# System Design for Organic Pulse Oximeter

Yasser Khan, Claire M. Lochner, Adrien Pierre, and Ana Claudia Arias*
Department of Electrical Engineering and Computer Sciences
University of California, Berkeley
Berkeley, California 94720
*Email: acarias@eecs.berkeley.edu

***Abstract*—Wearable medical devices that would benefit from mechanical flexibility and new form factors represent a great shift in direction of research in the field of printed electronics. The minimal functionality desired from wearable medical devices is the monitoring of vital signs. Pulse rate and blood oxygenation are considered primary vital signs that help to evaluate the general physical health of a person. The methods used to measure pulse rate and blood oxygenation with sensors based on organic light-emitting diodes (OLEDs) and organic photodiodes (OPDs) are reported here. Departing from the conventional practice of using red (630 nm) and infrared (940 nm) light for measuring pulse oxygenation, we have successfully implemented solution processed red (626 nm) and green (532 nm) OLEDs fabricated from polyfluorene blends in an all-organic optoelectronic pulse oximeter sensor. The red and green OLEDs operate at 9 V, 1 kHz, and transmit light through a human index finger. The transmitted light is sensed by an OPD placed on the opposite side of the finger. After filtering and amplification, the photoplethysmogram (PPG) signal is obtained and used to accurately measure pulse rate and blood oxygenation.**

***Keywords*—Organic light-emitting diodes, Organic photodiodes, Pulse rate monitoring, Blood oxygenation, Flexible sensors.**

## I. Introduction

Wearable medical devices can encourage healthy living by providing individuals with feedback on personal vital signs. In-home implementation of these sensors have the potential to reduce prolonged hospital stays and cut health care costs [1]. Recent advances have led to the development of sensors in wearable and flexible form factors, capable of measuring body temperature [2], pulse rate [3], [4], blood pressure [5], and blood oxygenation [6] in real time. Flexible and printed sensors are appealing in the biomedical domain because flexibility combined with large areas can result in an improvement of the overall sensor performance [7], [8], [9]. In this work, we focus on using organic light-emitting diodes (OLEDs) and organic photodiodes (OPDs) as a non-invasive medical sensor for measuring pulse rate and arterial blood oxygenation. We discuss the methodology used in pulse oximetry using red and green light, in addition to the essential circuit components, specifically, the OLED driver and OPD read circuit for the oximeter system.

## II. Pulse Oximetry with Red and Green Light

In pulse oximetry two different light wavelengths are used as the optical source, and the transmitted or reflected light is collected using a photodiode. The wavelengths are chosen in the areas of the spectrum where oxy-hemoglobin ($HbO_2$) and deoxy-hemoglobin ($Hb$) absorb differently. Pulse rate and oxygen saturation in the blood can be calculated by taking the ratio of absorption at these wavelengths. Conventionally, pulse oximeters use red (630 nm) and infrared (940 nm) light as optical sources. Oxy-hemoglobin ($HbO_2$) and deoxy-hemoglobin ($Hb$) have different absorption at these wavelengths, as shown

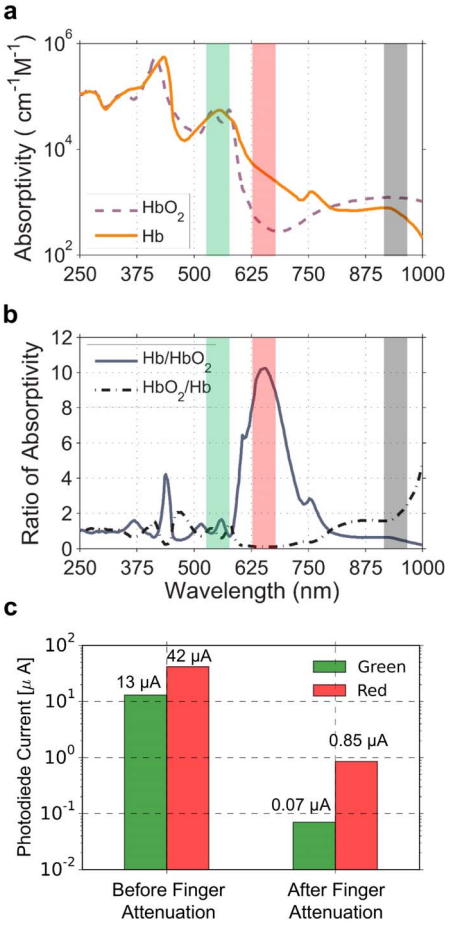


Fig. 1. **Optical wavelength considerations for organic pulse oximeter. (a)** Absorptivity of oxy-hemoglobin, $HbO_2$ (purple dashed line) and deoxy-hemoglobin, $Hb$ (orange solid line) are shown as a function of wavelength. Three operation regions for oximetry - green, red, and infrared are highlighted. **(b)** Ratio of absorptivities: $Hb/HbO_2$ (blue solid line) and $HbO_2/Hb$ (black dashed and dotted line) are shown. For pulse oximetry, combinations of red and infrared or red and green light can be used, as there is a contrast between the absorptivities of $Hb$ and $HbO_2$ at these wavelengths. **(c)** Sensed photodiode current ($I_{PD}$) during oximetry. The left bar charts show measured $I_{PD}$ when excited with green and red OLEDs before an index finger is placed in between, and the right bar charts show $I_{PD}$ after the light is attenuated through the index finger. There is a noticeable attenuation of green light. Nonetheless, pulse signal can be reconstructed from these attenuated light signals.

in Fig. 1**a**. Similar absorption difference exists at red and green wavelengths, which is highlighted in Fig 1**a**. These characteristics become apparent in Fig. 1**b**, where absorptivity ratio of $Hb$ and $HbO_2$ ($Abs_{Hb/HbO_2}$) is shown as a function of wavelength. In the red regime, $Abs_{Hb/HbO_2} \approx 10$, while in the infrared and the green regime, $Abs_{Hb/HbO_2} < 2$. Therefore, the combination of red and infrared or red and green light can be used. We used red and green OLEDs due to fact that solution-processable near-infrared OLEDs suffer from lower efficiencies [10].

In addition to specific wavelengths, light attenuation and OLED irradiance also need to be taken into account. Green light is significantly attenuated while traveling through the skin and tissue whereas red light is more efficiently transmitted. In Fig. 1**c**, light attenuation through an index finger is shown for both red and green light. In the case of red light, 2% of the incident light passes through the finger and is consequently collected by the photodiode, while only 0.05% green light passes through the index finger. This results in lower photoplethysmogram (PPG) signal intensity for green wavelengths. This loss due to scattering can be addressed by increasing the OLED irradiance or boosting the amplifier gain at the OPD receiver circuit end. Utilizing these strategies, we have reconstructed the PPG signal for both red and green light.

## III. Oximetry Measurement Methodology and Sensor Circuits

Portable oximeters use microcontrollers for controlling the sensor probe as well as to process and transmit pulse and oxygenation data [11]. A commonly used process flow for oximetry is shown in Fig. 2**a**. The light sources are placed on top of the finger and a photodiode is placed at the opposite end. The OLEDs are controlled using an OLED driver circuit and the sensed signal is read using an OPD read circuit. A microcontroller is used as the host data processing and transmitting unit. Once the PPG signal is acquired, a peak detection algorithm is applied on the signal to obtain the pulse rate.

Analytically, blood oxygenation ($SO_2$) is quantified from the concentration of oxy-hemoglobin $C_{HbO_2}$ and deoxy-hemoglobin $C_{Hb}$ [12], [13]:

$$SO_2 = \frac{C_{HbO_2}}{C_{HbO_2} + C_{Hb}} \tag{1}$$

In the transmission mode, Beer-Lambert's law states that the intensity of light traveling through a medium decreases exponentially with distance. Transmission $T$ is given by,

$$T = I_0 \exp(-\varepsilon C d) \tag{2}$$

Here, $I_0$ is the incident light intensity, $\varepsilon$ is the molar absorptivity with units of L mM$^{-1}$cm$^{-1}$, $C$ is the concentration of the absorbent medium, and $d$ is the optical path length through the medium.

The absorbance, A, is now defined as,

$$A = -\ln \frac{T}{I_0} = \varepsilon C d \tag{3}$$

The ratio of the red and green absorptions, $R_{os} = \frac{A_{rd}}{A_{gr}}$ can be obtained from the PPG signal. Arterial oxygen saturation ($S_aO_2$) can be calculated using Eq. 4. Here, $\varepsilon_{rd,Hb}$ and $\varepsilon_{gr,Hb}$ are the molar absorptivity of deoxy-hemoglobin at red ($\lambda$ = 626 nm) and green ($\lambda$ = 532 nm) wavelengths. Similarly, $\varepsilon_{rd,HbO_2}$ and $\varepsilon_{gr,HbO_2}$ are the molar absorptivity of oxy-hemoglobin at red ($\lambda$ = 626 nm) and green ($\lambda$ = 532 nm) wavelengths.

$$S_aO_2(R_{os}) = \frac{\varepsilon_{rd,Hb} - \varepsilon_{gr,Hb} R_{os}}{(\varepsilon_{rd,Hb} - \varepsilon_{rd,HbO_2}) + (\varepsilon_{gr,HbO_2} - \varepsilon_{gr,Hb}) R_{os}} \tag{4}$$

Since Beer-Lambert's Law does not account for scattering in tissue (versus a glass cuvette), an empirical calibration curve is then used to calculate blood oxygenation.

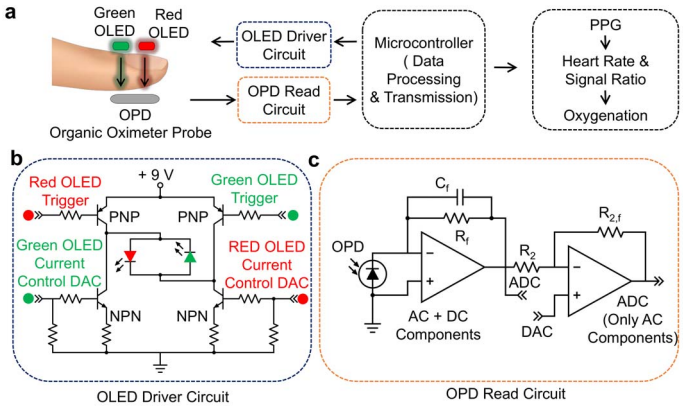


Fig. 2. **Pulse oximeter system with organic optoelectronic sensor. (a)** Process flow to acquire photoplethysmogram (PPG) signal by using green and red organic light-emitting diodes (OLEDs). Green and red OLEDs are placed on top of the subject's finger and the transmitted light is collected by using an organic photodiode (OPD). A microcontroller controls the OLEDs using an OLED driver circuit, and acquires the PPG signal (OPD current signal) utilizing an OPD read circuit. PPG data is extracted by processing both green and red light signals. This information yields heart rate and the absorption ratio ($R_{os}$) data, from which oxygenation can be calculated. **(b)** OLED driver circuit. The OLEDs are driven using a 9 V source in a H bridge configuration. Two PNP bipolar junction transistors (BJTs) handle the OLED triggering, while two NPN BJTs control the drive current using digital to analog (DAC) signals from the microcontroller. **(c)** OPD read circuit. The current signal is read and amplified in two stages. In the first stage, both AC and DC part of the signal is amplified, and at the output side the analog signal is connected to an analog to digital converter (ADC) for DC level tracking. The DC level is used in the second stage amplifier for DC level elimination. In the second stage, just the AC part of the signal is amplified and read using another ADC. This signal is then used for pulse and oxygenation calculations.

### A. OLED Driver Circuit

To achieve the necessary PPG signal intensity, the OLEDs are driven at 9 V with 20 mA of drive current. Most microcontrollers operate at 3.3 V, therefore an external OLED driver circuit is necessary to drive the OLEDs (Fig 2**b**). The driver uses H bridge configuration to sequentially operate the red and green OLEDs at 1 kHz. OLED triggering is controlled using PNP bipolar junction transistors (BJTs). An additional level shifter is necessary to translate trigger signal from 3.3 V to 9 V. On the other hand, two NPN BJTs control the drive current using DAC signals from the microcontroller. Here the level shifter also translates 3.3 V signal to 9 V. The software controls and varies the OLED intensity so that a minimum

PPG signal is obtained. This software control ensures that the system would take into account different skin tones and finger thickness in order to provide the irradiance needed to collect the PPG signal.

### B. OPD Read Circuit

PPG signals are extracted from the OPD current in two stages. In the first stage, both the AC (pulsating blood pulse signal) and the DC (signal from skin, tissue, and bones) parts of the signal are amplified. A low-pass filter is implemented in the first stage to reduce unwanted high-frequency noise. At the output of the first stage, a DC tracker is implemented to track the DC level of the signal, which is taken out in the second stage as shown in Fig. 2**c**. In the second stage, only the AC part of the signal is amplified and the DC is taken out using a digital to analog converter (DAC). Finally, the PPG signal is recorded using the ADC of the microcontroller.

## IV. Pulse Oximetry Results

Pulse rate and oxygenation results can be obtained from the ratio of the red and green absorptions $R_{os} = \frac{A_{rd}}{A_{gr}}$. The modular approach in circuit design allows fine control of the OLED irradiance and the amplifier gain. Therefore, if the received light signal is low, both OLED drive current and the amplifier gain can be increased to enhance PPG signal intensity. We employed both strategies to obtain sufficient signal intensities from where pulse signal can be resolved. Recorded green and red PPG signals are shown in Fig. 3 (green and red curves). The gray curve shows the pulse rate extracted by peak detection from the red and green PPG signals. The ratio of red and green absorptions ($R_{os}$) is shown in the blue curve, and the yellow curve shows arterial oxygen saturation ($SaO_2$) that is calculated from the calibration curve. These results were compared to the data collected from a commercially available oximeter that uses red and infrared solid state LEDs. We have shown that the organic oximeter probe accurately measures pulse rate and oxygenation with errors of 1% and 2%, respectively [6].

## V. Conclusion

In this work, we have described the methodology and circuit design implemented for an organic oximeter probe. We used the combination of red and green light instead of the standard combination of red and infrared light. Photoplethysmogram (PPG) signal from red and green OLEDs are acquired, and are used to extract pulse rate and blood oxygenation rates on a human volunteer. We have established that higher OLED irradiance contributes to the enhanced transmission mode PPG signal; we used 20 mA of drive current at 9 V to obtain the PPG signal. Additionally, the implementation of higher transimpedance amplifier gain is essential when increasing the signal intensity. Overall, we designed and demonstrated an organic oximeter probe, which accurately measures pulse rate and blood oxygenation. In a flexible band-aid like form factor the organic optoelectronic pulse oximetry sensor described here has the potential to diversify possible sensing locations on the human body and reduce sensor production cost via large-area scalability and inexpensive manufacturing.

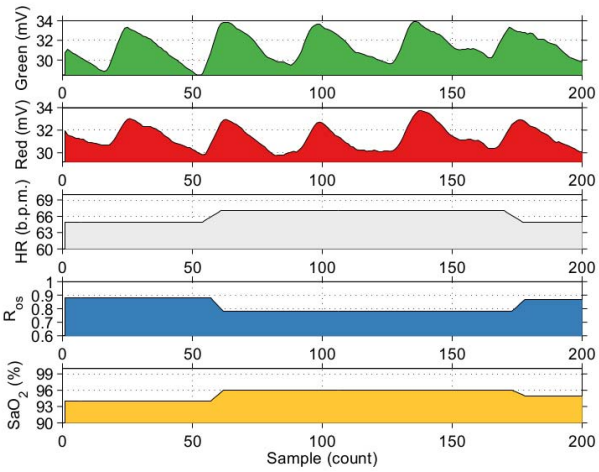


Fig. 3. **Pulse oximetry results using green and red OLEDs interfaced with an OPD.** The green and red signals depict the obtained photoplethysmogram (PPG) signal. The peaks resulted from the systolic phases of the cardiac rhythm and the troughs are from the diastolic phases. The gray curve shows the heart rate (HR) extracted by peak detection from the PPG signals. The blue signal is the absorption ratio of red and green, $R_{os} = A_{rd}/A_{gr}$. Finally, the yellow signal shows the calculated oxygenation values. Motion artifacts are observed in the measurements, which can be reduced by using better probe holder design.


## Acknowledgment

This work was supported in part by the National Science Foundation under Cooperative Agreements No. ECCS-1202189 and UTA-12000944, ARL W911NF-09-3-001 under RFP 12-159 and by the NSF Graduate Fellowship Research Program under Grant No. DGE-1106400. We thank Cambridge Display Technology Limited (CDT) for supplying OLED materials.


## References


[1] K. Hung, C. Lee, and S.-O. Choy, "Ubiquitous health monitoring: Integration of wearable sensors, novel sensing techniques, and body sensor networks," in *Mobile Health*. Springer, 2015, pp. 319–342.

[2] J. Yang, D. Wei, L. Tang, X. Song, W. Luo, J. Chu, T. Gao, H. Shi, and C. Du, "Wearable temperature sensor based on graphene nanowalls," *RSC Advances*, vol. 5, no. 32, pp. 25 609–25 615, 2015.

[3] Y. Mendelson, R. Duckworth, and G. Comtois, "A wearable reflectance pulse oximeter for remote physiological monitoring," in *Engineering in Medicine and Biology Society, 2006. EMBS'06. 28th Annual International Conference of the IEEE*. IEEE, 2006, pp. 912–915.

[4] G. Schwartz, B. C.-K. Tee, J. Mei, A. L. Appleton, D. H. Kim, H. Wang, and Z. Bao, "Flexible polymer transistors with high pressure sensitivity for application in electronic skin and health monitoring," *Nature Communications*, vol. 4, p. 1859, 2013.

[5] S. S. Thomas, V. Nathan, C. Zong, E. Akinbola, A. L. P. Aroul, L. Philipose, K. Soundarapandian, X. Shi, and R. Jafari, "Biowatcha wrist watch based signal acquisition system for physiological signals including blood pressure," in *Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE*. IEEE, 2014, pp. 2286–2289.

[6] C. M. Lochner, Y. Khan, A. Pierre, and A. C. Arias, "All-organic optoelectronic sensor for pulse oximetry," *Nature Communications*, vol. 5, p. 5745, 2014.

[7] S. L. Swisher, M. C. Lin, A. Liao, E. J. Leeflang, Y. Khan, F. J. Pavinatto, K. Mann, A. Naujokas, D. Young, S. Roy, M. R. Harrison, A. C. Arias, V. Subramanian, and M. M. Maharbiz, "Impedance sensing device enables early detection of pressure ulcers in vivo," *Nature Communications*, vol. 6, p. 6575, 2015.

[8] D.-H. Kim, R. Ghaffari, N. Lu, and J. A. Rogers, "Flexible and stretchable electronics for biointegrated devices," *Annual Review of Biomedical Engineering*, vol. 14, pp. 113–128, 2012.

[9] P. Leleux, J.-M. Badier, J. Rivnay, C. Bénar, T. Hervé, P. Chauvel, and G. G. Malliaras, "Conducting polymer electrodes for electroencephalography," *Advanced Healthcare Materials*, vol. 3, no. 4, pp. 490–493, 2014.

[10] J. R. Sommer, R. T. Farley, K. R. Graham, Y. Yang, J. R. Reynolds, J. Xue, and K. S. Schanze, "Efficient near-infrared polymer and organic light-emitting diodes based on electrophosphorescence from (tetraphenyltetranaphtho [2, 3] porphyrin) platinum (ii)," *ACS Applied Materials & Interfaces*, vol. 1, no. 2, pp. 274–278, 2009.

[11] J. Lebak, J. Yao, and S. Warren, "Implementation of a standards-based pulse oximeter on a wearable, embedded platform," in *Engineering in Medicine and Biology Society, 2003. Proceedings of the 25th Annual International Conference of the IEEE*, vol. 4. IEEE, 2003, pp. 3196–3198.

[12] J. Webster, *Design of Pulse Oximeters*, ser. Series in Medical Physics and Biomedical Engineering. Taylor & Francis, 2002.

[13] M. Yelderman and W. New Jr, "Evaluation of pulse oximetry," *Anesthesiology*, vol. 59, no. 4, pp. 349–351, 1983.