in Figure 11.

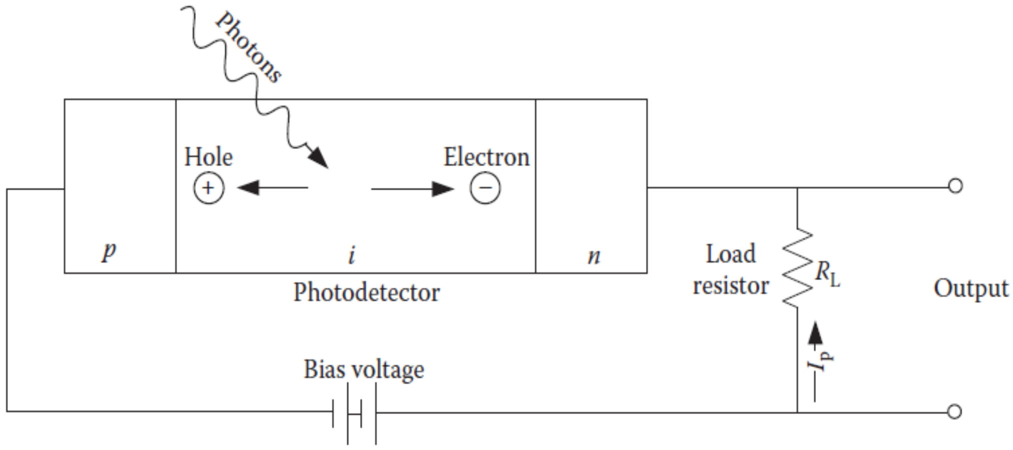


Figure 11 Schematic diagram of PIN photodiode [13]

The light is normally focused on intrinsic(depletion) region. Photons coming to depletion region must have greater energy compared to band-gap energy of the semiconductor material, otherwise the PIN photodiode cannot convert it to electron.

Since PIN photodiode has no internal gain, its responsivity to incoming light is always less than one unit. But they have very high bit rates, for some of them it is reported more than 100 Gbps [26-28].

2.2.2. APD photodetectors

APD is a very sensitive semiconductor device that covert incoming photons to electrons. As we have mentioned PIN photodiodes can only convert one photon to a pair of electron and hole without any internal gain. If we are amplifying its output current or voltage, it will produce some level of noises as well. An APD has internal built-in gain through avalanche multiplication. Its typical gain is between (50 to 300) [29].

The APDs are composed of *n*-type layer, a thin *p*-type layer, an intrinsic π-layer and a highly doped *p*-layer as shown in Figure 12, it shows electric field strength E(x) is maximum in *n+p* junction.

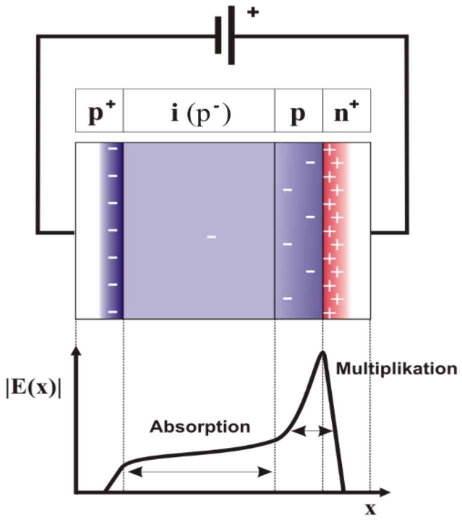


Figure 12 APD photodiode schematic diagram (www.wikipedia.com)

2.2.3. PMT photodetectors

Photomultiplier tube (PMT) is from family of vacuum tubes, it is called phototube as well. It is composed of photocathode, focusing electrodes, electron multiplier (several dynodes) and anode. It is constructed with an evacuated glass that is very high glass to metal seal. The PMT schematic diagram is shown in Figure 13. Its operation can be clearly shown from figure, when light enters from input window, it reaches photocathode at which electrons are then excited and ejected from cathode surface. These electrons are then accelerated and directed to electron multiplier by focusing electrode. When these electrons reach first dynode, they are multiplied by process o secondary emission. The secondary emission process is performed at each dynode.

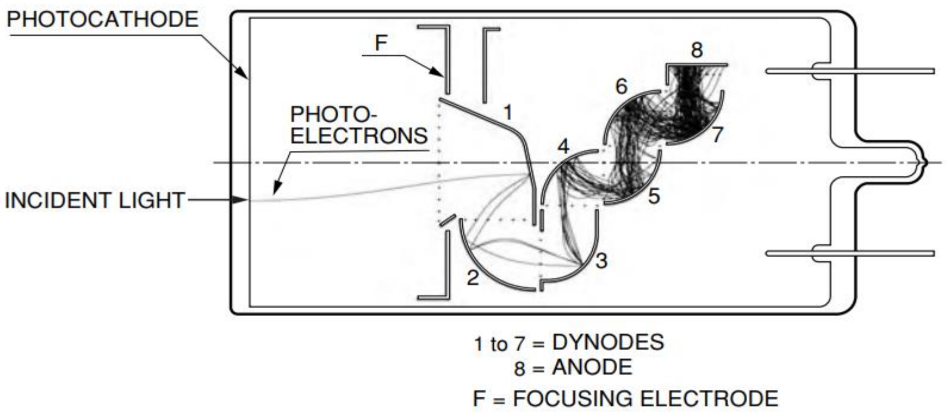


Figure 13 PMT schematic diagram [Hamamatsu]

PMTs can have very high secondary emission that can multiply the electron flow, therefore can have average gain in between 10^3 to 10^5 range [30]. We have mentioned earlier that APDs have gain of up to 300, that is very small compared PMTs gain. PMTs has very high sensitivity to light detection and have low noise. PMTs are very suitable for UV communications, especially for NLOS UV communication systems, for low noise and very high sensitivity.

We have studied that APDs have internal amplifications but amplification of PMTs are much larger. Silicon based APDs are operates very speedy compare to PMs, but they introduce high level of noises [30].

Chapter 3

UV communications

3.1. UV link configurations

In indoor communication links the light will be reflected by walls, ceiling or other obstacles, but when considering outdoor communication link the light will be scattered or absorbed by air molecules and other atmospheric particles. When there is fog or bad weather condition IR an VLC are not applicable due their channel characteristics. Both IR and VLC cannot establish a communication link when there is a blockage like building or no alternative or LOS link. Therefore, UV has high potential when there is blockage, no alternative link, since it has unique scattering characteristics which can enable it to have an NLOS communication link in such conditions [2].

We can have four types of link configuration for UV communication systems. These are directed LOS, diffused LOS, NLOS and tracked configurations. all four types are illustrated in Figure 14. And we will briefly describe each of the above configurations.

3.1.1. Directed LOS configuration

Direct LOS configuration is used for point to point communication. It could be used for indoor or outdoor environments. It needs low power requirements for transmission, since it is directed LOS and needs narrow FOV for communications. This configuration has some advantages that provides the highest data rate compare to other configurations, it is not affected by multipath distortion, if we consider a smaller FOV for receiver it would help to significantly reduce environmental lighting noises [31]. There are some disadvantages for this configuration such as, mobile or devices that are not fixed at one position are not supported by this configuration. They have very small coverage area.

The overlapping area in NLOS UV configurations is directly related to receiving photons from transmitter to the receiver. This overlapping area is called scattering area, its size is related to the field of view (FOV) of transmitter and receiver and the angle between transmitter and receiver. This scattering area in three-dimensional (3D) view becomes scattering volume.

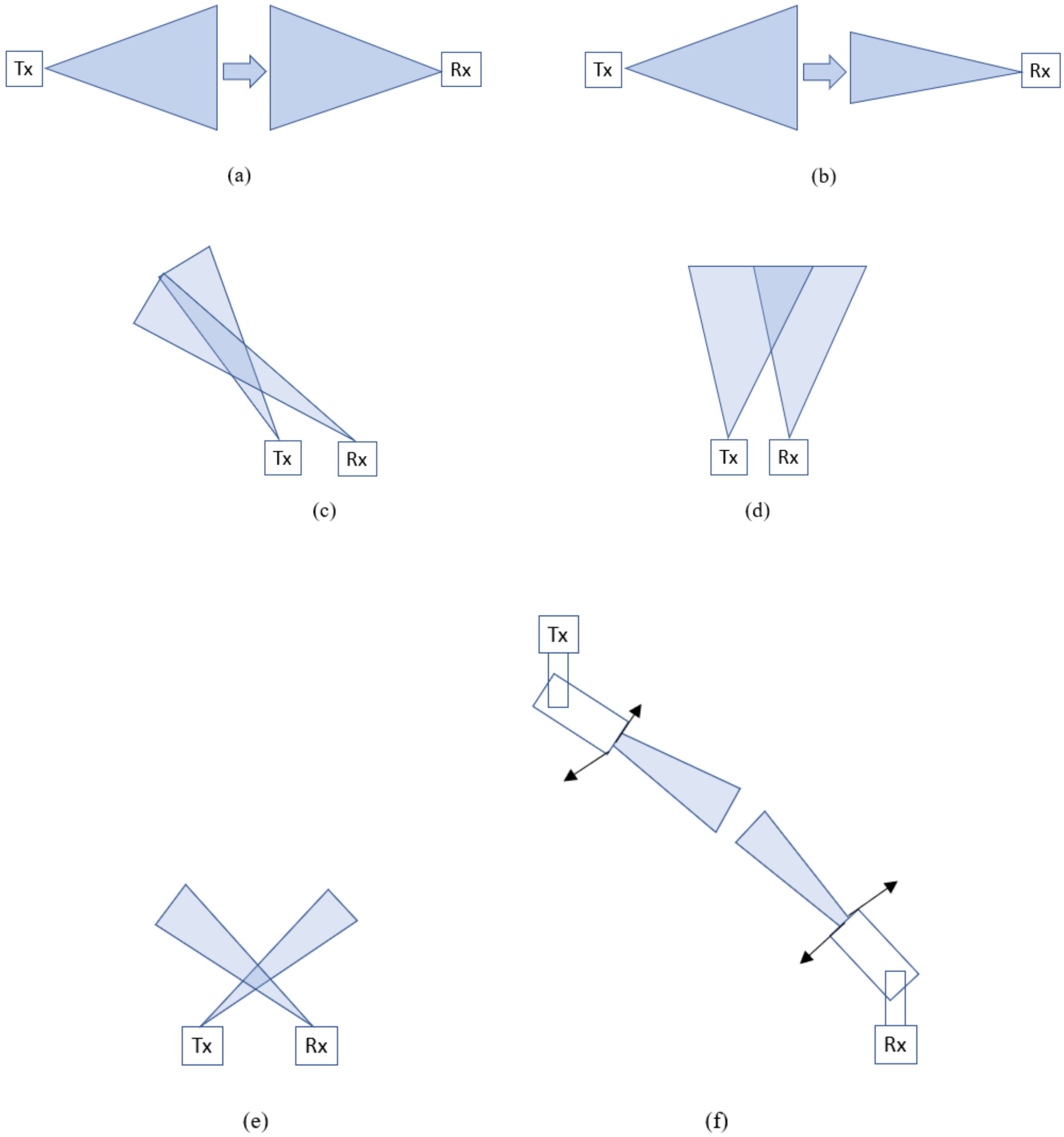


Figure 14 (a) Directed LOS configuration system (b) Diffused LOS configuration system (c – e) NLOS configuration systems. (f) Tracked configuration system

In above mentioned configurations, there is highest bandwidth in Figure 14 (a). That is directed LOS configuration, for diffused LOS configuration in Figure 14 (b) there is smaller bandwidth compared to (a), since the channel delay spread is increased. But for NLOS configurations as in Figure 14 (d) has minimum channel bandwidth due to long channel delay spread, while bandwidth is increasing to configuration of Figure 14 (c) and 14(e) [3].

3.1.2. Diffused LOS configuration

Diffused LOS configuration is very suitable for indoor or short-range communication link. It uses wide beam transmitters with wide FOV receivers. Its receiver can detect signal of transmitter for different path. While this type of transmission faces higher path loss and need high power transmitters. This type of configuration is generally used for point o multipoint communications systems. When detectors have large sizes, they face inter symbol interference (ISI) that minimizes the system speed.

3.1.2. NLOS configuration

NLOS configuration is establishing a communication link between transmitter and receiver, where propagation path is obstructed by a physical object in between. This obstacle could be building, trees, high power transmission lines, hills and other physical obstacles.

NLOS configuration link decrease the power efficiency. Compare to other wavelengths UV wavelengths are potentially suitable for NLOS communications as we have discussed it earlier.

3.1.3. Tracked configuration

In indoor tracked configurations transmitter and receivers are mounted in ceiling and table respectively. While there is capability of moving receiver in this configuration, since it receives reflection by physical objects inside room including walls and ceiling. Therefore, receiver alignment is not needed for such configuration link. For its LOS configuration link, as transmitter beam is narrow and directed to receiver, it needs to us lower power for transmitting information compared to diffused and NLOS links.

3.2. UV communication system application areas

UV communication systems are improving, there are several application areas for them, but their application areas are still emerging and extending due to new development and achievements in their communication systems. It can be used where security of communication and low power are very important compared to wavelength range and bandwidth [1].

Generally, UV communication systems can be applied for both civilian or military applications. It could be short range data communication [32-33], mobile connections [1], surveillance sensor networks, as fire or missile plume detection [8], for homeland security, between unmanned aerial vehicles UAVs and attended terminals, underwater communication system [39]. Some application areas are declared here in Figure 15 below.

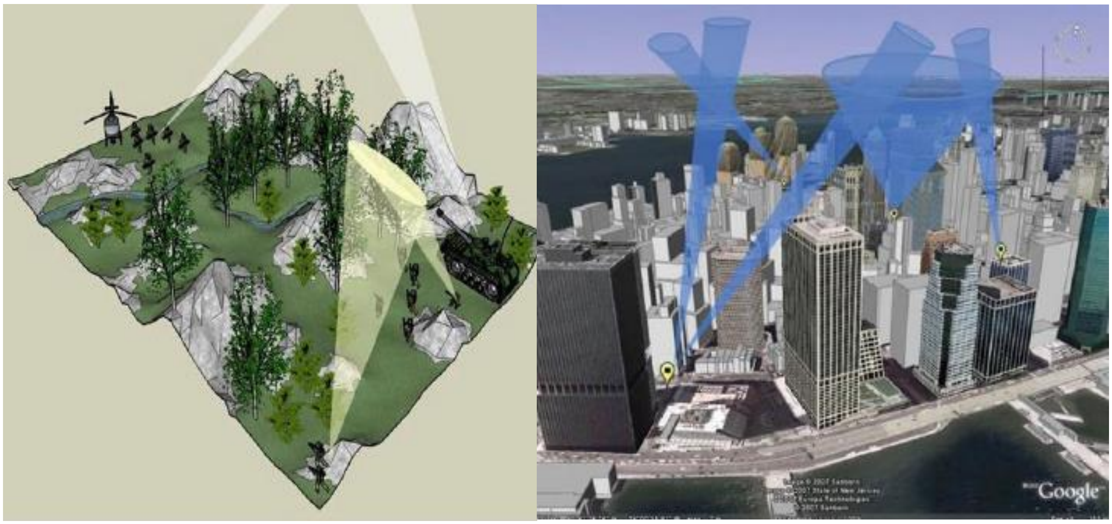


Figure 15 UV communication system with various obstacles [30]

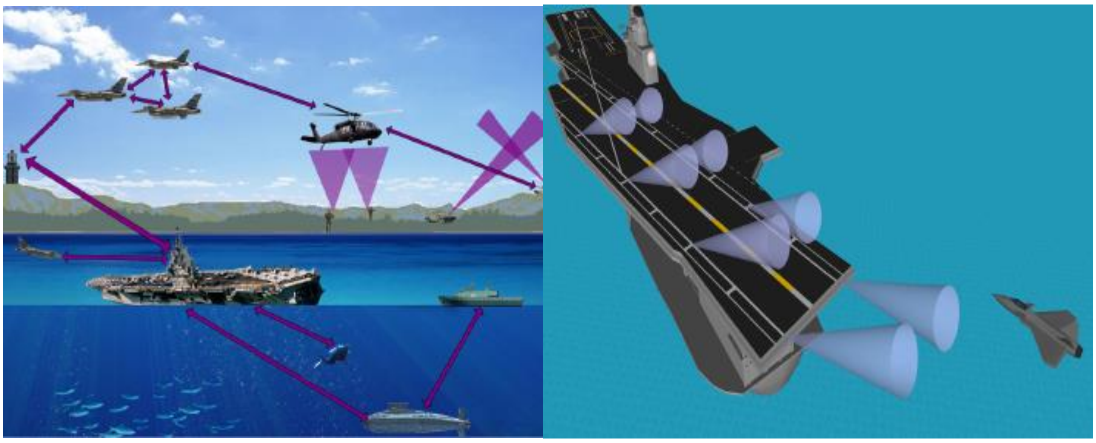
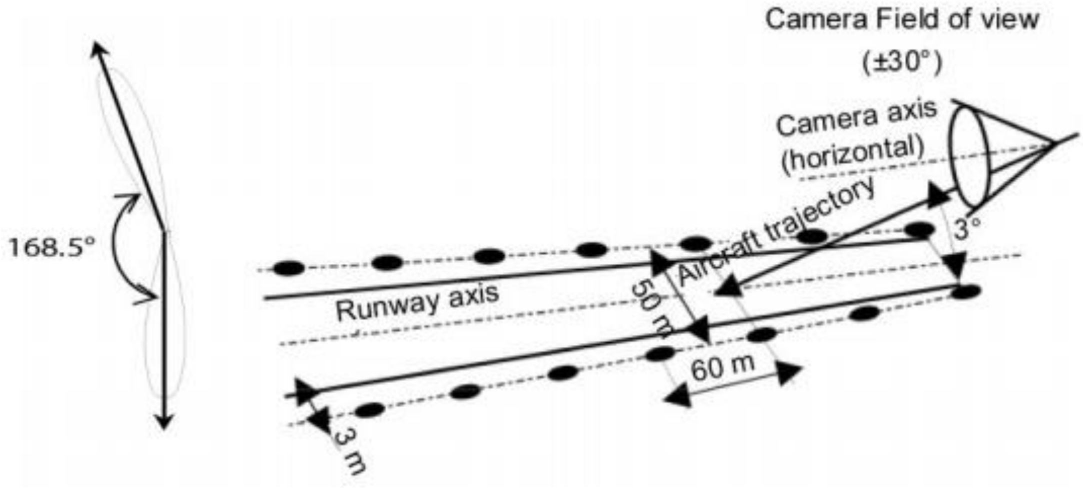


Figure 16 UV communication system for military application [30]

UV communication system have very wide range of applications more areas of applications could be used as very stable light source for sensors [34-35] and imaging [8-9], tactical battlefield [36], aircraft landing aid under low visibility atmospheric conditions [8]. UV communication systems are applicable in urban area as a backup network in case of disasters.



(a) (b)

Figure 17 (a) Angular dependency of runway light intensity in polar coordinates, horizontal plane. (b) Positioning of light sources along the runway. [8]

3.3. UV Safety for humans

Since UV radiations are significantly hazardous when fair protection guidelines are not considered. Over exposure to UV radiations can cause skin cancer, long term skin damage like wrinkles, eye damage and may disorganize human immune system [38]. Therefore, to do short range UV communication experiment, safety is very important issue to be considered. The American Conference of Governmental Industrial Hygienists (ACGIH, 2005) has set threshold limit value (TLV) of light exposure for human body safety under limited continuous period.

According to ACGIH the maximum permissible effective radiant exposure within 8 hrs continuous period for UV-band-C is 3 mJ/cm^2 and for UV-band-B is 4 mJ/cm^2, while this TLV limit for 365 nm is 30,000 mJ/cm2, this clearly shows that 365 nm is much safer compared to UV-band-B and band-C.

The graph of ACGIH TLVs for ultraviolet radiations with all UV wavelengths between 180 nm to 400 nm is shown here in Figure 18. If adult people are working under exposure of UV radiations but the exposure is in TLVs of ACGIH, they will not face any negative effect of erythema (sunburn) or photokeratitis (electric arc during welding or snow-blindness).

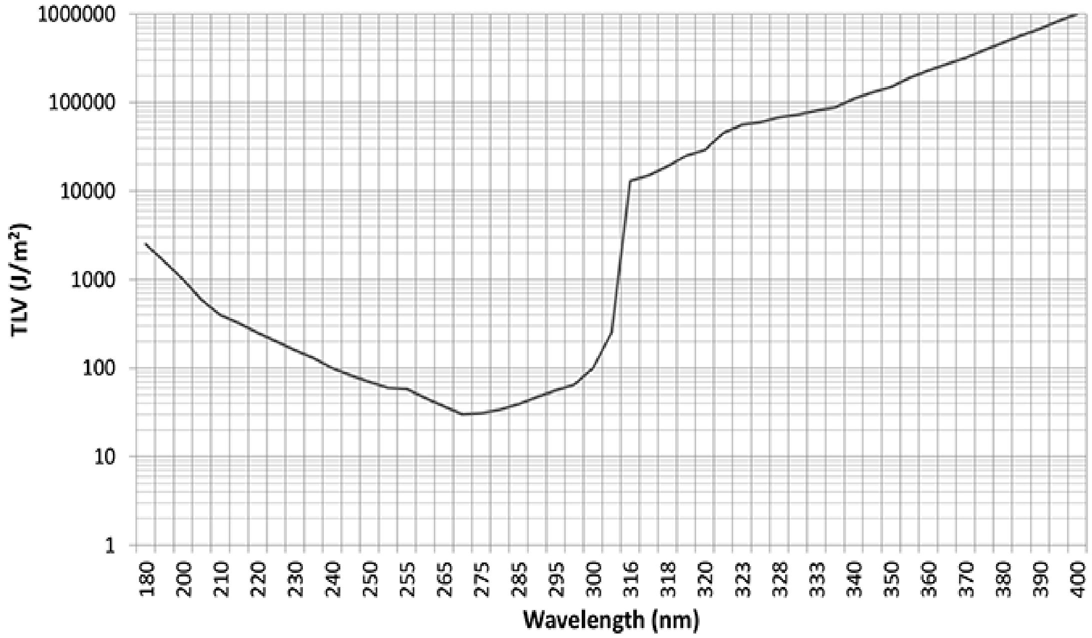


Figure 18 ACGIH TLVs for various UV wavelengths [ACGIH, 2005]

According to ACGIH TLVs for over exposure of UV light in spectral region of UV-band-B and C, the body part that will be potentially at risk are eye (cornea, conjunctiva, lens) and skin and adverse health effects are photokeratitis, photoconductivity, cataract genesis, erythema, elastosis and skin cancer. while over exposure of UV light in spectral region of UV-band-A can damage eye(lens) and adverse health effect is cataract genesis.

Self-protection and controls are always important and by considering some controls and awareness of the damages can reduce over exposure situations. Those self-protective controls can include protective clothes, hats, sun glasses, and sun screen. Mostly damages due to over exposure of solar radiations are in outdoor environments such as construction companies' workers, fishing workers, road construction workers, military and police, people who are doing ski, farming workers and other outdoor service workers. According to [37], workers who are in indoor environments are in exposure of solar in range of 10 to 20% of outdoor workers.

Chapter 4

Proposed UV communication system

We propose and experimentally explores UV-WDM with VLC using UV-band-A LED and VLC-blue LED in short range communication system. To mitigate noises and LED nonlinearity we will use Volterra decision feedback equalizer, and therefore we would be able to achieve higher data rate up to 64 Mbps with bit error rate (BER) under the forward error correction (FEC) 3.8 x 10-3.

4.1. Experimental Setup

The experimental setup of our proposed UV-WDM system is shown in Figure 19. An ultraviolet LED (Thorlabs M365D2) with typical output power of 1400 mW and a central wavelength of 365 nm is used with a blue color LED (Thorlabs M470D2) with typical output power of 710 mW and a central wavelength of 470 nm in transmitter side.

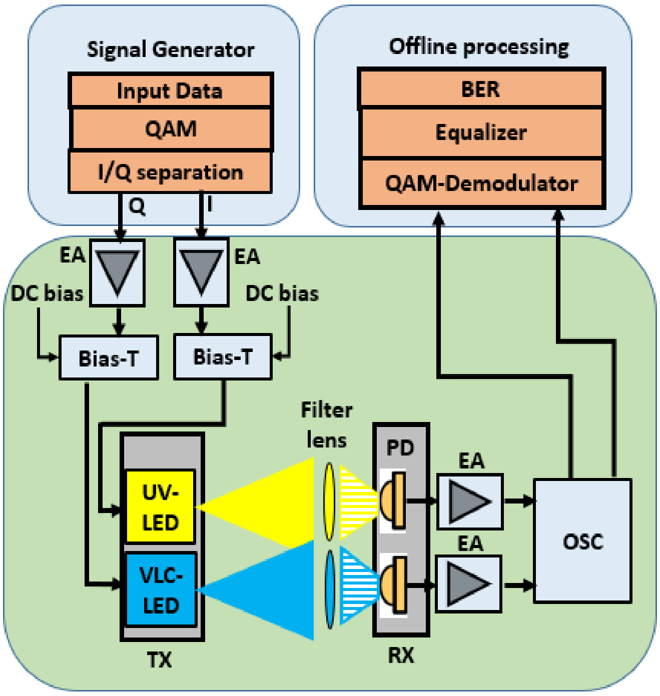


Figure 19 Block diagram of proposed UV communication system (EA: electrical amplifier, OSC: oscilloscope, DC: direct current).

M365D2 LED on a Metal-Core Printed Circuit Board (MCPCB) with M470D2 LED on an MCPCB is shown in Figure 20 (a) and our UV-WDM experimental view is shown in Figure 20 (b). The LEDs are circled as Tx and detectors are circled and point as Rx in below figure.

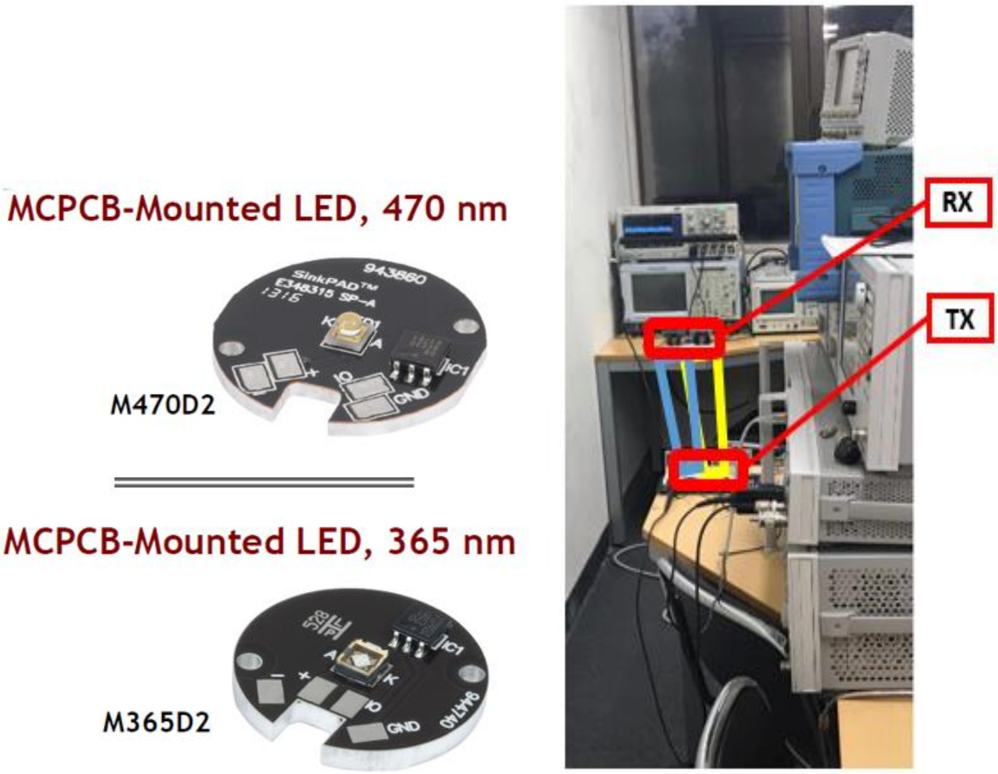
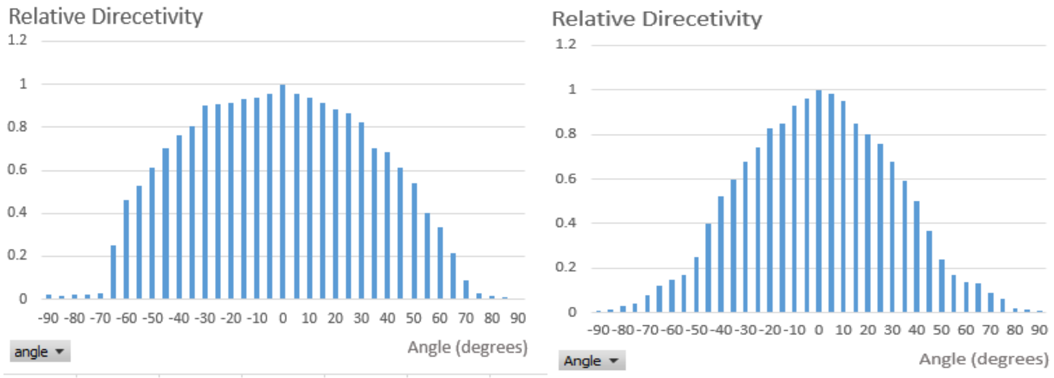


Figure 20 (a) Tx- LEDs mounted on MCPCP [Thorlabs] (b) Experimental view of the UV-WDM communication system

The relative directivity curve of UV LED is shown in Figure 21 (a) and relative directivity of VLC-LED is shown in Figure 21 (b). UV-LED has viewing full angle of 120 degrees and VLC LED has viewing full angle of 80 degrees.



(a) (b)

Figure 21 (a) Relative directivity curve of UV-LED. (b) Relative directivity curve of VLC-blue-LED

Firstly, the bit sequence is mapped to QAM modulation, then it is orthogonally shaped to I/Q. We have used vector signal generator N5172B to provide I/Q signals for both LEDs. Here I signal is for UV LED while Q signal is for blue LED. The generated signals are then pre-amplified by a 30-dB electrical amplifier. The signal is combined with DC-bias voltage for each LED by bias-tee and then each one is used to drive its own LED.

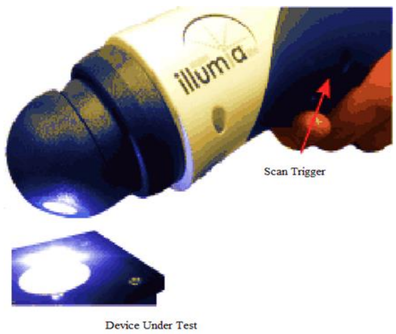
At the receiver, we have used commercial PIN photodiodes (Hmamatsu S6967) for detecting the signals. Prior to photodiodes optical filter lenses are used to filter out UV and blue lights. One lens (Thorlabs FB370-10) for UV light and one (Thorlabs FB470-10) for blue light. The received signals are then amplified by (20 dB) amplifier. MDO3024 digital oscilloscope is used for display and record of the received signals. In offline processing MATLAB program is used to analyze the signals.

Chapter 5

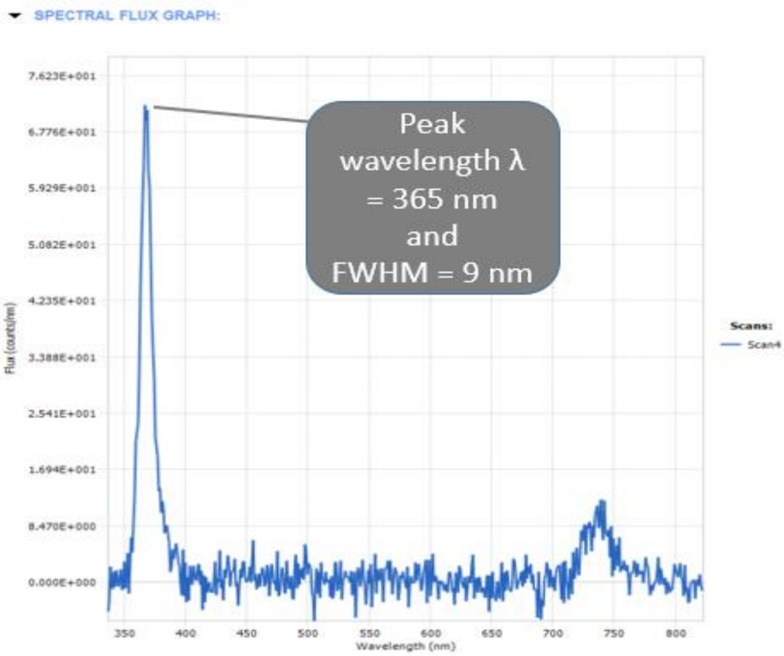
Results and discussions

5.1. Spectral Measurements

The spectral flux measurements were performed using illumia-lite portable light measurement system. The measurement device is shown in Figure 22 (a). It measures light's spectral flux in few centimeters. Since its calibration files were in range of 380 nm to 820 nm, we have added calibration files from 340 nm to 880 nm. We were able to do the spectral measurements of UV-band-A LED and VLC-blue LED, the result of UV-LED is drawn here in Figure 22 (b).



(a)



(b)

Figure 22 (a) illumia Lite MtrX measurement device. (b) UV-band-A LED spectral measurement

In this experiment we have considered 2s exposure time and three scans, while taking average of the three scans is plotted as result of spectral measurements. The result of UV-spectral measurements shows that peak wavelength is 365 nm. The flux measurement (luminous flux in lumens) per wavelength.

We conducted same experimental scan conditions with 2s of exposure time and three scans to average for VLC-LED. And its spectral flux measurements are depicted in Figure 23. The measurement shows that peak wavelength is 470 nm with FWHM of 9 nm.

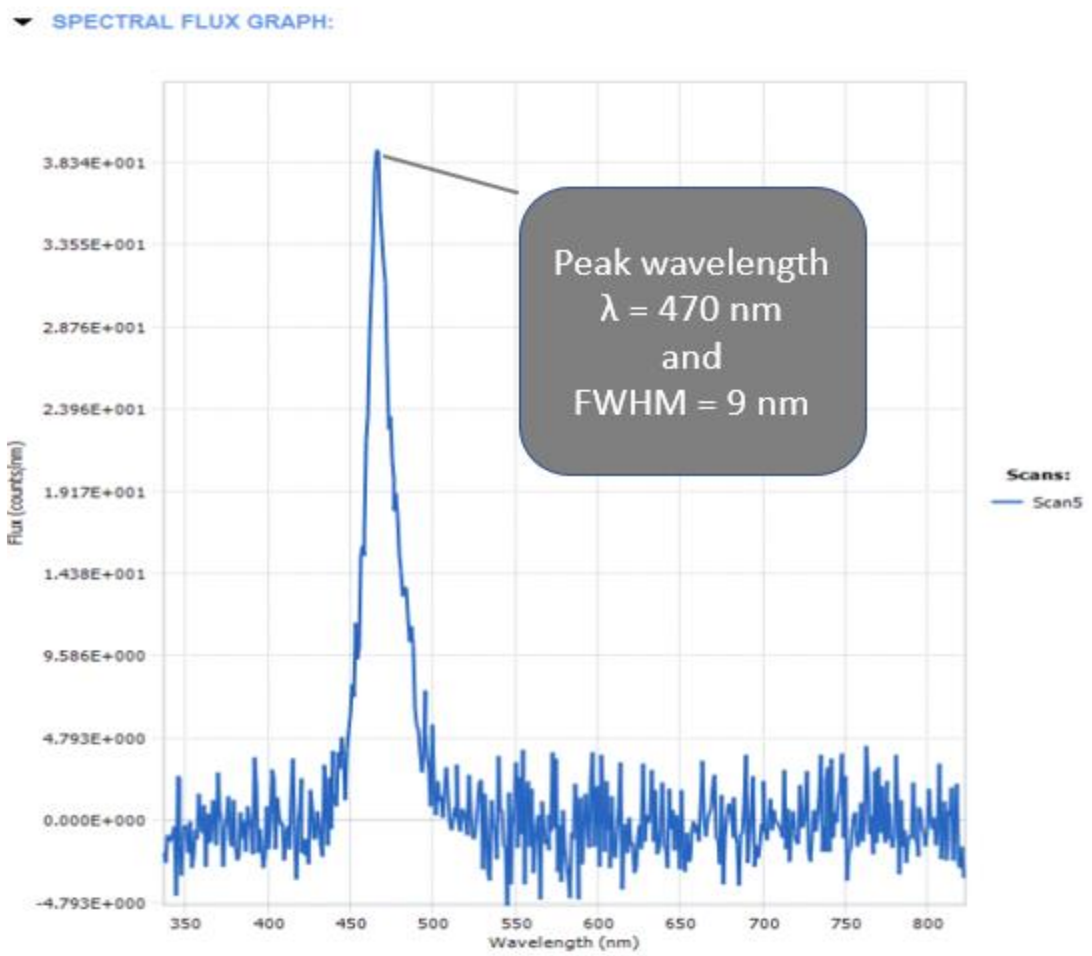


Figure 23 UV-band-A LED spectral measurement

5.2. Path Loss measurement

Since we are doing short range indoor experiment and propagation loss due to scattering and absorption is very low, therefore we have used Lambertian pathloss calculation for a system with optical band pass filters as described previously in our experimental setup and 20 dB amplifier gain for several distances from 0.6 to 4.2 m. Then we compared this measurement with experimental path loss measurement for different distances of UV-LED deploying a LOS link as shown in Figure 24. As it is clear from figure our UV-LED seems to be even better up to 2 m, but since simulation is considered near ideal condition we have little higher pathloss when distance is increased.

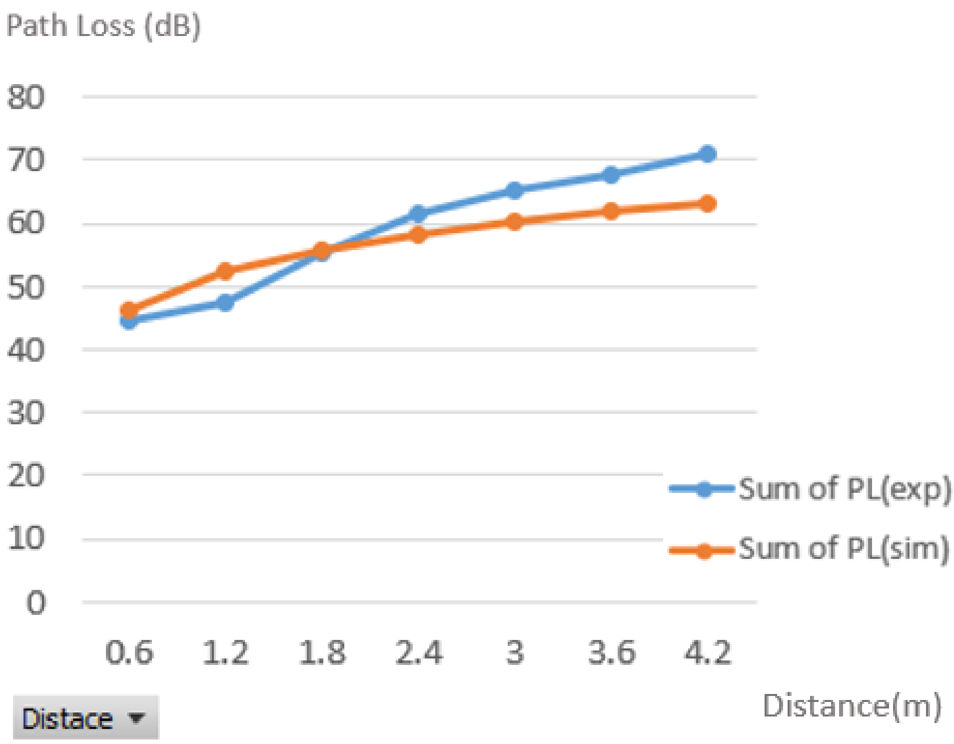


Figure 24 Path loss experimentally and simulation (Lambertian)

5.3. SNR Measurements

An experiment was performed to measure the environmental noises for both LEDs. As the result of experiment total noise voltage level for UV receiver was 14 mV, while it was 53.6 mV for blue-light receiver, approximately four-fold of the UV receiver. This higher noise level directly affects its SNR measurement level to be lower compared to

UV receiver as shown in Figure 25. In this experiment same power 3.2 W was considered for both LEDs.

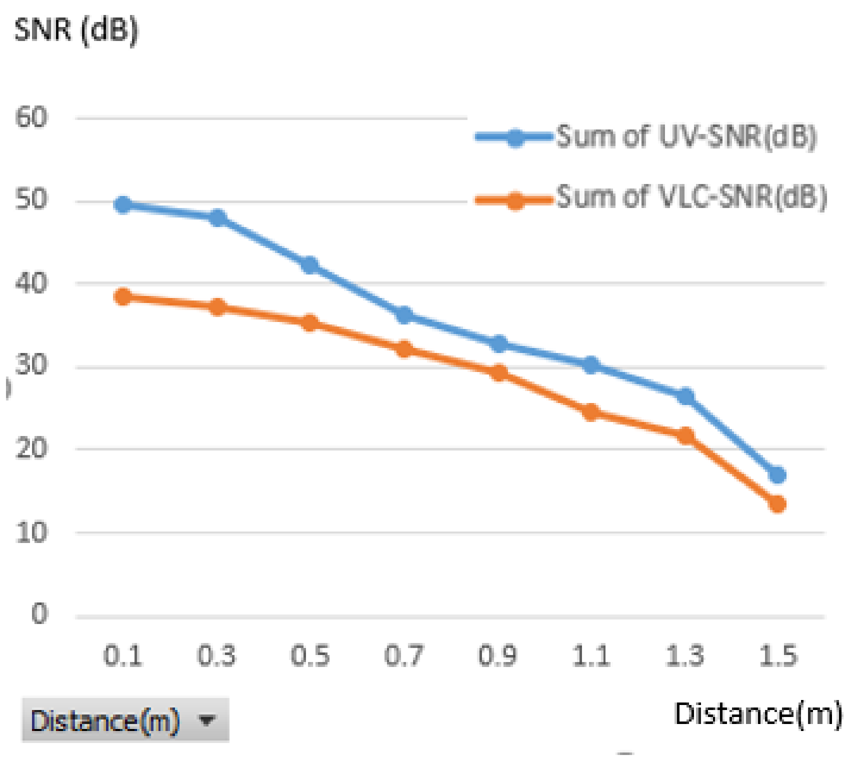


Figure 25 SNR measurement versus distance

5.4. BER measurements

To measure BER of our UV-WDM communication system, we have conducted several experiments. Firstly, we measured BER of the system with various data rates and then we calculated BER versus angle between Tx and Rx considering number of data rates. We will go through both mentioned measurements separately.

5.4.1. BER versus data rate of the system

We have measured the BER versus data rate of the UV communication system for several data rates from 34 to 75 Mbps as its result is drawn in Figure 26 for a threshold level of 3.8 x 10-3. The drive current for UV-LED is 1000 mA and its bias voltage is provided 4.0 V, while the drive current for blue-LED is 900 mA and 3.2 V for its biasing.

VDFE equalizer is used here to compensate nonlinearity of LEDs. Generally, VDFE is used for cancellation of inter symbol interference ISI and mitigation of nonlinearity of LEDs, therefore it helped to increase the data rate with better performance. For 4QAM when applying lower data rates as 34 Mbps to 56 Mbps the BER is much lower, but when we increase it to 64 Mbps its BER level is crossing the FEC threshold level. By applying 16-QAM scheme, system BER performance improved and we achieved data rate of 64 Mbps under FEC threshold level for our system.

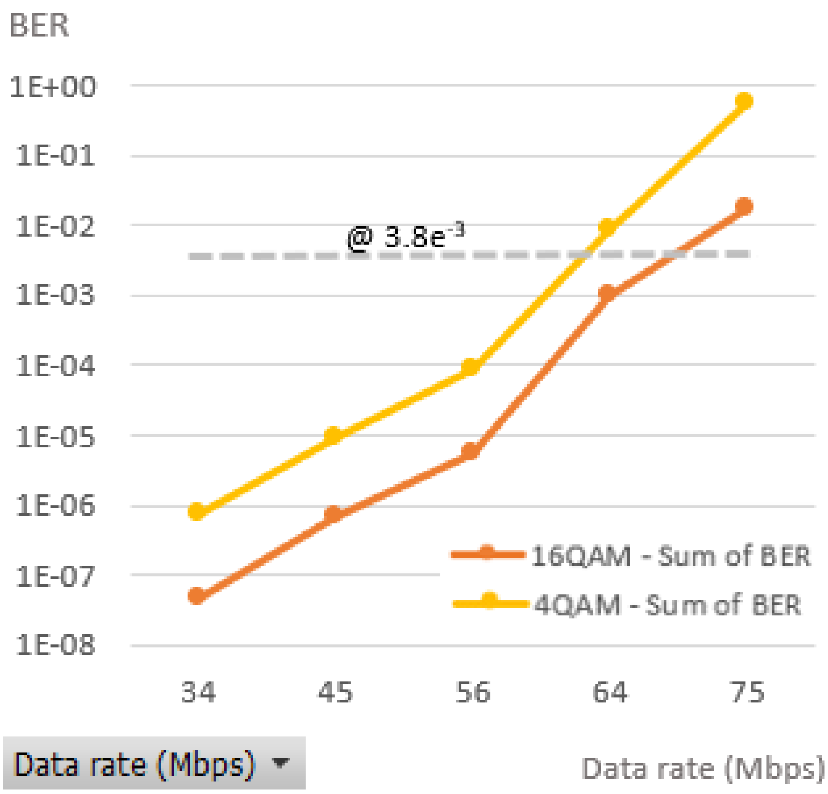


Figure 26 BER vs data rate for different order of QAM at 1.5 m

5.4.2. BER versus various angles between Tx and Rx

WE have measured BER of our UV communication system with various angles between transmitter and receiver for FEC threshold level of $3.8e^{-3}$. The result is shown in figure 27. We have put our receiver in points with different angles but same distance of 1.5 m from transmitter.

The result of experiment shows that for 4QAM we can achieve 34 Mbps with BER below FEC up to 10 degrees of angle, while for 16QAM we can achieve 64 Mbps with BER below threshold level of FEC up to 10 degrees of angle.

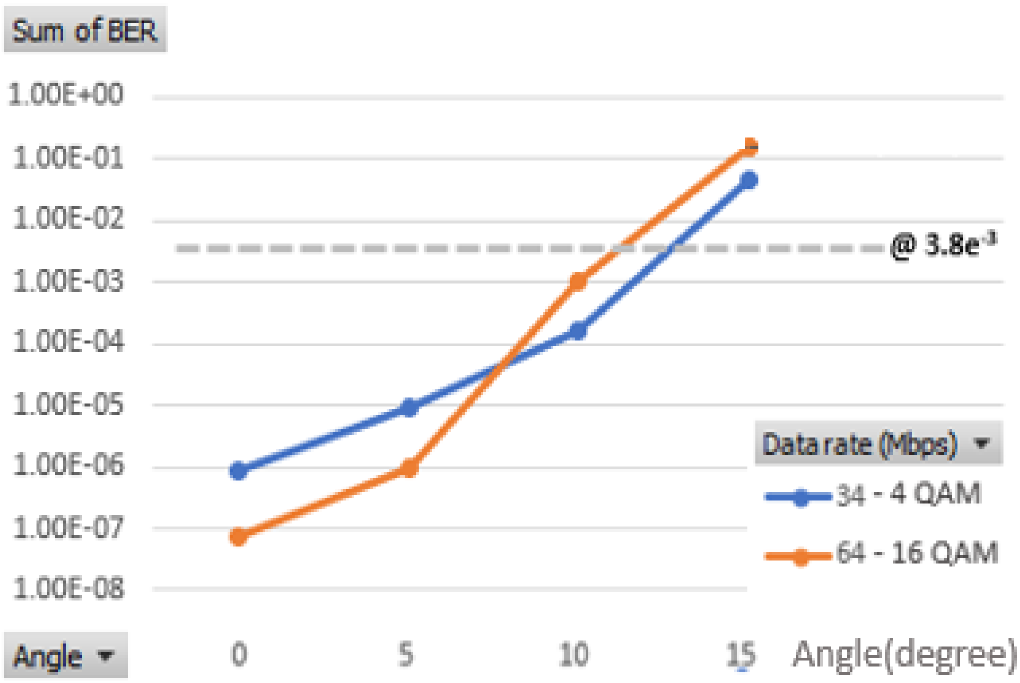


Figure 27 BER versus angle between LEDs and PDs

Chapter 6

Conclusion

In this paper we have reported UV-WDM with VLC and considering Volterra nonlinear equalizer with UV-365 nm and VLC-470 nm and achieved higher data rate 64 Mbps with BER under FEC threshold of 3.8 x 10-3. We had firstly performed an experiment to measure UV-band-A path loss, since path loss of UV-band-A is much lower compared to other UV-bands. We have compared our experimental results with a simulation-based measurement for several distances. The result of our experiment clears that our UV transmitter path loss perform better than a condition which is near to ideal situation.

Secondly, we conducted an experiment for environmental noise measurement at receiver side for both of our system detectors. Both LEDs are considered to have same conditions. As the result of experiment total noise voltage level for UV receiver was 14 mV, while it was 53.6 mV for blue-light receiver, approximately four-fold of the UV receiver. This higher noise level directly affected VLC detector in SNR measurement level to be in lower compared to UV receiver.

We have measured the BER for several data rate of the UV-WDM communication system from 34 to 75 Mbps for an FEC threshold level of 3.8 x 10-3. To improve BER performance we used VDFE nonlinear equalizer here to compensate nonlinearity of LEDs spectral characteristics. We achieved that for 4QAM when applying lower data rates such as 34 Mbps to 56 Mbps, its BER is much lower, but when we increase it to 64 Mbps its BER level is crossing the FEC threshold level. Therefore, we can have 56 Mbps data rate by using 4QAM. When we applied 16-QAM scheme, system BER performance improved and we achieved data rate of 64 Mbps under FEC threshold level for our system.

We used diffused LOS link to measure our system performance not in a directed LOS link, but in configurations to have direction angles between Tx and Rx. We measured BER of our UV communication system with various angles between transmitter and receiver for FEC threshold level. We have put our receiver in points with different angles but same distance of 1.5 m from transmitter. The result of experiment shows that for 4QAM we can achieve 34 Mbps with BER below FEC up to 10 degrees of angle, while for 16QAM we can achieve 64 Mbps with BER below threshold level of FEC up to 10 degrees of angle.

To the best of our knowledge it is the first time using WDM for UV communication system. Considering non-LOS link can be followed as a future path. To improve further system performance, we should consider higher nonlinear terms for equalizer.

References

[1]. M Uysal, C Capsoni, Z Ghassemlooy, A Boucouvalas, E Udvary. Optical wireless communications: an emerging technology. Springer, 2016.

[2]. AK Majumdar, “Advanced Free Space Optics (FSO): A Systems Approach”, 2014

[3]. X. Sun, B.S. Ooi, “HIGH DATA RATE OPTICAL WIRELESS COMMUNICATIONS BASED ON ULTRAVIOLET BAND”, October 2017

[4]. Kahle, A. B., Weill, G., Carter, W. D., Ulaby, F. T., Siqueira, P., Nashashibi, A., and Sarabandi, K. (2003). RADIATION (SOLAR). Proceedings of the IEEE, 63:137-147.

[5]. Y. Xing, M. Zhang, “Experimental Study of a 2x2 MIMO Scheme for ultraviolet communications”, IEEE, ICOCN, 978-1-5090-3491-8, Sept. 2016,

[6]. D. Kedar, and S. Arnon, “Subsea ultraviolet solar-blind broadband free-space optics communication,” Opt. Eng. 48(4), 046001 (2009).

[7]. E. S. Fishburne, M. E. Neer, and G. Sandri,“Voice communication via scattered ultraviolet radiation,”Tech. Rep. 274, Aero-nautical Research Associates of Princeton, Inc., Princeton,NJ 1976.

[8]. C. Lavigne, G. Durand, and A. Roblin, “Simulation comparison of aircraft landing performance in foggy conditions aided by different UV sensors,”Appl. Opt 48(12), 2203-2213(2009).

[9]. C. Lavigne, G. Durand, and A. Roblin, “Ultraviolet light propagation under low visibility atmospheric conditions and its application to aircraft landing aid,” Appl. Opt 45(36), 9140-9150 (2006)

[10]. Ghassemlooy, Z., Popoola, W., Rajbhandari, S. (2013). Optical Wireless Communications. Boca Raton: CRC Press, https://doi.org/10.1201/b12687

[11]. MP Lin, CJ Chen, LW Shan, MC Wu, Fabrication and characterization of 395 nm ultraviolet GaN light-emitting diodes, Solid-State Electronics, 2017

[12]. Sun, X.; Zhang, Z.; Chaaban, A.; Ng, T. K.; Shen, C.; Chen, R.; Yan, J.; Sun, H.; Li, X.; Wang, J.; Li, J.; Alouini, M.-S.; Ooi, B. S. 71-Mbit/s ultraviolet-B LED communication link based on 8-QAM-OFDM modulation. Opt. Express 2017, 25, 23267– 23274, DOI: 10.1364/OE.25.023267

[13] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, Optical Wireless Communications: System and Channel Modelling with MATLAB. Boca Raton, FL, USA: CRC Press, 2013

[14]. Y Muramoto, M Kimura, S Nouda, Development and future of ultraviolet light-emitting diodes: UV-LED will replace the UV lamp, Semiconductor Science and Technology, 2014

[15]. R Guzman, Footwear with black light LED, US Patent 7,181,870, 2007

[16]. Museum of Science, Boston, Harvard University astronomers and Smithsonian Institution DEMONSTRATIONS MANUAL [PDF file], Retrieved from https://www.cfa.harvard.edu/seuforum/exhibit/resources/DemoManual.pdf

[17]. UV-Technik Speziallampen GmbH, May 2016, Operating Manual UVC Low Pressure Lamps [PDF file], Retrieved from https://www.uvtechnik.com/uv-technik/produkte/pdf en/uvc_low_pressure_lamps.pdf

[18]. Helios Quartz, 2016, UV Lamp [PDF file], Retrieved from http://www.heliosquartz.com/wp-content/uploads/2016/01/Helios-Quartz_UV-LAMPS_eng.pdf

[19]. Aquafine Corporation, 2017, UV LAMP TECHNOLOGIES [PDF file], Retrieved from https://www.aquafineuv.com/cms portals/aqua_com/cms/static/resources/AquafineUVLampTechnologies.pdf

[20]. M. R.Krames, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers , and M. G. Craford, “Status and Future of High-Power Light-Emitting Diodes for Solid State Lighting,” J. Disp. Technol.3(2), 160–175 (2007)

[21]. S. Pimputkar, J. S.Speck, S. P. DenBaars, and S.Nakamura, “Prospects for LED lighting” Nat. Photonics 3(4), 180–182 (2009)

[22]. 51C. Lee, C. Shen, H. M. Oubei, M. Cantore, B. Janjua, T. K. Ng, R. M. Farrell, M. M. El-Desouki, J. S. Speck, S. Nakamura, B. S. Ooi, S. P. Denbaars, "2 Gbit/s data transmission from an unfiltered laser-based phosphor-converted white lighting communication system", Opt. Express, 23(23), 29779-29787 (2015)

[23]. 54B. Janjua, H. M. Oubei, J. R. D. Retamal, T. K. Ng, C. T. Tsai, H. C. Kuo, G. R. Lin, J. H. He, B. S. Ooi, "Going beyond 4 Gbps data rate by employing RGB laser diodes for visible light communication", Opt. Express, 23(14), 18746-18753 (2015).

[24]. C. Shen, C. Lee, T. K. Ng, S. Nakamura, J. S. Speck, S. P. DenBaars, A. Y. Alyamani, M. M. El-DesouKi, B. S. Ooi, "High-speed 405-nm super luminescent diode (SLD) with 807-MHz modulation bandwidth," Opt. Express, 24(18), 20281-20286 (2016)

[25]. G Keiser, Optical Fiber Communications, 3rd ed New York: McGraw-Hill, 2000

[26]. K Kishino, M S Unlu, J I Chyi, J Reed, L Arsenault and H Morkoc, Resonant cavity-enhanced (RCE) photodetectors, IEEE Journal of Quantum Electronics, 27, 2025–2034, 1991

[27]. W Yih-Guei, K S Giboney, J E Bowers, M J W Rodwell, P Silvestre, P Thiagarajan and G Robinson, 108 GHz GaInAs/InP p-i-n photodiodes with integrated bias tees and matched resistors, IEEE Photonics Technology Letters, 5, 1310–1312, 1993

[28]. K Kato, Ultrawide-band/high-frequency photodetectors, IEEE Transactions on Microwave Theory and Techniques, 47, 1265–1281, 1999

[29]. R M Gagliardi and S Karp, Optical Communications, 2nd ed New York: John Wiley & Sons Inc, 1995

[30]. L Liao, Long Distance Non-Line-of-Sight Ultraviolet Communication Channel Analysis and Experimental Verification, UC Riverside, 2015

[31]. A M Street, P N Stavrinou, D C Obrien and D J Edwards, Indoor optical wireless systems—A review, Optical and Quantum Electronics, 29, 349–378, 1997

[32]. S. Arnon, and D. Kedar, “Non-line-of-sight underwater optical wireless communication network,” J. Opt. Soc. Am 26(3), 530-539 (2009).

[33]. G. A. Shaw, A. M. Siegel, and J. Model, “Extending the range and performance of non-line-of sight ultraviolet communication links” Proc. SPIE 6231, 62310C (2006)

[34]. D. Kedar, and S. Arnon, “Non-line-of-sight optical wireless sensor network operating in multiscattering channel,”Appl. Opt 45(33), 8454-8461 (2006).

[35]. D. Kedar, and S. Arnon, “Subsea ultraviolet solar-blind broadband free-space optics communication,” Opt. Eng. 48(4), 046001 (2009)

[36]. B. Charles, B. Hughes, A. Erickson, J. Wilkins, and E. Teppo, "An ultraviolet laser based communication system for short range tactical applications," Proc. SPIE 2115, 79–86 (1994)

[37]. World Health Organization, 2002, global solar UV index-a practical guide [PDF file], Retrieved from https://www.who.int/uv/publications/en/UVIGuide.pdf

[38]. World Health Organization (WHO). Ultraviolet Radiation as a Hazard in the Workplace (2003) (PDF)

[39]. XIAOBIN. S, WENQI. C, "375-nm ultraviolet-laser based non-line-of sight underwater optical communication", OPTICS EXPRESS, Vol. 26, No. 10, 14 May 2018, pp. 12870-12877

[40]. D Han, X Fan, K Zhang, R Zhu, Research on multiple-scattering channel with Monte Carlo model in UV atmosphere communication, Applied optics, 2013

[41]. H Ding, G Chen, AK Majumdar, BM Sadler, Z Xu, Modeling of non-line-of-sight ultraviolet scattering channels for communication, IEEE journal on selected areas in communications, Vol. 27, NO. 9, 2009

Research Achievement

Patmal Mohammad Hamed, Liu Jiang, and Shigeru Shimamoto, "Short-range high data rate WDM ultraviolet-A LED-based communication link", in a proceeding of IEICE conference on "Compositive Information Communication Technologies and Applications for Future Network Systems", Waseda University Nishiwaseda Campus (Tokyo), March 19 – 22, 2018.

Patmal Mohammad Hamed, Liu Jiang, and Shigeru Shimamoto, "Short-range high data rate WDM ultraviolet-A LED-based communication link", in a proceeding of WUHU workshop 2018, on Network, Waseda University Nishiwaseda Campus (Tokyo), November 30 – December 1, 2018