بسم الله الرحمن الرحيم

Design and Implementation of Portable Hemoglobin Concentration and Fat Percentage

Project Team

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Electrical Engineering Department

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By the guidance of our supervisor, and by the acceptance of all members in the testing committee, this project is delivered to department of electrical and computer engineering in the college of engineering and technology, to be as a partial fulfillment of the requirement of the department for the degree of B.sc.

Supervisor signature

Testing committee signature

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جامعة بوليتكنك فلسطين

الخليل – فلسطين

كلية الهندسة

دائرة الهندسة الكهربائية

Design and Implementation of Portable Hemoglobin Concentration and Fat Percentage

فريق المشروع

مصعب درامنة　　　　　　　　　　مصطفى رباية

بناء على نظام كلية الهندسة وإشراف ومتابعة المشرفة المباشر على المشروع وموافقة أعضاء اللجنة المناقشة، تم تقديم هذا العمل إلى دائرة الهندسة الكهربائية. وذلك للوفاء بمتطلبات درجة البكالوريوس في هندسة الأجهزة الطبية.

توقيع المشرفة

توقيع اللجنة المناقشة

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توقيع رئيس الدائرة

Abstract

Obesity is the accumulation of fat under the skin and within the components of the whole body in general, it is one of the centauries sickness that resulting from malnutrition, and causes many serious diseases, especially heart disease, diabetes and sleep apnea; so obese people resort to many ways to get rid of them.

However, usually, the negative side effects of the methods used to get rid of obesity are not considered. One of the most important negative effects is the iron deficiency in the blood, which is the result of the lack of hemoglobin. Hence, there is a need for a device that measures the body's fat percentage and at the same time monitors the rate of hemoglobin in the blood too.

This device will facilitate doctors to diagnostic diseases that related to blood and obesity, which are usually symptoms are similar to a large extent and difficult to distinguish them only with the proportion of hemoglobin in the blood and body fat percentage, in addition ,the device will allow individuals in domestic use to ensure the effectiveness of their methods of disposal of obesity.

On the one hand, the device that was design to measure hemoglobin in blood based on the optical non-invasive method. CBC and our project results have a mean 15.4027, 14.3297 respectively, and STD 1.42585, 1.43076 respectively.

On the other hand, the device was design to measure fat based on measure body impedance. The US navy method and our device results have a mean 33.0606, 32.9769 respectively and STD 8.47311, 8.28586 respectively.

الملخص

السمنة هي تراكم الدهون تحت الجلد وداخل مكونات الجسم بشكل عام، وهي مرض من أمراض العصر ناتج عن سوء التغذية، ويتسبب بالعديد من الأمراض الخطيرة خاصة أمراض القلب و السكري و توقف التنفس الإنسدادي أثناء النوم؛ لذلك يلجأ المصابون بالسمنة إلى استخدام طرق عديدة تخلصهم منها.

لكن في كثير من الأحيان لا يتم النظر إلى الآثار السلبية التي تسببها الطرق المستخدمة في التخلص من السمنة، وأحد أهم هذه الآثار السلبية هو التسبب بنقص الحديد في الدم الذي يكون كنتيجة لنقص الهيموغلوبين في الدم؛ من هنا ظهرت الحاجة لوجود جهاز يقيس نسبة الدهون في الجسم وفي نفس الوقت يقوم بمراقبة نسبة الهيموغلوبين في الدم.

سيسهل هذا الجهاز على الأطباء تشخيص الأمراض التي لها علاقة بالدم والسمنة والتي في العادة تكون أعراضها متشابهة لحدٍ كبير ويصعب تمييزها إلا بوجود نسبة الهيموغلوبين في الدم و نسبة الدهون في الجسم , بالإضافة إلى ذلك سيسمح الجهاز للأفراد في الاستخدام المنزلي التأكد من مدى فاعلية طرقهم في التخلص من مرض السمنة .

يعتمد الجهاز الذي تم تصميمه في قياس نسبة الهيموغلوبين في الدم بطريقة ضوئية غير مباشرة، بعد اخذ العينات و تحليل النتائج، وكان المتوسط الحسابي للأجهزة المخبرية (CBC) و الجهاز الذي تم تصميمه 14.3297،15.4027 على التوالي، و الانحراف المعياري 1.42585 ، 1.43076 على التوالي.

من ناحية أخرى، يعتمد الجهاز الذي تم تصميمه في قياس نسبة الدهون في الجسم على قياس ممانعة الجسم لمرور التيار الكهربائي من خلاله. تم اخذ عينات و تم تحليل النتائج، و كان المتوسط الحسابي لمعيار القياس الأمريكي 33.0606، 32.9769 على التوالي, وكان الانحراف المعياري 8.4731, 8.28586 على التوالي.

اهداء

إلى......

الى الارض الطهور، أرض الرسالات ومهجع الأنبياء، منبع القادة والعظماء، ارض الاسراء والمعراج...فلسطين

الى من ضحوا بدمائهم الزكية من اجل رفعه هذا الوطن العظيم، الى نبراس الحرية ومنارة طريق العزة،

الى الاكرم منا جميعا .... الشهداء

الى أعظم الكائنات في هذا الزمان، الى ينبوع الحب والحنان، الى القلب الدافئ دائم العطاء، الى الوجه الذي نرى فيه كل صباح طريق الامل، والأغنية التي تترنم على الحانها في اوقات العمل، الى المربية الساهرة القائمة العاملة الحنونة العطوف الغالية

الى والى والى .... امي

الى من تعجز عن وصفه الكلمات، وتقف حائرة امام عظمه تضحياته الحروف، الى من يحرق سنوات عمره ليضيء لنا بها طريق النجاح، ماذا اقول فيك وانت أجمل ما قيل. لن اقول سوى اعانني الله على برك

لن اقول لك الا ...."انا ومالي لابي "

الى الجواهر الثمينة الذين بدونهم لا يكتمل معنى الحياه، الى عقد اللآلئ الثمين ..اخوتي

"ان الحوت في البحر، والطير في السماء، ليصلون على معلم الناس الخير "

الى من حملوا أقدس رسالة في الحياة، الى الذين مهدوا لنا طريق العلم والمعرفة،

الى جميع اساتذتنا الافاضل ...نخص منهم المهندسة فداء الجعافرة ,الدكتور علي عمرو و الدكتور رمزي القواسمي على الكم الهائل من الجهد والدعم الذي قدموه لنا

الى كل من ساهم في انجاح هذا العمل ودعمنا به ماديا او معنويا او فكريا، الى كل الأحبة والاصدقاء

الى كل من دعا لنا من قلبه وتمنى لنا الدعم والتوفيق

نهدي هذا العمل لمن نحمل لهم من تقدير وامتنان. املين المولى عز وجل ان نفيد به الوطن الام

الشكر

نشكر الله العلي القدير الذي أنعم عليَّ بنعمة العقل والدين. القائل في محكم التنزيل

"وَفَوْقَ كُلِّ ذِي عِلْمٍ عَلِيمٌ".... صدق الله العظيم.

وقال رسول الله (صلي الله عليه وسلم):

"من صنع إليكم معروفاً فكافئوه، فإن لم تجدوا ما تكافئونه به فادعوا له حتى تروا أنكم كافأتموه"

وأيضا وفاءً وتقديراً واعترافاً منا بالجميل نتقدم بجزيل الشكر لأولئك المخلصين الذين لم يأنوا جهداً في مساعدتنا في مجال البحث العلمي، ونخص بالذكر

المهندسة: **فداء الجعافرة**

صاحبة الفضل في توجيهنا ومساعدتنا في تجميع المادة البحثية فجزاها الله كل خير

ولا ننسى أن نتقدم بجزيل الشكر

للدكتور: **رمزي القواسمي**

والمهندس: **علي عمرو**

اللذان قاما بتوجيهنا طيلة هذه الدراسة

وأخيراً، أتقدم بجزيل شكري إلي كل من مدوا لي يد العون والمساعدة في إخراج هذه الدراسة على أكمل وجه، ونخص بالذكر:

أ.هلال ربايعه

عبد الرحمن درامنة

فريق العمل

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List of Abbreviation

RBC: RED BLOOD CELLS

WBC: White Blood Cell

Hb: Hemoglobin

HbO2: Oxygenated Hemoglobin

BMI: Body Mass Index

BIA: BIOELECTRICAL IMPEDANCE ANALYSIS

BFP: Body Fat Percentage

LPF: Low Pass Filter

HbO_2: Oxyhemoglobin

μa^{Hb}: Absorption Coefficient

CBC: Count Blood Cell

Chapter One Introduction

1.1 Overview

This project discusses the measure of hemoglobin concentration by non-invasive method, and calculate the fat percentage.
The CBC measure the hemoglobin concentration by add diluent to blood sample and translate to WBC chamber and add lysis to damage the RBC membrane and measure the hemoglobin concentration. The disadvantage of this method that the measure not real time and required to take a blood sample.

The body fat percentage (BFP) of a human or other living being is the total mass of fat divided by total body mass; body fat includes essential body fat and storage body fat. Essential body fat is necessary to maintain life and reproductive functions. However, increase of body fat percentage may causes some dangerous illnesses, especially hart faller.

1.2 Motivation

The hemoglobin concentration and fat percentage are the most common analysis, but there is no device contain this tow analysis, so we designed portable device can be used in home, work, hospital and laboratorys to measure the hemoglobin concentration and body fat percentage .

1.3 Objectives

- Measure the hemoglobin concentration by non-invasive method.
- Monitoring the hemoglobin concentration on real time
- Calculate the body fat percentage

1.4 Importance

- The portable device that we built are low cost
- The device can be use easily.
- The device give result within two minutes
- Safety device
- No sample taken

1.5 Time schedule

Table 1.1: Time schedule

Data / Task	1st Month	2nd Month	3rd Month	4th Month	5th Month	6th Month	7th Month	8th Month
Task1								
Task2								
Task 3								
Task 4								
Task 5								
Task 6								
Task 7								
Task 8								
Task 9								

- **Task 1**:Dentification of Project Idea
- **Task 2:** Literature Review
- **Task 3:** Data collection
- **Task 4:** Multisim Design
- **Task 5:** Documentation
- **Task 6:** Prepare the documentation
- **Task 7:** Bought The Item Required
- **Task 8:** Implement The IC'S and Programming

- **Task 9:** Sample Taken and Analysis

1.6 Literature Review:

1.6.1 Measure of Hemoglobin Concentration

Hemoglobin concentration can measured by several method:

1- CBC:

The common method that uses in laboratories and hospitals, this method require to take blood sample, and put the sample into device and give the result after several minutes. The advantage of this method is best accuracy, measure several parameter at the same time.

Disadvantage of CBC method is take a blood sample and measure not on real time.

2- Spectrophotometry:

This method of measure need a blood sample that put of cuvette, the cuvette containing a blood sample, when the wavelength that has been selected passes through the cuvette the hemoglobin absorbed some of this light. While the other light transmitted and detected by the decorator (photo-diode or phototransistor). After that, the hemoglobin concentration calculated by using Beers law. This method not widely used.

3- Optical Methods:

A method that we need to use in our project. The oxyhemoglobin and deoxygenated hemoglobin absorption are the same at 810nm and the water absorption of wavelength greater than 1200nm is greater than oxyhemoglobin and deoxygenated hemoglobin absorption. So using wavelength of 1300 nm to make greater different of absorption to fine the hemoglobin concentration by beer lambert low as describe in chapter 3. The advantage of this method no need to take blood sample and real time measure. Disadvantage the accuracy no the same of CBC.

1.6.2 Body Fat Measurement:

Body fat percentage can measured by:

1- Body Mass Index (BMI):

The BMI is a parameter widely used for indicating the degree of obesity (or slimness) of a patient. Advantage of BMI is simplicity of this parameter, BMI calculated by dividing the weight of a person in kilogram on the square of his height in meters.

2- Bioelectrical Impedance Analysis (BIA):

A method that we used in our project. By passing constant current source modulated with 50kH in the body and measure the voltage, simply by amperes law, we can calculate the impedance of the body and measure the fat percentage as described in chapter 3.

Chapter Two Anatomy and Physiology

2.1 Blood

2.1.1 Introduction

The human body contains eleven-organ system. The Integumentary System, The Skeletal System , Muscular System , Nervous System, Endocrine System, Cardiovascular System, Lymphatic & Immune System , Respiratory System, Digestive System, Urinary System and Reproductive System. Each of them need foodstuffs, such as Nourishment, Electrolytes, Hormones, Vitamins, Antibodies, Heat and Oxygen to operate metabolic process. Moreover, they produce the nourishment and metabolic waste product. Therefore, they need transport for these products to its target. The blood has this function and other.

2.1.2 Blood

Is a connective tissue in fluid form. It is considered as the 'fluid of life' because it carries oxygen from lungs to all parts of the body, and carbon dioxide from all parts of the body to the lungs.

It is known as 'fluid of growth' because it carries nutritive substances from the digestive system and hormones from endocrine gland to all the tissues. The blood also called the 'fluid of health'**;** because it protects the body against the diseases and gets rid of the waste products and unwanted substances by transporting them to the excretory organs like kidneys [1].

2.1.3 PROPERTIES OF BLOOD

1- Color :

Blood is red in color. Arterial blood is scarlet red because it contains more oxygen and venous blood is purple red because of more carbon dioxide.

2- Volume:

The average volume of blood in a normal adult is about 5L. In newborn baby, the volume is 450 ml. It about 8% of the body weight in normal young healthy adult, weight about 70 kg.

3- Reaction and PH:

Blood is slightly alkaline and its pH in normal conditions is 7.4.

4- Viscosity:

Blood is five time more viscous than water [1].

2.1.4 COMPOSITION OF BLOOD

Blood contain cells called formed element, and liquid protein know as plasma.

The formed element formed 45% and plasma formed 55% of total blood as shown in figure (2.1) [1].

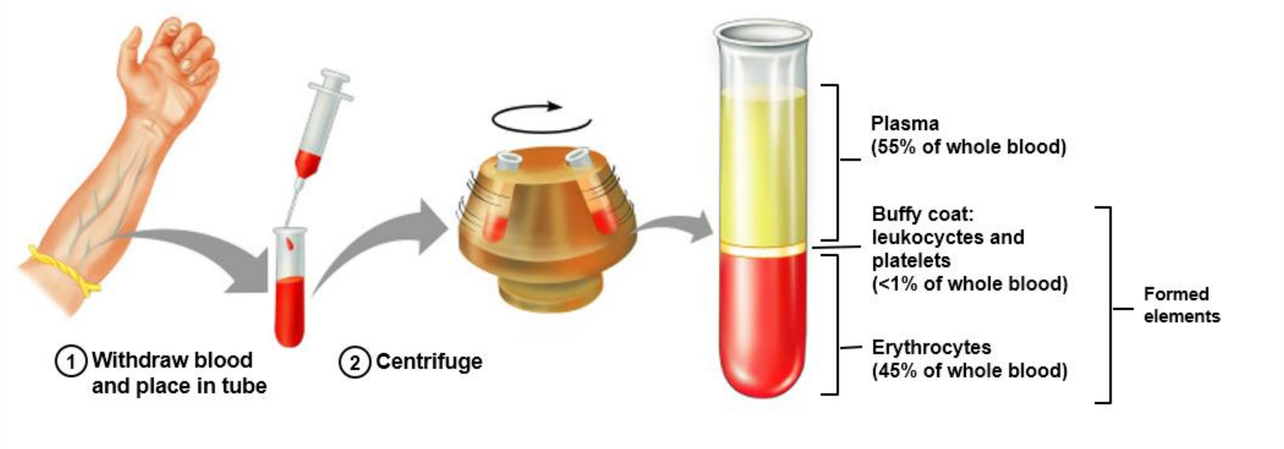


Figure 2.1: Composition of Blood[1].

2.1.5 Blood Cells

Three types of cells are present in the blood:

1. Red blood cells (RBC) or erythrocytes.
2. White blood cells (WBC) or leukocytes.
3. Platelets or thrombocytes.

2.1.6 Red Blood Cells

Red blood cells are the non-nucleated formed elements in the blood. Red color of the red blood cell is due to the presence of the coloring pigment called hemoglobin. RBC's play vital role of transport of respiratory gas. RBC's are large in number compared to the WBC and platelets [1].

2.1.6.1 Normally Value of Red Blood Cells

RBC count about 4.5-5milion/cu.mm, for adult mails it about 5milion/cu.mm. For females it about 4.5milion/cu.mm [1].

2.1.6.2 Morphology of Red Blood Cells

1- Normal Shape

Normal RBC's are disk shaped and biconcave, this shape help in equal and rapid diffusion of oxygen and squeeze through the capillaries very easily without getting damage as shown in figure (2.2) [1].

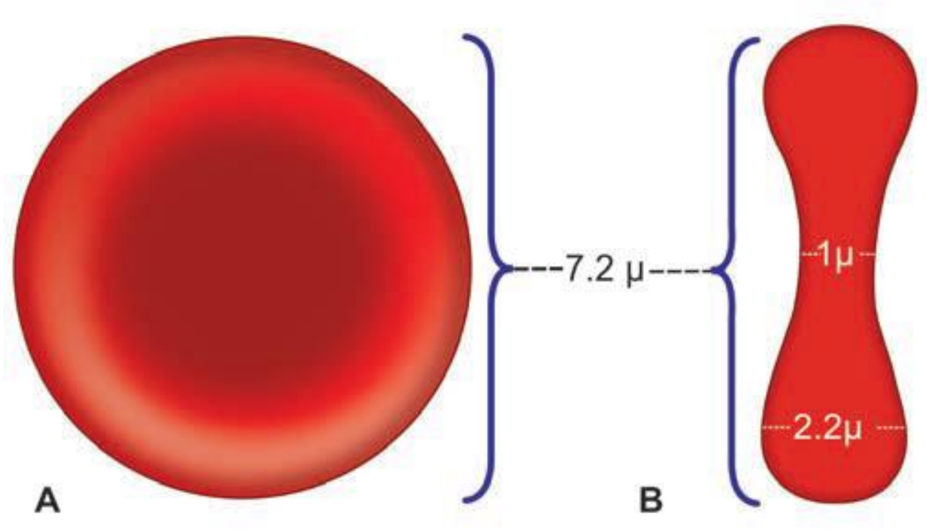


Fig 2.2: Dimensions of RBC.A. Surface view, B. Sectioned view[1].

2. Normal Size:

1- Diameter: 7.2 μ (6.9 to 7.4 μ).

2- Thickness: At the periphery, it is thicker with 2.2 μm, and at the center, it is thinner with1 μm. This difference in thickness is because of the biconcave shape.

3- Surface area: 120 sq. μ.

4- Volume: 85 to 90 cu μ [1].

2.1.6.3 Functions of Red Blood Cells

1- Transport of oxygen from lung to tissue.

Oxygen is very important of metabolic proses. Hemoglobin of RBC is combine with oxygen to form oxyhemoglobin, which transport 98% of oxygen.

2- Transport of carbon dioxide from tissue to lung.

Hemoglobin of RBC is combine with carbon dioxide to form car hemoglobin, which transport 30% of carbon dioxide.

3- Buffering Action in Blood.

Hemoglobin of RBC are regulate hydrogen ion concentration, since hemoglobin is good buffer.

4-Excretory Function

Waste product of metabolic activities removed by blood and carry to excretory organs like kidney, skin, liver, etc., for excretion.

5-Transport of Hormones and Enzymes

Blood transport hormones from endocrine to its target organ or tissue and like so translate enzymes.

6- Regulate of Water Balance

Water content of the blood is freely interchangeable with interstitial fluid. This helps in the regulation of water content of the body.

7-Regulation of Acid-Base Balance

Plasma protein and hemoglobin work, which blood contain, help in the regulation of acid-base balance [1].

2.1.7 Hemoglobin

It is a chromo protein, it forming 95% of dry weight of RBC and 30 to 34% of wet weight,

Hemoglobin contain Iron, which containing coloring matter of red RBC [1].

2.1.7.1 Normal Hemoglobin concentration

Average hemoglobin content in blood is 14 to 16 g/dL. However, the value varies depending upon the age and sex of the individual.as show in table (2.1).

Table 2.1: Reference ranges of Hb [1].

Age	**Hb**
At birth	25gl/dl
After 3rd month	20g/dl
After 1st year	17g/dl
From puberty onwards	14 to 16 g/dl

At birth, the RBC count is 8 to 10 million/cu mm of blood. The count decreases within 10 days after birth due to destruction of RBCs causing physiological jaundice in some newborn babies. However, in infants and growing children, the cell count is more than the value in adults [1].

There are different in Hb concentration between adult male and female as show in table (2.2).

Table 2.2: difference in Hg between male and female[1].

male	female
15 g/dL	14.5 g/dL

During reproductive period of females, the count is less than that of males [1].

2.1.7.2 Hemoglobin Structure

Hb is roughly spherical and comprises four-polypeptide chain, two alpha and two beta with heme group as shown in figure (2.3). The single atom of iron in the ferrous (Fe^{+2}) located at center of heme group.

Fe^{+2} form is in unstable or loose form. In some abnormal conditions, the iron is converted into ferric (Fe^{+3}) state, which is a stable form.The heme is metallo-porphyrin incidentally responsible for red color of blood [1].

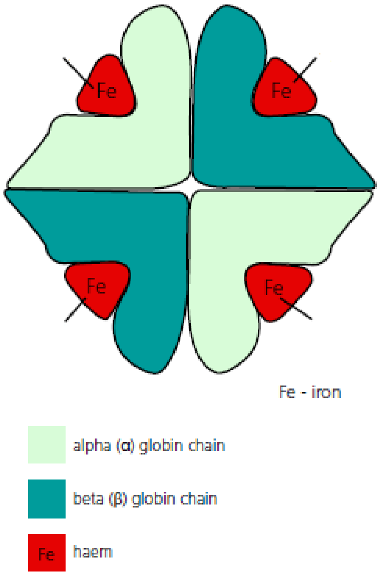


Fig 2.3: hemoglobin structure [1].

2.1.7.3 Hemoglobin Functions

1. Transport of Respiration Gases

This is the main function of hemoglobin. The hemoglobin translate:

1-Oxygen from lung to tissue:

The oxygen is binds with hemoglobin, this physiology process called oxygenation.

The iron stile as ferrous (Fe^{+2}) forming oxyhemoglobin. The oxygen is very important to metabolism process

2-carbon dioxide from tissue to lung:

The carbon dioxide is binds with hemoglobin formatting carboxyhemoglobin. The CO_2 is metabolism main waste product.

2. Buffer action:

Hemoglobin of RBC are regulate hydrogen ion concentration, since hemoglobin is good buffer [1].

Lipids and Their Structures

2.2.1 Introduction

Lipids: Organic molecule of biological origin that is insoluble in water (hydrophobic) and soluble in nonpolar solvents.

Lipids do have both nonpolar and polar regions; however, the majority of the molecule is nonpolar (due to large nonpolar tails). Since "like dissolves like", lipids are soluble in nonpolar solvents [2].

Lipids are stored in an adipose tissue and liver. They are mostly consumed in the form of neutral fats, which are also known as triglycerides.

Triglycerides are made up of glycerol nucleus and free fatty acids. They form the major constituent in foods of animal origin and much less in foods of plant origin [1].

2.2.2 Types of lipids and their structure:

There are eight types of lipids, fatty acids, waxes, Triglycerides, phospholipids, prostaglandins, steroid, lipophilic vitamins and cholesterol [2].

However, I will only go into two, fatty acids and Triglycerides.

1-fatty acids:

Structure: Carboxylic acid and long, unbranched hydrocarbon chain, unbranched hydrocarbon chain. Most have an even number of carbon, most common: 12-20 carbon.

Function: Precursor to other lipids.
Fat stored in adipose tissue called neutral fat or tissue fat [2].

2- Triglycerides:

Structure: Fatty acid and glycerol.

Functions: Energy Storage [2].

2.2.3 Body Fat Percentage:

Is the relation of fat mas to the all body mass ,equation (2) show the formula of BFP. The body is made of various amount of organ, tissue and water. That why the different in body fat percentage. Fig (2.4) show example of two body.

$$BFP = \frac{Fat\ Mas}{Body\ Mas} \qquad 2.1$$

Fig 2.4: different body fat percent of two patient [2].

There are different in body fat percent between female and male as show in table (2.3) [2].

Table 2.3: the different between female and male [2].

Comparator	**Female**	**mail**
Body building competition /high level anorexic	8-12%	3-4%
Figure competitor /extremely thin model	13-15%	6-9%
Athletic/model	16-19%	10-15%
Athletic/average	20-25%	15-20%
Average/overweight	25-35%	20-30%
Overweight/obese	35%+	30%+

Chapter **Three** **Theoretical Background**

3.1 Measurements of Hemoglobin Concentration

3.1.1. Introduction

As explained previously in Ch2, the hemoglobin has very important functions in a human body so need arises to measure hemoglobin concentration in the blood. Several methods are used for determining total hemoglobin, the most common methods used now in laboratories classified as invasive methods, such as Spectrophotometry and Hemiglobincyanide. Spectrophotometry method used spectrophotometric analysis of light absorbencies based on the Beer-Lambert law, but Hemiglobincyanide method depends on varying in conductivities of blood at different concentrations of hemoglobin.

The invasive methods laboratory require taking a blood sample. Then it is sent to a laboratory for analysis, and results reported back later; that mean having a delay between the blood collection and its analysis. So taking of blood sample cannot be performed continuously in real time for extended intervals. All these things supports need to find a new type of methods that determine the hemoglobin concentration non-invasively.

Many of techniques that can be used for determining the hemoglobin concentration non-invasively, one of this techniques that used in pulse oximetry, it based on the difference in absorption of light at two different wavelengths by various hemoglobin concentrations. Other techniques depend on a change in electrical admittance (conductivity) as a result of a change in blood volume and its concentration.

3.1.2 Methods of Determine Hemoglobin Concentration Invasively

3.1.2.1 Spectrophotometry

This technique used in many clinical laboratory instruments that including the measurement of hemoglobin concentration. As shown in Figure (3.1) the spectrophotometer consists of light source, wavelength selector, cuvette, and detector.

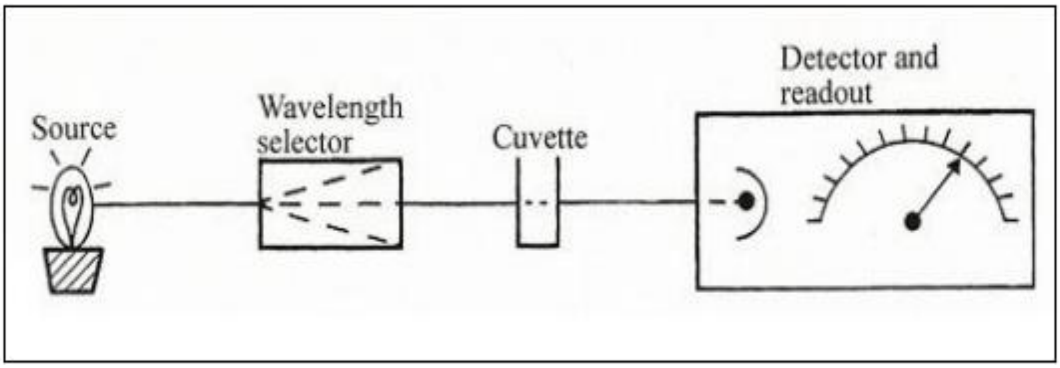


Fig 3.1**:** Block diagram of a spectrophotometer [3]

The light source must give a wide range of wavelengths, so tungsten or xenon lamp has been used. After the light be emitted from light source, it enters to wavelength selector to select the appropriate wavelength for measure hemoglobin concentration.

The cuvette containing a blood sample, when the wavelength that has been selected passes through the cuvette the hemoglobin absorbed some of this light . while the other light transmitted and detected by the decorator(photo-diode or photo-transistor). After that, the hemoglobin concentration calculated by using Beers law [3].

3.1.2.2 Hemiglobincyanide Method

This technique commonly used in many devices including Hematology Analyzer (CBC) and Blood Gas Analyzer. In this method The chemical composition of hemoglobin is changed, where the hemoglobin convert to be cyanmethemoglobin. The cyanmethemoglobin has a relatively broad absorption maximum at a wavelength of 540 nm, at this wavelength the hemoglobin concentration can be measured by using a spectrophotometrically method.

A blood sample sent to lysing chamber. in this chamber, the sample is diluted by a lysing agent which causes rupture the red blood cell membranes to release the hemoglobin. Then converts the hemoglobin to cyanmethemoglobin by adding a Drabik's reagent, the Drabik's reagent consist of iron, potassium, cyanide, and sodium bicarbonate.

By using a spectrophotometrically method the absorbance at a particular wavelength is measured and related to the hemoglobin concentration. The hemoglobin concentration is determined from the absorbance.

Sometimes used a method that converts the hemoglobin to azidemethemoglobin for quantifying the hemoglobin content of the blood. In this method, an azidemethemoglobin reagent contains a lyzing chemical, an oxidizing chemical, and an azide, used to formed the azidemethemoglobin. The methemoglobin formed by oxidize the ferrous iron in oxyhemoglobin to be ferric iron. Then the combined of the methemoglobin with the azide formed the azidemethemoglobin. This stable compound absorbance, as opposed to cyanmethemoglobin absorbance. And the azidemethemoglobin absorbance can also be measured spectrophotometrically for determining the hemoglobin concentration [4].

3.1.3 Methods of Determine Hemoglobin Concentration Non-Invasively

3.1.3.1 Optical Methods

Hemoglobin has different forms in the blood. such as oxyhemoglobin, reduced hemoglobin, carboxyhemoglobin, and methemoglobin. Oxyhemoglobin (HbO_2) and reduced hemoglobin (Hb) are main forms that are available in the blood. The other forms are available only in traces.Oxyhemoglobin is mainly available in arteries and the reduced hemoglobin is available in veins, but in capillaries, both the forms are available [3].

The oxyhemoglobin and reduced hemoglobin have a different absorption of light at different wavelengths. Figure (3.2) it shows the variation in molar extinction coefficient of light (μ_a) of the two hemoglobin forms with wavelength variation. The pulse oximetry method based on this Property for finding the oxygenation of hemoglobin percentage (SaO2). However, in our project we want to use the point, which the most hemoglobin forms, has same absorption to find determine hemoglobin concentration.

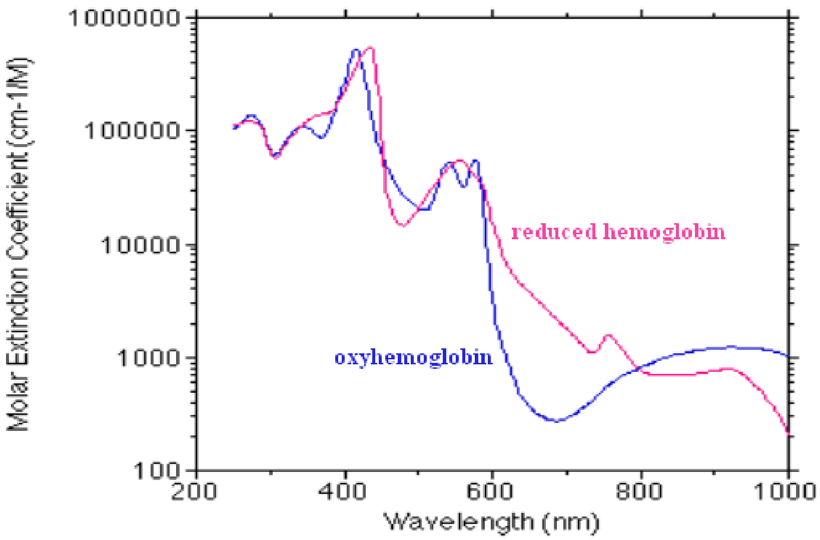


Fig 3.2: Molar extinction coefficient of light of oxyhemoglobin and reduced hemoglobin [5].

Beer-Lambert law:

The Beer-Lambert law describes the reduction of light, which is travelling through a homogeneous medium; contain an absorbing substance as shown in equation (3.1). Also this law allow to find the concentration of a single substance or more than one absorbing substance.

$$I = I_0 e^{-\mu_a d} \quad (3.1)$$

Where:

I: the transmitted light.

I_0: the incident light.

μ_a: the absorption coefficient.

d: the optical path length along the medium.

The concentration of a single substance is determined if the absorbance of light is measured at different wavelengths (μa) and the extinction coefficient (ε) of the substances are known as shown in equation (3.2). in case that more than one absorbing substance is present rthe total absorbance (At) of a medium with n absorbing substances is given as equation (3.3).

$$\mu_a = \varepsilon * C \quad (3.2)$$

$$At = \sum_{i=1}^{n} \varepsilon_i(\lambda) c_i d_i \quad (3.3)$$

The unscattered absorbance A is defined as the negative natural logarithm of the transmittance ratio (I to I_0):

$$At = -\log\frac{I}{I_0} \quad (3.4)$$

From figure (3.3) at wavelength of 810nm absorption spectra of HbO2 and Hb is identical, and it noted the water has insignificantly small absorption coefficient. Thus can be considered the absorption at these wavelengths is the absorption spectra of total hemoglobin. However, at wavelength above 1200nm the water absorption closely matching the oxygenated and non-oxygenated hemoglobin.

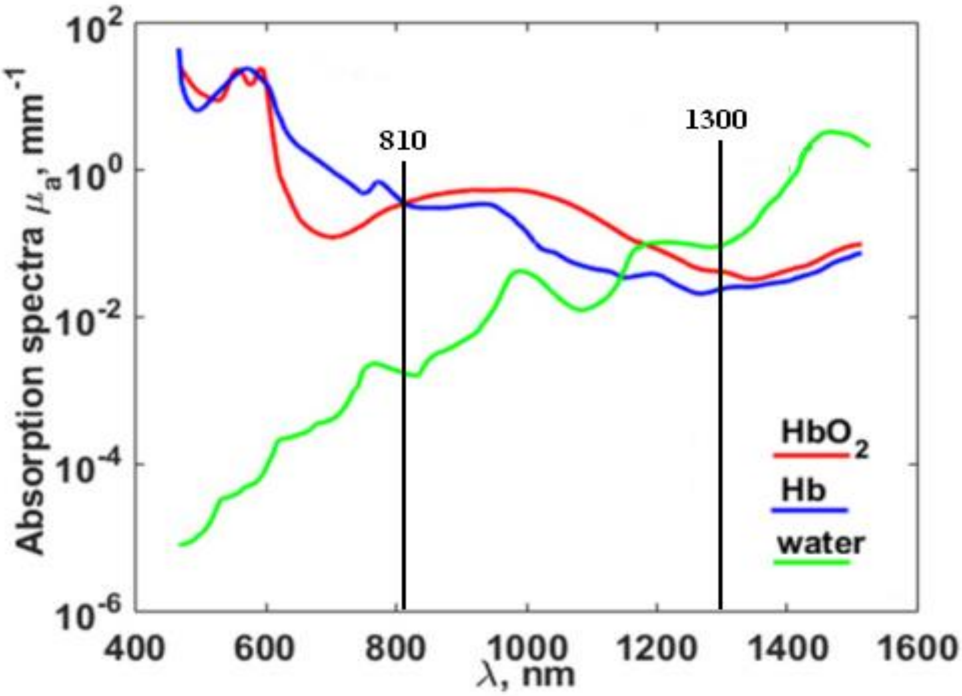


Fig 3.3: Optical absorption coefficients of oxyhemoglobin and reduced hemoglobin and water [6].

To isolate the presence of water in the blood it is necessary to select a second wavelength in this region, which the absorption coefficient of hemoglobin (HbO2 and Hb) is closely to the water, the selected wavelength to isolate the presence of water is (1300nm).

The determination of hemoglobin concentration measurement is performed using the ratio between total absorbance at wavelength 810nm (λ_1) to total absorbance at wavelength 1300nm (λ_2), this ratio is referred to as H as shown in equation (3.5).

$$H = \frac{A(t), \lambda 1}{A(t), \lambda 2} = \frac{\mu_a^{HbO}, (\lambda 1)}{\mu_a^{H2O}, (\lambda 2)} \quad (3.5)$$

The absorption coefficient (μ_a) that calculated by equation (3.2) it's the absorption coefficient per unit of concentration in Molar, thus The absorption coefficient of hemoglobin (μ_a^{Hb}) is inversely related with molar mass of hemoglobin (M_{Hb}). And it calculated as:

$$\mu_a^{Hb} = \ln(10) \frac{\varepsilon^{Hb}(\lambda) C_{Hb}}{M_{Hb}} \quad (3.6)$$

Using the equation (3.5) and equation (3.6) the hemoglobin concentration (C_{Hb}) calculated as:

$$C_{Hb} = \ln(10) \frac{H . \mu_a^{H2O}(\lambda_2) M_{Hb}}{\varepsilon_{Hb}(\lambda_1)} \quad (3.7)$$

The absorption of light by hemoglobin and water varies with the pulsatile flow of blood into the tissues, so the absorption varies with the same frequency as the heartbeat. With each heartbeat, the volume of blood vessels increases the vessels tissues, while the remaining tissue volume remains constant that makes the output signal has two component, DC and AC component. Thus the incident light (I_0) that enter to vessels it be DC and the transmitted light(I) be AC and DC, by applying this on equation (3.4) it became as:

$$At = -\log \frac{I_{AC+DC}}{I_{DC}} \quad (3.8)$$

By using the second form of the total absorbance in equation (3.4), the ratio between total absorbance at wavelength 810nm (λ_1) to total absorbance at wavelength 1300nm (λ_2) be as:

$$H = \frac{A(t), \lambda 1}{A(t), \lambda 2} = \frac{\ln(\frac{I(Ac + Dc), \lambda 1}{I(Dc), \lambda 1})}{\ln(\frac{I(Ac + Dc), \lambda 2}{I(Dc), \lambda 2})} \quad (3.9)$$

3.1.3.2 Conductance Methods:

This technique using an electrical admittance finger cuff. Electrodes are placed in the interior of an annular cuff, which is then filled with an electrolyte solution. With the finger inserted through the cuff, the change in blood volume in the finger translates to a change in electrical admittance (conductivity) of the finger. Submerging the finger in an electrolyte solution whose admittance is equal to that of the finger compensates for pulsatile variation in conductivity, after which the conductivity of the electrolyte solution can be related to the conductivity of arterial vessels and then correlated to the hemoglobin concentration [7].

Disadvantage:

Although the accuracy reported for the conductance, method is promising, albeit in a limited patient population, little recent work has been disclosed on this technique. Difficulties associated with probing conductivity include variations with temperature, intra-and extracellular water/ion content, and other blood constituents. Because conductance monitors only a single value, rejection sodium ion concentration variation becomes a limiting factor, particularly in a noninvasive setting where varying whole blood ion content cannot be measured and thus cannot be normalized, hindering the potential overall efficacy of this technique [7].

3.1.3.3 Optoacoustic Method

The optoacoustic technique is based on the generation of ultrasound waves by short laser pulses. The rapid thermal expansion of the tissue through laser absorption creates an optoacoustic wave; hemoglobin has a higher absorption coefficient than surrounding tissue, enhancing optically induced thermal modulation.

The superficial radial artery is an effective location for optoacoustic stimulation in the NIR because it located close to the skin surface; this accessibility facilitates irradiation and optoacoustic wave detection. The absorption coefficient of blood depends on the hemoglobin concentration, oxyhemoglobin saturation, and laser pulse wavelength. In arteries, oxyhemoglobin saturation approaches 100%. Registration and analysis the optoacoustic signal generated from blood vessels yield information about the total hemoglobin concentration. Fig 2 shows the variation in optoacoustic signal with hemoglobin concentration in a tissue phantom [8].

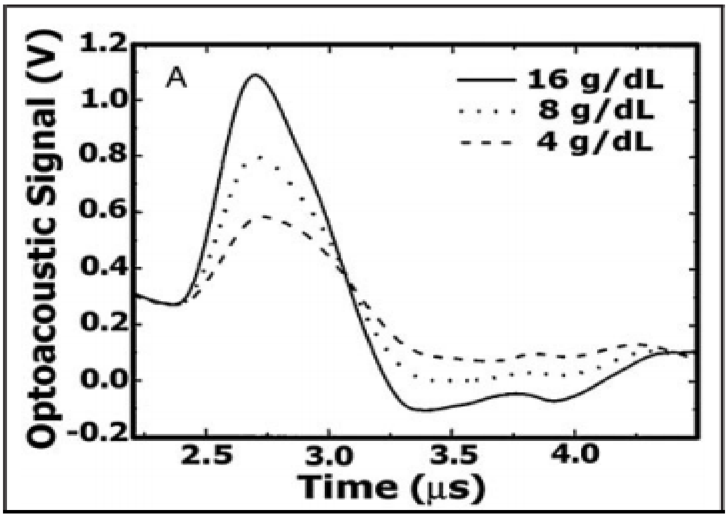


Fig 3.4: Typical optoacoustic signals measured from the

Radial artery phantom with varied hemoglobin concentration [8].

3.1.3.4 Other Methods

There are many other methods for hemoglobin Measurement that haven't been mentioned that including:

1- Diffuse reflectance spectroscopy.
2- Photoplethysmography.
3- Imaging Based Technique.

3.2 Body Fat Measurement

3.2.1 Introduction

The obesity causes many of diseases; these diseases are more dangerous for a patient than obesity itself. For example, the obesity is one of the main causes of high blood pressure, diabetes, renal problems, and psychological problems.

To know whether that the cause of these diseases is obesity, it must know the determine the Body Fat Percentage (BFP) for the patient. Several methods are used for determining the BFP, such as Bioelectric Impedance Analysis, Hydrostatic Weighing Ultrasound Assessment of Fat and Skinfold methods.

After the BFP be determined it compared with standard ranges marked in special tables provided by WHO (World Health Organization).by using the Body fat ranges are shown in Figure(3.5), it can be decided about the patient health state[9].

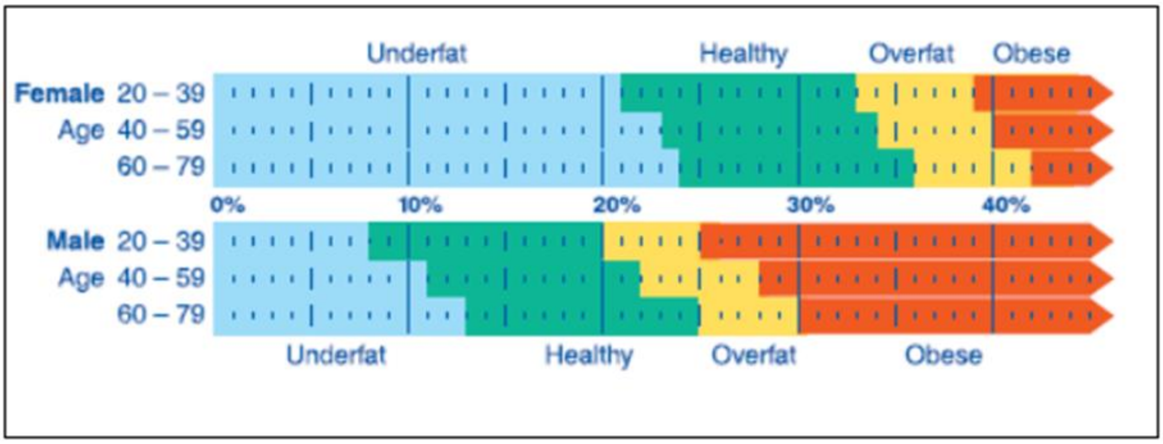


Figure (3.5): Ranges of fat mass (FM) from the WHO guidelines.

3.2.2 Methods of Body Fat Measurement

3.2.2.1 Body Mass Index (BMI)

The BMI is a parameter widely used for indicating the degree of obesity (or slimness) of a patient. Advantage of BMI is simplicity of this parameter as shown in equation (3.10), BMI calculated by dividing the weight of a person in kilogram on the square of his height in meters [10].

$$BMI = \frac{Weight(kg)}{(Height(M))^2} \qquad (3.10)$$

BMI ranging from less than 18.5 to more than 30. The table (3.1) below categorizes the level of BMI for each status of person weight.

Table 3.1: BMI and Weight Status [10]

BMI (kg/m2)	Weight Status
Below 18.5	Underweight
18.5 to 24.9	Healthy weight
25.0 to 29.9	Overweight
30.0 and above	Obese

- Problem With BMI :

BMI gives an indicator of obesity level of an examined person but it cannot tell anything about the body composition and body fat percentage for this patient. Muscle is heavier than fat so the muscle mass contributes to BMI more than fat. Muscular athlete and obese patient have the same weight and height, this means they have the same BMI, but in fact, the obese patient has a fat percentage more than the muscular patient. Thus the use only BMI can cause misinterpretation of the patient`s health state.

3.2.2.2 Bioelectrical Impedance Analysis (BIA)

BIA is used for body fat estimation by measure the direct impedance of patient then obtained the value of body fat. The impedance measured by passing an alternating current through the body tissues, then by measuring the voltage drop that is caused as a result of impedance of the body tissue for current passing, the impedance can be calculated.

In the body tissues, conductivity is caused as a result of the change in concentration of the ions between the Intra- and Extracellular liquid, the tissue consists of cells that have a membrane consists of two layers of fosfolipid which make the membrane a bad conductor for ions, this property gives the cells a capacitive property. However, the water across the body can be seen as a conductor, thus when an electrical current pass through the human body tissues caused resistance (caused by muscles) and reactance (caused by fat across the body), as shown in equation (3.11).

$$Z = \quad R + Xc \quad (3.11)$$

Where:

Z: Bioelectrical impedance.

R: Resistance.

Xc: Reactance.

The bioelectrical impedance is complex quantity, so it has a phase angle that depending on the tissue properties. In addition, the bioelectrical impedance can be calculated by the ratio between the output voltage electrodes and input current signal, as shown in equation (3.12).

$$Z\angle\theta = \frac{V\angle\theta1}{I\angle\theta2} \qquad 3.12$$

The relationship between resistance, reactance, and total impedance can be graphically represented with a phasor diagram, as shown in figure (3.6).

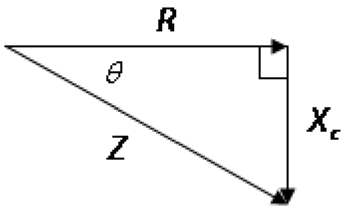


Figure 3.6: Graphical representation o impedance, resistance and reactance.

By using this phasor diagram, the Resistance(R) and Reactance (Xc) can be calculated through equations (3.13) and (3.14) respectively.

$$R = \sqrt{\frac{Z^2}{1+\tan^2\theta}} \quad (3.13)$$

$$X_C = R\tan\theta \quad (3.14)$$

The resistance (R) of an object is determined by a shape that is described as length (L) and surface area (A), and material type, which is described by resistivity (ρ), as shown in equation (3.15). Reactance (Xc) of an object as shown in equation (3.16), is defined as resistance to voltage variation across the object and is inversely related with signal frequency (F) and capacitance (C). In biological systems, resistance is caused by total water across the body, and reactance occurs due to the capacitance of the cell membrane [9].

$$R = \rho\frac{L}{A} \quad (3.15)$$

$$X_c = \frac{1}{2\pi FC} \quad (3.16)$$

The equation (3.12) using to find the resistance on an area and the human body resistance is happened by a volume of body , thus the equation (3.15) can be rewritten in terms of volume V_{body} as :

$$R = \rho \frac{L^2}{V} \quad (3.17)$$

The volume (V_{body}) in equation (3.17) is the volume of body without the body fat, that because the fat is considered as a non-conductor material. The fat free mass (FFM) can be calculated using the volume of body without the body fat(V_{body}) and the average density of the fluid in the body (d_{body}) as shown in equation (3.18).

$$V_{body} = \frac{FFM}{d_{body}} \ggg FFM = d_{body} \cdot \rho_{body} \frac{L^2}{R} \quad (3.18)$$

Although this equation is a good first approximation, but it does not account the Impedance Affected with variations in gender, age, weight, and other factors. By using this terms and equation (3.18), the fat-free mass (FFM) can be calculated the as shown in equation (3.19)[11].

$$FFM = 0.34 * \frac{H^2}{R} + 0.1534 * H + 0.273 * W - 0.127 * Age - 12.44 + 4.56 * G \ (3.19)$$

Where:

FFM (kg): Fat-Free Mass.

H (cm): patient height in centimeters.

R (Ω): real part of impedance.

W (kg): patient weight in kilograms.

G: gender (0 for female, one for male).

The amount of fat tissue within a body (body fat) be calculated by the equation (3.20):

$$\text{Body Fat (kg)} = W - \quad FFM \quad (3.19)$$

Moreover, the body fat percentage is calculate as:

$$\text{Body Fat \%} = \frac{FFM}{W} \times 100\% \; (3.20)$$

As previously shown the impedance measured by passing an alternating current through the body tissues. Therefore, to inject the current signal through the body, a surface electrodes is used, these electrodes called driving electrodes. After the current signal be injected, the voltage is measured using the other electrodes that called sensing electrodes.

There is two method for electrode connection; one of this method used two electrodes while the other method used four electrodes. As show in figure 3.7, the first method (Fig 3.7a) used only two electrodes for injecting the current signal and measuring voltage signal at the same time. However, in second method (Fig 3.7b) two electrodes used for injecting the current signal and another two electrodes used for measuring voltage signal. Used the second method is better than used the first method, because the first method has a voltage drop in the measured data as a result of contact impedance.

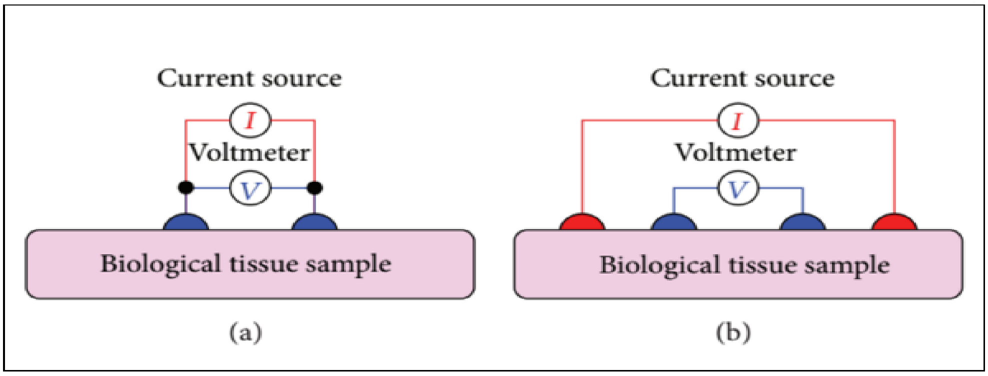


Fig 3.7: Bioelectrical impedance measurement in technique: (a) impedance measurement using two-electrode technique, (b) impedance measurement using four-electrode technique.

3.2.2.3 Other Methods

There many other different methods used in body fat measurement, these methods sorts to three types:

1- Indirect methods: such as Anthropometry.

2- Direct methods: such as Total Body Water and Total Body Counting and Neutron Activation.

3- Criterion methods: such as Body Density, Dual-Energy X-ray Absorptiometry and Computed Tomography and Magnetic Resonance Imaging.

1- Hydrostatic Weighing:

These method based on Archimedes' principle to determine body volume. It determines the volume of the body by submersion this body in water, the volume of water has been lost is equal to the body volume. By using body weight inside and outside water and the water density, the body density can be calculated. This number is then used to estimate body composition [12].

The disadvantage of this method:

1- High cost: as result of the needed to underwater scale. There is only found in a lab or a performance center.

2- Inconvenient: There is a need underwater to be the patient's lungs empty from the air as much as possible. This might be uncomfortable for some patients.

2- Ultrasound Assessment of Fat:

Ultrasound technology used for image the deeper tissues and assess the thickness of different tissues. This method used a prop that convert electrical current to ultrasound waves, this wave penetrate the skin surface to interior tissue. They then reflect from the fat and muscle to produce an echo. then used receiver within the probe to detecting the echo.

There are two types of ultrasound**:**

A-mode: this type determines the time that ultrasound waves needed to transmission through the tissues and back to the transducer. This time convert to distance indicates to the thickness of fat or muscles.

B-mode: this type provides a two-dimensional image for considerable detail and tissue differentiation.

Chapter Four System Design

4.1-Hemoglobin Concentration measurement

This chapter describes the practical elements hemoglobin sensor system developed in the investigation and the requirements to design system, as shown in figure (4.1).

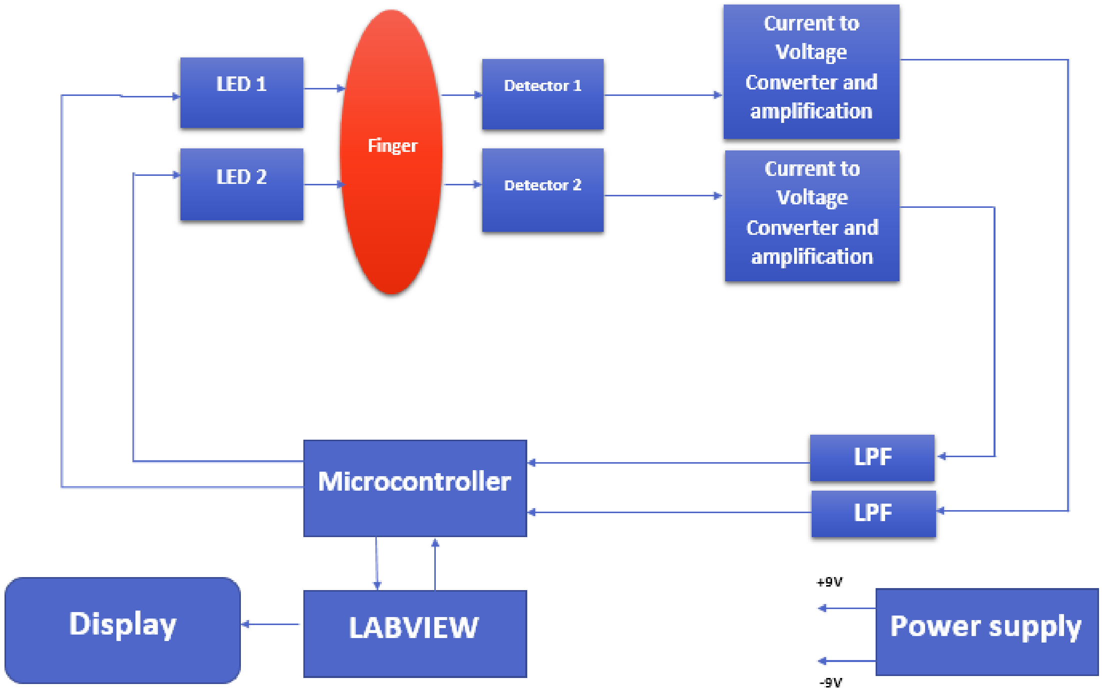


Fig4.1: block diagram of hemoglobin concentration measurement

The capture pulse wave above 1100nm, where water absorption dominates requires level of a high accuracy in the measurement system. Every module of the sensors system described in this chapter. Firstly, the light sources and the receiver unit, which are located within the sensor head, are characterized followed by description of the receiver and remaining system components, and the analysis of circuits and algorithmic [3].

The measurement should not depend on the oxygen saturation and that mean that the measurement is only practicable at the isosbetic point where the extinction coefficient of both hemoglobin derivate is identical as shown in figure (4.2). For the purpose of this investigation the wavelength was selected as 810nm, according to assumption water, the absorption coefficient of blood is similar to solution consisting HHb, HbO2, and plasma and the absorption of HHb and HbO_2 indistinguishable to the absorption of water above 1200nm, if the system is able to isolate the percentage of water in the blood it is therefore necessary to select second wavelength in this region which is outside the traditional optical diagnostic window. Finally, the determination of hemoglobin concentration measurement is performed at wavelength λ_1 =810nm and λ_2 =1300nm [3].

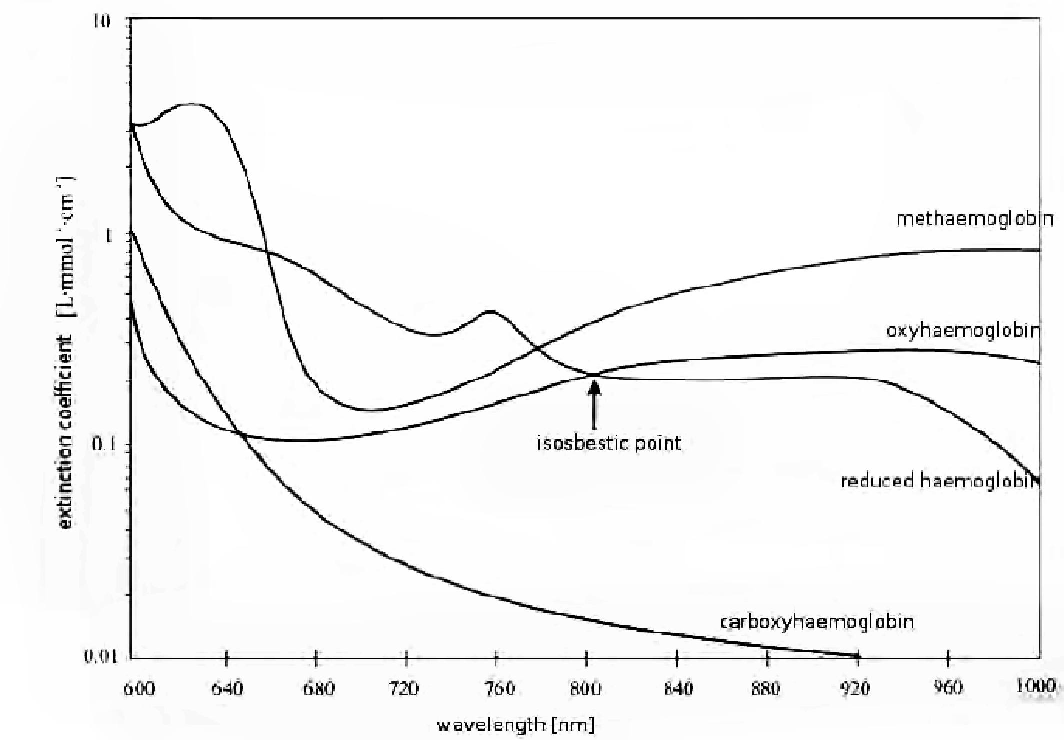


Fig 4.2: Absorptivity's (extinction coefficients) in L/(mmol·cm) of the four most common hemoglobin species at the wavelengths of interest in pulse oximetry[1].

4.1.1 LED1 Driving Circuit

In general, LED are much cheaper, robust, smaller and easy to use.so we use the diode ELD-810-250 to emit 810nm wavelength. To maintain diode emit (800-820) nm and specific value 810nm,with viewing angle 20° ,the current is 20mA (appendix1).The LED1 driving circuit shown in figure [4.3].

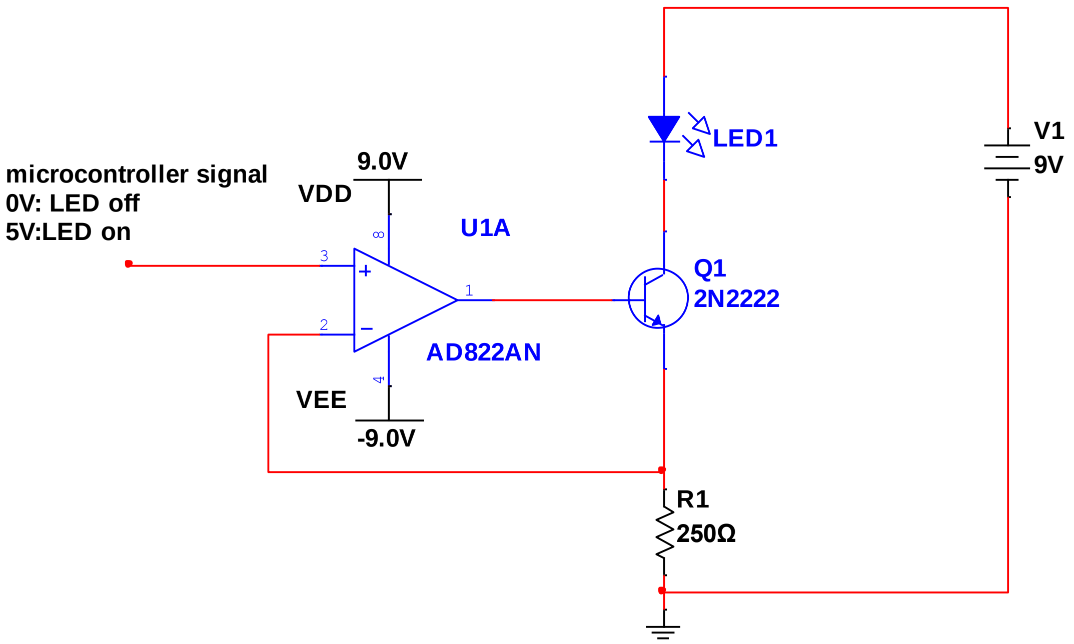


Fig4.3:LED1 driving circuit

To maintain the current 20mA, the resistor R1 calculate by equation (4.1).

$$R = \frac{Vc}{I} \quad (4.1)$$

$$R1 = \frac{5}{20mA} = 250\Omega$$

By stander resistance value, the standard resistance is 250Ω.

The microcontroller generate driving signal for LED1 as shown in figure (4.4).

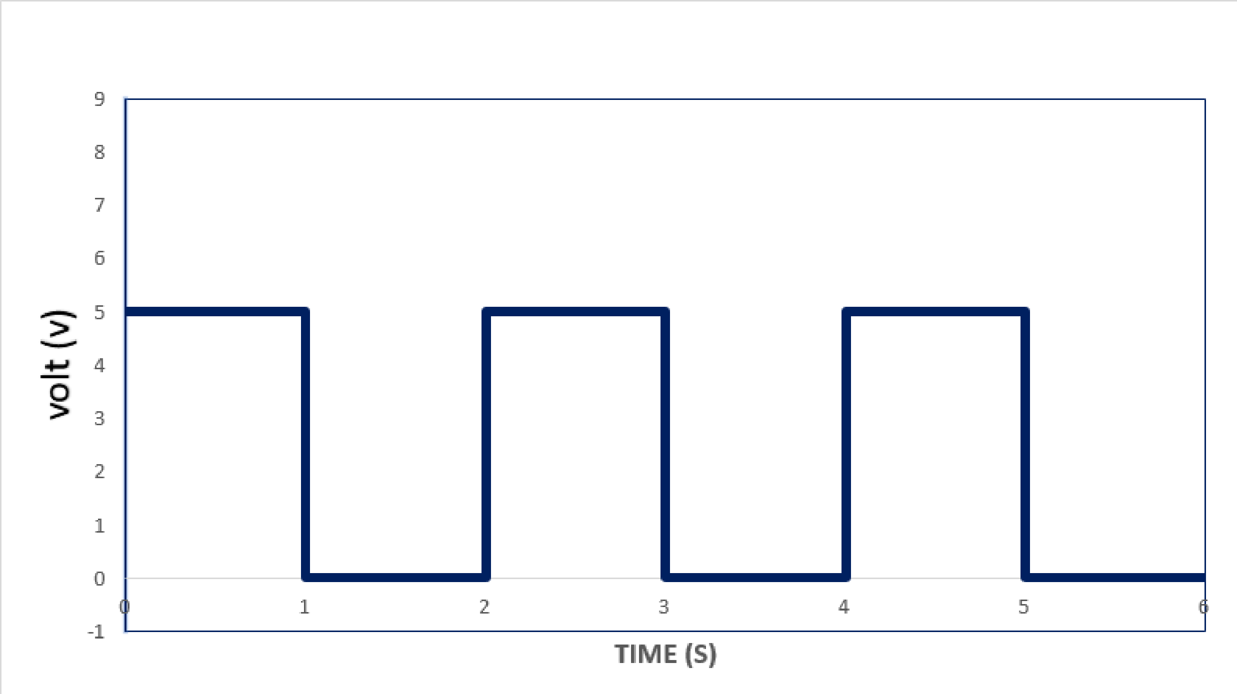


Fig 4.4: LED1 Period Time

The AD822 is a dual precision, low power FET input op amp that can operate from a single supply of 5 V to 30 V, or from dual supplies of ±2.5 V to ± 15 V. The op-amp AD822 is rail-to-rail op-amp, with CMRR=80dB, and its input impedance $=10^{13}$ Ω, with Offset voltage of 800 µV maximum. The input bias currents below 25 pA , 1.8 MHz unity-gain bandwidth and 3 V/µs slew rate. This op-amp used in this project (appendix2).

4.1.2 LED2 Driving Circuit

The diode ELD-1300-525 LED, to maintain the diode emit (1250-1350) nm and specific value 1300nm, with viewing angle 25° , the current is 20mA(apendix3). , by equation (4.1),

$$R2 = \frac{5}{20\text{mA}} = 250\ \Omega$$

By resistance standard value, the standard value is 240 Ω , with the same type of op-amp and transistor are used in driving LED2 circuit .as show in figure (4.5)

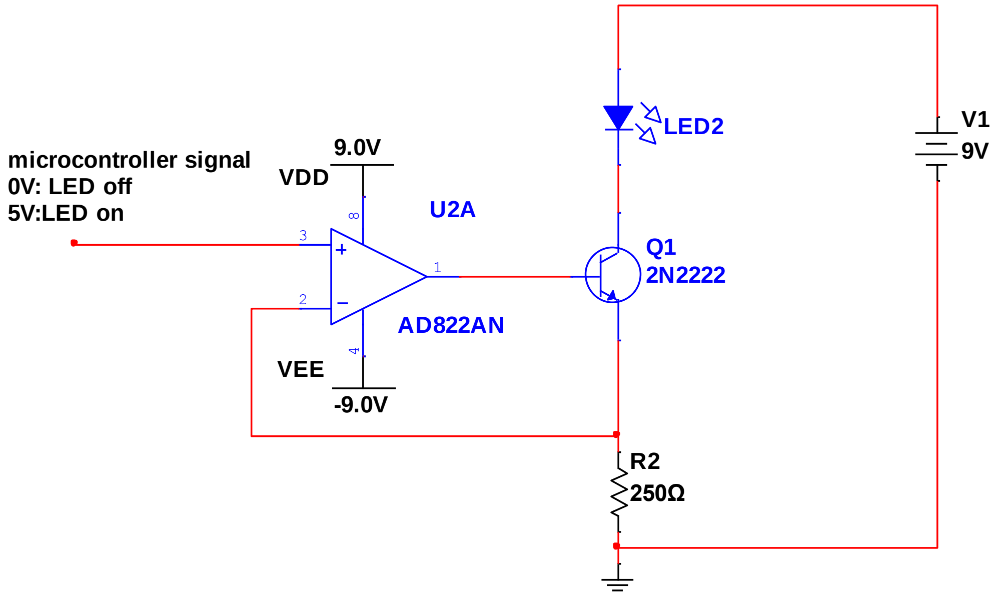


Fig4.5:LED2 driving circuit

The microcontroller generate driving signal for LED2 on as show in figure (4.6).

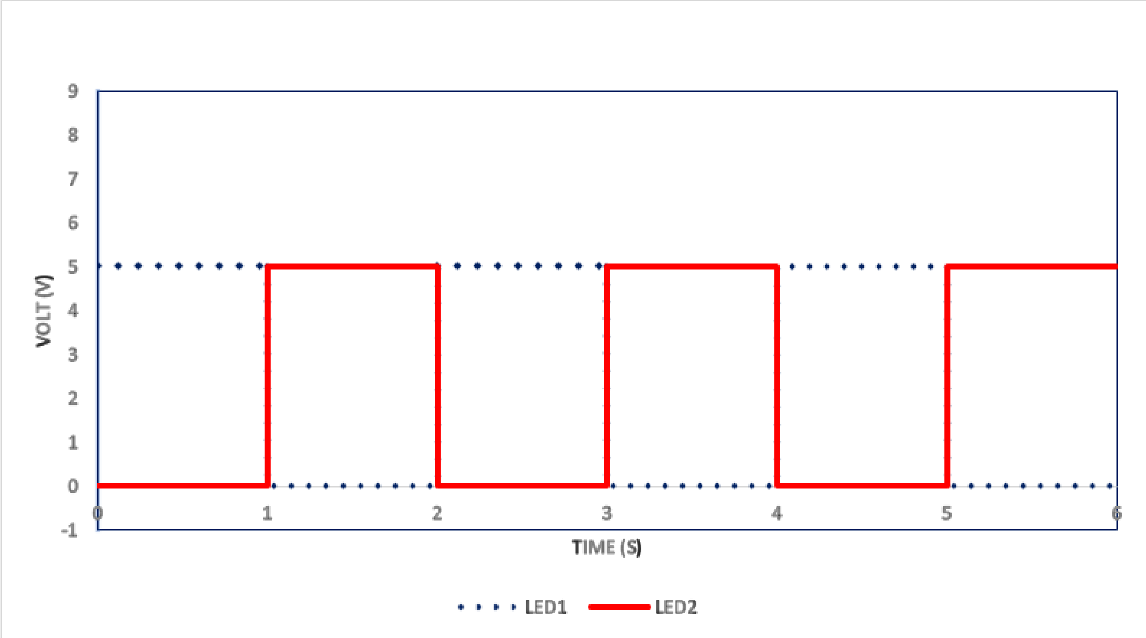


Fig 4.6:LED1 and LED2 period time

4.1.3 Current to Voltage Converter Circuit (Photodiode 1)

The photodiode S1337-33BR, with special response range (340-1100) nm and peak sensitivity 960nm, the output current at 810nm is 10µA. thus the resistance.

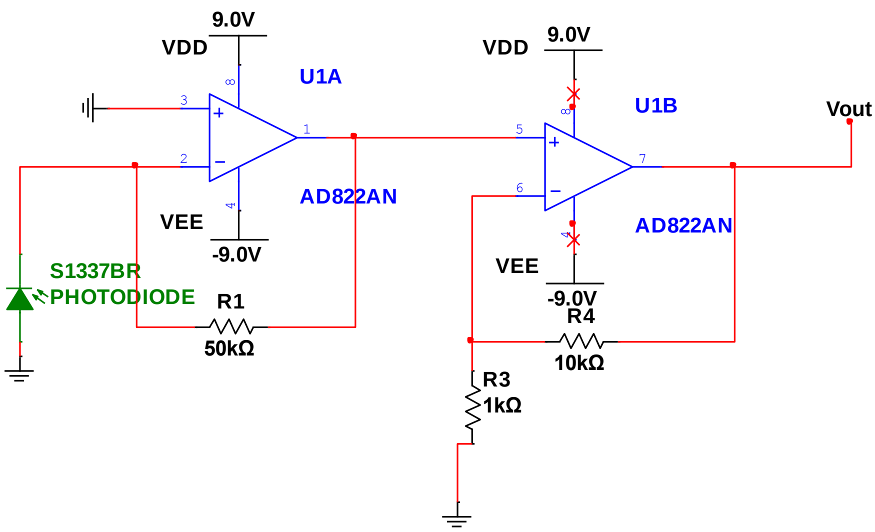


Fig 4.7: detector 1 driving circuit

The max o/p is 5V, and can be determine through equation (4.2).

$$Vout = (Ipd)(R1)\left(1 + \frac{R4}{R5}\right) \ldots\ldots\ldots\ldots..4.2$$

Let R1=50KΩ, and R3=1KΩ and R4=10KΩ

The microcontroller resolution low, and can't be process the small signal (signal with mV or small), so the amplification of transmit signal amplified another 10 times after current to voltage converter , thus the R4/R3 set to be 10, this reason will be describe well in chapter 5.

4.1.4 Current to Voltage Converter Circuit (Photodiode 2)

The photodiode InGaAs PIN photodiode G13176, with special response range (0.9-1.7) µm and peak sensitivity 1.55nm, with output 2µA at 1300nm (appendx5).

The current must convert to voltage to process by microcontroller as shown in figure (4.8).

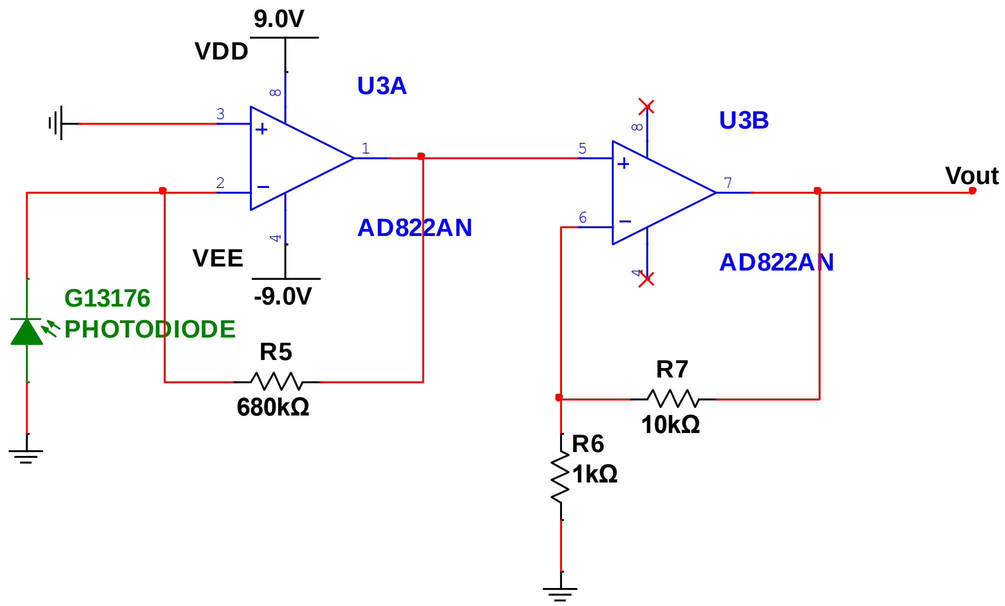


Fig 4.8: detector 2 driving circit

The max output is 5V, through equation (4.2):,

$$Vout = (Id)(R5)\left(1 + \frac{R7}{R8}\right)$$

Let R1=680kΩ, like detector 1, R6=1kΩ and R3=10kΩ,

4.1.5 Low Pass Filter

The output of the current to voltage converter circuit is than fed into a low pass filter with cutoff frequency of 40Hz. The low pass filter enable us to filter out unwanted signals. The low pass filter will essentially allow low frequency signals from 0Hz to the cut-off frequency of 40Hz, while blocking any higher frequencies. After the low pass filter, the output fed to any input port of an Arduino mega microcontroller.

A Low-pass filter that was used is Butterworth Sallen-Key a second order Low-Pass Filter. This filter is a simple active filter based on op-amps. The cutoff frequency (f_C) is set at 40Hz, the circuit shown in figure (4.9).

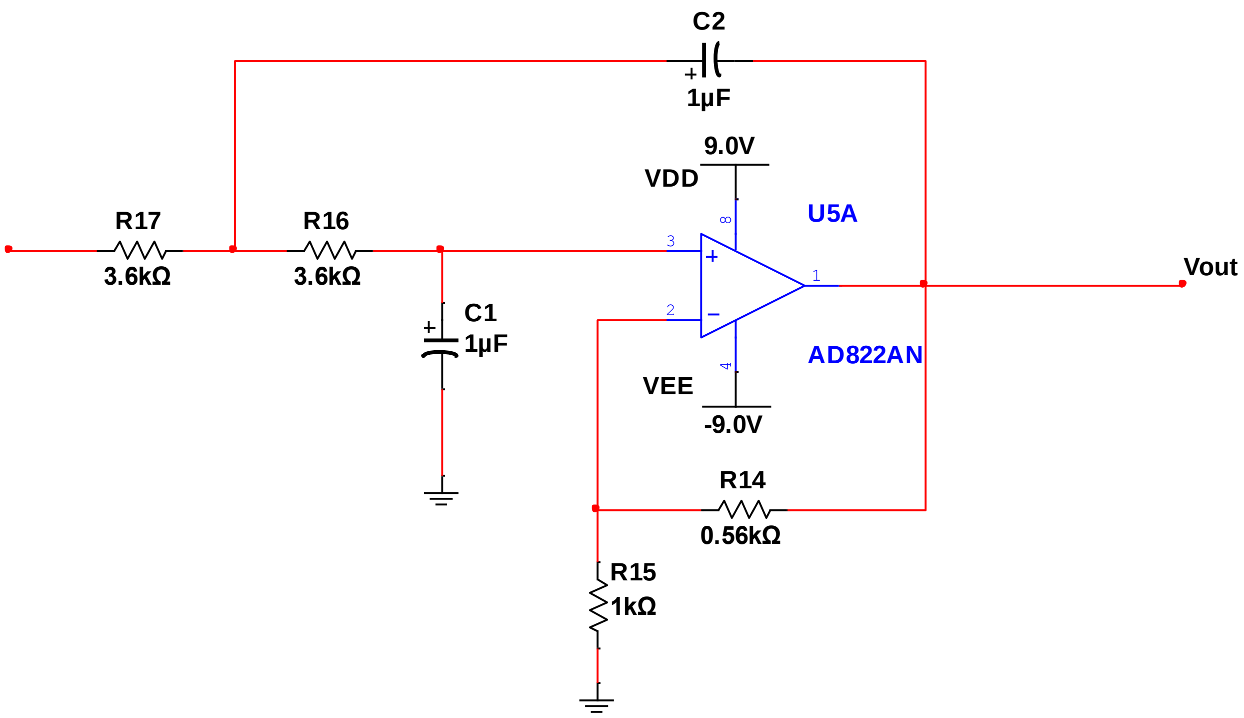


Fig 4.9: Sallen-key Second Order Low pass filter

A special case of the general Sallen-Key topology is the application of equal resistor values and equal capacitor values: R1 = R2 = R and C1 = C2 = C. The general transfer function changes to :

$$A(s) = \frac{A_0}{1+W_C R_C(3-A_0)s+(W_C R_C)^2 s^2} \qquad 4.3$$

With $$A_0 = 1 + \frac{R_{16}}{R_{13}}$$

$$a_1 = W_C R_C(3 - A_0)$$

$$b_1 = (W_C R_C)^2$$

Let C=1µF,so R1 con be calculated through equation 4.5:

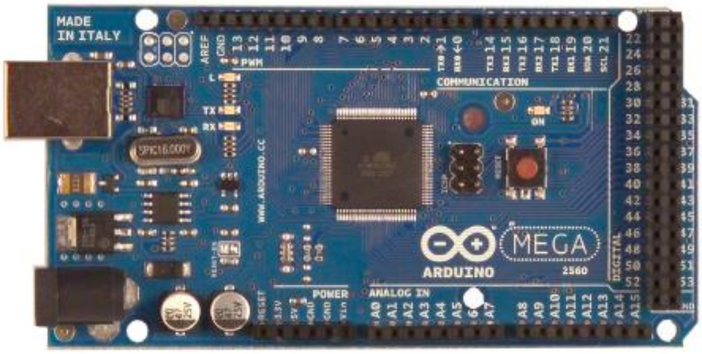
$$R = \frac{\sqrt{b_1}}{2\pi f_C C} = 3978.87\Omega \qquad 4.5$$

By standard resistance value, let R=3.6KΩ.A0 calculated through equation 4.6:

$$A_0 = 3 - \frac{a_1}{\sqrt{b_1}} = 1.58 \qquad 4.6$$

By standard resistance value, let R16=0.56K Ω, and R13=1KΩ.

4.1.6 Microcontroller



The microcontroller acquire the signal, proses signal, display result and control LED1and LED2 on off time.

The Arduino Mega 2560 has 16 I/O analog port, 54 digital I/O, and clock speed 16MHz (appendix6).

4.1.7 LABVIEW

LABVIEW (laboratory virtual instrument engineering workbench) also called virtual instrument of Vis, because their appearance and operation imitate physical instruments, such as oscilloscope and mustimeters. LABVIEW contains a comprehensive set of tools for acquiring, analyzing, displaying, and storing data, as well tools to help your troubleshoot your cade.

In this project, LABVIEW used to control LED1 and LED2 on and off time. at the same time, LABVIEW will acquire signals from two detectors, analysis signals and display result.

4.1.8 Signal Process

At isosbestic point, where the extinction of oxyhemoglobin and reduced hemoglobin are the same as shown in figure (4.2) does not depend of the oxygen saturation.

The absorption coefficient for reduced (μ_a^{HHB}) and oxyhemoglobin ($\mu_a^{HbO_2}$) can be calculate by the molar mass of hemoglobin (M_{HB}=64500g/mol), the concentration C_{Hb} and the appropriate extinction coefficient $\varepsilon^{HHb}(\lambda)$ and $\varepsilon^{HbO_2}(\lambda)$ (equation (4.6) and (4.7)).

$$\mu_a^{HbO_2}=\ln(10)\frac{\varepsilon^{HbO2}(\lambda)c_{Hb}}{M_{Hb}} = 2.303\frac{\varepsilon^{HbO2}(\lambda)c_{Hb}}{64500^{g}/_{l}} \qquad (4.6)$$

$$\mu_a^{HHb}=\ln(10)\frac{\varepsilon^{HHb}(\lambda)c_{Hb}}{M_{Hb}} = 2.303\frac{\varepsilon^{HHb}(\lambda)c_{Hb}}{64500^{g}/_{l}} \qquad (4.7)$$

The molar extinction coefficient is based on a common logarithm is considered with the coefficient ln (10), figure (4.9) shows the absorption spectra for blood (C_{Hb}=18g/l) for 400nm to 1800nm, above 1200nm the absorption coefficient of reduced and oxygenated hemoglobin is virtually indistinguishable and follows the water absorption

After the signal be acquired, the signal had Ac and Dc signal, the AC/DC ratio of both wavelength leads to equation (4.8):

$$H = \frac{A(t,810nm)}{A(t,1300nm)} = \frac{\ln(\frac{I(Ac+Dc),810nm}{I(Dc,810nm)}}{\ln(\frac{I(Ac+Dc),1300nm}{I(Dc,1300nm)}} \qquad (4.8)$$

At wavelength of 810nm, the absorption coefficient of water is insignification small in cooperation to the hemoglobin concentration. At wavelength of 1300nm, this situation is completely different, as shown in (figure 4.10); with water absorption, closely watching the oxygenated and non-oxygenated hemoglobin it can be assumed that equation (4.9) can be written as:

The absorption coefficient (μ^{Hb}) depends on the hemoglobin concentration (C_{Hb}) so equation (4.5) can be written as:

$$H = \ln(10)\frac{\varepsilon_{Hb}(\lambda_{810})C_{Hb}}{\mu_a^{H2O}(\lambda_{1300})M_{Hb}} \qquad (4.9)$$

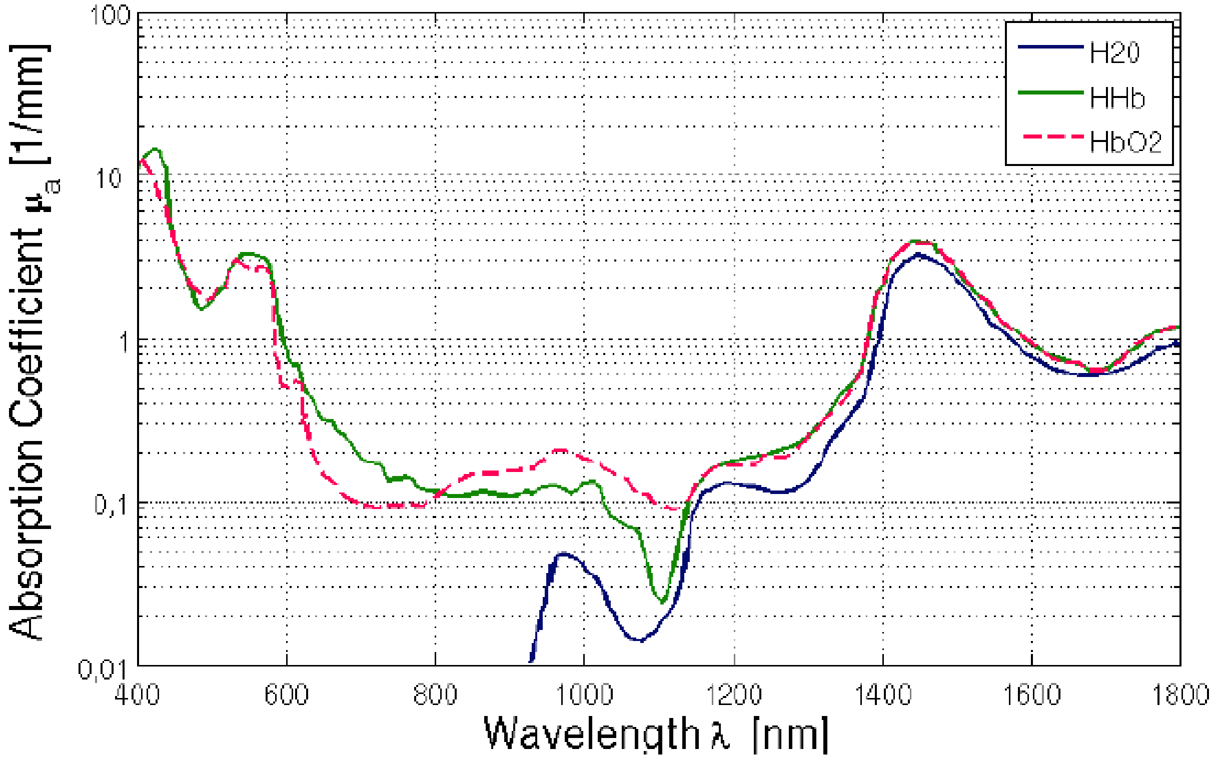


Figure 4.10: blood absorption spectra for oxyhemoglobin, reduced hemoglobin and water

Finally, the hemoglobin concentration can be determined by equation (4.10):

$$C_{Hb} = 0.434 \frac{H.\mu_a^{H2O}(\lambda_{1300})64500g/l}{\varepsilon_{Hb}(\lambda_{810})} \quad (4.10)$$

The extinction coefficient of hemoglobin is 4.23 [3], thus equation 4.10 can be write:

$$C_{Hb} = H(661.77)$$

The output signal have AC and DC component, the Ac signal generate by blood flowing, while DC component bone, tissue and vein without pulsatile of finger as shown in figure (4.11) [3]:

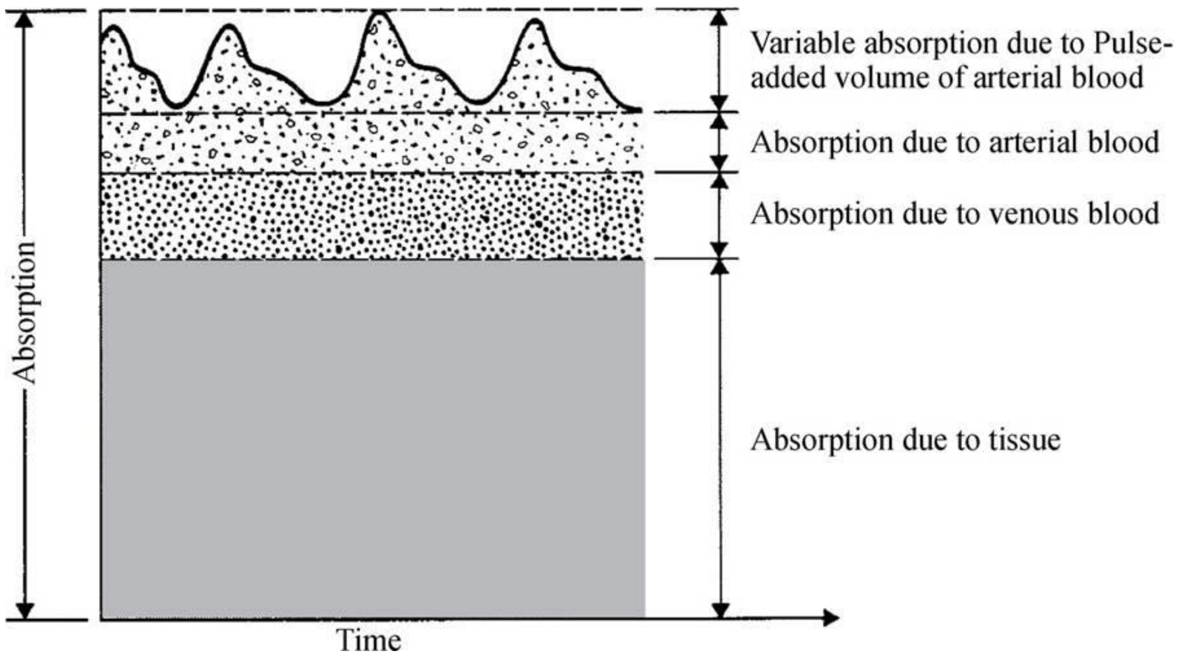


Fig 4.11: the Ac and DC component of blood flow signal

4.2 Fat monitor system design

The conceptual design of the Fat monitor system shown in Figure (4.12), it is composed two main parts; preparing part and processing part. In the Preparing part, the signal generated and prepared to be suitable for injection through the body. This part consists of oscillator, which implemented in AD5934 for generating a sinusoidal signal. The constant current source modulates a suitable constant current to the sinusoidal signal that generated from the previous stage. The stimulus electrode connect with one wrist to insert the signal through the body.

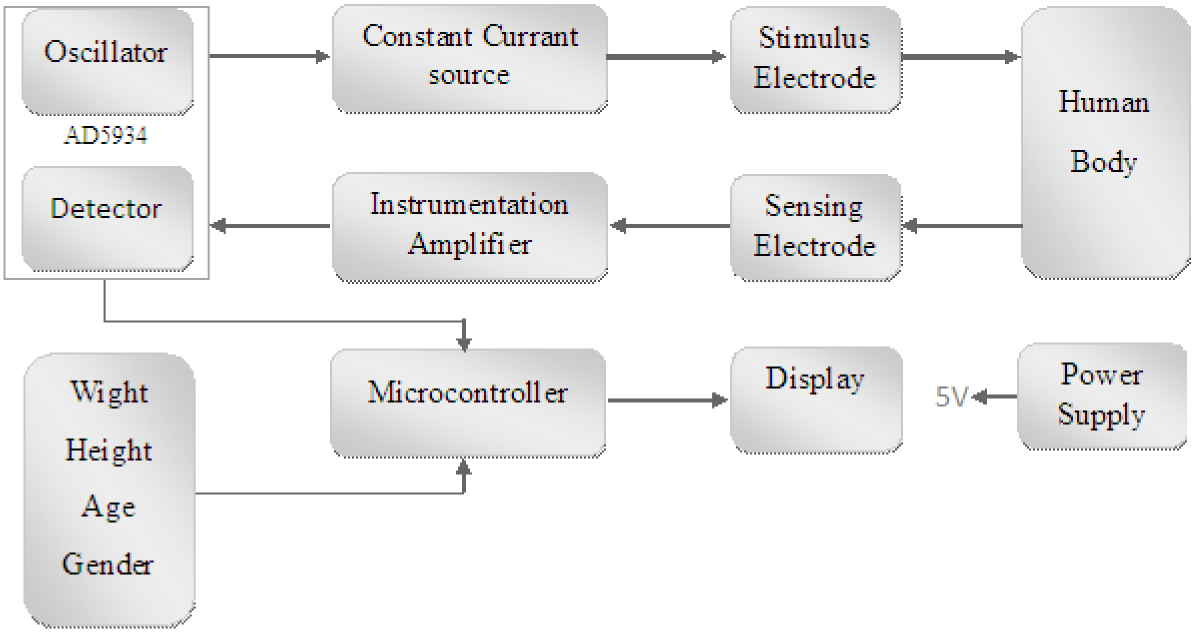


Fig4.12: Main Block Diagram for the Fat Percentage System

On the other hand, the main function of the processing parts are processing the receiving data, and display result. This part contains sensing electrodes connect with other wrist for receive the signal and transport it to Instrumentation Amplifier, the output of the Instrumentation Amplifier is a voltage drop as result of impedance. The output from the constant current source and the Instrumentation Amplifier are enter to the detector, which implemented in AD5934, this part calculate the impedance amplitude an phase. Then the signal reaches to the microcontroller, which process, analyze this signal, and finally display the result on a screen.

The following sections describe the principle of operation of each stage deeply.

4.2.1 Signal Oscillator

In this part, a sinusoidal signal generate for carrying the constant current that injects through the body. The passing of this signal through the body has different effects on the body depends on the signal amplitude, frequency and time.

The electrical energy indicates how much the effect on human body, this energy deposited as heat. As show in equation (4.11), the heating of tissues increases according to the square of the applied voltage. Therefore, we need low voltage amplitude to get less effect.

$$E = \frac{V^2 t}{R} \quad (4.11)$$

The signal frequency that applied on the body sorts to three types, low frequencies (less than 1 KHz), medium frequencies (1 KHz-100 KHz) and high frequencies (more than 100 KHz). The low frequencies have thermal effects on the tissues, and the high frequencies have stimulation effect, but the medium frequency have low thermal and stimulation effects; thus to get the conduction of a painless and imperceptible electrical current we need to use signal have a

The skin impedance being inversely proportional to the frequency of applied signal. In low frequencies range, it is more than kilo-ohm, but in medium frequencies range, it is just a few ohms.in most research the frequency that used is 50 KHz [13].

The AD5934 chip provide to oscillate a sinusoidal signal with frequency range between (1KHz-100KHz) and voltage rang between (1.98V-0.198V), therefore we can configure the AD5934 to oscillate a suitable sinusoidal signal with 50KHz frequency[appendix 9].

4.2.2 Constant Current Source:

The impedance calculated by divided the voltage on the current, as previously shown in equation (3.12) in ch3. The voltage amplitude of the signal is varies depending on tissue properties but the current amplitude must be constant. The constant current circuit using for achieving a signal has constant current amplitude.

The passing of current through the body tissue causes dangerous effects. These effects vary from little pain and thermal effects to ventricular fibrillation, burn and injury, the increasing of current amplitude increase the dangerous of this effects, thus we need a small constant amplitude of current. Most research has identified the appropriate current value at 800µA [14].

The circuit configuration on Figure 4.13 is simply an operation amplifier in an inverting configuration. The voltage to current configuration given by equation 4.14

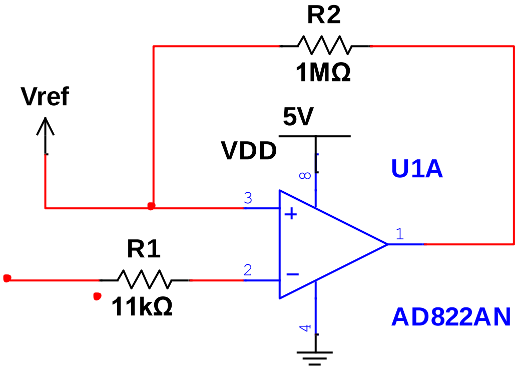


Fig (4.13): constant current source circuit.

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$$I = \frac{Vin}{ZL} \qquad (4.14)$$

This circuit chosen in our project because the simplicity of its design, the simple design means less parts, lower cost and less power consume.

The constant current source connects with the stimulation electrode and the sensing electrode as shown in figure (4.14) below.

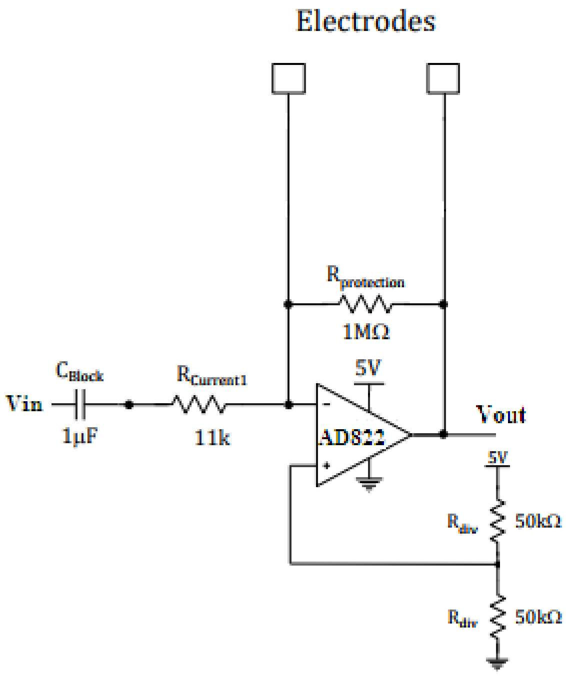

Fig (4.14): constant current source circuit2 with the electrodes.

The output voltage from this circuit given by equation (4.15) below.

$$Vout = VIn\left(\frac{\text{rbody}||\frac{1}{\text{SCbody}}||\text{Rprotect}}{\text{Rcurrent}}\right) + Vref\left(-\frac{\text{Rbody}||\frac{1}{\text{SCbody}}||\text{Rprotect}}{\text{Rcurrent}} + 1\right) \quad (4.15)$$

$$Vref = Vs * \frac{Rdiv}{Rdiv + Rdiv} \quad (4.16)$$

$$Vref = 5 * \frac{50K}{50K + 50K} = 2.5V$$

This circuit converts the output signal of the AD5934 chip (V_{AD}) to current waveform (I_{BODY}). That injected into the body. The $R_{current}$ is the voltage to current factor following Ohms Law. Equation (4.17) shows the mathematical relation between (V_{AD}) and (I_{Body}). The resistor (R_{Body}) and the capacitor (C_{Body}) are models for the typical skin impedance.

$$\text{I BODY} = \frac{\text{VAD}}{\text{Rcurrent}} \quad (4.17)$$

$$\text{I BODY} = \frac{3}{11k} = 272.72\mu A$$

V_{AD} generated with a 2.24V offset. However, for safety reasons, it is not desired to have DC voltage across the body when measuring skin impedance. To eliminate this DC bias, the circuit includes a blocking capacitor connected to the negative input terminal of the AD822 operational amplifier.

4.2.3 Stimulus and sensing electrodes

The electrodes used to inject the current into the body and measure the voltage difference. The electrode that used to inject the current called current electrode or stimulus electrode, and the electrode that used to measure the voltage called voltage electrode or sensing electrode. Figure (4.15) shows these electrodes.

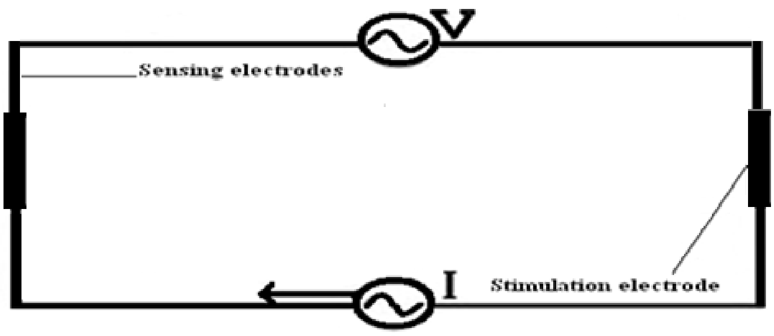

Fig 4.15: the sensing stimulation electrodes

Here we need to use two metal rods separated by an insulating material to work as stimulation and sensing electrodes. In two electrodes that will be used, It must be made from a metal has high conductivity to avoid as much as possible the voltage drop that may be happening. As shown in Table (4.1) the metals that have high conductivity are expensive, the better metal that has an appropriate price and a good conductivity is the Copper. Thus, all electrodes that used made from Copper.

Table (4.1): conductivity of some metals

Metal	Conductivity ($s/m*10^6$)
Silver	62.89
Copper	59.77
Gold	42.55
Aluminum	37.66
Nickel	14.6
Iron	10.29

The two electrodes attached to the subject's body, the electrodes can be attached either on both wrists or one wrist and an ankle on the same side of the body. Then, a current of 200µA sent through the body in order to find the impedance.

4.2.4 Instrumentation Amplifier

After the current signals passes through the body, an adequate amplification is needed to ensure the signal flowing back to AD5934. As shown in Figure (4.16), the voltage difference across both ends of electrodes fed into an AD620 instrumentation amplifier.

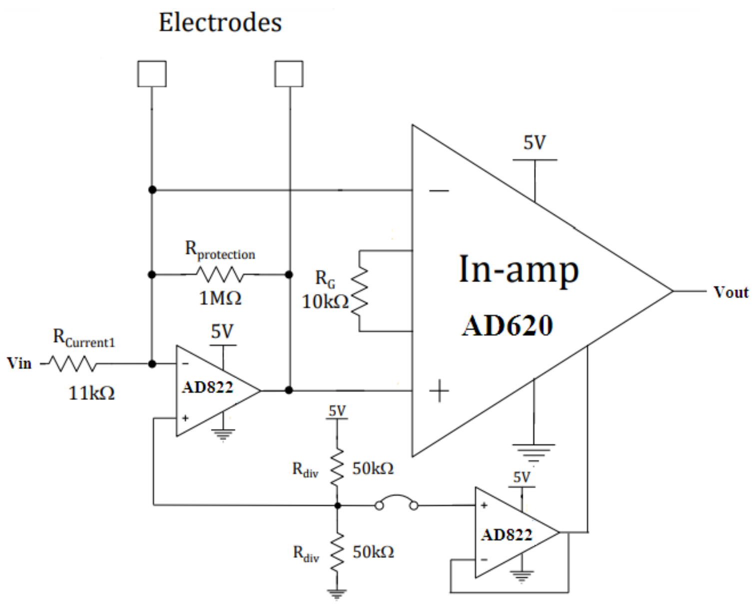

Fig 4.16**:** Instrumentation Amplifier connection.

the Instrumentation Amplifier designed to amplify two signals with a same factor without amplifying the noise in two signals, after that the two signals entered to a Difference Amplifier which get the difference between the two signals without noise. The output signal of this circuit given as equation (4.18).

$$Vout = G * (V+ - V-) \quad (4.18)$$

$$G = \frac{49.4K\Omega}{RG} + 1 \qquad (4.19)$$

$$2 = \frac{49.4K\Omega}{RG} + 1 \rightarrow RG = 49.4K\Omega$$

4.2.5 Voltage to Current Converter

The input signal of AD5934 must be a current signal so we need to convert the voltage V_{INA} (the voltage signal out from Instrumentation Amplifier) back into the current. This is achieved by the resistor $R_{Current2}$ which connected with the output of the Instrumentation Amplifier as shown in figure (4.18). The current created by this voltage to current converter (I_{VC}) is equal to:

$$Ivc = \frac{VINA}{\text{RCurrent2}} \qquad (4.20)$$

4.2.6 Transimpedance Amplifier

The transimpedance amplifier included in the AD5934 chip converts I_{VC} into V_{ADC} according to the following equation:

$$RFB = \frac{(Vpk + VDD\backslash 2 - VDCOFSET)}{IcvMax} = \frac{1.5V}{IcvMax} \qquad (4.21)$$

We set the gain of 3 for the Transimpedance Amplifier to utilize the ADC's maximum range. To achieve this gain we set the Rcurrent2 to 10K and the RFB to 30K as shown in figure (4.18). Large resistor values chosen to minimize the power consumption of the instrumentation amplifier.

4.2.7 AD5934 Chip Connection

The AD5934 chip gets the sinusoidal signal on pin 6, thus we connect pin 6 with the constant current source. The $R_{Current2}$ connect and R_{RF} connect with pins 5 and 4. In addition, as shown in figure (4.17) the pins 9, 10 and 11 connect 5V and the pins, 12, 13 and 14 connect with the ground line[appendix 8].

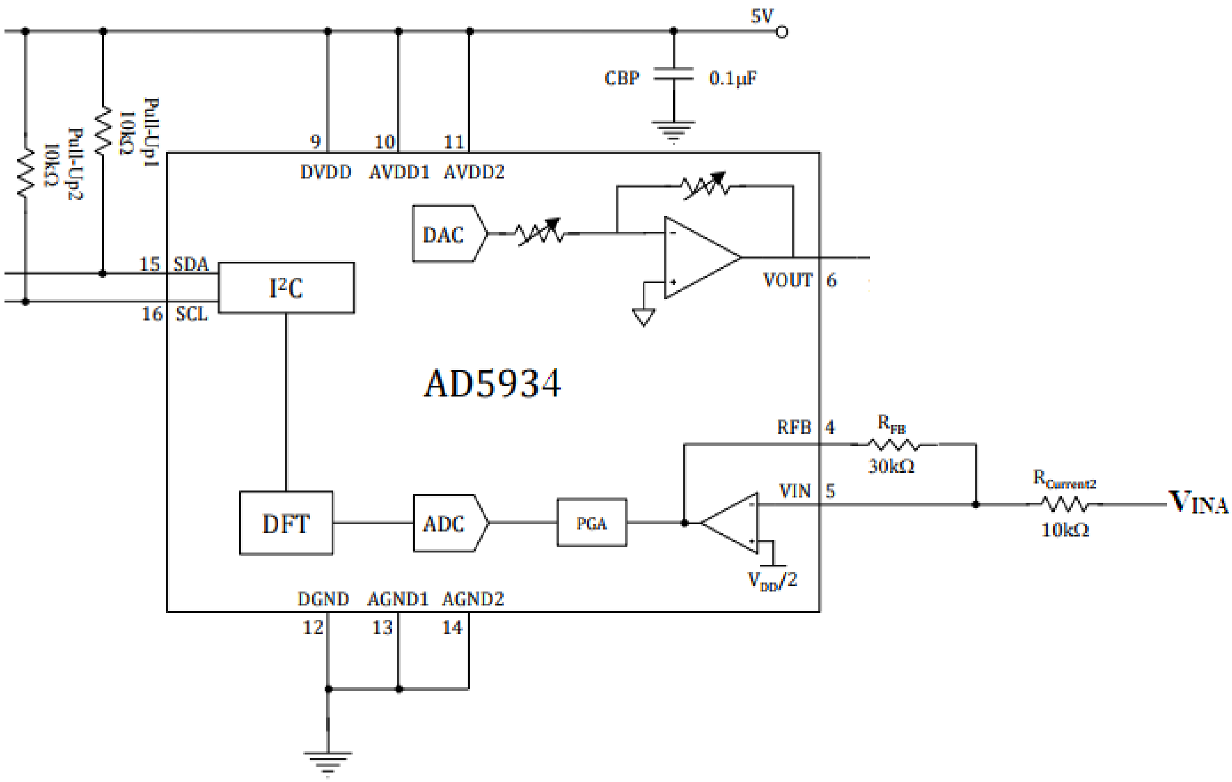

Fig 4.17: AD5934 chip connection.

The AD5934 chip works by a system called the I2C system, this system allows for the chip the operation and exchange of data with all devices that the chip consists from them through two wires only, the first wire called a serial data line (SDA) and the second wire called a serial clock line (SCL). Each element in the chip has a code or predefined number during manufacturing. The controller then communicates with each device according to its own code and operates according to the clock. Thus we connected the SDA and SCL pins with the microcontroller to control the elements in the AD5934 chip for convert the output signal from the human body to data about impedance [7].

4.2.8 Microcontroller

The Arduino mega microcontroller goes through four main steps: initialization the AD5934 chip, configuration of the AD5934 chip, running impedance sweep, and finally save the data in a file. These steps visualized in the flow diagram in Figure (4.18).

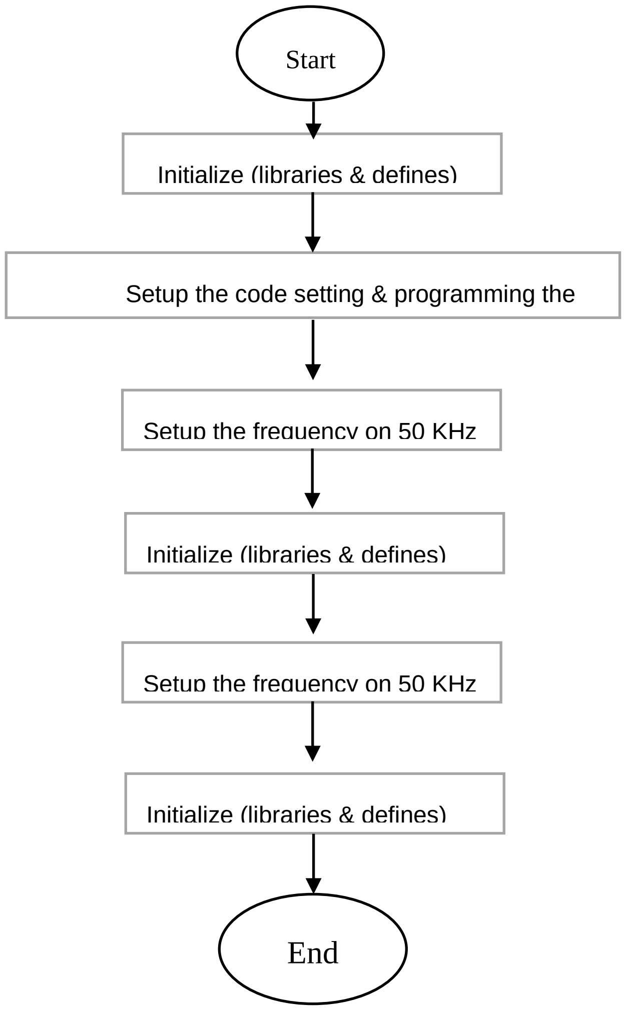

Fig 4.18: Arduino mega flow diagram.

4.3 Power Supply

Each part of system need different power, hemoglobin circuit powered with ±9V, fat circuit powered with 5v.thus the system need two different power .figure 4.19 show the power supply circuit.

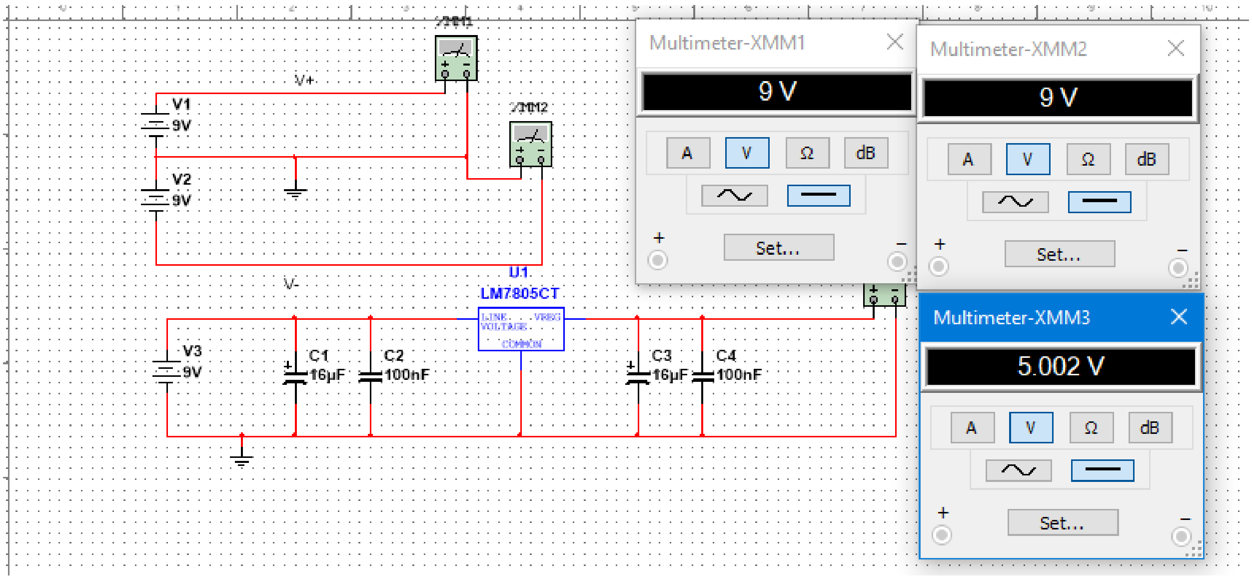

Fig 4.19: power supply circuit

The LM7805 is liner regulator, to obtain output voltage of 5V, capacitance are set as shown in figure 4.19. The approximation of a current consumption shown in table 4.1[appendix 10].

Table 4.1: total current consumption

Circuit	**approximation of a current consumption**
LED circuit	40mA
Detector 1 driving circuit	0.2mA
Detector 2 driving circuit	0.1mA
LPF	0.5mA
Regulator	4.2mA
SN74LS04N	20µA
AD822	16µA
AD620	1.3mA
AD5934	10mA
Total Current	56.336mA

Thus, we used chargeable battery 9V with 170mA

System schematic diagram shown in appendix 11.

Chapter Five Results and Analysis

5.1 Result and Analysis for Hemoglobin

Chapter four described all necessary electrical component to determine the hemoglobin concentration by non-invasive method. This chapter describe the result and analysis of system.

5.1.1 System Implementation

First stage of this system is LED's and detectors driving circuit, figure 5.1 show LED's and detectors implement in prop.

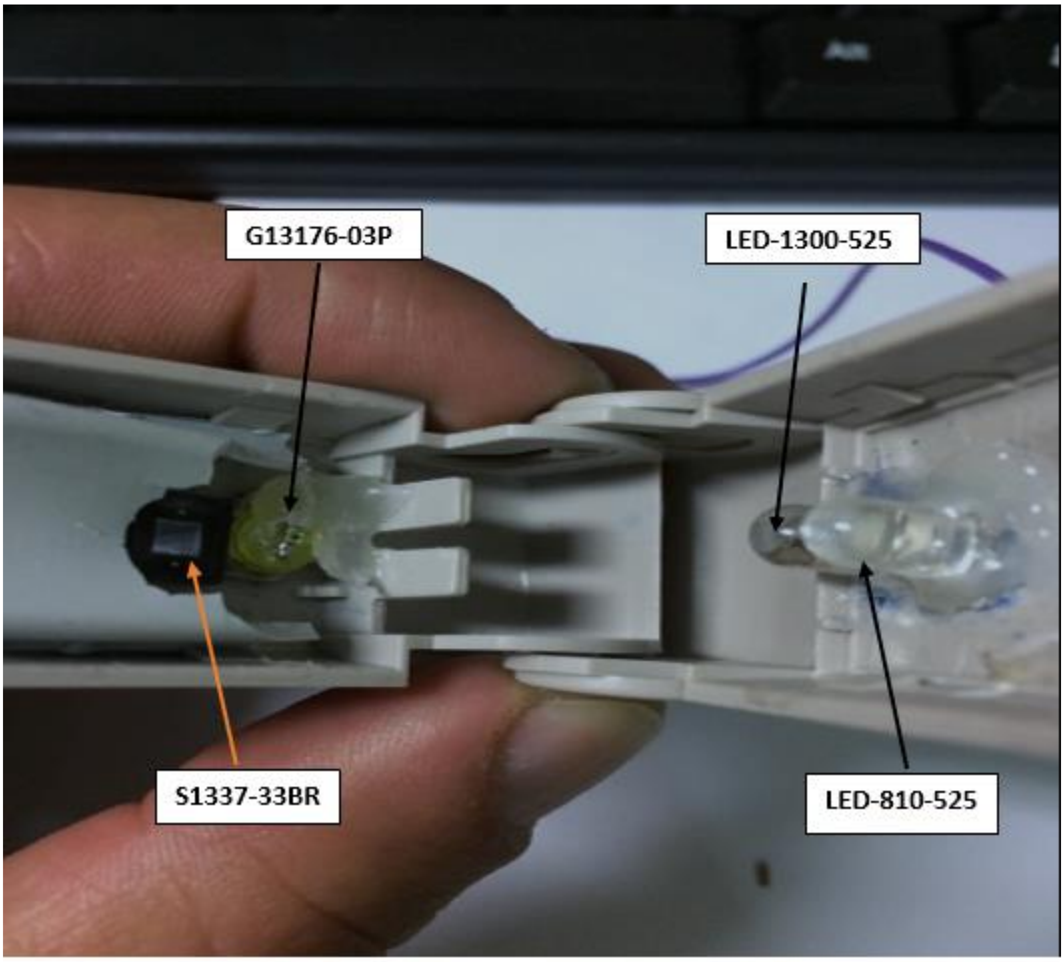

Fig5.1: LED and detector implementation

The LED 810nm in opposite side of S1337-33BR photodiode, the same as LED 1300nm and G13176 photodiode. The IC implementation shown in figure 5.2

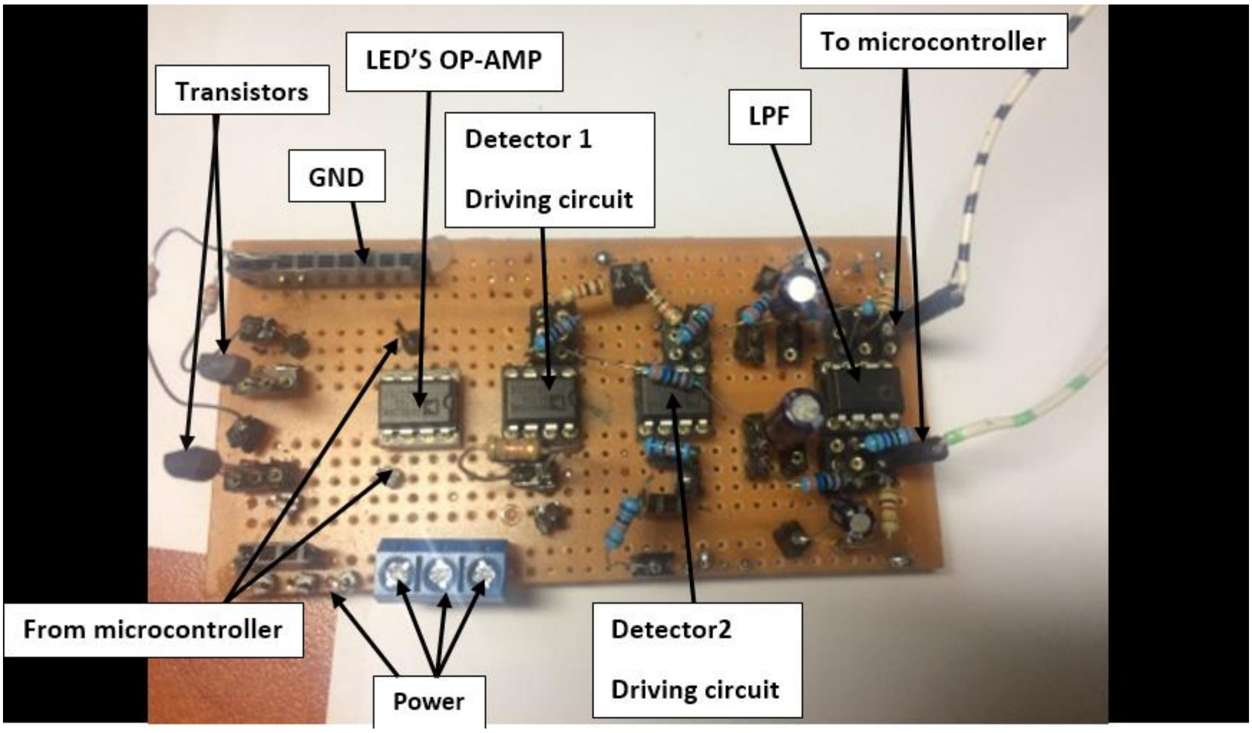

Fig 5.2: Chip implementation

The IC solid well in copper board.

5.1.2 Results of Hemoglobin Concentration

When no light detect by photodiode S1337-33BR the output is zero, as explained in figure 5.3

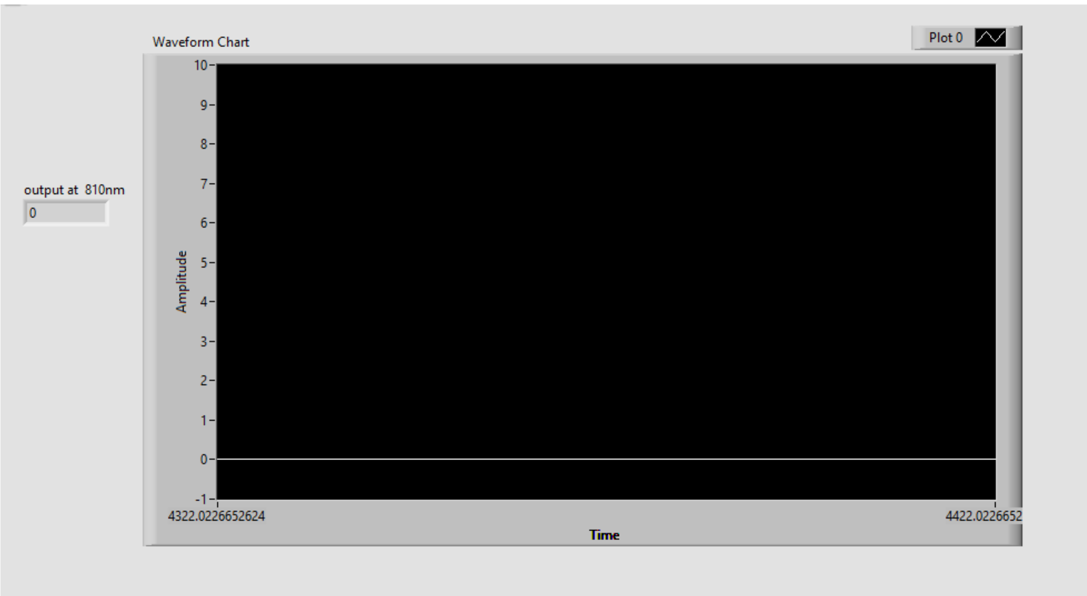

Fig5.3: output of detector1 when darkness

When full illumination light, the output of detector 1 is 5V as explain in figure 5.4.

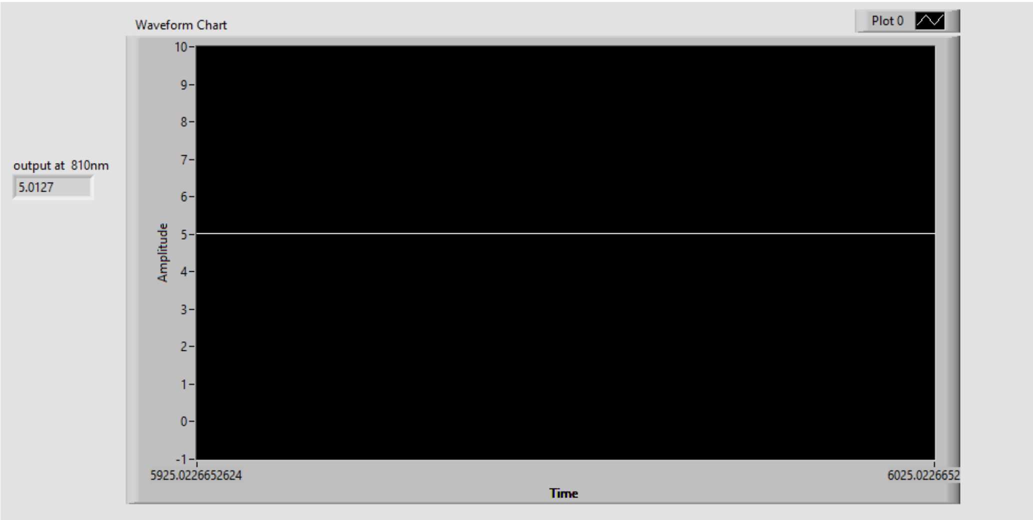

Fig 5.4: output of detector 1 when full illumination

When figure put to prop, the output of several sample between 0.5mV and 3mv, thus we need to amplify by factor 11 to give good rage for microcontroller to acquire and proses signal well, figure 5.5 show the output of detector 1 without gain factor 11.

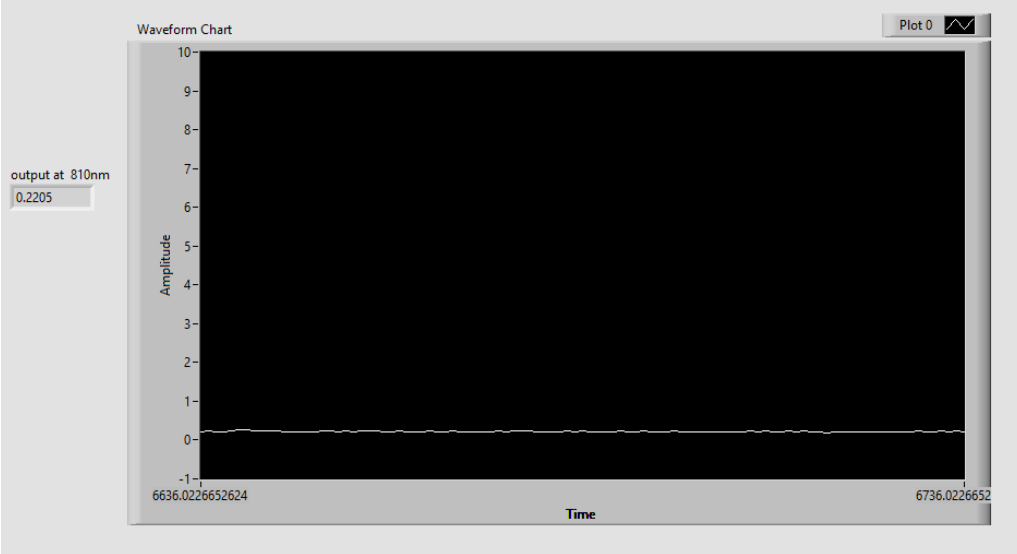

Fig 5.5: output of current to voltage converter (no addition gain)

After adding addition gain, the output signal amplifying, thus the microcontroller can proses the signal as well. Figure 5.6 show output with addition gain.

Fig 5.6: output of detector 1 after gain added

In addition, for detector 2 the output at dark is zero and for full illumination the output is 5 volt as explain in figure 5.7 and 5.8.

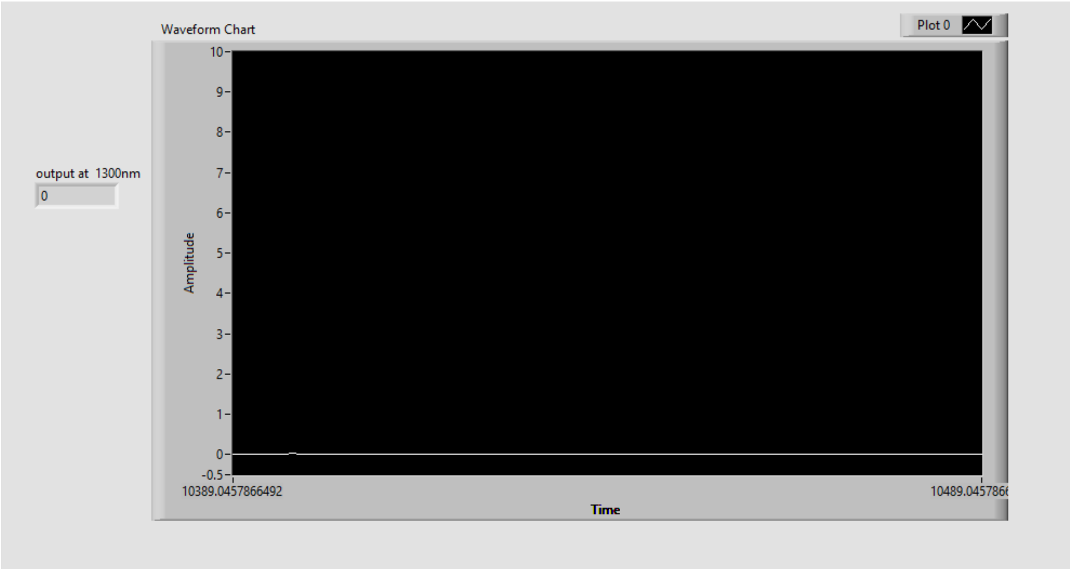

Fig5.7: output of current to voltage converter2 when dark

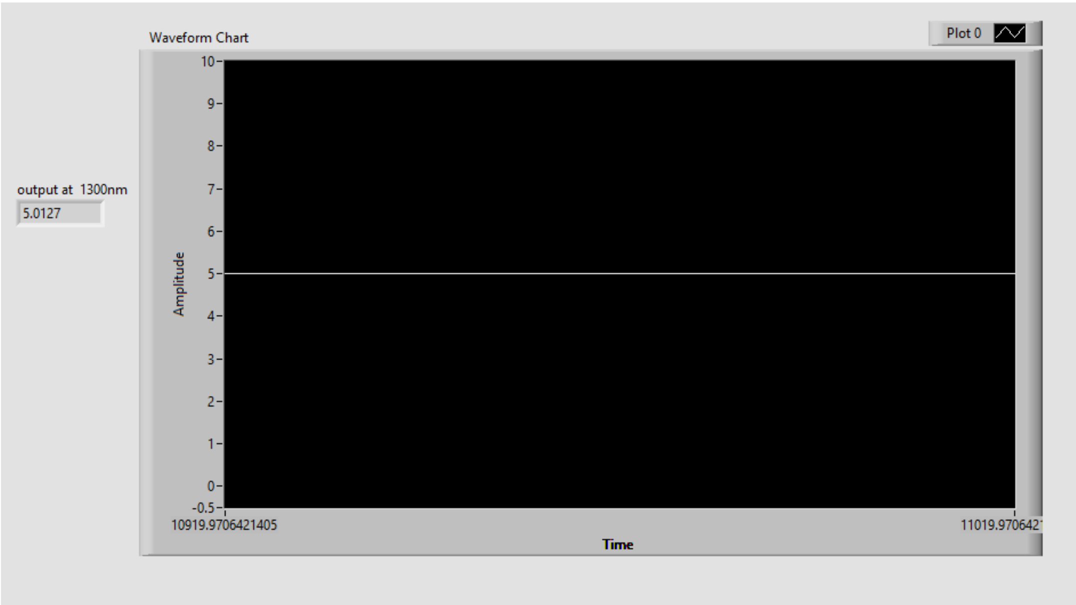

Fig5.8: output of current to voltage converter when full illumination

In addition, the output of acquire signal without adding addition gain is shown in figure 5.9, and output of signal after addition gain added is show in figure 5.10.

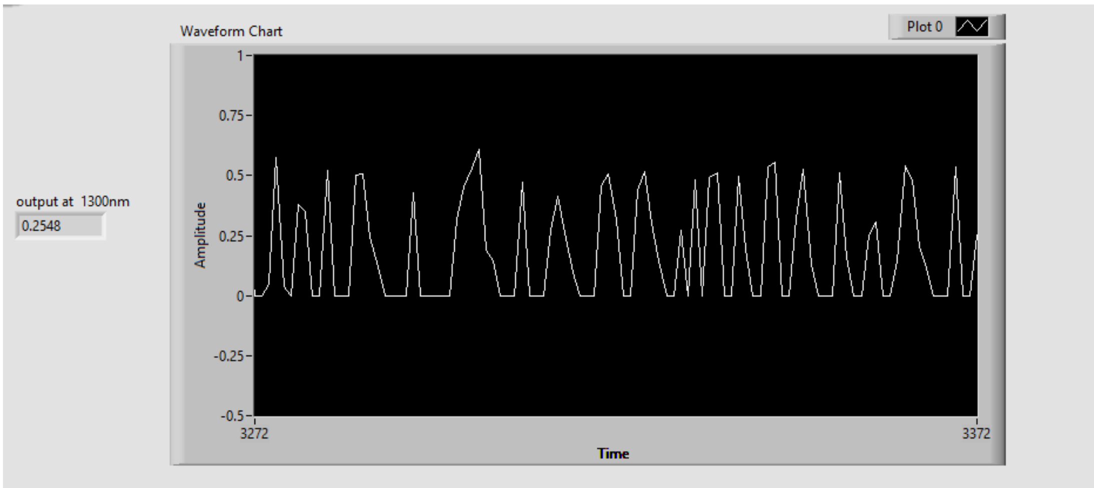

Fig 5.9: output of detector 2 without addition gain

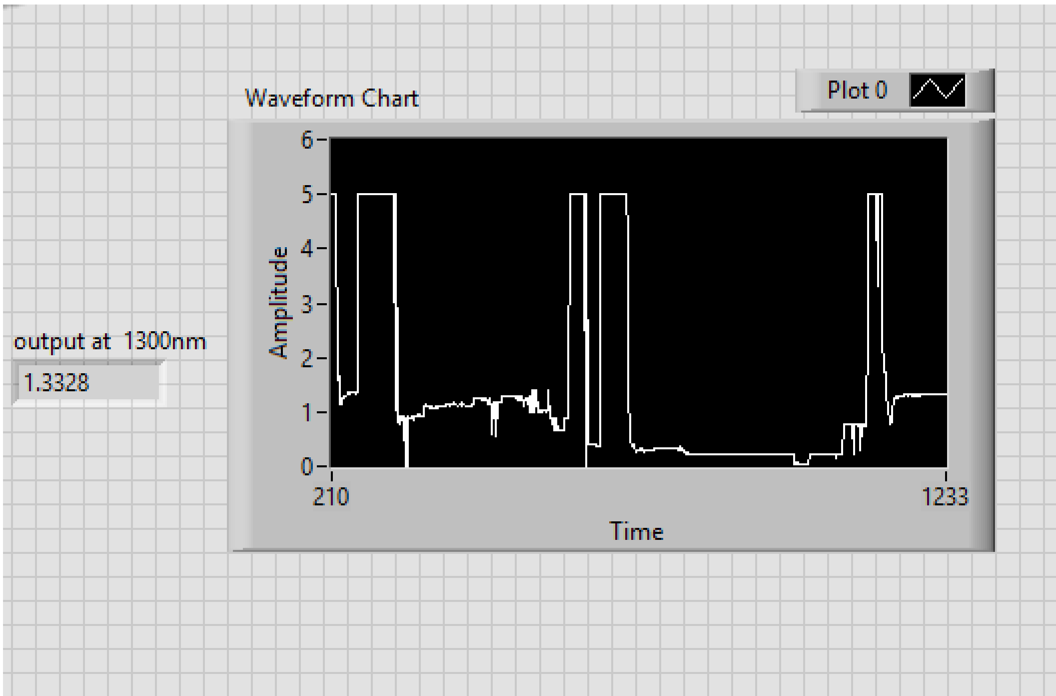

Fig 5.10: output of detector 2 after addition gain added

As described in chapter three and four, the acquire signal well be proses to find the hemoglobin concentration, figure 5.11 show sample taken and front panel of LABVIEW.

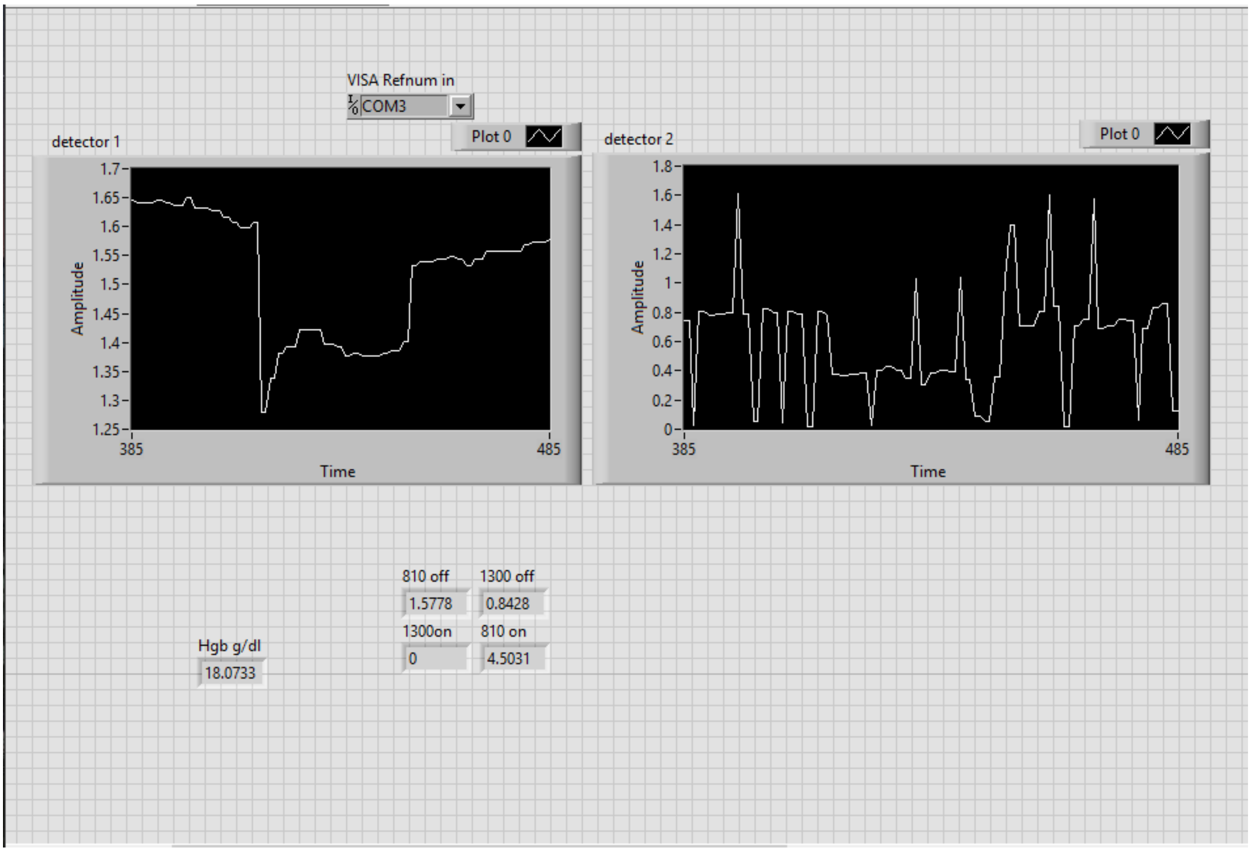

Fig 5.11: front panel of LABVIW and sample taken

The block diagram of LABVIW show the control and proses signals (appendix 12)

5.1.3 Hemoglobin analysis

The table 5.1 explain 38 sample was take, and the statistical analysis between our device and CBC explain in table 5.2

Table5.1: Hgb sample taken

#	age	Result of CBC	Result(out device)	%Error
1	19	15.6	14.23	8.782051
2	20	16.7	15.8	5.389222
3	20	13.5	13	3.703704
4	22	18.2	16.1	11.53846
5	19	14.6	15.4	5.479452

#	age	Result of CBC	Result(out device)	%Error
6	23	17.5	16.3	6.857143
7	24	13.2	11	16.66667
8	23	15.3	16.5	7.843137
10	23	14.6	15.2	4.109589
11	19	14.9	16	7.38255
12	20	13.6	12.1	11.02941
13	22	16.4	14.6	10.97561
14	21	15.4	14.2	7.792208
15	21	13.8	12.3	10.86957
16	18	15.6	14.7	5.769231
17	20	17.9	15.7	12.2905
18	22	13.5	12.7	5.925926
19	19	14.3	13	9.090909
20	18	15.1	13.8	8.609272
21	23	13.4	13	2.985075
22	20	16.5	15.2	7.878788
23	19	14.3	13.7	4.195804
24	23	16	15.2	5
25	21	14.4	13.1	9.027778
26	20	16.2	15.5	4.320988
27	19	14.9	12.99	12.81879
28	19	17.9	16.3	8.938547
29	22	15.2	14	7.894737
30	20	13.7	12.88	5.985401
31	22	17.4	16	8.045977
32	18	17.8	16.9	5.05618
33	20	14.6	13.1	10.27397
34	23	15.5	14.2	8.387097
35	20	14.8	13.2	10.81081
36	20	15.2	14.6	3.947368
37	19	17	15.1	11.17647
38	21	15.4	13.5	12.33766
			MAX	16.66667
			MIN	2.985075

Table 5.2: statistical analysis

Variables	CBC	Our Device
Mean	15.4027	14.3297
N	37	37
Standard Deviation	1.42585	1.43076
Std.Error Mean	0.23441	0.23522
Paired Samples Confidence		
Correlation	0.806	
Sig.	0	
Paired Samples Test		
Paired Differences		
Mean	1.07297	
Std.Devition	0.88976	
Std.Error Mean	0.14628	
95%Confidence Interval	**Lower**	0.77631
	Upper	1.36963
t	7.335	
df	36	

The mean value of our device is 14.3297±0.2322, and CBC 1.42585 ±0.23441. The result of CBC take from different type of devices. CBC devices also add diluent and lysis to blood sample to measure the hemoglobin concentration and other component of blood, this material make different of measurement result between company's devices. In addition, the skin of humans have different, such as skin color, thickness and softness, technical methods and the resolution of microcontroller low. Which make percentage of error between CBC device and our device. The CBC device throughput sample with one-minute maximum, our device give five result in one minute.

5.2 Fat Percentage Results and Analysis

Chapter three and four, described the main circuit to measure the fat percentage by impedance method. This chapter described system implementation, results and analysis

5.2.1 System Implementation of Fat Percentage Monitor

Chapter four describe the main circuit necessary. Fig5.12 show the system implementation and main system component.

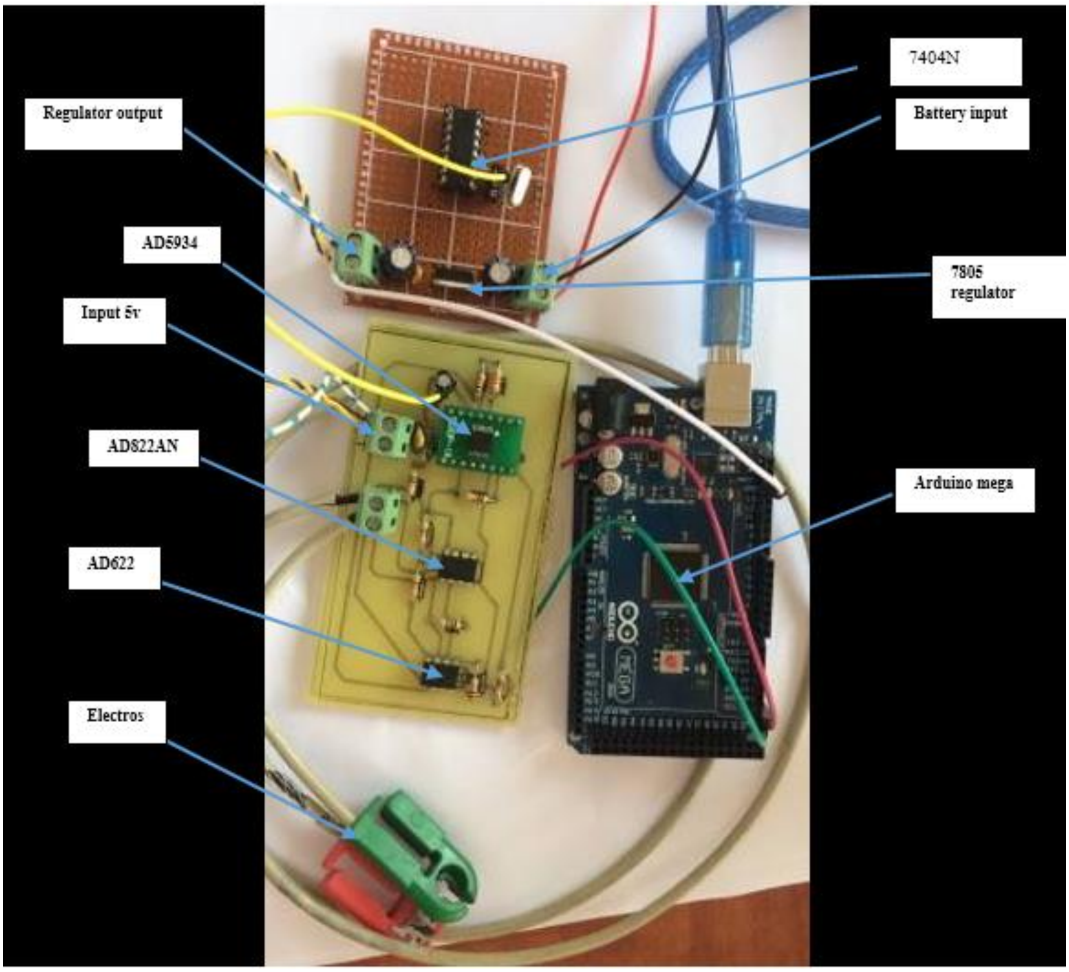

Fig 5.12: system implementation

5.2.2 Results of fat monitor

The code of Arduino written to get the impedance from the AD5934 [appendix 13]. The Arduino acquire the magnitude and save it in file. LABVIEW read the file and take average of magnitude. User can input the high, age, weight and gender and take the result. Fig 5.13 show LABVIEW front panel, the LABVIEW block diagram show the main proses component [appendix14].

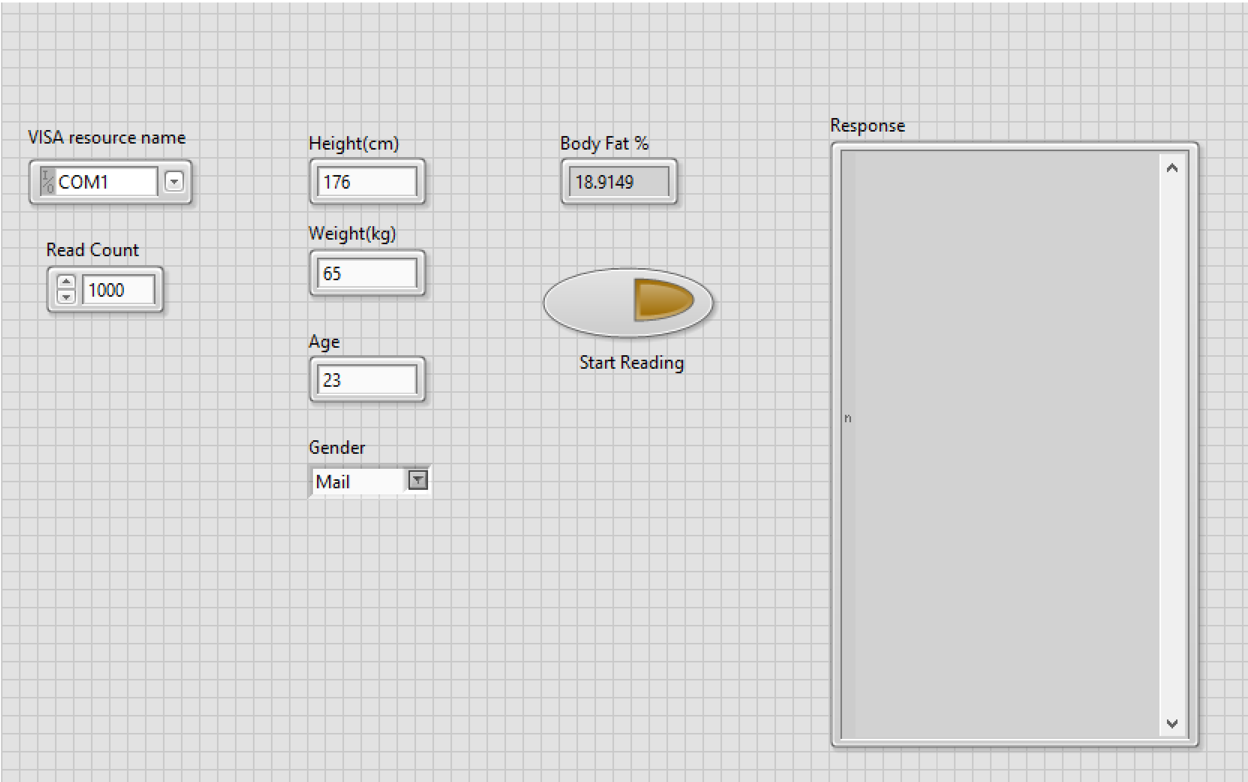

Fig5.13: LABVIEW front panel and fat percent computing

5.2.3 Fat Percentage Analysis

The table 5.3 show the 18 sample taken. Table 5.4 show the statistical analysis of out device and US navy method of determine the fat percentage.

Table 5.3: Fat percentage samples

#	age	height	weight	impedance	our device	US navy method	error
1	23	167	65	1800	23.3	23.59	1.229334
2	20	182	75	2562	30	29.2	2.739726
3	18	185	83	3297	34.4	32.8	4.878049
4	21	165	73	2235	33.4	35.1	4.843305
5	19	164	68	1523	27.32	28.9	5.467128
6	23	176	71	2051	28.59	27.8	2.841727
7	25	169	96	3020	43.44	45.1	3.68071
8	22	180	102	3254	42.92	45.8	6.28821
9	22	186	73	2098	26.87	27.1	0.848708
10	22	173	63	1564	21.33	21.2	0.613208
11	21	178	84	2787	36.2	36.1	0.277008
12	21	176	98	3271	42.43	41.6	1.995192
13	23	183	55	3210	40.27	39	3.25641
14	20	157	56	1325	19.17	18.5	3.621622
15	18	178	86	2961	36.92	37.1	0.485175
16	25	168	93	3058	42.76	42.3	1.08747
17	23	178	65	1815	22.814	23.3	2.085837
18	22	176	95	3127	41.45	40.6	2.093596
						MAX ERROR	6.28821
						MIN ERROR	0.277008

Table 5.4: statistical analysis of fat percentage

Variables	Our Device	US Navy
Mean	32.9769	33.0606
N	18	18
Standard Deviation	8.28586	8.47311
Std.Error Mean	1.953	1.99713
Paired Samples Confidence		
Correlation	0.99	
Sig.	0	
Paired Samples Test		
Paired Differences		
Mean	-0.08367	
Std.Devition	1.19439	
Std.Error Mean	0.28152	
95%Confidence Interval	**Lower**	-0.67762
	Upper	0.51029
t	-0.297	
df	17	

The mean value of the US navy and our device was 33.0606±8.47311, 32.9769±8.28586 respectively. The previous statistical analysis demonstrated that there is no much statistically significant different between our device and US navy method.

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Chapter Six Future Work and recommendation

- Use microcontroller with high resolution
- Take more blood sample in laboratory, and correct the percentage of error.
- Real time monitoring the peripheral blood pressure and heart rate.
- Develop phone application to send a result and control sample time. In addition, save results.
- Add diagnostic to each device.

Challenges:

- Choose spatial IC's, LED and detectors.
- Export electronics part take time.
- Sample taken

Appendices

Appendix 1

Appendix 2

Appendix 3

Appendix 4

Appendix 5

Appendix 6

Appendix 7

Appendix 8

Appendix 9

Appendix 10

Appendix 11

Appendix 12

Appendix 13

Appendix 14

Appendix 1

ROITHNER LASERTECHNIK GmbH
WIEDNER HAUPTSTRASSE 76 1040 VIENNA AUSTRIA
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v 1.1 17.10.2014

ELD-810-525

- Infrared Light Emitting Diode
- 810 nm, 45 mW
- Viewing angle: 20°
- Package: 5 mm clear epoxy

Description

ELD-810-525 is a AlGaAs based Light Emitting Diode with a typical peak wavelength of 810 nm and an optical output power of 45 mW. It is mounted on a lead frame and encapsulated in a standard clear 5 mm epoxy package.

Maximum Ratings *(T_{CASE}=25°C)*

Parameter	Symbol	Values Min.	Values Max.	Unit
Power Dissipation	P_D		240	mW
Forward Current	I_F		100	mA
Peak Forward Current	I_{FP}		200	mA
Operating Temperature	T_{CASE}	- 20	+ 85	°C
Storage Temperature	T_{STG}	- 40	+ 100	°C
Junction Temperature	T_J		+ 100	°C

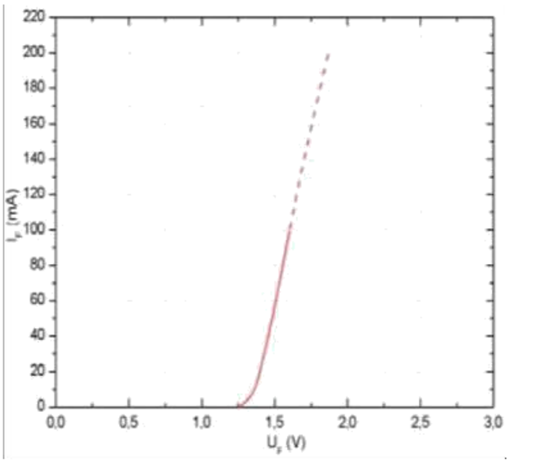
Optical and Electrical Characteristics *(T_{CASE}=25°C)*

Parameter	Symbol	Conditions	Values Min.	Values Typ.	Values Max.	Unit
Peak Wavelength	λ_P	I_F=20mA	800	810	820	nm
Spectral Half Width (FWHM)	$\Delta\lambda_{0,5}$	I_F=20mA		30		nm
Radiated Power	Φ_E	I_F=20mA	6	9		mW
Radiated Power *	Φ_E	I_F=100mA	30	45		mW
Radiant Intensity	I_E	I_F=20mA	25	35		mW/sr
Radiant Intensity *	I_E	I_F=100mA		170		mW/sr
Forward Voltage	V_F	I_F=20mA		1.4	1.7	V
Forward Voltage	V_F	I_F=100mA		1.6		V
Reverse Voltage	V_R	I_R=10µA	5			V
Viewing Angle	φ	I_F=100mA		20		deg.
Rise Time	t_R	I_F=100mA		40		ns
Fall Time	t_F	I_F=100mA		40		ns

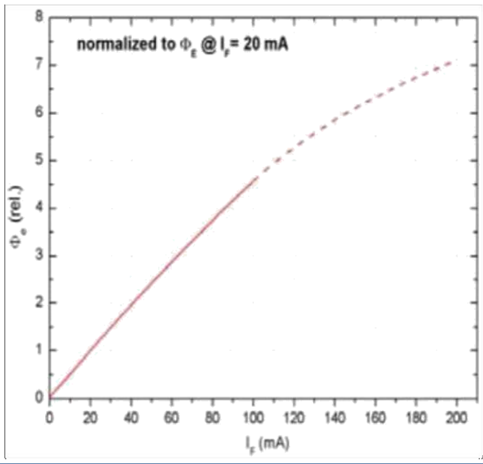
** measured after 30s current flow*

Typical Performance Curves

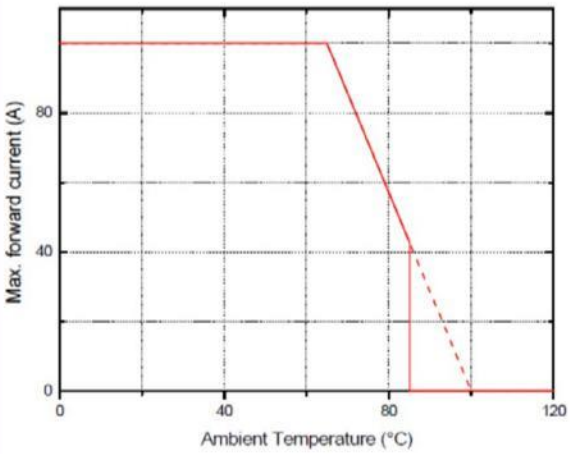
Forward Current vs. Forward Voltage



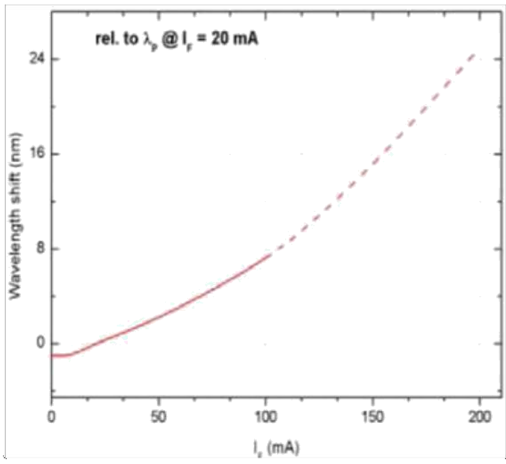
Radiant Power vs. Forward Current



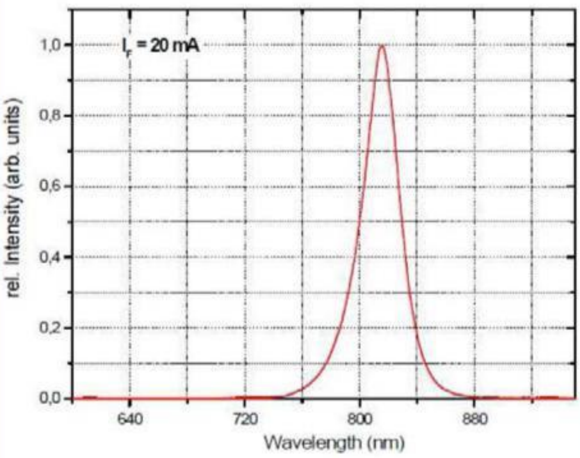
Allowed Forward Current vs. Ambient Temperature



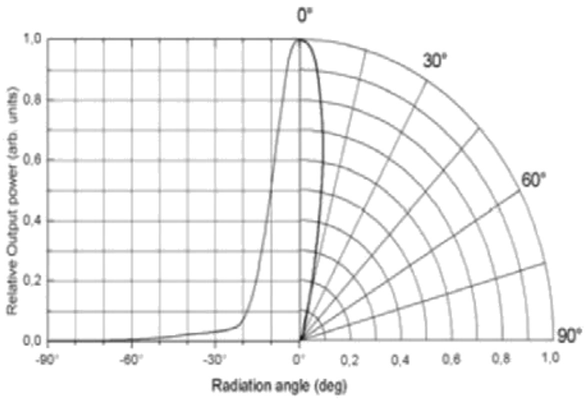
Typical Wavelength Shift vs. Forward Current



Relative Spectral Emission

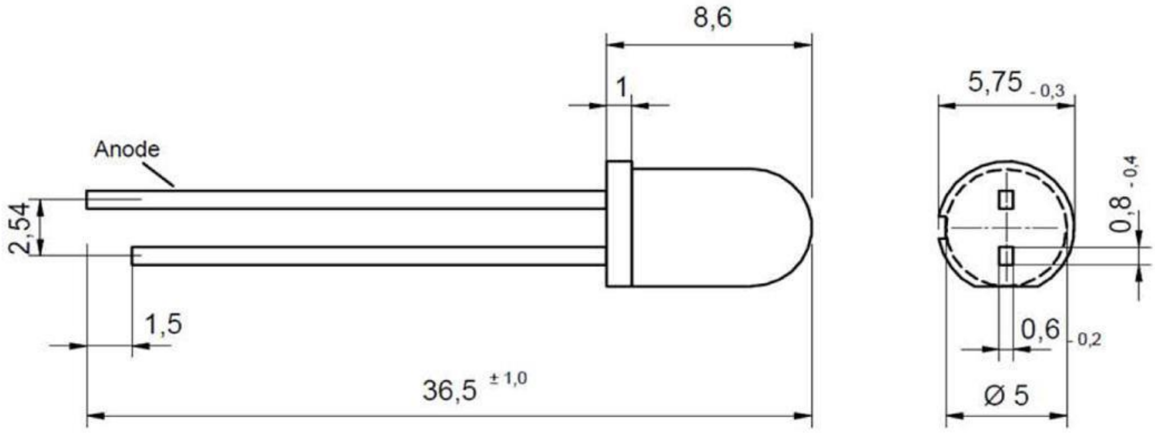


Radiation Characteristics



Outline Dimensions

ELD-810-525	5 mm epoxy



All Dimensions in mm

Precautions

Cautions:

DO NOT look directly into the emitted light or look through the optical system. To prevent in adequate exposure of the radiation, wear protective glasses.

Operation:

- Check your connection circuits before turning on the LED
- Mind the LED polarity: LED anode is marked by long pin
- Do only operate LEDs with a current source

Soldering:

- Do avoid overheating of the LED
- Do avoid electrostatic discharge (ESD)
- Do avoid mechanical stress, shock, and vibration
- Do only use non-corrosive flux
- Do only cut the leads at room temperature with an ESD protected tool
- Do not solder closer than 3 mm from base of the header
- Do form leads prior to soldering
- Do not impose mechanical stress on the header when forming the leads
- Do not apply current to the LED until it has cooled down to room temperature after soldering

Static Electricity:

LEDs are **sensitive to electrostatic discharge (ESD)**. Precautions against ESD must be taken when handling or operating these LEDs. Surge voltage or electrostatic discharge can result in complete failure of the device.

Appendix 2

Single Supply, Rail-to-Rail Low Power FET-Input Op Amp

AD822

FEATURES

TRUE SINGLE SUPPLY OPERATION
- **Output Swings Rail to Rail**
- **Input Voltage Range Extends Below Ground**
- **Single Supply Capability from +3 V to +36 V**
- **Dual Supply Capability from 61.5 V to 618 V**

HIGH LOAD DRIVE
- **Capacitive Load Drive of 350 pF, G =**
- **1 Minimum Output Current of 15 mA**

EXCELLENT AC PERFORMANCE FOR LOW POWER
- **800 mA Max Quiescent Current per Amplifier**
- **Unity Gain Bandwidth: 1.8 MHz**
- **Slew Rate of 3.0 V/ms**

GOOD DC PERFORMANCE
- **800 mV Max Input Offset Voltage**
- **2 mV/8C Typ Offset Voltage Drift**
- **25 pA Max Input Bias Current**

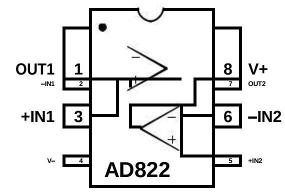
LOW NOISE
- **13 nV/ÖHz @ 10 kHz**

NO PHASE INVERSION

APPLICATIONS

Battery Powered Precision Instrumentation
Photodiode Preamps
Active Filters
12- to 14-Bit Data Acquisition Systems
Medical Instrumentation
Low Power References and Regulators

CONNECTION DIAGRAM
8-Pin Plastic DIP, Cerdip and SOIC



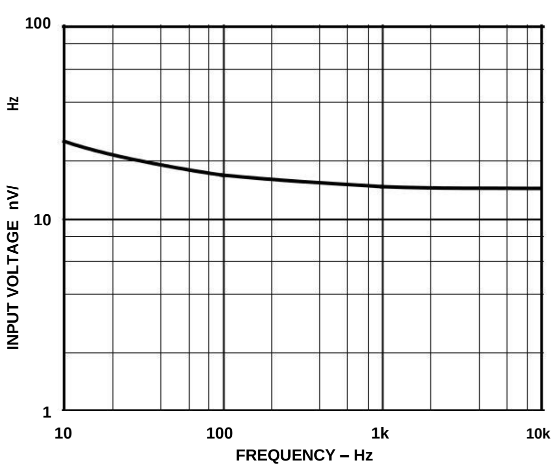
PRODUCT DESCRIPTION

The AD822 is a dual precision, low power FET input op amp that can operate from a single supply of +3.0 V to 36 V, or dual supplies of ±1.5 V to ± 18 V. It has true single supply capability with an input voltage range extending below the negative rail, allowing the AD822 to accommodate input signals below ground in the single supply mode. Output voltage swing extends to within 10 mV of each rail providing the maximum output dynamic range.

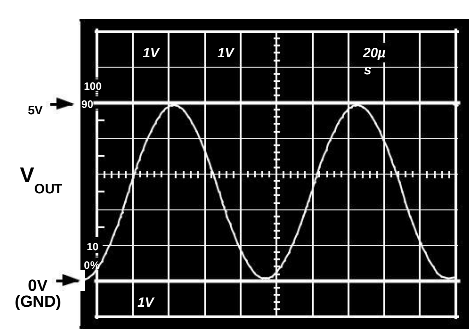
Offset voltage of 800 µV max, offset voltage drift of 2 µV/°C, input bias currents below 25 pA and low input voltage noise provide dc precision with source impedances up to a Gigaohm. 1.8 MHz unity gain bandwidth, –93 dB THD at 10 kHz and 3 V/µs slew rate are provided with a low supply current of 800 µA per amplifier. The AD822 drives up to 350 pF of direct capacitive load as a follower, and provides a minimum output current of 15 mA. This allows the amplifier to handle a wide range of load conditions. This combination of ac and dc performance, plus the outstanding load drive capability, results in an exceptionally versatile amplifier for the single supply user.

The AD822 is available in four performance grades. The A and B grades are rated over the industrial temperature range of –40°C to +85°C. There is also a 3 volt grade—the AD822A-3V, rated over the industrial temperature range. The mil grade is rated over the military temperature range of –55°C to +125°C and is available processed on standard military drawing.

The AD822 is offered in three varieties of 8-pin package: plastic DIP, hermetic cerdip and surface mount (SOIC) as well as die form.



Input Voltage Noise vs. Frequency



Gain of +2 Amplifier; V_S = +5, 0, V_{IN} = 2.5 V Sine Centered at 1.25 Volts, R_L = 100 kW

REV. A

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 617/329-4700 Fax: 617/326-8703

AD822–SPECIFICATIONS (V_S = 0, 5 volts @ T_A = +258C, V_{CM} = 0 V, V_{OUT} = 0.2 V unless otherwise noted)

Parameter	Conditions	AD822A Min	AD822A Typ	AD822A Max	AD822B Min	AD822B Typ	AD822B Max	AD822S[1] Min	AD822S[1] Typ	AD822S[1] Max	Units
DC PERFORMANCE											
Initial Offset			0.1	0.8		0.1	0.4		0.1	0.8	mV
Max Offset over Temperature			0.5	1.2		0.5	0.9		0.5		mV
Offset Drift			2			2			2		mV/°C
Input Bias Current	V_{CM} = 0 V to 4 V		2	25		2	10		2	25	pA
at T_{MAX}			0.5	5		0.5	2.5		0.5		nA
Input Offset Current			2	20		2	10		2	20	pA
at T_{MAX}			0.5			0.5			1.5		nA
Open-Loop Gain	V_O = 0.2 V to 4 V										
	R_L = 100 k	500	1000		500	1000		500	1000		V/mV
T_{MIN} to T_{MAX}		400			400						V/mV
	R_L = 10 k	80	150		80	150		80	150		V/mV
T_{MIN} to T_{MAX}		80			80						V/mV
	R_L = 1 k	15	30		15	30		15	30		V/mV
T_{MIN} to T_{MAX}		10			10						V/mV
NOISE/HARMONIC PERFORMANCE											
Input Voltage Noise											
0.1 Hz to 10 Hz			2			2			2		mV p-p
f = 10 Hz			25			25			25		nV/ÖHz
f = 100 Hz			21			21			21		nV/ÖHz
f = 1 kHz			16			16			16		nV/ÖHz
f = 10 kHz			13			13			13		nV/ÖHz
Input Current Noise											
0.1 Hz to 10 Hz			18			18			18		fA p-p
f = 1 kHz			0.8			0.8			0.8		fA/ÖHz
Harmonic Distortion	R_L = 10 k to 2.5 V										
f = 10 kHz	V_O = 0.25 V to 4.75 V		–93			–93			–93		dB
DYNAMIC PERFORMANCE											
Unity Gain Frequency			1.8			1.8			1.8		MHz
Full Power Response	V_O p-p = 4.5 V		210			210			210		kHz
Slew Rate			3			3			3		V/ms
Settling Time											
to 0.1%	V_O = 0.2 V to 4.5 V		1.4			1.4			1.4		ms
to 0.01%			1.8			1.8			1.8		ms
MATCHING CHARACTERISTICS											
Initial Offset				1.0			0.5			1.6	mV
Max Offset Over Temperature				1.6			1.3				mV
Offset Drift			3			3					mV/°C
Input Bias Current				20			10			20	pA
Crosstalk @ f = 1 kHz	R_L = 5 kW		–130			–130			–130		dB
f = 100 kHz			–93			–93			–93		dB
INPUT CHARACTERISTICS											
Common-Mode Voltage Range[2]		–0.2		4	–0.2		4	–0.2		4	V
T_{MIN} to T_{MAX}		–0.2		4	–0.2		4				V
CMRR	V_{CM} = 0 V to +2 V	66	80		69	80		66	80		dB
T_{MIN} to T_{MAX}		66			66						dB
Input Impedance											
Differential			10^{13}||0.5			10^{13}||0.5			10^{13}||0.5		W||pF
Common Mode			10^{13}||2.8			10^{13}||2.8			10^{13}||2.8		W||pF
OUTPUT CHARACTERISTICS											
Output Saturation Voltage[3]											
$V_{OL}–V_{EE}$	I_{SINK} = 20 mA		5	7		5	7		5	7	mV
T_{MIN} to T_{MAX}				10			10				mV
$V_{CC}–V_{OH}$	I_{SOURCE} = 20 mA		10	14		10	14		10	14	mV
T_{MIN} to T_{MAX}				20			20				mV
$V_{OL}–V_{EE}$	I_{SINK} = 2 mA		40	55		40	55		40	55	mV
T_{MIN} to T_{MAX}				80			80				mV
$V_{CC}–V_{OH}$	I_{SOURCE} = 2 mA		80	110		80	110		80	110	mV
T_{MIN} to T_{MAX}				160			160				mV
$V_{OL}–V_{EE}$	I_{SINK} = 15 mA		300	500		300	500		300	500	mV
T_{MIN} to T_{MAX}				1000			1000				mV
$V_{CC}–V_{OH}$	I_{SOURCE} = 15 mA		800	1500		800	1500		800	1500	mV
T_{MIN} to T_{MAX}				1900			1900				mV
Operating Output Current		15			15			15			mA
T_{MIN} to T_{MAX}		12			12						mA
Capacitive Load Drive			350			350			350		pF
POWER SUPPLY											
Quiescent Current T_{MIN} to T_{MAX}			1.24	1.6		1.24	1.6		1.24		mA
Power Supply Rejection	V_S+ = 5 V to 15 V	70	80		66	80		70	80		dB
T_{MIN} to T_{MAX}		70			66						dB

(V_S = 65 volts @ T_A = +258C, V_{CM} = 0 V, V_{OUT} = 0 V unless otherwise noted)

Parameter	Conditions	AD822A Min	AD822A Typ	AD822A Max	AD822B Min	AD822B Typ	AD822B Max	AD822S[1] Min	AD822S[1] Typ	AD822S[1] Max	Units
DC PERFORMANCE											
Initial Offset			0.1	0.8		0.1	0.4		0.1		mV
Max Offset over Temperature			0.5	1.5		0.5	1		0.5		mV
Offset Drift			2			2			2		mV/°C
Input Bias Current	V_{CM} = –5 V to 4 V		2	25		2	10		2	25	pA
at T_{MAX}			0.5	5		0.5	2.5		0.5		nA
Input Offset Current			2	20		2	10		2		pA
at T_{MAX}			0.5			0.5			1.5		nA
Open-Loop Gain	V_O = –4 V to 4 V										
	R_L = 100 k	400	1000		400	1000		400	1000		V/mV
T_{MIN} to T_{MAX}		400			400						V/mV
	R_L = 10 k	80	150		80	150		80	150		V/mV
T_{MIN} to T_{MAX}		80			80						V/mV
	R_L = 1 k	20	30		20	30		20	30		V/mV
T_{MIN} to T_{MAX}		10			10						V/mV
NOISE/HARMONIC PERFORMANCE											
Input Voltage Noise											
0.1 Hz to 10 Hz			2			2			2		mV p-p
f = 10 Hz			25			25			25		nV/Ö Hz
f = 100 Hz			21			21			21		nV/Ö Hz
f = 1 kHz			16			16			16		nV/Ö Hz
f = 10 kHz			13			13			13		nV/Ö Hz
Input Current Noise											
0.1 Hz to 10 Hz			18			18			18		fA p-p
f = 1 kHz			0.8			0.8			0.8		fA/Ö Hz
Harmonic Distortion	R_L = 10 k										
f = 10 kHz	V_O = ± 4.5 V		–93			–93			–93		dB
DYNAMIC PERFORMANCE											
Unity Gain Frequency			1.9			1.9			1.9		MHz
Full Power Response	V_O p-p = 9 V		105			105			105		kHz
Slew Rate			3			3			3		V/ms
Settling Time											
to 0.1%	V_O = 0 V to ± 4.5 V		1.4			1.4			1.4		ms
to 0.01%			1.8			1.8			1.8		ms
MATCHING CHARACTERISTICS											
Initial Offset				1.0			0.5			1.6	mV
Max Offset Over Temperature				3			2			2	mV
Offset Drift			3			3					mV/°C
Input Bias Current				25			10			25	pA
Crosstalk @ f = 1 kHz	R_L = 5 kW		–130			–130			–130		dB
f = 100 kHz			–93			–93			–93		dB
INPUT CHARACTERISTICS											
Common-Mode Voltage Range[2]		–5.2		4	–5.2		4	–5.2		4	V
T_{MIN} to T_{MAX}		–5.2		4	–5.2		4				V
CMRR	V_{CM} = –5 V to +2 V	66	80		69	80		66	80		dB
T_{MIN} to T_{MAX}		66			66						dB
Input Impedance											
Differential			10^{13}||0.5			10^{13}||0.5			10^{13}||0.5		W||pF
Common Mode			10^{13}||2.8			10^{13}||2.8			10^{13}||2.8		W||pF
OUTPUT CHARACTERISTICS											
Output Saturation Voltage[3]											
V_{OL}–V_{EE}	I_{SINK} = 20 mA		5	7		5	7		5	7	mV
T_{MIN} to T_{MAX}	I_{SOURCE} = 20 mA			10			10				mV
V_{CC}–V_{OH}			10	14		10	14		10	14	mV
T_{MIN} to T_{MAX}				20			20				mV
V_{OL}–V_{EE}	I_{SINK} = 2 mA		40	55		40	55		40	55	mV
T_{MIN} to T_{MAX}				80			80				mV
V_{CC}–V_{OH}	I_{SOURCE} = 2 mA		80	110		80	110		80	110	mV
T_{MIN} to T_{MAX}				160			160				mV
V_{OL}–V_{EE}	I_{SINK} = 15 mA		300	500		300	500		300	500	mV
T_{MIN} to T_{MAX}				1000			1000				mV
V_{CC}–V_{OH}	I_{SOURCE} = 15 mA		800	1500		800	1500		800	1500	mV
T_{MIN} to T_{MAX}				1900			1900				mV
Operating Output Current		15			15			15			mA
T_{MIN} to T_{MAX}		12			12						mA
Capacitive Load Drive			350			350			350		pF
POWER SUPPLY											
Quiescent Current T_{MIN} to T_{MAX}			1.3	1.6		1.3	1.6		1.3		mA
Power Supply Rejection	V_S+ = 5 V to 15 V	70	80		66	80		70	80		dB
T_{MIN} to T_{MAX}		70			66						dB

AD822–SPECIFICATIONS (V_S = 615 volts @ T_A = +258C, V_{CM} = 0 V, V_{OUT} = 0 V unless otherwise noted)

Parameter	Conditions	AD822A Min	AD822A Typ	AD822A Max	AD822B Min	AD822B Typ	AD822B Max	AD822S[1] Min	AD822S[1] Typ	AD822S[1] Max	Units
DC PERFORMANCE											
Initial Offset			0.4	2		0.3	1.5		0.4	2.0	mV
Max Offset over Temperature			0.5	3		0.5	2.5		0.5		mV
Offset Drift			2			2			2		mV/°C
Input Bias Current	V_{CM} = 0 V		2	25		2	12		2	25	pA
	V_{CM} = –10 V		40			40			40		pA
at T_{MAX}	V_{CM} = 0 V		0.5	5		0.5	2.5		0.5		nA
Input Offset Current			2	20		2	12		2	20	pA
at T_{MAX}			0.5			0.5			1.5		nA
Open-Loop Gain	V_O = +10 V to –10 V										
	R_L = 100 k	500	2000		500	2000		500	2000		V/mV
T_{MIN} to T_{MAX}		500			500						V/mV
	R_L = 10 k	100	500		100	500		150	400		V/mV
T_{MIN} to T_{MAX}		100			100						V/mV
	R_L = 1 k	30	45		30	45		30	45		V/mV
T_{MIN} to T_{MAX}		20			20						V/mV
NOISE/HARMONIC PERFORMANCE											
Input Voltage Noise											
0.1 Hz to 10 Hz			2			2			2		mV p-p
f = 10 Hz			25			25			25		nV/ÖHz
f = 100 Hz			21			21			21		nV/ÖHz
f = 1 kHz			16			16			16		nV/ÖHz
f = 10 kHz			13			13			13		nV/ÖHz
Input Current Noise											
0.1 Hz to 10 Hz			18			18			18		fA p-p
f = 1 kHz			0.8			0.8			0.8		fA/ÖHz
Harmonic Distortion	R_L = 10 k										
f = 10 kHz	V_O = ± 10 V		–85			–85			–85		dB
DYNAMIC PERFORMANCE											
Unity Gain Frequency			1.9			1.9			1.9		MHz
Full Power Response	V_O p-p = 20 V		45			45			45		kHz
Slew Rate			3			3			3		V/ms
Settling Time											
to 0.1%	V_O = 0 V to ± 10 V		4.1			4.1			4.1		ms
to 0.01%			4.5			4.5			4.5		ms
MATCHING CHARACTERISTICS											
Initial Offset				3			2			0.8	mV
Max Offset Over Temperature				4			2.5			1.0	mV
Offset Drift			3			3					mV/°C
Input Bias Current				25			12			25	pA
Crosstalk @ f = 1 kHz	R_L = 5 kW		–130			–130			–130		dB
f = 100 kHz			–93			–93			–93		dB
INPUT CHARACTERISTICS											
Common-Mode Voltage Range[2]		–15.2		14	–15.2		14	–15.2		14	V
T_{MIN} to T_{MAX}		–15.2		14	–15.2		14				V
CMRR	V_{CM} = –15 V to 12 V	70	80		74	90		70	90		dB
T_{MIN} to T_{MAX}		70			74						dB
Input Impedance											
Differential			10^{13}‖0.5			10^{13}‖0.5			10^{13}‖0.5		W‖pF
Common Mode			10^{13}‖2.8			10^{13}‖2.8			10^{13}‖2.8		W‖pF
OUTPUT CHARACTERISTICS											
Output Saturation Voltage[3]											
$V_{OL}–V_{EE}$	I_{SINK} = 20 mA		5	7		5	7		5	7	mV
T_{MIN} to T_{MAX}				10			10				mV
$V_{CC}–V_{OH}$	I_{SOURCE} = 20 mA		10	14		10	14		10	14	mV
T_{MIN} to T_{MAX}				20			20				mV
$V_{OL}–V_{EE}$	I_{SINK} = 2 mA		40	55		40	55		40	55	mV
T_{MIN} to T_{MAX}				80			80				mV
$V_{CC}–V_{OH}$	I_{SOURCE} = 2 mA		80	110		80	110		80	110	mV
T_{MIN} to T_{MAX}				160			160				mV
$V_{OL}–V_{EE}$	I_{SINK} = 15 mA		300	500		300	500		300	500	mV
T_{MIN} to T_{MAX}				1000			1000				mV
$V_{CC}–V_{OH}$	I_{SOURCE} = 15 mA		800	1500		800	1500		800	1500	mV
T_{MIN} to T_{MAX}				1900			1900				mV
Operating Output Current		20			20			20			mA
T_{MIN} to T_{MAX}		15			15						mA
Capacitive Load Drive			350			350			350		pF
POWER SUPPLY											
Quiescent Current T_{MIN} to T_{MAX}			1.4	1.8		1.4	1.8		1.4		mA
Power Supply Rejection	V_S+ = 5 V to 15 V	70	80		70	80		70	80		dB
T_{MIN} to T_{MAX}		70			70						dB

(V_S = 0, 3 volts @ T_A = +258C, V_{CM} = 0 V, V_{OUT} = 0.2 V unless otherwise noted)

Parameter	Conditions	AD822A-3 V Min	Typ	Max	Units
DC PERFORMANCE					
Initial Offset			0.2	1	mV
Max Offset over Temperature			0.5	1.5	mV
Offset Drift			1		mV/°C
Input Bias Current	V_{CM} = 0 V to +2 V		2	25	pA
at T_{MAX}			0.5	5	nA
Input Offset Current			2	20	pA
at T_{MAX}			0.5		nA
Open-Loop Gain	V_O = 0.2 V to 2 V				
	R_L = 100 k	300	1000		V/mV
T_{MIN} to T_{MAX}		300			V/mV
	R_L = 10 k	60	150		V/mV
T_{MIN} to T_{MAX}		60			V/mV
	R_L = 1 k	10	30		V/mV
T_{MIN} to T_{MAX}		8			V/mV
NOISE/HARMONIC PERFORMANCE					
Input Voltage Noise					
0.1 Hz to 10 Hz			2		mV p-p
f = 10 Hz			25		nV/ÖHz
f = 100 Hz			21		nV/ÖHz
f = 1 kHz			16		nV/ÖHz
f = 10 kHz			13		nV/ÖHz
Input Current Noise					
0.1 Hz to 10 Hz			18		fA p-p
f = 1 kHz			0.8		fA/ÖHz
Harmonic Distortion	R_L = 10 k to 1.5 V				
f = 10 kHz	V_O = ± 1.25 V		–92		dB
DYNAMIC PERFORMANCE					
Unity Gain Frequency			1.5		MHz
Full Power Response	V_O p-p = 2.5 V		240		kHz
Slew Rate			3		V/ms
Settling Time					
to 0.1%	V_O = 0.2 V to 2.5 V		1		ms
to 0.01%			1.4		ms
MATCHING CHARACTERISTICS					
Initial Offset				1	mV
Max Offset Over Temperature				2	mV
Offset Drift			2		mV/°C
Input Bias Current				10	pA
Crosstalk @ f = 1 kHz	R_L = 5 kW		–130		dB
f = 100 kHz			–93		dB
INPUT CHARACTERISTICS					
Common-Mode Voltage Range[2]		–0.2		2	V
T_{MIN} to T_{MAX}		–0.2		2	V
CMRR	V_{CM} = 0 V to +1 V	60	74		dB
T_{MIN} to T_{MAX}		60			dB
Input Impedance					
Differential			10^{13}||0.5		W||pF
Common Mode			10^{13}||2.8		W||pF
OUTPUT CHARACTERISTICS					
Output Saturation Voltage[3]					
$V_{OL}-V_{EE}$	I_{SINK} = 20 mA		5	7	mV
T_{MIN} to T_{MAX}				10	mV
$V_{CC}-V_{OH}$	I_{SOURCE} = 20 mA		10	14	mV
T_{MIN} to T_{MAX}				20	mV
$V_{OL}-V_{EE}$	I_{SINK} = 2 mA		40	55	mV
T_{MIN} to T_{MAX}				80	mV
$V_{CC}-V_{OH}$	I_{SOURCE} = 2 mA		80	110	mV
T_{MIN} to T_{MAX}				160	mV
$V_{OL}-V_{EE}$	I_{SINK} = 10 mA		200	400	mV
T_{MIN} to T_{MAX}				400	mV
$V_{CC}-V_{OH}$	I_{SOURCE} = 10 mA		500	1000	mV
T_{MIN} to T_{MAX}				1000	mV
Operating Output Current		15			mA
T_{MIN} to T_{MAX}		12			mA
Capacitive Load Drive			350		pF
POWER SUPPLY					
Quiescent Current T_{MIN} to T_{MAX}			1.24	1.6	mA
Power Supply Rejection	V_S+ = 3 V to 15 V	70	80		dB
T_{MIN} to T_{MAX}		70			dB

NOTES

[1]See standard military drawing for 883B specifications.

[2]This is a functional specification. Amplifier bandwidth decreases when the input common-mode voltage is driven in the range ($+V_S$ – 1 V) to $+V_S$. Common-mode error voltage is typically less than 5 mV with the common-mode voltage set at 1 volt below the positive supply.

[3]$V_{OL}–V_{EE}$ is defined as the difference between the lowest possible output voltage (V_{OL}) and the minus voltage supply rail (V_{EE}).
$V_{CC}–V_{OH}$ is defined as the difference between the highest possible output voltage (V_{OH}) and the positive supply voltage (V_{CC}).

Specifications subject to change without notice.

CAUTION

ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on the human body and test equipment and can discharge without detection. Although the AD822 features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.

ABSOLUTE MAXIMUM RATINGS[1]

Supply Voltage . . . . ±18 V
Internal Power Dissipation
  Plastic DIP (N) . . . . Observe Derating Curves
  Cerdip (Q) . . . . Observe Derating Curves
  SOIC (R) . . . . Observe Derating Curves
Input Voltage . . . . ($+V_S$ + 0.2 V) to –(20 V + V_S)
Output Short Circuit Duration . . . . Indefinite
Differential Input Voltage . . . . ±30 V
Storage Temperature Range (N) . . . . –65°C to +125°C
Storage Temperature Range (Q) . . . . –65°C to +150°C
Storage Temperature Range (R) . . . . –65°C to +150°C
Operating Temperature Range
  AD822A/B . . . . –40°C to +85°C
  AD822S . . . . –55°C to +125°C
Lead Temperature Range (Soldering 60 sec) . . . . +260°C

NOTES

[1]Stresses above those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. This is a stress rating only and functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

[2]8-Pin Plastic DIP Package: θ_{JA} = 90°C/Watt
8-Pin Cerdip Package: θ_{JA} = 110°C/Watt
8-Pin SOIC Package: θ_{JA} = 160°C/Watt

MAXIMUM POWER DISSIPATION

The maximum power that can be safely dissipated by the AD822 is limited by the associated rise in junction temperature. For plastic packages, the maximum safe junction temperature is 145°C. For the cerdip packages, the maximum junction temperature is 175°C. If these maximums are exceeded momentarily, proper circuit operation will be restored as soon as the die temperature is reduced. Leaving the device in the "overheated" condition for an extended period can result in device burnout. To ensure proper operation, it is important to observe the derating curves shown in Figure 24.

While the AD822 is internally short circuit protected, this may not be sufficient to guarantee that the maximum junction temperature is not exceeded under all conditions. With power supplies ±12 volts (or less) at an ambient temperature of +25°C or less, if the output node is shorted to a supply rail, then the amplifier will not be destroyed, even if this condition persists for an extended period.

ORDERING GUIDE

Model[1]	Temperature Range	Package Description	Package Option
AD822AN	–40°C to +85°C	8-Pin Plastic Mini-DIP	N-8
AD822BN	–40°C to +85°C	8-Pin Plastic Mini-DIP	N-8
AD822AR	–40°C to +85°C	8-Pin SOIC	R-8
AD822BR	–40°C to +85°C	8-Pin SOIC	R-8
AD822AR-3V	–40°C to +85°C	8-Pin SOIC	R-8
AD822AN-3V	–40°C to +85°C	8-Pin Plastic Mini-DIP	N-8
AD822A Chips	–40°C to +85°C	Die	
Standard Military Drawing[2]	–55°C to +125°C	8-Pin Cerdip	Q-8

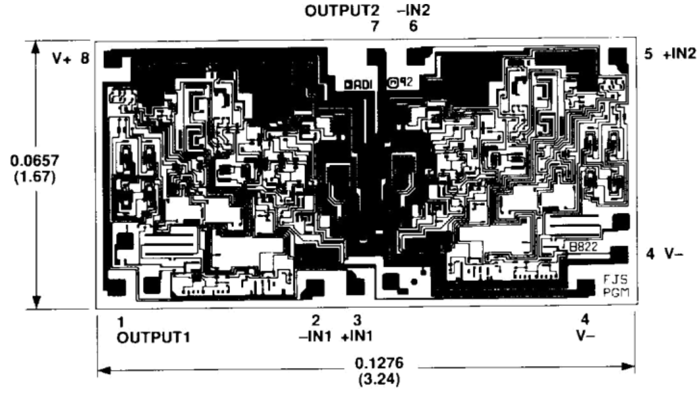
NOTES

[1]Spice model is available on ADI Model Disc.

[2]Contact factory for availability.

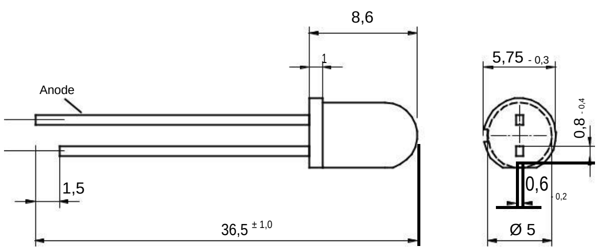
METALIZATION PHOTOGRAPH

Contact factory for latest dimensions.
Dimensions shown in inches and (mm).



Appendix 3

Radiation	Type	Technology	Case
Infrared	MQW	InGaAs/InP	5 mm plastic lens



Description

High-power, high-speed infrared LED in standard 5 mm package, housing without standoff leads

Note: Special packages with standoff available on request

Applications

Optical communications, safety equipment, automation

Maximum Ratings

T_{amb} = 25°C, unless otherwise specified

Parameter	Test conditions	Symbol	Value	Unit
Forward current (DC)		I_F	100	mA
Peak forward current	(t_P ≤ 50 µs, t_P /T = 1/2)	I_{FM}	200	mA
Power dissipation		P_D	150	mW
Operating temperature range		T_{amb}	-20 to +80	°C
Storage temperature range		T_{stg}	-55 to +100	°C
Soldering temperature	t ≤ 5 s, 3 mm from case	T_{sd}	260	°C

Optical and Electrical Characteristics

T_{amb} = 25°C, unless otherwise specified

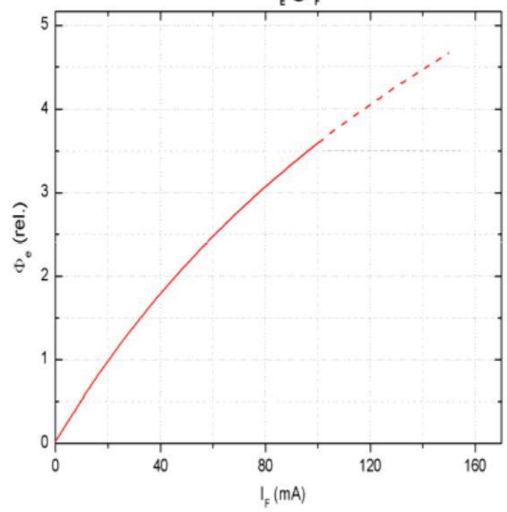
Parameter	Test conditions	Symbol	Min	Typ	Max	Unit
Forward voltage	I_F = 20 mA	V_F		0.85	1.0	V
Forward voltage*	I_F = 100 mA	V_F		0.95		V
Reverse voltage	I_R = 100 µA	V_R	5			V
Radiant power	I_F = 20 mA	Φ_e	1.6	2.2		mW
Radiant power*	I_F = 100 mA	Φ_e		8.5		mW
Radiant intensity	I_F = 20 mA	I_e		10		mW/sr
Radiant intensity*	I_F = 100 mA	I_e		38		mW/sr
Peak wavelength	I_F = 20 mA	λ_p	1250	1300	1350	nm
Spectral bandwidth at 50%	I_F = 20 mA	$\Delta\lambda_{0.5}$		70		nm
Viewing angle	I_F = 20 mA	ϕ		25		deg.
Switching time	I_F = 20 mA	t_r, t_f		10		ns

*measured after 30s current flow

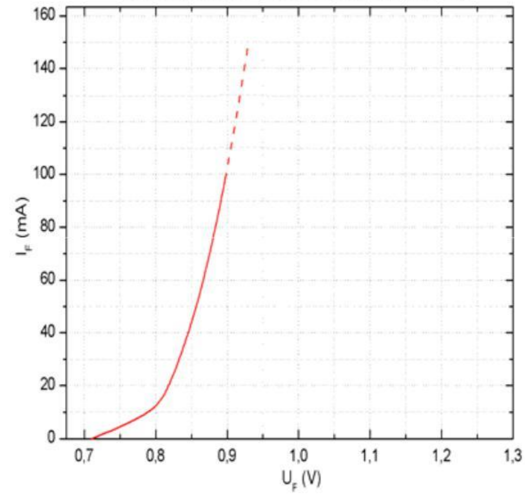
Note: All measurements carried out on *EPIGAP* equipment

EPIGAP Optoelektronik GmbH, D-12555 Berlin, Köpenicker Str.325 b, Haus 201
Tel.: +49-30-6576 2543, Fax : +49-30-6576 2545

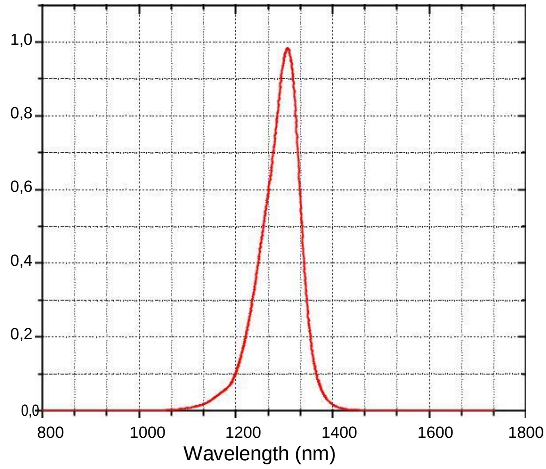
Radiant power vs. forward current (typical)
normalized to Φ_E @ I_F = 20 mA



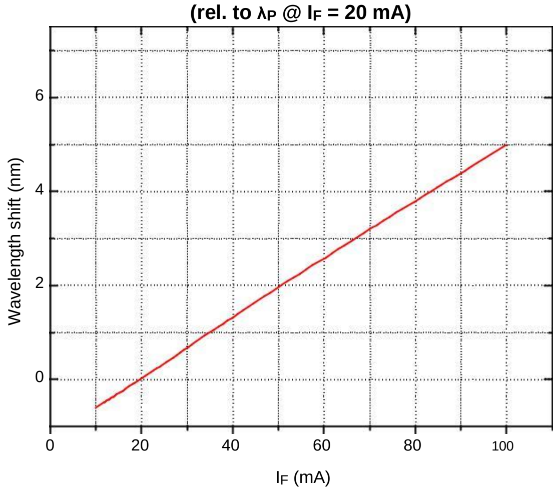
Forward current vs. forward voltage (typical)



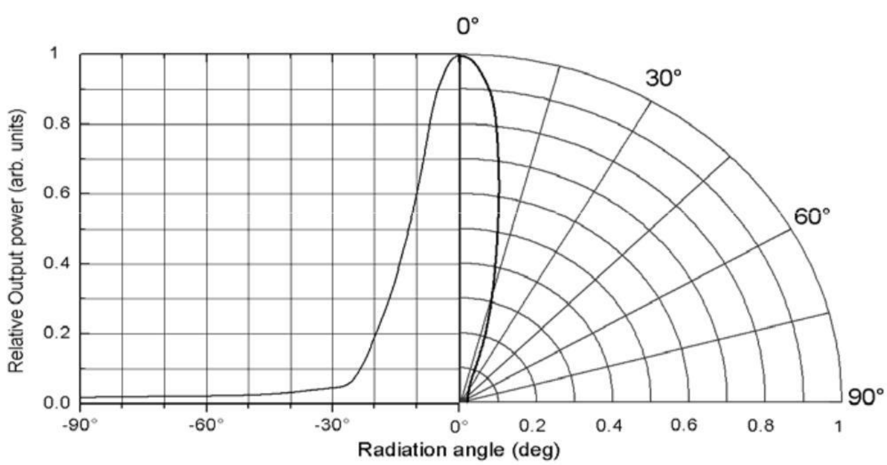
Spectral power distribution (typical)
at I_F = 20 mA



Typical wavelength shift vs. forward current
(rel. to λ_P @ I_F = 20 mA)



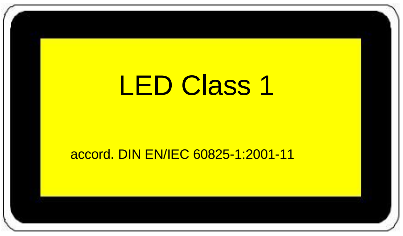
Typical radiant pattern



Remarks concerning optical radiation safety*

Up to maximum forward current, at continuous operation, this LED may be classified as LED product *Class 1* , according to standard IEC 60825-1:A2. *Class 1* products are safe to eyes and skin under reasonably predictable conditions. This implicates a direct observation of the light beam by means of optical instruments.

*Note: Safety classification of an optical component mainly depends on the intended application and the way the component is being used. Furthermore, all statements made to classification are based on calculations and are only valid for this LED "as it is", and at continuous operation. Using pulsed current or altering the light beam with additional optics may lead to different safety classifications. Therefore these remarks should be taken as recommendation and guideline only.



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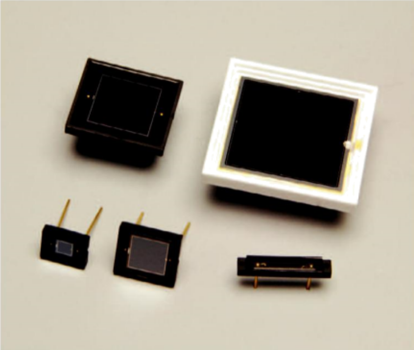
Appendix 4

HAMAMATSU
PHOTON IS OUR BUSINESS



Si photodiodes

S1337 series

For UV to IR, precision photometry

These Si photodiodes have sensitivity in the UV to near IR range. They are suitable for low-light-level detection in analysis and the like.

Features

- **High UV sensitivity: QE 75% (λ=200 nm)**
- **Low capacitance**

Applications

- **Analytical equipment**
- **Optical measurement equipment**

Structure / Absolute maximum ratings

Type no.	Window material	Package (mm)	Photosensitive area size (mm)	Effective photosensitive area (mm^2)	Absolute maximum ratings: Reverse voltage V_R max (V)	Operating temperature Topr (°C)	Storage temperature Tstg (°C)
S1337-16BQ*	Quartz	2.7 × 15	1.1 × 5.9	5.9	5	-20 to +60	-20 to +80
S1337-16BR	Resin potting						
S1337-33BQ*	Quartz	6 × 7.6	2.4 × 2.4	5.7			
S1337-33BR	Resin potting						
S1337-66BQ*	Quartz	8.9 × 10.1	5.8 × 5.8	33			
S1337-66BR	Resin potting						
S1337-1010BQ*	Quartz	15 × 16.5	10 × 10	100			
S1337-1010BR	Resin potting						
S1337-21*	Unsealed	25.5 × 25.5	18 × 18	324		0 to +60	0 to +80

* Refer to "Precautions against UV light exposure."

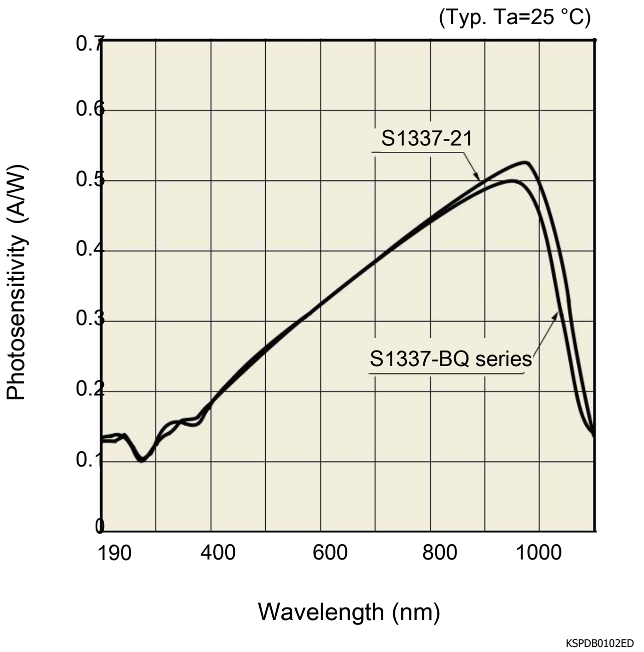
Note: Exceeding the absolute maximum ratings even momentarily may cause a drop in product quality. Always be sure to use the product within the absolute maximum ratings.

Electrical and optical characteristics (Typ. Ta=25 °C, unless otherwise noted)

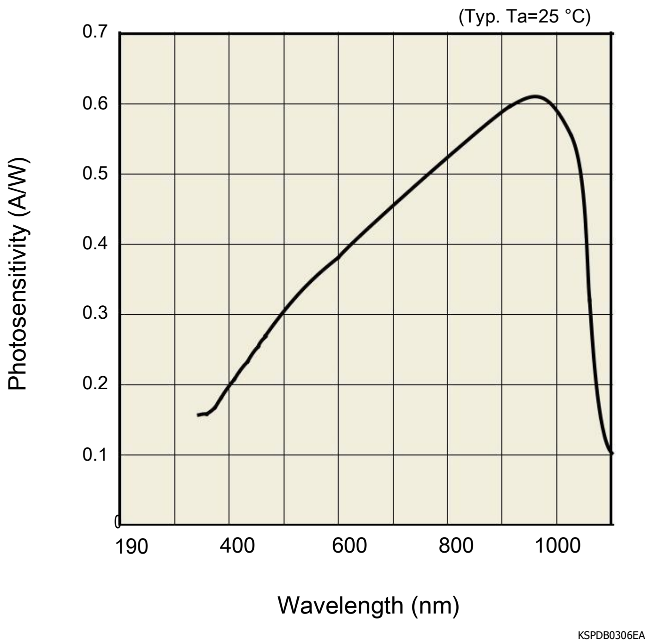
Type no.	Spectral response range λ (nm)	Peak sensitivity wavelength λp (nm)	Photosensitivity S (A/W) λp	200 nm Min.	200 nm Typ.	He-Ne laser 633 nm	GaAs LED 930 nm	Short circuit current Isc 100 *lx* Min. (µA)	Typ. (µA)	Dark current ID V_R=10 mV Max. (pA)	Temp. coefficient of ID TCID (times/°C)	Rise time tr V_R=0 V R_L=1 kΩ (µs)	Terminal capacitance Ct V_R=0 V f=10 kHz (pF)	Shunt resistance Rsh V_R=10 mV Min. (GΩ)	Typ. (GΩ)	Noise equivalent power NEP ($W/Hz^{1/2}$)
S1337-16BQ	190 to 1100	960	0.5	0.10	0.12	0.33	0.5	4.0	5.3	50	1.15	0.2	65	0.2	0.6	1.0×10^{-14}
S1337-16BR	340 to 1100		0.62	-	-	0.4	0.6	4.4	6.2							8.4×10^{-15}
S1337-33BQ	190 to 1100		0.5	0.10	0.12	0.33	0.5	4.0	5.0	30		0.2	65	0.3	1	8.1×10^{-15}
S1337-33BR	340 to 1100		0.62	-	-	0.4	0.6	4.4	6.2							6.5×10^{-15}
S1337-66BQ	190 to 1100		0.5	0.10	0.12	0.33	0.5	20	27	100		1	380	0.1	0.4	1.3×10^{-14}
S1337-66BR	340 to 1100		0.62	-	-	0.4	0.6	22	33							1.0×10^{-14}
S1337-1010BQ	190 to 1100		0.5	0.10	0.12	0.33	0.5	65	78	200		3	1100	0.05	0.2	1.8×10^{-14}
S1337-1010BR	340 to 1100		0.62	-	-	0.4	0.6	70	95							1.5×10^{-14}
S1337-21	190 to 1100		0.52	0.10	0.13	0.34	0.51	200	250	500		8	4000	0.02	0.1	2.5×10^{-14}

Spectral response

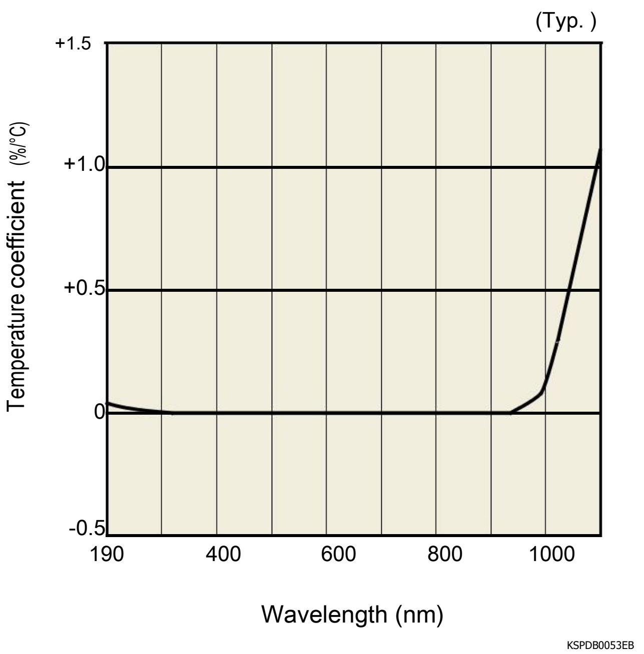
S1337BQ series, S1337-21



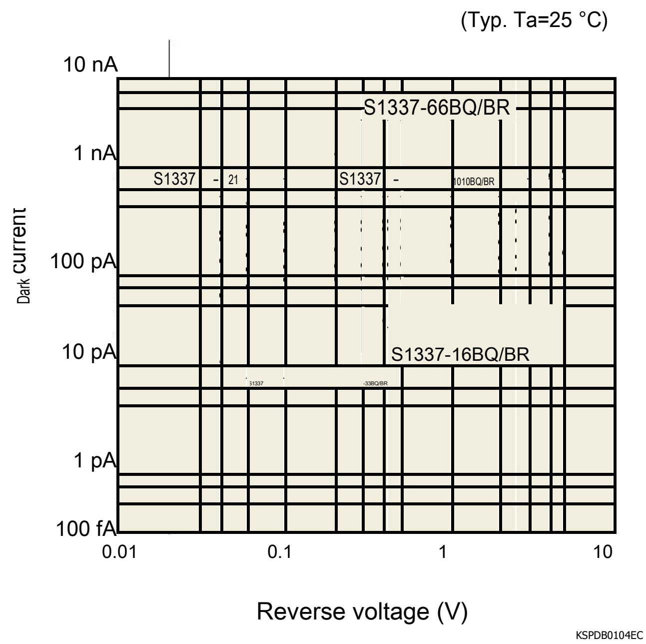
S1337-BR series



Photosensitivity temperature characteristics

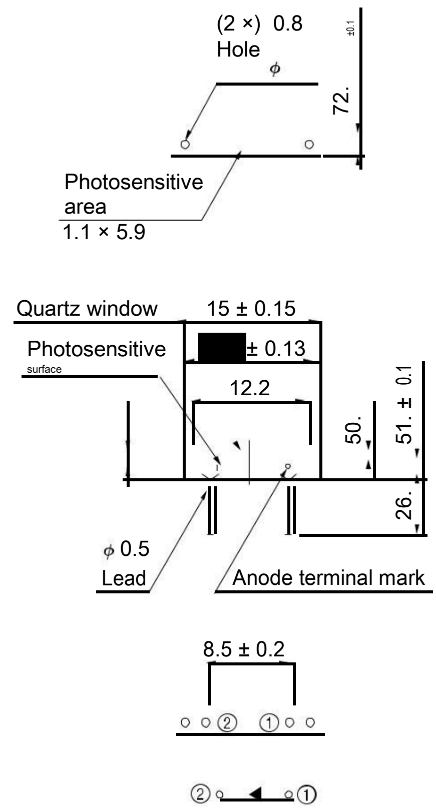


Dark current vs. reverse voltage



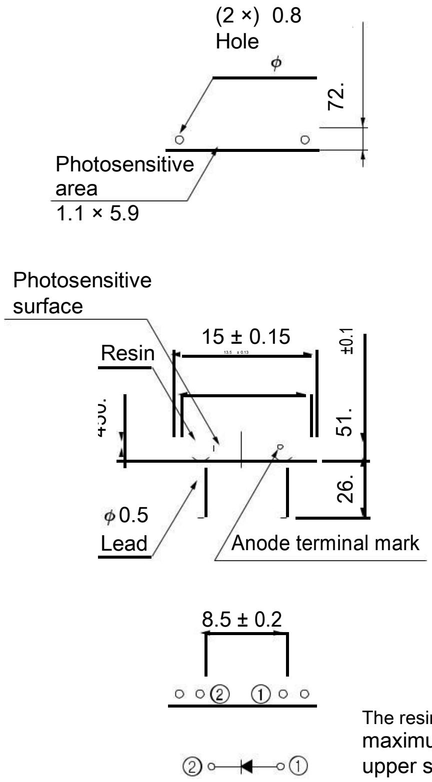
Dimensional outlines (unit: mm)

S1337-16BQ



KSPDA0105EB

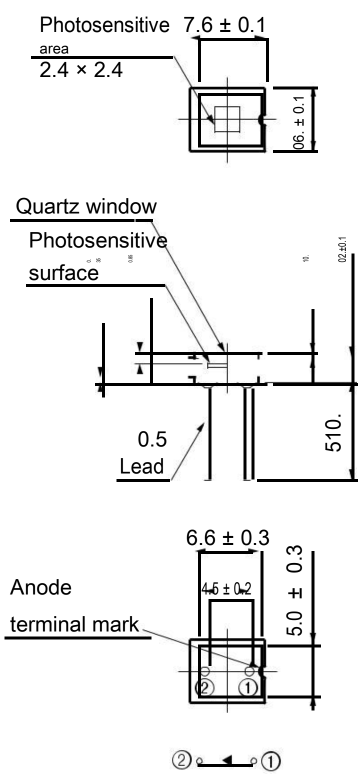
S1337-16BR



The resin potting may extend a maximum of 0.1 mm above the upper surface of the package.

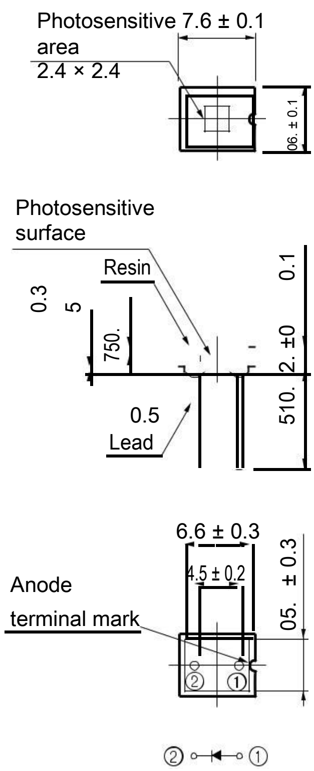
KSPDA0106EB

S1337-33BQ



KSPDA0107EB

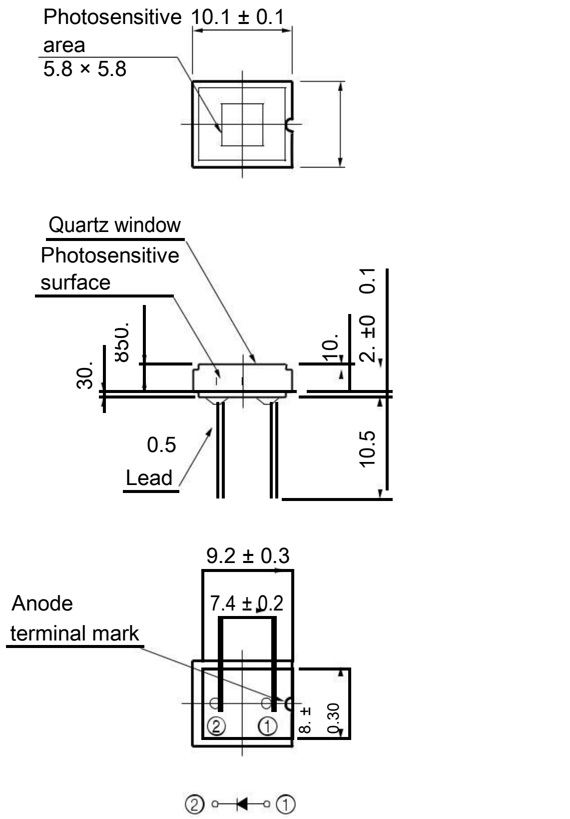
S1337-33BR



The resin potting may extend a maximum of 0.1 mm above the upper surface of the package.

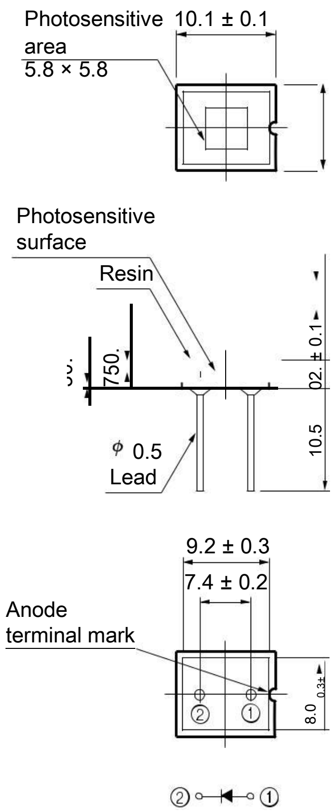
KSPDA0108EB

S1337-66BQ



KSPDA0109EB

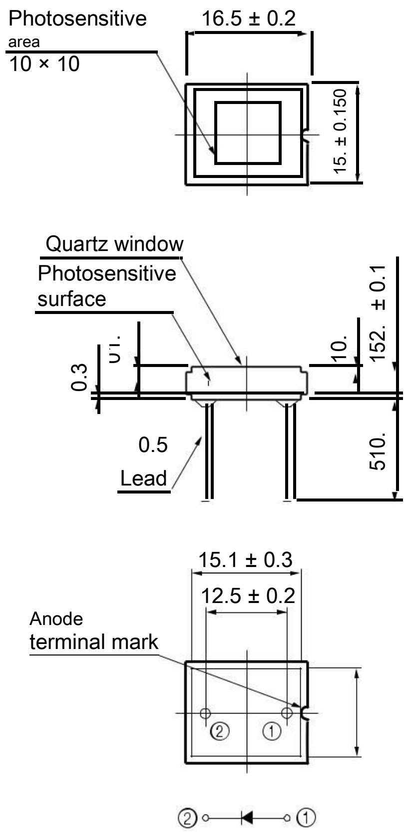
S1337-66BR



The resin potting may extend a maximum of 0.1 mm above the upper surface of the package.

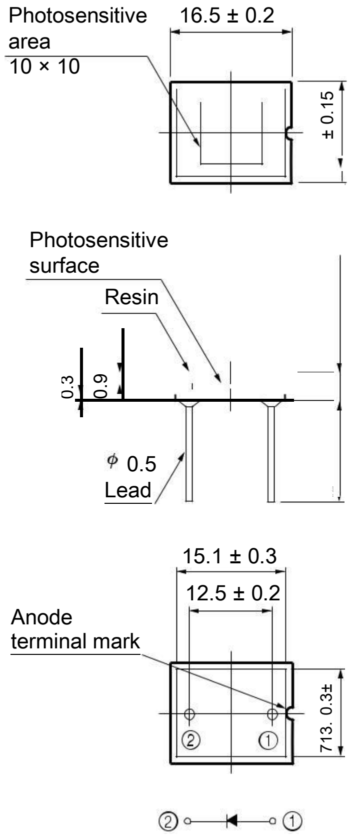
KSPDA0110EB

S1337-1010BQ



KSPDA0111EB

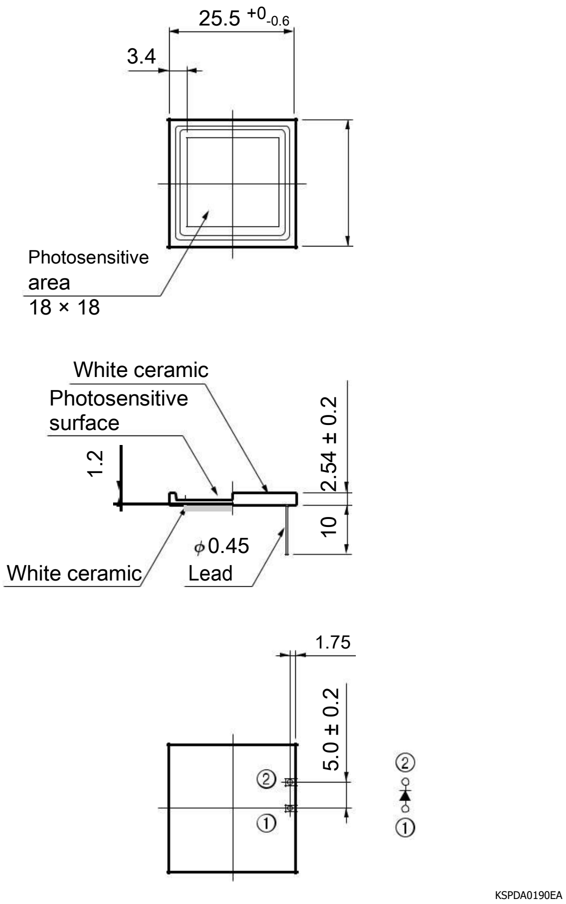
S1337-1010BR



The resin potting may extend a maximum of 0.1 mm above the upper surface of the package.

KSPDA0112EB

S1337-21



Precautions against UV light exposure

· When UV light irradiation is applied, the product characteristics may degrade. Such examples include degradation of the product's UV sensitivity and increase in dark current. This phenomenon varies depending on the irradiation level, irradiation intensity, usage time, and ambient environment and also varies depending on the product model. Before employing the product, we recommend that you check the tolerance under the ultraviolet light environment that the product will be used in.

· Exposure to UV light may cause the characteristics to degrade due to gas released from the resin bonding the product's component materials. As such, we recommend that you avoid applying UV light directly on the resin and apply it on only the inside of the photosensitive area by using an aperture or the like.

Related information

www.hamamatsu.com/sp/ssd/doc_en.html

■ Precautions

· Disclaimer
· Metal, ceramic, plastic package products

■ Technical information

· Si photodiode/Application circuit examples

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Cat. No. KSPD1032E07 Oct. 2015 DN

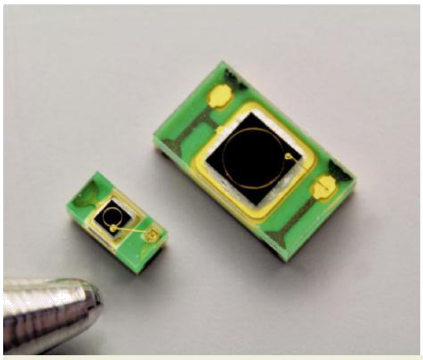
Appendix 5

HAMAMATSU
PHOTON IS OUR BUSINESS

NEW

InGaAs PIN photodiodes

G13176 series



Surface mount type COB (chip on board) package

The G13176 series is a small-size near infrared detector available in a surface mount COB package. Its size is drastically reduced compared to the previous metal package type (G12180-003A/-010A). The spectral response covers a range from 0.9 to 1.7 μm (with peak sensitivity wavelength at 1.55 μm). This product features high sensitivity and low noise. In addition to opti-cal communication, you can use this product for analysis, measurement, and the like. The small package makes this product suitable for integration into hand-held devices and mobile devices. The modified resin has improved the refl ow resistivity as compared to the previous product (G11777-003P).

Features

- **Low noise**
- **High sensitivity**
- **High-speed response**
- **Photosensitive area: ϕ0.3 mm, ϕ1.0 mm**
- **Surface mount type**
- **Small size COB package**
- **Low cost**
- **Compatible lead-free reflow soldering**

Application

- **Measurement**
- **Analysis**
- **Light level monitor**

Structure

Parameter	Symbol	G13176-003P	G13176-010P	Unit
Window material	-	Silicone resin		-
Package	-	Glass epoxy		-
Photosensitive area	-	ϕ0.3	ϕ1.0	mm

Absolute maximum ratings

Parameter	Symbol	Condition	Value	Unit
Reverse voltage	V_R		10	V
Operating temperature	Topr	No dew condensation*1	-25 to +105	°C
Storage temperature	Tstg	No dew condensation*1	-40 to +105	°C

Note: Handle the G13176 series with tweezers or gloves. Do not touch with bare hands. As the resin area of the G13176 series is soft, do not allow sharp or hard objects to come in contact with it, or apply external force to it.
Exceeding the absolute maximum ratings even momentarily may cause a drop in product quality. Always be sure to use the product within the absolute maximum ratings.

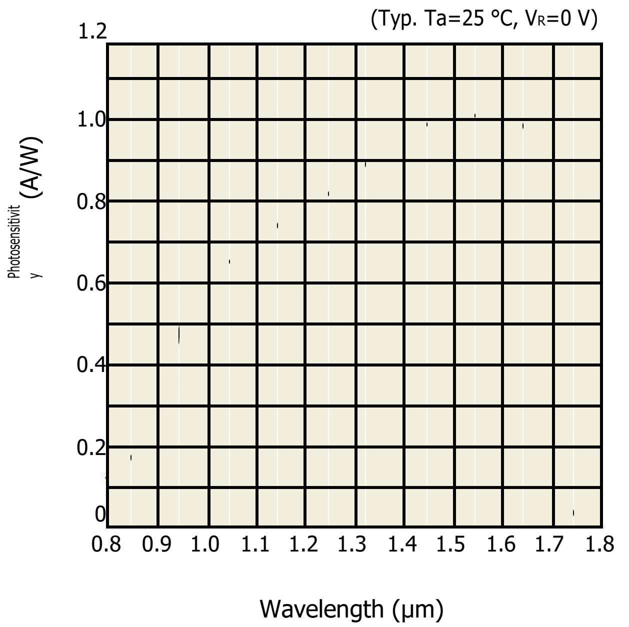
*1: When there is a temperature difference between a product and the surrounding area in high humidity environment, dew condensation may occur on the product surface. Dew condensation on the product may cause deterioration in characteristics and reliability.

The G13176 series may be damaged by electrostatic discharge, etc. Be careful when using the G13176 series.

Electrical and optical characteristics (Ta=25 °C)

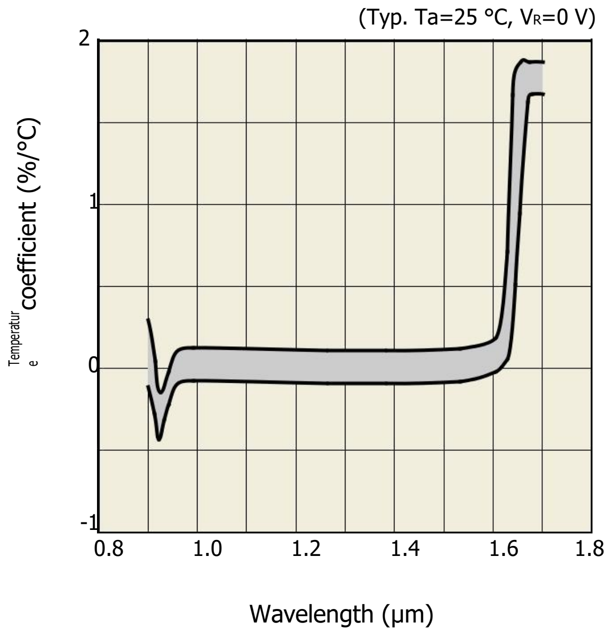
Parameter	Symbol	Condition	G13176-003P			G13176-010P			Unit
			Min.	Typ.	Max.	Min.	Typ.	Max.	
Spectral response range	λ	10% or more of the value at peak	-	0.9 to 1.7	-	-	0.9 to 1.7	-	μm
Peak sensitivity wavelength	λp		-	1.55	-	-	1.55	-	μm
Photosensitivity	S	λ=1.3 μm	0.75	0.85	-	0.75	0.85	-	A/W
		λ=λp	0.85	1	-	0.85	1	-	
Dark current	I_D	V_R=5 V	-	0.1	0.8	-	0.8	4	nA
Cutoff frequency	fc	V_R=5 V, R_L=50 Ω	300	600	-	25	60	-	MHz
Terminal capacitance	Ct	V_R=5 V, f=1 MHz	-	5	8	-	55	120	pF
Shunt resistance	Rsh	V_R=10 mV	100	700	-	25	125	-	MΩ
Detectivity	D*	λ=λp	1.5×10^{12}	5×10^{12}	-	1.5×10^{12}	5×10^{12}	-	$cm \cdot Hz^{1/2}/W$
Noise equivalent power	NEP	λ=λp	-	5×10^{-15}	2×10^{-14}	-	1.4×10^{-14}	4×10^{-14}	$W/Hz^{1/2}$

Spectral response



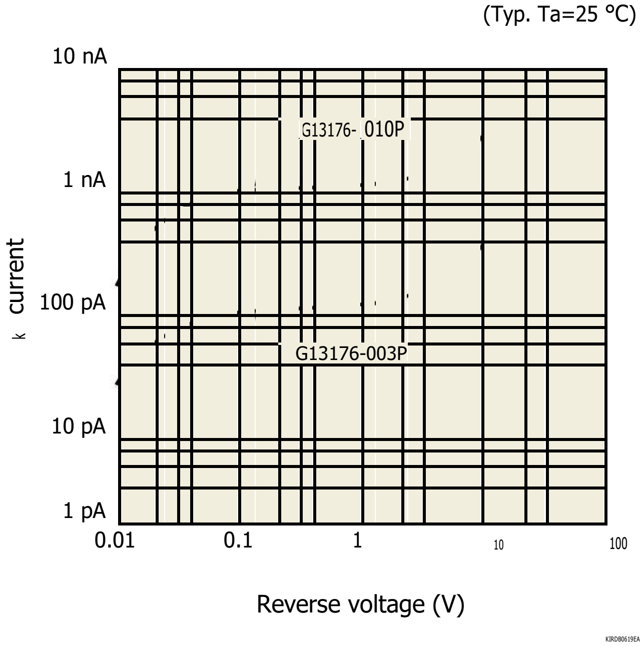
KIRDB0617EA

Photosensitivity temperature characteristics

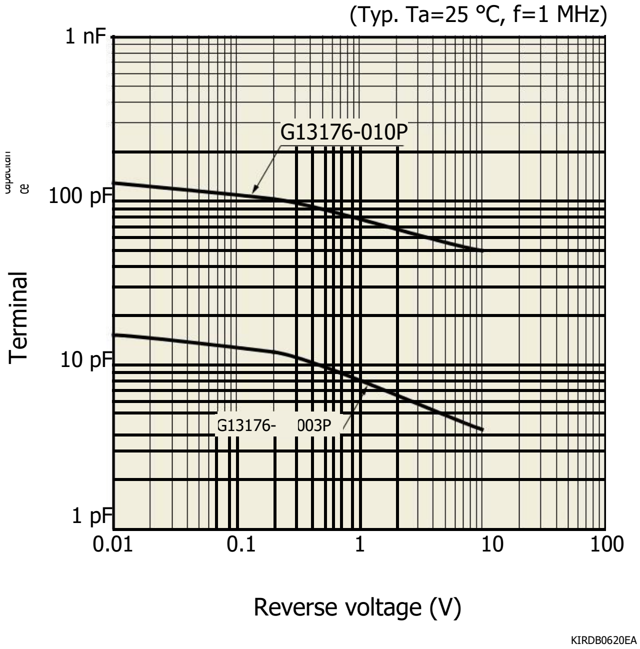


KIRDB0618EA

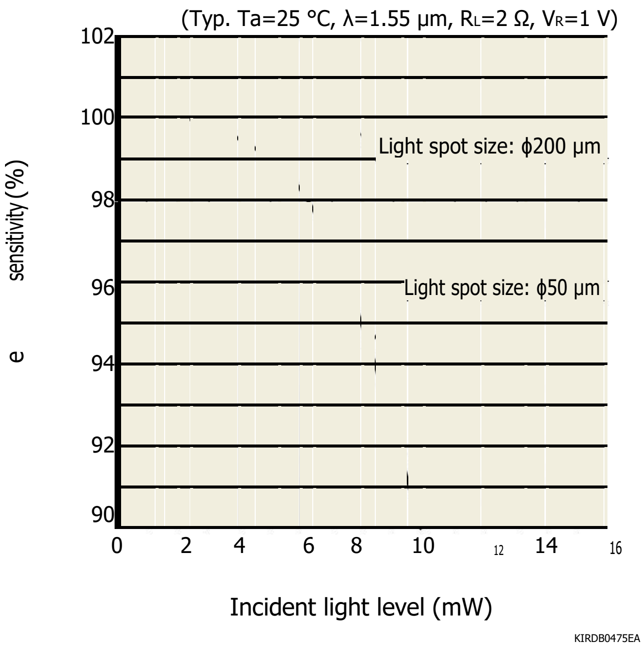
Dark current vs. reverse voltage



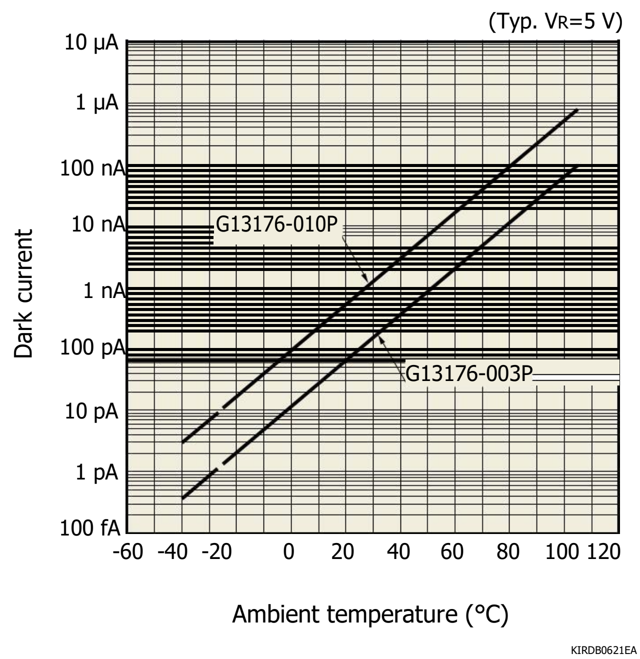
Terminal capacitance vs. reverse voltage



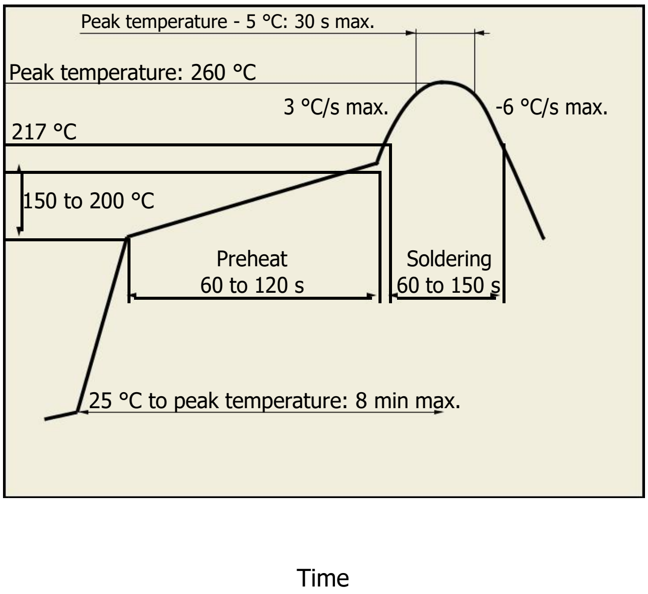
Linearity



Dark current vs. ambient temperature



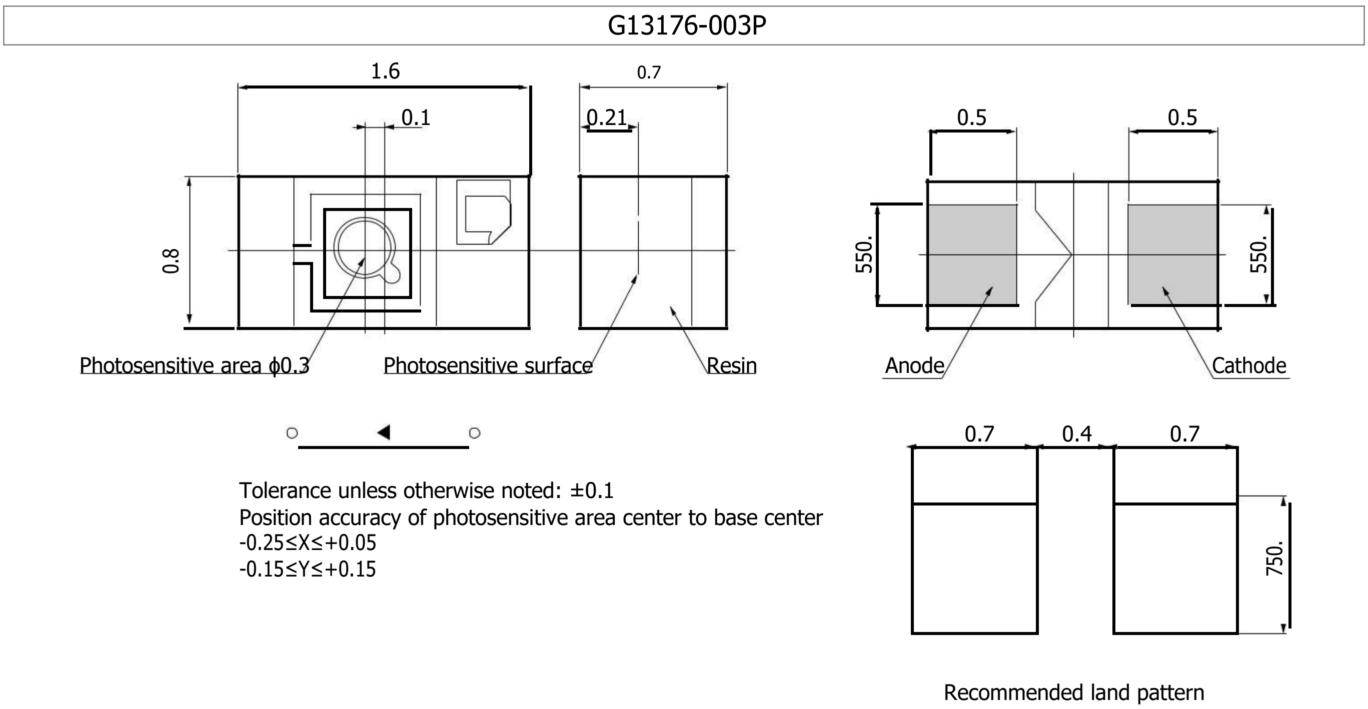
Recommended solder reflow conditions



- After unpacking, store the device in an environment at a temperature range of 5 to 30 °C and a humidity of 60% or less, and perform reflow soldering within 1 year.
- Therminal stress applied to the device during reflow soldering differs depending on the PC board and reflow oven being used.
- When setting the reflow conditions, make sure that the reflow soldering process does not degrade device reliability.

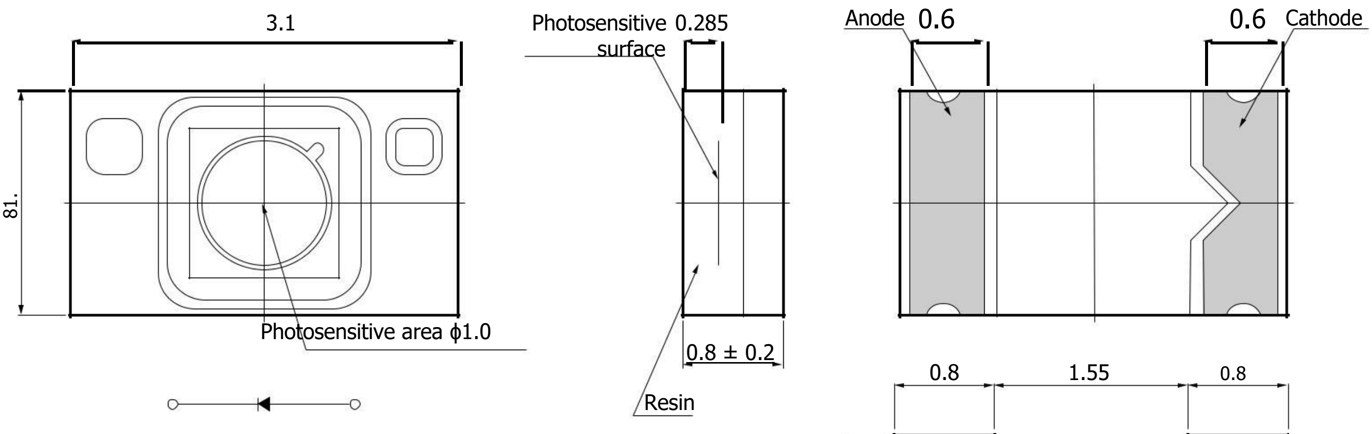
KIRDB0622EA

Dimensional outlines (unit: mm)

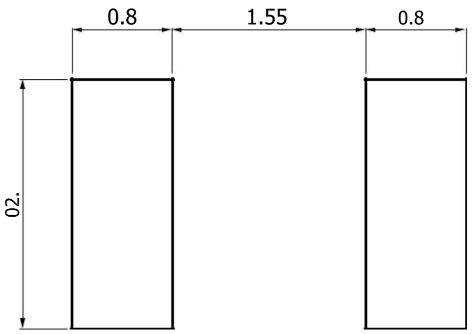


KIRDA0251EA

G13176-010P



Tolerance unless otherwise noted: ±0.1
Position accuracy of photosensitive area center to base center
-0.2≤X≤+0.2
-0.2≤Y≤+0.2



Recommended land pattern

KIRDA0252EA

Related information

www.hamamatsu.com/sp/ssd/doc_en.html

■ Precautions
- Disclaimer
- Surface mount type products

■ Technical information
- Infrared detector

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Appendix 6

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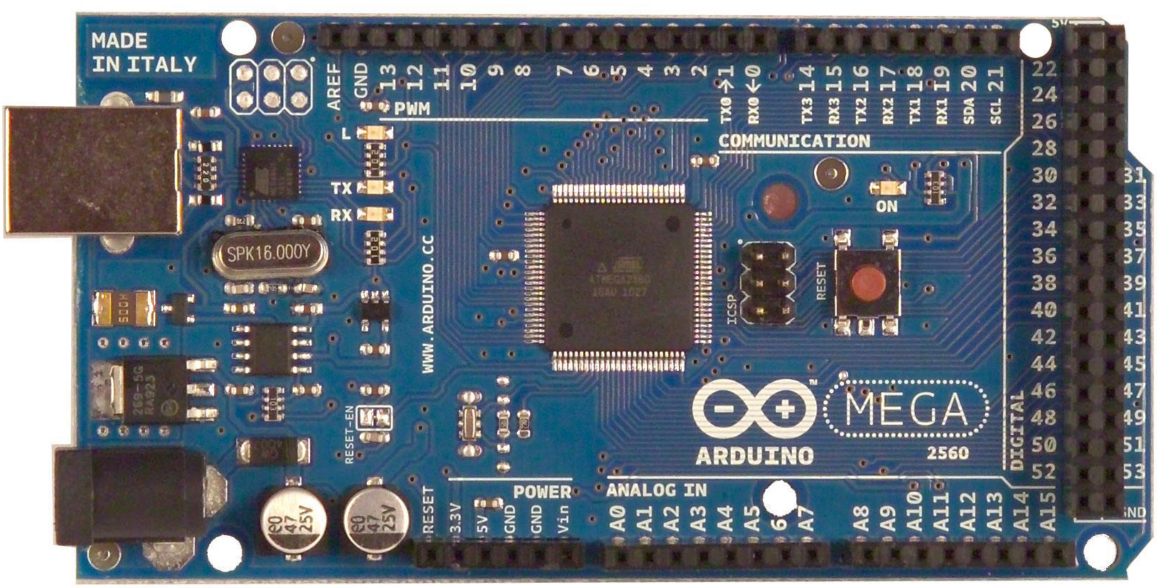
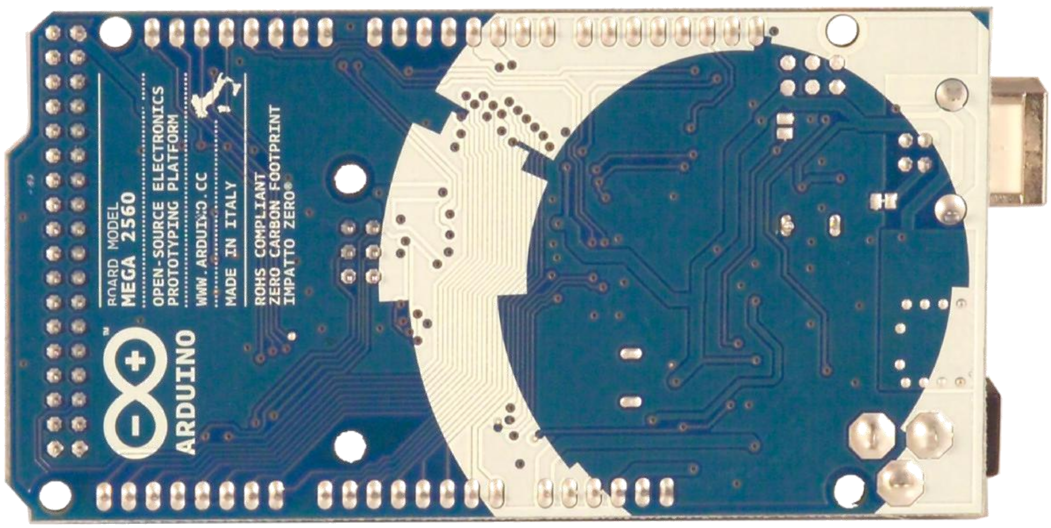
La robotique à votre service! - Robotics at your service!

ARDUINO

Arduino Mega 2560 Datasheet





Overview

The Arduino Mega 2560 is a microcontroller board based on the ATmega2560 (datasheet). It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The Mega is compatible with most shields designed for the Arduino Duemilanove or Diecimila.

Schematic & Reference Design

EAGLE files: arduino-mega2560-reference-design.zip

Schematic: arduino-mega2560-schematic.pdf

Summary

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 14 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

Power

The Arduino Mega can be powered via the USB connection or with an external power supply. The power source is selected automatically.

External (non-USB) power can come either from an AC-to-DC adapter (wall-wart) or battery. The adapter can be connected by plugging a 2.1mm center-positive plug into the board's power jack. Leads from a battery can be inserted in the Gnd and Vin pin headers of the POWER connector.

The board can operate on an external supply of 6 to 20 volts. If supplied with less than 7V, however, the 5V pin may supply less than five volts and the board may be unstable. If using more than 12V, the voltage regulator may overheat and damage the board. The recommended range is 7 to 12 volts.

The Mega2560 differs from all preceding boards in that it does not use the FTDI USB-to-serial driver chip. Instead, it features the Atmega8U2 programmed as a USB-to-serial converter.

The power pins are as follows:

- **VIN.** The input voltage to the Arduino board when it's using an external power source (as opposed to 5 volts from the USB connection or other regulated power source). You can supply voltage through this pin, or, if supplying voltage via the power jack, access it through this pin.
- **5V.** The regulated power supply used to power the microcontroller and other components on the board. This can come either from VIN via an on-board regulator, or be supplied by USB or another regulated 5V supply.
- **3V3.** A 3.3 volt supply generated by the on-board regulator. Maximum current draw is 50 mA.
- **GND.** Ground pins.

Memory

The ATmega2560 has 256 KB of flash memory for storing code (of which 8 KB is used for the bootloader), 8 KB of SRAM and 4 KB of EEPROM (which can be read and written with the EEPROM library).

Input and Output

Each of the 54 digital pins on the Mega can be used as an input or output, using pinMode() , digitalWrite(), and digitalRead() functions. They operate at 5 volts. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor (disconnected by default) of 20-50 kOhms. In addition, some pins have specialized functions:

- **Serial: 0 (RX) and 1 (TX); Serial 1: 19 (RX) and 18 (TX); Serial 2: 17 (RX) and 16 (TX); Serial 3: 15 (RX) and 14 (TX).** Used to receive (RX) and transmit (TX) TTL serial data. Pins 0 and 1 are also connected to the corresponding pins of the ATmega8U2 USB-to-TTL Serial chip.
- **External Interrupts: 2 (interrupt 0), 3 (interrupt 1), 18 (interrupt 5), 19 (interrupt 4), 20 (interrupt 3), and 21 (interrupt 2).** These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value. See the attachInterrupt() function for details.
- **PWM: 0 to 13.** Provide 8-bit PWM output with the analogWrite() function.
- **SPI: 50 (MISO), 51 (MOSI), 52 (SCK), 53 (SS).** These pins support SPI communication using the SPI library. The SPI pins are also broken out on the ICSP header, which is physically compatible with the Uno, Duemilanove and Diecimila.
- **LED: 13.** There is a built-in LED connected to digital pin 13. When the pin is HIGH

value, the LED is on, when the pin is LOW, it's off.
- **I2C: 20 (SDA) and 21 (SCL).** Support I2C (TWI) communication using the Wire library (documentation on the Wiring website). Note that these pins are not in the same location as the I2C pins on the Duemilanove or Diecimila.

The Mega2560 has 16 analog inputs, each of which provide 10 bits of resolution (i.e. 1024 different values). By default they measure from ground to 5 volts, though is it possible to change the upper end of their range using the AREF pin and analogReference() function.

There are a couple of other pins on the board:

- **AREF.** Reference voltage for the analog inputs. Used with analogReference().
- **Reset.** Bring this line LOW to reset the microcontroller. Typically used to add a reset button to shields which block the one on the board.

Communication

The Arduino Mega2560 has a number of facilities for communicating with a computer, another Arduino, or other microcontrollers. The ATmega2560 provides four hardware UARTs for TTL (5V) serial communication. An ATmega8U2 on the board channels one of these over USB and provides a virtual com port to software on the computer (Windows machines will need a .inf file, but OSX and Linux machines will recognize the board as a COM port automatically. The Arduino software includes a serial monitor which allows simple textual data to be sent to and from the board. The RX and TX LEDs on the board will flash when data is being transmitted via the ATmega8U2 chip and USB connection to the computer (but not for serial communication on pins 0 and 1).
A SoftwareSerial library allows for serial communication on any of the Mega2560's digital pins.
The ATmega2560 also supports I2C (TWI) and SPI communication. The Arduino software includes a Wire library to simplify use of the I2C bus; see the documentation on the Wiring website for details. For SPI communication, use the SPI library.

Programming

The Arduino Mega can be programmed with the Arduino software (download). For details, see the reference and tutorials.
The ATmega2560 on the Arduino Mega comes preburned with a bootloader that allows you to upload new code to it without the use of an external hardware programmer. It

communicates using the original STK500 protocol (reference, C header files).
You can also bypass the bootloader and program the microcontroller through the ICSP (In-Circuit Serial Programming) header; see these instructions for details.

Automatic (Software) Reset

Rather then requiring a physical press of the reset button before an upload, the Arduino Mega2560 is designed in a way that allows it to be reset by software running on a connected computer. One of the hardware flow control lines (DTR) of the ATmega8U2 is connected to the reset line of the ATmega2560 via a 100 nanofarad capacitor. When this line is asserted (taken low), the reset line drops long enough to reset the chip. The Arduino software uses this capability to allow you to upload code by simply pressing the upload button in the Arduino environment. This means that the bootloader can have a shorter timeout, as the lowering of DTR can be well-coordinated with the start of the upload.
This setup has other implications. When the Mega2560 is connected to either a computer running Mac OS X or Linux, it resets each time a connection is made to it from software (via USB). For the following half-second or so, the bootloader is running on the Mega2560. While it is programmed to ignore malformed data (i.e. anything besides an upload of new code), it will intercept the first few bytes of data sent to the board after a connection is opened.
If a sketch running on the board receives one-time configuration or other data when it first starts, make sure that the software with which it communicates waits a second after opening the connection and before sending this data.
The Mega2560 contains a trace that can be cut to disable the auto-reset. The pads on either side of the trace can be soldered together to re-enable it. It's labeled "RESET-EN". You may also be able to disable the auto-reset by connecting a 110 ohm resistor from 5V to the reset line; see this forum thread for details.

USB Overcurrent Protection

The Arduino Mega2560 has a resettable polyfuse that protects your computer's USB ports from shorts and overcurrent. Although most computers provide their own internal protection, the fuse provides an extra layer of protection. If more than 500 mA is applied to the USB port, the fuse will automatically break the connection until the short or overload is removed.

Physical Characteristics and Shield Compatibility

The maximum length and width of the Mega2560 PCB are 4 and 2.1 inches respectively, with the USB connector and power jack extending beyond the former dimension. Three screw holes allow the board to be attached to a surface or case. Note that the distance between digital pins 7 and 8 is 160 mil (0.16"), not an even multiple of the 100 mil spacing of the other pins.

The Mega2560 is designed to be compatible with most shields designed for the Uno, Diecimila or Duemilanove. Digital pins 0 to 13 (and the adjacent AREF and GND pins), analog inputs 0 to 5, the power header, and ICSP header are all in equivalent locations. Further the main UART (serial port) is located on the same pins (0 and 1), as are external interrupts 0 and 1 (pins 2 and 3 respectively). SPI is available through the ICSP header on both the Mega2560 and Duemilanove / Diecimila. *Please note that I$_2$C is not located on the same pins on the Mega (20 and 21) as the Duemilanove / Diecimila (analog inputs 4 and 5).*

Appendix 7

250 kSPS, 12-Bit Impedance Converter, Network Analyzer

Data Sheet **AD5934**

FEATURES

Programmable output peak-to-peak excitation voltage to a maximum frequency of 100 kHz
Programmable frequency sweep capability with serial I²C interface
Frequency resolution of 27 bits (<0.1 Hz) Impedance measurement range from 1 kΩ to 10 MΩ Capable of measuring 100 Ω to 1 kΩ with additional circuitry Phase measurement capability System accuracy of 0.5%

2.7 V to 5.5 V power supply operation Temperature range: −40°C to +125°C 16-lead SSOP package

APPLICATIONS

Electrochemical analysis
Bioelectrical impedance analysis
Impedance spectroscopy
Complex impedance measurement
Corrosion monitoring and protection equipment
Biomedical and automotive sensors
Proximity sensing
Nondestructive testing
Material property analysis
Fuel/battery cell condition monitoring

GENERAL DESCRIPTION

The AD5934 is a high precision impedance converter system solution that combines an on-board frequency generator with a 12-bit, 250 kSPS, analog-to-digital converter (ADC). The frequency generator allows an external complex impedance to be excited with a known frequency. The response signal from the impedance is sampled by the on-board ADC and a discrete Fourier transform (DFT) is processed by an on-board DSP engine. The DFT algorithm returns a real (R) and imaginary (I) data-word at each output frequency.

Once calibrated, the magnitude of the impedance and relative phase of the impedance at each frequency point along the sweep is easily calculated using the following two equations:

$$Magnitude = \sqrt{R^2 + I^2}$$

$$Phase = \tan^{-1}(I/R)$$

A similar device, available from Analog Devices, Inc., is the AD5933, which is a 2.7 V to 5.5 V, 1 MSPS, 12-bit impedance converter, with an internal temperature sensor, available in a 16-lead SSOP.

FUNCTIONAL BLOCK DIAGRAM

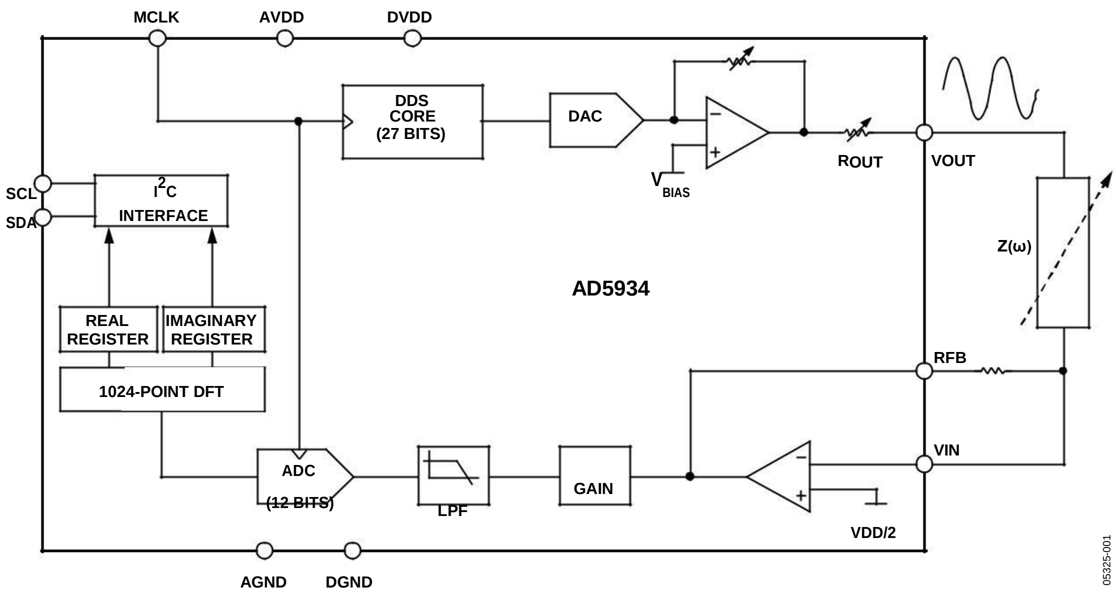


Figure 1.

Rev. E **Document Feedback**

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781.329.4700

Technical Support www.analog.com

SPECIFICATIONS

VDD = 3.3 V, MCLK = 16.776 MHz, 2 V p-p output excitation voltage @ 30 kHz, 200 kΩ connected between Pin 5 and Pin 6; feedback resistor = 200 kΩ connected between Pin 4 and Pin 5; PGA gain = ×1, unless otherwise noted.

Table 1.

Parameter	Y Version[1] Min	Typ	Max	Unit	Test Conditions/Comments
SYSTEM					
Impedance Range	1 k		10 M	Ω	100 Ω to 1 kΩ requires extra buffer circuitry, see Measuring Small Impedances section
Total System Accuracy		0.5		%	2 V p-p output excitation voltage at 30 kHz, 200 kΩ connected between Pin 5 and Pin 6
System Impedance Error Drift		30		ppm/°C	
TRANSMIT STAGE					
Output Frequency Range[2]	1		100	kHz	
Output Frequency Resolution		0.1		Hz	<0.1 Hz resolution achievable using direct digital synthesis (DDS) techniques
MCLK Frequency			16.776	MHz	Maximum system clock frequency
TRANSMIT OUTPUT VOLTAGE					
Range 1					
AC Output Excitation Voltage[3]		1.98		V p-p	Refer to Figure 4 for output voltage distribution
DC Bias[4]		1.48		V	DC bias of the ac excitation signal; see Figure 5
DC Output Impedance		200		Ω	T_A = 25°C
Short-Circuit Current to Ground at VOUT		±5.8		mA	T_A = 25°C
Range 2					
AC Output Excitation Voltage[3]		0.97		V p-p	See Figure 6
DC Bias[4]		0.76		V	DC bias of output excitation signal; see Figure 7
DC Output Impedance		2.4		kΩ	
Short-Circuit Current to Ground at VOUT		±0.25		mA	
Range 3					
AC Output Excitation Voltage[3]		0.383		V p-p	See Figure 8
DC Bias[4]		0.31		V	DC bias of output excitation signal; see Figure 9
DC Output Impedance		1		kΩ	
Short-Circuit Current to Ground at VOUT		±0.20		mA	
Range 4					
AC Output Excitation Voltage[3]		0.198		V p-p	See Figure 10
DC Bias[4]		0.173		V	DC bias of output excitation signal; see Figure 11
DC Output Impedance		600		Ω	
Short-Circuit Current to Ground at VOUT		±0.15		mA	
SYSTEM AC CHARACTERISTICS					
Signal-to-Noise Ratio		60		dB	
Total Harmonic Distortion		−52		dB	
Spurious-Free Dynamic Range					
Wide Band (0 MHz to 1 MHz)		−56		dB	
Narrow Band (±5 kHz)		−85		dB	

Parameter	Y Version[1] Min	Typ	Max	Unit	Test Conditions/Comments
RECEIVE STAGE					
Input Leakage Current		1		nA	To VIN pin
Input Capacitance[5]		0.01		pF	Pin capacitance between VOUT and GND
Feedback Capacitance, C_{FB}		3		pF	Feedback capacitance around current-to-voltage amplifier; appears in parallel with feedback resistor
ANALOG-TO-DIGITAL CONVERTER[5]					
Resolution		12		Bits	
Sampling Rate		250		kSPS	ADC throughput rate
LOGIC INPUTS					
Input High Voltage, V_{IH}	0.7 × VDD				
Input Low Voltage, V_{IL}			0.3 × VDD		
Input Current[6]			1	µA	T_A = 25°
Input Capacitance			7	pF	T_A = 25°C
POWER REQUIREMENTS					
VDD	2.7		5.5	V	
I_{DD}, Normal Mode		10	15	mA	VDD = 3.3 V
		17	25	mA	VDD = 5.5 V
I_{DD}, Standby Mode		7		mA	VDD = 3.3 V; see the Control Register section
		9		mA	VDD = 5.5 V
I_{DD}, Power-Down Mode		0.7	5	µA	VDD = 3.3 V
		1	8	µA	VDD = 5.5 V

[1] Temperature range for Y version = −40°C to +125°C, typical at +25°C.
[2] The lower limit of the output excitation frequency can be lowered by scaling the clock supplied to the AD5934.
[3] The peak-to-peak value of the ac output excitation voltage scales with supply voltage according to the following formula. VDD is the supply voltage. *Output Excitation Voltage* (V p-p) = [2/3.3] × *VDD*
[4] The dc bias value of the output excitation voltage scales with supply voltage according to the following formula. VDD is the supply voltage. *Output Excitation Voltage* (V p-p) = [2/3.3] × *VDD*
[5] Guaranteed by design or characterization, not production tested. Input capacitance at the VOUT pin is equal to pin capacitance divided by open-loop gain of current-to-voltage amplifier.
[6] The accumulation of the currents into Pin 8, Pin 15, and Pin 16.

I²C SERIAL INTERFACE TIMING CHARACTERISTICS

VDD = 2.7 V to 5.5 V; all specifications T_{MIN} to T_{MAX}, unless otherwise noted (see Figure 2).

Table 2.

Parameter[1]	Limit at T_{MIN}, T_{MAX}	Unit	Description
f_{SCL}	400	kHz max	SCL clock frequency
t_1	2.5	µs min	SCL cycle time
t_2	0.6	µs min	t_{HIGH}, SCL high time
t_3	1.3	µs min	t_{LOW}, SCL low time
t_4	0.6	µs min	$t_{HD, STA}$, start/repeated start condition hold time
t_5	100	ns min	$t_{SU, DAT}$, data setup time
t_6[2]	0.9	µs max	$t_{HD, DAT}$, data hold time
	0	µs min	$t_{HD, DAT}$, data hold time
t_7	0.6	µs min	$t_{SU, STA}$, setup time for repeated start
t_8	0.6	µs min	$t_{SU, STO}$, stop condition setup time
t_9	1.3	µs min	t_{BUF}, bus free time between a stop and a start condition
t_{10}	300	ns max	t_R, rise time of SDA when transmitting
	0	ns min	t_R, rise time of SCL and SDA when receiving (CMOS compatible)
t_{11}	300	ns max	t_F, fall time of SCL and SDA when transmitting
	0	ns min	t_F, fall time of SDA when receiving (CMOS compatible)
	250	ns max	t_F, fall time of SDA when receiving
	20 + 0.1 C_b[3]	ns min	t_F, fall time of SCL and SDA when transmitting
C_b	400	pF max	Capacitive load for each bus line

[1]Guaranteed by design and characterization, not production tested.
[2]A master device must provide a hold time of at least 300 ns for the SDA signal (referred to $V_{IH\,MIN}$ of the SCL signal) to bridge the undefined falling edge of SCL.
[3]C_b is the total capacitance of one bus line in pF. Note that t_R and t_F are measured between 0.3 VDD and 0.7 VDD.

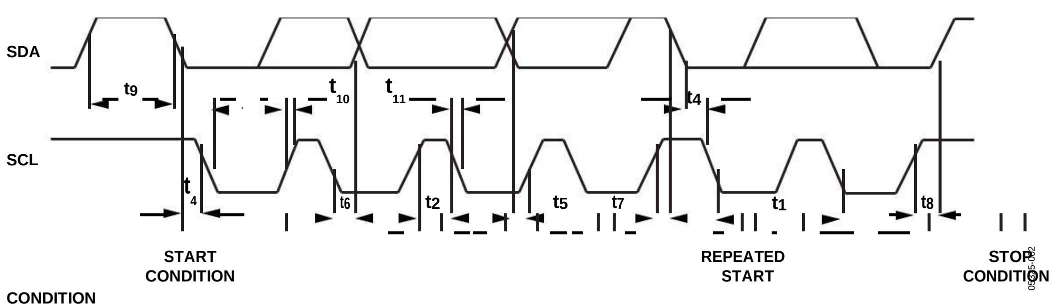


Figure 2. I²C Interface Timing Diagram

ABSOLUTE MAXIMUM RATINGS

T_A = 25°C, unless otherwise noted.

Table 3.

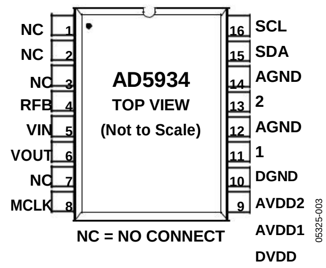
Parameter	Rating
DVDD to GND	−0.3 V to +7.0 V
AVDD1 to GND	−0.3 V to +7.0 V
AVDD2 to GND	−0.3 V to +7.0 V
SDA/SCL to GND	−0.3 V to VDD + 0.3 V
VOUT to GND	−0.3 V to VDD + 0.3 V
VIN to GND	−0.3 V to VDD + 0.3 V
MCLK to GND	−0.3 V to VDD + 0.3 V
Operating Temperatures	
Extended Industrial Range (Y Grade)	−40°C to +125°C
Storage Temperature Range	−65°C to +160°C
Maximum Junction Temperature	150°C
SSOP Package, Thermal Impedance	
θ_{JA}	139°C/W
θ_{JC}	136°C/W
Reflow Soldering (Pb-Free)	
Peak Temperature	260°C
Time at Peak Temperature	10 sec to 40 sec

Stresses at or above those listed under Absolute Maximum Ratings may cause permanent damage to the product. This is a stress rating only; functional operation of the product at these or any other conditions above those indicated in the operational section of this specification is not implied. Operation beyond the maximum operating conditions for extended periods may affect product reliability.

ESD CAUTION

ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.

PIN CONFIGURATION AND FUNCTION DESCRIPTIONS



NOTES:
1. IT IS RECOMMENDED TO TIE ALL SUPPLY CONNECTIONS (PIN 9, PIN 10, AND PIN 11) AND RUN FROM A SINGLE SUPPLY BETWEEN 2.7V AND 5.5V.
2. IT IS ALSO RECOMMENDED TO CONNECT ALL GROUND SIGNALS TOGETHER (PIN 12, PIN 13, AND PIN 14).

Figure 3. Pin Configuration

Table 4. Pin Function Descriptions

Pin No.	Mnemonic	Description
1 to 3, 7	NC	No Connect. Do not connect to this pin.
4	RFB	External Feedback Resistor. Connect from Pin 4 to Pin 5. This pin sets the gain of the current-to-voltage amplifier on the receive side.
5	VIN	Input to Receive Transimpedance Amplifier. VIN presents a virtual earth voltage of VDD/2.
6	VOUT	Excitation Voltage Signal Output.
8	MCLK	The master clock for the system is supplied by the user.
9	DVDD	Digital Supply Voltage.
10	AVDD1	Analog Supply Voltage 1. Used for powering the analog core.
11	AVDD2	Analog Supply Voltage 2. Used for internal references.
12	DGND	Digital Ground.
13	AGND1	Analog Ground 1.
14	AGND2	Analog Ground 2.
15	SDA	I^2C® Data Input.
16	SCL	I^2C Clock Input.

SYSTEM DESCRIPTION

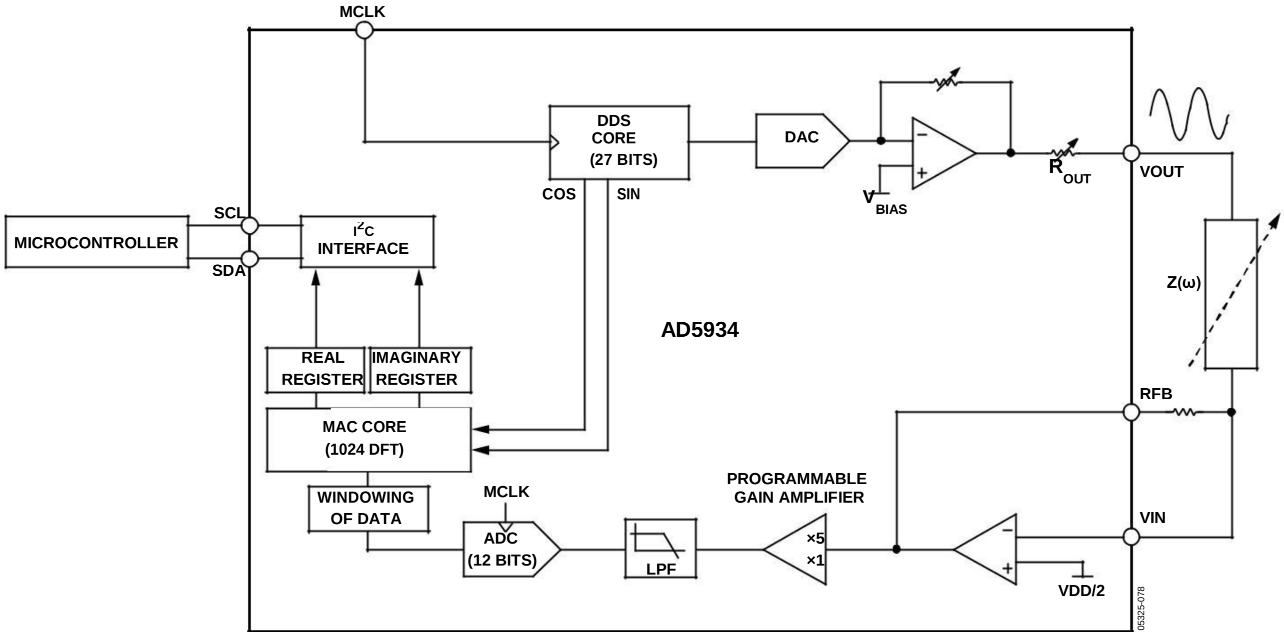


Figure 14. Block Overview

The AD5934 is a high precision, impedance converter system solution that combines an on-board frequency generator with a 12-bit, 250 kSPS ADC. The frequency generator allows an external complex impedance to be excited with a known frequency. The response signal from the impedance is sampled by the on-board ADC and DFT processed by an on-board DSP engine. The DFT algorithm returns both a real (R) and imaginary (I) data-word at each frequency point along the sweep. The impedance magnitude and phase is easily calculated using the following equations:

$$Magnitude = \sqrt{R^2 + I^2}$$

$$Phase = \tan^{-1}(I/R)$$

To characterize an impedance profile Z(ω), generally a frequency sweep is required such as that shown in Figure 15.

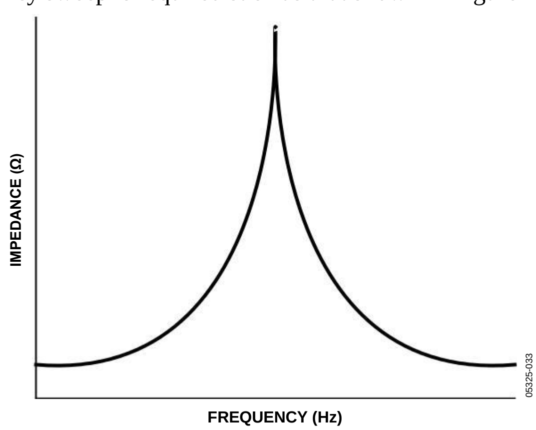


Figure 15. Impedance vs. Frequency Profile

The AD5934 permits the user to perform a frequency sweep with a user-defined start frequency, frequency resolution, and number of points in the sweep. In addition, the device allows the user to program the peak-to-peak value of the output sinusoidal signal as an excitation to the external unknown impedance connected between the VOUT and VIN pins.

Table 5 gives the four possible output peak-to-peak voltages and the corresponding dc bias levels for each range for 3.3 V. These values are ratiometric with VDD. So for a 5 V supply:

$$\textit{Output Excitation Voltage for Range 1} = 1.98 \times \frac{5.0}{3.3} = 3\text{ V p} - \text{p}$$

$$\textit{Output DC Bias Voltage for Range 1} = 1.48 \times \frac{5.0}{3.3} = 2.24\text{ V p} - \text{p}$$

Table 5. Voltage Levels Respective Bias Levels for 3.3 V

Range No.	Output Excitation Voltage Amplitude	Output DC Bias Level
1	1.98 V p-p	1.48 V
2	0.99 V p-p	0.74 V
3	383 mV p-p	0.31 V
4	198 mV p-p	0.179 V

The excitation signal for the transmit stage is provided on-chip using DDS techniques that permit subhertz resolution. The receive stage receives the input signal current from the unknown impedance, performs signal processing, and digitizes the result. The clock for the DDS is generated from an external reference clock that is provided by the user at MCLK.

TRANSMIT STAGE

As shown in Figure 16, the transmit stage of the AD5934 is made up of a 27-bit phase accumulator DDS core that provides the output excitation signal at a particular frequency. The input to the phase accumulator is taken from the contents of the start frequency register (see Register Address 0x82, Register Address 0x83, and Register Address 0x84). Although the phase accumulator offers 27 bits of resolution, the start frequency register has the three most significant bits (MSBs) set to 0 internally; therefore, the user has the ability to program only the lower 24 bits of the start frequency register.

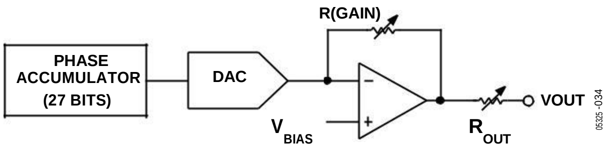


Figure 16. Transmit Stage

The AD5934 offers a frequency resolution programmable by the user down to 0.1 Hz. The frequency resolution is programmed via a 24-bit word loaded serially over the I^2C interface to the frequency increment register.

The frequency sweep is fully described by the programming of three parameters: the start frequency, the frequency increment, and the number of increments.

Start Frequency

This is a 24-bit word that is programmed to the on-board RAM at Register Address 0x82, Register Address 0x83, and Register Address 0x84 (see the Register Map section). The required code loaded to the start frequency register is the result of the formula shown in Equation 1, based on the master clock frequency and the required start frequency output from the DDS.

$$\text{Start Frequency Code} = \left(\frac{\text{Required Output Start Frequency}}{\left(\frac{MCLK}{16}\right)}\right) \times 2^{27} \quad (1)$$

For example, if the user requires the sweep to begin at 30 kHz and has a 16 MHz clock signal connected to MCLK, the code that needs to be programmed is given by

$$\text{Start Frequency Code} = \left(\frac{30\text{ kHz}}{\frac{16\text{ MHz}}{16}}\right) \times 2^{27} = \text{0x3D70A3}$$

The user programs the value of 0x3D to Register Address 0x82, the value 0x70 to Register Address 0x83, and the value 0xA3 to Register Address 0x84.

Frequency Increment

This is a 24-bit word that is programmed to the on-board RAM at Register Address 0x85, Register Address 0x86, and Register Address 0x87 (see the Register Map section). The required code loaded to the frequency increment register is the result of the formula shown in Equation 2, based on the master clock frequency and the required increment frequency output from the DDS.

$$\text{Frequency Increment Code} = \left(\frac{\text{Required Frequency Increment}}{\left(\frac{MCLK}{16}\right)}\right) \times 2^{27} \quad (2)$$

For example, if the user requires the sweep to have a resolution of 10 Hz and has a 16 MHz clock signal connected to MCLK, the code that needs to be programmed is given by

$$\text{Frequency Increment Code} = \left(\frac{10\text{ Hz}}{\frac{16\text{ MHz}}{16}}\right) \equiv \text{0x00053E}$$

The user programs the value 0x00 to Register Address 0x85, the value 0x05 to Register Address 0x86, and the value 0x3E to Register Address 0x87.

Number of Increments

This is a 9-bit word that represents the number of frequency points in the sweep. The number is programmed to the on-board RAM at Register Address 0x88 and Register Address 0x89 (see the Register Map section). The maximum number of points that can be programmed is 511.

For example, if the sweep needs 150 points, the user programs the value 0x00 to Register Address 0x88 and the value 0x96 to Register Address 0x89.

Once the three parameter values are programmed, the sweep is initiated by issuing a start frequency sweep command to the control register at Register Address 0x80 and Register Address 0x81 (see the Register Map section). Bit D2 in the status register (Register Address 0x8F) indicates the completion of the frequency measurement for each sweep point. Incrementing to the next frequency sweep point is under the control of the user. The measured result is stored in the two register groups that follow: 0x94, 0x95 (real data) and 0x96, 0x97 (imaginary data) that should be read before issuing an increment frequency command to the control register to move to the next sweep point. There is the facility to repeat the current frequency point measurement by issuing a repeat frequency command to the control register. This has the benefit of allowing the user to average successive readings. When the frequency sweep has completed all frequency points, Bit D3 in the status register is set, indicating the completion of the sweep. Once this bit is set, further increments are disabled.

FREQUENCY SWEEP COMMAND SEQUENCE

The following sequence must be followed to implement a frequency sweep:

1. Enter standby mode. Prior to issuing a start frequency sweep command, the device must be placed in standby mode by issuing an enter standby mode command to the control register (Register Address 0x80 and Register Address 0x81). In this mode, the VOUT and VIN pins are connected internally to ground so there is no dc bias across the external impedance or between the impedance and ground.
2. Enter initialize mode. In general, high Q complex circuits require a long time to reach steady state. To facilitate the measurement of such impedances, this mode allows the user full control of the settling time requirement before entering start frequency sweep mode where the impedance measurement takes place.

   An initialize with start frequency command to the control register enters initialize mode. In this mode, the impedance is excited with the programmed start frequency but no measurement takes place. The user times out the required settling time before issuing a start frequency sweep command to the control register to enter the start frequency sweep mode.
3. Enter start frequency sweep mode. The user enters this mode by issuing a start frequency sweep command to the control register. In this mode, the ADC starts measuring after the programmed number of settling time cycles elapses. The user can program an integer number of output frequency cycles (settling time cycles) to Register Address 0x8A and Register Address 0x8B before beginning the measurement at each frequency point (see Figure 24).

   The DDS output signal is passed through a programmable gain stage to generate the four ranges of peak-to-peak output excitation signals listed in Table 5. The peak-to-peak output excitation voltage is selected by setting Bit D10 and Bit D9 in the control register (see the Control Register section) and is made available at the VOUT pin.

RECEIVE STAGE

The receive stage comprises a current-to-voltage amplifier, followed by a programmable gain amplifier (PGA), antialiasing filter, and ADC. The receive stage schematic is shown in Figure 17. The unknown impedance is connected between the VOUT and VIN pins. The first stage current-to-voltage amplifier configuration means that a voltage present at the VIN pin is a virtual ground with a dc value set at VDD/2. The signal current that is developed across the unknown impedance flows into the VIN pin and develops a voltage signal at the output of the current-to-voltage converter. The gain of the current-to voltage amplifier is determined by a user-selectable feedback resistor connected between Pin 4 (RFB) and Pin 5 (VIN). It is important for the user to choose a feedback resistance value which, in conjunction with the selected gain of the PGA stage, maintains the signal within the linear range of the ADC (0 V to VDD).

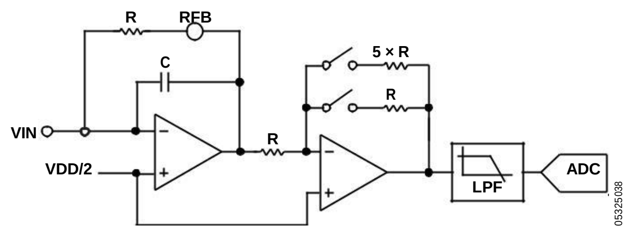


Figure 17. Receive Stage

The PGA allows the user to gain the output of the current-to-voltage amplifier by a factor of 5 or 1 depending upon the status of Bit D8 in the control register (see the Register Map section Register Address 0x80). The signal is then low-pass filtered and presented to the input of the 12-bit, 250 kSPS ADC.

The digital data from the ADC is passed directly to the DSP core of the AD5934 that performs a DFT on the sampled data.

DFT OPERATION

A DFT is calculated for each frequency point in the sweep. The AD5934 DFT algorithm is represented by

$$X(f) = \sum_{n=0}^{1023} \left(x(n)(\cos(n) - j\sin(n)) \right)$$

where:
$X(f)$ is the power in the signal at the Frequency Point f.
$x(n)$ is the ADC output.
$\cos(n)$ and $\sin(n)$ are the sampled test vectors provided by the DDS core at the Frequency f.

The multiplication is accumulated over 1024 samples for each frequency point. The result is stored in two 16-bit registers representing the real and imaginary components of the result. The data is stored in twos complement format.

IMPEDANCE CALCULATION

MAGNITUDE CALCULATION

The first step in the impedance calculation for each frequency point is to calculate the magnitude of the DFT at that point.

The DFT magnitude is given by

$$Magnitude = \sqrt{R^2 + I^2}$$

where:
R is the real number stored at Register Address 0x94 and Register Address 0x95.
I is the imaginary number stored at Register Address 0x96 and Register Address 0x97.

For example, assume the results in the real data and imaginary data registers are as follows at a frequency point:

Real Data Register = 0x038B = 907 decimal

Imaginary Data Register = 0x0204 = 516 decimal

$$Magnitude = \sqrt{(907^2 + 516^2)} = 1043.506$$

To convert this number into impedance, it must be multiplied by a scaling factor called the gain factor. The gain factor is calculated during the calibration of the system with a known impedance connected between the VOUT and VIN pins.

Once the gain factor is calculated, it can be used in the calculation of any unknown impedance between the VOUT and VIN pins.

GAIN FACTOR CALCULATION

An example of a gain factor calculation follows, with these assumptions:

Output excitation voltage = 2 V p-p
Calibration impedance value, $Z_{CALIBRATION}$ = 200 kΩ PGA gain = ×1
Current-to-voltage amplifier gain resistor = 200 kΩ Calibration frequency = 30 kHz

The typical contents of the real data and imaginary data registers after a frequency point conversion would then be

Real Data Register = 0xF064 = −3996 decimal

Imaginary Data Register = 0x227E = +8830 decimal

$$Magnitude = \sqrt{(-3996)^2 + (8830)^2} = 9692.106$$

Gain Factor =

$$\frac{Admittance}{Code} = \frac{\frac{1}{Impedance}}{Magnitude}$$

$$Gain\ Factor = \frac{\frac{1}{200\ k\Omega}}{9692.106} = 515.819 \times 10^{-12}$$

IMPEDANCE CALCULATION USING GAIN FACTOR

The next example illustrates how the calculated gain factor derived previously is used to measure an unknown impedance. For this example, assume that the unknown impedance is 510 kΩ.

After measuring the unknown impedance at a frequency of 30 kHz, assume that the real data and imaginary data registers contain the following data:

Real Data Register = 0xFA3F = −1473 decimal

Imaginary Data Register = 0x0DB3 = +3507 decimal

$$Magnitude = \sqrt{((-1473)^2 + (3507)^2)} = 3802.863$$

The measured impedance at the frequency point is then given by

$$Impedance = \frac{1}{Gain\ Factor \times Magnitude}$$

$$= \frac{1}{515.819273 \times 10^{-12} \times 3802.863\ \Omega} = 509.791\ k\Omega$$

GAIN FACTOR VARIATION WITH FREQUENCY

Because the AD5934 has a finite frequency response, the gain factor also shows a variation with frequency. This variation in gain factor results in an error in the impedance calculation over a frequency range. Figure 18 shows an impedance profile based on a single-point gain factor calculation. To minimize this error, the frequency sweep should be limited to as small a frequency range as possible.

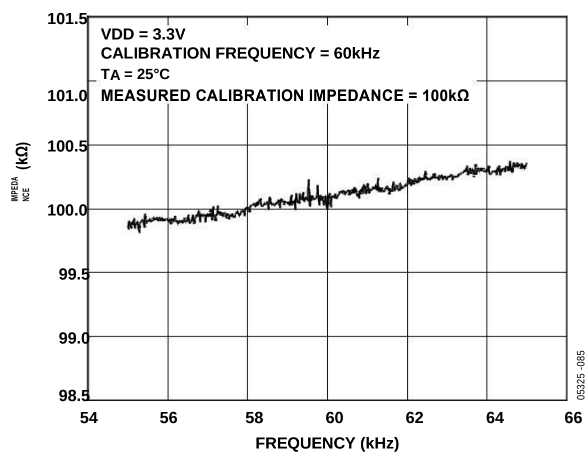


Figure 18. Impedance Profile Using a Single-Point Gain Factor Calculation

2-POINT CALIBRATION

Alternatively, it is possible to minimize this error by assuming that the frequency variation is linear and adjusting the gain factor with a 2-point calibration. Figure 19 shows an impedance profile based on a 2-point gain factor calculation.

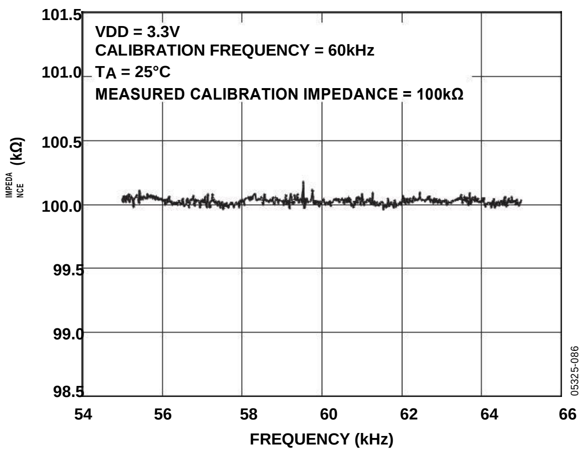


Figure 19. Impedance Profile Using a 2-Point Gain Factor Calculation

2-POINT GAIN FACTOR CALCULATION

This is an example of a 2-point gain factor calculation assuming the following:

Output excitation voltage = 2 V p-p
Calibration impedance value, $Z_{UNKNOWN}$ = 100.0 kΩ
PGA gain = ×1
Supply voltage = 3.3 V
Current-to-voltage amplifier gain resistor = 100 kΩ
Calibration frequencies = 55 kHz and 65 kHz

Typical values of the gain factor calculated at the two calibration frequencies read

Gain factor calculated at 55 kHz is 1.031224×10^{-9}.
Gain factor calculated at 65 kHz is 1.035682×10^{-9}.
Difference in gain factor (ΔGF) is
$1.035682 \times 10^{-9} - 1.031224 \times 10^{-9} = 4.458000 \times 10^{-12}$.
Frequency span of sweep (ΔF) is 10 kHz.

Therefore, the gain factor required at 60 kHz is given by

$$\frac{4.458000\text{E} -12}{10 \text{ kHz}} \times 5 \text{ kHz} + 1.031224 \times 10^{-9}$$

The required gain factor is 1.033453×10^{-9}.

The impedance is calculated as previously described in the Impedance Calculation section.

GAIN FACTOR SETUP CONFIGURATION

When calculating the gain factor, it is important that the receive stage is operating in its linear region. This requires careful selection of the excitation signal range, current-to-voltage gain resistor and PGA gain. The gain through the system shown in Figure 20 is given by

$$\text{Output Excitation Voltage Range} \times \frac{\text{Gain Setting Resistor}}{Z_{UNKNOWN}} \times \text{PGA Gain}$$

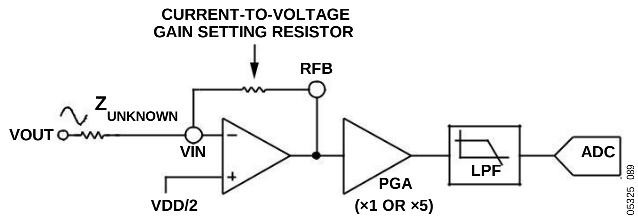


Figure 20. System Voltage Gain

For this example, assume the following system settings:

VDD = 3.3 V
Gain setting resistor = 200 kΩ
$Z_{UNKNOWN}$ = 200 kΩ
PGA setting = ×1

The peak-to-peak voltage presented to the ADC input is 2 V p-p. However, had the user chosen a PGA gain of ×5, the voltage would saturate the ADC.

GAIN FACTOR RECALCULATION

The gain factor must be recalculated for a change in any of the following parameters:

- Current-to-voltage gain setting resistor
- Output excitation voltage
- PGA gain

GAIN FACTOR TEMPERATURE VARIATION

The typical impedance error variation with temperature is in the order of 30 ppm/°C. Figure 21 shows an impedance profile with a variation in temperature for 100 kΩ impedance using a 2-point gain factor calibration.

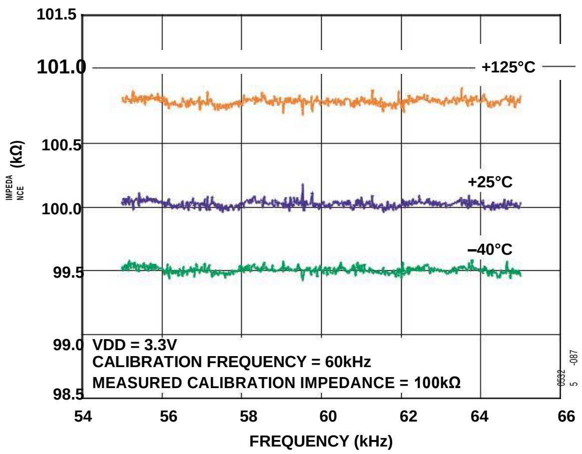


Figure 21. Impedance Profile Variation with Temperature Using a 2-Point Gain Factor Calibration

IMPEDANCE ERROR

Refer to Circuit Note CN-0217 on the AD5933 product page, which highlights a method to improve accuracy. The EVAL-AD5933EBZ board can be used to evaluate the AD5934 performance.

MEASURING THE PHASE ACROSS AN IMPEDANCE

The AD5934 returns a complex output code made up of a separate real and imaginary components. The real component is stored at Register Address 0x94 and Register Address 0x95, and the imaginary component is stored at Register Address 0x96 and Register Address 0x97 after each sweep measurement. These correspond to the real and imaginary components of the DFT and not the resistive and reactive components of the impedance under test.

For example, it is a common misconception to assume that if a user was analyzing a series RC circuit that the real value stored in Register Address 0x94 and Register Address 0x95 and the imaginary value stored in Register Address 0x96 and Register Address 0x97 would correspond to the resistance and capacitive reactance, respectfully. However, this is incorrect because the magnitude of the impedance (|Z|) can be calculated by calculating the magnitude of the real and imaginary components of the DFT given by the following formula:

$$Magnitude = \sqrt{R^2 + I^2}$$

After each measurement, multiply it by the calibration term and invert the product. Therefore, the magnitude of the impedance is given by the following formula:

$$Impedance = \frac{1}{Gain\ Factor \times Magnitude}$$

Where the gain factor is given by

$$Gain\ Factor = \frac{Admittance}{Code} = \frac{\left(\frac{1}{Impedance}\right)}{Magnitude}$$

The user must calibrate the AD5934 system for a known impedance range to determine the gain factor before any valid measurement can take place. Therefore, the user must know the impedance limits of the complex impedance ($Z_{UNKNOWN}$) for the sweep frequency range of interest. The gain factor is simply determined by placing a known impedance between the input/ output of the AD5934 and measuring the resulting magnitude of the code. The AD5934 system gain settings need to be chosen to place the excitation signal in the linear region of the on-board ADC.

Because the AD5934 returns a complex output code made up of real and imaginary components, the user is also able to calculate the phase of the response signal through the signal path of the AD5934. The phase is given by the following formula:

$$Phase\ (\text{rads}) = \tan^{-1}(I/R) \quad (3)$$

The phase measured by Equation 3 accounts for the phase shift introduced to the DDS output signal as it passes through the internal amplifiers on the transmit and receive side of the AD5934, along with the low-pass filter, and also the impedance connected between the VOUT and VIN pins of the AD5934.

The parameters of interest for many users are the magnitude of the impedance ($|Z_{UNKNOWN}|$) and the impedance phase (ZØ).The measurement of the impedance phase (ZØ) is a 2-step process.

The first step involves calculating the AD5934 system phase. The AD5934 system phase can be calculated by placing a resistor across the VOUT and VIN pins of the AD5934 and calculating the phase (using Equation 3) after each measurement point in the sweep. By placing a resistor across the VOUT and VIN pins, there is no additional phase lead or lag introduced to the AD5934 signal path, and the resulting phase is due entirely to the internal poles of the AD5934, that is, the system phase.

Once the system phase is calibrated using a resistor, the second step involves calculating the phase of any unknown impedance can be calculated by inserting the unknown impedance between the VIN and VOUT terminals of the AD5934 and recalculating the new phase (including the phase due to the impedance) using the same formula. The phase of the unknown impedance (ZØ) is given by

$$Z\text{Ø} = (\Phi unknown - \nabla system)$$

where:

$\nabla system$ is the phase of the system with a calibration resistor connected between VIN and VOUT.

$\Phi unknown$ is the phase of the system with the unknown impedance connected between VIN and VOUT.

ZØ is the phase due to the impedance, that is, the impedance phase.

Note that it is possible to calculate the gain factor and to calibrate the system phase using the same real and imaginary component values when a resistor is connected between the VOUT and VIN pins of the AD5934, for example, measuring the impedance phase (ZØ) of a capacitor.

The excitation signal current leads the excitation signal voltage across a capacitor by −90 degrees. Therefore, an approximate −90 degrees phase difference between the system phase responses measured with a resistor and the system phase responses measured with a capacitive impedance exists.

As previously outlined, if the user wants to determine the phase angle of the capacitive impedance (ZØ), the user first must determine the system phase response (∇system) and subtract this from the phase calculated with the capacitor connected between VOUT and VIN (Φunknown).

Figure 22 shows the AD5934 system phase response calculated using a 220 kΩ calibration resistor (R_{FB} = 220 kΩ, PGA = ×1) and the repeated phase measurement with a 10 pF capacitive impedance.

One important point to note about the phase formula used to plot Figure 22 is that it uses the arctangent function that returns a phase angle in radians and, therefore, it is necessary to convert from radians to degrees.

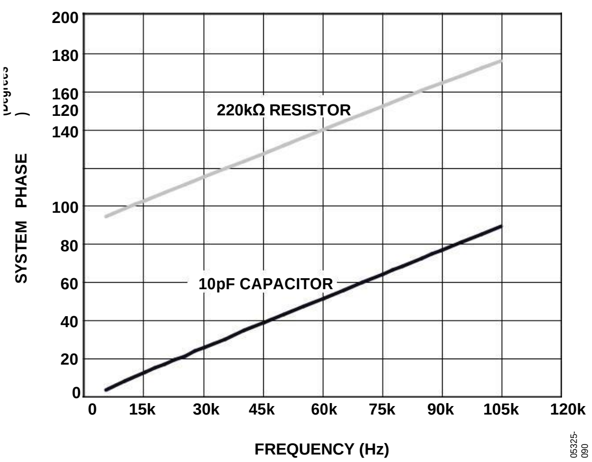


Figure 22. System Phase Response vs. Capacitive Phase

The phase difference (that is, ZØ) between the phase response of a capacitor and the system phase response using a resistor is the impedance phase of the capacitor (ZØ) and is shown in Figure 23.

In addition, when using the real and imaginary values to interpret the phase at each measurement point, care should be taken when using the arctangent formula. The arctangent function only returns the correct standard phase angle when the sign of the real and imaginary values are positive, that is, when the coordinates lie in the first quadrant. The standard angle is taken counterclockwise from the positive real x-axis. If the sign of the real component is positive and the sign of the imaginary component is negative, that is, the data lies in the second quadrant, the arctangent formula returns a negative angle, and it is necessary to add an additional 180° to calculate the correct standard angle. Likewise, when the real and imaginary components are both negative, that is, when data lies in the third quadrant, the arctangent formula returns a positive angle, and it is necessary to add an additional 180° to calculate the correct standard phase. When the real component is positive and the imaginary component is negative, that is, the data lies in the fourth quadrant, the arctangent formula returns a negative angle, and it is necessary to add an additional 360° to calculate the correct standard phase.

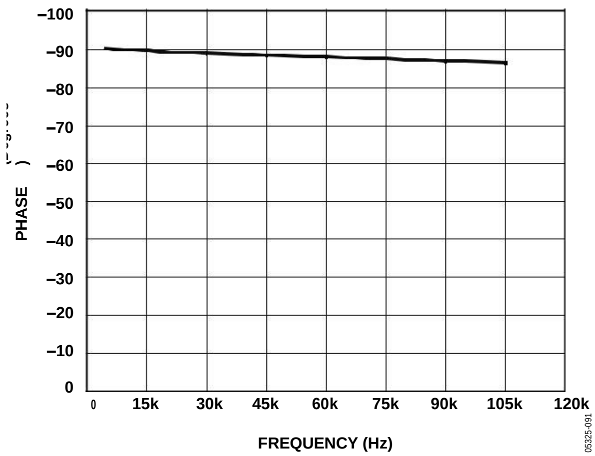


Figure 23. Phase Response of a Capacitor

Therefore, the correct standard phase angle is dependent upon the sign of the real and imaginary components, which is summarized in Table 6.

Table 6. Phase Angle

Real	Imaginary	Quadrant	Phase Angle
Positive	Positive	First	$\tan^{-1}(I/R) \times \frac{180°}{\pi}$
Positive	Negative	Second	$180° + \tan^{-1}(I/R) \times \frac{180°}{\pi}$
Negative	Negative	Third	$180° + \tan^{-1}(I/R) \times \frac{180°}{\pi}$
Negative	Positive	Fourth	$360° + \tan^{-1}(I/R) \times \frac{180°}{\pi}$

Once the magnitude of the impedance (|Z|) and the impedance phase angle (ZØ, in radians) are correctly calculated, it is possible to determine the magnitude of the real (resistive) and imaginary (reactive) components of the impedance ($Z_{UNKNOWN}$) by the vector projection of the impedance magnitude onto the real and imaginary impedance axis using the following formulas:

The real component is given by

$$|Z_{REAL}| = |Z| \times \cos(ZØ)$$

The imaginary component is given

by $|Z_{IMAG}| = |Z| \times \sin(ZØ)$

PERFORMING A FREQUENCY SWEEP

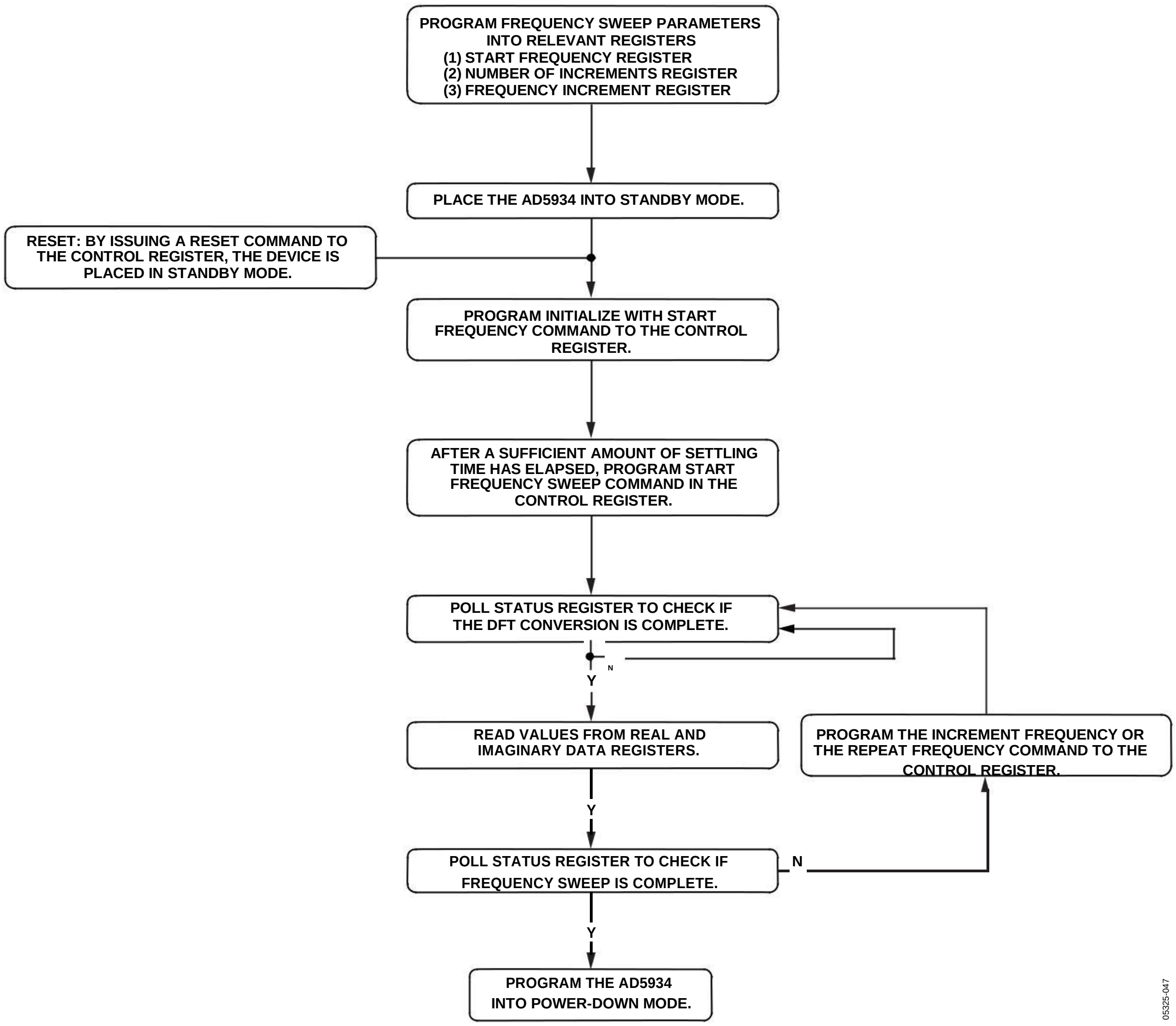


Figure 24. Frequency Sweep Flowchart

REGISTER MAP

Table 7.

Register Name	Register Address	Bits	Function
Control	0x80	D15 to D8	Read/write
	0x81	D7 to D0	Read/write
Start Frequency	0x82	D23 to D16	Read/write
	0x83	D15 to D8	Read/write
	0x84	D7 to D0	Read/write
Frequency Increment	0x85	D23 to D16	Read/write
	0x86	D15 to D8	Read/write
	0x87	D7 to D0	Read/write
Number of Increments	0x88	D15 to D8	Read/write
	0x89	D7 to D0	Read/write
Number of Settling Time Cycles	0x8A	D15 to D8	Read/write
	0x8B	D7 to D0	Read/write
Status	0x8F	D7 to D0	Read only
Real Data	0x94	D15 to D8	Read only
	0x95	D7 to D0	Read only
Imaginary Data	0x96	D15 to D8	Read only
	0x97	D7 to D0	Read only

CONTROL REGISTER (REGISTER ADDRESS 0x80, REGISTER ADDRESS 0x81)

The AD5934 contains a 16-bit control register (Register Address 0x80 and Register Address 0x81) that sets the control modes. The default value of the control register upon reset is as follows: D15 to D0 is reset to 0xA008 upon power-up.

The four MSBs of the control register are decoded to provide control functions, such as performing a frequency sweep, powering down the part, and controlling various other functions defined in the control register map.

The user can choose to write only to Register Address 0x80 and to not alter the contents of Register Address 0x81. Note that the control register should not be written to as part of a block write command. The control register also allows the user to program the excitation voltage and set the system clock. A reset command to the control register does not reset any programmed values associated with the sweep (that is, start frequency, number of increments, frequency increment). After a reset command, an initialize with start frequency command must be issued to the control register to restart the frequency sweep sequence (see Figure 24).

Table 8. D10 to D9 Control Register Map

D10	D9	Range No.	Output Voltage Range
0	0	1	2.0 V p-p typical
0	1	3	200 mV p-p typical
1	0	4	400 mV p-p typical
1	1	2	1.0 V p-p typical

Table 9. D11 and D8 to D0 Control Register Map

Bits	Description
D11	No operation
D8	PGA gain; 0 = ×5, 1 = ×1
D7	Reserved; set to 0
D6	Reserved; set to 0
D5	Reserved; set to 0
D4	Reset
D3	Reserved; set to 1
D2	Reserved; set to 0
D1	Reserved; set to 0
D0	Reserved; set to 0

Table 10. D15 to D12 Control Register Map

D15	D14	D13	D12	Description
0	0	0	0	No operation
0	0	0	1	Initialize with start frequency
0	0	1	0	Start frequency sweep
0	0	1	1	Increment frequency
0	1	0	0	Repeat frequency
1	0	0	0	No operation
1	0	0	1	No operation
1	0	1	0	Power-down mode
1	0	1	1	Standby mode
1	1	0	0	No operation
1	1	0	1	No operation

Control Register Decode

Initialize with Start Frequency

This command enables the DDS to output the programmed start frequency for an indefinite time. Initially, it is used to excite the unknown impedance. When the output unknown impedance has settled after a time determined by the user, the user must initiate a start frequency sweep command to begin the frequency sweep.

Start Frequency Sweep

In this mode, the ADC starts measuring after the programmed number of settling time cycles has elapsed. The user has the ability to program an integer number of output frequency cycles (settling time cycles) to Register Address 0x8A and Register Address 0x8B before the commencement of the measurement at each frequency point (see Figure 24).

Increment Frequency

The increment frequency command is used to step to the next frequency point in the sweep. This usually happens after data from the previous step is transferred and verified by the DSP. When the AD5934 receives this command, it waits for the programmed number of settling time cycles before beginning the ADC conversion process.

Repeat Frequency

There is the facility to repeat the current frequency point measurement by issuing a repeat frequency command to the control register. This command allows users to average successive readings.

Power-Down Mode

The default state at power-up of the AD5934 is power-down mode. The control register contains the code 1010,0000,0000,0000 (0xA000). In this mode, both the output and input pins, VOUT and VIN, are connected internally to GND.

Standby Mode

This mode powers up the part for general operation. In standby mode, the VIN and VOUT pins are internally connected to GND.

Reset

A reset command allows the user to interrupt a sweep. The start frequency, number of increments, and frequency increment register contents are not overwritten. An initialize with start frequency command is required to restart the frequency sweep command sequence.

Output Voltage Range

The output voltage range allows the user to program the excitation voltage range at VOUT.

PGA Gain

The PGA gain allows the user to amplify the response signal into the ADC by a multiplication factor of ×5 or ×1.

START FREQUENCY REGISTER (REGISTER ADDRESS 0x82, REGISTER ADDRESS 0x83, REGISTER ADDRESS 0x84)

The start frequency register contains the 24-bit digital representation of the frequency from where the subsequent frequency sweep is initiated. For example, if the user requires the sweep to start from a frequency of 30 kHz using a 16.0 MHz clock, the user must program the value 0x3D to Register Address 0x82, the value 0x70 to Register Address 0x83, and the value 0xA3 to Register Address 0x84. Doing this ensures the output frequency starts at 30 kHz.

The start frequency code is

Start Frequency Code =

$$\frac{30\ \text{kHz}}{\left(\frac{16\ \text{MHz}}{16}\right)} \times 2^{27} \equiv \text{0x3D70A3}$$

The default value of the start frequency register upon reset is as follows: D23 to D0 are not reset at power-up. After the reset command, the contents of this register are not reset.

FREQUENCY INCREMENT REGISTER (REGISTER ADDRESS 0x85, REGISTER ADDRESS 0x86, REGISTER ADDRESS 0x87)

The frequency increment register contains a 24-bit representation of the frequency increment between consecutive frequency points along the sweep. For example, if the user requires an increment step of 30 Hz using a 16.0 MHz clock, the user must program the value 0x00 to Register Address 0x85, the value 0x0F to Register Address 0x86, and the value 0xBA to Register Address 0x87.

The formula for calculating the frequency increment is given by

Frequency Increment Code =

$$\frac{10\ \text{Hz}}{\left(\frac{16\ \text{MHz}}{16}\right)} \times 2^{27} \equiv \text{0x00053E}$$

The user programs the value 0x00 to Register Address 0x85, the value 0x05 to Register Address 0x86, and the value 0x3E to Register Address 0x87.

The default value of the frequency increment register upon reset is as follows: D23 to D0 are not reset at power-up. After the reset command, the contents of this register are not reset.

NUMBER OF INCREMENTS REGISTER (REGISTER ADDRESS 0x88, REGISTER ADDRESS 0x89)

The default value of the number of increments register upon reset is as follows: D8 to D0 are not reset at power-up. After a reset command, the contents of this register are not reset.

Table 11. Number of Increments Register

Reg Addr	Bits	Description	Function	Format
0x88	D15 to D9 D8	Don't care Number of increments	Read or write Read or write	Integer number stored in binary format
0x89	D7 to D0	Number of increments	Read or write	Integer number stored in binary format

This register determines the number of frequency points in the frequency sweep. The number of frequency points is represented by a 9-bit word, D8 to D0. D15 to D9 are don't care bits. This register in conjunction with the start frequency register and the frequency increment register determine the frequency sweep range for the sweep operation. The maximum number of increments that can be programmed is 511.

NUMBER OF SETTLING TIME CYCLES REGISTER (REGISTER ADDRESS 0x8A, REGISTER ADDRESS 0x8B)

The default value of the number of settling time cycles register upon reset is as follows: D10 to D0 are not reset at power-up. After a reset command, the contents of this register are not reset.

This register determines the number of output excitation cycles allowed to passthrough the unknown impedance after receipt of a start frequency sweep, increment frequency, or repeat frequency command, before the ADC is triggered to perform a conversion of the response signal. The number of settling time cycles register value determines the delay between a start frequency sweep/ increment frequency/repeat frequency command and the time an ADC conversion commences. The number of cycles is represented by a 9-bit word, D8 to D0. The value programmed into the number of settling time cycles register can be increased by a factor of 2 or 4, depending on the status of Bits D10 to D9. The five most significant bits, D15 to D11, are don't care bits.

The maximum number of output cycles that can be programmed is 511 × 4 = 2044 cycles. For example, consider an excitation signal of 30 kHz, the maximum delay between the programming of this frequency and the time that this signal is first sampled by the ADC is ≈ 511 × 4 × 33.33 μs = 68.126 ms. The ADC takes 1024 samples, and the result is stored as real data and imaginary data in Register Address 0x94 to Register Address 0x97. The conversion process takes approximately 1 ms using a 16.777 MHz clock.

STATUS REGISTER (REGISTER ADDRESS 0x8F)

The status register is used to confirm that particular measurement tests have been successfully completed. Each of the bits from D7 to D0 indicate the status of a specific functionality of the AD5934.

Bit D0 and Bit D4 to Bit D7 are treated as don't care bits; these bits do not indicate the status of any measurement.

The status of Bit D1 indicates the status of a frequency point impedance measurement. This bit is set when the AD5934 completes the current frequency point impedance measurement. This bit indicates that there is valid real data and imaginary data in Register Address 0x94 to Register Address 0x97. This bit is reset on receipt of a start frequency sweep, increment frequency, repeat frequency, or reset command. This bit is also reset at power-up.

The status of Bit D2 indicates the status of the programmed frequency sweep. This bit is set when all programmed increments to the number of increments register are complete. This bit is reset at power-up and on receipt of a reset command.

Table 12. Status Register 0x8F

Control Word	Description
0000 0001	Reserved
0000 0010	Valid real/imaginary data
0000 0100	Frequency sweep complete
0000 1000	Reserved
0001 0000	Reserved
0010 0000	Reserved
0100 0000	Reserved
1000 0000	Reserved

Table 13. Number of Settling Times Cycles Register

<table>
<tr><th>Register Address</th><th>Bits</th><th colspan="3">Description</th><th>Function</th><th>Format</th></tr>
<tr><td rowspan="8">0x8A</td><td>D15 to D11</td><td colspan="3">Don't care</td><td rowspan="8">Read or write</td><td rowspan="8">Integer number stored in binary format</td></tr>
<tr><td rowspan="6">D10 to D9</td><td colspan="3">2-bit decode</td></tr>
<tr><td>D10</td><td>D9</td><td>Description</td></tr>
<tr><td>0</td><td>0</td><td>Default</td></tr>
<tr><td>0</td><td>1</td><td>No of cycles ×2</td></tr>
<tr><td>1</td><td>0</td><td>Reserved</td></tr>
<tr><td>1</td><td>1</td><td>No of cycles ×4</td></tr>
<tr><td>D8</td><td colspan="3">MSB number of settling time cycles</td></tr>
<tr><td>0x8B</td><td>D7 to D0</td><td colspan="3">Number of settling time cycles</td><td>Read or write</td><td>Data</td></tr>
</table>

Valid Real/Imaginary Data

This bit is set when data processing for the current frequency point is finished, indicating real/imaginary data available for reading. The bit is reset when a start frequency sweep/increment frequency/repeat frequency DDS command is issued. In addition, this bit is reset to 0 when a reset command is issued to the control register.

Frequency Sweep Complete

This bit is set when data processing for the last frequency point in the sweep is complete. This bit is reset when a start frequency sweep command is issued to the control register. This bit is also reset when a reset command is issued to the control register.

REAL AND IMAGINARY DATA REGISTERS (16 BITS— REGISTER ADDRESS 0x94, REGISTER ADDRESS 0x95, REGISTER ADDRESS 0x96, REGISTER ADDRESS 0x97)

These registers contain a digital representation of the real and imaginary components of the impedance measured for the current frequency point. The values are stored in 16-bit, twos complement format. To convert this number to an actual impedance value, the magnitude, $\sqrt{(Real^2 + Imaginary^2)}$, must be multiplied by an admittance/code number (called a gain factor) to give the admittance and the result inverted to give the impedance. The gain factor varies for each ac excitation voltage/gain combination.

The default value upon reset: these registers are not reset at power-up or on receipt of a reset command. Note that the data in these registers is only valid if Bit D1 in the status register is set, indicating that the processing at the current frequency point is complete.

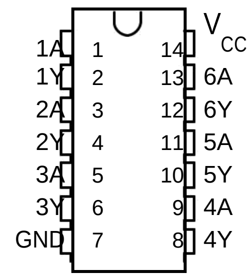
Appendix 8

- Dependable Texas Instruments Quality and Reliability

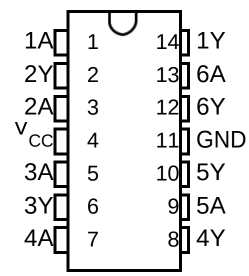
description/ordering information

These devices contain six independent inverters.

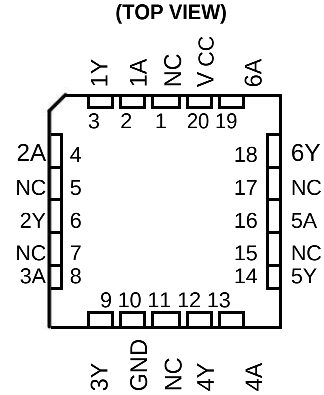
SN5404 . . . J PACKAGE
SN54LS04, SN54S04 . . . J OR W PACKAGE
SN7404, SN74S04 . . . D, N, OR NS
PACKAGE SN74LS04 . . . D, DB, N, OR NS
PACKAGE (TOP VIEW)



SN5404 . . . W PACKAGE
(TOP VIEW)



SN54LS04, SN54S04 . . . FK PACKAGE
(TOP VIEW)



NC − No internal connection

Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

ORDERING INFORMATION

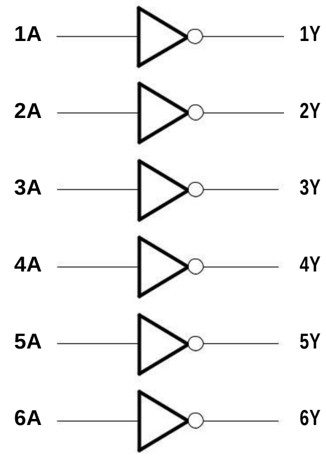
T_A	PACKAGE†		ORDERABLE PART NUMBER	TOP-SIDE MARKING
0°C to 70°C	PDIP − N	Tube	SN7404N	SN7404N
		Tube	SN74LS04N	SN74LS04N
		Tube	SN74S04N	SN74S04N
	SOIC − D	Tube	SN7404D	7404
		Tape and reel	SN7404DR	
		Tube	SN74LS04D	LS04
		Tape and reel	SN74LS04DR	
		Tube	SN74S04D	S04
		Tape and reel	SN74S04DR	
	SOP − NS	Tape and reel	SN7404NSR	SN7404
		Tape and reel	SN74LS04NSR	74LS04
		Tape and reel	SN74S04NSR	74S04
	SSOP − DB	Tape and reel	SN74LS04DBR	LS04
−55 °C to 125°C	CDIP − J	Tube	SN5404J	SN5404J
		Tube	SNJ5404J	SNJ5404J
		Tube	SN54LS04J	SN54LS04J
		Tube	SN54S04J	SN54S04J
		Tube	SNJ54LS04J	SNJ54LS04J
		Tube	SNJ54S04J	SNJ54S04J
	CFP − W	Tube	SNJ5404W	SNJ5404W
		Tube	SNJ54LS04W	SNJ54LS04W
		Tube	SNJ54S04W	SNJ54S04W
	LCCC − FK	Tube	SNJ54LS04FK	SNJ54LS04FK
		Tube	SNJ54S04FK	SNJ54S04FK

† Package drawings, standard packing quantities, thermal data, symbolization, and PCB design guidelines are available at www.ti.com/sc/package.

FUNCTION TABLE
(each inverter)

INPUT A	OUTPUT Y
H	L
L	H

logic diagram (positive logic)



$Y = \overline{A}$

absolute maximum ratings over operating free-air temperature range (unless otherwise noted)†

Supply voltage, V_{CC} (see Note 1) . . . . 7 V
Input voltage, V_I: '04, 'S04 . . . . 5.5 V
'LS04 . . . . 7 V
Package thermal impedance, θ_{JA} (see Note 2): D package . . . . 86°C/W
DB package . . . . 96°C/W
N package . . . . 80°C/W
NS package . . . . 76°C/W
Storage temperature range, T_{stg} . . . . −65 °C to 150°C

† Stresses beyond those listed under “absolute maximum ratings” may cause permanent damage to the device. This are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under “recommended operating conditions” is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

NOTES: 1. Voltage values are with respect to network ground terminal.
2. The package thermal impedance is calculated in accordance with JESD 51-7.

recommended operating conditions (see Note 3)

		SN5404			SN7404			UNIT
		MIN	NOM	MAX	MIN	NOM	MAX	
V_{CC}	Supply voltage	4.5	5	5.5	4.75	5	5.25	V
V_{IH}	High-level input voltage	2			2			V
V_{IL}	Low-level input voltage			0.8			0.8	V
I_{OH}	High-level output current			−0.4			−0.4	mA
I_{OL}	Low-level output current			16			16	mA
T_A	Operating free-air temperature	−55		125	0		70	°C

NOTE 3: All unused inputs of the device must be held at V_{CC} or GND to ensure proper device operation. Refer to the TI application report, *Implications of Slow or Floating CMOS Inputs*, literature number SCBA004.

electrical characteristics over recommended operating free-air temperature range (unless otherwise noted)

PARAMETER	TEST CONDITIONS‡			SN5404			SN7404			UNIT
				MIN	TYP§	MAX	MIN	TYP§	MAX	
V_{IK}	V_{CC} = MIN,	I_I = − 12 mA				−1.5			−1.5	V
V_{OH}	V_{CC} = MIN,	V_{IL} = 0.8 V,	I_{OH} = −0.4 mA	2.4	3.4		2.4	3.4		V
V_{OL}	V_{CC} = MIN,	V_{IH} = 2 V,	I_{OL} = 16 mA		0.2	0.4		0.2	0.4	V
I_I	V_{CC} = MAX,	V_I = 5.5 V				1			1	mA
I_{IH}	V_{CC} = MAX,	V_I = 2.4 V				40			40	∝A
I_{IL}	V_{CC} = MAX,	V_I = 0.4 V				−1.6			−1.6	mA
I_{OS} ¶	V_{CC} = MAX			−20		−55	−18		−55	mA
I_{CCH}	V_{CC} = MAX,	V_I = 0 V			6	12		6	12	mA
I_{CCL}	V_{CC} = MAX,	V_I = 4.5 V			18	33		18	33	mA

‡ For conditions shown as MIN or MAX, use the appropriate value specified under recommended operating conditions. § All typical values are at V_{CC} = 5 V, T_A = 25°C.
¶ Not more than one output should be shorted at a time.

switching characteristics, V_{CC} = 5 V, T_A = 25°C (see Figure 1)

PARAMETER	FROM (INPUT)	TO (OUTPUT)	TEST CONDITIONS	SN5404 SN7404 MIN	TYP	MAX	UNIT
t_{PLH}	A	Y	R_L = 400 Ω, C_L = 15 pF		12	22	ns
t_{PHL}					8	15	

recommended operating conditions (see Note 3)

		SN54LS04 MIN	NOM	MAX	SN74LS04 MIN	NOM	MAX	UNIT
V_{CC}	Supply voltage	4.5	5	5.5	4.75	5	5.25	V
V_{IH}	High-level input voltage	2			2			V
V_{IL}	Low-level input voltage			0.7			0.8	V
I_{OH}	High-level output current			−0.4			−0.4	mA
I_{OL}	Low-level output current			4			8	mA
T_A	Operating free-air temperature	−55		125	0		70	°C

NOTE 3: All unused inputs of the device must be held at V_{CC} or GND to ensure proper device operation. Refer to the TI application report, *Implications of Slow or Floating CMOS Inputs*, literature number SCBA004.

electrical characteristics over recommended operating free-air temperature range (unless otherwise noted)

PARAMETER	TEST CONDITIONS†			SN54LS04 MIN	TYP‡	MAX	SN74LS04 MIN	TYP‡	MAX	UNIT
V_{IK}	V_{CC} = MIN,	I_I = − 18 mA				−1.5			−1.5	V
V_{OH}	V_{CC} = MIN,	V_{IL} = MAX,	I_{OH} = −0.4 mA	2.5	3.4		2.7	3.4		V
V_{OL}	V_{CC} = MIN,	V_{IH} = 2 V	I_{OL} = 4 mA		0.25	0.4			0.4	V
			I_{OL} = 8 mA					0.25	0.5	
I_I	V_{CC} = MAX,	V_I = 7 V				0.1			0.1	mA
I_{IH}	V_{CC} = MAX,	V_I = 2.7 V				20			20	µA
I_{IL}	V_{CC} = MAX,	V_I = 0.4 V				−0.4			−0.4	mA
I_{OS}§	V_{CC} = MAX			−20		−100	−20		−100	mA
I_{CCH}	V_{CC} = MAX,	V_I = 0 V			1.2	2.4		1.2	2.4	mA
I_{CCL}	V_{CC} = MAX,	V_I = 4.5 V			3.6	6.6		3.6	6.6	mA

† For conditions shown as MIN or MAX, use the appropriate value specified under recommended operating conditions.
‡ All typical values are at V_{CC} = 5 V, T_A = 25°C.
§ Not more than one output should be shorted at a time, and the duration of the short-circuit should not exceed one second.

switching characteristics, V_{CC} = 5 V, T_A = 25°C (see Figure 2)

PARAMETER	FROM (INPUT)	TO (OUTPUT)	TEST CONDITIONS	SN54LS04 SN74LS04 MIN	TYP	MAX	UNIT
t_{PLH}	A	Y	R_L = 2 kΩ, C_L = 15 pF		9	15	ns
t_{PHL}					10	15	

recommended operating conditions (see Note 3)

		SN54S04			SN74S04			UNIT
		MIN	NOM	MAX	MIN	NOM	MAX	
V_{CC}	Supply voltage	4.5	5	5.5	4.75	5	5.25	V
V_{IH}	High-level input voltage	2			2			V
V_{IL}	Low-level input voltage			0.8			0.8	V
I_{OH}	High-level output current			−1			−1	mA
I_{OL}	Low-level output current			20			20	mA
T_A	Operating free-air temperature	−55		125	0		70	°C

NOTE 3: All unused inputs of the device must be held at V_{CC} or GND to ensure proper device operation. Refer to the TI application report, *Implications of Slow or Floating CMOS Inputs*, literature number SCBA004.

electrical characteristics over recommended operating free-air temperature range (unless otherwise noted)

PARAMETER	TEST CONDITIONS†			SN54S04			SN74S04			UNIT
				MIN	TYP‡	MAX	MIN	TYP‡	MAX	
V_{IK}	V_{CC} = MIN,	I_I = − 18 mA				−1.2			−1.2	V
V_{OH}	V_{CC} = MIN,	V_{IL} = 0.8 V,	I_{OH} = −1 mA	2.5	3.4		2.7	3.4		V
V_{OL}	V_{CC} = MIN,	V_{IH} = 2 V,	I_{OL} = 20 mA			0.5			0.5	V
I_I	V_{CC} = MAX,	V_I = 5.5 V				1			1	mA
I_{IH}	V_{CC} = MAX,	V_I = 2.7 V				50			50	μA
I_{IL}	V_{CC} = MAX,	V_I = 0.5 V				−2			−2	mA
I_{OS}§	V_{CC} = MAX			−40		−100	−40		−100	mA
I_{CCH}	V_{CC} = MAX,	V_I = 0 V			15	24		15	24	mA
I_{CCL}	V_{CC} = MAX,	V_I = 4.5 V			30	54		30	54	mA

† For conditions shown as MIN or MAX, use the appropriate value specified under recommended operating conditions.
‡ All typical values are at V_{CC} = 5 V, T_A = 25°C.
§ Not more than one output should be shorted at a time, and the duration of the short-circuit should not exceed one second.

switching characteristics, V_{CC} = 5 V, T_A = 25°C (see Figure 1)

PARAMETER	FROM (INPUT)	TO (OUTPUT)	TEST CONDITIONS		SN54S04 SN74S04			UNIT
					MIN	TYP	MAX	
t_{PLH}	A	Y	R_L = 280 Ω,	C_L = 15 pF		3	4.5	ns
t_{PHL}						3	5	
t_{PLH}	A	Y	R_L = 280 Ω,	C_L = 50 pF		4.5		ns
t_{PHL}						5		

Appendix 9

Low Cost Low Power Instrumentation Amplifier

AD620

FEATURES

Easy to use
- **Gain set with one external resistor (Gain range 1 to 10,000)**
- **Wide power supply range (±2.3 V to ±18 V)**
- **Higher performance than 3 op amp IA designs**
- **Available in 8-lead DIP and SOIC packaging**
- **Low power, 1.3 mA max supply current**

Excellent dc performance (B grade)
- **50 μV max, input offset voltage**
- **0.6 μV/°C max, input offset drift**
- **1.0 nA max, input bias current**
- **100 dB min common-mode rejection ratio (G = 10)**

Low noise
- **9 nV/√Hz @ 1 kHz, input voltage noise**
- **0.28 μV p-p noise (0.1 Hz to 10 Hz)**

Excellent ac specifications
- **120 kHz bandwidth (G = 100)**
- **15 μs settling time to 0.01%**

APPLICATIONS

Weigh scales
ECG and medical instrumentation
Transducer interface
Data acquisition systems
Industrial process controls
Battery-powered and portable equipment

Table 1. Next Generation Upgrades for AD620

Part	Comment
AD8221	Better specs at lower price
AD8222	Dual channel or differential out
AD8226	Low power, wide input range
AD8220	JFET input
AD8228	Best gain accuracy
AD8295	+2 precision op amps or differential out
AD8429	Ultra low noise

CONNECTION DIAGRAM

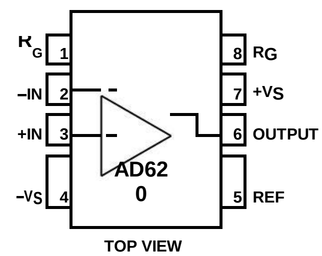


Figure 1. 8-Lead PDIP (N), CERDIP (Q), and SOIC (R) Packages

PRODUCT DESCRIPTION

The AD620 is a low cost, high accuracy instrumentation amplifier that requires only one external resistor to set gains of 1 to 10,000. Furthermore, the AD620 features 8-lead SOIC and DIP packaging that is smaller than discrete designs and offers lower power (only 1.3 mA max supply current), making it a good fit for battery-powered, portable (or remote) applications.

The AD620, with its high accuracy of 40 ppm maximum nonlinearity, low offset voltage of 50 μV max, and offset drift of 0.6 μV/°C max, is ideal for use in precision data acquisition systems, such as weigh scales and transducer interfaces. Furthermore, the low noise, low input bias current, and low power of the AD620 make it well suited for medical applications, such as ECG and noninvasive blood pressure monitors.

The low input bias current of 1.0 nA max is made possible with the use of Superϐeta processing in the input stage. The AD620 works well as a preamplifier due to its low input voltage noise of 9 nV/√Hz at 1 kHz, 0.28 μV p-p in the 0.1 Hz to 10 Hz band, and 0.1 pA/√Hz input current noise. Also, the AD620 is well suited for multiplexed applications with its settling time of 15 μs to 0.01%, and its cost is low enough to enable designs with one in-amp per channel.

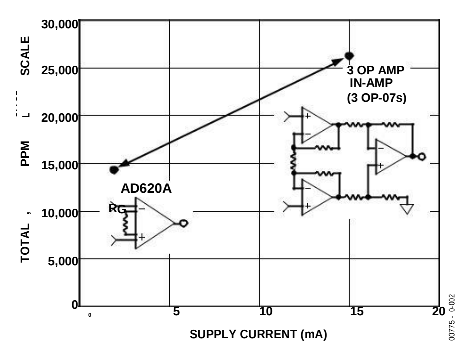


Figure 2. Three Op Amp IA Designs vs. AD620

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
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Fax: 781.326.8703

AD620* Product Page Quick Links

Last Content Update: 09/23/2016

Comparable Parts

View a parametric search of comparable parts

Evaluation Kits

- AD62x, AD822x, AD842x Series InAmp Evaluation Board

Documentation

Application Notes

- AN-244: A User's Guide to I.C. Instrumentation Amplifiers
- AN-245: Instrumentation Amplifiers Solve Unusual Design Problems
- AN-282: Fundamentals of Sampled Data Systems
- AN-589: Ways to Optimize the Performance of a Difference Amplifier
- AN-671: Reducing RFI Rectification Errors in In-Amp Circuits

Data Sheet

- AD620: Low Cost, Low Power Instrumentation Amplifier
- AD620: Military Data Sheet

Technical Books

- A Designer's Guide to Instrumentation Amplifiers, 3rd Edition, 2006

User Guides

- UG-261: Evaluation Boards for the AD62x, AD822x and AD842x Series

Tools and Simulations

- In-Amp Error Calculator
- Inamp Common-Mode Range / Gain Calculator
- AD620 SPICE Macro-Model

Reference Designs

- CN0146

Reference Materials

Analog Dialogue

- Ask The Applications Engineer-10
- ECG Front-End Design is Simplified with MicroConverter®
- Low-Power, Low-Voltage IC Choices for ECG System Requirements

Technical Articles

- Auto-Zero Amplifiers
- High-performance Adder Uses Instrumentation Amplifiers
- Input Filter Prevents Instrumentation-amp RF-Rectification Errors
- Protecting Instrumentation Amplifiers
- The AD8221 - Setting a New Industry Standard for Instrumentation Amplifiers

Design Resources

- AD620 Material Declaration
- PCN-PDN Information
- Quality And Reliability
- Symbols and Footprints

Discussions

View all AD620 EngineerZone Discussions

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Visit the product page to see pricing options

Technical Support

Submit a technical question or find your regional support number

SPECIFICATIONS

Typical @ 25°C, V_S = ±15 V, and R_L = 2 kΩ, unless otherwise noted.

Table 2.

		AD620A			AD620B			AD620S[1]			
Parameter	**Conditions**	**Min**	**Typ**	**Max**	**Min**	**Typ**	**Max**	**Min**	**Typ**	**Max**	**Unit**
GAIN	G = 1 + (49.4 kΩ/R_G)										
Gain Range		1		10,000	1		10,000	1		10,000	
Gain Error[2]	V_{OUT} = ±10 V										
G = 1			0.03	0.10		0.01	0.02		0.03	0.10	%
G = 10			0.15	0.30		0.10	0.15		0.15	0.30	%
G = 100			0.15	0.30		0.10	0.15		0.15	0.30	%
G = 1000			0.40	0.70		0.35	0.50		0.40	0.70	%
Nonlinearity	V_{OUT} = −10 V to +10 V										
G = 1–1000	R_L = 10 kΩ		10	40		10	40		10	40	ppm
G = 1–100	R_L = 2 kΩ		10	95		10	95		10	95	ppm
Gain vs. Temperature											
	G = 1			10			10			10	ppm/°C
	Gain >1[2]			−50			−50			−50	ppm/°C
VOLTAGE OFFSET	(Total RTI Error = V_{OSI} + V_{OSO}/G)										
Input Offset, V_{OSI}	V_S = ±5 V to ± 15 V		30	125		15	50		30	125	μV
Overtemperature	V_S = ±5 V to ± 15 V			185			85			225	μV
Average TC	V_S = ±5 V to ± 15 V		0.3	1.0		0.1	0.6		0.3	1.0	μV/°C
Output Offset, V_{OSO}	V_S = ±15 V		400	1000		200	500		400	1000	μV
	V_S = ± 5 V			1500			750			1500	μV
Overtemperature	V_S = ±5 V to ± 15 V			2000			1000			2000	μV
Average TC	V_S = ±5 V to ± 15 V		5.0	15		2.5	7.0		5.0	15	μV/°C
Offset Referred to the Input vs. Supply (PSR)	V_S = ±2.3 V to ±18 V										
G = 1		80	100		80	100		80	100		dB
G = 10		95	120		100	120		95	120		dB
G = 100		110	140		120	140		110	140		dB
G = 1000		110	140		120	140		110	140		dB
INPUT CURRENT											
Input Bias Current			0.5	2.0		0.5	1.0		0.5	2	nA
Overtemperature				2.5			1.5			4	nA
Average TC			3.0			3.0			8.0		pA/°C
Input Offset Current			0.3	1.0		0.3	0.5		0.3	1.0	nA
Overtemperature				1.5			0.75			2.0	nA
Average TC			1.5			1.5			8.0		pA/°C
INPUT											
Input Impedance											
Differential			10‖2			10‖2			10‖2		GΩ_pF
Common-Mode			10‖2			10‖2			10‖2		GΩ_pF
Input Voltage Range[3]	V_S = ±2.3 V to ±5 V	$-V_S + 1.9$		$+V_S - 1.2$	$-V_S + 1.9$		$+V_S - 1.2$	$-V_S + 1.9$		$+V_S - 1.2$	V
Overtemperature		$-V_S + 2.1$		$+V_S - 1.3$	$-V_S + 2.1$		$+V_S - 1.3$	$-V_S + 2.1$		$+V_S - 1.3$	V
	V_S = ± 5 V to ±18 V	$-V_S + 1.9$		$+V_S - 1.4$	$-V_S + 1.9$		$+V_S - 1.4$	$-V_S + 1.9$		$+V_S - 1.4$	V
Overtemperature		$-V_S + 2.1$		$+V_S - 1.4$	$-V_S + 2.1$		$+V_S + 2.1$	$-V_S + 2.3$		$+V_S - 1.4$	V

Parameter	Conditions	AD620A Min	AD620A Typ	AD620A Max	AD620B Min	AD620B Typ	AD620B Max	AD620S[1] Min	AD620S[1] Typ	AD620S[1] Max	Unit
Common-Mode Rejection											
Ratio DC to 60 Hz with											
1 kΩ Source Imbalance	V_{CM} = 0 V to ± 10 V										
G = 1		73	90		80	90		73	90		dB
G = 10		93	110		100	110		93	110		dB
G = 100		110	130		120	130		110	130		dB
G = 1000		110	130		120	130		110	130		dB
OUTPUT											
Output Swing	R_L = 10 kΩ										
	V_S = ±2.3 V to ± 5 V	$-V_S$ + 1.1		$+V_S$ − 1.2	$-V_S$ + 1.1		$+V_S$ − 1.2	$-V_S$ + 1.1		$+V_S$ − 1.2	V
Overtemperature		$-V_S$ + 1.4		$+V_S$ − 1.3	$-V_S$ + 1.4		$+V_S$ − 1.3	$-V_S$ + 1.6		$+V_S$ − 1.3	V
	V_S = ±5 V to ± 18 V	$-V_S$ + 1.2		$+V_S$ − 1.4	$-V_S$ + 1.2		$+V_S$ − 1.4	$-V_S$ + 1.2		$+V_S$ − 1.4	V
Overtemperature		$-V_S$ + 1.6		$+V_S$ – 1.5	$-V_S$ + 1.6		$+V_S$ – 1.5	$-V_S$ + 2.3		$+V_S$ – 1.5	V
Short Circuit Current			±18			±18			±18		mA
DYNAMIC RESPONSE											
Small Signal –3 dB Bandwidth											
G = 1			1000			1000			1000		kHz
G = 10			800			800			800		kHz
G = 100			120			120			120		kHz
G = 1000			12			12			12		kHz
Slew Rate		0.75	1.2		0.75	1.2		0.75	1.2		V/µs
Settling Time to 0.01%	10 V Step										
G = 1–100			15			15			15		µs
G = 1000			150			150			150		µs
NOISE											
Voltage Noise, 1 kHz	Total RTI Noise = $\sqrt{(e^2_{ni}) + (e_{no}/G)^2}$										
Input, Voltage Noise, e_{ni}			9	13		9	13		9	13	nV/√Hz
Output, Voltage Noise, e_{no}			72	100		72	100		72	100	nV/√Hz
RTI, 0.1 Hz to 10 Hz											
G = 1			3.0			3.0	6.0		3.0	6.0	µV p-p
G = 10			0.55			0.55	0.8		0.55	0.8	µV p-p
G = 100–1000			0.28			0.28	0.4		0.28	0.4	µV p-p
Current Noise	f = 1 kHz		100			100			100		fA/√Hz
0.1 Hz to 10 Hz			10			10			10		pA p-p
REFERENCE INPUT											
R_{IN}			20			20			20		kΩ
I_{IN}	V_{IN+}, V_{REF} = 0		50	60		50	60		50	60	µA
Voltage Range		$-V_S$ + 1.6		$+V_S$ − 1.6	$-V_S$ + 1.6		$+V_S$ − 1.6	$-V_S$ + 1.6		$+V_S$ − 1.6	V
Gain to Output		1 ± 0.0001			1 ± 0.0001			1 ± 0.0001			
POWER SUPPLY											
Operating Range[4]		±2.3		±18	±2.3		±18	±2.3		±18	V
Quiescent Current	V_S = ±2.3 V to ±18 V		0.9	1.3		0.9	1.3		0.9	1.3	mA
Overtemperature			1.1	1.6		1.1	1.6		1.1	1.6	mA
TEMPERATURE RANGE											
For Specified Performance		−40 to +85			−40 to +85			−55 to +125			°C

[1] See Analog Devices military data sheet for 883B tested specifications.
[2] Does not include effects of external resistor R_G.
[3] One input grounded. G = 1.
[4] This is defined as the same supply range that is used to specify PSR.

ABSOLUTE MAXIMUM RATINGS

Table 3.

Parameter	Rating
Supply Voltage	±18 V
Internal Power Dissipation[1]	650 mW
Input Voltage (Common-Mode)	$\pm V_S$
Differential Input Voltage	25 V
Output Short-Circuit Duration	Indefinite
Storage Temperature Range (Q)	−65°C to +150°C
Storage Temperature Range (N, R)	−65°C to +125°C
Operating Temperature Range	
AD620 (A, B)	−40°C to +85°C
AD620 (S)	−55°C to +125°C
Lead Temperature Range	
(Soldering 10 seconds)	300°C

[1] Specification is for device in free air:
8-Lead Plastic Package: θ_{JA} = 95°C
8-Lead CERDIP Package: θ_{JA} = 110°C
8-Lead SOIC Package: θ_{JA} = 155°C

Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other condition s above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

ESD CAUTION

ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.

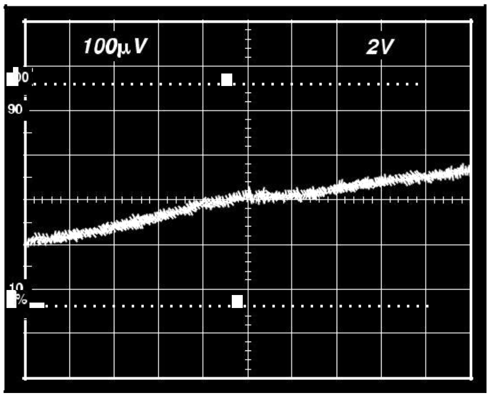


Figure 33. Gain Nonlinearity, G = 100, R_L = 10 kΩ (100 μV = 10 ppm)

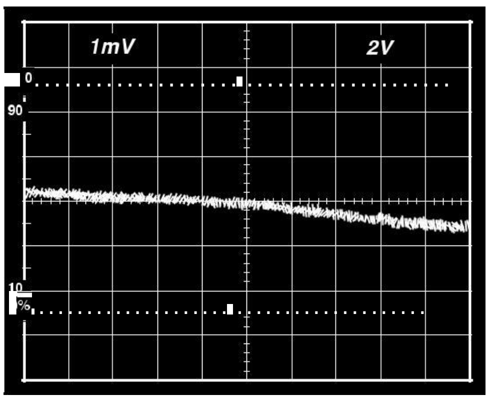


Figure 34. Gain Nonlinearity, G = 1000, R_L = 10 kΩ (1 mV = 100 ppm)

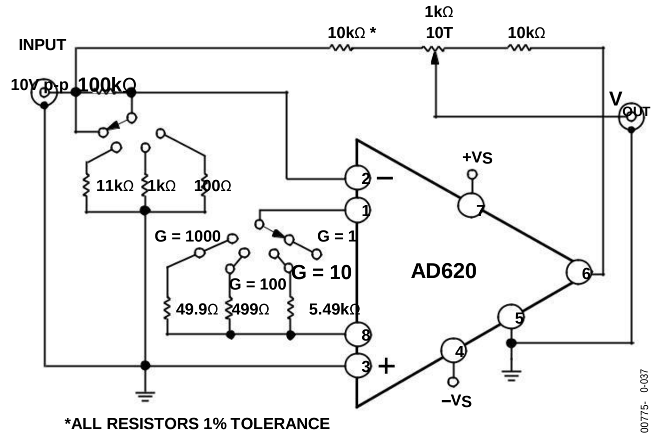


Figure 35. Settling Time Test Circuit

THEORY OF OPERATION

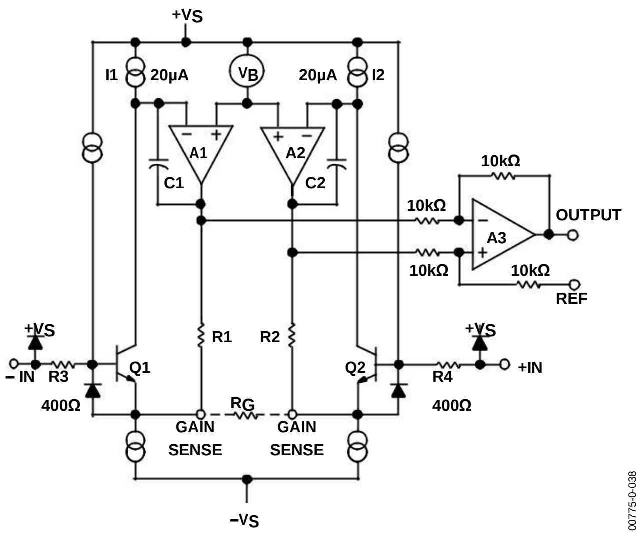


Figure 36. Simplified Schematic of AD620

The AD620 is a monolithic instrumentation amplifier based on a modification of the classic three op amp approach. Absolute value trimming allows the user to program gain *accurately* (to 0.15% at G = 100) with only one resistor. Monolithic construction and laser wafer trimming allow the tight matching and tracking of circuit components, thus ensuring the high level of performance inherent in this circuit.

The input transistors Q1 and Q2 provide a single differential-pair bipolar input for high precision (Figure 36), yet offer 10× lower input bias current thanks to Superбeta processing. Feedback through the Q1-A1-R1 loop and the Q2-A2-R2 loop maintains constant collector current of the input devices Q1 and Q2, thereby impressing the input voltage across the external gain setting resistor R_G. This creates a differential gain from the inputs to the A1/A2 outputs given by $G = (R1 + R2)/R_G + 1$. The unity-gain subtractor, A3, removes any common-mode signal, yielding a single-ended output referred to the REF pin potential.

The value of R_G also determines the transconductance of the preamp stage. As R_G is reduced for larger gains, the transconductance increases asymptotically to that of the input transistors. This has three important advantages: (a) Open-loop gain is boosted for increasing programmed gain, thus reducing gain related errors. (b) The gain-bandwidth product (determined by C1 and C2 and the preamp transconductance) increases with programmed gain, thus optimizing frequency response. (c) The input voltage noise is reduced to a value of 9 nV/√Hz, determined mainly by the collector current and base resistance of the input devices.

The internal gain resistors, R1 and R2, are trimmed to an absolute value of 24.7 kΩ, allowing the gain to be programmed accurately with a single external resistor.

The gain equation is then

$$G = \frac{49.4\,k\Omega}{R_G} + 1$$

$$R_G = \frac{49.4\,k\Omega}{G - 1}$$

Make vs. Buy: a Typical Bridge Application Error Budget

The AD620 offers improved performance over “homebrew” three op amp IA designs, along with smaller size, fewer components, and 10× lower supply current. In the typical application, shown in Figure 37, a gain of 100 is required to amplify a bridge output of 20 mV full-scale over the industrial temperature range of −40°C to +85°C. Table 4 shows how to calculate the effect various error sources have on circuit accuracy.

Regardless of the system in which it is being used, the AD620 provides greater accuracy at low power and price. In simple systems, absolute accuracy and drift errors are by far the most significant contributors to error. In more complex systems with an intelligent processor, an autogain/autozero cycle removes all absolute accuracy and drift errors, leaving only the resolution errors of gain, nonlinearity, and noise, thus allowing full 14-bit accuracy.

Note that for the homebrew circuit, the OP07 specifications for input voltage offset and noise have been multiplied by √2. This is because a three op amp type in-amp has two op amps at its inputs, both contributing to the overall input error.

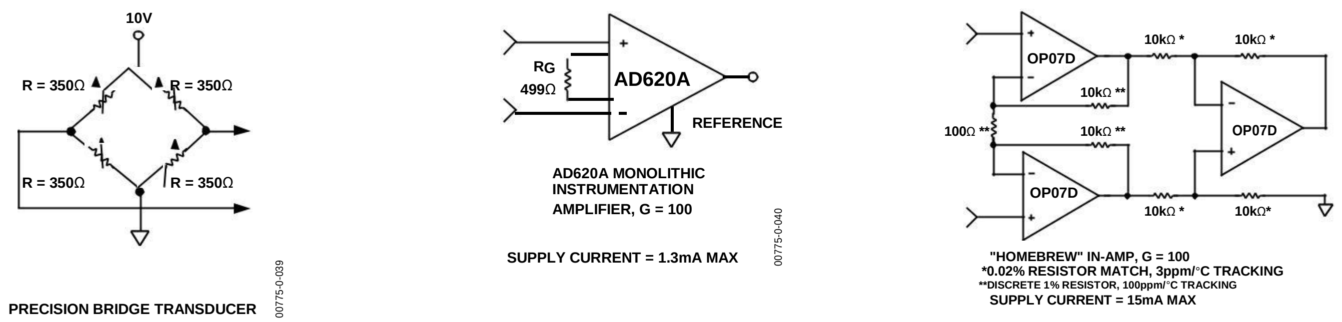


Figure 37. Make vs. Buy

Table 4. Make vs. Buy Error Budget

			Error, ppm of Full Scale	
Error Source	**AD620 Circuit Calculation**	**"Homebrew" Circuit Calculation**	**AD620**	**Homebrew**
ABSOLUTE ACCURACY at T_A = 25°C				
Input Offset Voltage, µV	125 µV/20 mV	(150 µV × √2)/20 mV	6,250	10,607
Output Offset Voltage, µV	1000 µV/100 mV/20 mV	((150 µV × 2)/100)/20 mV	500	150
Input Offset Current, nA	2 nA ×350 Ω/20 mV	(6 nA ×350 Ω)/20 mV	18	53
CMR, dB	110 dB(3.16 ppm) ×5 V/20 mV	(0.02% Match × 5 V)/20 mV/100	791	500
		Total Absolute Error	7,559	11,310
DRIFT TO 85°C				
Gain Drift, ppm/°C	(50 ppm + 10 ppm) ×60°C	100 ppm/°C Track × 60°C	3,600	6,000
Input Offset Voltage Drift, µV/°C	1 µV/°C × 60°C/20 mV	(2.5 µV/°C × √2 × 60°C)/20 mV	3,000	10,607
Output Offset Voltage Drift, µV/°C	15 µV/°C × 60°C/100 mV/20 mV	(2.5 µV/°C × 2 × 60°C)/100 mV/20 mV	450	150
		Total Drift Error	7,050	16,757
RESOLUTION				
Gain Nonlinearity, ppm of Full Scale	40 ppm	40 ppm	40	40
Typ 0.1 Hz to 10 Hz Voltage Noise, µV p-p	0.28 µV p-p/20 mV	(0.38 µV p-p × √2)/20 mV	14	27
		Total Resolution Error	54	67
		Grand Total Error	14,663	28,134

G = 100, V_S = ±15 V.
(All errors are min/max and referred to input.)

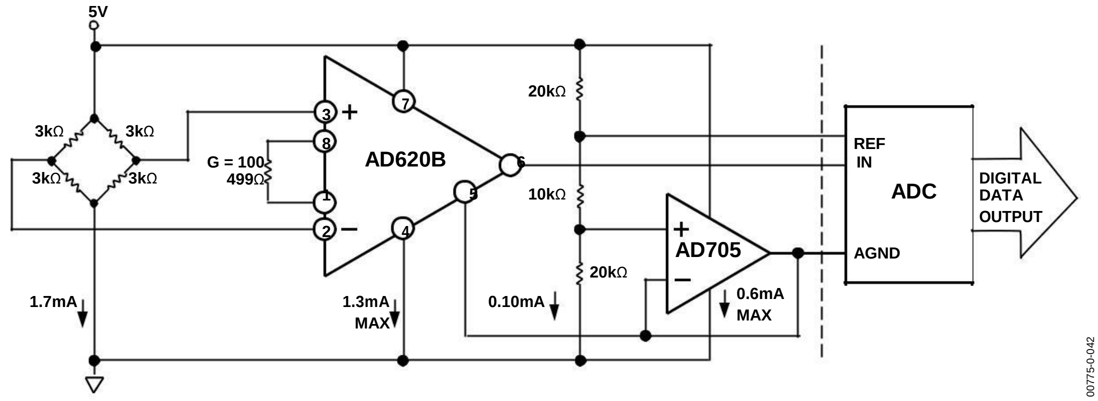


Figure 38. A Pressure Monitor Circuit that Operates on a 5 V Single Supply

Pressure Measurement

Although useful in many bridge applications, such as weigh scales, the AD620 is especially suitable for higher resistance pressure sensors powered at lower voltages where small size and low power become more significant.

Figure 38 shows a 3 kΩ pressure transducer bridge powered from 5 V. In such a circuit, the bridge consumes only 1.7 mA. Adding the AD620 and a buffered voltage divider allows the signal to be conditioned for only 3.8 mA of total supply current.

Small size and low cost make the AD620 especially attractive for voltage output pressure transducers. Since it delivers low noise and drift, it also serves applications such as diagnostic noninvasive blood pressure measurement.

Medical ECG

The low current noise of the AD620 allows its use in ECG monitors (Figure 39) where high source resistances of 1 MΩ or higher are not uncommon. The AD620's low power, low supply voltage requirements, and space-saving 8-lead mini-DIP and SOIC package offerings make it an excellent choice for battery-powered data recorders.

Furthermore, the low bias currents and low current noise, coupled with the low voltage noise of the AD620, improve the dynamic range for better performance.

The value of capacitor C1 is chosen to maintain stability of the right leg drive loop. Proper safeguards, such as isolation, must be added to this circuit to protect the patient from possible harm.

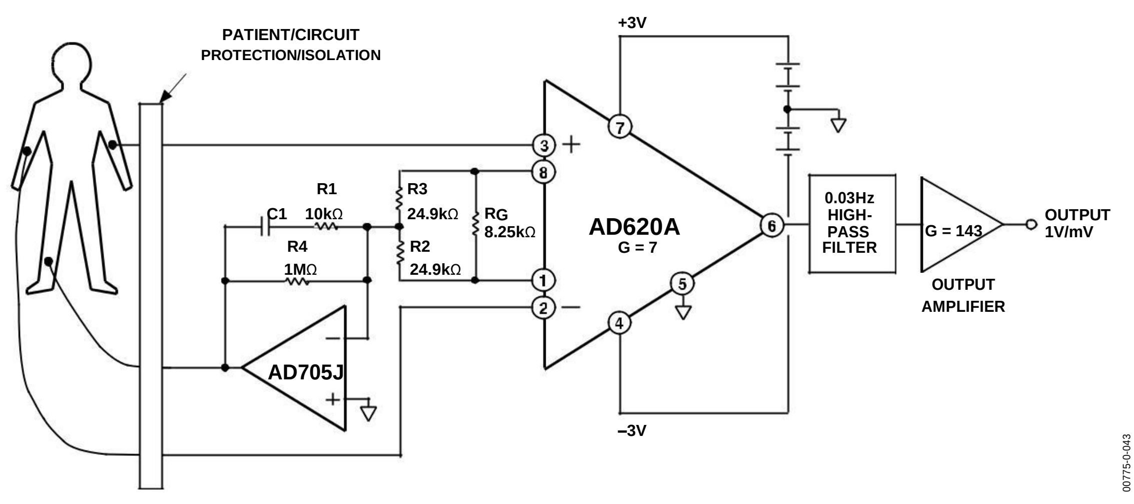


Figure 39. A Medical ECG Monitor Circuit

Precision V-I Converter

The AD620, along with another op amp and two resistors, makes a precision current source (Figure 40). The op amp buffers the reference terminal to maintain good CMR. The output voltage, V_X, of the AD620 appears across R1, which converts it to a current. This current, less only the input bias current of the op amp, then flows out to the load.

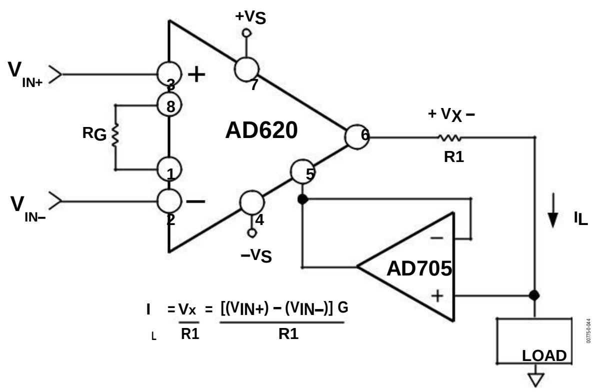


Figure 40. Precision Voltage-to-Current Converter (Operates on 1.8 mA, ±3 V)

GAIN SELECTION

The AD620 gain is resistor-programmed by R_G, or more precisely, by whatever impedance appears between Pins 1 and 8. The AD620 is designed to offer accurate gains using 0.1% to 1% resistors. Table 5 shows required values of R_G for various gains. Note that for G = 1, the R_G pins are unconnected ($R_G = \infty$). For any arbitrary gain, R_G can be calculated by using the formula:

$$R_G = \frac{49.4k\Omega}{G-1}$$

To minimize gain error, avoid high parasitic resistance in series with R_G; to minimize gain drift, R_G should have a low TC—less than 10 ppm/°C—for the best performance.

Table 5. Required Values of Gain Resistors

1% Std Table Value of R_G(Ω)	Calculated Gain	0.1% Std Table Value of R_G(Ω)	Calculated Gain
49.9 k	1.990	49.3 k	2.002
12.4 k	4.984	12.4 k	4.984
5.49 k	9.998	5.49 k	9.998
2.61 k	19.93	2.61 k	19.93
1.00 k	50.40	1.01 k	49.91
499	100.0	499	100.0
249	199.4	249	199.4
100	495.0	98.8	501.0
49.9	991.0	49.3	1,003.0

INPUT AND OUTPUT OFFSET VOLTAGE

The low errors of the AD620 are attributed to two sources, input and output errors. The output error is divided by *G* when referred to the input. In practice, the input errors dominate at high gains, and the output errors dominate at low gains. The total V_{OS} for a given gain is calculated as

Total Error RTI = input error + (output error/G)

Total Error RTO = (input error × G) + output error

REFERENCE TERMINAL

The reference terminal potential defines the zero output voltage and is especially useful when the load does not share a precise ground with the rest of the system. It provides a direct means of injecting a precise offset to the output, with an allowable range of 2 V within the supply voltages. Parasitic resistance should be kept to a minimum for optimum CMR.

INPUT PROTECTION

The AD620 safely withstands an input current of ±60 mA for several hours at room temperature. This is true for all gains and power on and off, which is useful if the signal source and amplifier are powered separately. For longer time periods, the input current should not exceed 6 mA.

For input voltages beyond the supplies, a protection resistor should be placed in series with each input to limit the current to 6 mA. These can be the same resistors as those used in the RFI filter. High values of resistance can impact the noise and AC CMRR performance of the system. Low leakage diodes (such as the BAV199) can be placed at the inputs to reduce the required protection resistance.

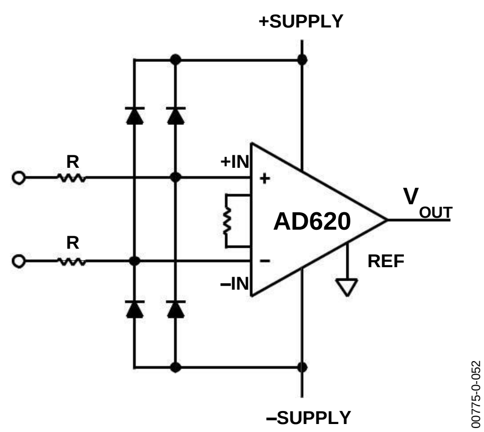


Figure 41. Diode Protection for Voltages Beyond Supply

RF INTERFERENCE

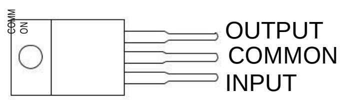
All instrumentation amplifiers rectify small out of band signals. The disturbance may appear as a small dc voltage offset. High frequency signals can be filtered with a low pass R-C network placed at the input of the instrumentation amplifier. Figure 42 demonstrates such a configuration. The filter limits the input

Appendix 10

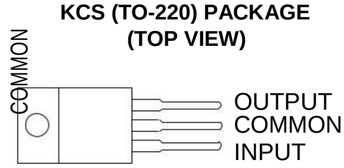
∝ A7800 SERIES POSITIVE-VOLTAGE REGULATORS

- 3-Terminal Regulators
- Output Current up to 1.5 A
- Internal Thermal-Overload Protection
- High Power-Dissipation Capability
- Internal Short-Circuit Current Limiting
- Output Transistor Safe-Area Compensation

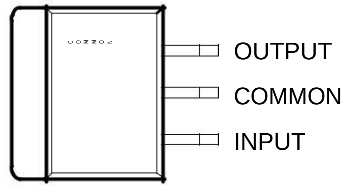
KC (TO-220) PACKAGE (TOP VIEW)



KCS (TO-220) PACKAGE (TOP VIEW)



KTE PACKAGE (TOP VIEW)



description/ordering information

This series of fixed-voltage integrated-circuit voltage regulators is designed for a wide range of applications. These applications include on-card regulation for elimination of noise and distribution problems associated with single-point regulation. Each of these regulators can deliver up to 1.5 A of output current. The internal current-limiting and thermal-shutdown features of these regulators essentially make them immune to overload. In addition to use as fixed-voltage regulators, these devices can be used with external components to obtain adjustable output voltages and currents, and also can be used as the power-pass element in precision regulators.

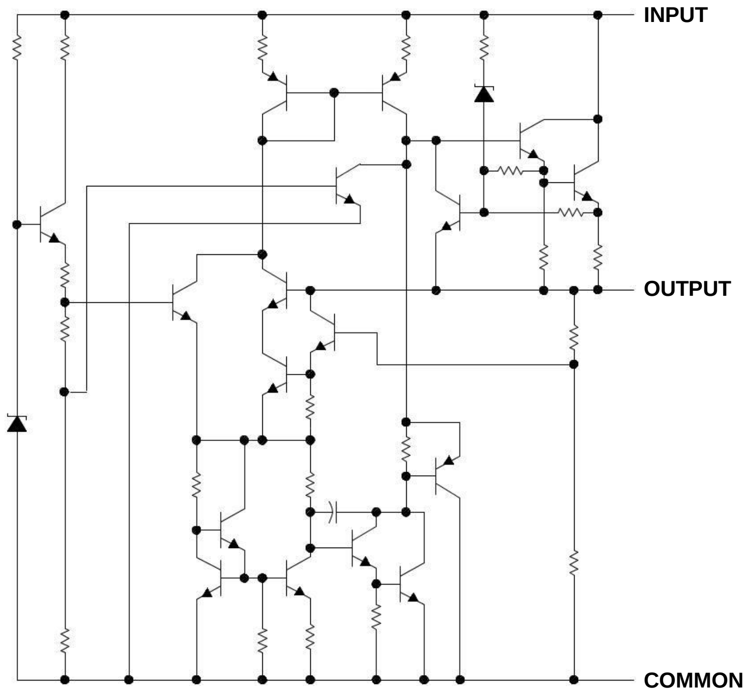
ORDERING INFORMATION

T_J	$V_{O(NOM)}$ (V)	PACKAGE†		ORDERABLE PART NUMBER	TOP-SIDE MARKING
0° C to 125° C	5	POWER-FLEX (KTE)	Reel of 2000	∝ A7805CKTER	∝ A7805C
		TO-220 (KC)	Tube of 50	∝ A7805CKC	∝ A7805C
		TO-220, short shoulder (KCS)	Tube of 20	∝ A7805CKCS	
	8	POWER-FLEX (KTE)	Reel of 2000	∝ A7808CKTER	∝ A7808C
		TO-220 (KC)	Tube of 50	∝ A7808CKC	∝ A7808C
		TO-220, short shoulder (KCS)	Tube of 20	∝ A7808CKCS	
	10	POWER-FLEX (KTE)	Reel of 2000	∝ A7810CKTER	∝ A7810C
		TO-220 (KC)	Tube of 50	∝ A7810CKC	∝ A7810C
	12	POWER-FLEX (KTE)	Reel of 2000	∝ A7812CKTER	∝ A7812C
		TO-220 (KC)	Tube of 50	∝ A7812CKC	∝ A7812C
		TO-220, short shoulder (KCS)	Tube of 20	∝ A7812CKCS	
	15	POWER-FLEX (KTE)	Reel of 2000	∝ A7815CKTER	∝ A7815C
		TO-220 (KC)	Tube of 50	∝ A7815CKC	∝ A7815C
		TO-220, short shoulder (KCS)	Tube of 20	∝ A7815CKCS	
	24	POWER-FLEX (KTE)	Reel of 2000	∝ A7824CKTER	∝ A7824C
		TO-220 (KC)	Tube of 50	∝ A7824CKC	∝ A7824C

† Package drawings, standard packing quantities, thermal data, symbolization, and PCB design guidelines are available at www.ti.com/sc/package.

Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

schematic



absolute maximum ratings over virtual junction temperature range (unless otherwise noted)†

Input voltage, V_I: ∝ A7824C . . . . 40 V
All others . . . . 35 V
Operating virtual junction temperature, T_J . . . . 150° C
Lead temperature 1,6 mm (1/16 inch) from case for 10 seconds . . . . 260° C
Storage temperature range, T_{stg} . . . . –65° C to 150° C

† Stresses beyond those listed under “absolute maximum ratings” may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under “recommended operating conditions” is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

package thermal data (see Note 1)

PACKAGE	BOARD	θ_{JC}	θ_{JA}
POWER-FLEX (KTE)	High K, JESD 51-5	3° C/W	23° C/W
TO-220 (KC/KCS)	High K, JESD 51-5	3° C/W	19° C/W

NOTE 1: Maximum power dissipation is a function of T_J(max), θ_{JA}, and T_A. The maximum allowable power dissipation at any allowable ambient temperature is $P_D = (T_J(max) - T_A)/\theta_{JA}$. Operating at the absolute maximum T_J of 150° C can affect reliability.

recommended operating conditions

			MIN	MAX	UNIT
V_I	Input voltage	µ A7805C	7	25	V
		µ A7808C	10.5	25	
		µ A7810C	12.5	28	
		µ A7812C	14.5	30	
		µ A7815C	17.5	30	
		µ A7824C	27	38	
I_O	Output current			1.5	A
T_J	Operating virtual junction temperature	µ A7800C series	0	125	°C

electrical characteristics at specified virtual junction temperature, V_I = 10 V, I_O = 500 mA (unless otherwise noted)

PARAMETER	TEST CONDITIONS	T_J†	µ A7805C			UNIT
			MIN	TYP	MAX	
Output voltage	I_O = 5 mA to 1 A, V_I = 7 V to 20 V, P_D ≤ 15 W	25° C	4.8	5	5.2	V
		0° C to 125° C	4.75		5.25	
Input voltage regulation	V_I = 7 V to 25 V	25° C		3	100	mV
	V_I = 8 V to 12 V			1	50	
Ripple rejection	V_I = 8 V to 18 V, f = 120 Hz	0° C to 125° C	62	78		dB
Output voltage regulation	I_O = 5 mA to 1.5 A	25° C		15	100	mV
	I_O = 250 mA to 750 mA			5	50	
Output resistance	f = 1 kHz	0° C to 125° C		0.017		Ω
Temperature coefficient of output voltage	I_O = 5 mA	0° C to 125° C		–1.1		mV/° C
Output noise voltage	f = 10 Hz to 100 kHz	25° C		40		µ V
Dropout voltage	I_O = 1 A	25° C		2		V
Bias current		25° C		4.2	8	mA
Bias current change	V_I = 7 V to 25 V	0° C to 125° C			1.3	mA
	I_O = 5 mA to 1 A				0.5	
Short-circuit output current		25° C		750		mA
Peak output current		25° C		2.2		A

† Pulse-testing techniques maintain the junction temperature as close to the ambient temperature as possible. Thermal effects must be taken into account separately. All characteristics are measured with a 0.33-µ F capacitor across the input and a 0.1-µ F capacitor across the output.

electrical characteristics at specified virtual junction temperature, V_I = 14 V, I_O = 500 mA (unless otherwise noted)

PARAMETER	TEST CONDITIONS		T_J†	µA7808C			UNIT
				MIN	TYP	MAX	
Output voltage	I_O = 5 mA to 1 A,	V_I = 10.5 V to 23 V,	25°C	7.7	8	8.3	V
	P_D ≤ 15 W		0°C to 125°C	7.6		8.4	
Input voltage regulation	V_I = 10.5 V to 25 V		25°C		6	160	mV
	V_I = 11 V to 17 V				2	80	
Ripple rejection	V_I = 11.5 V to 21.5 V,	f = 120 Hz	0°C to 125°C	55	72		dB
Output voltage regulation	I_O = 5 mA to 1.5 A		25°C		12	160	mV
	I_O = 250 mA to 750 mA				4	80	
Output resistance	f = 1 kHz		0°C to 125°C		0.016		Ω
Temperature coefficient of output voltage	I_O = 5 mA		0°C to 125°C		–0.8		mV/°C
Output noise voltage	f = 10 Hz to 100 kHz		25°C		52		µV
Dropout voltage	I_O = 1 A		25°C		2		V
Bias current			25°C		4.3	8	mA
Bias current change	V_I = 10.5 V to 25 V		0°C to 125°C			1	mA
	I_O = 5 mA to 1 A					0.5	
Short-circuit output current			25°C		450		mA
Peak output current			25°C		2.2		A

† Pulse-testing techniques maintain the junction temperature as close to the ambient temperature as possible. Thermal effects must be taken into account separately. All characteristics are measured with a 0.33-µF capacitor across the input and a 0.1-µF capacitor across the output.

electrical characteristics at specified virtual junction temperature, V_I = 17 V, I_O = 500 mA (unless otherwise noted)

PARAMETER	TEST CONDITIONS		T_J†	µA7810C			UNIT
				MIN	TYP	MAX	
Output voltage	I_O = 5 mA to 1 A,	V_I = 12.5 V to 25 V,	25°C	9.6	10	10.4	V
	P_D ≤ 15 W		0°C to 125°C	9.5	10	10.5	
Input voltage regulation	V_I = 12.5 V to 28 V		25°C		7	200	mV
	V_I = 14 V to 20 V				2	100	
Ripple rejection	V_I = 13 V to 23 V,	f = 120 Hz	0°C to 125°C	55	71		dB
Output voltage regulation	I_O = 5 mA to 1.5 A		25°C		12	200	mV
	I_O = 250 mA to 750 mA				4	100	
Output resistance	f = 1 kHz		0°C to 125°C		0.018		Ω
Temperature coefficient of output voltage	I_O = 5 mA		0°C to 125°C		–1		mV/°C
Output noise voltage	f = 10 Hz to 100 kHz		25°C		70		µV
Dropout voltage	I_O = 1 A		25°C		2		V
Bias current			25°C		4.3	8	mA
Bias current change	V_I = 12.5 V to 28 V		0°C to 125°C			1	mA
	I_O = 5 mA to 1 A					0.5	
Short-circuit output current			25°C		400		mA
Peak output current			25°C		2.2		A

† Pulse-testing techniques maintain the junction temperature as close to the ambient temperature as possible. Thermal effects must be taken into account separately. All characteristics are measured with a 0.33-µF capacitor across the input and a 0.1-µF capacitor across the output.

electrical characteristics at specified virtual junction temperature, V_I = 19 V, I_O = 500 mA (unless otherwise noted)

PARAMETER	TEST CONDITIONS	T_J†	µA7812C MIN	µA7812C TYP	µA7812C MAX	UNIT
Output voltage	I_O = 5 mA to 1 A, V_I = 14.5 V to 27 V, P_D ≤ 15 W	25° C	11.5	12	12.5	V
		0° C to 125° C	11.4		12.6	
Input voltage regulation	V_I = 14.5 V to 30 V	25° C		10	240	mV
	V_I = 16 V to 22 V			3	120	
Ripple rejection	V_I = 15 V to 25 V, f = 120 Hz	0° C to 125° C	55	71		dB
Output voltage regulation	I_O = 5 mA to 1.5 A	25° C		12	240	mV
	I_O = 250 mA to 750 mA			4	120	
Output resistance	f = 1 kHz	0° C to 125° C		0.018		Ω
Temperature coefficient of output voltage	I_O = 5 mA	0° C to 125° C		–1		mV/° C
Output noise voltage	f = 10 Hz to 100 kHz	25° C		75		µV
Dropout voltage	I_O = 1 A	25° C		2		V
Bias current		25° C		4.3	8	mA
Bias current change	V_I = 14.5 V to 30 V	0° C to 125° C			1	mA
	I_O = 5 mA to 1 A				0.5	
Short-circuit output current		25° C		350		mA
Peak output current		25° C		2.2		A

† Pulse-testing techniques maintain the junction temperature as close to the ambient temperature as possible. Thermal effects must be taken into account separately. All characteristics are measured with a 0.33-µF capacitor across the input and a 0.1-µF capacitor across the output.

electrical characteristics at specified virtual junction temperature, V_I = 23 V, I_O = 500 mA (unless otherwise noted)

PARAMETER	TEST CONDITIONS	T_J†	µA7815C MIN	µA7815C TYP	µA7815C MAX	UNIT
Output voltage	I_O = 5 mA to 1 A, V_I = 17.5 V to 30 V, P_D ≤ 15 W	25° C	14.4	15	15.6	V
		0° C to 125° C	14.25		15.75	
Input voltage regulation	V_I = 17.5 V to 30 V	25° C		11	300	mV
	V_I = 20 V to 26 V			3	150	
Ripple rejection	V_I = 18.5 V to 28.5 V, f = 120 Hz	0° C to 125° C	54	70		dB
Output voltage regulation	I_O = 5 mA to 1.5 A	25° C		12	300	mV
	I_O = 250 mA to 750 mA			4	150	
Output resistance	f = 1 kHz	0° C to 125° C		0.019		Ω
Temperature coefficient of output voltage	I_O = 5 mA	0° C to 125° C		–1		mV/° C
Output noise voltage	f = 10 Hz to 100 kHz	25° C		90		µV
Dropout voltage	I_O = 1 A	25° C		2		V
Bias current		25° C		4.4	8	mA
Bias current change	V_I = 17.5 V to 30 V	0° C to 125° C			1	mA
	I_O = 5 mA to 1 A				0.5	
Short-circuit output current		25° C		230		mA
Peak output current		25° C		2.1		A

† Pulse-testing techniques maintain the junction temperature as close to the ambient temperature as possible. Thermal effects must be taken into account separately. All characteristics are measured with a 0.33-µF capacitor across the input and a 0.1-µF capacitor across the output.

electrical characteristics at specified virtual junction temperature, V_I = 33 V, I_O = 500 mA (unless otherwise noted)

PARAMETER	TEST CONDITIONS		T_J†	µA7824C			UNIT
				MIN	TYP	MAX	
Output voltage	I_O = 5 mA to 1 A,	V_I = 27 V to 38 V,	25°C	23	24	25	V
	P_D ≤ 15 W		0°C to 125°C	22.8		25.2	
Input voltage regulation	V_I = 27 V to 38 V		25°C		18	480	mV
	V_I = 30 V to 36 V				6	240	
Ripple rejection	V_I = 28 V to 38 V,	f = 120 Hz	0°C to 125°C	50	66		dB
Output voltage regulation	I_O = 5 mA to 1.5 A		25°C		12	480	mV
	I_O = 250 mA to 750 mA				4	240	
Output resistance	f = 1 kHz		0°C to 125°C		0.028		Ω
Temperature coefficient of output voltage	I_O = 5 mA		0°C to 125°C		–1.5		mV/°C
Output noise voltage	f = 10 Hz to 100 kHz		25°C		170		µV
Dropout voltage	I_O = 1 A		25°C		2		V
Bias current			25°C		4.6	8	mA
Bias current change	V_I = 27 V to 38 V		0°C to 125°C			1	mA
	I_O = 5 mA to 1 A					0.5	
Short-circuit output current			25°C		150		mA
Peak output current			25°C		2.1		A

† Pulse-testing techniques maintain the junction temperature as close to the ambient temperature as possible. Thermal effects must be taken into account separately. All characteristics are measured with a 0.33-µF capacitor across the input and a 0.1-µF capacitor across the output.

APPLICATION INFORMATION

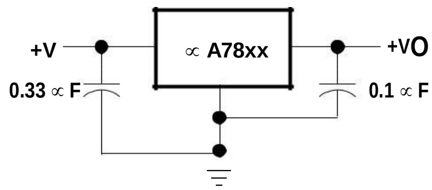


Figure 1. Fixed-Output Regulator

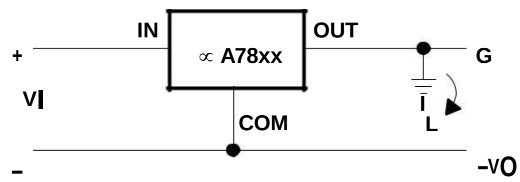
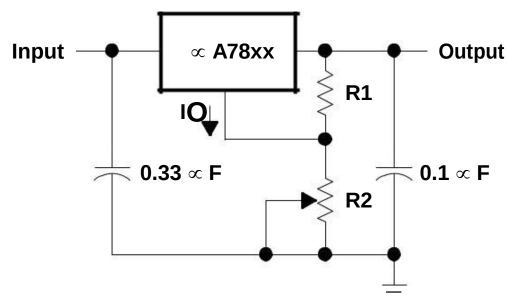


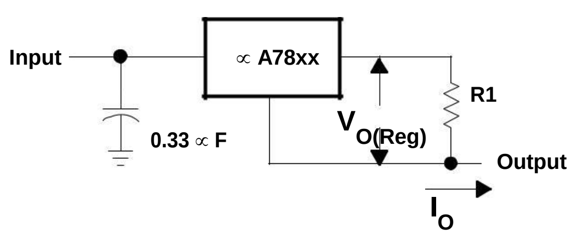
Figure 2. Positive Regulator in Negative Configuration (V_I Must Float)



NOTE A: The following formula is used when V_{XX} is the nominal output voltage (output to common) of the fixed regulator:

$$V_O + V_{xx}) \quad \frac{V_{xx}}{R1)} \quad I_Q \ R2$$

Figure 3. Adjustable-Output Regulator



I_O = (V_O/R1) + I_O Bias Current

Figure 4. Current Regulator

APPLICATION INFORMATION

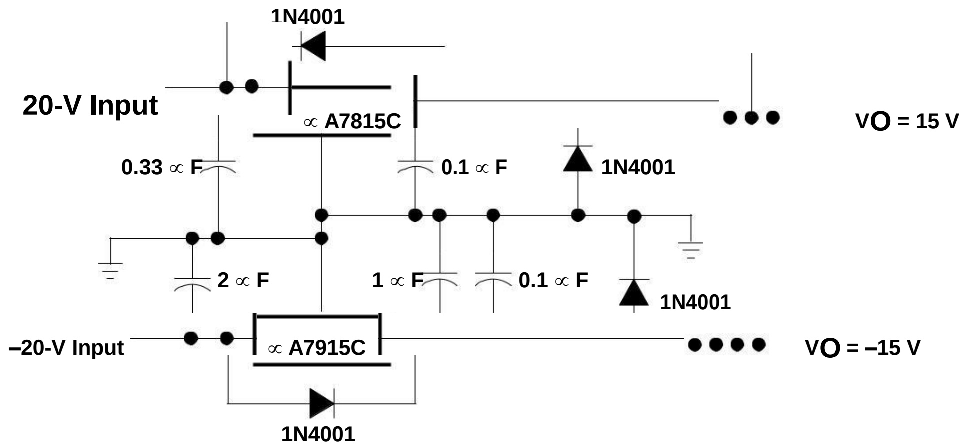


Figure 5. Regulated Dual Supply

operation with a load common to a voltage of opposite polarity

In many cases, a regulator powers a load that is not connected to ground but, instead, is connected to a voltage source of opposite polarity (e.g., operational amplifiers, level-shifting circuits, etc.). In these cases, a clamp diode should be connected to the regulator output as shown in Figure 6. This protects the regulator from output polarity reversals during startup and short-circuit operation.

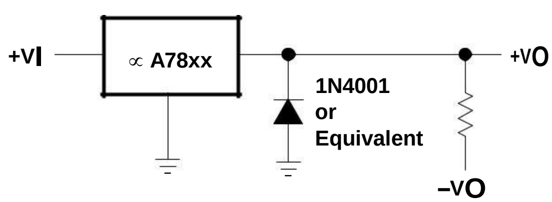


Figure 6. Output Polarity-Reversal-Protection Circuit

reverse-bias protection

Occasionally, the input voltage to the regulator can collapse faster than the output voltage. This can occur, for example, when the input supply is crowbarred during an output overvoltage condition. If the output voltage is greater than approximately 7 V, the emitter-base junction of the series-pass element (internal or external) could break down and be damaged. To prevent this, a diode shunt can be used as shown in Figure 7.

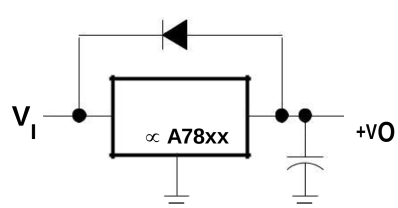
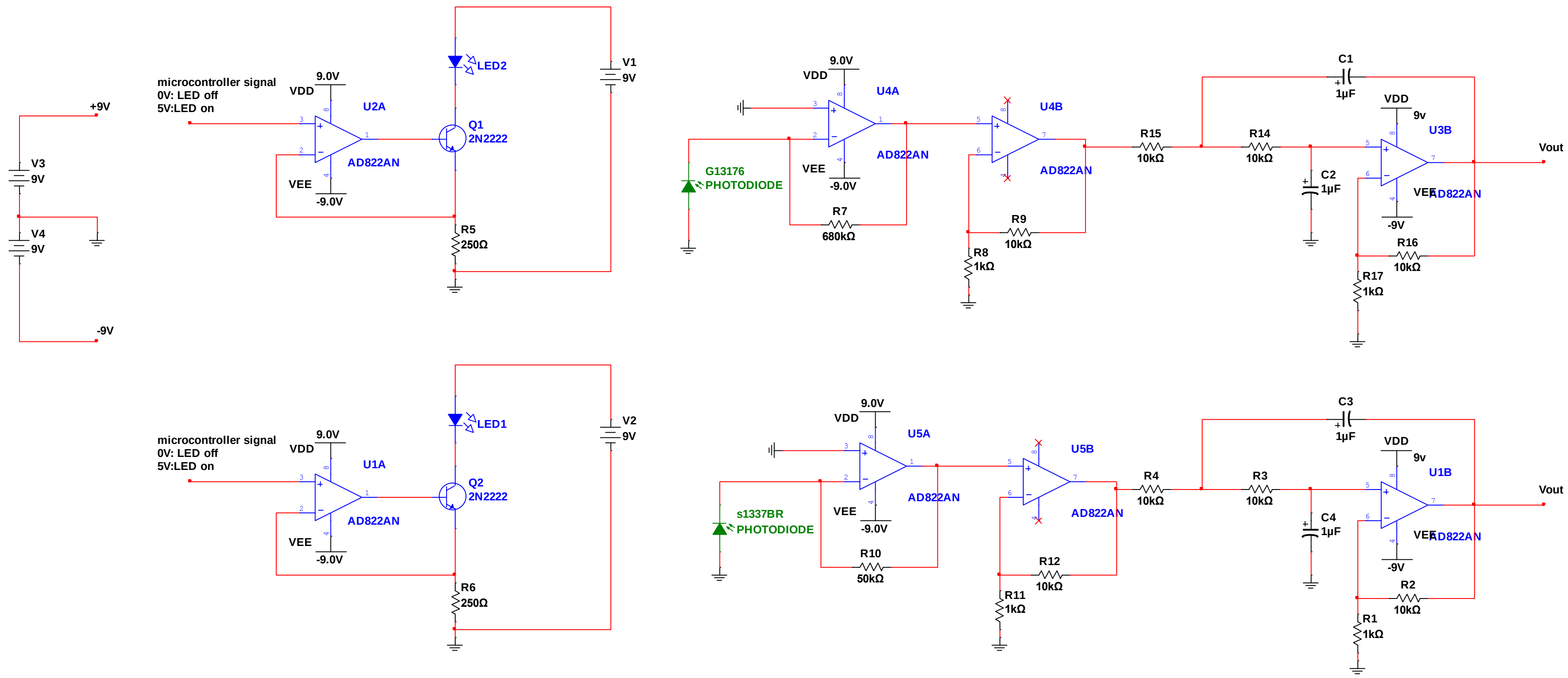
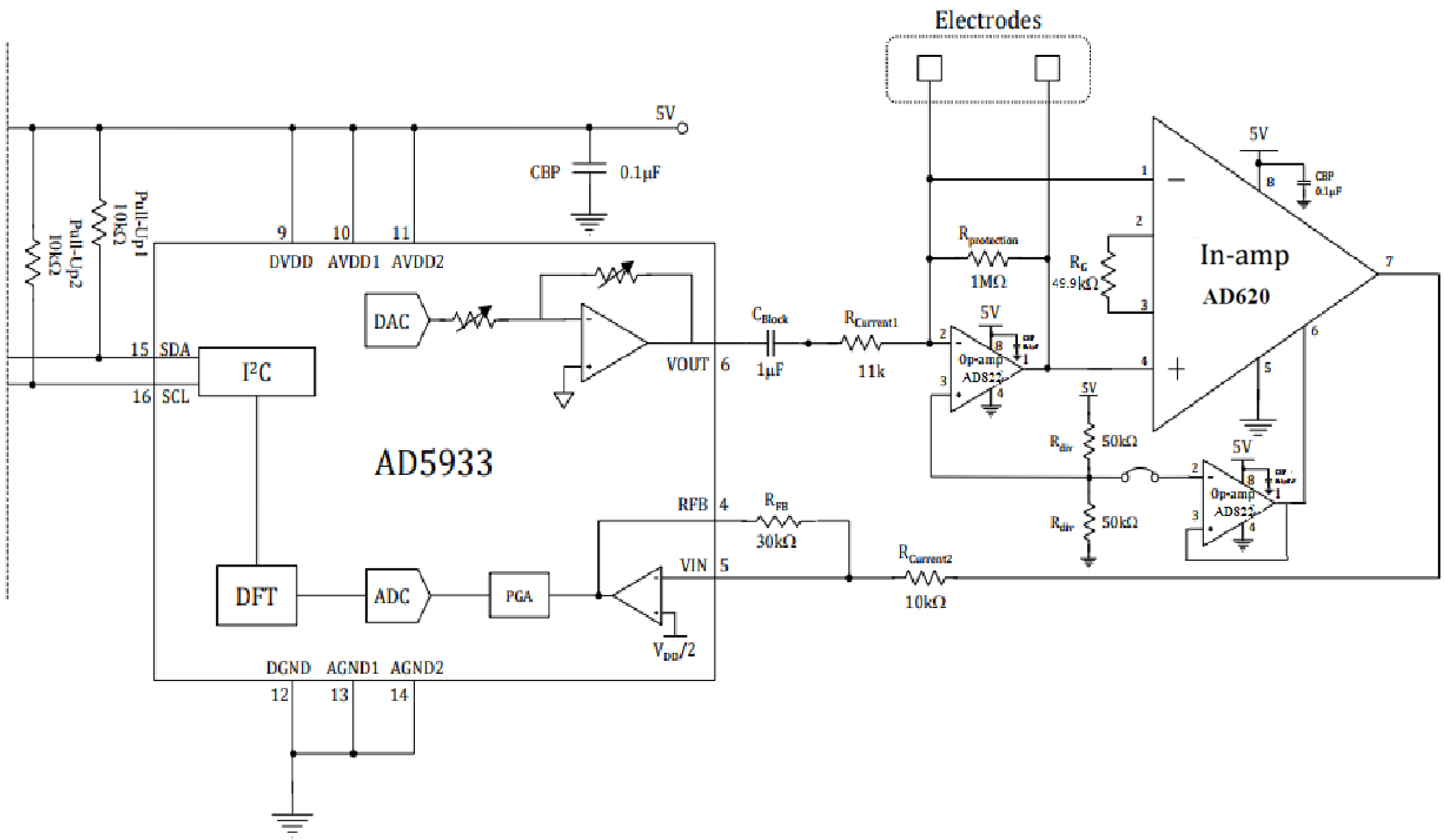


Figure 7. Reverse-Bias-Protection Circuit

Appendix 11

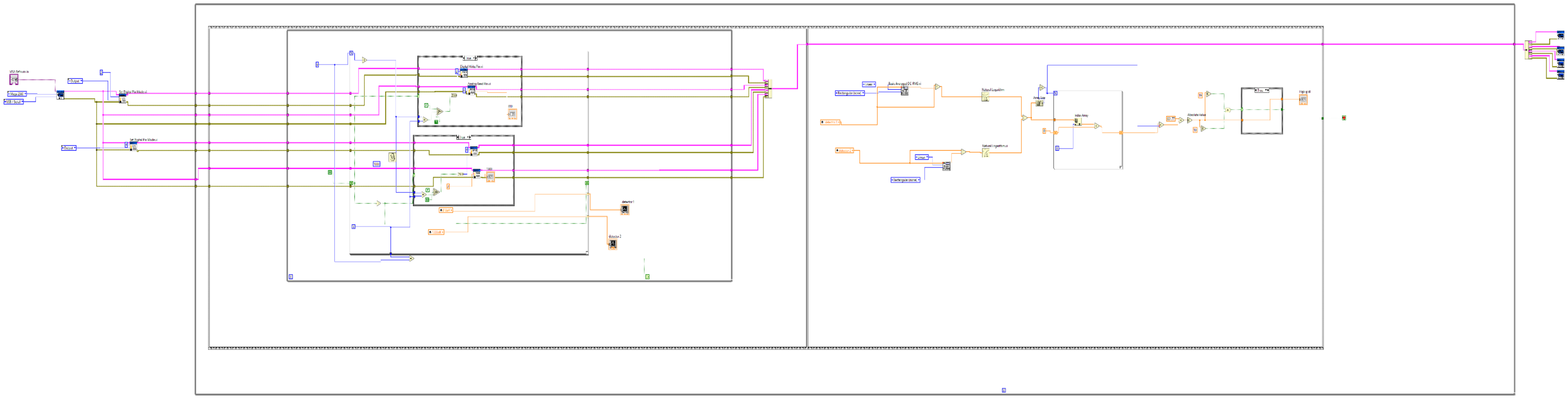


Schematic diagram of HGB system



Schematic diagram for fat percentage

Appendix 12



Appendix 13

```
#include <Arduino.h>
#include <Wire.h>



// Output frequency from AD5934
#include <Wire.h>



#define AD5934_add 0x0D // device address
#define ClockFreq 16000000 // External Clock Frequency
#define StartFreqV 50000
#define IncrFreqV 0
#define Number 20
#define CalReg 1000

int printval; // Value storage
int c = 0;



void setup()
{
  Serial.begin(9600);



  Wire.begin();
  Serial.println("Start");
  delay(100);
  Reset();
  // Use internal CLOCK!?!?! - Only for AD5933 :(
  // Set PtP value?
  // Set PGA gain?
```

```
  // Calibration sequence?
  /*
  bool AD5933::calibrate(double gain[], int phase[], int real[], int imag[],
  int ref, int n) {
  // Perform the frequency sweep
  if (!frequencySweep(real, imag, n)) {
  return false;
  }
  // For each point in the sweep, calculate the gain factor and phase
  for (int i = 0; i < n; i++) {
  gain[i] = (double)(1.0/ref)/sqrt(pow(real[i], 2) + pow(imag[i], 2));
  // Phase?
  // TODO: phase
  }
  return true;
  }
  */
  // hex of (freq/(ClockFreq/16))*2^27 = Start Frequency = (82=14;83=7A;84=E1 - 10kHz)
  // hex of (freq/(ClockFreq/16))*2^27 = Incr Frequency = (85=00;86=05;87=3E - )
  // The user programs the value 0x00 to Register Address 0x85,
  // the value 0x05 to Register Address 0x86, and the value 0x3E to Register Address 0x87.
}

void loop()
{
   AD5934(0x0D);
  if (c == 0)
  {
    Serial.println("Start");
    delay(100);
    Reset(); // Reset AD5934
```

```
delay(10);
StartFreq(StartFreqV); // Write start frequency data 5 khz
delay(10);
IncrFreq(IncrFreqV); // Frequency increment register 175 Hz
delay(10);
IncrNumb(Number); // Number of increments register 511
delay(10);

//set PGA Gain
// Out voltage set?

PowerM(1); // Standby mode
Reset(); // Reset
delay(10);
// printval = ic_read(0x87); //What is last register for freq incr?
// Serial.println(printval, HEX);

// Initialize frequency
ic_write(0x80, B00010001); //Start Freq Init and set gain to 1x!

// Start frequency sweep
Control(1);

/*Here it starts to get interesting*/
// Check if sweep is complete
int f = 0;
int i = 0;
Serial.println("Frequency        Magnitude");
delay(100);

//Sweep happens here:
```

```
while ((ic_read(0x8F) & 0x07) < 4)
{
  delay(10);
  byte valid = ic_read(0x8F);
  delay(1);
  while (valid != 2) // Wait until valid data is stored
  {
    valid = ic_read(0x8F) & 2;
  }
  if (valid == 2) //When complete - continue
  {
    // Get real values
    byte Real_1 = ic_read(0x94); // Byte 1
    byte Real_2 = ic_read(0x95); // Byte 2
    short Real = (Real_1 << 8) | Real_2; // Add bytes together

    byte Im_1 = ic_read(0x96); // Byte 1
    byte Im_2 = ic_read(0x97); // Byte 2
    short Im = (Im_1 << 8) | Im_2; // Add bytes together
    float frequency = f*IncrFreqV+StartFreqV; // Calculate current frequency
    // double angle_degree = angle(Real, Im);
    // Twos:
    int Rreal = Real;
    int Rim = Im;
    double Mreal = pow(Real,2);
    double Mim = pow(Im,2);
    double magnitude = sqrt(Mreal+Mim);

      Serial.print(frequency);
      Serial.print("; ");
      // Serial.print(Real_1, BIN);
```

```
        // Serial.print("|");
        // Serial.print(Real_2, BIN);
        // Serial.print(" | ");
        Serial.print(Rreal);
        Serial.print("; ");
        // Serial.print(Im_1, BIN);
        // Serial.print("|");
        // Serial.print(Im_2, BIN);
        // Serial.print(" | ");
        Serial.print(Rim);
        Serial.print("; ");
        Serial.println(magnitude);
        f++; // Increase frequency counter
      }
      else
      {
       Serial.println(valid, BIN);
      }
      Control(2); //Increment frequency
      // B0  0  1  0  0  0  0 1 //Start
      // B0  0  1  1  0  0  0 1 //Incr Frequency
      // B1  0  1  0  0  0  0 1 //Power-down mode
      // B1  0  1  1  0  0  0 1 //Standby mode
      // B15 14 13 12 11 10 9 8
      i++; //Increment counter
    }
    // Power down
    PowerM(2);
    Serial.println("Power Down");
  }
c = c + 1;
```

```
  if (c == 0)
  {
    c = 1; // Stop?
  }
}

double angle(int Real, int Im)
{
  double angle_deg;
  double angle_deg_ad;
  angle_deg = atan2(abs(Im), abs(Real)) * (180/PI);
  if (Real >= 0 && Im >= 0)
  {
    angle_deg_ad = angle_deg;
  }
  else
    if (Real >= 0 && Im <= 0)
    {
      angle_deg_ad = 360 - angle_deg;
    }
  else
    if (Real < 0 && Im < 0)
    {
      angle_deg_ad = 180 + angle_deg;
    }
  else
  {
    angle_deg_ad = 180 - angle_deg;
  }
  return angle_deg_ad;
}
```

```
void ic_write(int address, int data)
{
  Wire.beginTransmission(AD5934_add);
  Wire.write(address); // address specifier
  Wire.write(data); // value specifier
  Wire.endTransmission();
  delay(1);
}

int ic_read(int address)
{
  int initial_val;
  Wire.beginTransmission(AD5934_add);
  Wire.write(address);
  Wire.endTransmission();
  delay(1);
  Wire.requestFrom(AD5934_add, 1);
  while (Wire.available() == 0)
  {
  }
  initial_val = Wire.read();
  return initial_val;
}

////////////////////////////////////////////////////////////////////////


void _AD_Write(int address, int data)
{
```

```
  Wire.beginTransmission(AD5934_add);
  Wire.write(address); // address specifier
  Wire.write(data); // value specifier
  Wire.endTransmission();
  delay(1);
}

int _AD_Read(int address)
{
  Wire.beginTransmission(AD5934_add);
  Wire.write(address);
  Wire.endTransmission();
  delay(1);
  Wire.requestFrom(AD5934_add, 1);
  while (Wire.available() == 0);

  int initial_val = Wire.read();
  return initial_val;
}

int _Split(int Value, int num) // Spilts a 32bit word into bytes
{
  if (sizeof(Value) > 2 && num == 1)
  {
    int shiftVal = Value >> 8;
    return highByte(shiftVal); // High byte gets written first
  }
  if (num == 2)
  {
    int shiftVal = Value >> 8;
    return lowByte(shiftVal);
```

```
 }
 if (num == 3)
 {
  return lowByte(Value);
 }
 else
  return 0;
}

int _FreqtoHex(int freq, int type) // Frequency & FreqInc or FreqStart?
{
 int reg = 0;
 if (type == 1)
  reg = 0x82; // Start Frequency register first byte
 else if (type == 2)
  reg = 0x85; // Increment Frequency register first byte
 else
 {
  return 0;
 }

 int Hexed = freq * pow(2, 27) / (ClockFreq/ 16);
 _AD_Write(reg, _Split(Hexed, 1)); // byte 1
 reg++;
 _AD_Write(reg, _Split(Hexed, 2)); // byte 2
 reg++;
 _AD_Write(reg, _Split(Hexed, 3)); // byte 3
 return 1; // Success (?) - first determine IC write success too?
}

void Reset()
```

```
{
  _AD_Write(0x81, B00010000);
}

void StartFreq(int SFreq)
{
  _FreqtoHex(SFreq, 1);
}

void IncrFreq(int IFreq)
{
  _FreqtoHex(IFreq, 2);
}

void IncrNumb(int number)
{
  _AD_Write(0x88, _Split(number, 2));
  _AD_Write(0x89, _Split(number, 3));
}

//I am not sure if this will work, seeing as there are two control registers!
int PowerM(int mode)
{
  if (mode == 1) //Standby
  {
    _AD_Write(0x80, B10110001);
    return true;
  }
  if (mode == 2) //Pdown
  {
    _AD_Write(0x80, B10100000);
```

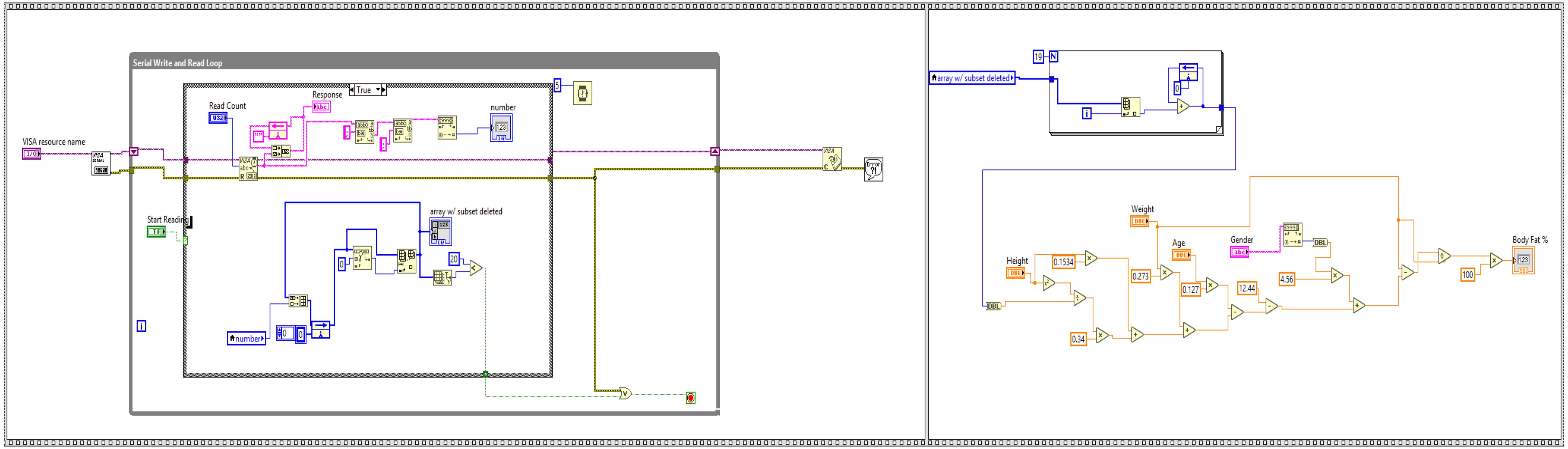
```
    return true;
  }
  if (mode == 3) //On
  {
    _AD_Write(0x80, B00000000);
    return true;
  }
  else
  {
    return false;
  }
}

void Control(int Cmd)
{
  if(Cmd == 1) //Start Sweep
  {
    _AD_Write(0x80, B00100001);
  }
  if(Cmd == 2) //Increment Frequency
  {
    _AD_Write(0x80, B00110001);
  }

}

void AD5934(int Add)
{
 //test
}
```

Appendix 14


Serial Write and Read Loop
VISA resource name
Read Count
Response
True
number
Start Reading
array w/ subset deleted
20
5
19
array w/ subset deleted
Weight
Age
Gender
Height
0.1534
0.273
0.127
12.44
4.56
0.34
100
Body Fat %

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