

DESIGN AND FABRICATION OF HYBRID PPG SENSOR SYSTEM FOR HEART RATE MONITORING

ファジャナ アクタ ジアマ

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DESIGN AND FABRICATION OF HYBRID PPG SENSOR SYSTEM FOR HEART RATE MONITORING

By

Farjana Akter Jhuma

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Professor Dr. Reiji Hattori

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ABSTRACT

A photoplethysmography (PPG) sensor has become an essential health condition monitoring device due to its non-invasive, inexpensive, convenient, and user-friendly technology. The advantage of low-cost processing and implementation convenience has made the PPG sensor suitable for monitoring basic health condition signs like heart rate (HR), pulse and respiration rate, peripheral oxygen saturation (SpO_2), and heart rate variability. PPG sensor employs a light source (LED or OLED) and detector (PD or OPD) for detecting the light transmitted through or reflected from the human skin. Commercially available all inorganic PPG sensors are expensive and fragile and can be replaced by all organic PPG sensors. However, all organic PPG sensors suffer from the lifetime shortage of OLED. Considering these issues, a reflective mode hybrid PPG sensor system with a combination of inorganic LED and wrap-around circular-shaped OPD with a proper driving circuit is proposed in this study. The use of LED and OPD on different substrates allowed easy fabrication of OPD using a solution process with design freedom.

The P3HT:PC₆₁BM bulk heterojunction was adopted for the active layer of the OPD which can detect light in the visible light spectrum covering the red, green, and blue LED illumination. The OPD performance was analyzed for different LED illumination conditions, i.e., LED light wavelength and luminous intensity as well as OPD biasing voltage in the negative directions to observe the effect on dark and photocurrent density of the OPD. The obtained photocurrent density showed up to 3–4 orders of magnitude higher than the dark current density when illuminated with red, green, and blue LED illuminations at zero bias conditions making it suitable for PPG signal detection. An almost linear relationship of the photocurrent density with the LED luminous intensity at different applied voltages in the negative direction ensured the OPD's operation ability in various luminous intensity and biasing conditions. An OPD with an area of 16 mm² maintaining a 0.65 mm distance between LED and OPD was optimized for the application in a hybrid PPG sensor for ensuring effective light harvest through observing its performance in terms of design variations like OPD inner periphery shape, LED-to-OPD distance, and OPD active area.

A driving circuit was designed with a combination of TIA, filtering, and amplifier circuit for the conversion of the small OPD signal to a voltage signal, filtering the signal for reduction of noise coming from undesired frequency range and amplifying to a suitable range for ADC

operation of the MCU unit. The hybrid PPG sensor could successfully detect the PPG signal from the fingertip of a human subject when the fabricated OPD glass substrate was connected to the customized PCB with all the components of the driving circuit and LED mounted on it. The MCU unit controlled the operation of the LED as well as the ADC sampling and UART communication for acquiring the accurate PPG signal.

The acquired PPG signal was preprocessed by a combination of moving average and Butterworth band-pass filter to remove the noise induced by finger motion while doing the measurement. Using FFT analysis, the heart rate was calculated from the collected PPG signal with an acceptable range of error when compared to a commercially available PPG sensor device.

For considering the power management of the device, PPG signals were obtained for different LED duty cycles and luminous intensity, i.e., brightness. Though the higher duty cycle improved the heart rate calculation accuracy, it needed more power compared to the lower duty cycle conditions. To have a trade-off between these two factors, a 50% duty cycle was maintained throughout the measurement using the hybrid sensor. However, the LED luminous intensity variation showed negligible effect on the heart rate accuracy indicating that the sensor can be operated at lower brightness conditions consuming lower power.

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moving average and Butterworth bandpass filter with a cut-off frequency of 0.5 Hz-16 Hz to remove unwanted frequency signals.

Figure 5.2 Process of heart rate estimation

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LIST OF ABBREVIATIONS

AC	alternating current
ADC	analog to digital converter
AFE	analog front end
BHJ	bulk heterojunction
BLE	Bluetooth low energy
DC	direct current
DFT	discrete Fourier transform
ECG	electrocardiography
EMD	empirical mode decomposition
EQE	external quantum efficiency
ETL	electron transport layer
FFT	fast Fourier transform
FIR	finite impulse response
FPCB	flexible printed circuit board
HTL	hole transport layer
HOMO	highest occupied molecular orbital
HR	heart rate
LED	light-emitting diode
LDR	linear dynamic range
LUMO	lowest occupied molecular orbital
MCU	microcontroller unit
NEP	noise equivalent power
NIR	near-infrared
OLED	organic light emitting diode
OPD	organic photodetector
OPT	organic phototransistor
OPV	organic photovoltaic
OSC	organic solar cell
PCB	printed circuit board

PD	photodetector
PPG	photoplethysmography
PRI	pulse repetition interval
PWM	pulse width modulation
RLS	recursive least squares
ROA	reflectance oximeter array
SCB	serial communication block
SpO2	peripheral oxygen saturation
TIA	transimpedance amplifier
UART	Universal asynchronous receiver-transmitter

CHAPTER I

INTRODUCTION

1.1 OVERVIEW Of HYBRID PPG SENSOR

A photoplethysmography (PPG) sensor is a health condition monitoring device that measures the blood volume changes through the arteries during each cardiovascular pulsation cycle by sensing the light reflected or transmitted from the human skin. It is an inexpensive, non-invasive, convenient, and user-friendly device for monitoring health conditions and avoiding potential illness. The advantage of low-cost processing and implementation convenience of the PPG sensor has made it suitable for monitoring basic health condition signs like heart rate (HR), pulse and respiration rate, peripheral oxygen saturation (SpO_2), and heart rate variability [1-3]. Though heart rate can be measured by electrocardiogram (ECG), and the piezoelectric effect, it is unsuitable for measuring peripheral oxygen saturation for high sensitivity to artificial muscle movements during portable operations [4, 5]. The PPG sensor employs the combination of one light source and detector to estimate the heart rate whereas for estimation of the SpO_2 it needs two different light sources with different wavelengths [6].

The conventional PPG sensor prepared with silicon and other inorganic photodetectors supports high carrier mobility, tunable bandgap, and low exciton binding energy, however, it is still expensive, fragile, and needs a complicated fabrication process. Moreover, its roughness to the skin interface sometimes results in data inaccuracy and limited sight of application to the human body [7-9]. Organic optoelectronic devices (organic light emitting diode, OLED, and organic photodetector, OPD) have become a good alternative to overcome these issues during the last decade for their advantageous behaviors like lightweight and flexibility, cost-effective and simple fabrication process. The fabrication ability on large size areas compared to the restricted size of the general silicon-based photodiode (PD) makes them a preferable option for wearable medical devices. Additionally, the design freedom of optoelectronic devices allows

different types of structural combinations of OPD and OLED, which can be very efficient for PPG signal acquisition from the skin interface with lower power consumption [9-12].

The hybrid PPG sensor that we proposed in this work for a reflective mode operation is based on the combination of an inorganic commercially available light-emitting diode (LED) and an organic photodetector OPD. The system structure for the hybrid PPG sensor consists of three basic parts, i.e., inorganic-organic optoelectronic devices, a driver circuit including the trans-impedance amplifier (TIA), analog filters, and amplifiers, a microcontroller unit (MCU) for controlling LED operations and analog-to-digital (ADC) conversion of PPG signal, and a signal processing media, i.e., PC as illustrated in Figure 1.1. The LED and the OPD in different substrates provided the freedom to design and fabricate the OPD with a varied choice. Once the OPD was fabricated, it was connected to the LED mounted on a customized printed circuit board (PCB) with the driving circuit via two spring header pins and fixed with a device holder for easy measurement conditions and protection from ambient noise.

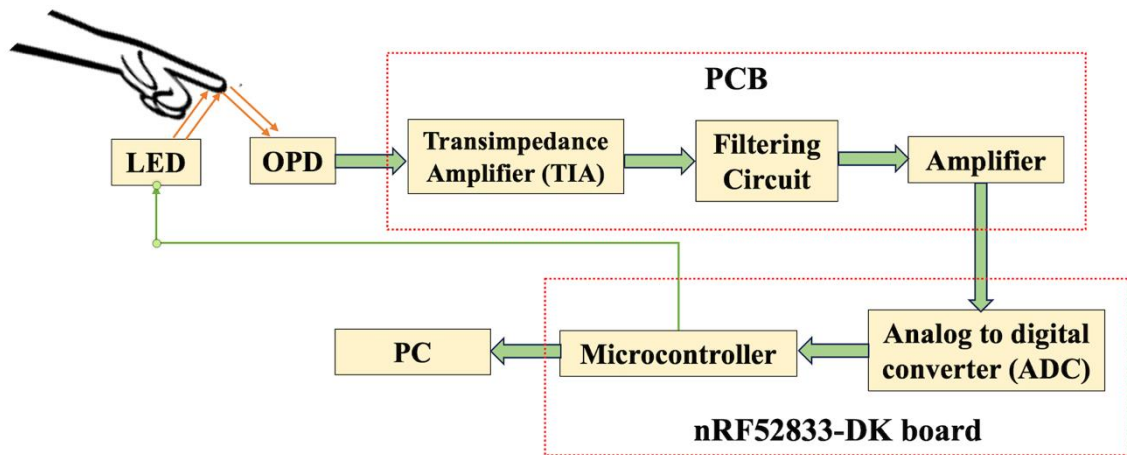


Figure 1.1: Block diagram of the proposed hybrid PPG sensor system

This thesis demonstrates a hybrid (inorganic-organic) PPG sensor system. It designs and fabricates organic photodetector with varying geometrical conditions, i.e., the distance between OPD and LED, OPD inner periphery structure and area of OPD, and evaluates the OPD performance in terms of dark and photocurrent density and their ratio, i.e., the on/off ratio for

different illumination condition of LED (wavelengths, luminous intensity) and varying OPD biasing voltages. It also addresses the process of PPG signal acquisition and HR calculation with the combination of optimized OPD and inorganic LED along with other components of the hybrid system and evaluates the sensor system performance for varying LED duty cycles and luminous intensity affecting the power consumption of the system.

1.2 MOTIVATION AND PROBLEM STATEMENT

The increasing concern for monitoring vital health signs in regular conditions as well as during physical activities has imposed importance in the field of wearable medical devices performance enhancement for personal health care. PPG sensor devices have been developed for constantly monitoring human performance noninvasively and with ease. PPG sensors measuring HR, SpO₂, and other health conditions with accuracy and reliability can gain the trust of medical professionals for an accurate assessment of their patients. Furthermore, the PPG sensor device can be a useful tool for timely monitoring, identifying, and diagnosing various cardiovascular-related diseases like atherosclerosis and arterial stiffness [6].

Currently, many commercial pulse meters and pulse oximeter devices are available on the market employing the PPG sensors with inorganic optoelectronics. However, to improve power consumption, signal quality, and flexibility, all organic optoelectronics (OLED and OPD) in PPG sensor devices have been adopted as a solution with the advantage of their flexibility and design freedom. However, all-organic PPG sensor devices, though supporting continuous health monitoring at low power measurement conditions, experience a lifetime shortage of OLED in some practical perspectives. Furthermore, OLEDs with small device areas in organic sensors operated at relatively high brightness can become a challenge for reducing the degradation of the OLED in case of high-brightness operation [13]. Hybrid PPG sensor configuration, i.e., the combination of inorganic LED and OPD can become a solution to this problem supporting the independent and easy fabrication of OPD with design freedom without degrading the LED.

1.3 RESEARCH OBJECTIVE

This research project aims to develop a new hybrid PPG sensor system design for the efficient detection of PPG signals and monitoring health conditions like heart rate using the system. The objectives of this research can be summarized as follows:

- I. To design and fabricate organic photodetector devices with different geometrical conditions used for developing the PPG sensor system.
- II. To observe the performance of the OPD devices for different light wavelengths and luminous intensity and OPD biasing voltage for optimization of OPD.
- III. To develop the driver circuit for the PPG sensor for processing the PPG signals before HR calculation.
- IV. To design a customized printed circuit board (PCB) containing the LED and the driving circuits together
- V. To evaluate the sensor system performance in terms of varying LED duty cycle and luminous intensity for power consumption management.

1.4 THESIS ORGANIZATION

This thesis consists of six chapters organized as follows:

Chapter One gives an overview of the proposed hybrid PPG sensor, the problem statement, and motivation after this work, followed by research objectives.

Chapter Two briefly explains the fundamentals of the PPG, i.e., its principle and operation modes. It gives a brief overview of the optoelectronic components of the PPG sensor system, i.e., the light emitter LED, and the light detector OPD. It also comprises some literature review and related works, previously done on PPG sensor devices.

Chapter Three discusses briefly the design and fabrication process of the OPD. The dark and photocurrent density dependence on different illumination conditions, i.e., LED luminous intensity variation, LED wavelength, and OPD biasing voltages is presented. Following that, OPD performance in terms of design variation, i.e., OPD inner periphery geometry, OPD to LED distance, and OPD area is also presented.

Chapter Four discusses the system design developed for the proposed hybrid PPG sensor system. The driver circuit and its stages are explained. The MCU unit, the device holder design, and the sensor system assembly process are also presented in this chapter. The PPG signal acquisition process is also presented in this chapter.

Chapter Five illustrates the algorithm for calculating the heart rate from the obtained PPG signal from the hybrid PPG sensor. It also contains the results of the proposed PPG sensor system's performance and accuracy in the case of heart rate measurement for different LED duty cycles and luminous intensity conditions with power consumption management consideration.

Chapter Six summarizes the outcomes of all analyses throughout the study. Future works and recommendations for improving the sensor system performances are also included.

CHAPTER II

HYBRID PPG SENSOR FUNDAMENTALS

2.1 INTRODUCTION

The popularity of the PPG sensor technology for heart rate monitoring techniques has increased in the last decade due to its cost-effectiveness, operation simplicity, and user-friendly interface to human body parts. This chapter presents the fundamentals of PPG, i.e., its principle and operation modes. It also represents the basics of optoelectronic components regarding the hybrid PPG sensor and some literature reviews about the PPG sensor previously studied by the researchers.

2.2 PPG FUNDAMENTALS

Photoplethysmography is a non-invasive optical sensing technique of microvascular blood volume changes in tissues due to the circulatory system's pulsatile nature. The method estimates the volumetric changes in blood depending on the optical properties of human tissue such as absorption, reflection, and transmission under a specific wavelength of light. The light emitter placed close to the tissue surface emits light of a particular wavelength which travels through the tissue and some portion of it gets absorbed. The unabsorbed light either transmits through the tissue or reflects from the tissue surface and is collected at the detector placed near the skin surface as the photoplethysmography, i.e., the PPG signal. Figure 2.1 summarizes the process involved in the PPG technique. The ease and simplicity, low power consumption, and ease of implementation of the PPG technique compared to other techniques like electrocardiography (ECG) have made it an attractive area of research in the biomedical and health sectors in recent years. Apart from its application in health monitoring, it also has the potential to be used for biometric authentication.

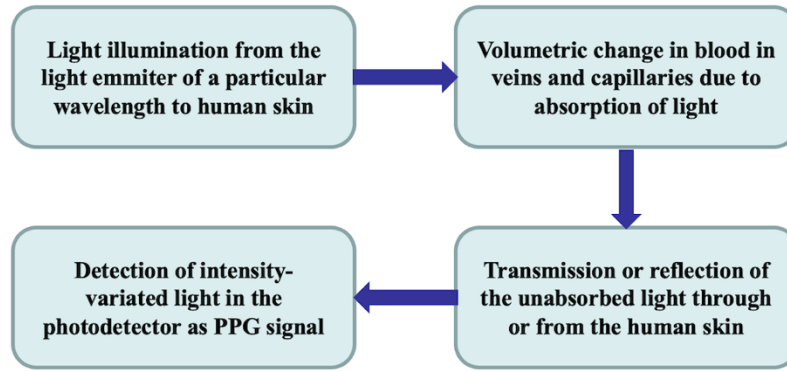


Figure 2.1: Summary of the PPG technique

2.2.1 PRINCIPLE OF PPG

A sequence of alternating contraction and relaxation of the atria and ventricles for pumping blood throughout the body is defined as the cardiac cycle. The frequency of this cardiac cycle is known as heart rate (HR) in beats per minute. HR, a vital sign of the human physical and mental state can be measured using electrical, and optical sensors. In the case of electrical measurement, depolarization signals from the heart muscles are measured using skin electrodes, known as the electrocardiography (ECG) method. In optical measurement, a PPG sensor is used to monitor HR [14].

PPG sensor device uses a light source and a light detector for measuring the light transmitted through or reflected from the body tissues. During the systolic phase of each heartbeat, contraction of the heart muscle pumps blood from the heart chamber to the arteries increasing the blood pressure. On the other hand, during the diastolic phase, heart chambers fill again with blood reducing the blood pressure. This blood volume change during each heartbeat causes variable light absorption leading to variation of reflected or transmitted light as a PPG signal. In other words, small pulsatile components regarding the varied reflected or transmitted light from the skin are produced during each pulse cycle for the change in synchronized blood volume with each heartbeat [15, 16].

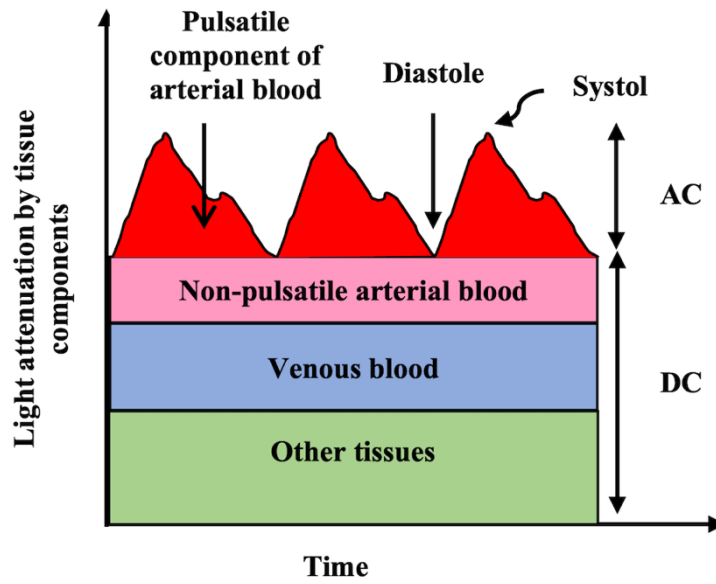


Figure 2.2: The schematic of PPG signal composition

PPG signal detected in the photodetector has two components- an alternating (AC) component due to the variable absorption of the pulsatile arterial blood, and a steady-state (DC) component resulting from the venous, capillaries, tissue, bone, and other non-pulsatile components of blood, as shown in Figure 2.2. Both the AC and DC components are superimposed together. The AC component can be used for heart rate measurement, as it results from the synchronized arterial blood volume change with heartbeat. The DC component related to the other non-pulsatile component needs to be removed for analyzing the AC component. The AC component comprises a very small portion of the whole signal. As a result, the PPG signal needs to be filtered and amplified before use for heart rate detection [17-19].

2.2.2 MODES of PPG

For obtaining a PPG signal from a PPG sensor, two modes of operation are generally adopted- the transmissive mode and the reflective mode. Figure 2.3 shows the schematic setup of the light detector and emitter in two different modes of PPG.

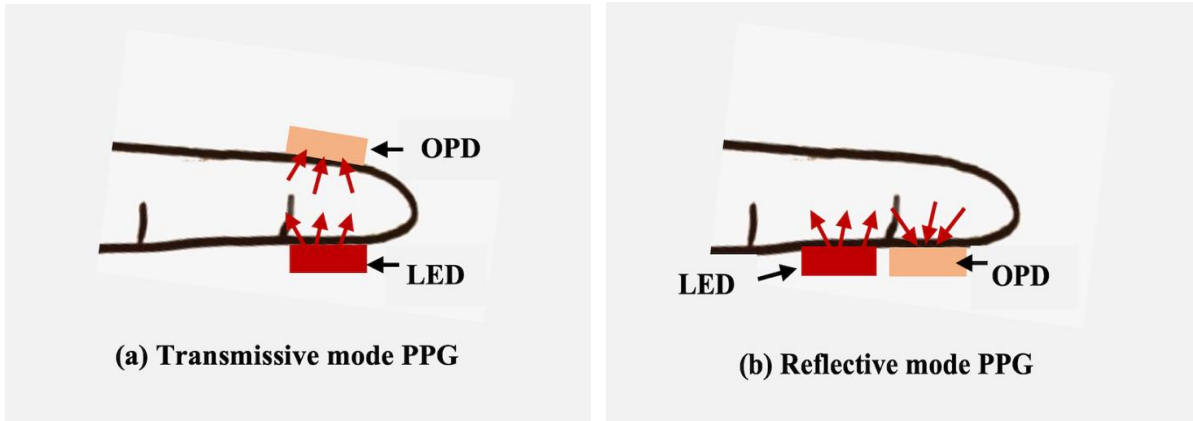


Figure 2.3: (a) Transmissive mode of PPG (LED and OPD on the opposite side). (b) Reflective mode of PPG (LED and OPD on the same side)

In the case of transmissive mode, the light source and detector are placed on opposite sides of the tissue as shown in Figure 2.3 (a). The light from the LED passes through the finger and is received on the PD from the other side. On the other hand, in reflective mode, illustrated in Figure 2.3 (b), the LED and PDs are placed side by side and use light reflection from the skin tissue instead of illumination from the tissue. While in the transmissive mode, the PD receives only the light transmitted through blood vessels in the finger, the PD in the reflective mode receives both the reflected light from blood vessels in the finger and the direct LED illumination. As a result, the ratio of the AC component to the DC component in the transmissive mode leads to a higher value compared to the ratio in the reflective mode. Conversely, conventional transmissive mode PPG suffers from a low signal-to-noise ratio and limitations of sensing locations, i.e., fingertips, toes, and earlobes only [7, 20]. Furthermore, it gives inaccurate results when used in a cold environment or in the case of finger motion. In contrast, in the reflective mode PPG sensor, signals can be obtained from any part of the body, supporting user-friendly monitoring [21, 22]. However, in the reflective mode PPG, it becomes challenging to monitor health condition measurements, i.e., oxygen saturation measurements on various body locations, such as the torso or limbs, due to the higher density of fat and lower density of blood vessels in those areas [23]. Therefore, using a PPG sensor in reflective mode on body locations with low-fat density, such as the fingertips, wrist, arms, neck, and forehead, is recommended.

2.3 OPTOELECTRONIC COMPONENTS OF HYBRID PPG SENSOR SYSTEM

Within the several components of a full PPG sensor system, the most important portion is the optoelectronic devices that comprise the light emitter and the detector. The light from the source passes through the skin and gets transmitted or reflected and this reflected or transmitted light variation results in a PPG signal that is used for monitoring the health condition.

2.3.1 LIGHT EMITTER, LED

A light-emitting diode (LED) is a semiconductor device that emits light as an electric current flows through it. Recent advances in the designing and manufacturing process of LED have enabled its use in display devices and other sensing applications like PPG sensors for health monitoring more efficiently.

In general, an LED works based on electroluminescence, i.e., emits light in response to an electrical current passing through it. When a forward bias is applied to a pn junction LED, the minority carrier electrons are accelerated from the n side to the p side and the minority holes go to the p side from the n side. This process accumulates more charges at the junction boundary increasing the concentration of the minority carriers. Some of these minority carriers recombine with the majority charge carriers resulting in the release of energy in terms of photons. As the amount of forward bias increases, the number of emitted photons increases and contributes to an increase in the light intensity. The color of this emitted radiation crucial for monitoring health signals like PPG is determined by the band gap of the constituent semiconductor material of the LED.

Most PPG sensors adopt LED as the light source. The intensity of light changes when light from the LED passes through the skin for the varying absorbance dependent on the concentration of absorbers and optical path length of the medium according to the Beer-Lambert law. The change light gets collected by the detector. LED light having a wavelength in the range of 390-600 nm (Blue, Green) can penetrate the superficial tissue in human skin while light with longer wavelengths, i.e., 600-1100 nm (Red and NIR) can penetrate further into the human skin [24]. Based on these characteristics, several researchers used multi-wavelength LEDs to obtain the PPG signal [25-28].

2.3.2 LIGHT DETECTOR, OPD

Organic photodiode (OPD), the light detector of the hybrid PPG sensor device has become more desirable in the last few decades. A fascinating combination of optoelectronics characteristics such as affordable manufacturing costs, lightweight, flexibility, and high photogeneration yield have made it a field of attraction for many researchers. Its advantageous behavior has made it compatible to be used in the fields of image sensing, health monitoring, spectrometry, and light communications summarized in Figure 2.4. The potential of organic semiconductors (OSCs) to control the spectral response in the form of OPD without applying any color filters was first demonstrated by Kudo et. al. in 1981 [29].

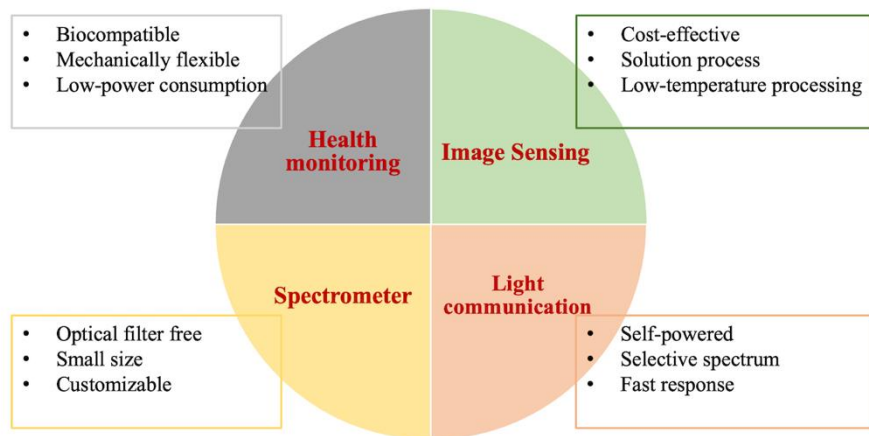


Figure 2.4: OPD application in the versatile sector

OPDs can offer several benefits over conventional photodiodes (PDs) made from silicon. They support the processing of large-area image sensors using the solution process on flexible substrates for their conformability with the thermo-mechanical properties of plastic [30]. Also, the solution processability at lower temperatures (below 150°C) has made them more feasible to use for industrially scalable coating processes, such as slot-die coating [31]. Although having a lot of advantages over the inorganic equivalents, the OPD longevity for long-term applications is an issue to be considered. However, recent research obtained an OPD lifetime of over 14000 hours under continuous operation using cutting-edge characteristics [32].

OPD operating mechanism adopts the photoelectric effect, i.e., electron emission caused by electromagnetic radiation (light) like that of an organic solar cell (OSC) [33, 34]. Photon absorption with energy higher than the band gap energy in an organic semiconductor layer results in a bounded electron-hole pair, i.e., exciton generation. This exciton diffuses to the donor-acceptor interface and shifts to lower energy states. The built-in voltage or extra reverse bias present at the interface then dissociates the excitons into free charge carriers- electrons and holes. The free charge carriers then transport through the organic semiconductor layer to the electron/hole transport layer and are finally collected at the electrodes. Figure 2.5 shows the basic working mechanism of an OPD. The generation of free charge carriers through efficient exciton dissociation is very crucial for the efficient performance of OPD. With several considerations like- molecular engineering i.e., designing the donor and acceptor, controlling the OPD morphology, and device design, free carrier generation can be improved in OPD which in turn improves its overall performance [35].

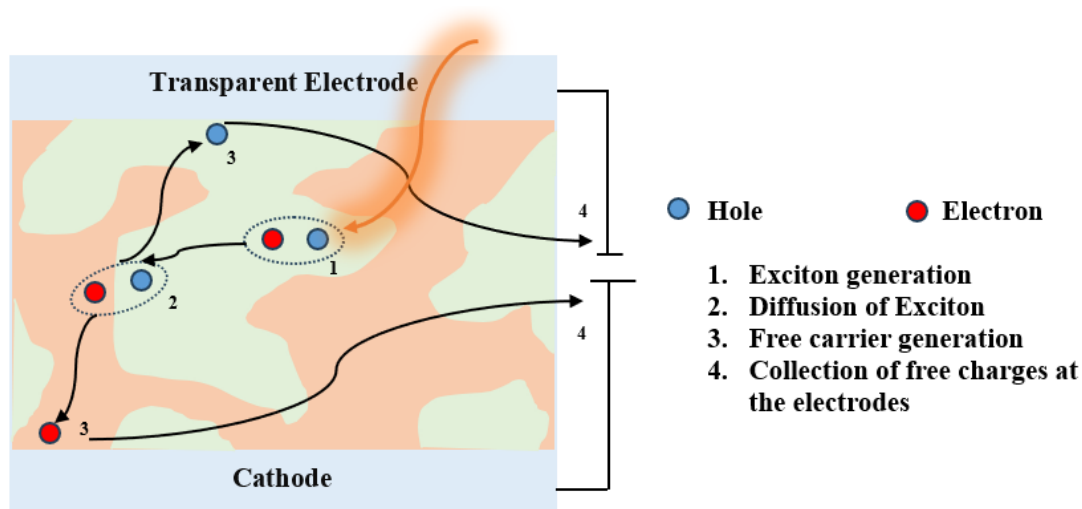


Figure 2.5: Working mechanism of OPD.

In most cases of OPD device fabrication, the bulk heterojunction (BHJ) structure is used to analyze its performance and functionality. Bulk heterojunction contains finely intermixed percolating networks from the electron donor and acceptor phase resulting in a large interface area between the electron donor and acceptor which facilitates higher exciton dissociation [36].

In a BHJ layer structure, a BHJ active layer is sandwiched between two electrodes or one interlayer between the active layer and anode, such as a hole transport layer (HTL) and interlayer between the active layer and cathode, known as electron transport layer (ETL).

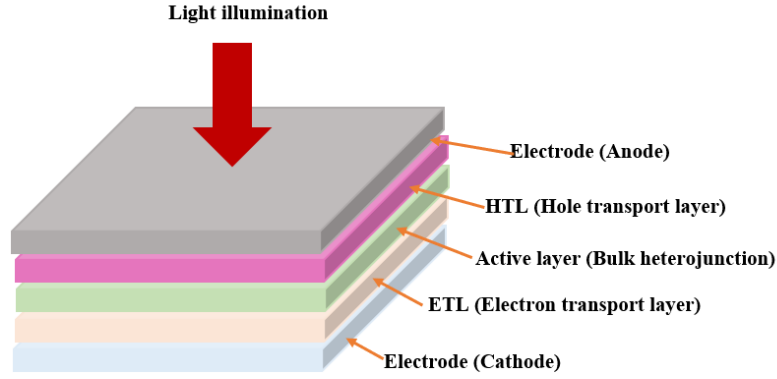


Figure 2.6: A typical BHJ OPD structure

A typical OPD adopting bulk heterojunction is depicted in Figure 2.6. An OPD typically works under reverse bias conditions rather than the forward bias applied in the case of organic photovoltaic (OPV) devices. An effective electric field due to sufficient reverse bias can extract all the photogenerated charges in OPD. This results in the generation of photocurrent independent of any kind of applied voltage.

OPD's efficient performance relies on some important figures of merit. Among them, the responsivity (R), external quantum efficiency (EQE), dark current density (J_{dark}), noise equivalent power (NEP), specific detectivity (D^*), linear dynamic range (LDR), and response speed are vital to be considered.

- i. Responsivity (R) of an OPD is the ratio of the photogenerated current (J_{ph}) and the incident light intensity (P_i) at a particular wavelength which can be expressed as

$$R = \frac{J_{ph}}{P_{in}}, \quad (2.1)$$

- ii. External quantum efficiency (EQE), also denoted as η can be described as the ratio of the generated carrier numbers to the number of incident photons. The unitless quantity can be described as

$$EQE = \frac{I_{ph} h\nu}{P_{in} q\lambda} = R \left(\frac{hc}{q\lambda} \right), \quad (2.2)$$

where h denotes the Planck's constant, c represents the light speed, q is the elementary charge and λ is the incident light wavelength. EQE value can exceed 100% when there is a photoconductive gain.

- iii. Dark current density (J_{dark}) is the current attained under the dark condition with a reverse bias applied to the OPD. It has to be controlled with different strategies as it can affect the device sensitivity, linear dynamic range, and detectivity negatively.
- iv. Noise equivalent power (NEP) is the lowest incident optical power which can result in a detectable output signal. It is generally used to measure detector sensitivity. It can be given by

$$NEP = \frac{i_{noise}}{R\sqrt{B}}, \quad (2.3)$$

where R denotes the responsivity and B stands for the normalized detection bandwidth. Three types of noise are in an OPD which can affect dominantly such as the flicker or $1/f$ noise, thermal noise, and shot noise. The experimental measurement of noise is difficult that's why only the shot noise resulting from the dark current is considered for finding the dominant contribution of the noise current.

- v. Specific detectivity (D^*) defines the NEP normalized by the device area and expressed as a unit of Jones (J). It can be expressed as

$$D^* = \frac{\sqrt{A}}{NEP} = \frac{R\sqrt{A}}{i_{noise}}, \quad (2.4)$$

where R , A , i_{noise} denote the responsivity, the device area, and the noise current respectively.

- vi. Linear Dynamic Range (LDR) defines the limit up to which the photocurrent can be proportional to the incident optical power. It is given by

$$LDR = 20 \log \log \left(\frac{J_{ph}(max)}{J_{ph}(min)} \right), \quad (2.5)$$

where $J_{ph}(max)$ and $J_{ph}(min)$ refer to the maximum and minimum current respectively.

- vii. The response speed is expressed using the response time, i.e., the rise time for the response to go 10% to 90% of its highest value and the decay time to go from 90% to 10% of the response.

2.4 RELATED WORKS ON ORGANIC AND HYBRID PPG SENSOR

Organic materials application in PPG sensors has contributed to a highly flexible cost-effective device with an easy and large fabrication scale. Lochner *et.al.* reported an all-organic transmissive mode PPG sensor with two organic green and red LED arrays and two OPDs [20]. For ensuring a high EQE, they adopted a blend of Poly({4,8-bis[(2-ethylhexyl)oxy]benzo [1,2-*b*:4,5-*b'*]dithiophene-2,6-diyl}{3-fluoro-2-[(2-ethylhexyl) carbonyl] thieno[3,4-*b*]thiophenediyl}) (PTB7) and [6,6]-phenyl C71-butyric acid methyl ester (PC₇₁BM). The fabricated OPD offered an EQE of 38% and 47% at green and red wavelengths respectively with a leakage current of 1 nA/cm² at 2V applied reverse bias condition. They succeeded in calculating the heart rate (60-70 beats per minute) and oxygenation (94-96%) from the PPG signal derived using inorganic with an error of 1% for the pulse rate and 2% for the oxygenation level.

Park *et.al.* proposed an ultra-flexible near-infrared (IR) responsive skin conformal PPG sensor with a BHJ active layer of PIPCP polymer acceptor and PC₆₁BM donor with an inverted structure configuration [37]. The 3 µm ultrathin OPD exhibited high operational durability in the case of extreme mechanical deformation with the stability of charge carrier transportation. Along with a commercial IR LED and the fabricated OPD, the author and his co-workers could gain repetitive systolic and diastolic pulse from which oxygenated situation and BPM of blood flux were calculated from the fingertip of an adult person. The peak-to-peak intensity of the gained signal went through a Fourier analysis, resulting in a 64 BPM heart rate lying in the acceptable range for an adult. They confirmed the possibilities of using skin-conformable electronics as a portable cardiovascular sensor for emergency health care services.

Khan and co-workers [7] reported a reflectance oximeter array (ROA) with a combination of eight OPDs and four red (612 nm), and four NIR (725 nm) OLEDs. The stacked ROA of OPDs and OLEDs with 0.5 cm emitter-detector spacing ensured skin conformability along with high SNR. Additional circuitry like the analog front end (AFE) sequentially drove the OLEDs and read out the OPD signals from the forearms and forehead of human volunteers. A mean error of 1.1% was observed while comparing the oxygen saturation with the proposed device and commercially available device.

Lee et. al. [13] presented a reflective patch-type sensor with a combination of flexible green and red OLEDs and wrap-around OPDs with ultralow power consumption. The OPD consisted of an active layer of the mixture of C70 and 4,4'-cyclohexylidenebis[*N,N*-bis (4-methylphenyl) benzenamine] (TAPC). Reliable heart rate and SpO₂ signal were obtained with the completed OPO sensor applied to different human body parts like the finger, wrist, neck, and nose and were obtained with very low power consumption by the OLEDs (31 μ W for the green OLED, 17 μ W for the red OLED). The presented results in the paper proposed the possibility of using an all-organic device as an all-day wearable health monitoring system with a high form-factor advantage.

Khan and his co-workers [38] reported reflection mode PPG sensors with different sensor geometry, OLED-OPD spacing, and optical barrier injection to reduce light scattering. All types of sensors consisted of printed red and NIR OLEDs along with OPDs with EQE of around 20%. The author and his co-workers observed 39.7% and 18.2% improvement in the magnitude of PPG signals for red and NIR channels using bracket geometry while it was 48.6% and 9.2% improvement in the case of circular geometry respectively compared to the rectangular structure. Using black tape as a blocking medium for scattered light, they reported a 26.5% improvement in PPG signal amplitude for the red channel. Based on the results for different geometry, they made a PPG sensor applicable to various locations of human skin. The study also indicated a skin-compatible PPG sensor with good SNR with the application of TM and IVW algorithms in a properly designed PPG sensor.

Fahed and co-workers [39] presented a monolithic reflective pulse oximeter consisting of a red OLED and an OPD. The ray-tracing method along with the Monte Carlo method was adopted for simulating two different structured devices (a combination of circular OLED and ring-shaped OPD for one case, Device-A and ring-shaped OLED and circular OPD for another structure, Device-B). The OPD structure comprised of DBP: C60-based active layer resulted

in an EQE of around 37% for both devices at 625 nm wavelength at zero bias condition. Both devices were applied to the fingers of healthy male persons at resting conditions to acquire PPG signals, with a 1.5% error compared to a commercially available pulse oximeter. The devices were also applied to different body positions like different fingers, forearms, wrists, and forearms, and successful signals were obtained from Device A. Their study suggested a newly designed device applicable in different positions of the human body acquiring PPG signal high SNR and low power consumption.

LEE et. al. [40] proposed a hybrid organic-inorganic device adopting inorganic LEDs and wrap-around OPD integrated by lamination. The layer-resolved analysis done through optical simulation resulted in a conclusion indicating close positioning of the light source and OPD for detecting meaningful PPG signal resulting from a deeper layer rather than the epidermis. For the active layer of OPD, PTB7-Th was adopted as the donor and IEICO-4F was used as the acceptor fabricated through the spin coating process. Both LED and OPD were fabricated on different substrates allowing independent preparation of OPD. The device applied to the bottom side of the finger was able to detect the PPG signals and SpO₂ levels with an average power consumption of about 35 μ W which is lower compared to the commercially available sensors. The proposed sensors exhibited a good performance (at over 90%) 40 days after fabrication which ensured its potentiality of being an ultralow power consumed pulse oximeter sensor for PPG signal detection.

Xu *et.al.* proposed an epidermal and flexible NIR PPG sensor with a low-power, highly sensitive organic phototransistor (OPT) with an inorganic LED [41]. Using an organic bulk heterojunction active layer and bilayer gate dielectric design, they achieved NIR OPT with high responsivity ($3.5 \cdot 10^{-15}$ A W⁻¹) under lower voltage (<3V) applied. The addition of ultrathin encapsulation allowed the device to be highly flexible and applicable to human skin directly. The sensor provided reliable heart rate variability monitoring at different postures of human subjects consuming low power.

2.5 SUMMARY

In this chapter, we briefly discussed the fundamentals of photoplethysmography (PPG), i.e., its operation principle and working modes. We also gave a brief overview of the optoelectronic part- LED light emitter and OPD photodetector of the PPG sensor system. In the end, we

presented some previous work about the PPG sensor prepared with either all organic optoelectronics or an inorganic-organic combination of optoelectronic devices.

CHAPTER III

OPD FABRICATION AND PERFORMANCE ANALYSIS

3.1 INTRODUCTION

Organic-based photodetectors (OPDs) have attracted researchers enormously during the past decade for their immense potential such as material tunability, low-cost solution-processability, mechanical flexibility, stretchability, lightweight, and applicability to large-area displays. These advantages have made OPDs comparable to conventional photodetectors with inorganic materials [42-46]. OPD can support broadband and narrowband detection, allowing it to be used in optical sensing and imaging, health monitoring, artificial vision, and photonic communication [15, 31, 47-48].

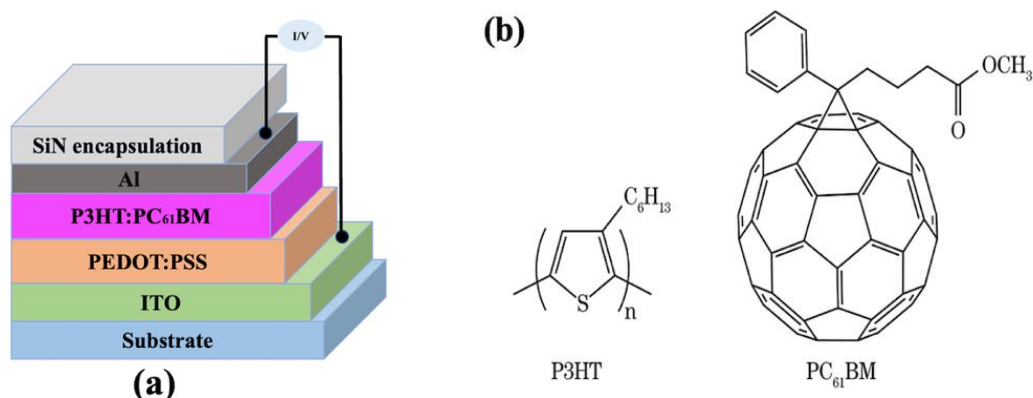
In general, the range of spectral response of OPD depends on the photon harvesting in the organic active layer material of the OPD. OPDs made from the combination of semiconducting polymers (electron donors) and buckminsterfullerene derivatives (electron acceptors) were proven to be capable of high detectivity and fast temporal response by many researchers [49-51]. The magnitude of the photocurrent density (J_{ph}) in OPD, depends highly on the intensity of the incident light [52]. Although the bulk heterojunction OPD suffers from a low response speed and high dark current issues, the photocurrent can be improved by reducing the recombination loss [53]. For any sensing application, the OPD must possess the combination of a low dark current and a high photocurrent along with a high on-off ratio for achieving an excellent photo response in reverse bias conditions.

In this chapter, we demonstrated the fabrication and realization of poly(3-hexylthiophene-2,5-diyl) (P3HT): [6,6]-phenyl C₆₁-butyric acid methylester (PC₆₁BM) bulk heterojunction OPD, the light detector of the PPG sensor using the cost-effective, simple, and easy solution process. The OPD performances such as dark and photocurrent densities at different illumination conditions such as varying LED luminous intensity, wavelength, and OPD biasing voltages

were characterized. The effect of various designs and areas of OPD was also considered for the device structure optimization for use in the PPG sensor systems.

3.2 OPD DEVICE STRUCTURE

The device structure layout of the OPD is shown in Figure 3.1a. At first, the ITO on the glass substrate works as the transparent electrode for making the electrical connection with the external circuits. Followingly, PEDOT:PSS is considered as the hole transport layer, that can support efficient carrier injection and charge collection at the electrode terminal [54]. A typical P3HT:PC₆₁BM blend was then adopted for the active layer due to its extensive use for organic photovoltaic devices even though its limited power conversion efficiency due to biomolecular recombination loss [55]. Figure 3.1b shows the chemical structure of the P3HT and PC₆₁BM material. Next, an aluminum top contact covers the device to block the direct illumination from the LED in some cases. Finally, the SiN encapsulation layer was used for the protection of the device from any environmental degradation. The energy diagram of the OPD layer materials is shown in Figure 3.1c.



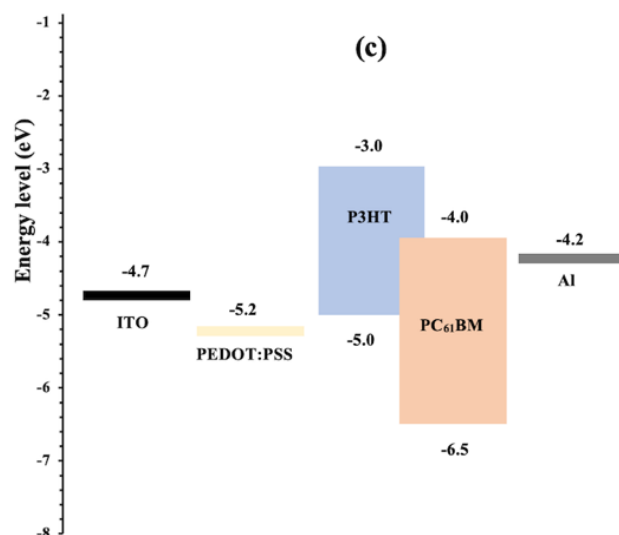


Figure 3.1: (a) Schematic of OPD device structure. (b) chemical structures of P3HT and PC₆₁BM. (c) energy level diagram of OPD layers.

3.3 OPD FABRICATION PROCESS AND CHARACTERIZATION

Commercially available indium-tin-oxide (ITO) coated glass substrates were precleaned and exposed to a photolithography process, followed by wet etching for the patterning of the transparent ITO-electrode. The patterned ITO -substrates were then cleaned in an ultrasonic bath of DI water, detergent solution, acetone, and isopropyl alcohol (IPA) several times for 5 min each sequentially and dried. The cleaned substrates were then subjected to UV/ozone treatment for 20 minutes for the removal of any remaining organic residues in the substrate. The filtered poly(3,4-ethylenedioxythiophene)-poly(styrene sulfonate) (PEDOT:PSS) (Clevious P VP AI 4083, Ossila Limited, UK) solution was spin-coated on the patterned ITO substrate at 3000 rpm for 60 sec and baked at 200°C for 10 min in the air to prepare the hole transport layer.

The P3HT (FUJIFILM Wako Chemicals, Japan) and PC₆₁BM (Sigma Aldrich, USA) mixture were used for preparing the bulk heterojunction active layer of the OPD. Both materials were dissolved in Chlorobenzene in a 1.8:1 ratio and the prepared solution was kept on magnetic stirring for 2 days before the deposition. The prepared solution was then deposited over the

PEDOT:PSS layer using spin coating at 1000 rpm speed for 50 sec followed by baking at 80°C for 5 min in a proper N₂ environment. Afterward, a 100 nm Al cathode was deposited over the active layer through a metal mask in the vacuum thermal evaporation process and then annealed at 150°C in an N₂ environment for 5 min. Finally, the fabricated OPD device was encapsulated with a silicon nitride (SiN) thin film layer by a plasma-enhanced chemical vapor deposition process and subjected to the electrical measurement procedure.

The OPD performance measurement, i.e., the dark and photocurrent measurements were carried out using a precision semiconductor parameter analyzer (Agilent 4156C) and a micro probing system (K157MP, Kyowa Riken, Japan) at room temperature. A commercially available RGB LED (HV-5RGB25, Inolux) was adopted as the light source for illuminating the OPD at the time of the measurement. Three different wavelengths red ($\lambda = 624$ nm), green ($\lambda = 525$ nm), and blue ($\lambda = 470$ nm mm) were used for OPD illumination for the photocurrent measurement with supply current controlled irradiation intensity. The luminous intensities of red, green, and blue LEDs were calculated from the measured illuminance by the light meter (AS ONE LM-332) and the distance between the LED and the light meter. The schematic for the measurement system and the actual measurement setup are shown in the following Figure 3.2.

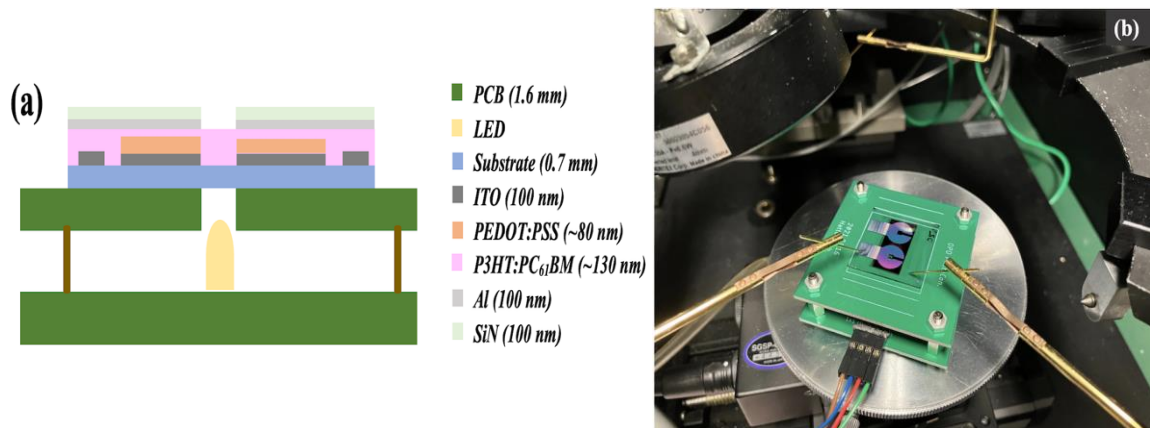


Figure 3.2: (a) Schematic of J - V measurement setup for the OPD. (b) actual image of the parameter analyzer and micro-probing system.

3.4 OPD PERFORMANCE FOR VARYING ILLUMINATION AND BIASING CONDITIONS

The fabricated OPD was tested for different LED illumination conditions, i.e., change in illumination wavelength and luminous intensity with different OPD biasing conditions for obtaining the dark and photocurrent density which in turn gives the on/off ratio necessary for the sensing application. This section briefly describes the effect of three different LED wavelengths representing three different illumination colors and their diverse luminous intensity on the OPD performance at different levels of applied bias to OPD in the negative direction.

3.4.1 EFFECT OF LED WAVELENGTH

Figure 3.3a shows the schematic of the OPD device (D1) structure and the look of the actual device. The device was illuminated with green, red, and blue light from the rear side as shown in Figure 3.2. The three LED lights chosen have wavelengths of 470 nm (λ_{blue}), 525 nm (λ_{green}), and 632 nm (λ_{red}) where they have an order of $\lambda_{blue} < \lambda_{green} < \lambda_{red}$. The photocurrent densities in the OPD, J - V characteristics are affected by the illumination of different LED colors which can be observed in Figure 3.3b.

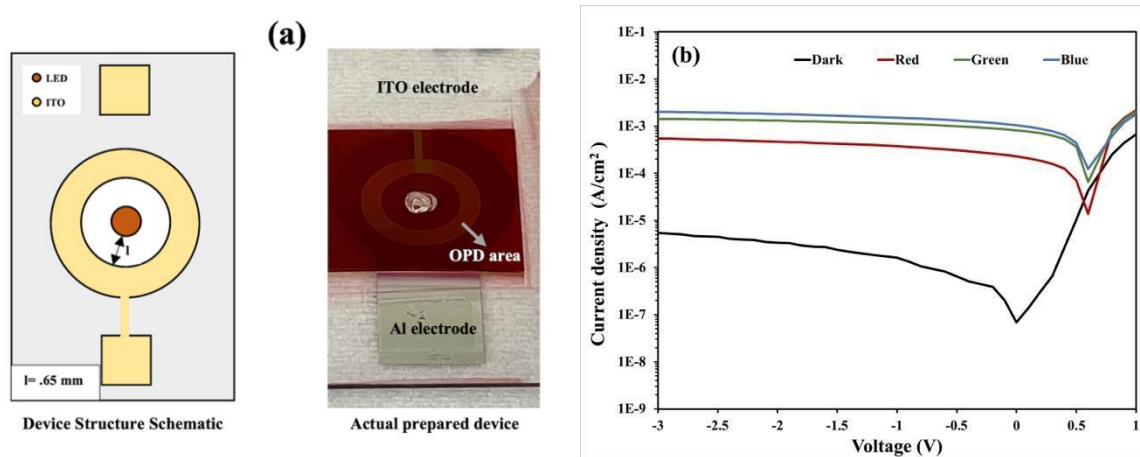


Figure 3.3: (a) Schematic of the structure and actual image of the fabricated D1 device. (b) the J - V characteristics of the D1 device.

The dark current density of the OPD depends, e.g., on the level of minority carrier injections such as the electron injection from the PEDOT:PSS layer to the lowest unoccupied molecular orbital (LUMO) of P3HT or PC₆₁BM and the hole injection from Al cathode to the highest occupied molecular orbital (HOMO) of the P3HT or PC₆₁BM [53]. The dark current density and photocurrent density for different LED color illumination obtained at different reverse bias voltages are summarized in Table 3.1. Under illumination conditions, the OPD photocurrent density shows up to 3–4 orders of magnitude higher than the dark current density at zero bias condition whereas it reduces to 2.5–3 orders of magnitude higher than the dark current at -1 V reverse bias for red, green, and blue incident lights.

Table 3.1: Current density of D1 device at different illumination conditions

Illumination condition	Current density (A/cm ²)				
	-3V	-2V	-1V	0V	1V
Dark	5.43E-6	3.35E-6	1.60E-6	6.93E-8	6.78E-4
Red	5.46E-4	4.70E-4	3.75E-4	2.27E-4	2.19E-3
Green	1.43E-3	1.31E-3	1.13E-3	8.17E-4	2.06E-3
Blue	2.03E-3	1.81E-3	1.51E-3	1.04E-3	1.80E-3

For the case of P3HT:PC₆₁BM heterostructure, it has been found by many researchers that the electron donor P3HT has large absorption in a visible wavelength region (380–660 nm) whereas the electron acceptor PC₆₁BM absorbs light in a UV wavelength region (280–380 nm) and their blended structure results in an absorption peak around 470–480 nm [56-58]. Due to the shoulder of the characteristic absorption bands, photons incident on the OPD from LED with a wavelength 470 nm (λ_{blue}) can efficiently generate excitons both in P3HT and PC₆₁BM, whereas photons incident from green and red LED (λ_{green} and λ_{red} respectively) can mainly produce excitons in P3HT acceptor only. The illumination of LED with shorter wavelengths, i.e., λ_{blue} can thus provide a larger number of CT exciton generation leading to a higher photocurrent density compared to that of the longer wavelengths (λ_{green} and λ_{red}). The relation of the current versus wavelength for the prepared P3HT:PC₆₁BM heterostructure in Figure 3.4

shows a higher current value near 470 nm corresponding to λ_{blue} , and it degrades gradually for longer wavelengths corresponding to λ_{green} and λ_{red} .

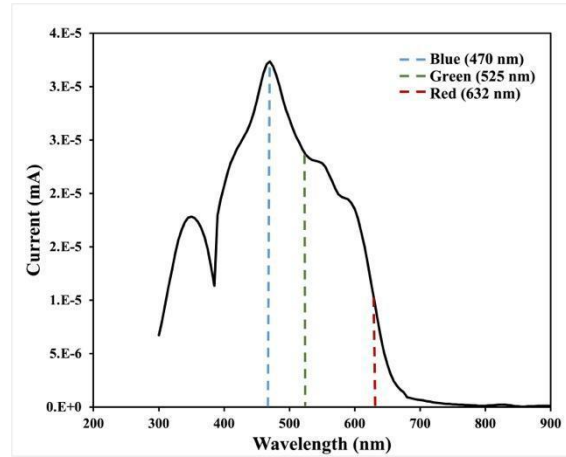


Figure 3.4: Photocurrent versus incident wavelength for the prepared P3HT:PC₆₁BM OPD device.

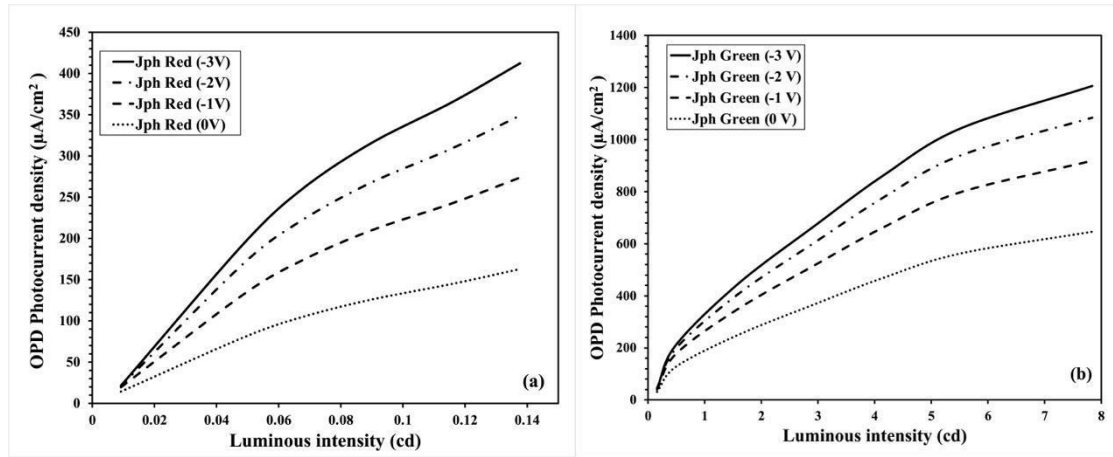
3.4.2 LED INTENSITY AND OPD BIASING EFFECTS

For any kind of sensing application, the OPD needs to exhibit a stable and persistent performance over a wide range of light intensity. This section discusses the performance of the OPD for increasing LED luminous intensity under different biasing conditions. The OPD photocurrent density, J_{ph} , highly depends on the intensity of the incident LED illumination. The magnitude of J_{ph} for a particular excitation wavelength, λ , and the light intensity, I_L , can be described by

$$|J_{ph}| = EQE \times \frac{q}{hc} I_L, \quad (3.1)$$

where EQE is the external quantum efficiency, h is the Planck constant, c is the light speed, and q is the elementary charge. The EQE depends on the combined process of photon absorption, excitons generation for conversion into free charge carriers, and collection of the carriers before recombination. Equation (3.1) indicates a proportional dependence of the photocurrent density on the light intensity as far as the EQE is unaffected. With increasing light intensity, the number of incident photons and thus the number of photogenerated carriers increases, which in turn increases the J_{ph} [59, 60]. Figure 3.5 shows the variation of our OPD

photocurrent densities, J_{ph} Red, J_{ph} Green, and J_{ph} Blue with the LED wavelengths λ_{red} , λ_{green} , and λ_{blue} , respectively, for different OPD biasing voltages (0 V, -1 V, -2 V, and -3V) with increasing LED luminous intensities, I_L . As a trend, the OPD photocurrent densities are roughly linearly correlated with the incident light intensities. However, a nonlinearity is observed as the light intensities are widely varied. A possible explanation of the deviation from the linearity is a decrease in the EQE due to the biomolecular recombination losses for an increasing charge carrier density [53, 55]. In the case of the J - V measurement, we used a point light source LED that did not perpendicularly impact the OPD surface. On the other hand, the luminous intensities in Figure 3.5 were calculated with a planer light source assumption, i.e., the photon numbers incident on the OPD are uniform over the area. This could be another source of deviation from the linearity mentioned above.



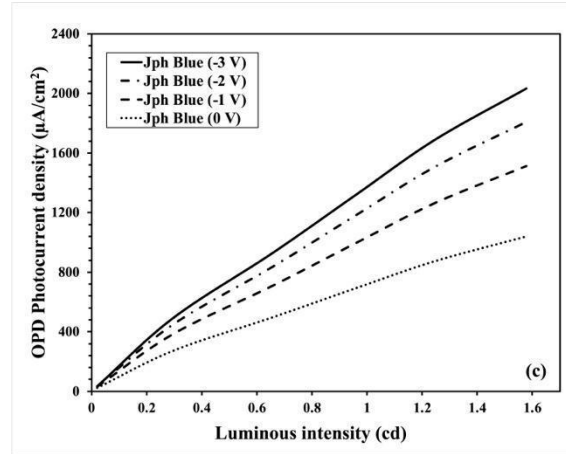


Figure 3.5: OPD photocurrent density vs LED luminous intensity curves with applied reverse bias condition for (a) red LED, (b) green LED, and (c) blue LED.

Application of reverse bias voltage generally improves the strength of the electric field at the junction of photodetector devices as it accelerates the carriers' drift velocity and reduces carriers' transit time, resulting in the enhancement of the charge collection and lowering the probability of carrier recombination losses [61]. The transit time, which is inversely proportional to the electric field, can be defined by

$$\tau_t = \frac{l^2}{\mu V}, \quad (3.2)$$

where V is the bias voltage, l is the space charge layer length at the junction of a conventional photodetector, and μ is the carrier mobility [62]. Although the conventional semiconductor theory is not fully applicable in the case of organic bulk heterojunction devices, the effect of an external field on the carrier collection and the reduction in biomolecular recombination is quite similar. Moreover, the dissociation of CT excitons coupled with a coulombic force requires an external field [63]. Due to the combined effects of field dependency, the magnitude of OPD photocurrent density J_p increases with the reverse bias applied which can be observed in Figure 3.5 where the OPD photocurrent magnitude increases for higher reverse bias (-1V to -3V) for LED with red, green, and blue colors.

3.5 OPD DESIGN VARIATIONS

OPD supports design freedom, which can benefit its application in some cases. In this section, we discuss the OPD performance for different design variations. For sensing applications, designing the OPD plays an important role in the sensor's efficient performance. The sensor's performance is significantly influenced by the design parameters of the OPD, including the shape of the OPD surface near the LED, the distance between the LED and the OPD, and the OPD's surface area. These parameters can critically affect the OPD's dark and photocurrent density, as well as the on/off ratio (ratio of photocurrent to dark current density), which are necessary for optimizing the detector's performance in any sensing application. Variations in OPD design can introduce noise, potentially affecting the signal acquisition procedure. Therefore, careful optimization of these parameters is needed to ensure reliable signal detection and overall sensor efficiency.

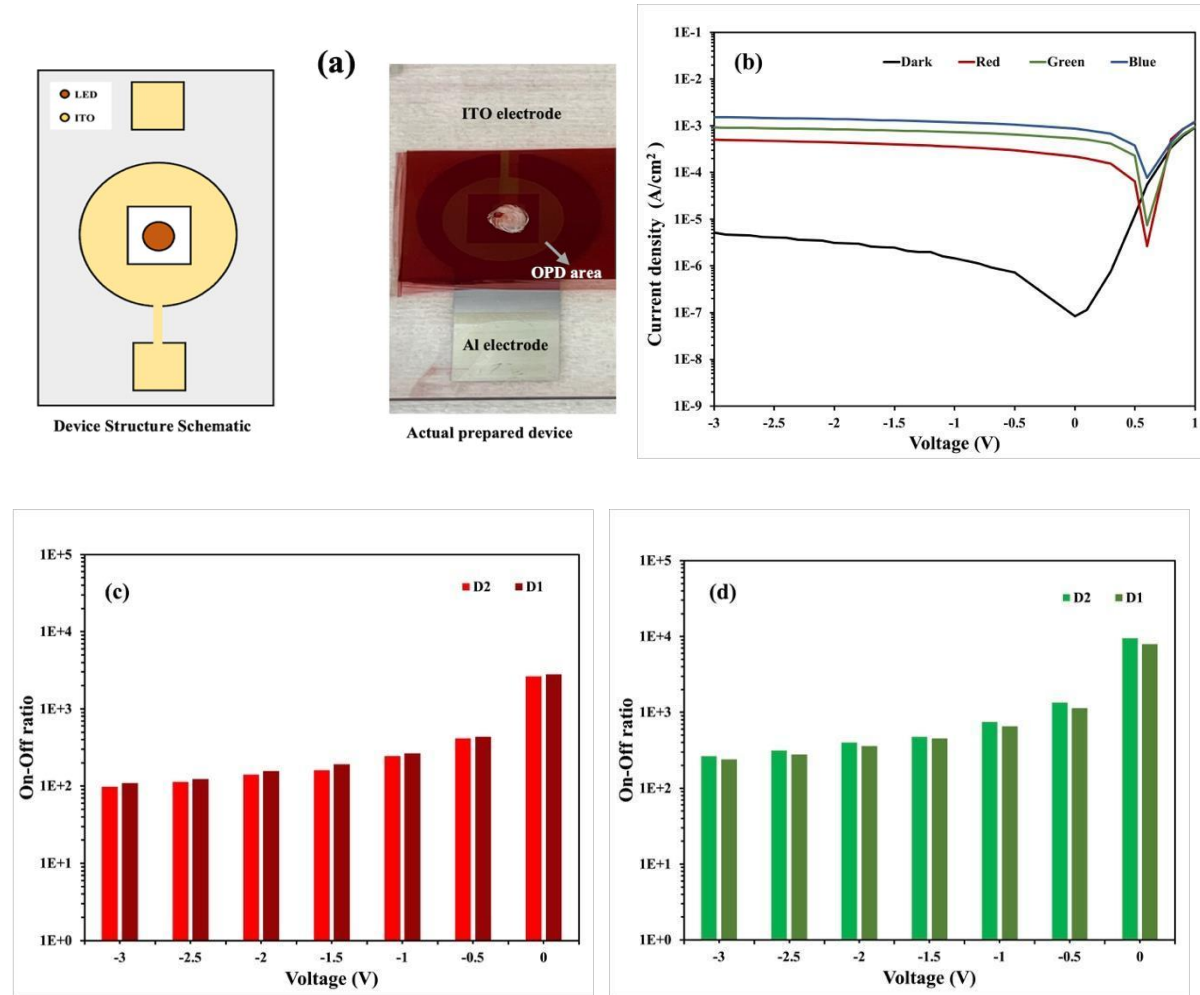
Table 3.2: Device configuration summary

Device label	Area (mm ²)	Inner periphery geometry	LED to OPD inner periphery distance, (<i>l</i>) (mm)
D1	16	Round	0.65
D2	16	Rectangular	0.65
D3	16	Full	0
D4	16	Round	1.15
D5	32	Round	0.65

3.5.1 OPD INNER PERIPHERY SHAPE

Khan *et.al.* showed different sensor geometries (OPD shapes) used for PPG signal analysis that affected the amplitude of the PPG signal obtained from the sensor [38]. In this work, we used two different geometries of the inner periphery of the OPD active area close to the LED. Device D1 has a circular inner periphery OPD area as shown in Figure 3.3, whereas D2 has a rectangular inner geometry (Figure 3.6). Most of the commercial LEDs used in any system have a rectangular shape rather than a dome shape. For rectangular-shaped LED, the rectangular inner periphery of the OPD area is convenient as it can collect the LED light from

all directions from equal distances. In contrast, for the dome-shaped LED, a circular OPD inner geometry is preferable from the same context. The schematic of the structure, image of the fabricated D2 device, the D2 J - V characteristics, and comparison graph of the on/off ratio for both D1 and D2 devices are shown in Figure 3.6.



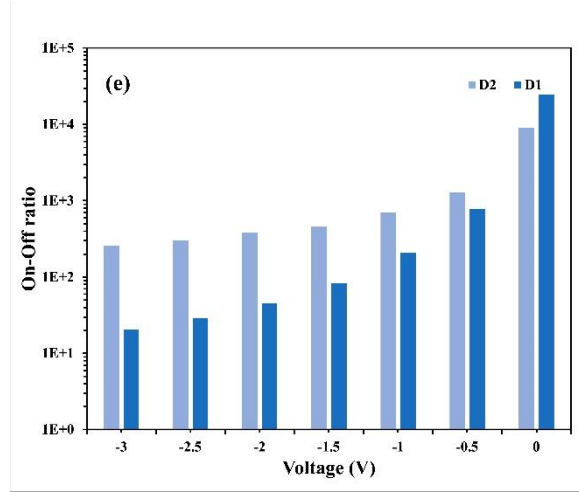


Figure 3.6: (a) Schematic of the structure and the image of fabricated D2 device. (b) J – V characteristics of the D2 device. (c–e) Comparison of the on/off ratio between D1 and D2 devices for red, green, and blue, respectively, LED illumination.

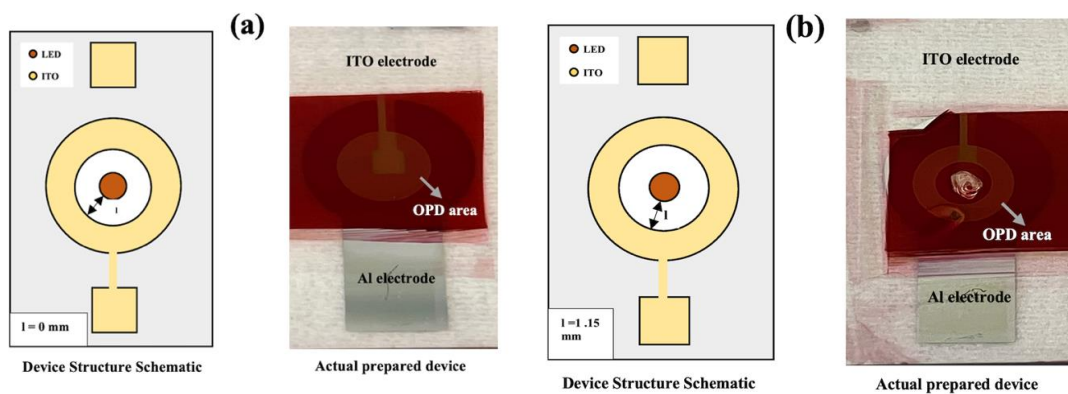
3.5.2 DISTANCE BETWEEN LED AND OPD

Distance from LED and OPD is also an important factor to be considered while designing OPD. Affiq *et. al.* suggested that the light source to detector distance in a reflectance PPG sensor should be kept less than 3mm for efficient signal detection [64]. In this work, we investigated three devices with varying distances between the LED and the OPD. Devices D3, D1, and D4 have distances (l), of 0 mm, 0.65 mm, and 1.15 mm, respectively, from the LED surface to the inner periphery of the OPD. The J – V curve of device D1 is shown in Figure 3.3 whereas the schematics of the structures and the J – V characteristics of D3 and D4 devices are shown in Figure 3.7. The dark and photocurrent of these three devices at zero bias conditions (0 V) are summarized in Table 3.3.

Table 3.3: Current density of OPD device for varying LED to OPD distance at different illumination conditions

LED to OPD distance, (<i>l</i>) (mm)	Current density (A/cm ²)			
	Dark	Red	Blue	Green
0 (device D3)	1.12E-8	2.81E-4	1.95E-3	9.75E-4
0.65 (device D1)	6.93E-8	2.27E-4	1.04E-3	8.17E-4
1.15 (device D4)	7.13E-8	2.12E-4	9.75E-4	7.95E-4

The OPD dark current increases with the increase in OPD to LED distance. However, the photocurrent shows a decreasing trend with increasing distance. According to the theoretical inverse-square law of radiation, the measured intensity of light has an inversely proportional relationship to the source-to-detector distance squared, (l^2) [65]. As the distance from LED to OPD increases, it reduces the number of absorbed photons by the OPD bulk heterojunction materials. In contrast, it increases the possibility of noise associated with light scattering which in turn reduces the photocurrent and increases the dark current.



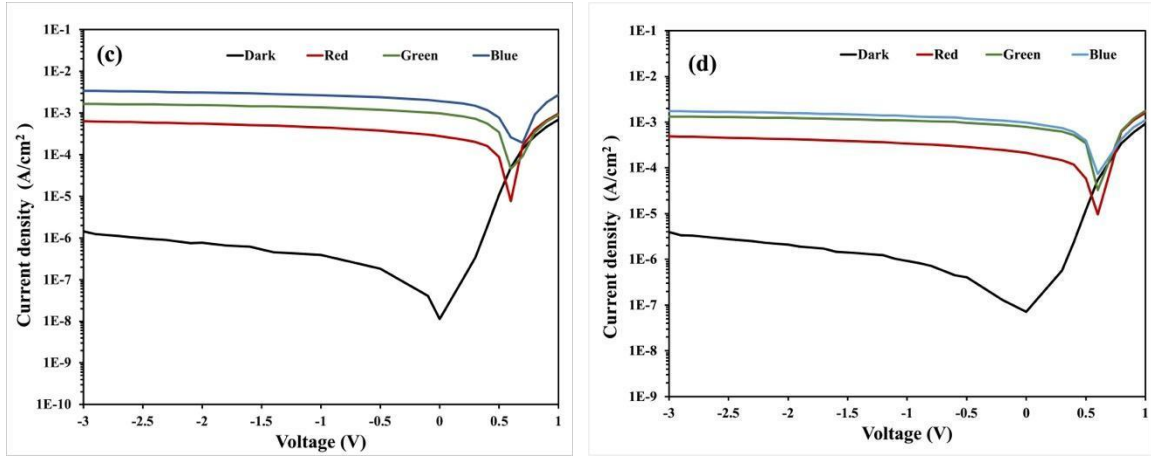
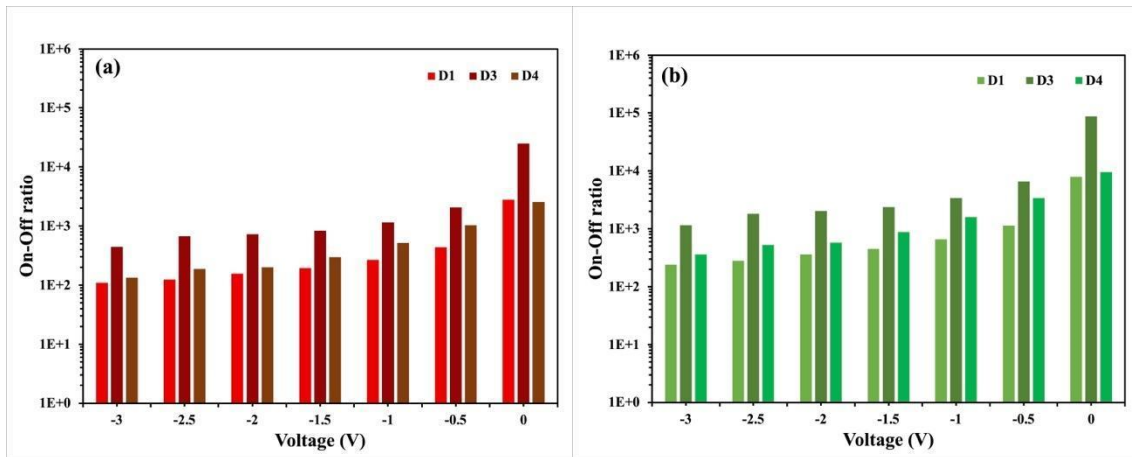


Figure 3.7: (a, b) Schematics of the structures and the image of fabricated devices D3 ($l=0mm$), and D4 ($l=1.15mm$), respectively (c, d) the J - V characteristics of devices D3 and D4, respectively.



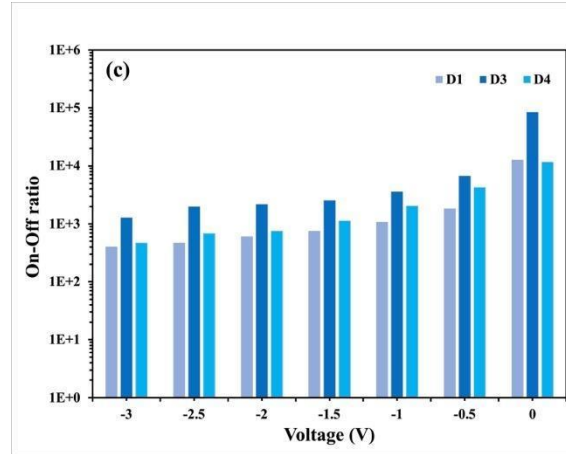


Figure 3.8: (a–c) Comparison of on/off ratio between D1($l = 0.65\text{mm}$), D3 ($l = 0\text{mm}$), and D4 ($l = 1.15\text{mm}$) devices for red, green, and blue, respectively, LED illumination.

The graphs of the on/off ratio comparison between D1, D3, and D4 devices are shown in Figure 3.8 for red, green, and blue incident illumination. A decreasing trend of the on/off ratio is observed as the source-to-detector distance (l) ($D3 > D1 > D4$) is increased. The trend of the on-off ratio is the consequence of the reducing photocurrent and the increasing dark current with increasing l as summarized in Table 3.3.

3.5.3 OPD area

Organic photodetector can be fabricated over a large area which makes it advantageous for many applications. OPD's area can affect both its dark and photocurrent density. Here, we investigated the effect of the area size by comparing two OPD devices with active areas of 16 mm^2 (D1) and 32 mm^2 (D5) with the same inner periphery (circular) and distance from the incident LED ($l = 0.65\text{ mm}$). The J – V curve of device D5 and graphs of the on-off ratio comparison between devices D1 and D5 are shown in Figure 3.9.

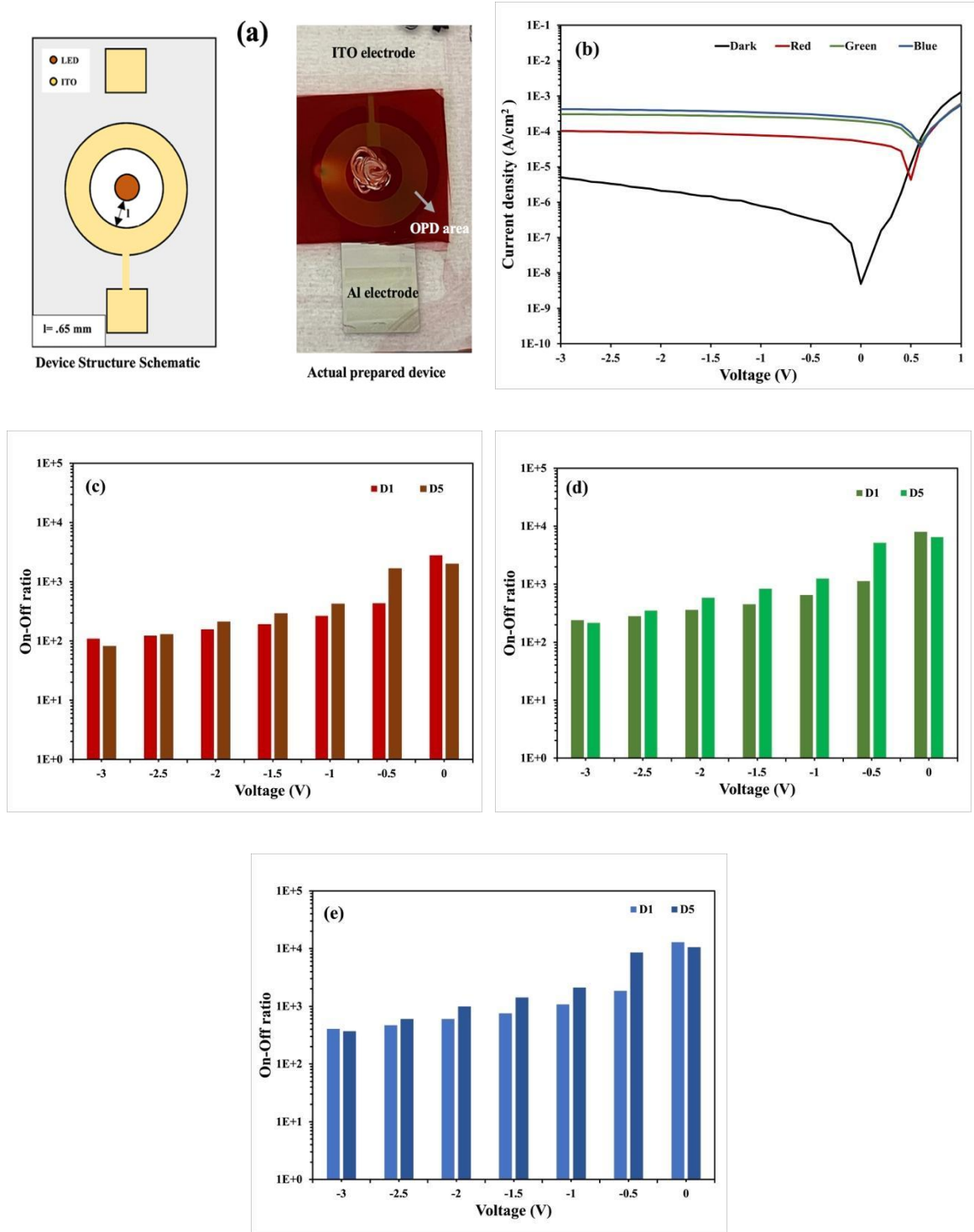


Figure 3.9: (a) Schematic of the structure and the image of fabricated D5 device. (b) $J-V$ characteristics of the D5 device, (c–e) Comparison of on/off ratio between D1 and D5 devices for red, green, and blue, respectively, LED illumination.

The increased active area allows more photons to be absorbed in the OPD and contributes to a larger number of charge carrier generation in total. If the LED incident is normal to the OPD active area and light intensity is uniform over the area, the value of the photocurrent density does not depend on the area according to the definition (A/cm^2). In this OPD-LED hybrid system used for measurement, the LED is a point source, i.e., the light spreads radially and it follows a path through reflection to reach the OPD active area (see Figure 3.2). Therefore, a larger OPD area has some disadvantages in uniform light illumination. In addition, it has been known that an increase in the area can enhance the probability of having defects that accelerate electron and hole recombination at low built-in junction potential and thus, the photocurrent density in organic bulk heterojunction is often area size dependent [66]. The above two factors should be the reason behind the lower photocurrent density of device D5 seen in Figure 3.9b compared to the other devices. The inferior zero bias on/off ratio of D5 compared to that of D1 seen in Figure 3.9c-e can be attributed to the lower photocurrent density in D5. However, as we discussed earlier, applying a reverse bias voltage decreases the probability of carrier recombination losses. This explains the superior on-off ratio of the D5 device at reverse bias conditions. However, At the highest reverse bias (-3 V), the on-off ratio of D5 is lowered again due to the increasing dark current possibly associated with minority carrier injections.

3.6 SUMMARY

In this chapter, we demonstrated the device structure and fabrication process of the OPD. The role of LED forward current and different OPD biasing conditions over the OPD performance was studied using an OPD-LED hybrid system. The results indicated a higher magnitude of OPD photocurrent at higher reverse bias conditions due to enhanced charge carrier generation and collection. The OPD J - V characteristics were also investigated for different LED lights having different wavelengths and a higher current density was observed for shorter incident wavelength, i.e., for blue LED. We have further investigated the OPD J - V characteristics and the on/off ratio for different shapes of the OPD inner periphery, different distances between the OPD and the incident LED, and different sizes of the OPD area. The obtained results suggested that the distance between LED and OPD should be minimized to obtain a low dark current and a high photocurrent, i.e., a high on/off ratio suitable for any kind of sensing application. The variation for the OPD area suggested that the OPD area should be larger if the

OPD is used at zero bias condition whereas OPD should possess a smaller area if it is used at a reverse bias condition.

CHAPTER IV

HYBRID PPG SENSOR SYSTEM DESIGN

4.1 INTRODUCTION

The hybrid PPG sensor system is composed of basic parts such as an optoelectronic device, a controlling and driving circuit, and a microcontroller unit (MCU). The optoelectronic portion of the device was briefly illustrated in Chapter II, and the prepared OPD performance was briefly discussed in terms of varying illumination and design conditions in Chapter III. This chapter contains the full illustration of each step of the driving circuit of the hybrid PPG sensor system. The PPG signal acquisition method and an algorithm for measuring the heart rate will also be presented.

4.2 PPG DRIVER CIRCUIT

The detecting and driving circuit of a hybrid PPG sensor for accurate and suitable PPG signal detection involves three main stages: a transimpedance amplifier (TIA) for current-to-voltage conversion, a filter circuit for removing noise and an amplifier for amplifying the signal suitable for ADC operation, as shown in Figure 4.1.

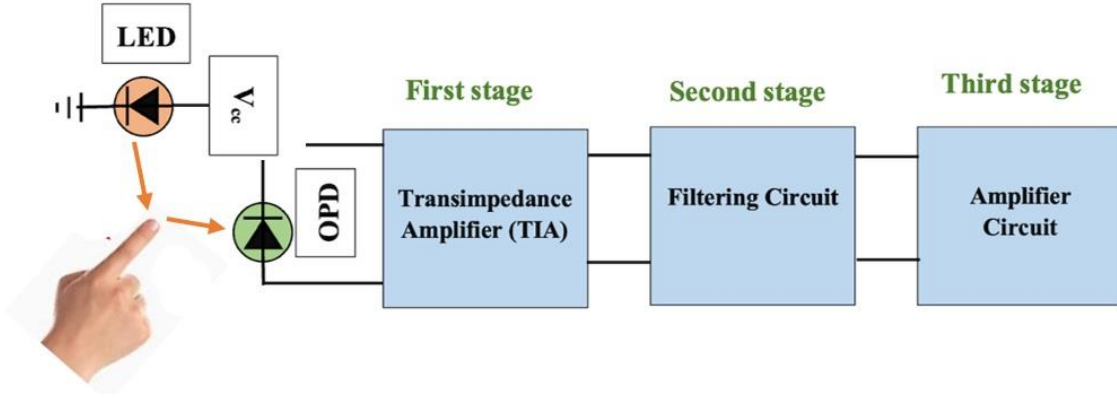


Figure 4.1: Driving circuit stages of hybrid PPG sensor

In the reflective mode PPG sensor, the photocurrent generated from the OPD as a response to reflected light from the skin interface and the blood vessel, is quite small, e.g., in the nanoampere-to-microampere range. In the first stage of the driving circuit, this photocurrent output of OPD is translated into a voltage signal through a current-to-voltage converter circuit for the required conversion. Next, it goes through several filtering stages to remove the noise from the surroundings and keep it in its desired frequency range. Finally, the filtered signal passes through an amplifier for its amplification to a desired level suitable for the analog-to-digital conversion (ADC) process before sending the data via universal asynchronous receiver transmitter (UART), serial communication block (SCB), or Bluetooth low energy (BLE) using the MCU.

4.2.1 TRANSIMPEDANCE AMPLIFIER (TIA)

A transimpedance amplifier (TIA) is a current-to-voltage converter circuit that converts the current output of an OPD to a voltage signal. It is used with the sensor having a more linear current response than the voltage response. TIA circuit must offer a low input impedance and low output impedance to avoid impedance mismatch in the circuit. One of the advantages of the TIA circuit is that it can offer a low impedance to the OPD and maintain isolation with the output voltage of the operational amplifier [67, 68]. It can convert the low-level current of devices like photodiodes to a voltage which is a very important stage for the sensor devices employing them.

Figure 4.2 illustrates the TIA circuit used for the hybrid PPG sensor system using a single supply.

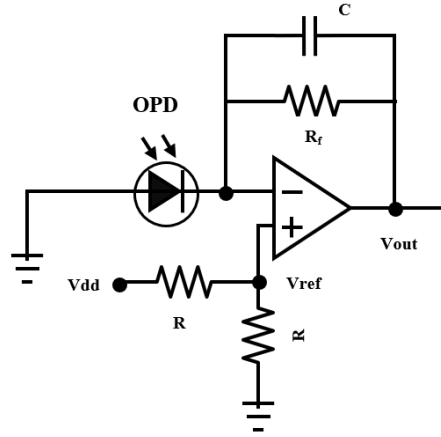


Figure 4.2: TIA circuit for hybrid PPG sensor system

The circuit adopts an inverting operational amplifier (op-Amp) for current-to-voltage conversion and a combination of a feedback resistor and capacitor to work as a low-pass filter for the improvement of signal treatment. The output voltage of the TIA circuit that is proportional to the input OPD current can be given by the equation,

$$V_{out} = -I_{in}R_f + V_{ref}(4.1)$$

where V_{out} is the output voltage, I_{in} is the input OPD current, R_f is the feedback resistance and V_{ref} is the reference voltage applied to the op-amp positive input pin. The gain of the TIA depends on the feedback resistance.

4.2.2 FILTERING CIRCUIT

The PPG signal obtained from the sensor is composed of two parts- an alternating current (AC) component and a direct current (DC) component. As previously discussed in Chapter II, the AC component of the PPG is the result of small variations due to the varied light intensity reflected from the skin when blood flows into and out of the finger. On the other hand, the DC component comes from the total reflected light detected by the photosensor. Before the

amplification stage of the signal, it is very important to eliminate this DC component and amplify only the AC component. If the raw signal is amplified without filtration, the DC part of the signal can lead the amplifier to saturation before getting the desired amplification of the AC, i.e., the time-varying part.

To eliminate the DC signal and improve signal-to-noise ratio (SNR), a band-pass filter (BPF) and a combination of low-pass and high-pass filters can be applied to the output voltage coming from the TIA circuit. In this hybrid PPG sensor system, a band-pass filter with a cut-off frequency band from 0.5 Hz to 16 Hz was applied to filter the obtained PPG signal. The applied LPF can eliminate the high-frequency noise induced by the ambient light fixture and appliances having a frequency in the range of 60 Hz–120 Hz. On the other hand, the HPF used can remove the DC signal with low frequency coming from the DC component of the PPG signal. However, the PPG signal should not be attenuated below 1 Hz, equal to one heartbeat per second.

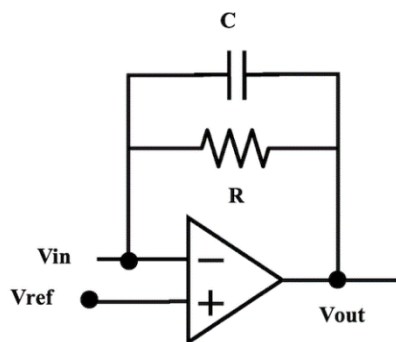


Figure 4.3: The basic low-pass filter circuit

The low pass filter, the first part of the band-pass filter, can be implemented with the parallel connection of a capacitor and a feedback resistor. Figure 4.3 shows the basic circuit of a low-pass filter with a cut-off frequency (f_c) that can be given by

$$f_c = \frac{1}{2RC} \quad (4.2)$$

Where R and C are the feedback resistor and capacitor respectively.

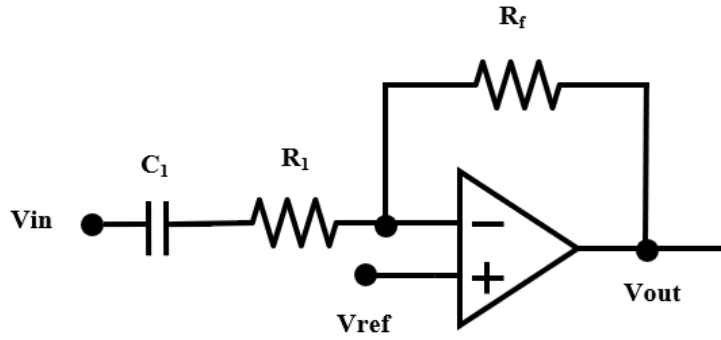


Figure 4.4: The basic high-pass filter circuit

The second part of the band-pass filter, i.e., the high-pass filter can be implemented with a capacitor in series with an input resistance. The basic high-pass filter circuit is shown in Figure 4.4. The voltage gain and cut-off frequency of the filter can be calculated using the following equations

$$A_v = -\frac{R_f}{R} \quad (4.3)$$

$$f_c = \frac{1}{2R_1C_1} \quad (4.4)$$

Where R_f is the feedback resistance and R_1 and C_1 are the input resistance and capacitance respectively.

However, these two filters, LPF and HPF, can be combined in one operational amplifier to implement a band pass filter. Therefore, it is important to choose the values of R and C with care to maintain the pass-band frequencies and the gains.

4.2.3 AMPLIFIER CIRCUIT

After the filtering of the PPG signal, it needs to be amplified to a desired level suitable for the ADC. An inverting op-Amp can be a suitable option for amplifying the low-amplitude PPG signal using a single supply. The fundamental amplifier circuit is shown in Figure 4.5.

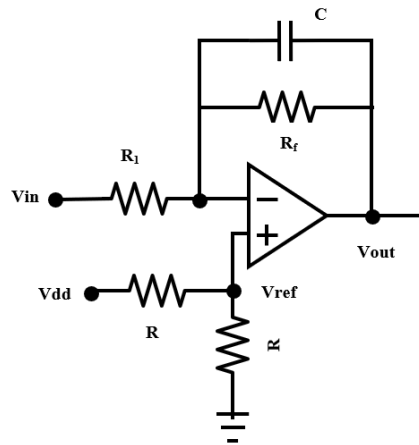


Figure 4.5: Amplifier circuit for sensor application.

The amplifier circuit can provide an output signal with amplitude near the Vdd power supply. The signal should be amplified in between 0 to Vdd instead of centered around 0V. To accomplish this, a virtual ground (V_{ref}) needs to be applied to amplify the changes concerning the ($V_{dd}/2$) volts. Figure 4.6 shows the basic V_{ref} generator circuit that has been applied to the hybrid PPG sensor system.

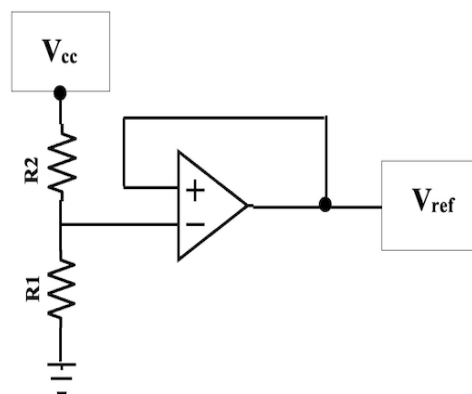


Figure 4.6: The V_{ref} generator circuit

The application of V_{ref} to the positive input of the op-Amp allows the shifting of the negative output signal to a positive level. By combining the above three stages, the filtered and amplified

PPG signals were obtained from the hybrid PPG sensor that was applied to the ADC for conversion into digital values for further processing of health monitoring conditions. All the components were chosen with proper care and consideration to minimize the size of the PCB as well as reduce the power consumption of the whole circuit.

Figure 4.7 shows the whole driving circuit of the hybrid PPG sensor system.

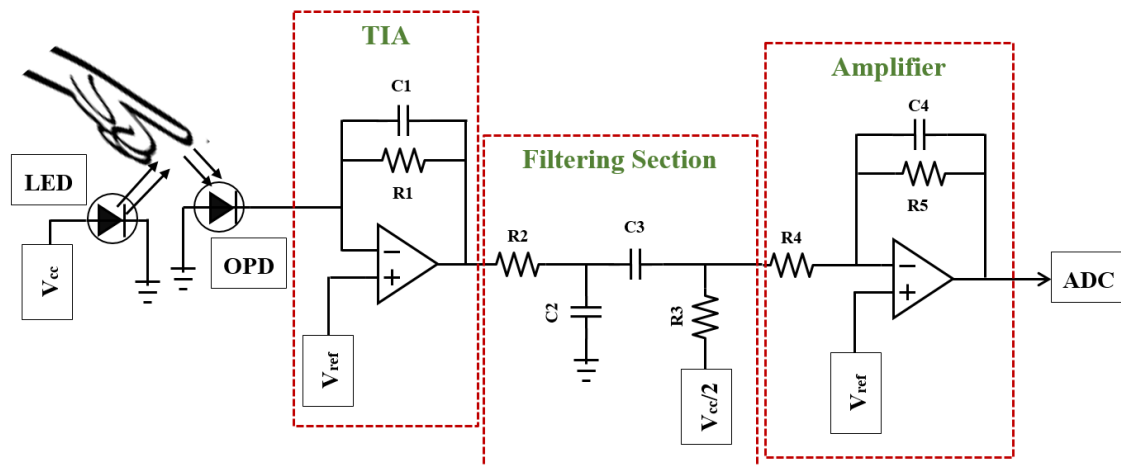


Figure 4.7: The driving circuit of the hybrid PPG sensor system

4.2.4 LTspice SIMULATION

To ensure proper functionality of the designed circuit, a simulation was performed with LTspice, a SPICE-based analog electronic circuit simulator computer software. A capture of the schematic circuit is displayed in Figure 4.8.

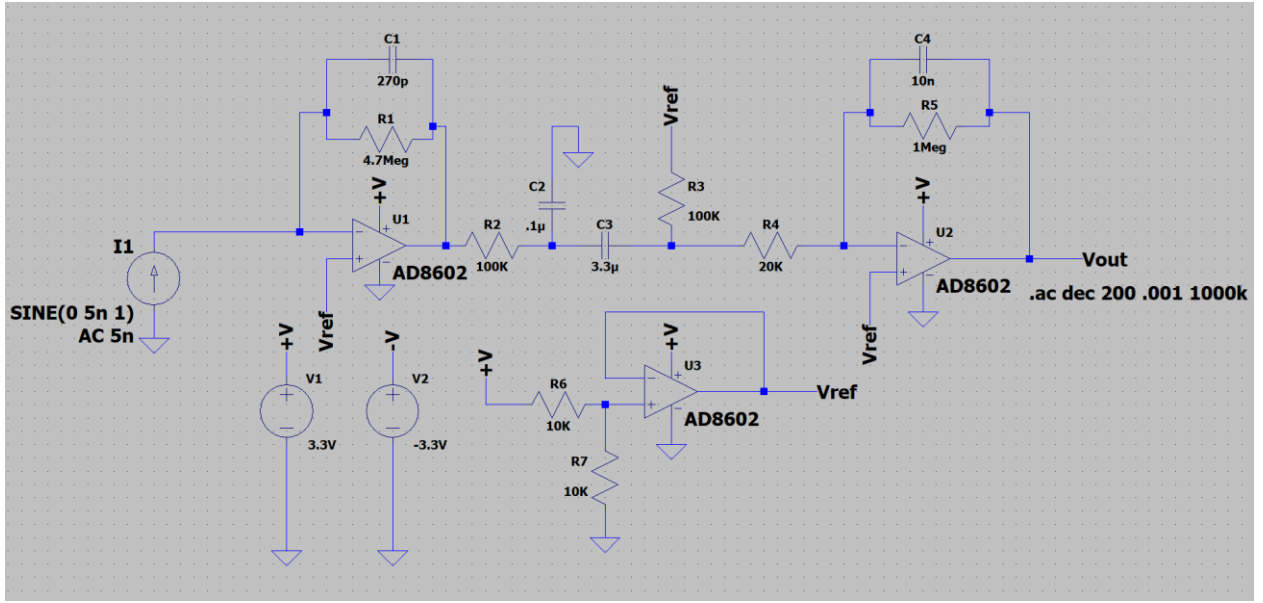


Figure 4.8: The analog circuit for detecting the PPG signal simulated on LTspice.

The photodetector was modeled as a current source. The circuit consists of two op-Amps and several resistors and capacitors. It also included the reference voltage generator employing one op-Amp and two resistors of the same value for providing the reference voltage as half of the supply voltage.

The circuit included several filter stages- a low-pass filter in the TIA circuit to remove high-frequency noise, a bandpass filter with a combination of low-pass and high-pass filter to the next for removing high-frequency ambient noise and DC signal, and a final low-pass filter with the amplifier side with a gain factor. The filters analyses are shown in below equations;

$$f_c(LPF1) = \frac{1}{2R_1C_1} = \frac{1}{2(4.7 \text{ Meg})(270 \text{ pF})} = 125 \text{ HZ} \quad (4.5)$$

$$f_c(LPF2) = \frac{1}{2R_2C_2} = \frac{1}{2(100K)(0.1 \mu F)} = 15.9 \text{ HZ} \quad (4.6)$$

$$f_c(HPF1) = \frac{1}{2R_3C_3} = \frac{1}{2(100 \text{ K})(3.3 \mu F)} = 0.48 \text{ HZ} \quad (4.7)$$

$$f_c(LPF1) = \frac{1}{2R_5C_4} = \frac{1}{2(1 \text{ Meg})(10 \text{ nF})} = 15.9 \text{ HZ} \quad (4.8)$$

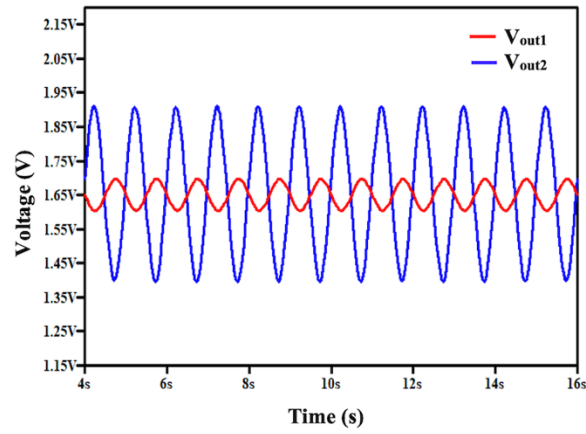


Figure 4.9: LTspice transient simulation of the driving circuit

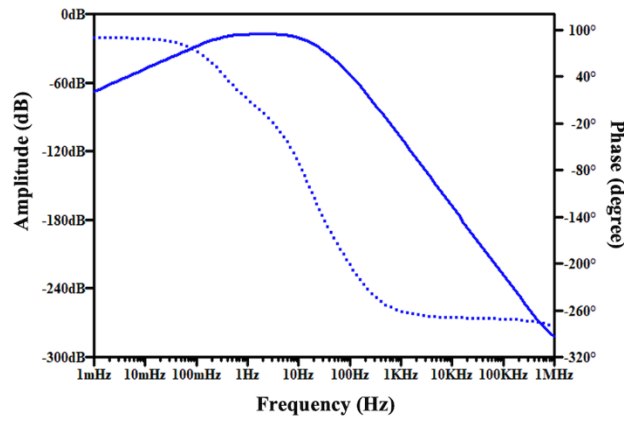


Figure 4.10: Amplitude and phase response of driving circuit in LTspice

The transient voltage response of the circuit after the first (V_{out1}) and second (V_{out2}) op-Amp is shown in Figure 4.9 denoting the amplification of the signal after the filter and amplifier circuit. Additionally, an AC analysis was also done to see the magnitude and phase response of the signal. Figure 4.10 shows the results of the AC analysis. The blue solid line denotes the amplitude of the signal whereas the blue dotted line shows the phase response.

4.2.5 PCB DESIGN

The customized PCB board was designed to include the driving circuit, the LED emitter, and the spring header pin to make the connection between the LED and the OPD using the Eagle software which is a scriptable electronic design automation application. The schematic and the PCB circuit design are shown in Figures 4.11a and 4.11b respectively whereas the image of the prepared PCB board with all the components is shown in Figure 4.12.

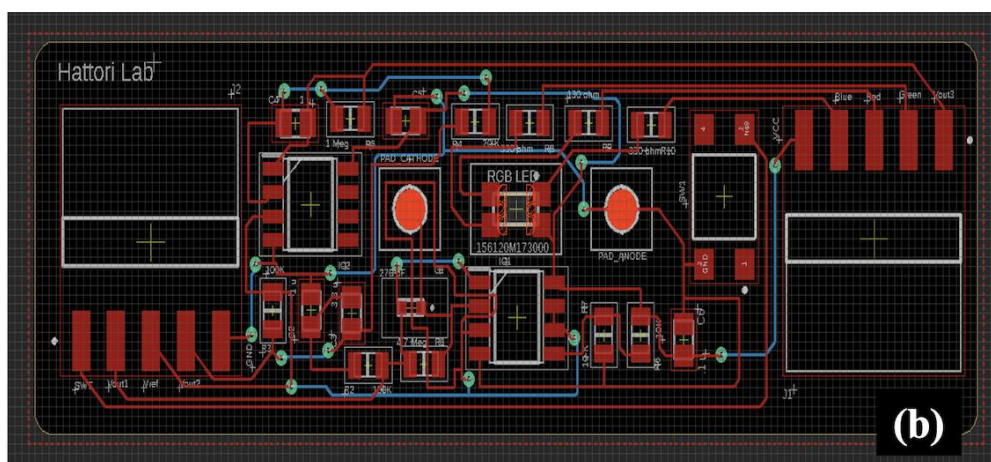
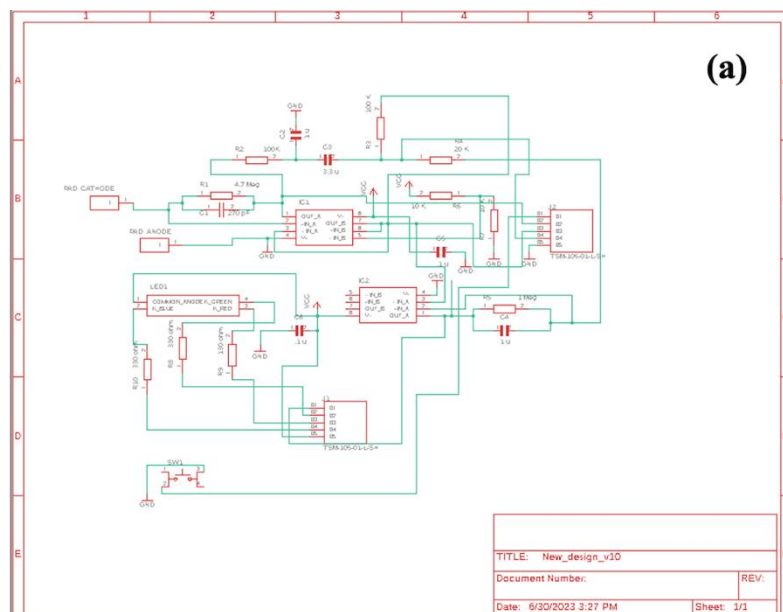


Figure 4.11: (a) Schematic of the PCB circuit in Eagle. (b) The PCB circuit diagram.

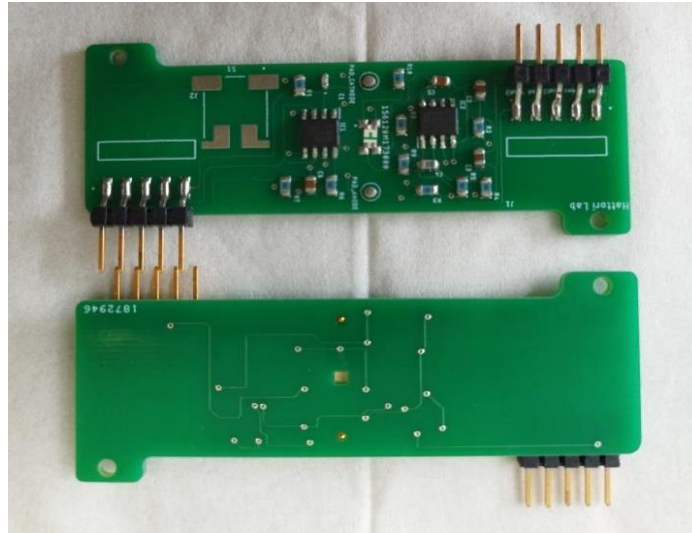


Figure 4.12: Customized PCB with LED and driving circuit

4.3 MICROCONTROLLER UNIT

The MCU module used in this work was the onboard interfaced MCU included in the nRF52833DK hardware development platform, which supports UART, BLE, and other communication protocols. The MCU on the nRF52833 DK runs the SEGGER J-Link OB interface that is used for programming and debugging the firmware of the nRF52833 system on chip (SoC). The SoC can communicate with the computer interface through USB or interface MCU-provided virtual COM port. Figure 4.13 shows the capture of the nRF52833DK board that contains the MCU unit as well as the output interface to make the connection with the customized PCB for operating the LED and getting the PPG signal for ADC operation.



Figure 4.13: nRF52833DK board with integrated MCU unit

The MCU unit was used for mainly three different works- controlling the LED duty cycle using the pulse width modulation (PWM) operation, the ADC sampling, and data acquisition through UART service. Figure 4.14(a-c) summarizes the process of PWM initialization for LED, the ADC initialization, and the UART initialization using the MCU for the processing of PPG data respectively.

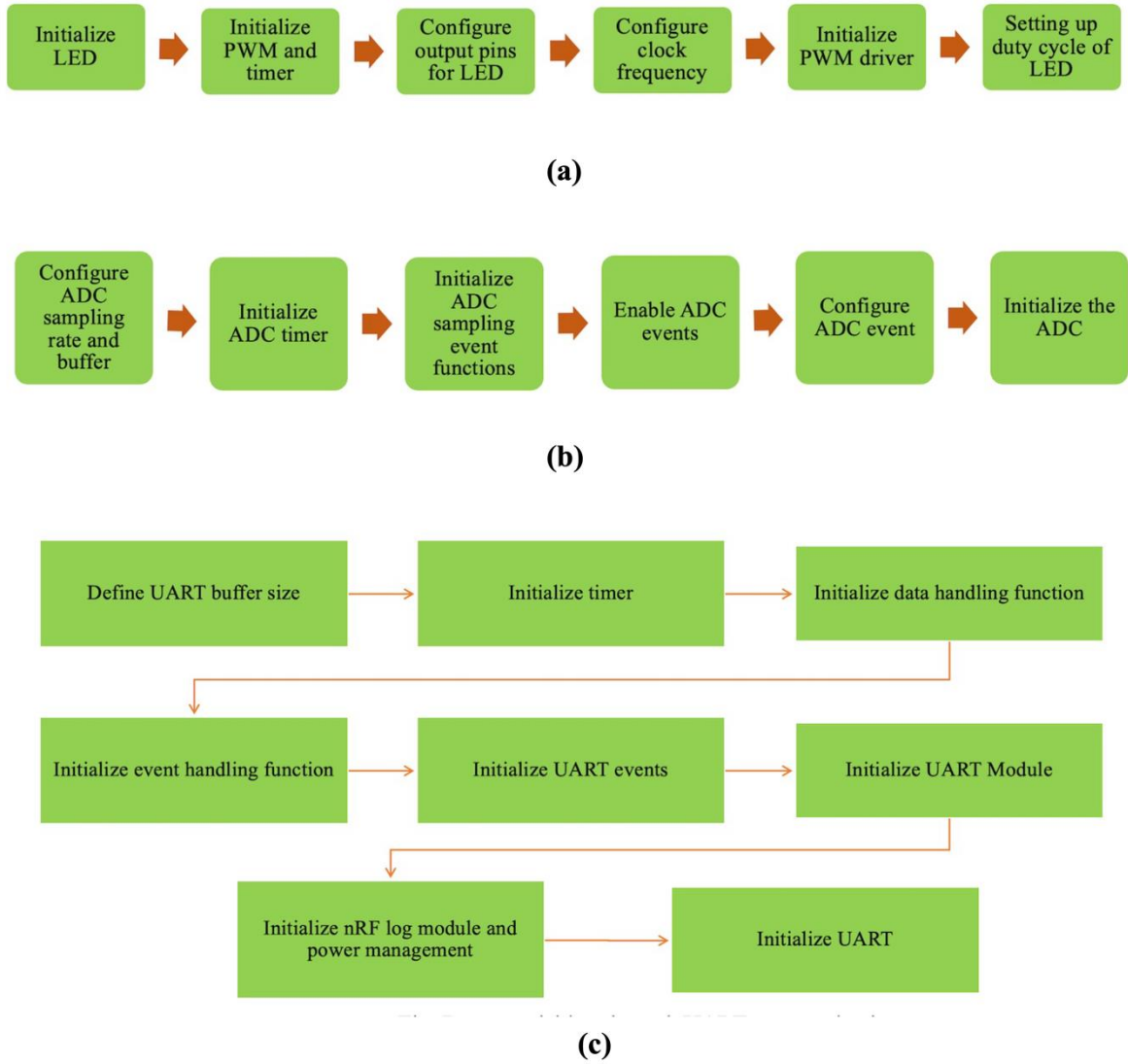


Figure 4.14: (a) LED duty cycle setting up overview. (b) ADC function initialization overview. (c) UART initialization for PPG data acquisition

4.4 THE DEVICE HOLDER DESIGN

As discussed previously in Chapter II, the light emitter LED, the driving circuit, and the organic photodetector are on different boards and substrates. To make an electrical connection between them spring header pins are used which are very small in size. To maintain the proper functionality of the sensor and get the accurate PPG, it is very crucial to maintain the electrical connection which can further be supported by a device holder to hold the PCB board and OPD

substrates together. The FreeCAD design of the device holder is shown in Figure 4.15a, whereas the image of the 3D-printed device holder is shown in Figure 4.15b.

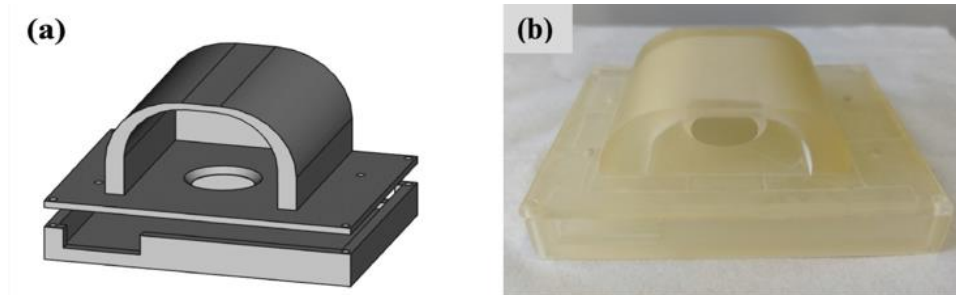


Figure 4.15: (a) FreeCAD design of the device holder. (b) Image of the 3D-printed device holder.

4.5 PPG SIGNAL ACQUISITION

The step-by-step process of arranging all the components for PPG detection using the hybrid PPG sensor is summarized in Fig. 4.16. First, the fabricated OPD on the glass substrate is attached to the PCB board by maintaining the accurate position for light signal harvest and ensuring proper electrical connection between them. In the next step, they are fit into the device holder and then connected to the nRF52833DK board, which holds the pins to connect the ADC of the MCU unit for further process of PPG signal detection.

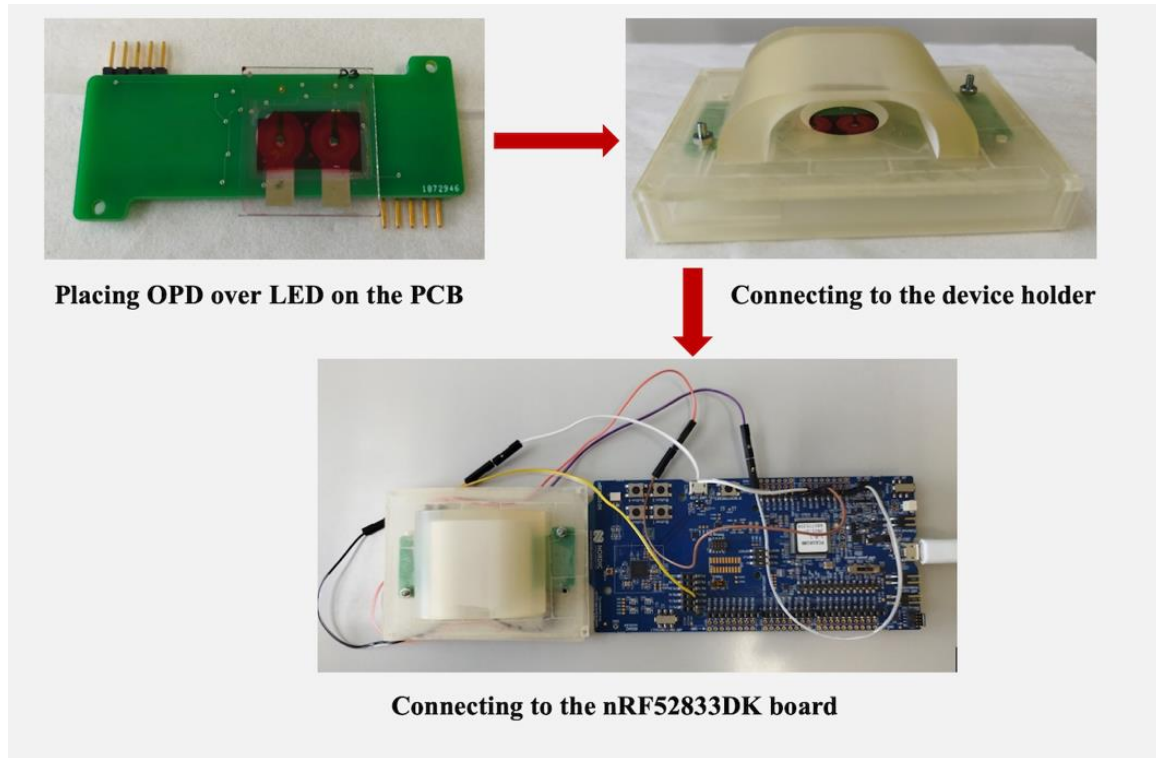


Figure 4.16: The steps of arranging the hybrid PPG sensor system.

Consideration of the PPG sampling rate is one of the keys to designing a PPG sensor as a lower sampling rate can reduce the power consumption. However, a low sampling rate often deteriorates the resolution of the PPG signal which leads to inaccurate measurement data [69,70]. Keeping this consideration in mind, the researchers employed a sampling frequency of 250 Hz or higher for the detection of accurate PPG for their healthcare product demonstrations in many cases [71-73]. In this study of the hybrid PPG sensor system for accurate PPG signal detection, we sampled the PPG signal at a rate of 250 Hz (4 ms) by the ADC operation. The sampling rate is sufficient for PPG detection as the frequency of the PPG signal ranges between 0.5–5 Hz. The LED was sequentially turned on for 64 ms and off for 64 ms during the PPG signal acquisition. During this total of 128 ms of LED pulse time, the ADC sampled the signal every 4 ms which is stored in the buffer of the microcontroller unit. Figure 4.17 shows the obtained PPG signal using the hybrid PPG sensor system from the fingertip of a human subject. There are some noisy fluctuations in the signal due to the finger motion while doing the measurement.

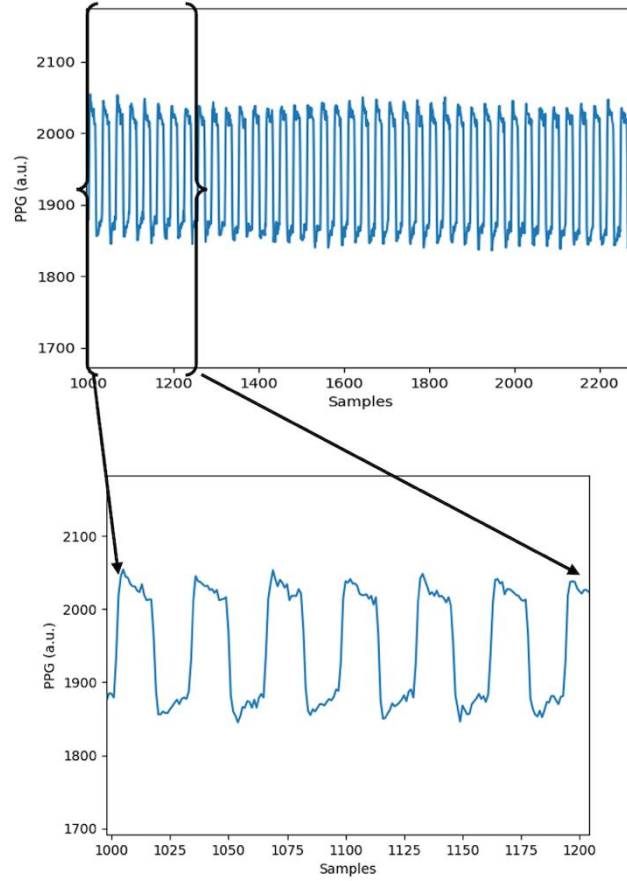


Figure 4.17: The acquired PPG signal from the hybrid PPG sensor.

4.6 SUMMARY

This chapter elaborated on the system design that has been adopted for the proposed hybrid PPG sensor system. The detecting and driving circuit including all its stages, the LTspice simulation, the design of the customized PCB board, the MCU, and the device holder proposed for the sensor were explained thoroughly. The system components organization and the acquisition process of the PPG signal were also explained.

CHAPTER V

HEART RATE MEASUREMENT

5.1 INTRODUCTION

Advancements in modern technologies have enabled continuous field monitoring of human health, e.g., monitoring heart conditions without going to medical centers and in the case of fitness and professional sports activities. The most commonly measured parameter is the heart rate (HR). Heart rate is the number of times the heart beats in a minute. Heart rate estimation from PPG has become a popular area of investigation.

5.2 HEART RATE CALCULATION ALGORITHM

The algorithm for heart rate extraction from the PPG signal typically consists of some basic steps. First, the PPG signal has to go through some preprocessing techniques such as smoothing, band-pass filtering, downsampling, and normalization. Secondly, the effect of motion artifacts has to be removed. For this process, generally, an accelerometer signal is used for reference sometimes. Also, other methods like- adaptive filtering, independent component analysis, empirical mode decomposition, wavelet decomposition, spectral subtraction, and Kalman filtering can be adopted for this. Third, the estimation of the heart rate of processed PPG signals by analyzing the spectral components of it after the removal of motion artifact [74].

Conventional PPG heart rate algorithms can be divided into two categories: one based on time-domain analysis, e.g., peak number algorithm, and another based on frequency-domain analysis, e.g., discrete Fourier transform (DFT), and fast Fourier transform (FFT).

Time-domain analysis involves a two-stage process for the extraction of heart rate information from the PPG signal. The first stage is the pre-processing stage which filters out noise-induced

portions from the PPG signal. The second stage involves heart rate extraction by decomposition of the PPG signal, Khan *et.al.* introduced a method based on ensemble empirical mode decomposition (EMD) that initially removes runaway errors, and then the use of recursive least squares (RLS) filters for further calculation of the heart rate [75].

Ye *et.al.* proposed a combined nonlinear adaptive filtering and signal decomposition for motion artifact removal [76]. Nevertheless, time-domain methods sometimes become unreliable in the case of motion noise exhibiting periodic and robust characteristics, leading to a challenge in extracting a clean PPG signal under such conditions.

Frequency-domain methods can be an alternative to time-domain approaches, as removing periodic disturbances in the frequency domain is quite easier than in the time domain. Salehizadeh *et.al.* proposed an accurate reconstruction technique for motion-corrupted PPG signals and heart rate based on time-varying spectral analysis that involved the calculation of the power spectral density of both PPG and accelerometer signals for each time shift within a windowed data segment [77]. From the comparison of the time-varying PPG spectrum and accelerometer data, it was easy to distinguish the frequency peaks of motion artifacts and the PPG spectrum.

Fukushima *et.al.* and Chen *et.al.* proposed a spectrum subtraction technique for the removal of the acceleration data spectrum from the PPG signal [78,79]. Sani *et.al.* and Aisuwarya *et.al.* introduced a simple fast Fourier transform (FFT) technique for the calculation of heart rate as FFT can reveal the signal frequency quite easily [80,81]. However, frequency domain analysis has limited effectiveness in the presence of irregular or aperiodic disturbances.

In this work, the heart rate was calculated using the FFT analysis. The obtained PPG signal was preprocessed using a moving average and Butterworth bandpass filter before the FFT analysis to remove the noisy fluctuations introduced while doing the measurement.

5.2.1 MOVING AVERAGE FILTER

The moving average, a Finite Impulse Response (FIR) smoothing filter is the most common filter in digital signal processing for its easier understanding and use that can be applied for smoothing signals from short-term overshoots or noisy fluctuations. Despite its simplicity, the

moving average filter is optimal for reducing random noise and retaining a sharp step response. The moving average filter operates by averaging several points from the input signal to produce each point in the output signal. In equation form, it can be written as

$$y[n] = \frac{1}{L} \sum_{k=0}^{L-1} (x[n-k]), n = L, L+1, \dots, M \quad (5.1)$$

where $y[n]$ is the output signal, L is the window size, and M is the data length.

5.2.2 BUTTERWORTH BAND-PASS FILTER

The Butterworth filter is a type of filter with a nearly flat frequency response over the passband region with no ripple. The transfer function of a Butterworth filter of order n is given by

$$|H(s)|^2 = \frac{1}{1 + (\frac{s}{\omega_c})^{2n}} \quad (5.2)$$

where s is the complex frequency variable, n is the filter order, and ω_c is the cutoff frequency.

Butterworth filters possess the following properties:

- i. **Flat Frequency Response:** The Butterworth filter is designed to provide a maximally flat frequency response in the passband. The amplitude response in the passband is as flat as possible.
- ii. **Roll-off Rate:** The roll-off rate, i.e., the slope of the filter after the passband of a Butterworth filter depends on filter order n . Higher-order filters can give steeper roll-off rates which means they can attenuate frequencies outside the passband more rapidly. Multiple poles can be integrated to get a steeper roll-off.
- iii. **Phase Response:** This filter has a linear phase response within its passband. This is a very important characteristic in the applications, and the phase relationship of the signal needs to be maintained critically.

This filter is often used for applications where a good trade-off between attenuation and phase response is required.

5.2.3 FFT ANALYSIS

A Fourier transform is a mathematical method for transferring a time domain signal onto a frequency domain signal for obtaining signal power information at certain frequencies. In the case of discrete signals, the Fourier transform is applied by the concept of Discrete Fourier Transform (DFT) defined as

$$Y(k) = \sum_{n=0}^{N-1} X(n)e^{-i\frac{2\pi}{N}nk} \quad (5.3)$$

where,

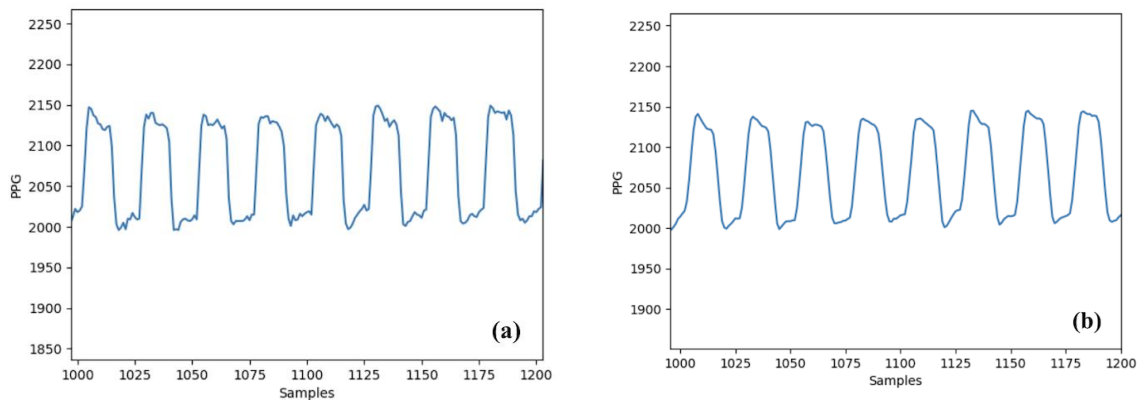
$$n = 0, 1, \dots, N-1.$$

DFT computation needs many complex operations which can be reduced by an algorithm called Fast Fourier Transform (FFT). The FFT algorithm breaks N points into $(N/2)$ points and then splits $(N/2)$ points into $(N/4)$ points and so on up to 1 point.

In this work, we applied FFT analysis as a tool to calculate the heart rate from the acquired PPG signal. Once the frequency of the signal was obtained from the spectrum, the heart rate was measured using the equation [80]

$$\text{Heart rate} = \text{Dominant Frequency} * 60 \quad (5.4)$$

The obtained PPG signal before and after the application of the moving average and Butterworth bandpass filter is shown in Figure 5.1.



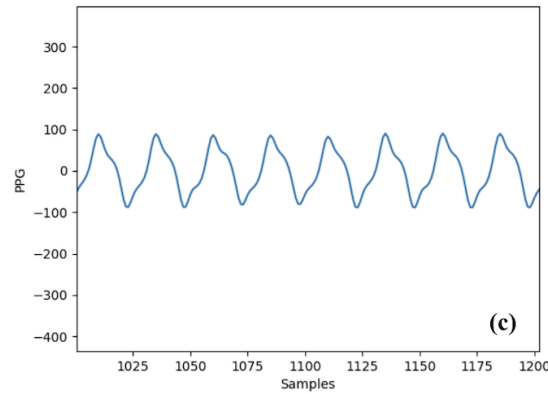


Figure 5.1: (a) PPG signal before filtering (some disturbance can be seen at the signal peak due to the disturbance introduced while measuring from a fingertip). (b) PPG signal after applying a moving average filter with a window size of 3 to smooth the signal. (c) PPG signal after moving average and Butterworth bandpass filter with a cut-off frequency of 0.5 Hz-16 Hz to remove unwanted frequency signals.

The algorithm used for the heart rate calculation is summarized by the following steps:

- Step 1. Acquisition of the PPG data from the hybrid PPG sensor.
- Step 2. Application of a moving average filter with a window size of 3 for smoothing the data
- Step 3. Bandpass filtering of the smooth PPG signal in the frequency range of 0.48 Hz to 16 Hz for removing unwanted frequency components
- Step 4. Applying FFT to the filtered signal
- Step 5. Finding the magnitude spectrum of FFT by calculating the absolute value of FFT and dividing it by FFT length
- Step 6. Calculating the frequency values corresponding to each FFT value
- Step 7. Finding the one-sided spectrum by multiplying the FFT magnitude by 2, excluding the DC and Nyquist frequency
- Step 8. Determining the dominant frequency at the range of 1Hz-4Hz by finding the local maxima

Step 9. Heart Rate calculation using the equation 5.4.

The process of heart rate estimation is summarized in Figure 5.2.

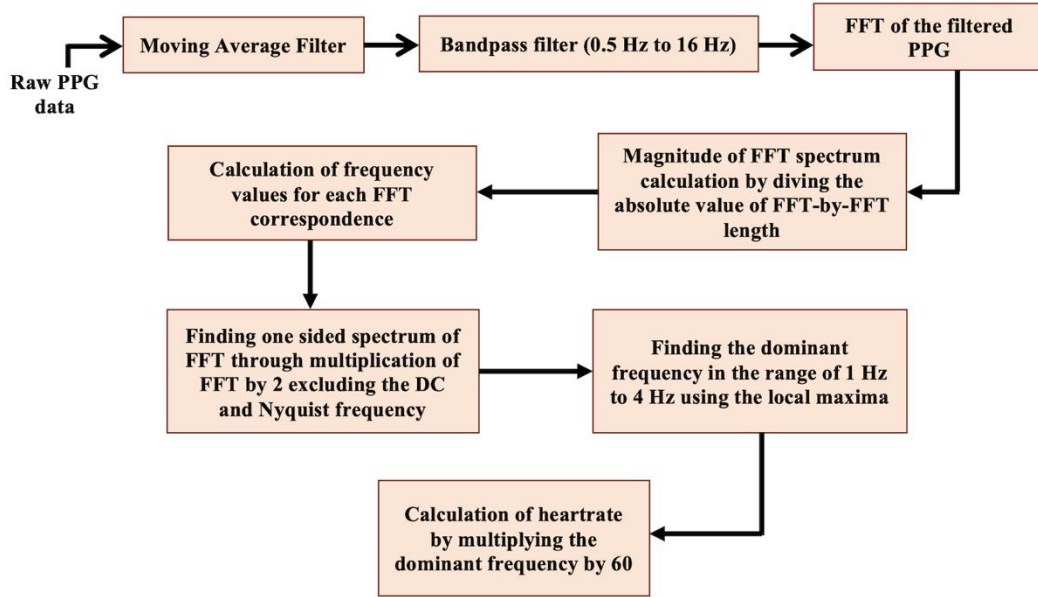


Figure 5.2: Process of heart rate estimation

5.3 POWER CONSUMPTION MANAGEMENT

For a portable PPG sensor device, the LED input power, and its power efficiency, as well as the power efficiencies of driving and readout circuits are mainly responsible for the total power consumption of the device. As the size of the sensor and battery capacity are limited to a certain level, it is necessary to reduce the power consumption of the sensor. Methods like adopting different sampling schemes and redesigning the TIA circuit were applied previously to reduce the power consumption of the PPG sensor which can result in some errors and needs complex circuit analysis in some cases [82, 83]. In this work, LED duty cycle and brightness control were adopted to control the power consumption of the hybrid PPG sensor which can easily be controlled by the PWM operation of the used microcontroller unit.

5.3.1 CONTROLLING LED DUTY CYCLE

LED power consumption depends highly on an LED's duty cycle, which consumes most of the power of a sensor system. LED duty cycle is the percentage of the time an LED is in its active state, i.e., the ratio of its on-time and the total pulse time. The larger the duty cycle of an LED, the brighter its illumination radiation. The rapid LED pulse can appear as a steady light to human eyes with a lower brightness that can be adjusted by changing the percentage of time the LED is in an on state. With an on-time of 100%, i.e., 100% duty cycle, the LED illuminance is at its highest state and consumes higher power. However, lowering the duty cycle reduces the brightness as well as the consumed power.

Thus, the PPG sensor's power consumption can be reduced by reducing the duty cycle of the LED with an increased pulse repetition interval (PRI). However, this phenomenon can deteriorate the heartbeat interval measurement accuracy because of the degraded signal-to-noise ratio and sampling error [83]. In this work, we obtained the PPG signal for different duty cycles (20%-80%) duty cycle with 128ms PRI for observing the effect on heart rate accuracy along with the power consumption of the LED. The LED duty cycle was controlled by the PWM operation of the microcontroller. The results for all the measurements with varying LED duty cycles are summarized in Table 5.1.

Table 5.1: Effects on heart rate accuracy and power consumption for varying duty cycle

Duty cycle (%)	Heart rate (bpm) variation			Power consumption of LED (mW)
	Heart rate from Nurse Angie (bpm)	Heart rate from hybrid PPG sensor (bpm)	Percentage error (%)	
20	80	84	5	13.754
30	82	86	4.88	20.631
40	79	82	3.78	27.508
50	90	87	3.33	34.385
60	81	83	2.47	41.262
70	85	83	2.35	48.139
80	86	84	2.32	55.016

From Table 5.1, it can be noticed that an improved duty cycle can provide more accuracy in the heart rate detection while consuming more power compared to the case in a lower duty cycle. For PPG signals obtained during the larger duty cycle, features can be extracted from the signal that helps to get the heart rate more accurately. On the contrary, a larger duty cycle needs more power to keep the LED on the on state. To make a balance between these two factors, we maintained a 50% duty cycle throughout all the other measurement conditions with our hybrid PPG sensor.

5.3.2 CONTROLLING LED BRIGHTNESS

Another way of controlling the power consumption of the PPG sensor is controlling the overall brightness, i.e., the luminous intensity of the LED light source. LED luminous intensity is the measurement of wavelength-weighted power radiated by it in a specific direction per constituent solid angle. LED luminous intensity has a proportional relationship to its consumed power which can be controlled by varying the current applied to it. LED luminous intensity can be controlled by the PWM operation or by controlling the LED current flowing through it. In this study, we varied the LED luminous intensity by controlling the LED current through the external circuit.

To observe the effect of LED luminous intensity on the power consumption and heart rate measurement, we varied the luminous intensity of the LEDs to a certain level. As the LED is very small, its luminous intensity was calculated in μcd range. The results for heart rate variation and power consumption for different LED luminous intensities are summarized in Table 5.2.

Table 5.2: Effects on heart rate accuracy and power consumption for varying LED luminous intensity

Luminous intensity (μcd)	Heart rate (bpm) variation			Power consumption of LED (mW)
	Heart Rate from Nurse Angie (bpm)	Heart Rate from hybrid PPG sensor (bpm)	Percentage error (%)	
7.68	88	85	3.4	3.310
48.64	84	81	3.7	4.496
445.44	86	89	3.37	12.457
609.28	88	85	3.4	16.290
919.04	91	88	3.29	28.577
1090.56	90	87	3.33	34.385

From Table 5.2, it can be seen that the power consumption value increases for increasing the luminous intensity i.e., the brightness of the LED. More photon extraction needs more power to be consumed. On the other hand, it is evident that the heart rate accuracy does not depend on the luminous intensity of the LED, which is within the acceptance range of error even with a low LED power consumption regime. This indicates that, as far as the reflected light harvesting is sufficient for the PPG signal acquisition, the sensor system can be operated with low brightness conditions to reduce power consumption which in turn can improve the battery lifetime of the sensor.

The data in Table 5.1 shows that increasing the LED duty cycle enhances sensor performance accuracy at the cost of higher power consumption. Conversely, Table 5.2 indicates that increasing LED brightness significantly raises power consumption without substantially reducing the error percentage. To optimize sensor performance, a trade-off can be maintained between these parameters. Operating the sensor at lower brightness with a higher duty cycle is recommended to achieve low power consumption while maintaining an acceptable error range for heart rate measurement.

5.4 SUMMARY

In this chapter, the detailed calculation algorithm for heart rate measurement was described. A small overview of the filters applied to the PPG signal for preprocessing and the FFT analysis was also given in this chapter. Later, two ways of power consumption management of the hybrid PPG sensor were introduced. The results for heart rate accuracy and power consumption in terms of varied LED duty cycles and LED luminous intensity were summarized.

CHAPTER VI

CONCLUSION AND FUTURE WORK

6.1 CONCLUSION

Photoplethysmography (PPG) sensors have become very useful in the field of wearable health monitoring devices. This non-invasive, easy-to-use, cost-effective technology has added a new dimension to monitoring a person's health continuously and avoiding potential illness. PPG, an essential bio-signal can be used for measuring the heart rate of a person that can be very helpful for detecting several heart diseases. There are many commercial PPG sensor devices available in the market based on conventional inorganic LEDs and PDs that face challenges with their fabrication process, cost, and power management. On the other hand, several researches have been done on all organic (combination of OLED and OPD) PPG sensors that face the issues with the lifetime shortage of OLED.

This research project aims to propose a hybrid (inorganic-organic) PPG sensor with a combination of commercially available LED and organic photodetector, OPD, and a proper driving circuit for acquiring accurate PPG signals for heart rate monitoring. The project gives careful consideration to the fabrication process of the OPD and its performance in terms of different LED illumination conditions and OPD biasing conditions as well as the design variation of the OPD. It implements the use of digital filters for the preprocessing of the noise-induced PPG signal before the calculation of heart rate using FFT analysis. The sensor performance in terms of heart rate measurement accuracy and power consumption management for different LED duty cycles and brightness is presented to ensure the hybrid sensor's applicability for health monitoring conditions. The thesis consists of six chapters organized as follows

Chapter 1 begins by providing a brief overview of the hybrid PPG sensor, the research motivation, and the problem statement, followed by the objectives of the research.

Chapter 2 gives an overview of PPG fundamentals, i.e., its principal and operation modes followed by a brief overview of the optoelectronic devices of the hybrid PPG sensor. Some literature reviews and previous works on PPG sensors are also discussed in this chapter.

Chapter Three gives a brief discussion about the design and fabrication process of the OPD as well as the performance of the OPD in terms of different illumination conditions, i.e., LED luminous intensity and LED wavelength, and OPD biasing conditions. Followingly, OPD performance analysis for various design variations, i.e., OPD inner periphery geometry, OPD to LED distance, and OPD area is also presented.

Chapter Four comprises the development of the system design for the proposed hybrid PPG sensor system including the driver circuit, the MCU unit, and the device holder design. The sensor system assembly and PPG signal acquisition process is also described.

Chapter Five discusses the heart rate calculation algorithm from the obtained PPG signal using the hybrid PPG sensor. It also includes the results of the proposed PPG sensor system's performance in terms of heart rate measurement accuracy for different LED duty cycles and luminous intensity conditions for power consumption management.

Chapter Six gives a summary of the findings throughout the dissertation. The thesis contribution to the current state of knowledge, future work, and recommendations are also presented.

In this work, the reflection mode of PPG was adopted for its advantages over the transmission mode, e.g., the freedom of use in different body parts. The reflective mode supports the positioning of LED and OPD on the same side allowing the collection of reflected light from the human skin layers. As the LED and OPD of the hybrid sensor are on different substrates, the reflective mode allowed us to make the connections between them easily which would have been difficult in the case of transmission mode.

This thesis addressed the significance of designing an effective OPD structure to improve the light detection ability. To detect the reflected light from the skin efficiently, the design optimization of the OPD is very crucial. The P3HT:PC₆₁BM bulk heterojunction OPD with the detection ability in the visible spectrum was fabricated using an easy solution process with a patterned electrode that allowed design variation of the OPD devices. The OPD device showed a photocurrent density up to 3–4 orders of magnitude higher than the dark current density when

illuminated with red, green, and blue LED illuminations at zero bias conditions which is suitable for PPG signal detection. The photocurrent density exhibited an almost linear relationship with the LED luminous intensity with increased value with applied voltage to the OPD in the negative direction which ensured its operation ability in various luminous intensity and biasing conditions. In addition, the design variation of the OPD in terms of its inner periphery shape, the distance between the light source and OPD, and the active device area helped to optimize the OPD structure to be used for the hybrid PPG sensor. An OPD with an area of 16 mm^2 maintaining a 0.65 mm distance between LED and OPD was chosen for the application in a hybrid PPG sensor for ensuring effective light harvest.

The driving circuit was designed with a combination of TIA, filtering, and amplifier circuit for the conversion of the small OPD signal to a voltage signal, filtering the signal for reduction of noise coming from undesired frequency range and amplifying to a suitable range for ADC operation of the MCU unit. The PCB design included all the components of this driving circuit, the LED light emitter, and the spring header pin for making the electrical connection between the circuit and the OPD on the different substrates. Once all the fabrication was done, they were all assembled properly and connected to the MCU unit embedded in the nRF52833DK board for the acquisition of the PPG signal through UART communication. The hybrid PPG sensor successfully detected the PPG signal from the fingertip of a human subject.

The acquired PPG signal was preprocessed using digital filters, i.e., a combination of moving average and Butterworth band-pass filter to remove the noise-induced from finger motion while doing the measurement. Using FFT analysis, the heart rate was calculated from the collected PPG signal with an acceptable range of error when compared to a commercially available PPG sensor device. The PPG signal was obtained for different LED duty cycles and luminous intensity, i.e., brightness taking into the consideration power management of the device. Though the higher duty cycle can improve the heart rate calculation accuracy, it requires more power compared to the lower duty cycle conditions. To make a trade-off between these two factors, a 50% duty cycle was maintained throughout the measurement using the hybrid sensor. However, the LED luminous intensity variation did not affect the heart rate accuracy too much indicating that the sensor can be operated at lower brightness conditions consuming lower power.

6.2 THESIS CONTRIBUTION

This research work focused on the prototyping of a hybrid PPG sensor with a combination of fabricated OPD and inorganic LED with proper driving circuits for acquiring accurate PPG signal and its use for heart rate measurement with power management consideration.

Secondly, the work presented the significance of designing and fabricating an effective OPD structure for any sensing application. The consideration of incident light wavelength and its luminous intensity, as well as the biasing condition of the OPD on its performance, can improve the sensor's performance. The attention given to the OPD design variation can ensure the optimization of OPD applicable to the hybrid PPG sensor as well as other sensor systems.

Thirdly, acquiring an accurate PPG signal and preprocessing it using digital filters to remove the noise-induced components before heart rate calculation using a simple FFT technique ensured the sensor's applicability for health condition monitoring. The consideration given to the LED duty cycle and luminous intensity helped the management of the power consumption of the hybrid PPG sensor.

6.3 FUTURE WORK AND RECOMMENDATIONS

Although the hybrid PPG sensor was able to acquire the PPG signal for heart rate measurement, more aspects of the sensor need to be considered for its enhancement, which is suggested as follows:

- The green and blue LED illumination of the RGB LED should be used for the acquisition of PPG signal to use them for the blood oxygen saturation (SpO₂) measurement which requires the varied signal that is the result of two different wavelengths.
- OPD needs to be fabricated on a flexible substrate and the LED and the driving circuit components should be mounted on a flexible PCB (FPCB) board to improve the hybrid PPG sensor's reliability, flexibility, and applicability as a wearable medical sensor.

- The sensor should be applied on different body parts with less density of fat such as the fingertips, wrist, arms, neck, and forehead to ensure its application as an efficient all-day health monitoring device.
- When using the PPG sensor on the fingertip more pressure has to be given to ensure the electrical connection between the OPD and the LED with the small spring header pin and driving circuit on the PCB resulting in distortion and weak PPG signal amplitude. Therefore, more options like silver paste should be used for making proper electrical connections which will help to put moderate pressure on the human body during the measurement condition.

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