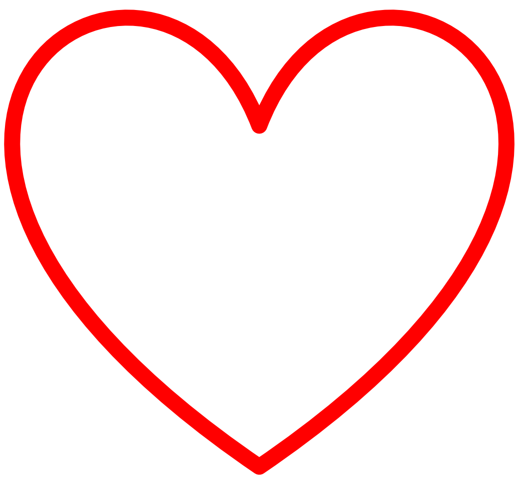
engineeringworldhealth

# Optical Heart Rate Monitor

## Laboratory Activities Handbook



**Answer Key**

# Contents

## Introduction

Devices that measure the heart rate can be found in almost all hospital areas and are important tools for diagnosis and monitoring. Although doctors and nurses can hear cardiac sounds in a patient's chest with a stethoscope, the body's extremities are better locations for continuous monitoring, especially during thoracic surgeries. This type of monitoring is possible because even small arteries in the body's extremities expand with the heart's contractions. The small volume variation can be detected with an optical sensor that measures the amount of red light absorbed in the tissue. The purpose of this activity is to teach engineering students the principles of biosignals measurement as well as electronics processing using EWH's Optical Heart Rate Monitor Kit.

The laboratory addresses theoretical principles that can be observed through practical assays. The measurements require a multimeter, function generator and an oscilloscope/acquisition board such as NI MyDAQ, which was used to measure the waveforms in this guide. Although the figures in this instruction show the socket version of EWH's Optical Heart Rate Monitor board, students can also solder the components directly to the PCB and follow most of the procedures.

## Optical Heart Rate Monitor Overview

Figure 1 shows the block diagram and signals waveforms of the Optical Heart Rate Monitor Kit. The sensor measures optical information from many tissues such as skin, muscle and blood vessels, but only the small arteries' volume changes is important for the measurement. Therefore, one needs to separate the small oscillations through the detector (high pass filter) and increase the pulse level with an amplifier. The resulting signal is strong enough to make a green light blink every time the heart beats. In order to decrease high frequency noises, one also use a low pass filter parallel to the pulse indicator.

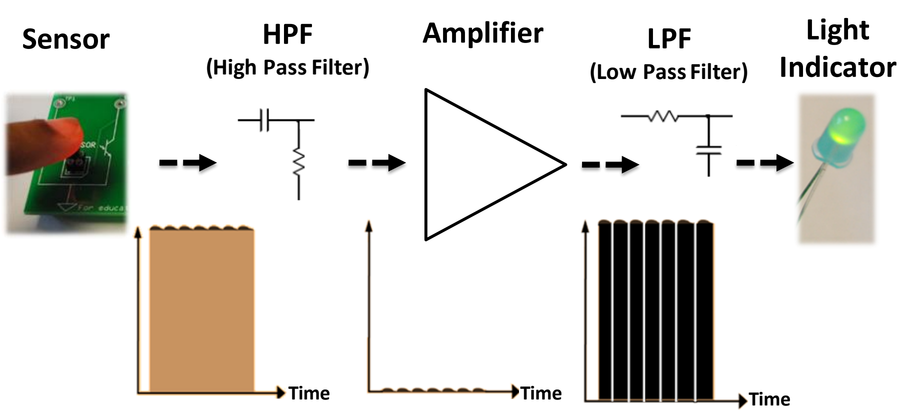



Figure 1 – Optical Heart Rate Monitor block diagram. The circuit is formed by sensor, high pass filter, amplifier, low pass filter and light indicator stages.

Figure 2 shows a schematic diagram of the Optical Heart Rate Monitor kit.

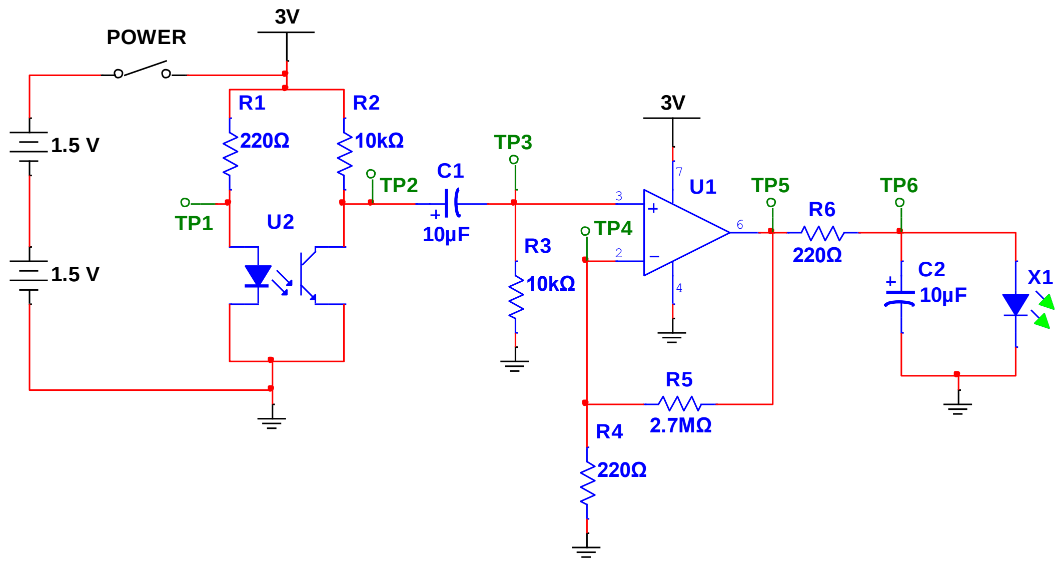



Figure 2 – Optical Heart Rate Monitor electronic schematic diagram.

## Bare Board Preparation

This section is <u>only</u> required for the Advanced Unassembled Version (bare board without any sockets already soldered). First, solder all the sockets in the positions shown in Figure 3.

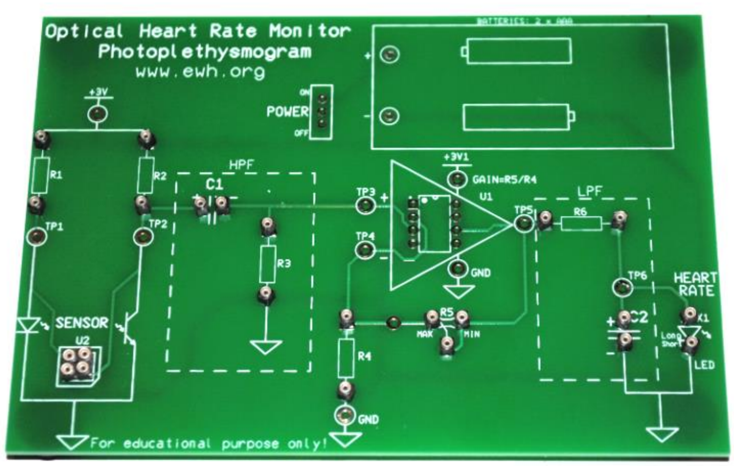



Figure 3 – Sockets placement on board.

Next, solder the amplifier socket in position U1, as shown in Figure 4.

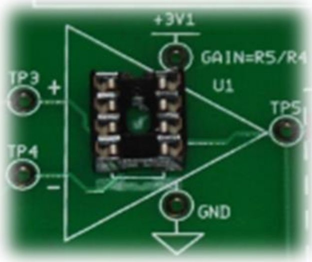


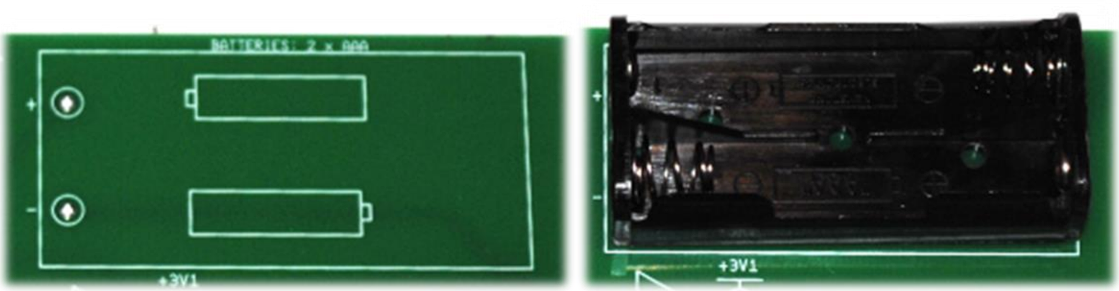

Figure 4 – Amplifier socket placement on board.

Solder the slide switch as shown in Figure 5.


(a) (b) (c)

Figure 5 –Slide switch symbol (a), silk screen drawing (b) and placement (c) in the power position.

Next assemble the battery holder, as seen in Figure 6.




(a) (b)

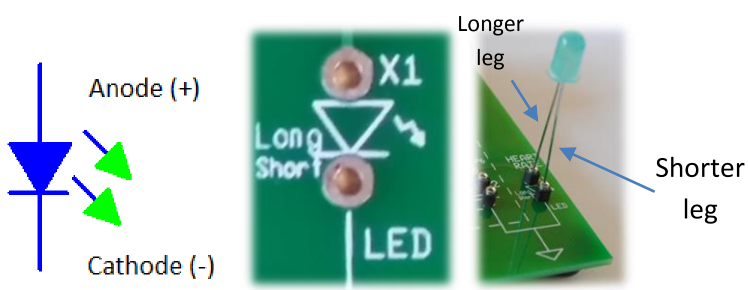
Figure 6 – Battery holder (a) silk screen and (b) placement.

The kit also includes four rubber feet to be placed underneath the corner holes as shown in Figure 7.

Figure 7 - Rubber feet to be placed underneath the corner holes.

## Light Indicator

To better understand the circuit and enable troubleshooting later, assemble the board from the output to the input sensor. First, connect or solder the Light Emitting Diode (LED) on the PCB. Figure 8 shows its symbol, silk screen drawing, and placement. If an LED is installed with the wrong polarity, it will not turn on. Be careful to place this component correctly on the "X1" position of the board. The anode (positive contact with longer wire) should be placed toward the upper side of the board and the cathode (negative contact with shorter wire) toward the lower side.




(a) (b) (c)

Figure 8 – Light emission diode (LED) schematic symbol (a), silk screen (b) and placement (c).

To test if the LED polarity is correct, place two AAA batteries in the holder, turn on the power switch, connect one side from the "R6" resistor on the contact on top of the TP6 (Figure 9), and place the other resistor wire in the "3V" contact. Notice that the resistor does not have polarity, so it does not matter which wire you place. If the light does not turn on, then the LED polarity is wrong.

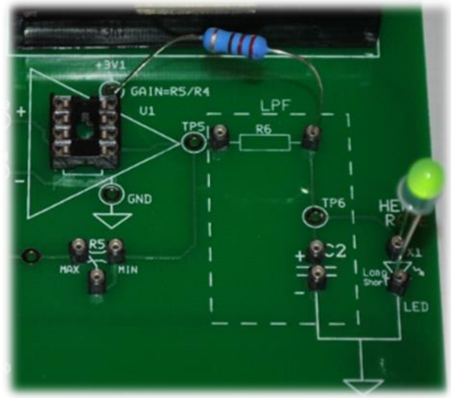



Figure 9 – Light emission diode (LED) polarity testing, connect R6 directly to + 3 V.

Connect a multimeter to measure the voltage in the LED as shown in Figure 10. Fill the measured values column of Table 2 with the voltage read and the expected current.

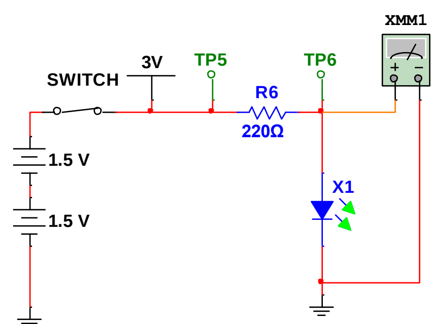



Figure 10 – Voltage and current measurement in the LED output circuit.

Use the green LED manufacture data from Table 1 to calculate the current in the datasheet specification column of Table 2.

Table 1 – LED operating characteristics.

| **OPERATING CHARACTERISTICS** (TA=25°C) | | Red -9320 | Yellow -9321 | Green -9327 |
|---|---|---|---|---|
| Luminous Intensity (mcd) | Min. | 1.2 | 1.2 | 1.2 |
| $I_F$=2mA | Typical | 2 | 1.8 | 1.8 |
| Peak Wavelength (nm) λ Peak | Typical | 635 | 583 | 565 |
| Viewing Angle (2Θ ½) | Typical | 50° | 50° | 50° |
| Forward Voltage (V) | Typical | 1.8 | 1.9 | 1.8 |
| $I_F$=2mA | Max. | 2.2 | 2.7 | 2.2 |
| Reverse Voltage (V), $I_R$=50μA | Min. | 5 | 5 | 5 |

*Θ ½ is the off axis angle at which the luminous intensity is half the axial luminous intensity*

Table 2 – Measured and calculated values for LED current.

| LED | Measured | Datasheet Specifications |
|---|---|---|
| **Voltage (V)** | *~1.93 (1.8 – 2.2 )* | 1.8 |
| **Current (mA)** | *~4.86* | (3-1.8)/220 = 5.45 |

Given the LED absolute maximum ratings in Table 3, calculate the lowest value of the resistance R6 that will not damage the component, using the manufacture data.

Table 3 – Green LED absolute maximum ratings.

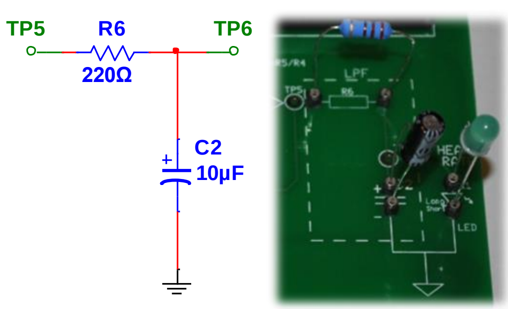
| **ABSOLUTE MAXIMUM RATINGS** (TA=25°C) | Red **-9320** | Yellow **-9321** | Green **-9327** |
|---|---|---|---|
| Power Dssipation (mW) | 27 | 36 | 24 |
| Derating (mA/°C) *From 92°C* | 1 | 1 | 1 |
| Forward Current (mA) | 7 | 7 | 7 |
| Peak Current (mA) *Pulse width = 10 μs* | 500 | 500 | 500 |
| Operating Temperature (°C) | -55/+100 | -55/+100 | -55/+100 |
| Storage Temperature (°C) | -55/+100 | -55/+100 | -55/+100 |
| Soldering Temperature | 260°C, 5 seconds, 1.6 mm from case | | |

*Solder Adherence per MIL-STD-202E, Method 208C*

$$R6_{MIN} = (3-1.8)/7m = 171\ \Omega$$

# Low Pass Filter

The Light Emitting Diode is supposed to show signals in the cardiac range (60 - 100 bpm/ 1 Hz to 1.67 Hz)[1]; however, body movements and other noise sources may cause extra blinking of the light indicator. Therefore it is helpful to add a low pass filter stage to the circuit output. Turn off the power switch and assemble the capacitor “C2” parallel to the LED, as seen in Figure 11.




(a) (b)

Figure 11 – Low pass filter schematic (a) and Capacitor C2 assembly on PCB.

The low pass filter cutoff frequency is shown in Equation 1:

$$f_C = \frac{1}{2.\pi.R6.C2} \tag{1}$$

where:

- $f_C$ is the cutoff frequency, (Hz)
- *R6* is the resistance value, (Ω)
- *C2* is the capacitance value, (F)

Calculate the low pass filter cutoff frequency for R6 = 220 Ω and C2 = 10 µF.

*Cutoff frequency* = 72.4 Hz

The low pass filter output gain (in the capacitor C2 - TP6) is given by Equation 2:

$$G_{LPF} = \frac{1}{\sqrt{1+(2.\pi.f.R6.C2)^2}} \tag{2}$$

where:

- *f* is the input signal frequency, (Hz)
- *R6* is the resistance value, (Ω)
- *C2* is the capacitance value, (F)

Use Equation 2 to calculate the low-pass filter output gain and amplitude values in Table 4 for an input signal of 3 Vpp with offset of + 1.5 V.

Table 4 – Low-pass filter output gain and amplitude for an input of 3 Vpp and an offset of + 1.5 V.

| Parameter | Frequency | | |
|---|---|---|---|
| | 10 Hz | 100 Hz | 1 kHz |
| **Gain** | 0.99 | 0.59 | 72 µ |
| **Amplitude (V)** | 2.97 | 1.77 | 0.21 m |
| **Maximum Voltage (V)** | 2.98 | 2.39 | 1.5001 |
| **Minimum Voltage (V)** | 0.015 | 0.62 | 1.4998 |

Turn off the power switch, and use a function generator to apply a signal of 3 Vpp (+1.5 V offset) with frequencies of 10 Hz, 100 Hz and 1 kHz in “TP5” (Figure 12). Use an oscilloscope to measure the voltage in the LED “TP6” draw the waveforms, and write the LED state in Figure 13.

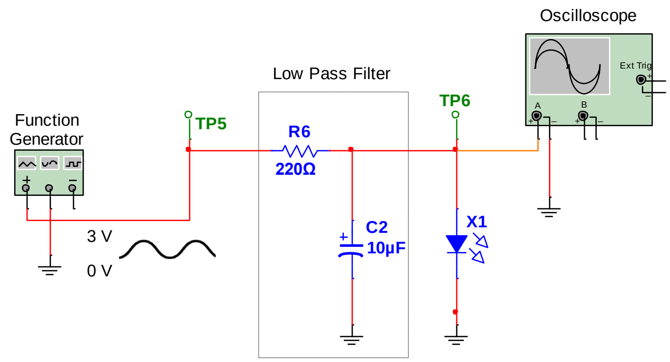
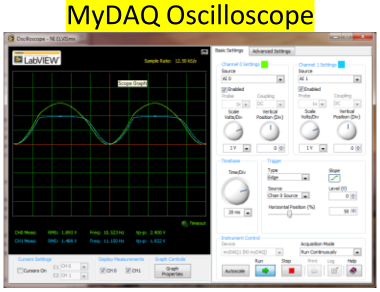



Figure 12 – Low Pass Filter frequency response measurement with LED as load.

10 Hz

MyDAQ Oscilloscope

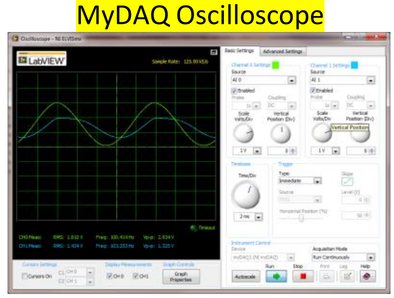


Voltage Resolution: 1 V
Time Resolution: 20 ms
Channel 0 – input TP5
Channel 1 – output TP6
LED STATE (BLINKS OR OFF): BLINKS

(a) Waveform in point TP6 with 3 V/10 Hz in the input.

100 Hz

MyDAQ Oscilloscope

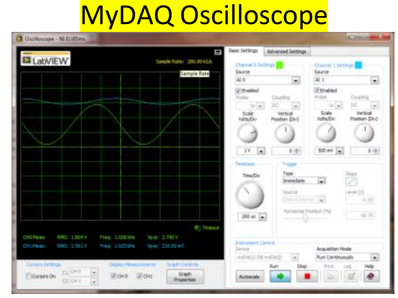


Voltage Resolution: 1 V
Time Resolution: 2ms
Channel 0 – input TP5
Channel 1 – output TP6
LED STATE (BLINKS OR OFF): BLINKS (WEAKER)

(b) Waveform in point TP6 with 3 V/100 Hz in the input

1 kHz

MyDAQ Oscilloscope



Voltage Resolution: 500 mV
Time Resolution: 200 µs
Channel 0 – input TP5
Channel 1 – output TP6
LED STATE (BLINKS OR OFF): OFF

(c) Waveform in point TP6 with 3 V/1 kHz in the input

Figure 13 – Low pass filter frequency response with LED as load.

Did the measured waveforms in Figure 13 show similar values as in Table 4? If they were not similar, explain why they were different?

The measured waveforms showed different values as expected for 10 Hz and 100 Hz because the LED forward voltage held the maximum output voltage in ~1.93 V.

Now turn off the power switch and remove the LED. Use a function generator again to apply the same signal (3 Vpp , +1.5 V offset, 10 Hz, 100 Hz and 1 kHz) in "TP5" (Figure 14). Use an oscilloscope to measure the voltage in "TP6" and draw the waveforms in Figure 15.

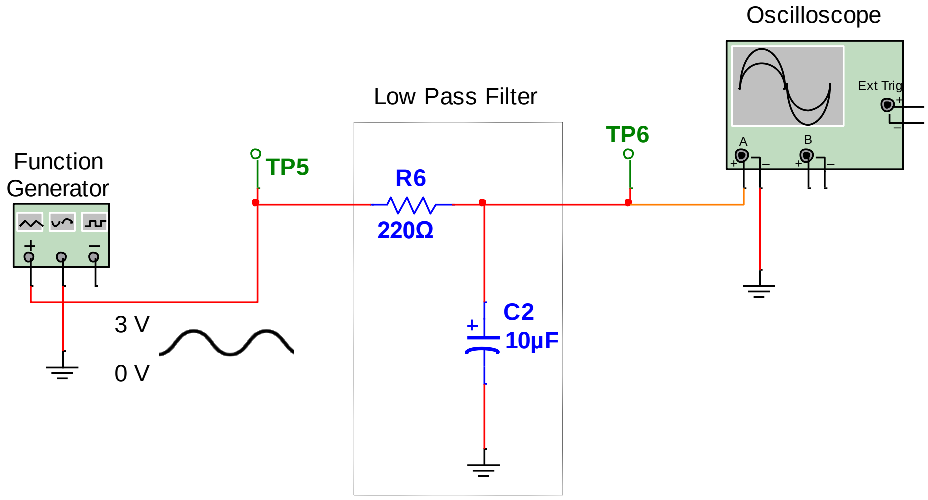
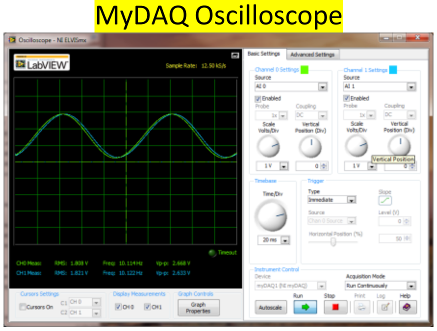



Figure 14 – Low Pass Filter frequency response measurement.

10 Hz

MyDAQ Oscilloscope

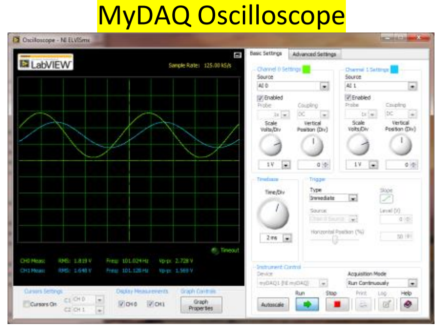


Voltage Resolution: 1 V
Time Resolution: 20 ms
Channel 0 – input TP5
Channel 1 – output TP6

(a) Waveform in point TP6 with 3 V/10 Hz in the input.

100 Hz

MyDAQ Oscilloscope

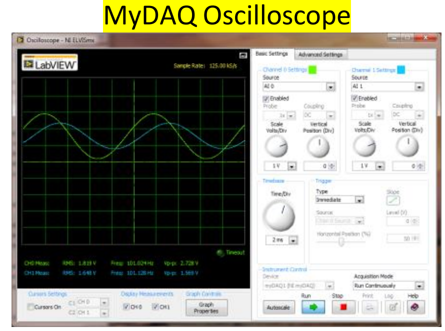


Voltage Resolution: 1 V
Time Resolution: 2ms
Channel 0 – input TP5
Channel 1 – output TP6

(b) Waveform in point TP6 with 3 V/100 Hz in the input

1 kHz

MyDAQ Oscilloscope



Voltage Resolution: 500 mV
Time Resolution: 200 µs
Channel 0 – input TP5
Channel 1 – output TP6

(c) Waveform in point TP6 with 3 V/1 kHz in the input

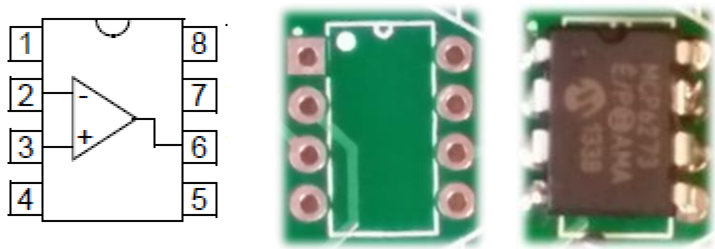
Figure 15 – Low pass filter frequency response without load

Did the measured waveforms in Figure 15 show similar values as in Table 4? If they were not similar explain why were they different?

The signal amplitude should be similar to the values calculated in Table 4.

## Amplifier

Turn off the power switch and install the amplifier integrated circuit (U1) on the board; Pay attention to place this component in the right polarity! The wrong pin layout on the PCB may burn the part since VDD (+ 3 V) and VSS (0 V) would be inverted. Figure 16 shows the amplifier symbol/pins layout, silk screen drawing, and the correct placement on the board.




(a) (b) (c)

Figure 16 – Integrated Circuit schematic symbol/top pins layout (a), silk screen drawing (b) and chip placement (c).

Add the resistances R5 and R6 as shown in Figure 17. This amplifier configuration is a now-inverter layout with a gain shown in Equation 3:

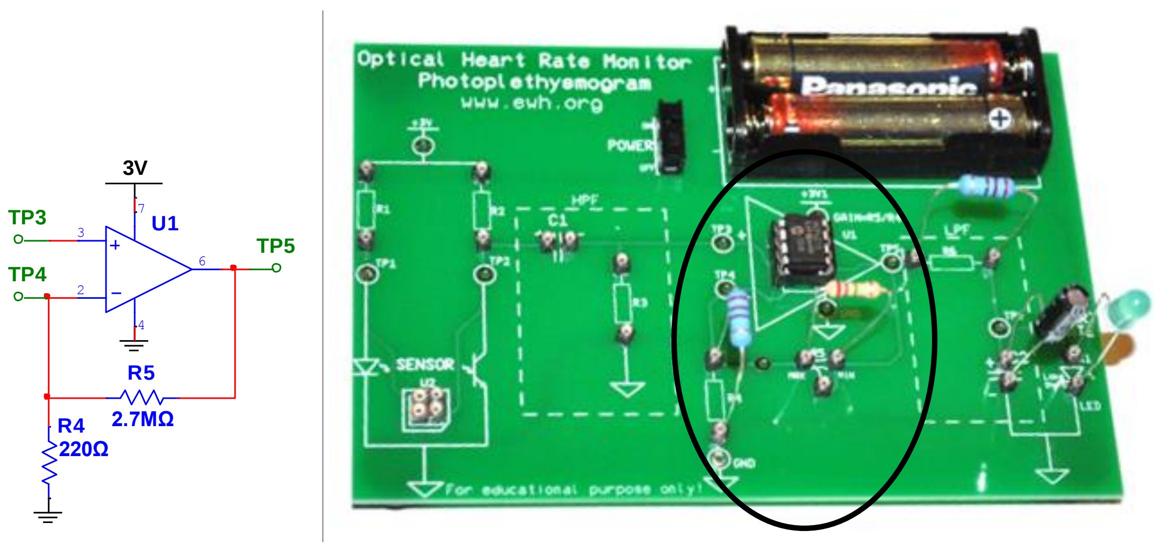



Figure 17 – Non-inverter amplifier configuration schematic and PCB assembly.

$$G = 1 + \frac{R5}{R4} \tag{3}$$

where:

- *G* is the amplifier gain, (N/A)
- *R5* is the resistance value, (Ω)
- *R6* is the resistance value, (Ω)

Calculate the amplifier gain for R5 = 2.7 MΩ and R4 = 220 Ω.

*Gain =* 12,273

The Optical Heart Rate Monitor amplifier is supposed to increase the amplitude of small signals in the range of 10 mV. Fill in Table 5 with the amplifier maximum and minimum output voltages for theoretical and real conditions with a signal of 10 mV AC (analog current/0 V offset) in the input.

Table 5 – Amplifier output voltages for theoretical and real conditions.

| Amplifier Output (input = **10 mV AC**) | Theoretical | Real (VDD = +3 V, VSS = 0 V) |
|---|---|---|
| ***Maximum*** | + 61.38 | 3 |
| ***Minimum*** | - 61.38 | 0 |

Since the gain is very high, the circuit behaves almost as a comparator. Connect the function generator with 10 mV/1 Hz AC in the amplifier input as shown in Figure 18. Turn on the board power and draw the amplifier input (TP3) and output (TP5) waveforms in Figure 19.

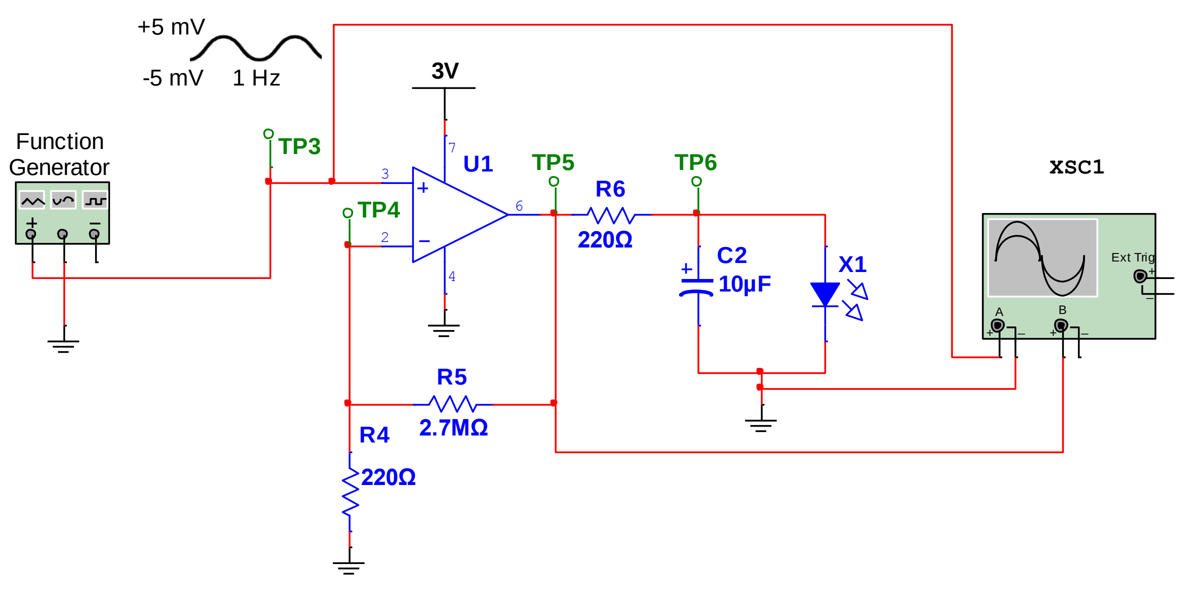
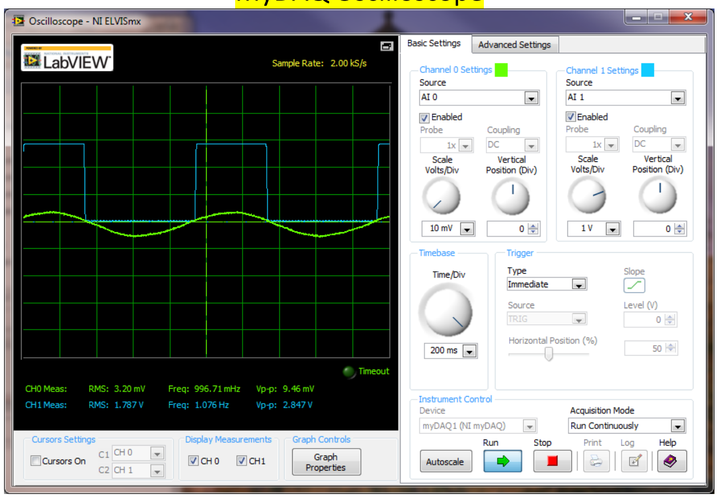



Figure 18 – Amplifier measurement schematic.

MyDAQ Oscilloscope




Voltage Resolution: 10 mV
Time Resolution: 200 ms

Voltage Resolution: 1 V
Time Resolution: 200 ms

(a) Waveform in amplifier input TP3 (Channel 0).

(b) Waveform in amplifier output TP5 (channel 1).

Figure 19 – Waveforms in the input and output of the amplifier "U1".

## High Pass Filter

Although the current circuit filters high frequencies, it still needs to be able to detect the small arterial pulses. Figure 20 shows a typical plethysmographic waveform. Although the cardiac rate is approximately 1 Hz, the strongest signal is found in the 2 Hz range. Therefore, one can detect the cardiac pulse using a high pass filter with cutoff frequency lower than 2 Hz).


Figure 20 – Typical plethysmographic waveform.

To assemble the filter, turn off the power switch and assemble the capacitor “C1” in series with the resistor R3, as seen in Figure 21.


(a) (b)

Figure 21 – High pass filter schematic (a) and assembly on PCB.

The high pass filter cutoff frequency is shown in Equation 4:

$$f_C = \frac{1}{2.\pi.R3.C1} \tag{4}$$

where:

- $f_C$ is the cutoff frequency, (Hz)
- *R3* is the resistance value, (Ω)
- *C1* is the capacitance value, (F)

Calculate the high pass filter cutoff frequency for R3 = 10 kΩ and C1 = 10 µF.

*Cutoff frequency* = 1.59 Hz

The high pass filter output gain (in the resistor R3 - TP3) is given by Equation 5:

$$G_{HPF} = \frac{2.\pi.f.R3.C1}{\sqrt{1 + (2.\pi.f.R3.C1)^2}} \tag{5}$$

where:

- $f$ is the input signal frequency, (Hz)
- $R3$ is the resistance value, (Ω)
- $C1$ is the capacitance value, (F)

Use Equation 4 to calculate the low-pass filter output gain and amplitude values for an input signal of 120 mVpp.

Table 6 – High-pass filter output gain and amplitude for an input of 120 mVpp.

| Parameter | Frequency | | |
|---|---|---|---|
| | 0.6 Hz | 1 Hz | 10 Hz |
| **HPF Gain** | 0.352 | 0.531 | 0.987 |
| **Amplitude (V)** | 42.3 m | 63.8 m | 118 m |

Turn off the power switch and use a function generator to apply a signal of 120 mVpp with frequencies of 10 Hz, 100 Hz and 1 kHz in “TP5” (Figure 12). Use an oscilloscope to measure the voltage in the LED “TP6”. Draw the waveforms and write the LED state in Figure 13.

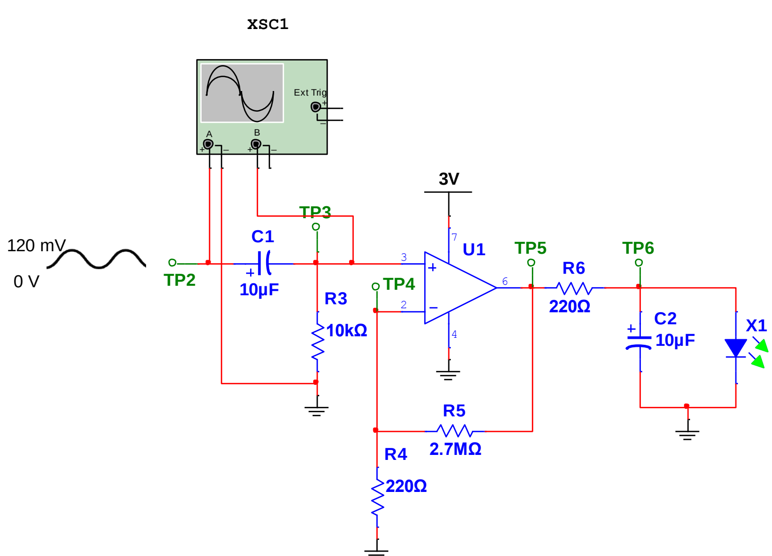
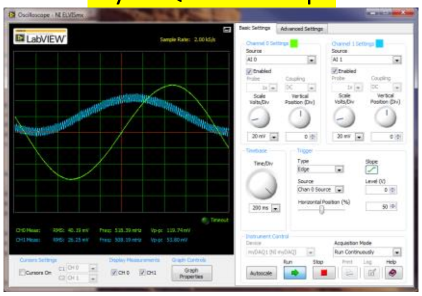



Figure 22 – High Pass Filter frequency response measurement schematic.

0.6 Hz

MyDAQ Oscilloscope

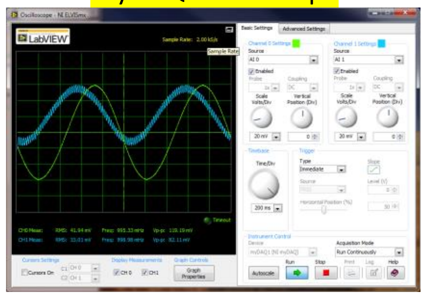


Voltage Resolution: 20 mV
Time Resolution: 200 ms
Channel 0 – input TP2
Channel 1 – output TP3

(a) Waveform in point TP3 with 120 mV/0.6 Hz in the input.

1 Hz

MyDAQ Oscilloscope

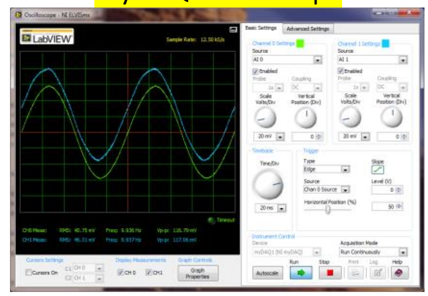


Voltage Resolution: 20 mV
Time Resolution: 200 ms
Channel 0 – input TP2
Channel 1 – output TP3

(b) Waveform in point TP3 with 120 mV/1 Hz in the input.

10 Hz

MyDAQ Oscilloscope



Voltage Resolution: _______50 mV________
Time Resolution: _______1 ms_______
Channel 0 – input TP2
Channel 1 – output TP3

(c) Waveform in point TP3 with 120 mV/10 Hz in the input.

Figure 23 – High pass filter frequency response with LED as load.

## Light Source and Optical Sensor

Figure 24 shows the electromagnetic absorbance spectra for different human skin components. Engineers normally use the range between 700 nm (red) to 1000 nm (infrared) for biological measurements, since the light beam can cross narrow parts of the body such as a fingertip or an earlobe.

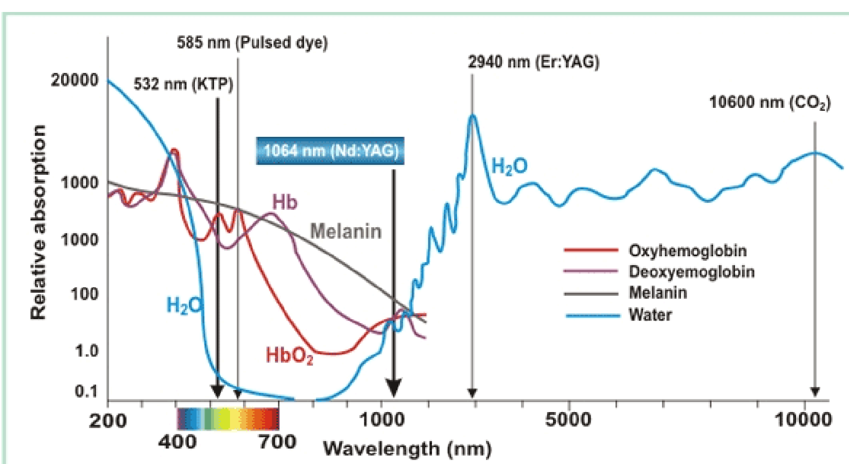



Figure 24 – Optical spectra of skin components[2].

There are two optical measurement approaches that can be used for physiological measurements: reflectance or transmittance, as seen in Figure 25.

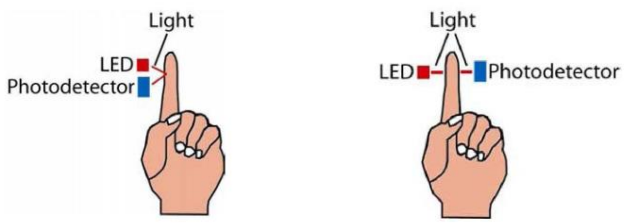



Figure 25 – Fingertip optical measurement approaches.

The reflectance measurement has the advantage that the light source and the sensor are placed on the same side, therefore being easier to assemble on a PCB. Figure 26 shows how light reflectance in the human finger is measured by the EWH Heart Rate Monitor Kit.

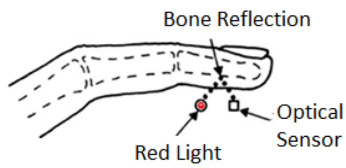
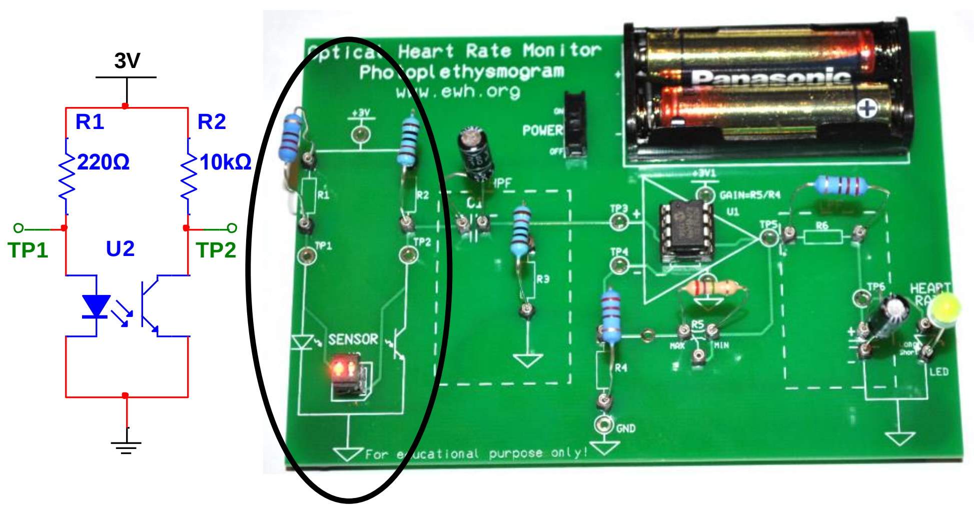



Figure 26 – Fingertip measurement of the Optical Heart Rate Monitor kit. The sensor measures the red light that reflects in tissues such as skin, muscle, blood vessels and bones.

Turn off the power switch and assemble the resistor R1, R2 and the Reflective Sensor (LED + Photodetector) in the PCB, as seen in Figure 27.




(a) (b)

Figure 27 – Photodetector circuit schematic (a) and PCB assembly (b).

Turn on the power switch and fill in Table 7 with the voltage measured in the photodetector collector contact (TP2) with and without the fingertip on the sensor “U2”, as shown in Figure 28.

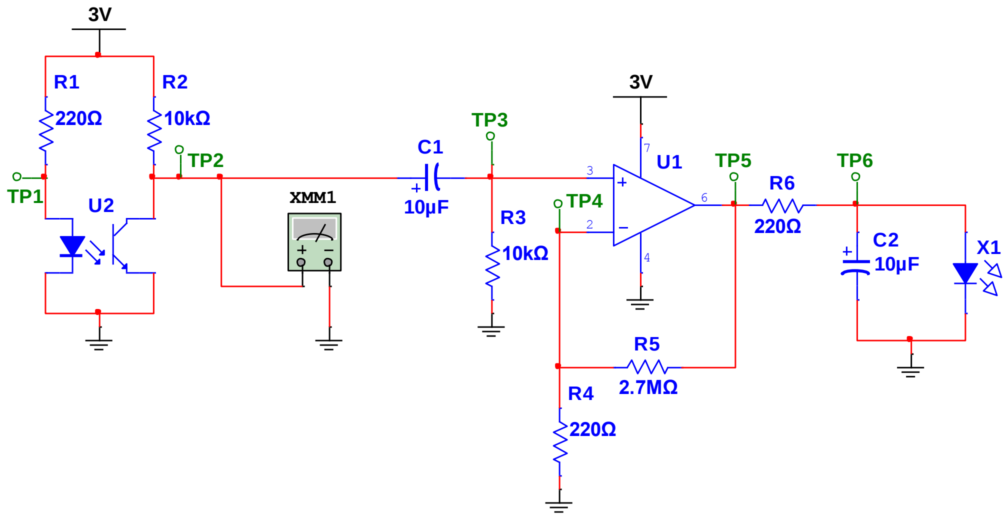


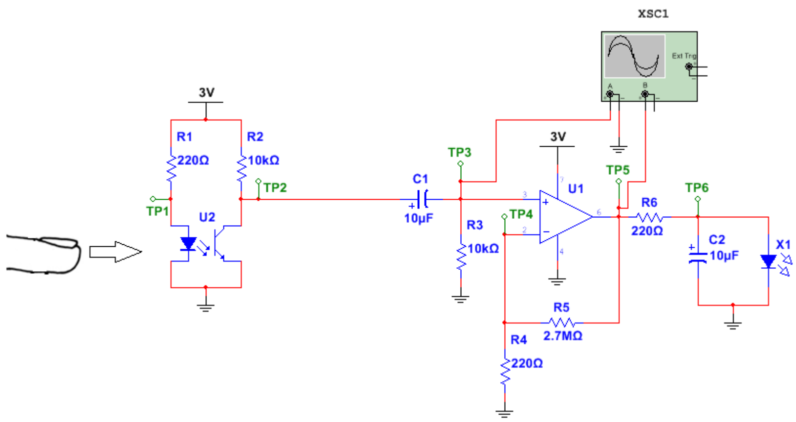

Figure 28 – Photodetector measurement schematic.

Table 7 – Photodetector test data.

| Sensor (U2) | Photodetector collector voltage (V) | LED State (ON, OFF or BLINKS) |
|---|---|---|
| **Without finger** | 2.921 | ON |
| **With finger** | 0.4 – 0.7 | OFF (for one second, then it blinks) |

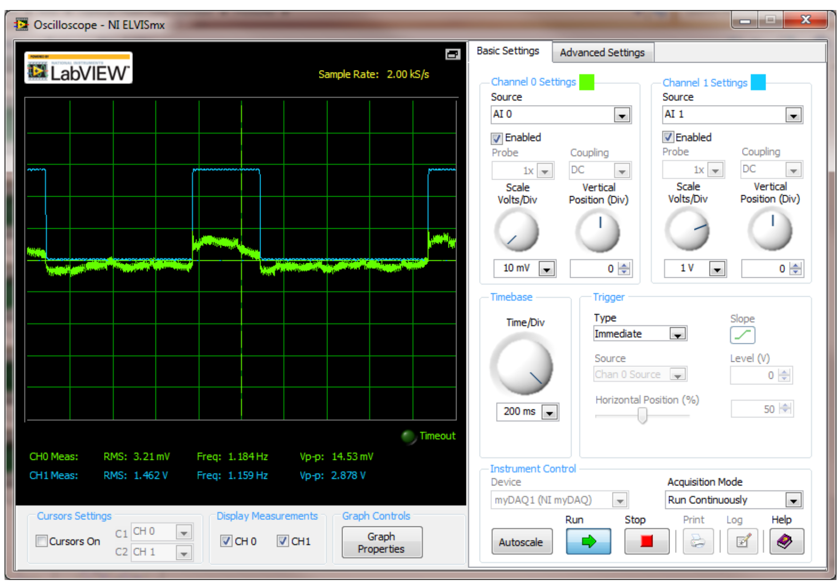
## Oscilloscope/Acquisition Board Measurements

Connect channel 1 of the oscilloscope to the test point “TP3” (Figure 29) and channel 2 to test point “TP5”. Turn on the board. Place the finger on the sensor “U2”; the green LED “X1” should start to blink, showing the heart rate after the time constant of the RC circuit (C1 and R3) is reached. Draw the waveforms in Figure 30.




(a) (b)

Figure 29 – Schematic (a) and picture (b) of the finger measurement with the Optical Heart Rate Monitor Kit. The schematic shows where to connect the oscilloscope to measure the input and output of the amplifier "U1".




Channel 0 - input
Voltage Resolution: 10 mV
Time Resolution: 200 ms

Channel 1 - output
Voltage Resolution: 1 V
Time Resolution: 200 ms

(a) Waveform in point TP3. (b) Waveform in point TP5.

Figure 30 – Waveforms in the input and output of the amplifier "U1".

# References

1. Tanaka, H., Monahan, K. D. & Seals, D. R. Age-predicted maximal heart rate revisited. *J. Am. Coll. Cardiol.* **37,** 153–156 (2001).

2. Everything Esthetic. at <http://www.everythingesthetic.com/products/lasers/spectra/>