Design and Simulation of a Heart Rate Monitor Circuit

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INTRODUCTION

Heart rate monitor which is also known as Electrocardiography (ECG), can be designed using a reflective optical sensor (TCRT1000). Design should be able to run by using a 9V battery. This 9V can be converted to 5V and 2.5V using LM2931 and TLE2425 voltage regulator IC respectively. Output waveform should be of peak to peak amplitude varying from 0.5 V to 1.5V, riding on a D pedestal of approximately 2.5V. This would require a voltage gain of approx. 60 dB to 75 dB to archive this output level. The circuit must implement have Automatic Gain Control to operate it for all type of skins.

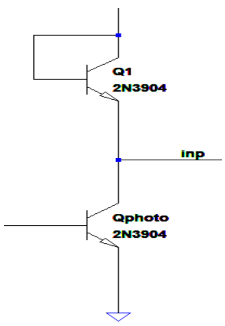
The bandwidth of the circuit should be between 0.3 Hz to 30 Hz approx. By liming the bandwidth, we can eliminate undesired signals from the circuit. Entire design needs a high gain which can be archived by cascading two gain stages using TLC2274 Op-Amp IC. We also require implementing a feedback loop by using non-linear circuit, to center the output waveform, which establishes a DC Baseline on the output.

CIRCUIT DESIGN

Entire circuit can be broken down into few small circuits for better understanding purpose.

1. **Reflective Optical Sensor:** Design starts with a reflective optimal sensor that senses the reflections from the blood. This sensor has a receiver and a transmitter section. The value of current generated by this transmitter depends on the reflection captured by receiver. If skin type is dark, reflections will be less, and vise-versa. To make the design independent of skin type we can use an *automatic gain control* circuit which is nothing, but a diode connected transistor which acts like a resistance. This resistance can change value when collector current is changed.

$$g_m = \frac{Ic}{UT}$$



This circuit can produce a output voltage of 259 µV. This voltage can be expressed as $Vo = -\left(\frac{ib}{IB}\right) UT$

Where i_b / I_B is constant and will be .1% or .001

U_T is a constant of value 25.9 mV.

This voltage becomes the input voltage of two stage cascade amplifier.

2. Two stage Cascade Amplifier:

To get an output voltage of 0.5V to 1.5V we need to boost our input voltage. To archive a boost, we need some very high gain amplifiers. This can be done by cascading two amplifiers in series as the gain multiplies together.

To determine the gain of each stage for output voltage of 0.5V to 1.5V we can calculate the minimum and maximum gain required of those amplifiers. That is

$$G_{min} = \frac{0.5V}{259\mu V} \cong 2000$$

$$G_{max} = \frac{1.5V}{259\mu V} \cong 6000$$

We can choose the gain of both the stages anywhere between 2000 to 6000. The best choose would be right in the middle which is 4000. This can be done by giving a gain of ~63 to each stage that makes the complete gain to 63 x 63 ≅ 4000.

First stage amplifier is a Voltage amplifier also known as or Series – Shunt Non-Inverting Amplifier. The gain of this amplifier can be given as

$$G_1 = 1 + \left(\frac{R2}{R1}\right) = 1 + \left(\frac{68.75K\Omega}{1K\Omega}\right) = 69.75$$

Second stage amplifier is a Transimpedance Amplifier also known as shunt-shunt negative feedback amplifier. This takes in the current and gives voltage at the output. Voltage to current conversion can be done by use of R_3 resistance, which also acts like a voltage to current convertor.

This stage also uses a Low pass filter circuit to limit the bandwidth of the circuit. This can be done using a capacitance in parallel with the resistance R_4. The value of this capacitor by the relation $\omega = \left(\frac{1}{2\Pi * R4 * C1}\right)$. If R_4 is 57 KΩ then C_1 can be selected as ~0.1µF to limit the frequency response within 30Hz.

The gain of this can be given as

$$G_2 = -\left(\frac{R4}{R3}\right)\left(\frac{1}{1+S\tau 1}\right) = \left(\frac{57K\Omega}{1K\Omega}\right) = -57$$

Both the amplifiers together give a gain of ~4000. But this output is inverted output of the desired output. To invert this output, we can pass this to an Inverting Amplifier having a gain of 1.

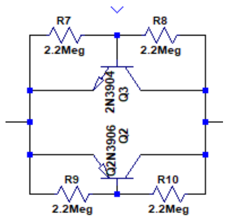
3. Inverting Amplifier:

Output of the two-stage cascade amplifier is inverted output of the desired output. To invert this output, we can pass this to an Inverting Amplifier having a gain of unity. Gain of this stage can be expressed as

$$G = -\frac{R6}{R5} = \frac{10K\Omega}{10K\Omega} = -1.$$

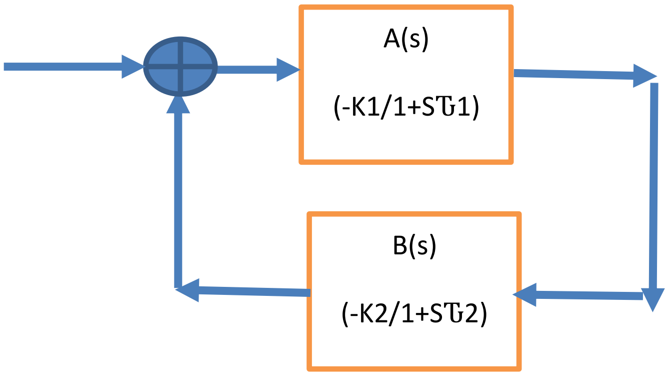
4. Negative feedback loop for output DC Baseline:

This circuit uses two circuits, one is VBE multiplier that uses one NPN and one PNP transistor. Only one is active at a time. The circuit also has four resistances with its equivalent resistance 2.2MΩ. This complete circuit acts as a resistance for next stage amplifier and passes the signal coming from stage 2 amplifier.



This resistance is connected to amplifier of unity gain that also a capacitor. This negative feedback is again given to the first stage amplifier to set an output DC baseline. That makes the circuit more stable.

Entire design can be expressed by using a control system. Which gives us a clear picture of the design and its frequency response.



The final gain of the circuit can be expressed as

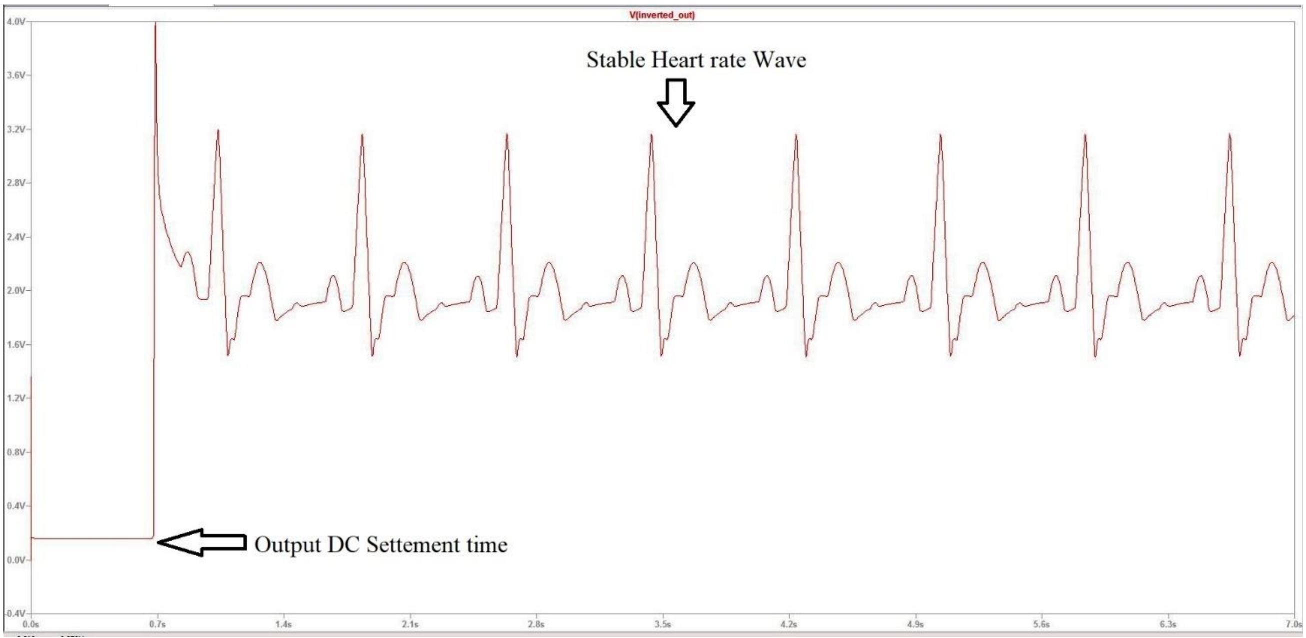
$$A_f = -\frac{K1(1+S\tau 2)}{(1+S\tau 1)(1+S\tau 2)+K} \text{ where } K = K_1 * K_2$$

$$\text{Where } \tau 1 = \frac{1}{\omega 1} \ \& \ \omega_1 = 2\Pi \text{ (30 Hz) and } \omega_2 = 2\Pi \left(\frac{0.3Hz}{K1}\right)$$

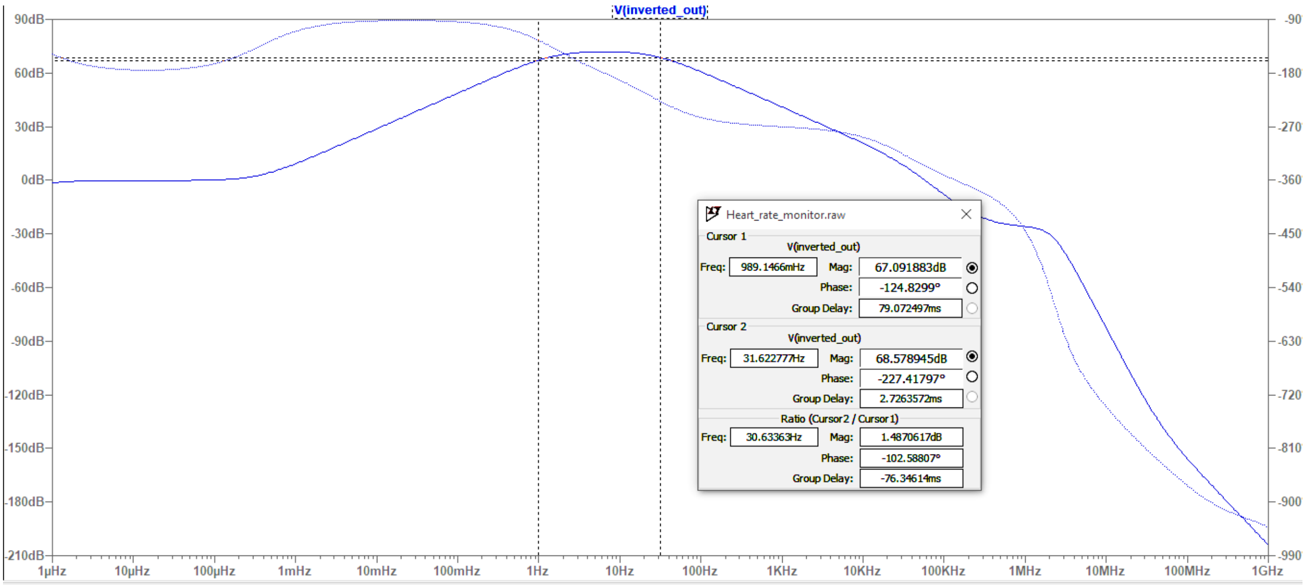
This complete circuit operates at a single voltage supply of +9V, using a battery. Complete design can be expressed as a block level design:

Design Outcomes

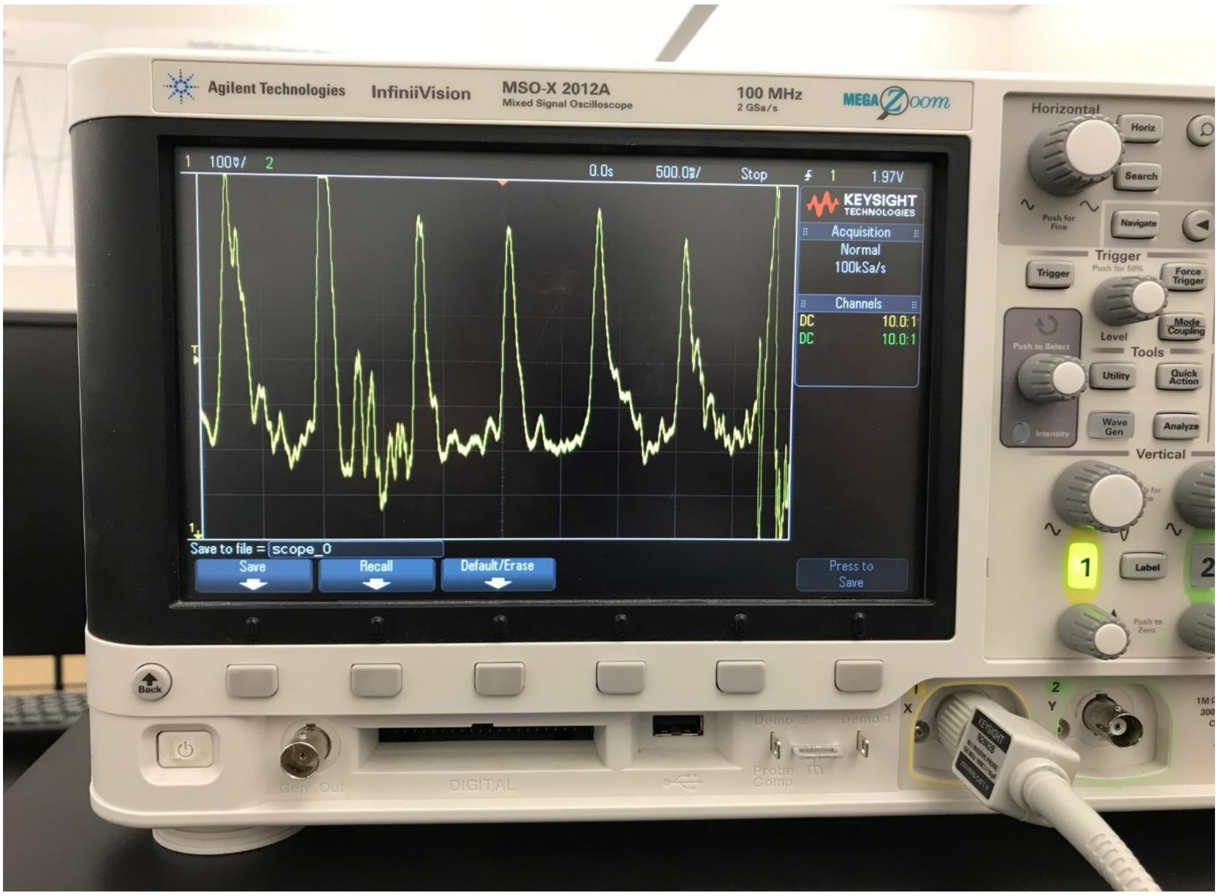
Below is the result of the simulation of the heart beat monitor system. This system takes time to establish an output DC baseline, which is less than 2 seconds. Once the DC Baseline has setup, the output becomes stable.



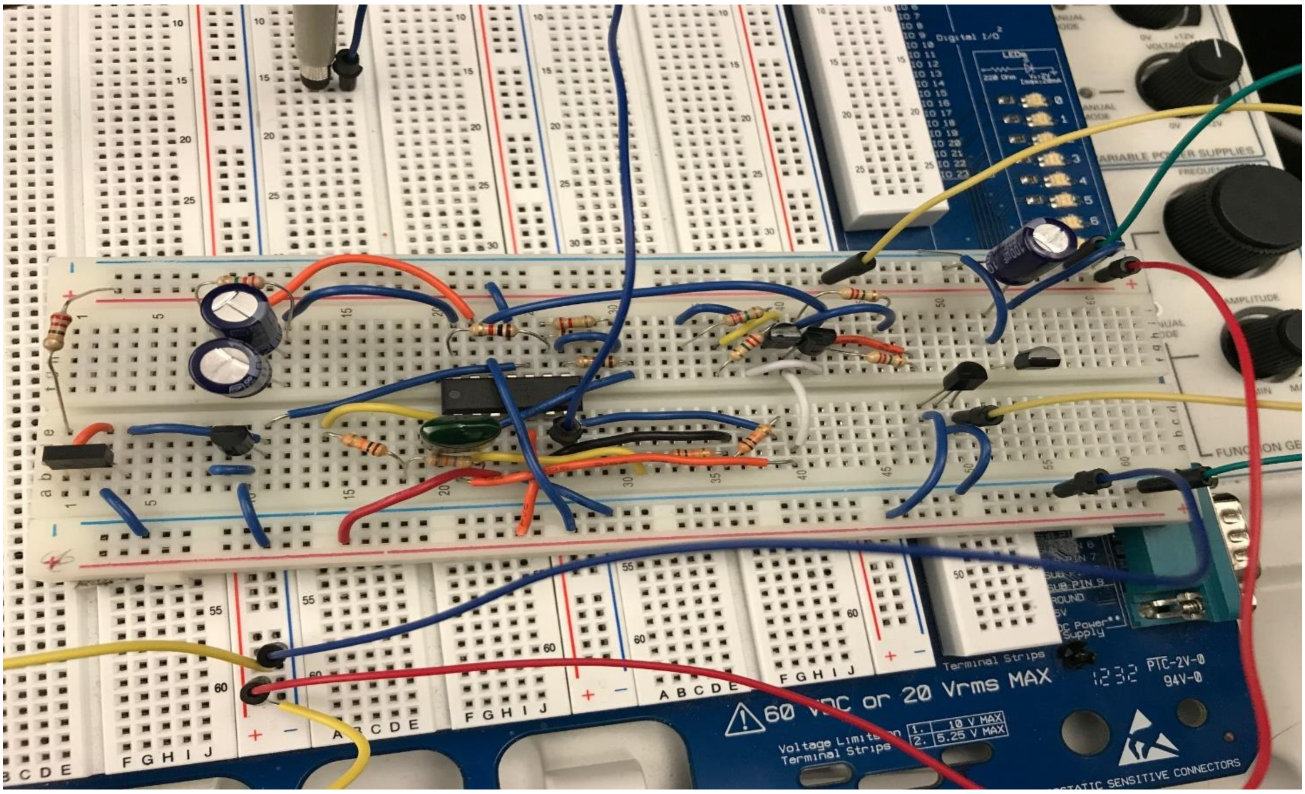
Below is the result of the gain acquired by the circuit at a given frequency. Gain of this design may vary from 2000 to 6000 that is 66 dB to 75 dB. The circuit gives a gain of approx. 67 dB at 1 Hz also the similar gain at 30Hz.



The given picture shown a heart rate monitor response, where each vertical block is of 100mV and horizontal block is of 500mS.

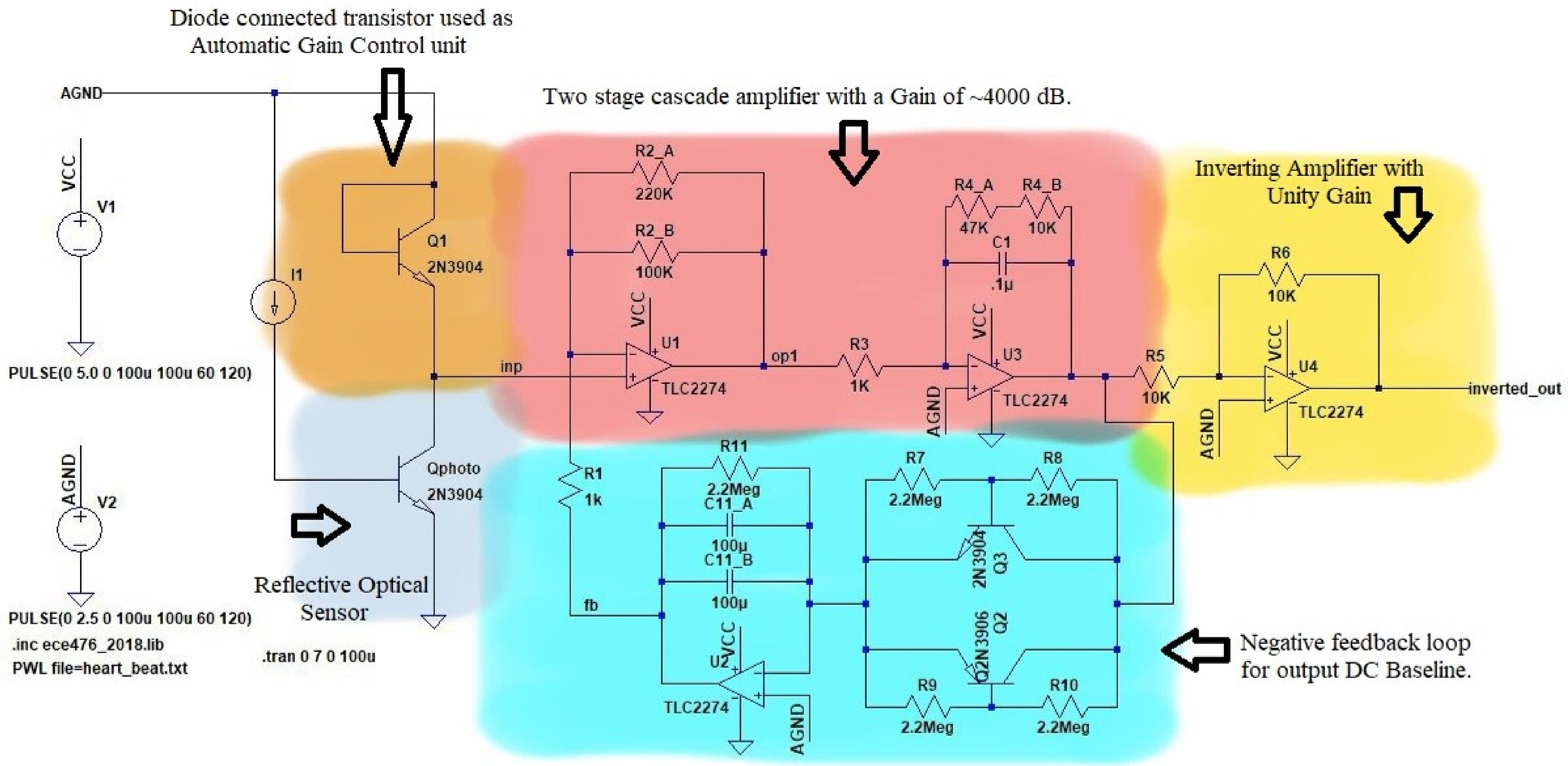


Actual Circuit made at the bread board



CONCLUSION

1. Designed and implemented heart rate monitor using the components provided in the parts kit.
2. Design meets the specifications given in the requirement sheet.
3. Learned the use of reflective optical sensor and automatic gain control circuit.
4. Learned how to limit the bandwidth response of a system by implementing Low pass filters.
5. Learned how to implement negative feedback loop to establish output DC Baseline.
6. The circuit operates at a single power supply by using +5 and +2.5 V Voltage regulator IC.


Diode connected transistor used as
Automatic Gain Control unit
Two stage cascade amplifier with a Gain of ~4000 dB.
Inverting Amplifier with
Unity Gain
AGND
VCC
V1
PULSE(0 5.0 0 100u 100u 60 120)
I1
Q1
2N3904
R2_A
220K
R2_B
100K
VCC
U1
TLC2274
inp
op1
R3
1K
R4_A
R4_B
47K
10K
C1
.1µ
VCC
U3
TLC2274
AGND
R6
10K
R5
10K
VCC
U4
TLC2274
AGND
inverted_out
Qphoto
2N3904
AGND
V2
PULSE(0 2.5 0 100u 100u 60 120)
.inc ece476_2018.lib
PWL file=heart_beat.txt
Reflective Optical
Sensor
.tran 0 7 0 100u
R1
1k
fb
R11
2.2Meg
C11_A
100µ
C11_B
100µ
VCC
U2
TLC2274
AGND
R7
2.2Meg
R8
2.2Meg
2N3904
Q3
2N3906
Q2
R9
2.2Meg
R10
2.2Meg
Negative feedback loop
for output DC Baseline.