Auto gain Ultra low signal transimpedance amplifier for Blood Diagnostic machine.

Saroj R Desai¹, Nilima V Warke² and Shivaji S Nawatake³

¹ P.G Scholar, V. E. S. Institute of Technology, Department of Instrumentation and Control Engineering, Chembur, Mumbai, India.
² Associate Professor, V. E. S.Institute of Technology, Department of Instrumentation Engineering, Chembur, Mumbai, India.
³ R & D Head, SIR Automation Industries, Navi Mumbai, India.

saroj.desai@ves.ac.in, nilima.warke@ves.ac.in, shivaji@sirautomation.com

Abstract. The front-end circuit of blood diagnostic machine consists of a light source, photodiode and transimpedance amplifier (TIA). Various researchers have used separate photodiode and the TIA circuit to measure absorbance for different wavelengths that made the circuit bulky and limited its application for measurement of specific parameters. At high gain of around 4000 plus normally any amplifier, including TIA becomes unstable. We are presenting here auto gain TIA that is stable and precise even at the gain of 4000. MSP432 32 BIT Arm Cortex 4 microcontroller with inbuilt precision analog to digital convertor is used for sensing, implementing auto gain selection logic and calculating the absorbance. With this circuit, we measured the absorbance up to 4.2 and satisfactory results with maximum error of 0.04 were achieved up to the range of 3.5 on the absorbance scale. Further, the performance of TIA is tested and found satisfactory for 300nm to 800nm wavelength range.

Keywords: Transimpedance amplifier, Low optical signal, Blood diagnostic machine, Microcontroller based auto gain amplifier.

Introduction
Blood Diagnostic Machine performs tests for determination of physiological and biochemical conditions. The blood sample is collected in vacutainer blood collecting tubes and some additives are added to settle it and then test can be performed.

The blood diagnostic machine uses the principle of spectrophotometry which is based on either fluorescence principle or absorbance principle [1-2]. It uses Beer-Lambert’s law, which states the relation between the absorption of light and the material property through which light is transmitted as given by eq (1) and (2)

\[ T = \frac{I}{I_0} = 10^{-\epsilon * C * I} \]  \hspace{1cm} (1)

\[ A = \epsilon * C * I = \log (T) \]  \hspace{1cm} (2)

Where, T is transmittance, A is Absorbance, I is the intensity of light transmitted through the sample, \(I_0\) is the intensity of light incident on the sample.

Block diagram of blood diagnostic machine is given in figure 1. Here, Optical source is used to generate signals, which is detected by the photodiode. This signal is amplified using TIA and given to a data
acquisition system and displayed.

![Figure 1: Block diagram of Blood Diagnostic Machine](image)

TIA is used to convert optical signal into an appropriate voltage which is then processed by the next stage of processing circuit. TIA with high gain is required to amplify low strength optical signal. But TIA becomes unstable at high gain. Many researchers have designed TIA for different applications like measurement of glucose, hemoglobin, blood group analysis. It is observed in the literature that the proper combination of photodiode and selecting corresponding design of TIA generates accurate results of blood parameters to measure different optical strength. But it makes a circuit bulky and limits its application to measure specific parameters [3-5]. The Designing of TIA plays an important role, such as precision in measurement, low noise and gain stability [6-10]. TIA with variable gain is the best solution to measure different strength of optical signal. To amplify different optical signal different gains can be used [11-15]. But it is always a difficult task to match the combination of resistor and capacitor to achieve proper bandwidth as per signal. Auto gain selection is required to avoid TIA to go into saturation for high strength of optical signal. So there is a need to design stable TIA, which amplifies low optical signals in the range of pA.

Here, the aim is to redesign the semiautomatic blood diagnostic machine in such a way that the internal signal conditioning circuit will be capable of detecting very low optical signal in order of pA and will be able to measure absorbance up to level 3.

1. **Proposed System**

The block diagram of the proposed system is as given below in figure 2 which is divided into two parts:

i) The front-end circuit consists of a photodiode and TIA with auto gain facility

ii) Microcontroller, recording and display unit.

The blood sample is placed between the light source-filter assembly and photodiode. Mechanical assembly with the stepper motors with efficient design of optical filter wheel is used to automate for precise measurement which supports inhale and exhale procedure of blood samples. Light is allowed to pass through the 10 mm passage of the blood sample using the software selected optical filter. Absorbance of light at a particular wavelength is measured. A precise auto gain-controlled TIA is used to amplify the signal. Auto gain is selected by the 32-bit microcontroller. All the gain resistances used to calculate gains are connected to analog multiplexer. Then the output is displayed on the LCD screen.

![Figure 2: Block Diagram of Proposed Blood Diagnostic Machine](image)
Proposed Specifications of Semi-Automatic Blood Diagnostic Machine are as given below:

- Linear Range measurement: 0.00 to 3.15 absorbance units (A)
- Photometric accuracy: +/-1% from 0 to 1.5A, ± 2% from 1.5A to 3.0A
- Sensitivity Area: (2.5 mm X 2.5mm) to (3 mm X 3mm)
- Optical measurement: Photo Diode
- Light Source: Tungsten lamp
- Types of filters: High quality narrow band interference
- Wavelength: Up to 12 nos. of wavelengths are proposed approximately between 300-800nm
- Sipping volume of Flow cell: 1000µl
- Triple cuvette system: 18µl flow cell 10mm² cuvette round tube for coagulation. 15 Positions at 37°C
- Incubator pump: Stepper motor controlled, highly reliable, low maintenance precision pump
- Power: 115 – 230 Volts ± 10%, 50 – 60 Hz
- Analysis Modes: Absorbance, End Point, Fixed Time, Kinetic, Differential & Ratio, PT, INR & APTT
- Microcontroller: MSP432P401R-high precision controller Arm 32 bits, Cortex M4 with a floating point unit design to develop a data acquisition system.

This work is focused on the design of TIA with auto-gain facility as highlighted in figure 2 for the above mentioned specifications for a blood diagnostic machine.

2. Methodology

Light source used for this experiment is the luminance film viewer.

2.1 Selection of Sensor

Si photodiode is selected because it offers very low dark current and allows reliable measurements in visible to near infrared range from low light to high light intensities.

2.2 Design of Transimpedance amplifier

TIA is used for amplifying the light dependent current of a photodiode. A small bias voltage derived to the op amp’s non-inverting input so that the output will not go in saturation in the absence of input current. The photocurrent which needs to be amplified is applied to the inverting input, causing the output voltage to change according to the eq (3).

\[ V_{out} = -I_{in} \times R_f \]

where,
- \( I_{in} \) is input photo current,
- \( R_f \) is feedback resistor.
- \( C_f \) is Feedback capacitor is used to maintain stability when gain changes.

TIA as shown in figure 3 is designed for low optical signal amplification. It is designed such that it will not lead to saturation for high strength of optical signal. So microcontroller based auto gain selection facility is provided. To provide different gains of 250, 750, 1000 and 4000, the values of the feedback resistances and capacitances are calculated by using eq. (4) and (5) respectively. The \( R_f \) values were selected for this design, one to ensure a range of maximum output voltage, with low-intensity absorbed signals and to ensure that the output voltage does not exceed the analog to digital convertor (ADC) reference voltage, with the highest intensity signals. The range of output generated is between few mV to 2.5V (ADC reference voltage)
Figure 3: Transimpedance Circuit with variable gain

\[ R_f = \frac{V_o(\text{max}) - V_o(\text{min})}{i_{\text{in}}(\text{max})} \]  

(4)

where,
- \( V_o(\text{max}) \) is maximum output voltage,
- \( V_o(\text{min}) \) is minimum output voltage,
- \( i_{\text{in}}(\text{max}) \) is maximum input current of photodiode.

A capacitor is placed in parallel with feedback resistor \( R_f \) to stabilize the transimpedance amplifier. The value of feedback capacitor is calculated using eq. (5).

\[ C_f = \frac{C_T}{\sqrt{2 \pi f_{\text{GBW}} R_f}} \]  

(5)

where,
- \( C_T \) is the total capacitance of the photodiode and op-amp,
- \( f_{\text{GBW}} \) is a gain bandwidth product of op-amp

2.3 Selection of Microcontroller

MSP 432P401R micro-controller of Texas Instruments is selected because it has in-build 14-bit SAR ADC. It has low power Processor i.e active: 80 µA/MHz. It is used to select the gain as per the program fed to it.

The feedback resistors of TIA are connected to the channels of analog multiplexer which is interfaced with the precision microcontroller. As per channel selection program, specific feedback resistor is selected and absorbance is calculated. For different intensity of light, the absorbance is measured as per flowchart shown in figure 4. Initially the threshold voltages are fed to the microcontroller as largest value (Y) and smallest value (X) of the measured voltage. The output of transimpedence amplifier is compared with these threshold voltages.

The initial reading of the incident light without filter is noted as \( P_0 \). Then, as per selected filter the equivalent voltage for light after absorption is noted as \( P \). The absorbance is calculated for each filter action as per formula fed to it and it is displayed on LCD display.

3. Result

The front-end circuit of the semiautomatic blood diagnostic machine, as shown in figure 2 was designed, constructed and tested at different light intensities. The PCB for the same circuit was designed in Altium Software and the schematic is as shown in figure 5.
Figure 4: Flowchart for channel selection and absorbance measurement

Figure 5: Schematic of front-end circuit of blood diagnostic machine
The performance of TIA was tested at different intensities of light and its output is compared with the transmission density step wedge film, i.e. absorber film available with 4 to 14 levels along with certificate as shown in figure 6.

**Figure 6**: Transmission Density Strip

The performance of TIA with different feedback resistors RF1, RF2 and RF3 at a fixed illumination of light intensity i.e 80Kcd/m² is tested and reported in Table1. Here, the absorption is calculated with observed voltage with absorption scale and without absorption scale and then compared with theoretical absorption.

Let, Va- Observed voltage with absorption scale  
Vb -Observed voltage without absorption scale

**Table1: Performance of TIA at feedback-RF1, RF2, RF3**

| Abs scaler | Actual Abs | Ra |  Vb |  Calcu|  Vb |  Calcu|  Vb |  Calcu|  Vb |
|------------|------------|----|----|-------|----|-------|----|-------|----|
| 1          | 0.15       | 0.18| 0.30| 0.22  | 0.98| 1.4   | 0.17| 2.372 | 3.26| 0.14 |
|            | 6          | 6   | 6   | 6     | 6   | 6     | 6   | 6     | 6   |
| 2          | 0.37       | 0.12| 0.30| 0.39  | 0.58| 1.4   | 0.40| 1.397 | 3.26| 0.37 |
|            | 4          | 6   | 6   | 6     | 6   | 6     | 6   | 6     | 6   |
| 3          | 0.67       | 0.06| 0.30| 0.65  | 0.30| 1.4   | 0.68| 0.672 | 3.26| 0.69 |
|            | 8          | 6   | 6   | 6     | 6   | 6     | 6   | 6     | 6   |
| 4          | 0.92       | 0.03| 0.30| 0.89  | 0.17| 1.4   | 0.93| 0.371 | 3.26| 0.94 |
|            | 9          | 6   | 6   | 6     | 6   | 6     | 6   | 6     | 6   |
| 5          | 1.46       | 0.01| 0.30| 1.44  | 0.04| 1.4   | 1.48| 0.102 | 3.26| 1.50 |
|            | 1          | 6   | 6   | 6     | 6   | 6     | 6   | 6     | 6   |
| 6          | 1.71       | 0.00| 0.30| 1.71  | 0.02| 1.4   | 1.73| 0.056 | 3.26| 1.77 |
|            | 6          | 6   | 6   | 6     | 6   | 6     | 6   | 6     | 6   |
| 7          | 1.91       | 0.00| 0.30| 2.01  | 0.01| 1.4   | 1.93| 0.035 | 3.26| 1.97 |
|            | 3          | 6   | 6   | 6     | 6   | 6     | 6   | 6     | 6   |
| 8          | 2.08       | 0.00| 0.30| 2.18  | 0.01| 1.4   | 2.12| 0.023 | 3.26| 2.15 |
|            | 2          | 6   | 6   | 6     | 6   | 6     | 6   | 6     | 6   |
| 9          | 2.27       | 0.00| 0.30| 2.49  | 0.00| 1.4   | 2.32| 0.014 | 3.26| 2.37 |
|            | 1          | 6   | 6   | 6     | 6   | 6     | 6   | 6     | 6   |

The graph of absorbance measured with different feedback resistors Vs Absorbance scale is plotted as shown in figure 7. It shows that, almost approximately the same values of absorbance were obtained at the output of TIA when compared with actual absorbance for values RF1, RF2, RF3.
The absorption test was carried out at 80, 85, 95, 110 and 130Kcd/m² light intensities. Table 2 shows that the results observed in light intensity of 80Kcd/m² when the output of the TIA is given to the microcontroller.

**Table 2: Performance of TIA when interfaced with microcontroller at 80Kcd/m²**

| Ch.No | When P0= 130 | Intensity in LUX= 80Kcd/m² |
|-------|--------------|---------------------------|
|       | ADC count    | Measured absorption       | Actual absorption | error |
| 3     | 1            | 3199                      | 0.14              | 0.15  | 0.01 |
| 3     | 2            | 1679                      | 0.43              | 0.44  | 0.01 |
| 3     | 3            | 937                       | 0.70              | 0.70  | 0.00 |
| 4     | 4            | 2298                      | 0.99              | 1.01  | 0.02 |
| 4     | 5            | 687                       | 1.41              | 1.41  | 0.00 |
| 5     | 6            | 2480                      | 1.59              | 1.61  | 0.02 |
| 5     | 7            | 1620                      | 1.78              | 1.8   | 0.02 |
| 6     | 8            | 1012                      | 2.00              | 2.01  | 0.01 |
| 6     | 9            | 3767                      | 2.29              | 2.19  | -0.10 |
| 6     | 10           | 1481                      | 2.72              | 2.61  | -0.11 |
| 6     | 11           | 625                       | 3.13              | 3.01  | -0.12 |
| 6     | 12           | 372                       | 3.41              | 3.37  | -0.04 |
| 6     | 13           | 259                       | 3.64              | 3.80  | 0.16 |
| 6     | 14           | 217                       | 3.75              | 4.17  | 0.42 |

where,

- \( P_0 \) – ADC count observed when there is no absorption of light (maximum voltage),
- \( P \) – ADC count observed when the gain is selected and voltage proportional to the photocurrent generated after absorption.

The graph of measured absorbance Vs absorbance scale is plotted and is shown as shown in figure 8.
Figure 8: Graphical Analysis of TIA interfaced with microcontroller

It is observed from figure 8 that the absorption calculated by microcontroller and actual absorption as per certificate of density strip is almost same.

4. Conclusion

Here, an ultra low signal TIA with auto-gain selector circuit is designed for blood diagnostic machine. The suitable TIA with auto gain facility is designed with selected photodiode for 300nm to 900nm wavelength which calculate absorbance precisely in the case of low optical signal. The front end circuit of the blood diagnostic machine is constructed and tested at different light intensities. Microcontroller MSP432P401R 32 BIT Arm Cortex 4 microcontroller with 14 bit inbuilt precision ADC is used to facilitate auto-gain selection, such that TIA is prevented to go into saturation. The experimental results showed that the designed TIA is stable and accurate up to gain 4000 at highest absorbance level. It is also observed that the photocurrent decreases as absorbance level increases. The photocurrent at the highest absorbance level is calculated which is approximately equal to 16 µA. It is found that the absorbance measured with this circuit is up to the range of 3.5 on the absorbance scale from 80 to 130Kcd/m². The results are found satisfactory with maximum error of 0.04 when compared with absorbance scale of transmission strip i.e. approximately 98.9% is achieved.

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References

[1] Marc J P Leiner Optical sensors for in vitro blood gas analysis Sensors and Actuators B: Chemical, Volume 29 Issues 1–3 October 1995 and Pages 169-173.
[2] Cano J B Buonasera K Pezzotti G Transduction methods used in biosensors: amperometry and fluorescence Rev. Fac. Ing. Univ. Antioquia N.º 72 September 2014 pp 104-115 Universidad de Antioquia Medellin, Colombia.
[3] Mishra B Dr.Sharma K Chaudhary P A Low Noise Op-Amp Transimpedance Amplifier for InGaAs Photodetectors International Research Journal of Engineering and Technology (IRJET) Volume 02 issue 05 Aug-2015.
[4] Shahdoost S Medi A Saniel N Design of low noise transimpedance amplifier with capacitive feedback Analog Integrated Circuits and Signal Processing 2016 DOI: 10.1007/s10470-015-0669-x.
[5] Raikham P Kumar R Shah R K Hazarika M Sonkar R K Non-invasive Blood Components Measurement using optical sensor system Interface International Conference on microwave and Photonics 9-11 February 2018.
[6] Boylestad R L Nashesky L Electronic Devices and circuit theory Pearson INDIA Education Services Pvt Ltd, 2015.
[7] Johnson M. Photodetection measurement maximizing performance in optical system McGraw-Hill Education 1st edition August 1 2003 ISBN 13: 978-0071409445 pp 27-48.

[8] Franco S Design with operational amplifiers and analog integrated circuits Tata McGraw Hill publication third edition 2002 ISBN-13:978-0-07-53044-7.

[9] Fauda S Adino T Aska Y Putra A Trans-impedance Amplifier (TIA) Design for Visible Light Communication (VLC) using Commercially Available OP-AMP 3rd International Conference on Information Technology Computer, and Electrical Engineering (ICITACEE 2016) Oct 19-21st, 2016 Semarang Indonesia.

[10] Caldwell J 1 MHz Single-Supply Photodiode Amplifier Reference Design TI Application Note TIDU535 pp. 1-19 November 2014.

[11] Sivaraman, P., A. Nirmal Kumar, and P. Prem. "Dynamic modeling and analysis of T-source electronic inverter using state space technique." Scientific Research and Essays 7, no. 38 (2012): 3269-3280.

[12] Fernandes J Pimenta S Filomena O Soares and Minas G A Complete Blood Typing Device for Automatic Agglutination Detection Based on Absorption Spectrophotometer IEEE Transactions on Instrumentation and Measurement Volume 64 Issue 1 Jan. 2015.

[13] Johannes Hubertus Antonius Brekelmans Variable Gain transimpedance Amplifier United State patent no. US 9,419,573 B2; Aug 16, 2016.

[14] Rushing A J Auto-ranging digital densitometer with lookup table US 6,331,832B1 Dec 18, 2001.

[15] Orozco L Programmable-Gain Transimpedance Amplifiers Maximize Dynamic Range in Spectroscopy Systems Analog Dialogue. 2013 47(5):1-5.