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Opto Semiconductors

Health monitoring

Application Note

Valid for:
BIOFY® / TopLED® D5140 / Chip LED® Sensors / Firefly® E1608 / Firefly® E2218 / PointLED®

Abstract

OSRAM Opto Semiconductors offers especially small and compact LEDs, photodiodes and integrated modules for health monitoring in wearable and automotive applications. This application note provides basic information on health monitoring as well as an overview of the potential products and electrical and optical design recommendations.

Further information:
AN088_Firefly® E1608 and Firefly® E2218 — Details on handling and processing
AN081_PointLED - It´s nice to be different

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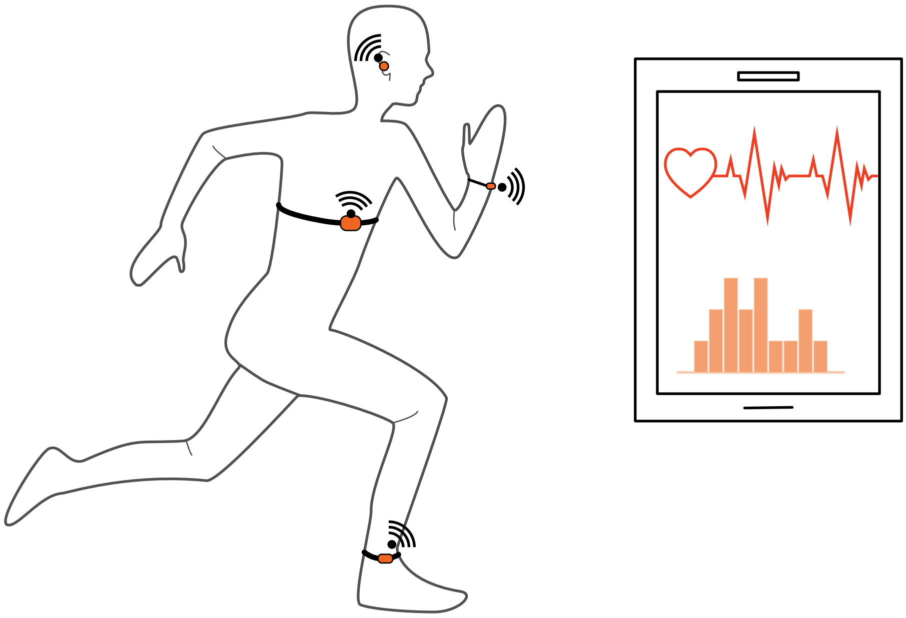
A. Basic information on health monitoring

Wearable applications enable the monitoring of vital signs for healthcare reasons and also for daily life activity tracking (Figure 1). OSRAM Opto Semiconductors product portfolio of LEDs and detectors offers the technical opto-electronic devices for heart rate monitoring and oxygen saturation measurements.

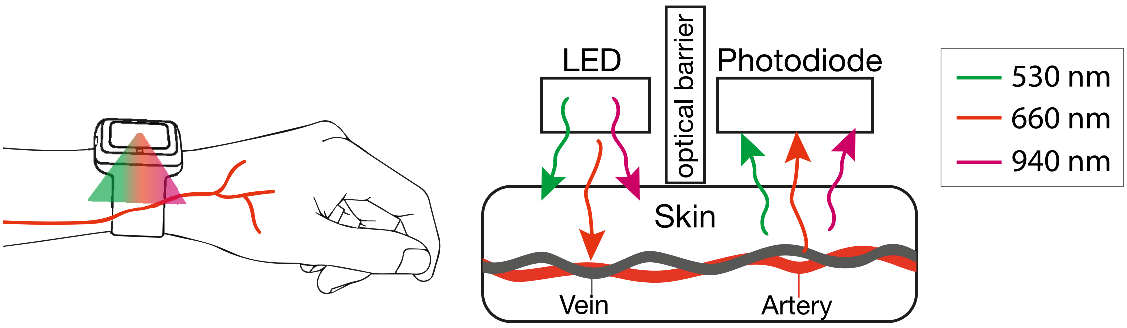
Figure 1: Wearable devices for health monitoring



Principle of heart rate monitoring and oxygen saturation measurement

With each cardiac cycle, the heart pumps blood through the circulatory system of the human body. Arteries periodically dilate and constrict as blood flows through and the arteries increase or decrease in volume with every heartbeat. To detect the change in volume caused by the pressure pulse, the skin is illuminated with an LED and the amount of light either transmitted or reflected to a photodetector is measured afterwards (Figure 2).

Figure 2: Functional principle for heart rate monitoring



The same procedure is used for oxygen saturation measurement. Here the principle is to measure the absorption of the hemoglobin in the blood. Oxygenated hemoglobin (HbO_2) has a significantly different absorption of light than non-oxygenated hemoglobin (Hb). To detect this difference, the skin is illuminated with one red and one IR LED light and a photodetector measures the absorption. The SpO_2 value is the quotient of the measured values.

B. Finding the right light source for health monitoring

For the system setup, integrated solutions (emitters and detectors integrated in a single package) are available and represent a compact alternative to discrete components.

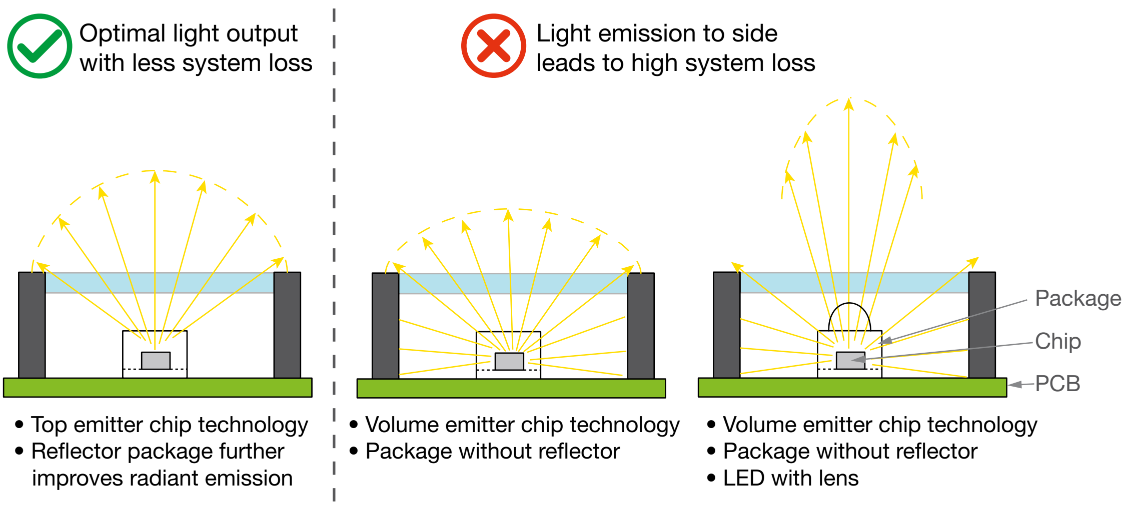
However, while both discrete components and integrated solutions are equally efficient and capable of delivering precise and accurate photoplethysmography (PPG) sensing, discrete components (single LEDs and photodetectors) offer more design freedom, because various geometries can be selected and various components can be combined depending on the system requirements.

To find the right light source, the LED design and the wavelength of the output light should be considered. Optical barriers between the LED and the photodiode are fundamental to avoid direct cross talk between emitters and detectors. Integrated solutions provide this option and discrete components should be selected accordingly, in order to achieve high-quality measurements.

The impact of the LED design

To obtain good measurement results, it is important to use the maximum possible light output. An LED with a top emitting chip reduces the side emissions of the light. Furthermore, a reflective package is helpful to reduce such emissions. Since LEDs with a volume emitter and a clear LED package will lead to a significant LED light output loss in the application, it is recommended to use top emitting LEDs with a reflective package. Figure 3 illustrates the impact of the LED design on the efficiency output. These characteristics are already considered in the integrated components offered by OSRAM Opto Semiconductors.

Figure 3: LED design for highest efficiency output

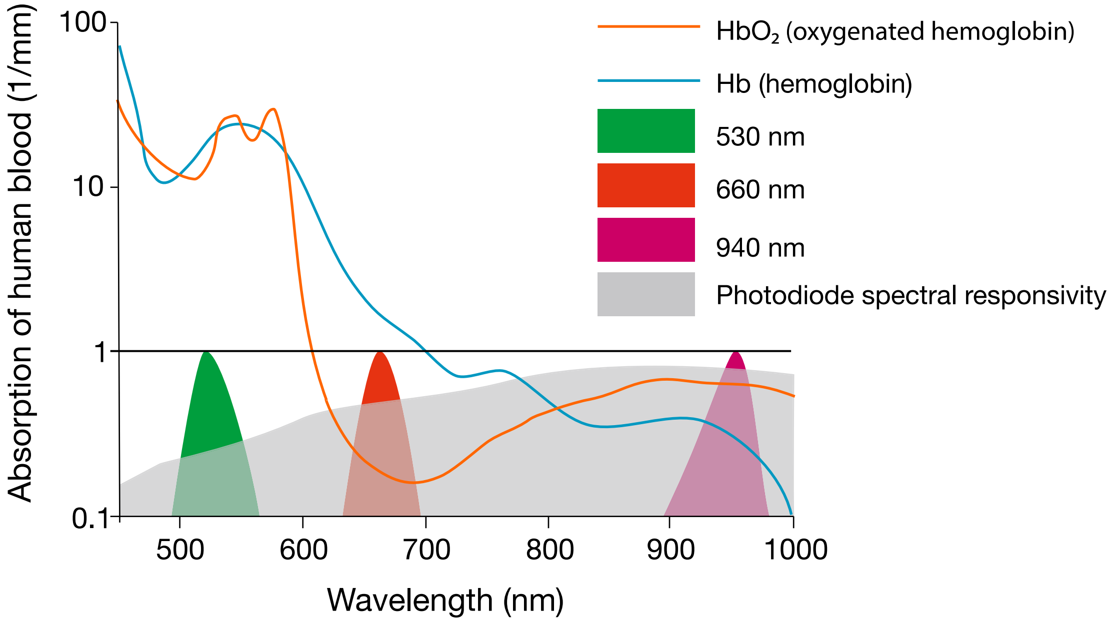


Another impact on the efficiency of the LED is the chip size. The larger the chip (at the same current) the smaller the current density. This results in more efficient operation and a lower V_F.

The impact of the light wavelength

Absorption of light in human blood mainly depends on hemoglobin. Figure 4 shows the absorption spectra of human blood (hemoglobin (Hb) and oxygenated hemoglobin (HbO_2)) versus the wavelength of light. It also includes the spectral responsivity of the photodiode (PD).

Figure 4: Absorption of human blood versus wavelength of light



Short wavelengths (from blue to yellow) are absorbed strongly. Green is therefore the best choice for heart rate measurement applications, although red and infrared can be successfully used in body locations with a higher concentration of arterial blood (e.g. fingertips, ears, and forehead). Light with longer wavelengths (from red to infrared) can be used for pulse oximetry applications. While red light with wavelengths around 660nm has a higher absorption for non-oxygenated hemoglobin (Hb), infrared light with wavelengths around 960nm has a higher absorption rate for oxygenated hemoglobin (HbO_2). As a result of the different absorption levels (Hb vs. HbO_2) the SpO_2 level can be calculated by the following formula:

$$SpO_2 = \frac{HbO_2}{Hb + HbO_2}$$

LEDs recommended for health monitoring

OSRAM Opto Semiconductors provides single color or multi-color emitters for using discrete components for heart rate monitoring.

The Firefly® E1608 provides major benefits for the customer. It enables flexible product designs, due to its compact size. The combination of various wavelengths and typical brightness levels, all matching the application, is possible.

The Firefly® 2218 provides a more efficient chip in a larger package design for highest system efficiency. This extends the battery life in wearable applications.

Furthermore, the PointLED® would be a suitable product as light source. Its essential characteristic is its round package with round reflector. The design allows a through hole assembly.

Table 1 provides an overview of all recommended emitters. This does not mean, however, that others LEDs cannot be used.

Table 1: Overview of recommended OSRAM Opto Semiconductors emitters

Emitter			Properties	Radiant intensity @ 20mA	Package Size (mm^3)
Firefly® E1608		CH DELSS1.22	•Compact package size •Enables flexible product designs	5.0 mW/sr (0.315 cd)	1.6 x 0.6 x 0.8
		CT DELSS1.12	•Compact package size •Enables flexible product designs	3.23 mW/sr (1.68 cd)	1.6 x 0.6 x 0.8
Firefly® 2218		CT DBLP31.12	•Highest system efficiency •More efficient chip	7.83 mW/sr (4.08 cd)	2.2 x 1.8 x 0.6
PointLED®		LT PWSG	•Round reflector •Round package •Through-hole assembly possible	5.23 mW/sr 2.68 cd	1.9 x 1.9 x 0.8

For further information on these recommended LEDs, please refer to the specific application notes, “AN088 Firefly® E1608 and Firefly® E2218 — Details on handling and processing” and “PointLED - It´s nice to be different”.

Multi-emitters, such as the Multi Chip LED offer the advantage that two or three colors are combined in one package. The SFH 7015 provides a red and infrared chip in a compact package and is therefore a good choice for oxygen saturation measurements. The SFH 7016 offers all three colors for vital signs measurement. Table 2 provides an overview on these multi-emitters.

Table 2: Overview of recommended multi-emitters

Emitter			Properties	Radiant intensity @ 20mA		Package Size (mm^3)
Multi Chip LED®		SFH 7015	•Compact package size •Enables flexible product designs	Red:	4 mW/sr	2.0 x 0.8 x 0.6
				IR:	3 mW/sr	
Multi Chip LED®		SFH 7016	•Compact package size •Enables flexible product designs	Green:	4 mW/sr	1.85 x 1.65 x 0.6
				Red:	4 mW/sr	
				IR:	3 mW/sr	

C. Detectors and integrated solutions for health monitoring

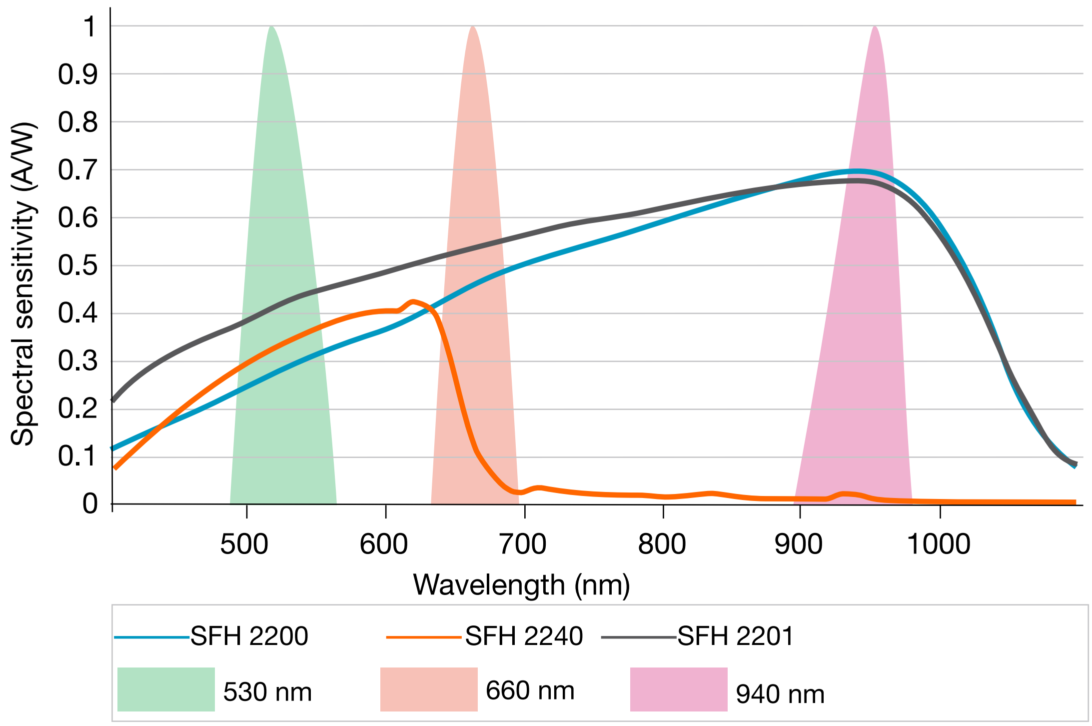
OSRAM Opto Semiconductors not only provides LEDs but also appropriate photodiodes and integrated solutions for health monitoring.

Figure 5 shows the different sensitivity of photodiodes. The SFH 2200 represents a standard photodiode, in comparison to the SFH 2201 (a green enhanced photodiode) and the SFH 2240 (a photodiode with IR-Cut filter).

The green enhanced photodiode SFH 2201 shows a higher sensitivity in green for improved HRM signal detection. In addition, it enables the measurement of red and IR signals for SpO_2 signals.

Photodiodes with an IR-Cut filter, such as the SFH 2240, are optimized for heart rate monitoring applications. Here the sensitivity to the wavelength range is focused on green. The IR suppression allows noise reduction, which reduces the pulse length and LED current. This leads to an improved HRM measurement and to power savings at the same time.

Figure 5: Sensitivity of photodiodes



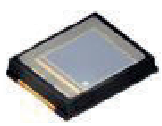
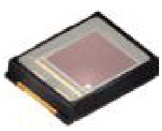
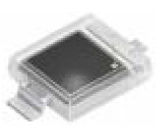
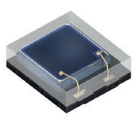
Detectors recommended for health monitoring

For example, an SFH 2240 diode can be used for the detection of the reflected light. This SMT pin photodiode was developed for bio monitoring and features high linearity and a fast switching time. The SFH 2440 photodiode is a good alternative. Both provide an IR Cut filter. However, in contrast to the SFH 2240, the SFH 2440 features a leaded package. For this reason the SFH 2240 enables more compact system assembly.

The SFH 2200, a broadband photodiode without an IR filter, can also be used. When using this photodiode, it must be considered that infrared ambient light is also detected. The miniature broadband photodiode SFH 2704 is an excellent alternative for applications where board space is a critical parameter. With a height of typ. 0.6 mm it is most suitable for extremely flat assemblies.

Table 3 provides an overview of the recommended detectors for health monitoring.

Table 3: Overview of recommended detectors

Photodiode			Properties	Photocurrent in µA in dependency of the wavelength for 0.1mW/cm²			Package Size (mm³) [Sensitive Area (mm²)]
				550 nm	660 nm	940 nm	
TOPLED® D5140		SFH 2200	•HRM •SpO_2 •Broadband •No filter •Leadless package	2.21	3.19	4.91	4.0 x 5.1 x 0.85 [7.02]
TOPLED® D5140		SFH 2201	•HRM •SpO_2	3.65	4.38	5.62	4.0 x 5.1 x 0.85 [8,12]
TOPLED® D5140		SFH 2240	•HRM with IR suppression •Fast switching time •Leadless package	2.60	1.83	0.15	4.0 x 5.1 x 0.85 [7.02]
DIL SMT		SFH 2440	•Fast switching time •Leaded package	2.60	1.83	0.15	3.9 x 6.5 x 1.15 [7.02]
Chip LED®		SFH 2704	•HRM •SpO_2 •Broadband •No filter •Leadless package	0.51	0.80	1.08	2.0 x 1.8 x 0.6 [1.51]

Integrated solutions recommended for health monitoring

Integrated components provide the Optical Front End (OFE), a combination of the discrete LED and photodiode, in one device (see also Figure 9: "Functional building blocks for a health monitoring system" (page 16)).

These integrated components for health monitoring applications offer the following advantages:

- No need for external light barrier design and mounting allows complex customized optical designs.
- Normally integrated components feature higher light efficacy, with potentially lower power consumption.
- The fixed distance specification between emitter and detector chips leads to good optical consistency in mass production (tolerance controlled on the component level).
- Single component handling, which reduces the board space
- Simplified SMT process

Table 4: Overview of recommended integrated modules

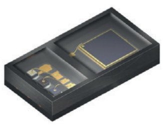
Module		Properties and Characteristics parameter	Package Size (mm³)
BIOFY® 	SFH 7050	•Multi-chip package •HRM •SpO_2 **Characteristics parameter:** Green: 1.3 mW/sr / Spectral sensitivity (detector): 0.26 A/W Red: 2.6 mW/sr Spectral sensitivity (detector): 0.47 A/W IR: 2 mW/sr Spectral sensitivity (detector): 0.77 A/W Radiation sensitive area: 1.7 mm^2	4.7 x 2.5 x 0.9
BIOFY® 	SFH 7060	•Multi-chip package •HRM •SpO_2 **Characteristics parameter:** Green: 1.4 mW/sr / Spectral sensitivity (detector): 0.27 A/W Red: 2.6 mW/sr Spectral sensitivity (detector): 0.47 A/W IR: 2 mW/sr Spectral sensitivity (detector): 0.77 A/W •Radiation sensitive area: 1.7 mm^2	7.2 x 2.5 x 0.9

Table 4: Overview of recommended integrated modules

Module		Properties and Characteristics parameter	Package Size (mm³)
BIOFY® 	SFH 7070	•Multi-chip package •HRM **Characteristics parameter:** Green: 3.8 mW/sr / Spectral sensitivity (detector): 0.31 A/W Radiation sensitive area: 3.46 mm^2	7.5 x 3.9 x 0.9
BIOFY® 	SFH 7072	•Multi-chip package •HRM •SpO_2 **Characteristics parameter:** Green (single emitter): 3.8 mW/sr / Spectral sensitivity •IR-Cut detector: 0.31 A/W •Broadband detector: 0.31 A/W Red: 4.8 mW/sr Spectral sensitivity •IR-Cut detector: 0.02 A/W •Broadband detector: 0.56 A/W IR: 3.9 mW/sr Spectral sensitivity •Broadband detector: 0.84 A/W Radiation sensitive area: •IR-Cut detector: 3.46 mm^2 •Broadband detector: 0.88 mm^2	7.5 x 3.9 x 0.9

D. Application set-up notes

Since no standards exist with regard to the skin tolerability of LEDs, the system must be set up with a glass cover between the monitoring application and the skin. This glass cover also protects the assembly against dust and water. However, it may affect the measurement quality.

The signal level (signal quality) is affected by the measurement system as well as by biological characteristics. At least 2 LEDs should be used in order to achieve reliable measurement results. Depending on the application, 2 to 6 LEDs may be used. These should be installed at a distance of less than 3.5 mm from the photodiode. The ideal distance for a good AC / DC signal depends on the application system and must be evaluated for the specific application.

The best measurement results can be achieved if the health monitoring system is placed as close to the skin as possible. Furthermore, it is essential that the spot chosen for the measurement exhibits good blood circulation. Good circulation results in a noticeable change of the blood volume within the arteries increasing the accuracy and stability of the measurement results.

The impact of the LED specification

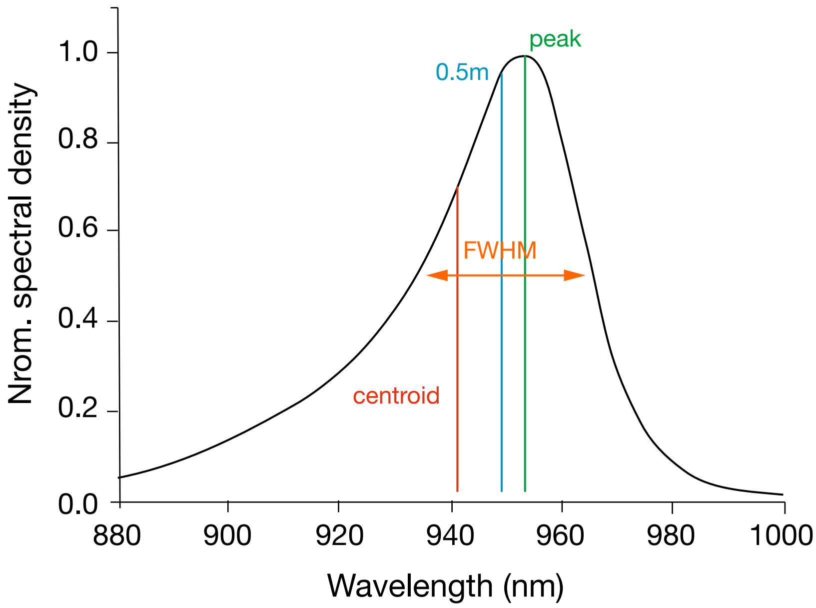
The following definitions are important in order to understand the impact of the LED specification on the overall device performance in a photoplethysmography application:

- Peak wavelength (λ_{peak}) is the wavelength of the peak of the spectral density curve (in most applications it is of little significance).
- The full width at half-maximum (FWHM, Dl), sometimes also called spectral bandwidth, is the wavelength distance between the spectral points where the spectral density S(λ) is 50 % of the peak value.
- The center wavelength ($\lambda_{0.5m}$) is the wavelength halfway between the two spectral points with spectral density of 50 % of the peak value.
- The centroid wavelength ($\lambda_{centroid}$) is the mean wavelength. It divides the spectrum into two equal parts. It is the most important definition for non-visual systems (like sensors) and relevant for this kind of photoplethysmography application. It can be calculated with the following equation:
- The dominant wavelength (λ_{dom}) is a colorimetric quantity. It is an important description for visual illumination systems as it describes the human perception of the color of an LED (within the visible spectrum)

For a symmetrical spectrum λ_{peak}, $\lambda_{0.5m}$ and $\lambda_{centroid}$ are identical. However, the highly efficient LEDs can feature slightly asymmetrical spectra, for example the LEDs inside the SFH 7050. Here λ_{peak} as well as $\lambda_{centroid}$ are defined, with $\lambda_{centroid}$ being the important wavelength concerning the application, i.e. the blood absorption coefficients. Figure 6 shows an example of the asymmetric spectrum of the 940 nm IR LED.

$$\lambda_{centroid} = \frac{\int_{\lambda_1}^{\lambda_2} \lambda \cdot S(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S(\lambda) d\lambda}$$

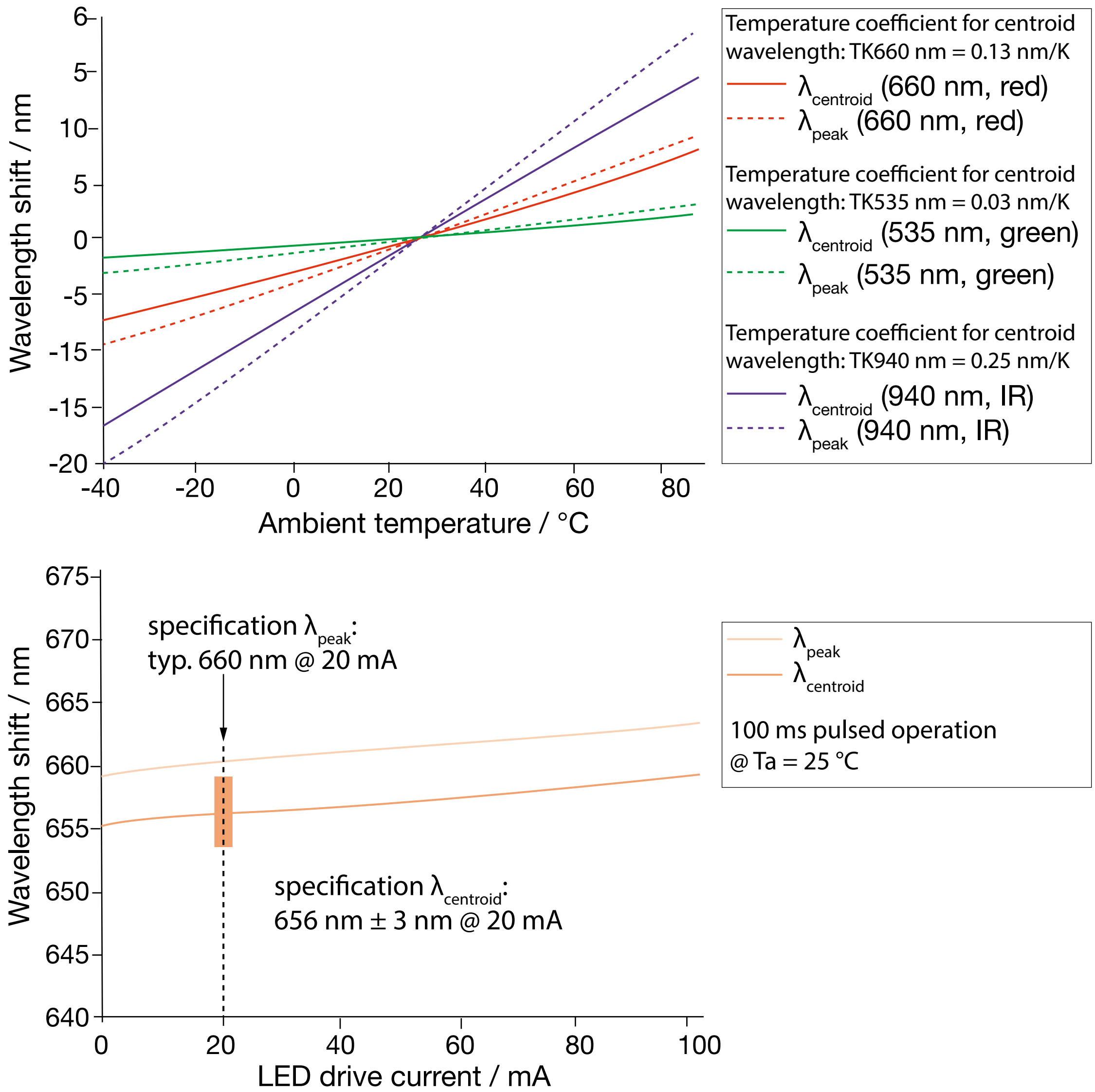
Figure 6: Asymmetric spectrum ($\lambda_{peak} \neq \lambda_{centroid}$) for defining the wavelength of an LED (example of the 940 nm IR LED)



The influence of wavelength shift

LEDs should have very tight wavelength specifications and no secondary peak. This ensures reproducible signal readings as the slope of the blood absorption coefficient (d_α/d_λ) is the highest. The LEDs should also feature a low temperature shift as well as a narrow spectral bandwidth. In general, the emitting wavelength depends on the ambient temperature and the driving conditions (pulse peak current, pulse width and duty cycle). Figure 7 shows an example of this temperature and driving current dependency. The temperature dependence of the emitter wavelength is relative to T_a = 25 °C at 20 ms pulse. The wavelength relevant for the application is $I_{centroid}$.

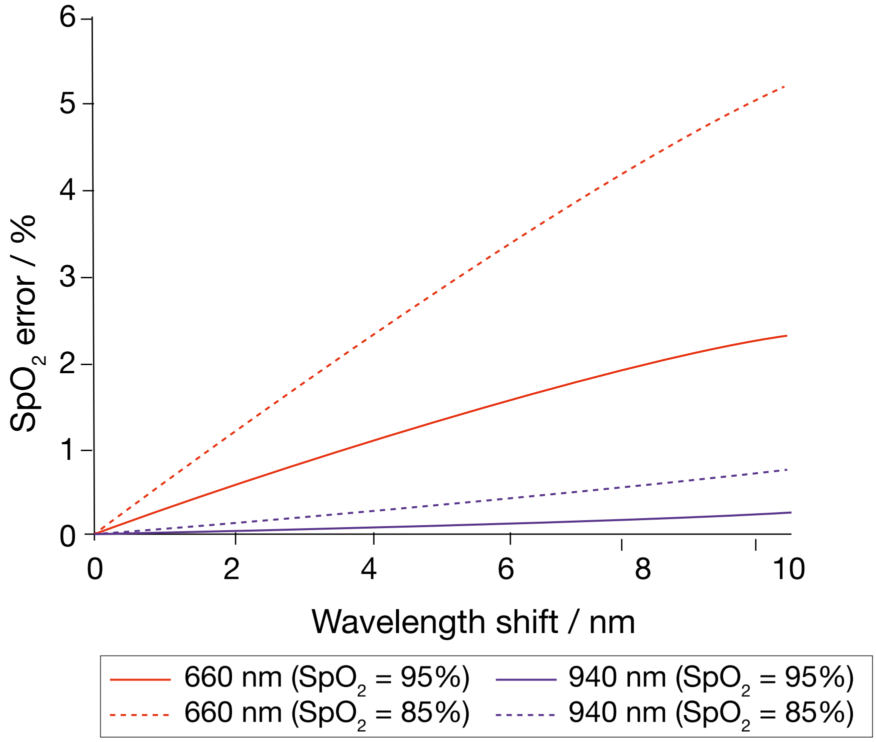
Figure 7: Example: Temperature dependence of the emitter wavelength and drive current dependency



Using short pulses also minimizes any temperature-dependent wavelength shift as well as spectral broadening due to internal heating of the LED (e.g. pulse width < 300 µs and repetition rate > 2 ms).

As is typical for visible LEDs, the wavelength shift of the red LED is most critical and must be compensated. Figure 8 presents an example of the influence of the emitter wavelength shift vs. SpO_2 measurement accuracy. The wavelength stability of the red LED is most critical. The lower the SpO_2 level, the higher the overall error due to the wavelength shift. In general, the wavelength stability of, for example, a 940 nm IR LED is non-critical compared to the 660 nm LED.

Figure 8: Example: SpO_2 error due to wavelength shift of the emitter

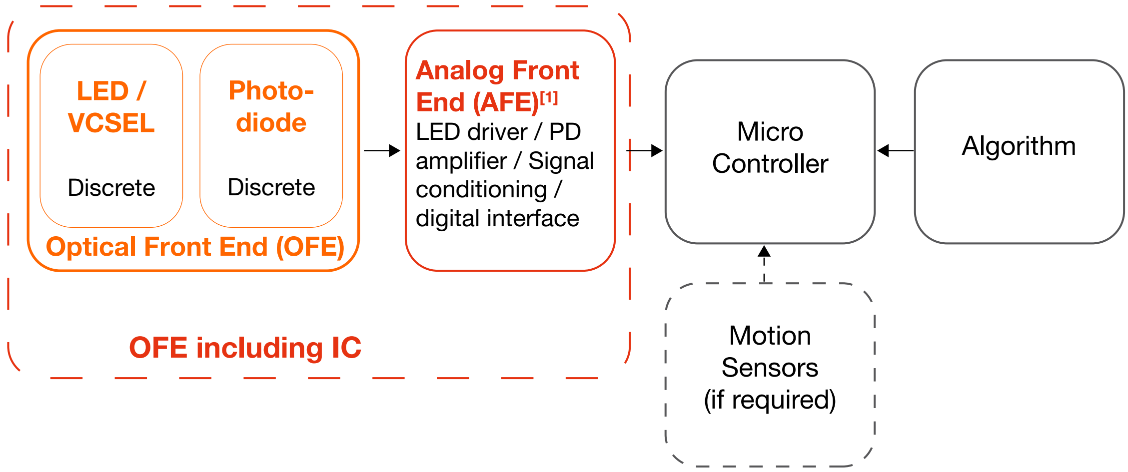


For highly accurate measurements it is recommended to compensate the wavelength shift of the LED. This can be done by e.g. monitoring the junction temperature ($\Delta\lambda = f(T_j)$) of LEDs. Implementation can be realized via ambient temperature measurement, either with a temperature sensor or e.g. via the junction voltage of an external Si-diode located close to the LED. This voltage is correlated to the ambient temperature, indicative for the wavelength shift of the LED during the particular operating conditions (calibration must be done e.g. during final device testing to obtain room temperature reference). Another, more complex method is via direct junction voltage measurement immediately after the LED pulse (e.g. biasing the LED with 1 µA and measuring the forward voltage drop, similar to Si-diodes).

Operating conditions

The entire health monitoring system consists of various functional building blocks, as shown in Figure 9.

Figure 9: Functional building blocks for a health monitoring system



The opto-electronic part in the building blocks describes the Optical Front End (OFE). It can be realized through discrete components (LEDs and photodiodes) or with an integrated module. The Analog Front End (AFE)[1] provides the analog signal processing (photodiode signal amplification and analog-to-digital conversion) and programmable LED driving. Several commercial chipsets are available. An integrated solution can also be selected here, which provides the LEDs, photodiodes and IC in one component.

Furthermore, the health monitoring system requires a suitable micro controller and a heart rate and motion compensation algorithm. In dynamic situations, motion sensors measure artefacts that arise from the user motion. A motion compensation feature is therefore necessary to obtain an accurate PPG measurement under these circumstances.

There are (slightly) different measurement requirements concerning the application scenario:

- Heart rate only
- Heart rate plus pulse oximetry

In case of heart rate only applications the DC component of the photocurrent can be neglected and only the periodicity of the AC component (I_{max} – I_{min}, frequency) is of interest. For pulse oximetry both the DC and the AC components (I_{min}, I_{max}) are required. Thus in general, a pure heart rate device is easier to

[1] Various evaluation boards are available for the AFE function block:
Texas Instruments Incorporated: The AFE4420 evaluation module (EVM)
Maxim Integrated: MAXREFDES101# HRM LED-Photodiode Board

implement as it requires only one LED. For most body locations the green LED might be the preferred choice. However, there is the option to drive the red as well as the IR LED. The IR LED might be advantageous as its light is invisible to the human eye. This can be a key criterion as in dark environments the green or red glow — if not shielded properly — might distract the user. In addition, the IR LED features the lowest forward voltage.

The signal level (signal quality) is affected by the measurement system as well as by biological characteristics.

The complete system includes the optical engine and sensor with LEDs for illumination and a photodiode for signal detection. The photocurrent can be split into a DC component (no information if only the heart rate is of interest) and the AC component. In addition, ambient light might be present (considered as AC+DC noise). Especially IR light can penetrate deeply into / through the skin. For example IR light from pulsed light sources (fluorescent or incandescent) or light from DC sources (like the sun) modulated by body movements can contribute to the optical signal as noise. The DC component of optical noise is usually subtracted due to an ambient light measurement immediately prior to or after the LED light measurement, resulting in an effective signal of:

$$I = I_{DC(signal)} + I_{AC(signal)} + I_{AC(noise)}$$

Important operating parameters influencing the signal quality:

- LED current
- LED on-time
- LED repetition rate

Increasing the LED current results in the following:

- $AC_{(pk-pk)}$ (= $I_{max} - I_{min}$) increases
- DC (= I_{min}) increases
- AC/DC ratio stays the same
- $AC_{(pk-pk)}$ to ambient light ratio increases
- SNR increases ($AC_{(pk-pk)}$ to electronic noise ratio or dark current increases)
- The energy consumption increases

Reducing the on-time of the LED provides the following results:

- Comparable AC/DC ratio
- Comparable AC to ambient light ratio
- Comparable AC to dark current ratio
- Possible reduction of SNR due to (potentially) more electronic noise from a shorter integration time
- Higher required bandwidth for the transimpedance amplifier (TIA)
- The larger system bandwidth makes it difficult to filter out (ambient) noise (in case ambient subtraction is performed in the digital domain)
- Reductions in energy consumption

Using an even larger photodiode would not result in an improved AC/DC ratio.

Increasing the repetition rate of the LED might result in higher accuracy of the signal at the expense of higher energy consumption. In essence the sampling rate needs to be high enough not to miss the peaks / troughts of the pulsatile signal.

In order to increase the battery life of wearable or mobile devices the LED on-time and LED current (depending on the noise level and the signal amplification) should be reduced as much as possible.

Finally, chipsets are available which include the complete analog signal processing (incl. LED driver) as well as analog-to-digital conversion. Detectors can be directly connected to these chipsets to enable fast and easy evaluation and design.

Don't forget: LED Light for you is your place to be whenever you are looking for information or worldwide partners for your LED Lighting project.

www.ledlightforyou.com

ABOUT OSRAM OPTO SEMICONDUCTORS

OSRAM, Munich, Germany is one of the two leading light manufacturers in the world. Its subsidiary, OSRAM Opto Semiconductors GmbH in Regensburg (Germany), offers its customers solutions based on semiconductor technology for lighting, sensor and visualization applications. OSRAM Opto Semiconductors has production sites in Regensburg (Germany), Penang (Malaysia) and Wuxi (China). Its headquarters for North America is in Sunnyvale (USA), and for Asia in Hong Kong. OSRAM Opto Semiconductors also has sales offices throughout the world. For more information go to www.osram-os.com.

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