DESIGN OF ENVIRONMENTAL MONITORING SYSTEMS PH SENSING

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Abstract

This document explains the design process and methods of a pH sensor and data logger. It shows how taking advantage of the unique spectral properties of a polymeric membrane, a circuit can be conceived to measure the acidity of a solution within a specific pH range. It also goes through the testing of said circuit and its embedding into an already built CO_2 monitoring device, as well as a basic programming code to make it work properly.

The project focuses on finding out whether this pH monitoring technique can be used as a cheaper alternative to classic methods, making use of already existing tools and the artificially synthetized membrane. It eventually proves as a high potential instrument for pH sensing, with large scope for improvement at an inexpensive cost, thus making it highly useful for unmanned environmental monitoring processes.

Table of Contents

List of Tables

List of Figures

List of Equations

List of Appendices

Chapter I

Introduction

Over the last decade, a special concern for the environment has been arising among more and more members of our society. It seems that human population is growing at such a rate that it doesn’t allow nature resources to recover from our exploit. The problem is real, and solutions have therefore to be conceived accordingly. But the first step towards a solution finding endeavour is, without a doubt, collecting as much information as possible about the problem itself. Environmental parameters need to be monitored in order to have numerical data that can be later used to build an appropriate solution.

At the same time, the era of technology has continued to advance at a similar rate as global warming, and its peak still seems far in the future. Wherever you look, automation is the order of the day and doesn’t look like it wants to stop doing so. While it may be one of the causes for environment endangering, it can also be, and in fact already is, a part of its solution. Therefore, taking both these factors and bringing them together is the next logical step on the list. Taking advantage of automated systems, monitoring environmental data gets much easier and faster.

Taking this issue into specifics, such idea is gaining strength all across research facilities, and the University of Alberta is conceiving new methods and devices to make it work. In detail, two products are developed there that show a lot of potential. On the one hand, the Department of Chemistry has devised a way to synthetize a polymeric fabric whose spectral properties vary with the pH of the solution it is soaked in. On the other hand, the Department of Electrical and Computer Engineering has designed and built a device that automatically takes samples of carbon dioxide, humidity and temperature.

Taking advantage of both these products, I have worked to join them into a bigger, more resourceful device. As pH measuring techniques have seen little to zero progress for the last few decades, I have also aimed to achieve a versatile product at an inexpensive price, with good precision and high robustness.

During the implementation of this project, corresponding to my stay as an exchange student in the city of Edmonton, I have tried to devise a hardware design specific for taking advantage of the polymeric membrane properties. I have also sought to calibrate it to work properly with a specific light source. Finally, I have attempted to embed said circuit into the aforementioned monitoring device, and consequently, to program it to make use of the new implemented functions.

By doing so, I’ve gone through a series of challenges I’ve need to work around, as described over these pages. It is a fact that technology and environment are not incompatible, and this project serves as a good attempt to put the former in service of the latter.

Chapter II
Background

1. pH

1.1. Definition

One of the most relevant chemical parameters to take into account when analyzing a solution is, without a doubt, its acidity (or lack thereof, then called an alkalinity). These two concepts are intricately related, just like hot and cold, and linked and measured in a scale called pH. Acids can range from most definitely dangerous substances that can cause severe burning (such as sulphuric acid) to cuisine enhancers (lemon juice, for instance); and every one of these solutions has a pH, a simple number ranging usually from 1 to 14.

Acids and alkalis (also called bases) are just chemicals that dissolve in water to form ions, either with spare or missing electrons. Whereas an acid does it to form positively charged hydrogen ions (H+), alkalis end up forming negatively charged hydroxide ions (OH-). Obviously, the stronger the acid (or base) the more hydrogen (or hydroxide) ions it will form when dissolved into water.

But what does pH actually mean? Always written like this (little p, big H), it is regarded as an indicator of how many hydrogen ions a substance forms when dissolved in a certain volume of water. It is not clear where the two letters come from, although it is widely agreed that they stand for something like “potential of Hydrogen”.

$$pH = -log_{10}[a_{H^+}]$$

Equation 1: pH formula

Technically, though, its proper definition holds it as “minus the logarithm of the hydrogen ion activity in a solution”, as seen in equation (1). Fortunately it is simpler than it sounds. The hydrogen ion activity can be defined by the molar concentration of hydronium in said solution, and it is easy to see that a typical value of 10-X will have a pH of X. The minus also means that the higher the acidity, the lower the pH. Figure (1) shows the exponential decreasing relationship between concentration of hydrogen ions and pH.

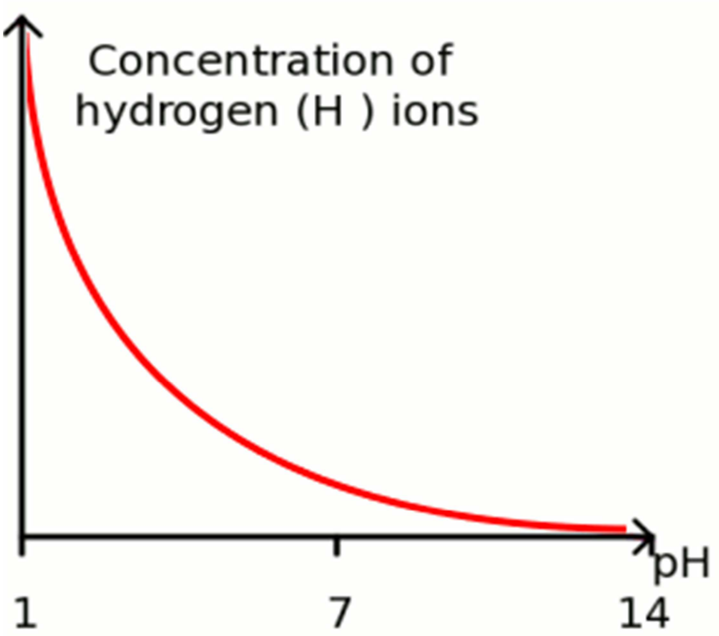


Figure 1: pH to [H^+] relationship

Thanks to the logarithm, the pH can tell the (probably gigantic) number of hydrogen ions within a solution using a simple small value. Not only that, but it also gives a pH of 1 for extremely acidic, pH 7 for neutral, and pH 14 for extremely alkaline. Note that extremely alkaline is just another way of saying incredibly weakly acidic.

1.2. Measuring systems and techniques

Having said that pH is a very important environmental parameter in nature, it is pertinent to ask ourselves the question: how can it be measured? And given the fact that technology moves at a way higher speed than the rest of the world, it is shocking to find out that the same two methods have been used continuously for the last sixty years, at least commercially. Based on the precision that can be achieved and, obviously, the price one is willing to spend, these following methods are found to be useful when it comes to measure pH.

- pH indicator

First of all, and as cheap as it can get, a pH indicator is a visual way to find out about acidity. Being just a weak acid or a weak base itself, the undissociated form of the indicator is a different color than its iogenic form. This means color change occurs over a range of hydrogen ion concentrations, called color change interval, and it is understood as a pH range.

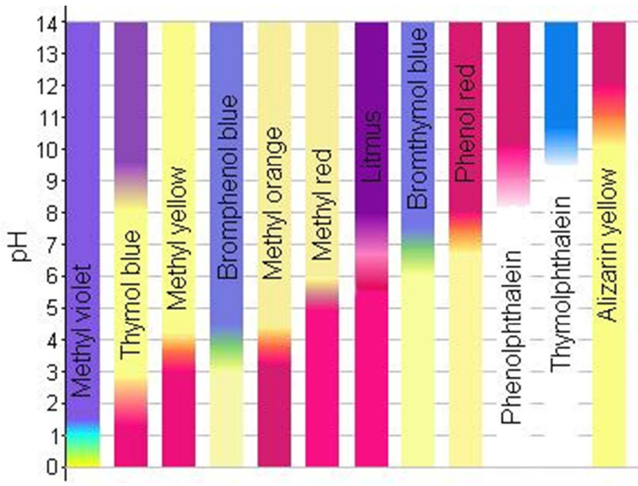


Figure 2: pH indicator chart

Weak acids are titrated in the presence of indicators which change under slightly alkaline conditions, while weak bases should be titrated in the presence of indicators which change under slightly acidic conditions. Based on the color of the strips, and comparing them to a chart as the one shown in figure (2), one can determine the pH range in which the measured solution is included.

- pH meter

While pH indicators are a good inexpensive way to figure out the approximate pH of a solution, their precision (or lack thereof) is their major drawback when such quality is intended. As a result, sometime during the 1930s, a much more accurate artefact was devised by American Radiometer worker Arnold Orville Beckman [1].

A pH meter, like the one shown in figure (3), actually measures the hydrogen ion concentration of a solution. But how does it do it? An acidic solution has far more positively charged hydrogen ions in it than an alkaline one, so it has greater potential to produce an electric current in a certain situation. In other words, it's a bit like a battery that can produce a greater voltage. A pH meter takes advantage of this and works like a voltmeter: it measures the voltage produced by the solution whose acidity is being measured, compares it with the voltage of a known solution, and uses the difference in potential between them to deduce the difference in pH.

Figure 3: Typical pH meter

To do so, a typical pH meter uses two basic components: the meter itself, which can be a moving-coil meter (one with a pointer that moves against a scale) or a digital meter (one with a numeric display), and either one or two probes that are inserted into the solution being tested. To make electricity flow through them, and close the circuit, two electrodes (electrical terminals) are introduced. Even if the meter has only one probe, two electrodes are used, both being built into the same probe.

Furthermore, the electrodes aren't like normal electrodes (simple pieces of metal wire); each one is a mini chemical set in its own right. The electrode that does the most important job, which is called the glass electrode, has a silver-based electrical wire suspended in a solution of potassium chloride, contained inside a thin bulb (or membrane) made from a special glass containing metal salts (typically compounds of sodium and calcium). The other electrode is called the reference electrode and has a potassium chloride wire suspended in a solution of potassium chloride (which is a neutral solution with a pH of 7). Both electrodes, along a simplified version of the setup, are shown in figure (4).

When the two electrodes are dipped into the tested solution, some of the hydrogen ions move toward the outer surface of the glass electrode and replace some of the metal ions inside it, while some of the metal ions move the other way around. This ion-swapping process is called ion exchange, and it's the key to how a glass electrode works. Ion-swapping also takes place on the inside surface of the glass electrode from the reference solution. The two solutions on either side of the glass have different acidity, so a different amount of ion-swapping takes place on the two sides of the glass. This creates a different degree of hydrogen-ion activity on the two surfaces of the glass, which means a different amount of electrical charge builds up on them. This charge difference means a tiny voltage (typically a few tens or hundreds of millivolts) appears between the two sides of the glass, which produces a difference in voltage between the silver electrode and the reference electrode that shows up as a measurement on the meter.

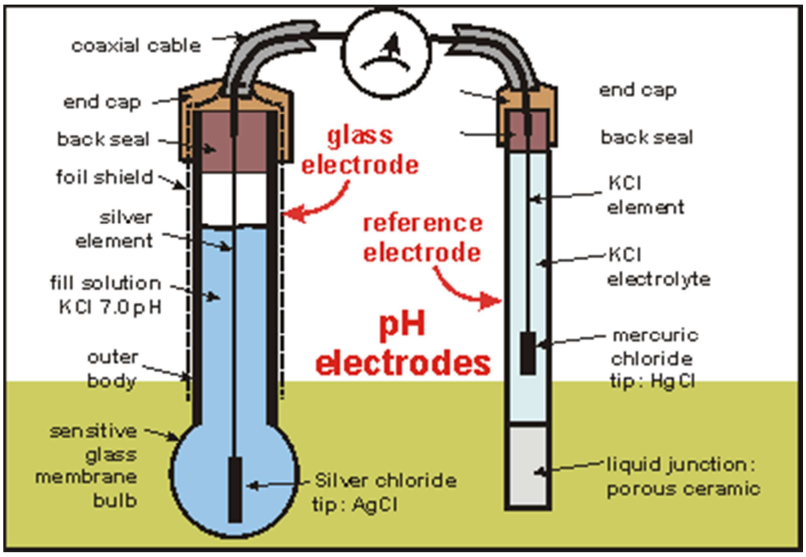


Figure 4: pH meter diagram

Although the meter is measuring voltage, what the pointer on the scale (or digital display) actually shows is a pH measurement. The bigger the difference in voltage between the solutions, the bigger the difference in hydrogen ion activity will be. If there is more hydrogen ion activity in the tested solution, it's more acidic than the reference solution and the meter shows this as a lower pH; in the same way, if there's less hydrogen ion activity in it, the meter shows this as a higher pH (more alkaline).

As good as these methods can be, they are separated by a world. As shown in figure (6), the difference in price is huge, but so is the difference in precision. The scope of this project is to ultimately find a method and/or instrument that can be found between the two current existing techniques, both in price and accuracy. Note: the price is not unitary (since pH indicators can be used only once), but rather includes the total number of strips one would have to buy to get the same number of tests as in the lifespan of an average pH meter before it loses too much accuracy.

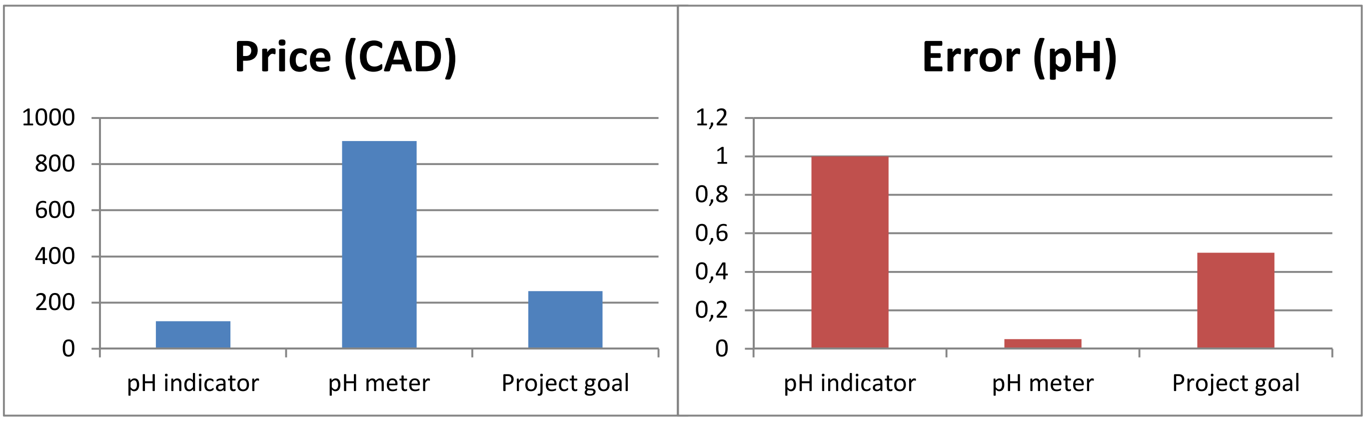


Figure 5: Average price and precision of current pH measuring methods and project goal

2. Etalon

2.1. Overview

The first step to creating an acidity sensing device is to find something that actually changes with pH, so that the change can be measured and related to the key parameter. The etalon fulfills this purpose.

Based on the Fabry-Perot[2] interferometer, the main advantage of this membrane is that its spectral properties change with pH, making it suitable as a sensor. It has been devised and synthesised by the Serpe Group in the University of Alberta Department of Chemistry for a wide range of purposes; this fabric is quite inexpensive and has a reduced size which makes it fit to be used as a portable sensor.

2.2. Synthesis and preparation

The Etalon is made of microgel film covered in gold coverslips. Microgel particles are synthesized by free radical precipitation polymerization. Briefly, NIPAm (11.9 mmol) and N, N'-methylene bisacrylamide (a cross linker, 0.703 mmol) are dissolved in 99 mL deionized (DI) water, and filtered through a 0.2 μm filter into a three necked round bottom flask. One end of the round bottom flask is fitted with a condenser, another with N2 and the last with a thermometer.

The solution is then purged with N2 for approximately one hour and a half at 70 °C. Next, AAc (1.43 mmol) is injected into the heated mixture and immediately initiated with ammonium persulphate (APS) and allowed to react for 4 hours under a N2 blanket at 70 °C. The solution is lastly cooled and filtered through a Whatman #1 filter and the filtrate centrifuged six times, removing the supernatant and redistributing it in DI water after each round of centrifugation to obtain a pure, concentrated microgel pellet.

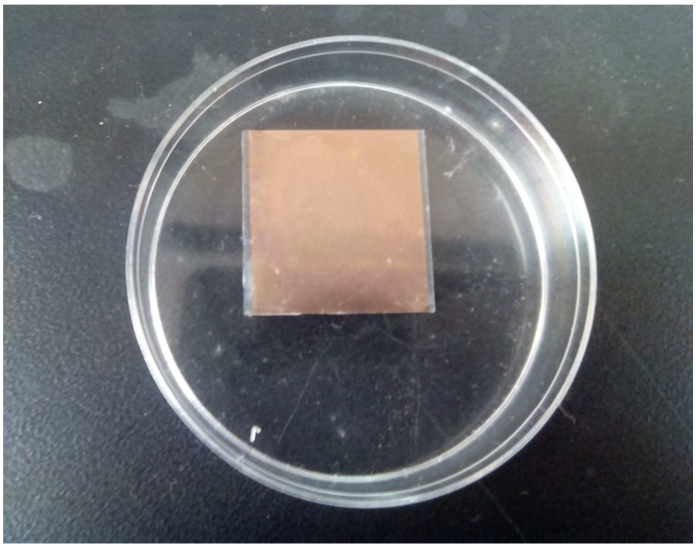


Figure 6: Etalon sample

On the other hand, Au coated coverslips (etalon underlayer) are fabricated by depositing 2 nm of Cr and 15 nm of Au on a 25 x 25 mm ethanol rinsed and N2 gas dried glass coverslip using a thermal evaporation system. The Cr/Au substrates are annealed at 250℃ for 3 hours and cooled to room temperature prior to microgel film deposition.

The concentrated microgel pellet left after the centrifugation is vortexed to loosen and homogenize the particles in the remaining solvent. A 40 μL aliquot of concentrated microgels are spread onto an annealed 25 mm x 25 mm Au-coated glass coverslip. The film is allowed to dry on a hotplate at 30 ºC for 30 minutes before the excess microgels are rinsed with deionized water. The samples are soaked overnight at 30 ºC in a deionized water bath. Finally, the samples are rinsed with deionized water, dried with

N2, and another Au overlayer (2 nm of Cr for adhesion, followed by 15 nm Au) is added. The completed device is soaked overnight in deionized water at 30 °C before undergoing a thorough spectral analysis.

2.3. Spectral properties

The device is called an etalon because it mimics the Fabry-Perot interferometer. When light is exposed to the device, the light enters and resonates within the cavity leading to constructive and destructive interference. The reflected light is collected and analyzed using a reflectance spectrometer. The comonomer AAc is an acidic monomer, rendering the whole microgel pH responsiveness, which means that at pH lower than the pKa of the AAc group (< 4.25), the microgel is in the neutral state. On the contrary, when ph levels are above said pKa, the microgels are negatively charged.

The charge-charge repulsion in the microgels at high pH causes them to swell. Similarly, as they are confined between the two gold "mirrors", their swelling causes the distance between the device's two mirrors to increase, leading to a simultaneous increase in the wavelength, as can be predicted from equation (2), where λ is the wavelength maximum of the peak, m is the peak order, n is the refractive index of the dielectric, d is the spacing between the mirrors and θ is the angle of incidence.

$$\lambda \cdot m = 2 \cdot n \cdot d \cdot \cos(\theta)$$

Equation 2: Etalon wavelength calculation

With this phenomenon, one is able to monitor the peak position as a function of solution pH. A color change can also be visually appreciated (due to the wavelength shift) when these membrane is immersed in different pH solutions.

2.4. Development tests

To know, as a first approach, how the membrane reacts to light, a red laser diode light was shined into the device, and both reflected and refracted beams were collected, separately, with the spectrometer USB2000+ by Ocean Optics (datasheet can be found in appendix D). The setup is shown in figure (7). The laser beam is collected with optic fibre, which goes straight to the Etalon; in a similar way, the reflected (or refracted) light is sent through optic fibre to the spectrometer using a screwable nozzle.

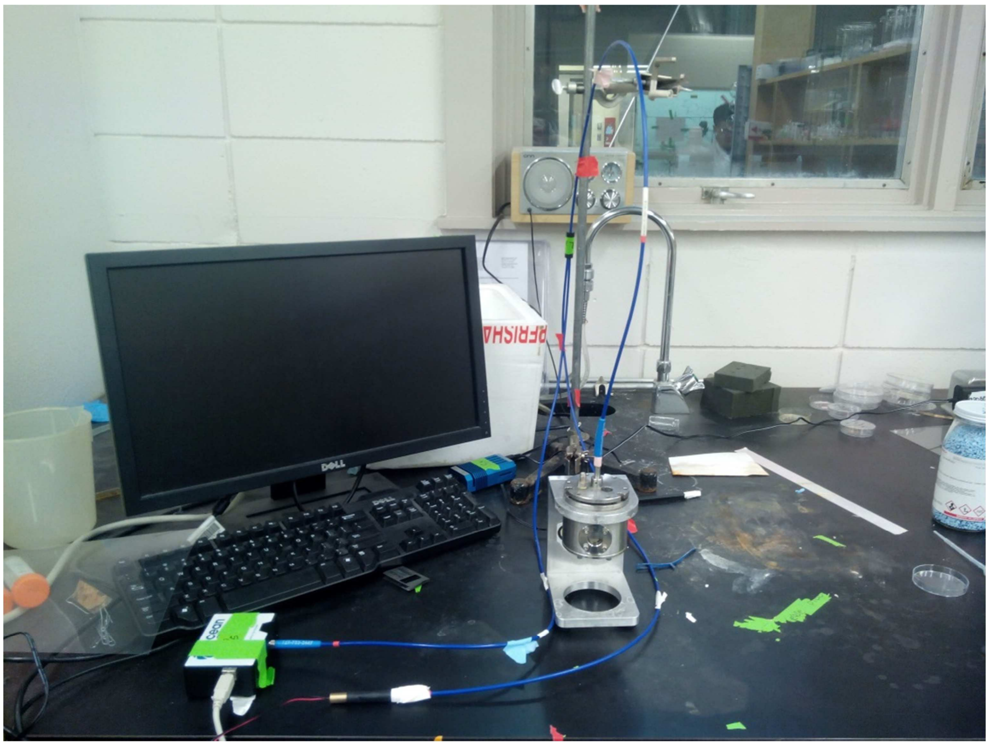


Figure 7: Development tests setup

For a specific pH value, the spectrometer collects the irradiance (µW/cm2) across the spectrum, up to 1200 nm (refer to appendix A). The obtained values showed that at peak wavelength (the wavelength at which the irradiance is higher, around 651 nm for the red light from the laser), irradiance decreases with pH, as shown in table (1), and later in figure (8).

pH	Collected beam	Peak wavelength (nm)	Absolute irradiance (µW/cm^2)
3	Reflected	651,22	17741,26
	Refracted	650,88	17832,54
4	Reflected	651,22	16570,99
	Refracted	651,22	16444,6
5	Reflected	651,22	13694,47
	Refracted	650,88	13453,4
6	Reflected	650,53	10782,85
	Refracted	651,22	11201,8

Table 1: irradiance values at λ = 651 nm

Looking both at the values and the chart, it can be easily appreciated that the decrease in irradiance is more pronounced when the collected light is reflected; furthermore, collecting refracted light proves to be much harder when it comes to setting up the optic fibre. Taking these facts into account, the conclusion was to use reflected light as a measurable parameter to later calculate pH.

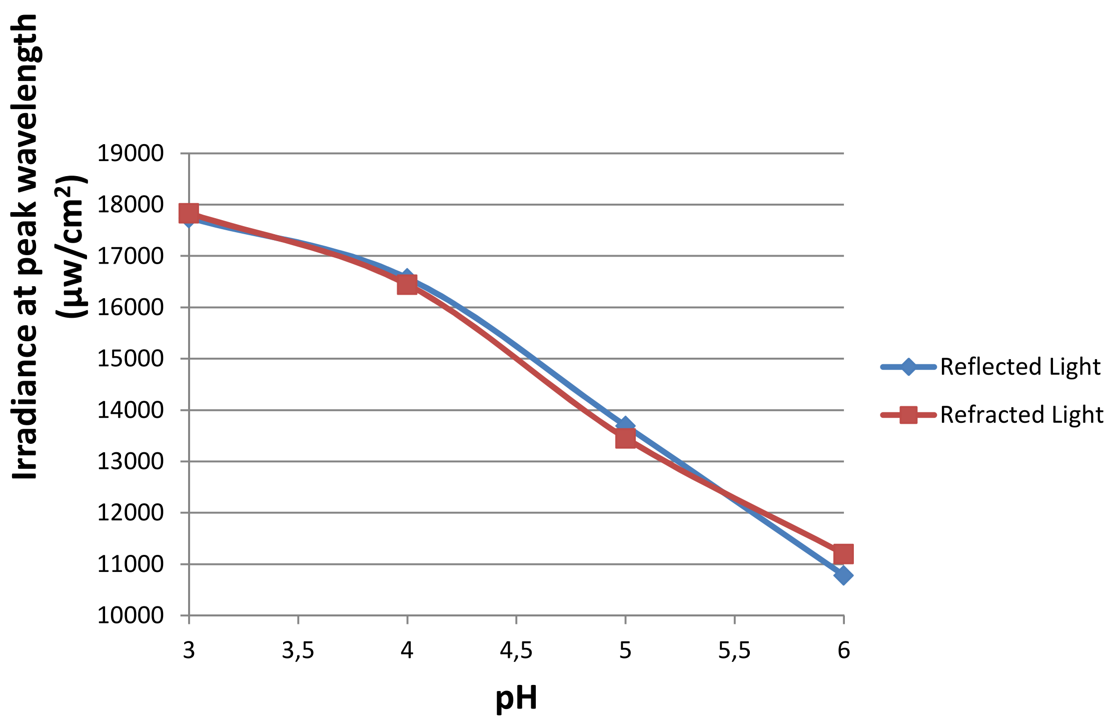


Figure 8: Irradiance and pH decreasing relationship

Unfortunately, the spectrometer is both too large and too expensive for the purpose of this project (cheap and embeddable), and it even needs a computer with specific software to collect the data. For this reason, new hardware has to be designed to meet the ultimate goals that were marked.

3. Wireless Gas Monitor and Data Logger

3.1. Overview

Once the sensing device has already been selected, the next step is finding something to embed it with. As the scope of this project asks for automated pH sensing and monitoring, a microprocessor and storing device, at least, are needed. Asher Watts, from the University of Alberta Department of Electrical and Computer Engineering, had previously developed a similar product, only for CO2, humidity and temperature, but with spare ports for both analog and digital outputs, as he reckoned some more environmental parameters could be added over time. Taking advantage of this, the Etalon, along with the required circuitry (refer to hardware design) can be embedded and the device reprogrammed to be used as a pH sensor as well.

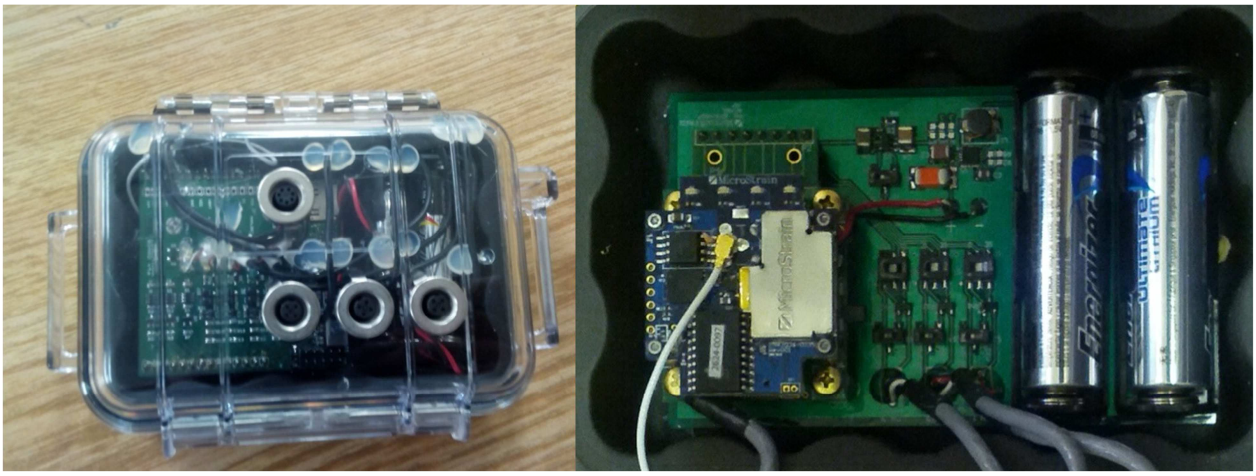


Figure 9: Wireless Gas Monitor and Data Logger

3.2. Basic functions

The CO2 Wireless Sensor platform is a low power solution for gas detection. Running on 4xAA batteries, it provides four analog and one digital sensor channels along with a Zigbee radio. It is built into two different boards: the main board (where the microprocessor, A/D converter and other inherent hardware is kept) and the conditioning board, where all the interfaces for inputs and outputs from and to the exterior have been built in.

The default configuration of the device is a single, digital CO2 gas sensor which captures relative humidity, temperature, and two carbon dioxide signals. All sensory information is stored on an SD Card and can be transmitted by Zigbee if configured to do so.

The sensor is initially set to wake up every 15 minutes to take measurements, but this can be changed to any time period greater than 30 seconds and shorter than 24 hours. In addition, by default, the device looks for user intervention, indicated by a green LED, for 3 seconds after being switched on or waking up from sleep mode. Since this is too energy intensive for regular operation, the option can be disabled before the device is deployed. A real time clock is included, and requires the Configuration Utility to get the time and date via user.

The internal memory of the logger can be accessed and edited to set how the device operates. Additionally, all sensors can be accessed and run independently for error checking and troubleshooting. The internal memory saves the operational state of the device. Upon waking up from sleep, microcontroller must reboot. To ensure that the user's settings are kept, the state is saved to the EEPROM inside of the device.

The Zigbee radio is controlled by Digital State 0, while the CO2 sensor is controlled by Digital State 1. When set to 0, the sensor is disabled. If the state is set to 1, the sensor is periodically power cycled with platform sleep and wake-up, and if state is 2, the CO2 sensor is put to sleep but never actually powered off. State 2 is necessary to prevent the sensor from losing detailed calibration information. If the sensor is left uncalibrated, state 1 is sufficient. The “deployed” state allows the device to determine whether it is supposed to be in the field or not. If this is set to 1, the platform stops looking for an external user and the CU is disabled, which makes it important for power saving.

In the event of a fault serious enough to reset the real time clock, the platform looks for external intervention for one hour. It continues to save data to the SD card under a default file name. This can indicate how many times the device has failed, and approximately how often. For a more detailed explanation of how the device works, see appendix B.

Chapter III

Main objectives

1. Hardware design

To measure pH using the etalon there is a need for a light source and a measuring device. To embed it to a small device such as the Wireless Gas Monitor, the used hardware has to be small enough to fit in. A low price can be achieved by using inexpensive source hardware and components.

Taking a look at Wireless Gas Monitor, it can be seen that spare digital and analog ports can be used for the purpose. The cheapest and most effective hardware option is to use the analog port, and use the internal Analog to Digital Converter to process the data.

2. Design validation

Once a hardware design has been selected and prototyped, there is a good chance it will not work on the first try. Functionality does require some testing for calibration to make the device work properly before the design is validated and ready to be manufactured properly.

Every prototype with whatever design has to undergo testing with the actual conditions (Etalon) so its flaws (or lack thereof) can be detected and fixed before the product is finished. This means that design and testing are based on concurrent engineering, since the feedback between them is what makes the product development flow.

3. Embedding

With the final hardware design in mind and working properly for the desired purpose, the product has to be manufactured according to the specifications. In this case, a new conditioning printed circuit board for the Wireless Gas Monitor should be designed and produced in accordance to the new components added, therefore obtaining an all-in-one inexpensive utility.

A complete embedding was not possible due to the lack of time, although both schematics and PCB were designed, missing only the manufacturing, as seen later on.

4. Programming

Since new hardware is added to the device, the CPU has to change its routines so the new functionalities can be applied successfully. For this purpose a JTAG is used to access, program and debug the microprocessor. The new sensor would take only a spare analog input, so the routine itself should not be a challenge.

Instead, the rather difficult aspect of this step is most likely the coordination between all inputs and outputs actuating with very little time window, and giving priorities to them with the use of, for instance, semaphores. Actual programming of the microprocessor was not possible due to the lack of time, although an algorithm was devised for the purpose, as seen later on in the pertinent section.

5. Software validation

Similarly to the design validation but for software, the program flashed into the microprocessor has to be properly checked and tested with actual situations. Results should be compared to manual hardware-only tests to see how accurate the embedding has been.

This whole process is intricately linked with the programming, making this step part of the concurring engineering procedure. Since the programming was not actually carried out to the microprocessor, this validation could not be done either, as it remains as a part of the future work for this project.

Chapter IV

Hardware design

1. Overview and requirements

1.1. Functionality

From the hardware point of view, the needs are dictated by what the Etalon requires to act as a sensor. Firstly, a light source is needed to shine waves from the visible spectrum to the membrane. The color maters, since the Etalon has different behaviour at different frequencies.

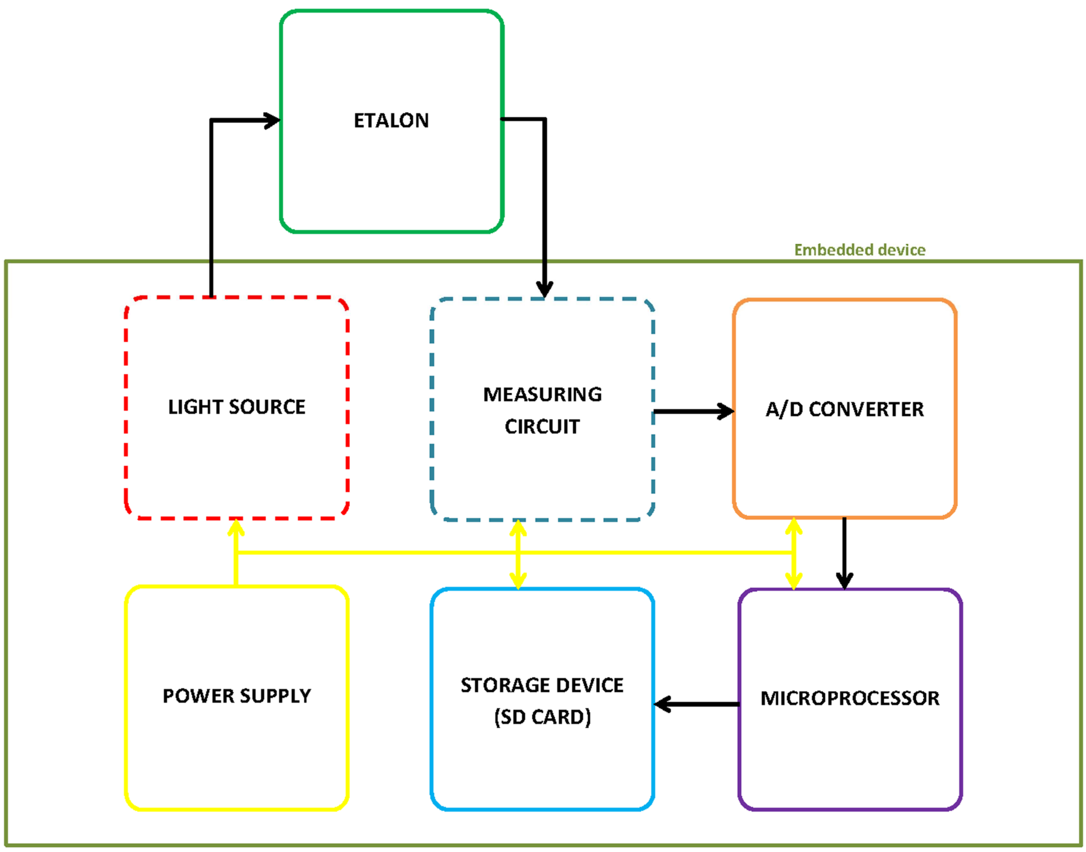


Figure 10: Hardware block diagram

The most important part of the circuitry is the one in charge of measuring the reflected light from the membrane. For this purpose, a photosensitive device has to be used; furthermore, the collected light has to be transformed into an analog signal so it can be converted to digital and transferred to the microprocessor.

The block diagram in figure (10) shows an overview of what the hardware functions are and how they are connected together; dashed blocks indicate which parts of the whole device have to be designed from scratch, while other parts are already designed and manufactured but may require intervention (such as programming).

1.2. Size and price

The conditioning board (the one where all interfaces for inputs and outputs are built) includes all the analog and digital ports and the involved circuitry to make use of them, if they are already in use. As such, the room is limited, as seen in figure (11), with a total size of 90 x 160 mm

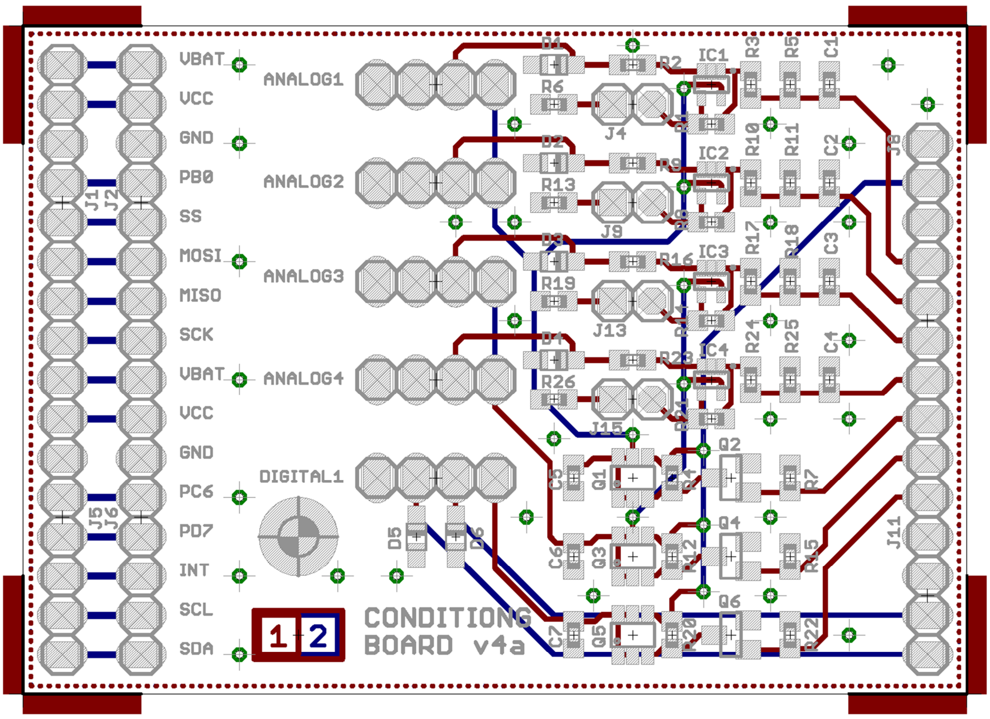


Figure 11: Original conditioning board

As a result, all components have to be small enough to fit in such space. Although during the testing the built prototypes don't have to be small, it has to be ensured that the same components are used to maintain the desired and achieved behaviour during the design validation. Hardware such as Integrated Circuits is very useful for a wide range of functionalities at a reduced space.

With these characteristics already defined, one has to take the price into account as well. There might be some components in the market with extremely good size, performance and/or sensitivity but at a way too high price; that means they are not good for this project either. Taking out the price of the Etalon and the Wireless Gas Monitor (including its previous components, still used in newer versions), it is safe to acknowledge that the total price of the components used for both light source and measuring circuit should be no more than 50 dollars (CAD).

2. Light source

To collect the light reflected by the Etalon, some has to be shined at it in the first place. For this reason, a compact light source should be used. As the optic fibre carries it to the membrane, the shining angle should be as reduced and straight as possible; also, its price should be low. The color of the shined light is one of the most important factors, and tests should be carried out with lights of different wavelengths (and therefore frequencies).

It would be ideal to get good irradiance at a low current consumption, as the 3.3V battery supply from the Wireless Gas Monitor is devised to work with power saving devices and methods. For this reason, only diode based lights were tested. For every tested light, a series resistor should be added to match its maximum current ratings, according to Ohm's law, depicted in equation (3):

$$V = R \cdot I$$

Equation 3: Ohm's law

Since the light itself sees an approximately constant voltage drop (light shines only if the supply voltage is equal or larger than this value), the series resistor to be added should be calculated as shown in equations (4) and (5):

$$V_{CC} - V_{DIODE} = R_{SERIES} \cdot I_F$$

Equation 4: Adapted Ohm's law for light source circuits

$$R_{SERIES} = \frac{V_{CC} - V_{DIODE}}{I_F}$$

Equation 5: Series resistor calculation

Where V_{CC} is the voltage provided by the Wireless Gas Monitor batteries (3.3V), I_F the maximum (nominal) forward current allowed by the light source, and V_{DIODE} represents the voltage drop across the diode. Once the resistor has been selected, a last calculation has to be done to ensure that the tension seen by the light source doesn't reach its maximum power dissipation rating (P_{DMAX}), as seen in equation (6):

$$P_D = I_F \cdot V_{DIODE} < P_{DMAX}$$

Equation 6: Power dissipation calculation

2.1. Red LED

Light Emitting Diodes are one of the best options as far as for low consumption light sources go. The selected device was the red SLI-570UT3F by Rohm; its datasheet can be found in Appendix C, and its main characteristics can be found in table (2).

Characteristic	Unit	Value
Peak wavelength (λ)	**nm**	630
Peak frequency (f)	**kHz**	475,86
Viewing angle (θ)	**deg**	25
Maximum forward current (I_F)	**mA**	50
Maximum peak current (I_P)	**mA**	200
Forward voltage (V_{LIGHT})	**V**	1,9
Maximum power dissipation (P_{DMAX})	**mW**	125
Calculated series resistance (R_{SERIES})	**Ω**	28
Calculated power dissipation (P_D)	**mW**	95

Table 2: Red LED main technical data

Despite the calculations, once tested, it was seen that the series resistor was too large to get a shiny enough light. Since the light is set to be operated only during very short intervals of time (no more than half a second), a resistor of 10 Ω was selected due to the obtained results (clear shiny red light); the current flow of 140 mA is still low enough compared to the maximum peak current allowed (200 mA).

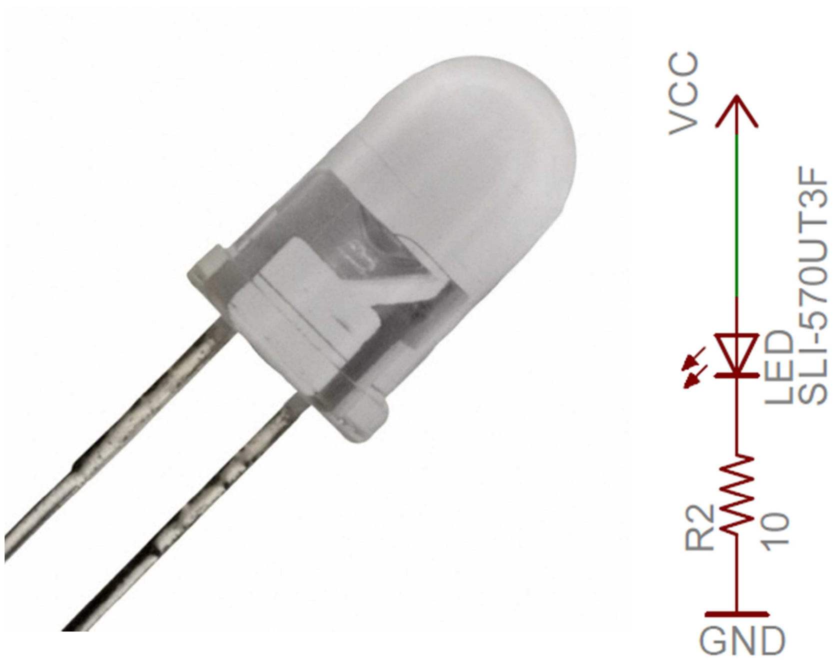


Figure 12: Red LED picture and circuit schematic

A picture of the LED, along with its according circuit schematic, can be seen in figure (12). At a price of 0.56$[3] (less if bought in bulk), this is a serious option to consider. However, when tested, although it showed some effectiveness, the obtained curve did not have a very pronounced slope (refer to chapter V). Therefore it was ultimately not selected as the light source to be used in the embedded device.

2.2. Green/Red LED

Another Light Emitting Diode that was tried was a dual one, meaning that depending on the direction in which it is connected, it shines a different light (it has two antiparallel LEDs). The selected device was the green/red LTL-293SJW by Lite-On; its datasheet can be found in Appendix C, and its main characteristics can be found in table (3).

Characteristic	Unit	Value
Peak wavelength (λ)	**nm**	565
Peak frequency (f)	**kHz**	530,61
Viewing angle (θ)	**deg**	25
Maximum forward current (I_F)	**mA**	30
Maximum peak current (I_P)	**mA**	120
Forward voltage (V_{LIGHT})	**V**	2,1
Maximum power dissipation (P_{DMAX})	**mW**	100
Calculated series resistance (R_{SERIES})	**Ω**	40
Calculated power dissipation (P_D)	**mW**	63

Table 3: Green/Red LED main technical data

Similarly to the red LED, once tested, it was seen that the series resistor was too large to get a shiny enough light. Since the light is set to be operated only during very short intervals of time (no more than half a second), a resistor of 15 Ω was selected due to the obtained results (clear shiny red light); the current flow of 80 mA is still low enough compared to the maximum peak current allowed (200 mA).

A picture of the LED, along with its according circuit schematic, can be seen in figure (13). At a price of 0.52$[3] (less if bought in bulk), this is a good device to test with the green light. However, when tested (only with green color, since there was already an option for red), the measuring circuit showed almost no response (refer to chapter V) to this kind of light, mainly because of the wavelength, viewing angle and irradiance. Therefore, it was ultimately not selected as the light source to be used in the embedded device.

Figure 13: Red/Green LED picture and circuit schematic

2.3. Red Laser Diode

As red is probably the best color for the spectral properties of the manufactured Etalon, another option is to try a Laser Diode. The selected device was the VLM-650-01-LPA by Infiniter, already used for the tests with the spectrometer; it comes with an integrated APC (Automatic Power Control) that regulates the output and the current if the supply voltage is within its operating range. This avoids the use of a series resistor for this device. Its datasheet can be found in Appendix C, and its main characteristics can be found in table (4).

Characteristic	Unit	Value
Peak wavelength (λ)	nm	651
Peak frequency (f)	kHz	460,51
Spot size (ϕ)	mm	5
Maximum operating current (I_{OP})	mA	35
Forward voltage (V_{LIGHT})	V	2,6
Power dissipation (P_D)	mW	5

Table 4: Red Laser Diode main technical data

As opposed to the LEDs, this device has a straight beam instead of a scattered light emission, which can be very helpful for the optic fibre to capture. It also has the advantage of the APC, which ensures a constant current consumption of 35 mA and a total power consumption of 5 mW. Besides, it had already been used for the Etalon development tests, and had successfully proven its usefulness.

Figure 14: Red Laser Diode picture and circuit schematic

A picture of the device, along with its according circuit schematic, can be seen in figure (14). At a price of 23.71$[3] (less if bought in bulk), it is by bar the more expensive option. However, when tested, it proved as the best light source for this kind of application (refer to chapter V), because of the aforementioned factors. As a result, this was the selected device to be embedded with the Wireless Gas Monitor.

2.4. Summary

Table (6) shows a summary of all the important characteristics of the different light sources that underwent testing; highlighted in green appears the best value for each feature (if applicable).

Device	Red LED	Red/Green LED	Red Laser Diode
Manufacturer	Rohm Semiconductor	Lite-On	Infiniter
Color	Red	Green	Red
Price	0,56 CAD/unit	0,52 CAD/unit	23,71 CAD/unit
Peak wavelength (λ)	630 nm	565 nm	651 nm
Peak frequency (f)	475,86 kHz	530,61 kHz	460,51 kHz
Viewing angle (θ)	25 deg	25 deg	N/A (straight beam)
Maximum forward current (I_F)	50 mA	30 mA	35 mA
Maximum peak current (I_P)	200 mA	120 mA	N/A (APC)
Forward voltage (V_{LIGHT})	1,9 V	2,1 V	2,6 V
Maximum power dissipation (P_{DMAX})	125 mW	100 mW	5 mW
Selected series resistance (R_{SERIES})	10 Ω	15 Ω	0 Ω (APC)
Total power dissipation (P_D)	266 mW	168 mW	3.5 mW

Table 5: Technical data summary for different light sources

Despite its high price, it is seen that the Laser Diode offers the most advantages with respect to the LEDs. This was later corroborated by the testing results; a more in-depth view of this issue can be found in chapter V.

2.5. Driver

During the testing, the prototype is powered with an external power supply, but when it comes to the final embedded product, it is batteries that do the job. For this reason, a laser driver would be very useful to save power. The schematic is shown in figure (15):

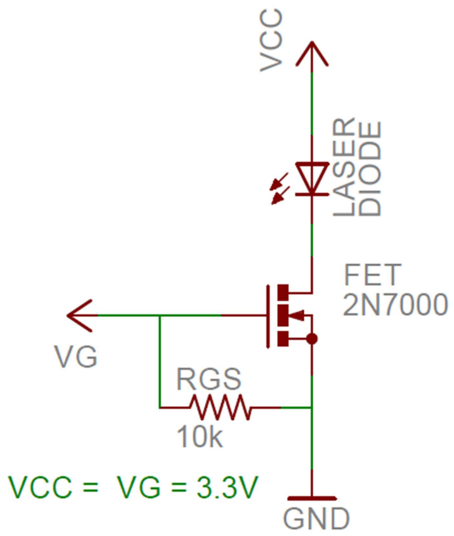


Figure 14: laser driver schematic

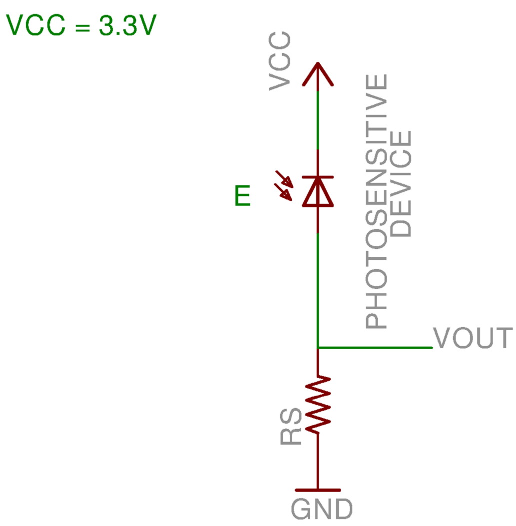
The transistor, a Fairchild 2N7000TA MOSFET (datasheet included in Appendix C), acts as a switch, allowing current to flow (and therefore the laser being turned on) only when a voltage above the threshold is applied at the gate. The microprocessor can be configured to output this gate voltage when desired, consequently controlling the laser at will.

The devised circuit is conceived as a low side driver (meaning it connects the load to the ground), and as such, a 10 kΩ pull-down resistor is added to prevent the transistor from driving when the gate is floating (high impedance status). The price of the FET is only 0.34$[3], thus making the add-on very inexpensive.

3. Measuring circuit

The cornerstone of the sensor is, of course, the hardware design involved in measuring the reflected light and thus providing an analog signal for the microprocessor to be converted and read. As previously said, a photosensitive device is needed to do so, whether it is a phototransistor or a photodiode; but besides that, many more factors need to be taken into account to design a feasible measuring circuit for the purpose.

The most basic option would be the one with a simple photosensitive device (acting as a current source for a specific pH) and a series resistor. The output voltage is simply calculated by Ohm's law, as seen in equation (6).



$$V_{OUT} = R_S \cdot I_E$$

Equation 6: Basic output voltage calculation

The problem with this design is it is way too simple. The accuracy it provides is too low for the goals that were set (it could not get better precision than the pH indicator strips). What's more, the range in which the Wireless Gas Monitor A/D converter works is 0 to 1.6 V: the circuit output lower limit is set by the current (no light, no current, no output voltage), but there is no upper limit; as a result, even though it can be more or less regulated by the resistor value, when there is too much current flowing, the output voltage would be out of range of the A/D converter.

Since this first approach could not be used as a measuring circuit for the desired purpose, a new method had to be devised. The final chosen circuit was ostensibly more complex, with more parts and uses (filters, amplifiers, buffer…), but the first dilemma was which photosensitive device to use.

3.1. Phototransistor

All transistors are actually sensitive to light. Phototransistors are designed specifically to take advantage of this fact. The most-common variant is an NPN bipolar transistor with an exposed base region. There, light striking the base replaces what would ordinarily be voltage applied to the base, so a phototransistor amplifies variations in the light striking it.

A common type of phototransistor, called a photobipolar transistor [4], is in essence a bipolar transistor encased in a transparent case so that light can reach the base–collector junction. While phototransistors have a higher responsivity for light they are not able to detect low levels very well and have long response times. The conceived circuit using this kind of device is shown in figure (16).

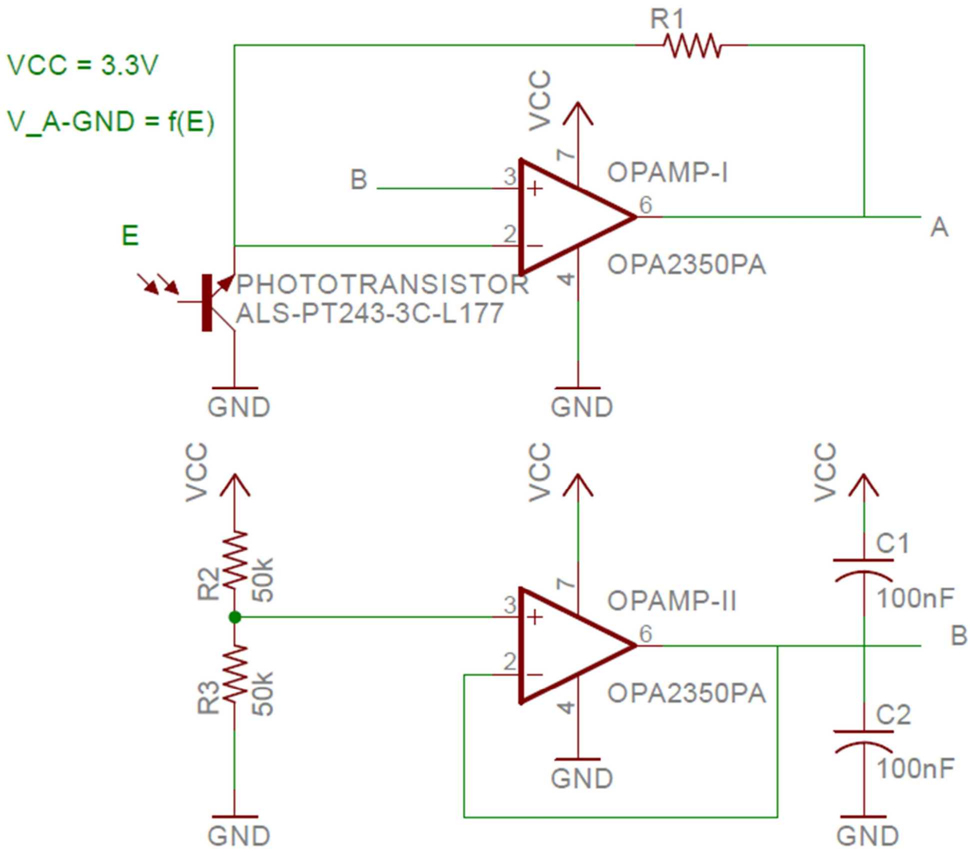


Figure 15: Phototransistor measuring circuit schematic

The lower part of the circuit is a buffer for a voltage divider: the non-inverting input of the operational amplifier is connected to half the supply voltage (that is, 1.6 V), while the inverting input is directly connected to the output, thus getting a nice clean output free of distortion from overloading, crosstalk and other electromagnetic interference. The capacitors act as filters for undesired frequencies.

The upper part of the circuit is what really matters. The phototransistor, an ALS-PT243-3C-L177 by Everlight (datasheet included in Appendix D), whose collector is connected to the ground (thus avoiding dark current), has its emitter directly connected to the inverting output of the operational amplifier. The feedback is closed through a resistor that determines the gain of the amplifier, while the non-inverting input is connected to the output of the voltage buffer. This sets an upper limit matching with that for the A/D converter (1.6 V), and keeps the lower limit since the amplifier negative power supply is connected to ground.

All operation amplifiers are OPA2350PA by Texas Instruments (datasheet included in Appendix D). Since the phototransistor has a long response time, a capacitor in parallel with the feedback resistor is not needed. Capacitors are K104K10X7RF5UH5 by Vishay and resistors H450KBYB by TE Connectivity (both datasheets can be found in Appendix D). The theoretical output voltage can be calculated using equations (7) and (8). As the operational amplifier is taken as an ideal model, the current flowing through the phototransistor flows entirely through the feedback resistor as well. Also, the non-inverting input and the inverting input have both the same potential (1.6 V).

$$\mathrm{I_{PT}} = \mathrm{I_{R1}} = \frac{\mathrm{V^{-}} - \mathrm{V_A}}{\mathrm{R_1}} = \frac{\frac{\mathrm{V_{CC}}}{2} - \mathrm{V_A}}{\mathrm{R_1}}$$

Equation 7: Current flow calculation

Therefore, the output voltage ends up being:

$$\mathrm{V_A} = \frac{\mathrm{V_{CC}}}{2} - \mathrm{R_1} \cdot \mathrm{I_{PT}}$$

Equation 8: Output voltage calculation using a phototransistor

However, when tested with different resistor values, the obtained results were far from good. Firstly, the low sensitivity at low light levels forced the use of a very high value feedback resistor (around 50 MΩ) to get a decent slope. But what really made this option unfeasible was the size of the photosensitive cell; being very small, it was extremely hard to aim the output beam from the Etalon to the spot, thus getting wide output variations with very faint fibre movement. With such a drawback, the phototransistor was ruled out as a candidate for the final embedded device.

3.2. Photodiode

Similarly to the phototransistor, a photodiode is a semiconductor device that converts light into current. The current is generated when photons are absorbed in the photodiode, which causes, funnily enough, the current to be driven from cathode to anode, as opposed to conventional diodes.

Their response times increase with the surface of their photosensitive cell. The main difference with respect to phototransistors is that photodiodes allow much less current to flow, meaning that they are more sensitive to low levels of light. The BPW34 (datashseet included in Appendix D), bv Vishay, was selected as a result. The conceived circuit using this type of device is shown in figure (17).

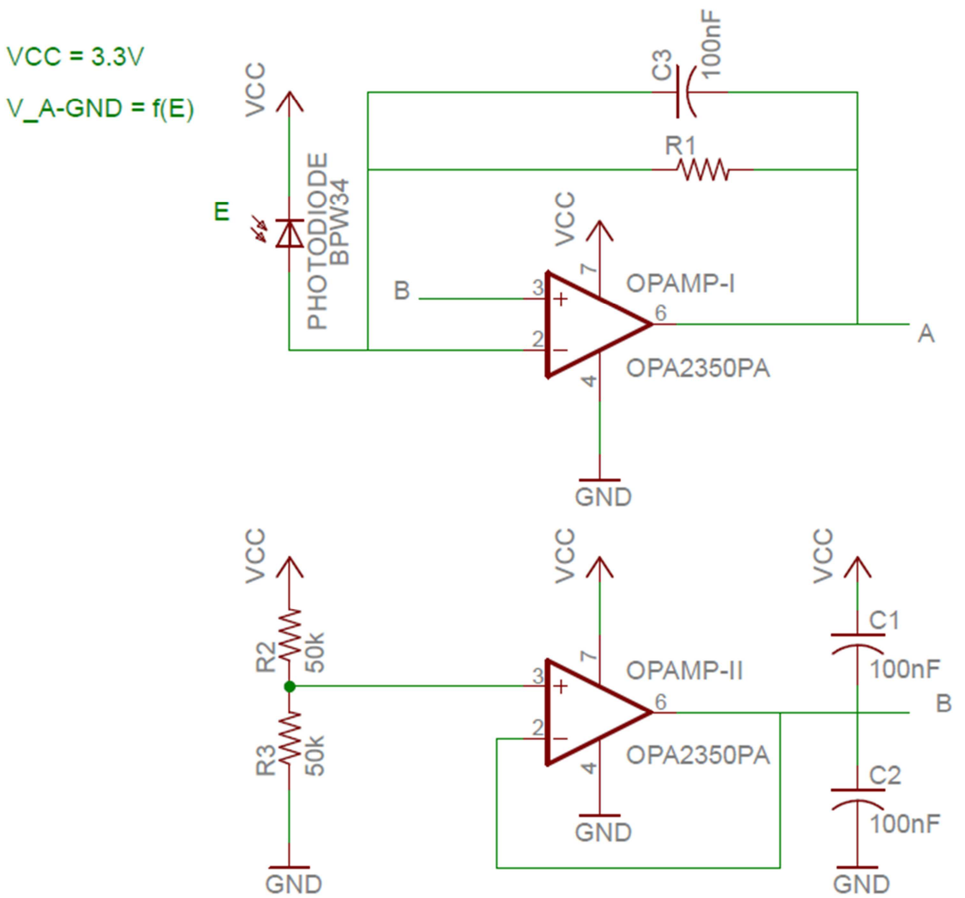


Figure 16: Photodiode measuring circuit schematic

The circuit is very similar to the original with a phototransistor. The main difference lies in the photodiode connection, as it is acting in photoconductive mode (anode to inverting input, cathode to supply voltage). This reduces the response time because the additional reverse bias decreases the junction's capacitance, thus improving the bandwidth. The reverse bias also increases the dark current without much change in the photocurrent.

Also note that a parallel capacitor in the feedback is used as a filter due to the faster response time. All the other components do not change. The calculations for the output voltage remain the same, only using the current through the photodiode, as seen in equation (9):

$$V_A = \frac{V_{CC}}{2} - R_1 \cdot I_{PD}$$

Equation 9: Output voltage calculation using a photodiode

With these data, one can create a chart of expected values for different current flow and feedback resistor values, as seen in table (6). This gives an idea of what to expect during the actual testing, as well as a rough clue of what current would correspond to each pH value.

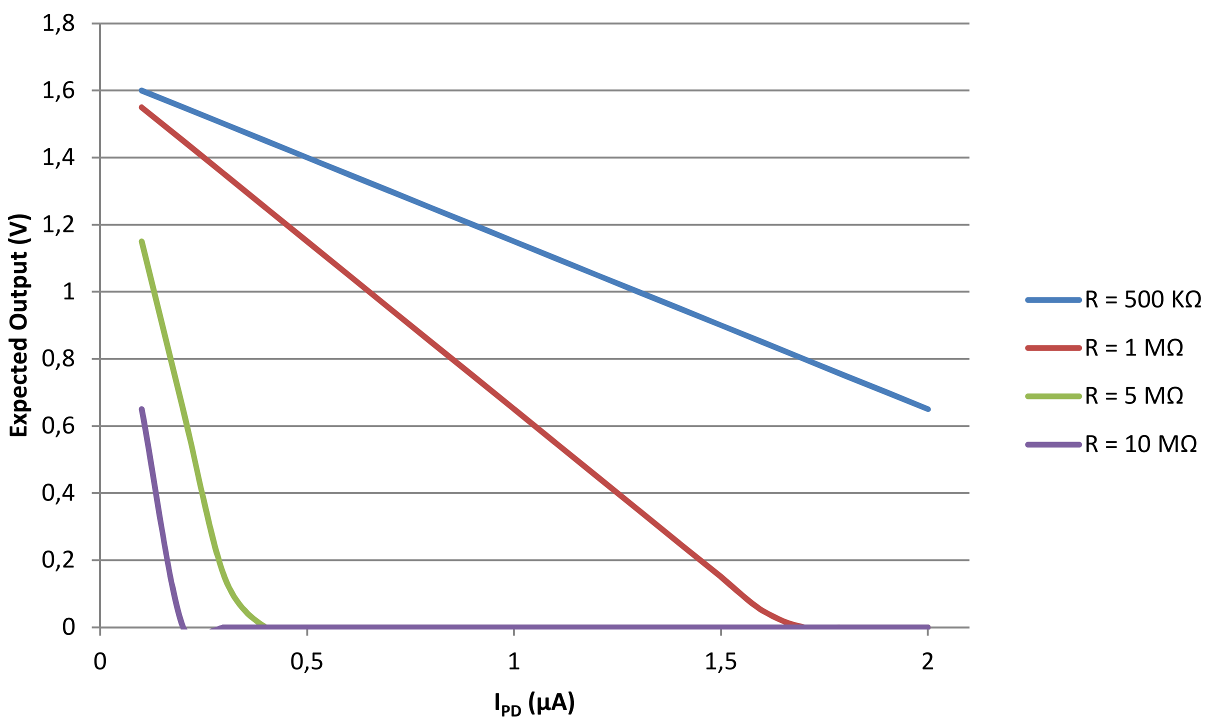


Figure 17: Expected output values for different feedback resistor values

As irradiance decreases with pH (as seen during Etalon development tests), the expectations are to see an increasing, although nonlinear, relationship between pH and output. This is later on corroborated during the testing (refer to chapter V); the same tests, carried out with the above resistor values, also prove that 1 MΩ is the best feedback resistor one can use to get a clean response to Ph. As such, H41M0BYB by TE Connectivity (datasheet included in Appendix D) was the resistor picked for the final embedded device.

4. Selected hardware

Once the tests were carried out, as seen in the next chapter, all the final components were picked to be part of the embedded device. This is seen in figure (19) and in table (6), which also includes the prices and datasheets of the hardware.

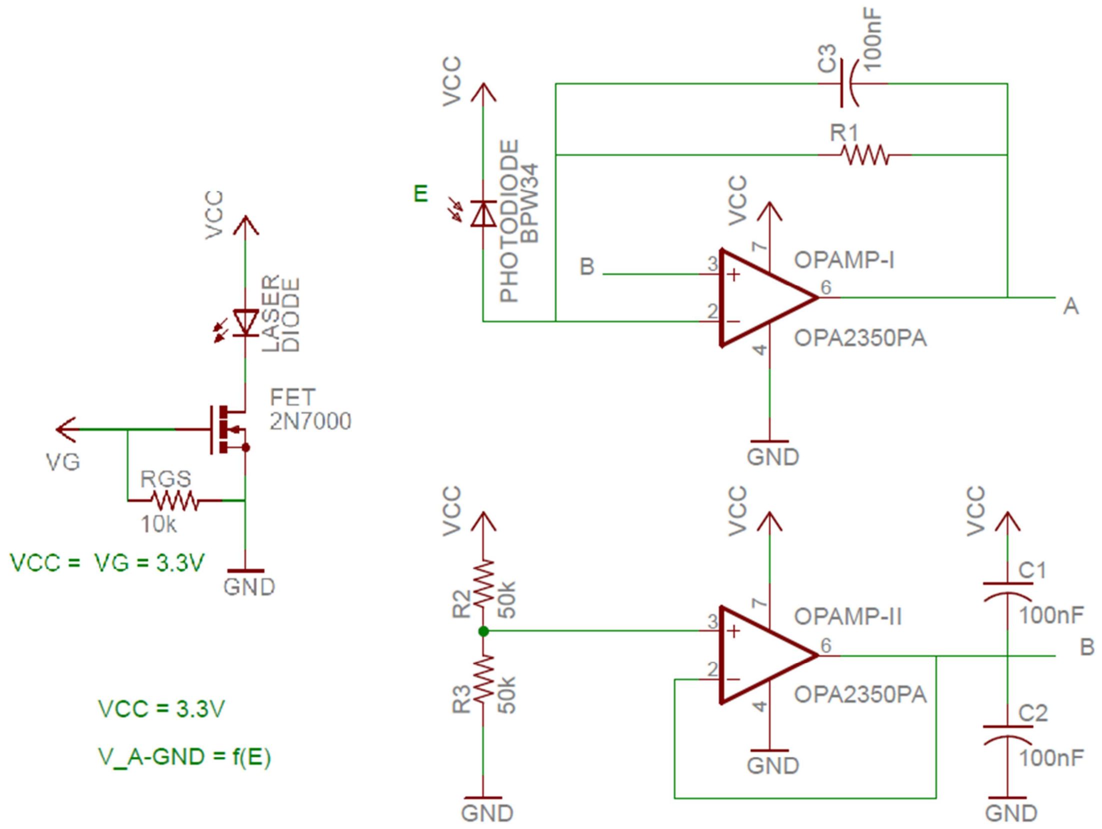


Figure 18: Overall selected circuit schematic

Component	Name in schematic	Type	Manufacturer	Value	Tolerance	Unit price	Quantity	Datasheet found in
VLM-650-01-LPA	LASERDIODE	Laser Diode	Infiniter	N/A	N/A	23,71 CAD	1	Appendix C
2N7000TA	FET	MOSFET	Fairchild	N/A	N/A	0,34 CAD	1	Appendix C
H410KBYB	RGS	Resistor	TE Connectivity	10 kΩ	0,1%	0,44 CAD	1	Appendix D
BPW34	PHOTODIODE	Photodiode	Vishay	N/A	N/A	1,06 CAD	1	Appendix D
OPA2350PA	OPAMP-I OPAMP-II	Operational Amplifier	Texas Instruments	N/A	N/A	4,56 CAD	1[5]	Appendix D
K104K10X7RF5UH5	C1 C2 C3	Ceramic Capacitor	Vishay	100 nF	10%	0,33 CAD	3	Appendix D
H41M0BYB	R1	Resistor	TE Connectivity	1 MΩ	0,10%	1 CAD	1	Appendix D
H450KBYB	R2 R3	Resistor	TE Connectivity	50 kΩ	0,10%	0,47 CAD	2	Appendix D

Table 6: Hardware summary

The total price comes as far as 33.04 CAD, which leaves around 200$ for the manufacture of both the Etalon and the Wireless Gas Monitor and Data Logger, and is still less than the 50 dollars originally budgeted.

Chapter V
Design validation

1. Equipment

To carry out the tests needed to validate the hardware design, a series of elements have to be set up properly, the most important one being, of course, the prototype board. It consists of a compact through-hole PCB with all the different light sources subject to test, along with the measuring circuit, as shown in figure (20):

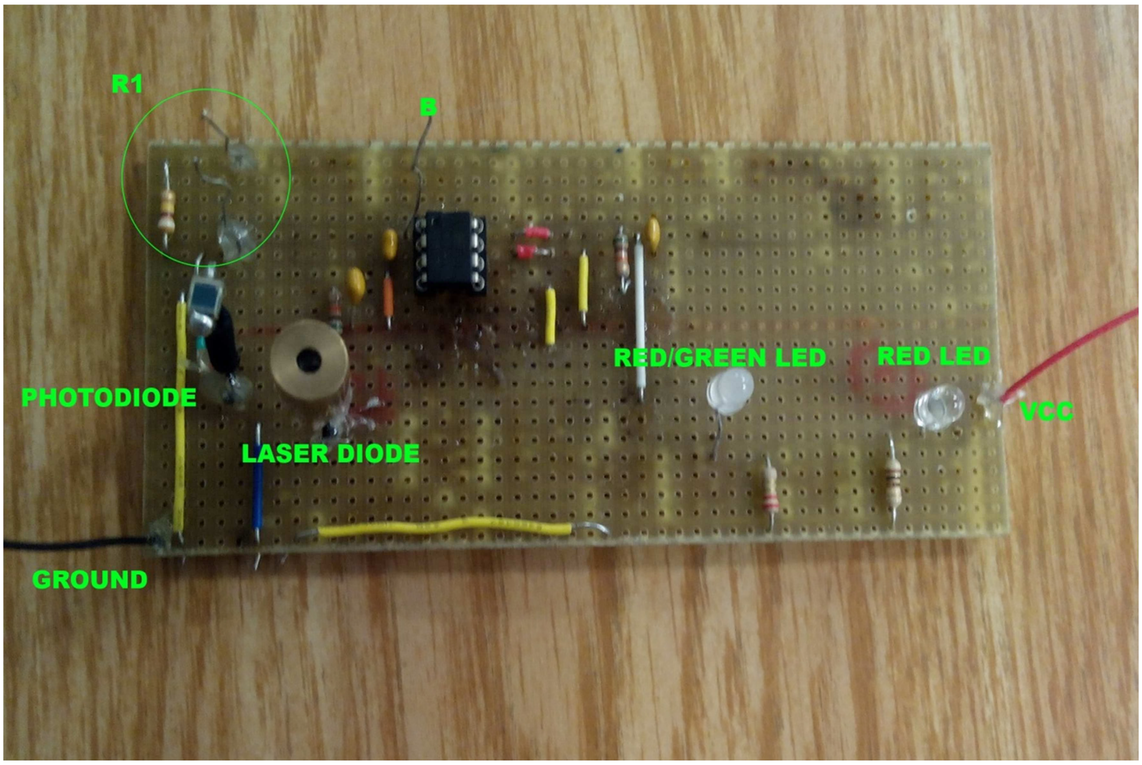


Figure 19: Prototype board

The R1 shown in the board is actually a mini circuit by itself, with a 10 MΩ resistor and two floating branches, where a different resistor can be attached in series or parallel to create different total values. Some of the values, if they are smaller than 1 MΩ, are obtained with the use of a decade [6], a knob-like adjustable resistor in steps of 10 Ω, very helpful for the purpose in question.

The whole Etalon setup is also needed; it is very similar to the one shown in figure (7), but with the thermoretractable tube attached to the light that is being tested, and the other end to the photodiode, instead of the spectrometer. Finally, a power supply is needed to feed the circuit, and a multimeter tester is used to measure the voltage output form the circuit test points, which is stored in an Excel file.

2. Methodology and procedure

The testing process is not complicated, but it does require some time due to the multiple possible combinations of light sources, resistors and pH conditions. The following steps describe the proper way to test the device:

1. The Etalon has to be soaked in a solution with a pH value of 3 and the starting resistor should be the one of lowest value, as these are the initial conditions. One also has to wait for pH stabilization, usually taking around 5 minutes.

2. The device should be powered with the external power supply, placing the thermoretractable tube on top of the desired light source.

3. Using the multimeter, the output voltage has to be measured and written down on an Excel sheet.

4. With the help of a basic (NaOH) solution, the pH of the test solution should be increased by half a unit. Waiting time for stabilization remains at around 5 minutes.

5. Steps 3 and 4 should be repeated until a pH value of 6.5 is reached (this value doesn’t have to be measured).

6. With the help of an acid (HCl) solution, the pH of the test solution should be decreased by half a unit, and 5 minutes have to pass until taking any measurement.

7. Voltage should be measured as in step 3.

8. Steps 6 and 7 have to be repeated until reaching a pH value of 3 again (measuring this value as well).

9. In the end, two measurements for each pH value should have been acquired, and their average is the relevant number for the test.

10. All of the steps have to be repeated for each different combination of resistor and light source.

3. Results

3.1. Red LED

The red LED, as shown in figure (21), works just fine as a light source with some of the resistor values, but does not really have a good resolution for the A/D converter.

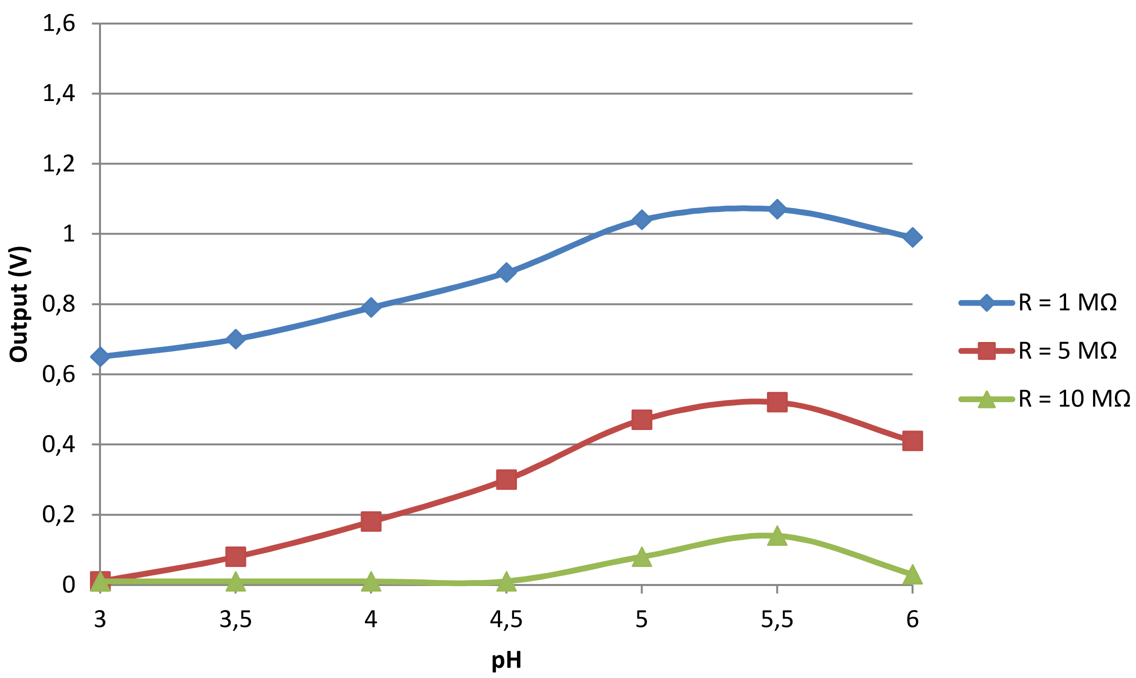


Figure 20: Red LED test results

At first sight, it is clearly seen that the 10 MΩ resistor is not useful, since the output is saturated to ground until the pH doesn't reach a value of 4.5. As for the other resistors, both show some interesting behaviour, but even the 5 MΩ one, which provides the most pronounced slope, barely makes use of half the ADC range, with a peak value of 0.52 V. As a result, this source was discarded as the final option for embedding.

3.2. Green LED

As opposed to the red LED, this light source is extremely useless for the sensing purpose, since, as seen in figure (22), the output is hardly modified by both pH and feedback resistor values.

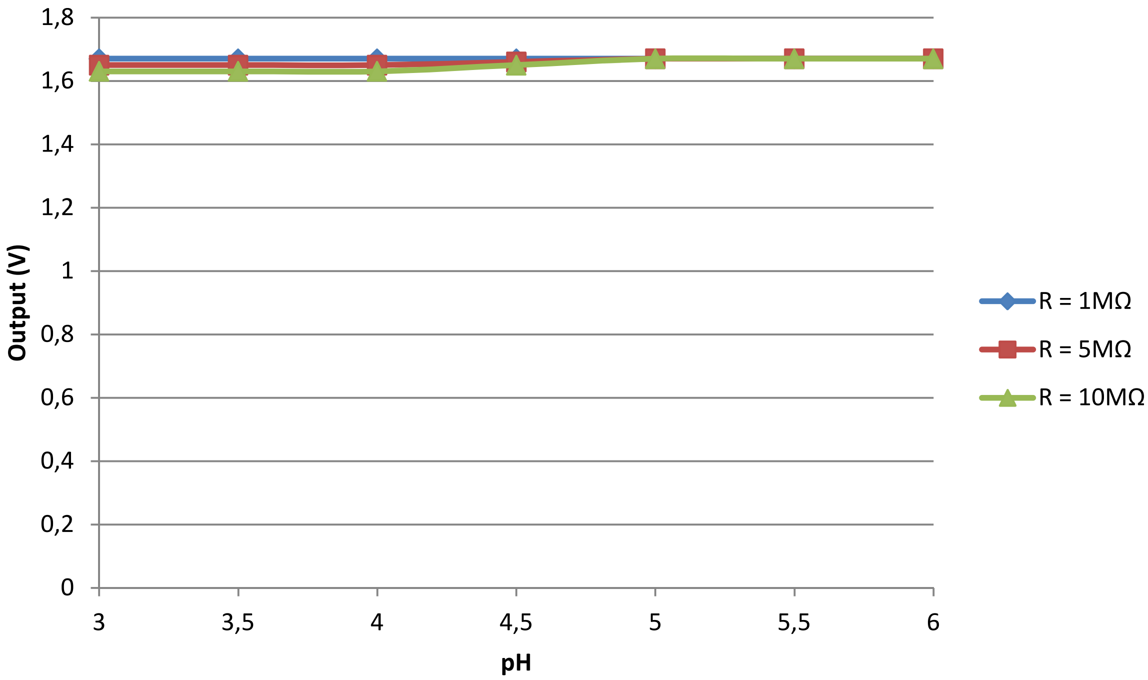


Figure 21: Green LED test results

The low sensitivity shown by the photodiode here might be due to different factors of the LED, such as the wavelength of the green color, the diffused packaging or the wide viewing angle. Whatever the reason for these results is, it is clear that this light source cannot be used as the final device for a sensing purpose.

3.3. Red Laser Diode

Similarly to the red LED, the red Laser Diode shows a good response with different resistor values, and, as shown in figure (23), all of them are included within the range of the A/D converter.

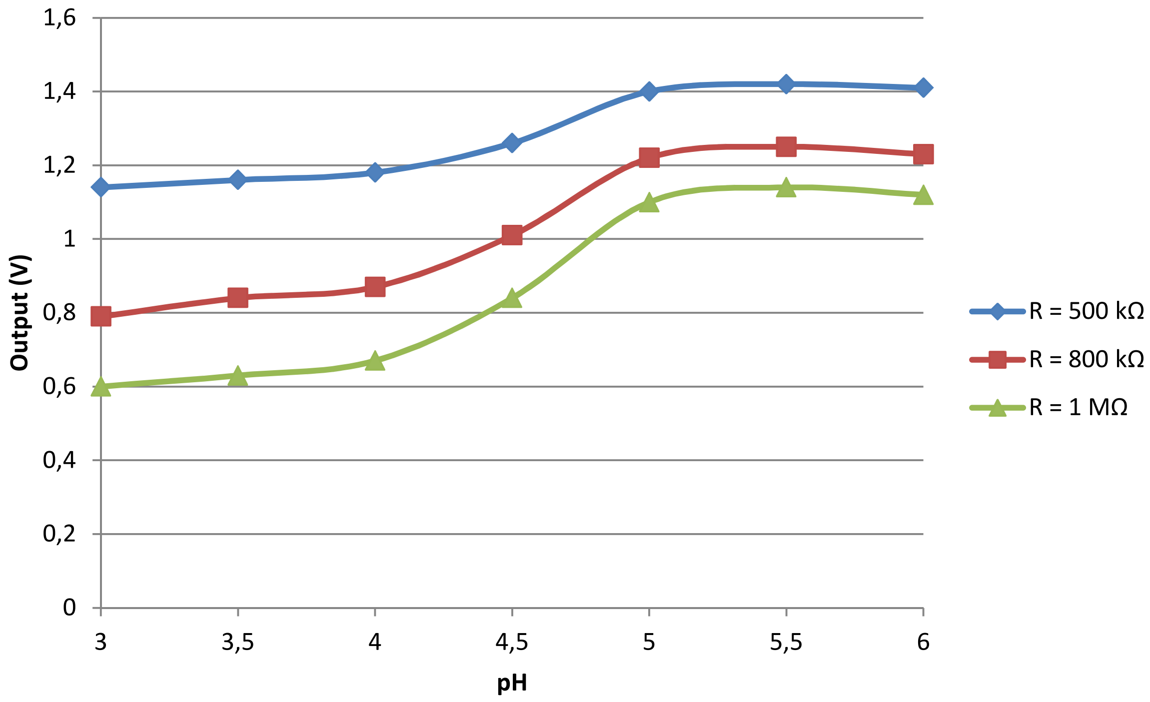


Figure 22: Red Laser Diode test results

However, looking at all the graphs, it can be seen that for two different pH values, the same output can be obtained, thus making the required calculations and data processing of the microprocessor much more complex and time and power consuming than desired. Taking this into account and seeing how between pH 4 and 5 the slope is perfectly clear and defined, this light source with a resistor value of 1 MΩ was picked to be embedded with the final device.

3.4. Useful range

For this Etalon, light source and measuring circuit in particular, pH can only be sensed with a good amount of precision between 4 and 5. Therefore, as said before, these were the values used when thinking of the programming of the microprocessor.

Seeing the shape of the curve that joins the three values, a good accurate trend line would be a second order polynomial one, as seen in equation (9):

$$pH = -2{,}3 \cdot V^2 + 6{,}52 \cdot V + 0{,}70$$

Equation 9: Parabolic model pH calculation

However, a linear trend line, shown in equation (10) would be much more power-friendly (as the microprocessor can do the calculations way faster), which is very important for the embedded device, as it runs on batteries. The loss of accuracy is not too severe, given the fact that the actual data only has three values.

$$\text{pH} = 2{,}29 \cdot \text{V} + 2{,}51$$

Equation 10: Linear model pH calculation

Focusing on the reliable values, then, it is also possible to compare the obtained results with the chart seen in figure (18), and see if they match the expectations; one can also roughly determine the current flow through the photodiode by overlaying both expected and real values, as seen in table (7).

Output (V)	pH	I_{PH} (µA)
0,67	4	0,98
0,84	4,5	0,81
1,1	5	0,55

Table 7: pH and current ideal matching

These matches aren’t accurate or significant, since they are based on the ideal model of the operational amplifier. Nonetheless, they can give a rough idea of what’s happening, and can be useful for future measurements or tests.

Chapter VI

Embedding

1. Schematic

Taking the devised circuits and embedding them into an already existing schematic is not very complex, but it does take some time. One has to take the existing power planes and connectors into account.

For instance, VAUX was used as the supply voltage of 3.3 V and the OPTICAL connector as the input for the photodiode current. This means that the photodiode is actually external (it has to be connected through the optical analog port). In a similar way, the driver gate is a direct output from the microprocessor, found in the main board (see Appendix B), while the laser itself is also external, outputted through an analog port. The updated schematic is shown in figure (24):

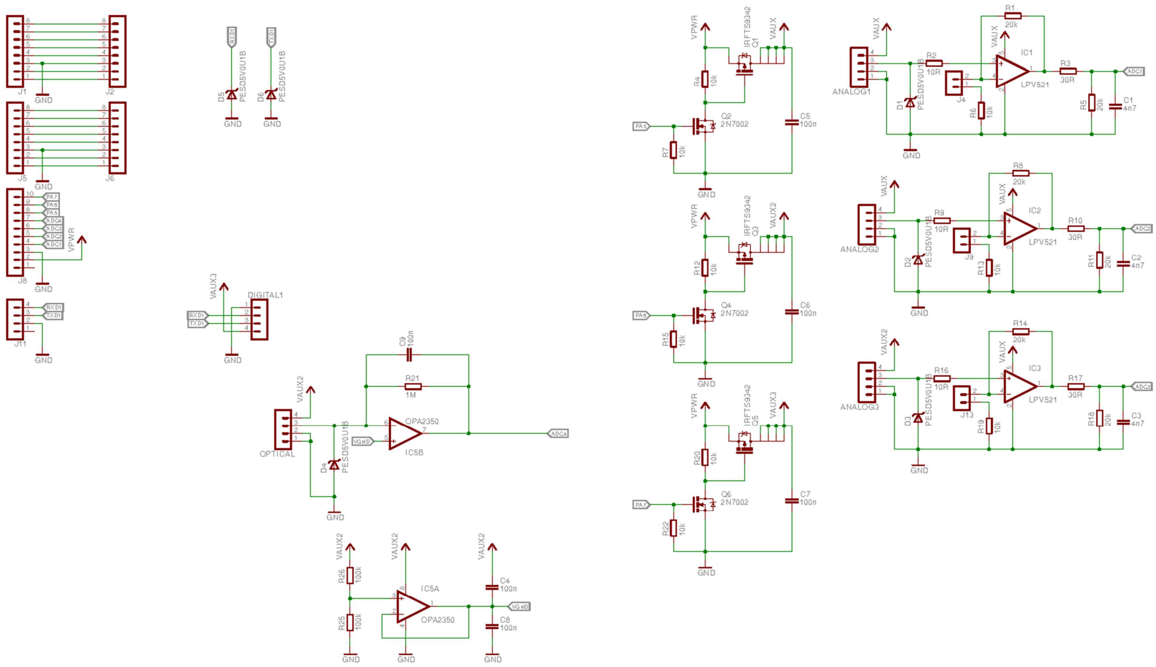


Figure 23: Conditioning board schematic

It can also be seen that a protection diode has been added between ground and the inverting output, as a circuit safety measure.

2. PCB

The hard part about embedding comes when designing the Printed Circuit Board [7], especially when a new design has to live together with more existing hardware that was previously there, as this is the case. The final PCB layout is shown in figure (25). As an important factor, notice that the right most connector is the gate to the Analog to Digital converter, and that the output voltage of the circuit happens to go there.

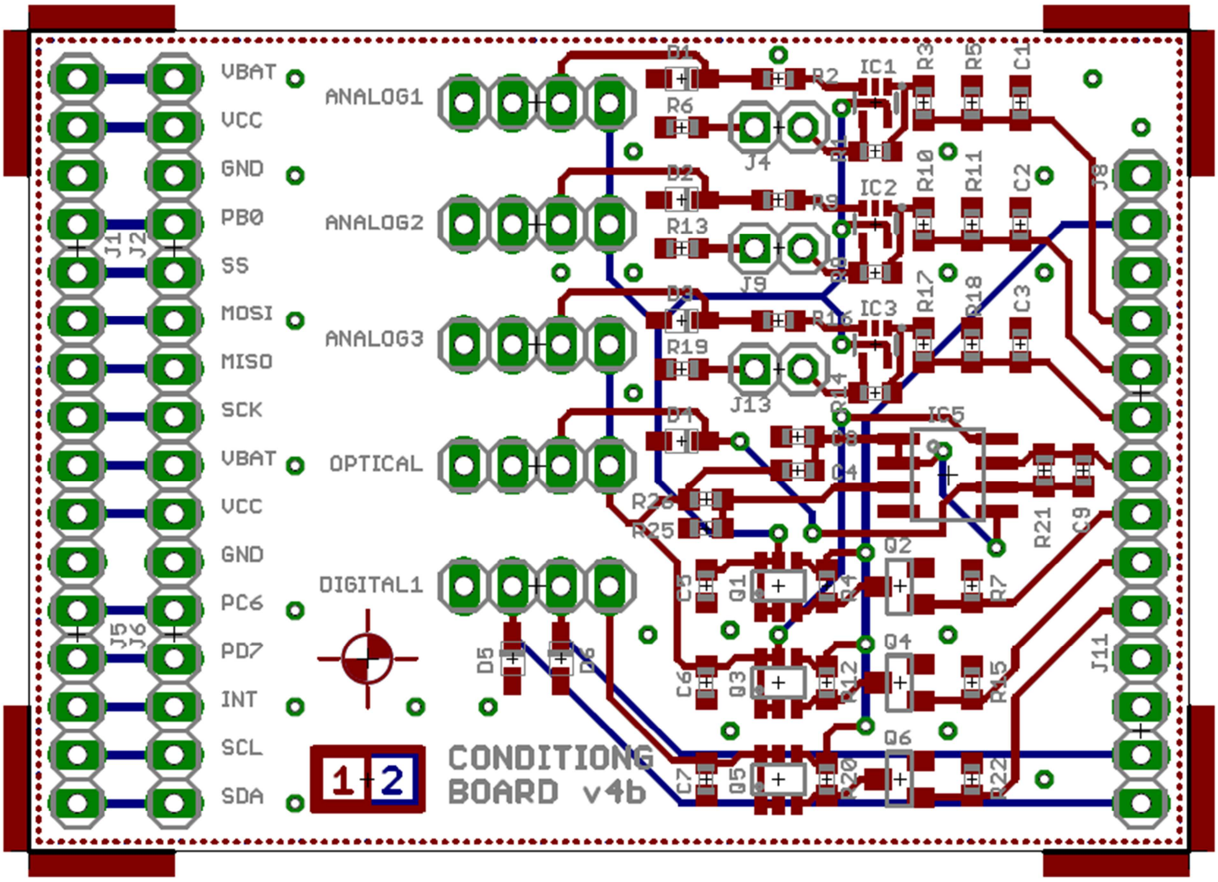


Figure 24: Conditioning printed circuit board

Unfortunately, due to the lack of time, since my stay in Edmonton was coming to an end, the manufacture of the board was not possible, but remains to be done in a future.

Chapter VII

Programming

1. Overview

To get the embedded device to function as an automatic sensor, data logger and monitor, it has to be programmed to do so. That is the reason a programmable flash microprocessor is included.

To perform the programming, a debugging device is needed; in this case an AVR JTAGICE mkII by Atmel (although it could be done with other devices, it is more intuitive if the JTAG and the microprocessor are manufactured by the same company) should be used. This device allows important and useful operations for debugging such as single stepping and break pointing.

Unfortunately, as said before, the time that was left of my stay was not enough to perform such a delicate step, and as of today, it remains to be yet implemented. However, a basic algorithm was devised as a guideline for a hypothetical future programming.

2. Algorithm

The algorithm uses the following main variables, and follows the flowchart seen in figure (26).

- *t*: time between samples
- *i*: sample number
- *time:* clock sampling time
- *k:* sampling mode
- *V:* measured voltage
- *pH:* calculated parameter
- *VpH:* storage matrix

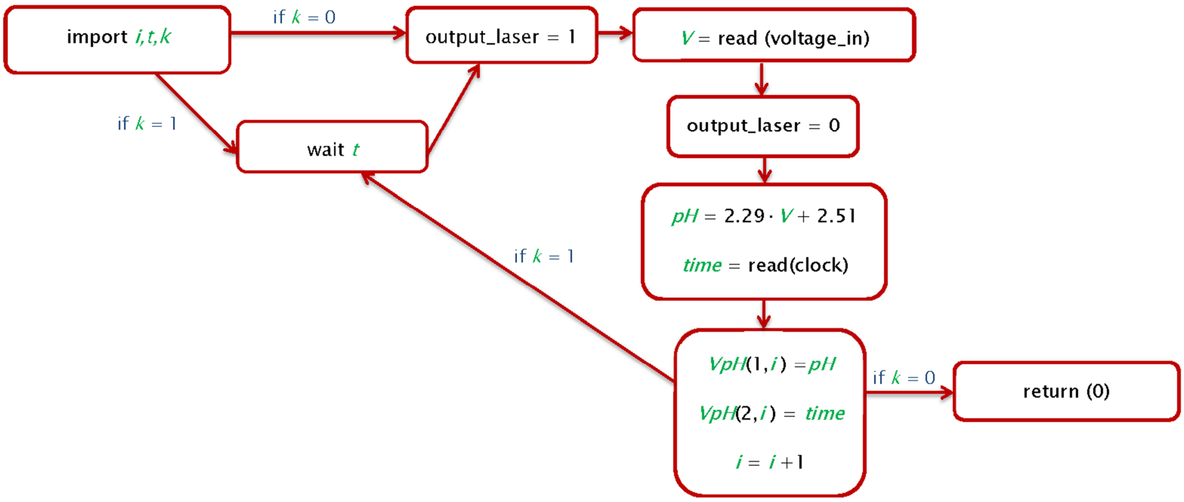


Figure 25: Algorithm flowchart

First of all, note that an external configuration file is conceived. This file includes information about the sample number (*i*), time between samples (*t*) and sampling mode (*k*). When the device is turned on, these variables are checked to determine the behaviour of the sensor.

The sample number is, by default, the immediate correlative number after the last sample. The time between samples is only used when the sampling mode is multiple ($k = 1$), meaning that automatic sampling in steps of *t* seconds is on. Otherwise, when the sampling mode is single ($k = 0$), *t* is not used and only a sample is taken immediately. The configuration file can be accessed at any time through the Zigbee radio included in the device.

Whatever the sampling mode is, after waiting a certain time (for multiple samples) or not (for a single sample), the laser drive gate is activated through the pertinent pin of the microprocessor (output_laser = 1), and the voltage, which is being converted in real time by the ADC to a digital value, is read through the appropriate input pin of said device, and its value stored in the relevant varable (*V* = read (voltage_in)). The laser is then immediately turn off to save power (output_laser = 0).

The microprocessor then does the needed calculations to get a pH value and reads the time from the real time clock included in the device. Both results are read into the variables *pH* and *time*, respectively.

Immediately after, these values are saved in the storage matrix (*VpH*), whose first row corresponds to the pH value and second row to the time the sample is taken. Each column represents a different sample. Also, the sample number (*i*) is automatically increased by one at the end of the operation.

Finally, depending on the sampling mode, the operation is interrupted (single mode), or the selected time *t* is waited to start the loop again.

Chapter VIII
Future work

1. Project completion

As previously said, and since this project was based entirely on my stay as an exchange student in the University of Alberta, the lack of time prevented from implementing everything that would have made this enterprise complete. As a guideline, these are the main points that still remain to be taken care of and that, hopefully, in the future, myself or someone else will work in:

- A complete embedding with PCB assembly is a milestone for this kind of projects. With the current gerber (PCB file type) data, a new board could already be manufactured, and all the components assembled.

- Although a basic algorithm has been provided, the real programming of the device is a whole different story. One needs to write an efficient sfotware and debug it using the proper tools to ensure its validity.

- In parallel with the programming and debugging, the software validation, as said in Chapter III, has to be carried out. The only way to verify the usefulness of the code is to test it with actual situations, that is, with the Etalon and solutions of known pH, thus creating a concurrent engineering process that hopefully ends with a working device and software.

2. Device optimization

The device itself offers a lot of opportunities; one of the reasons this project was done in the first place was its flexibility. Here are a couple of suggestions to make the most of it enhance its performance.

- Currently, the pH sensor would only work with solutions with a pH value within the range of 4 and 5, which is a major drawback for its purpose. However, due to the nature of the Etalon, small alterations during the synthetizing process can lead to large desired changes in behaviour, meaning that it may be sensitive to other wavelengths and pH ranges.

  One can take advantage of this fact to create a pH sensor based on multiple etalons and light sources, thus increasing its working range. Of course, the code and circuitry would be far more complex, but the possibility is very attractive as it can have a great effect on the overall device use.

- After using the device for CO_2, humidity, temperature and pH sensing and monitoring, spare analog and digital ports still remain there to be used. More environmental parameters can be added to create an all-in-one environmental sensing and logging device, which, remarkably, is the ultimate goal of the overall project.

Chapter IX
Conclusion

It has been seen that this project has been a partial success by itself, but mostly, it has been a great accomplishment as a setup for next studies or developments in the field. The initial goal of designing and building an inexpensive device capable of sensing and monitoring, among others parameters, the pH of the environment, has been partly achieved.

A circuit has been devised and built as a prototype, and it has proved to work almost perfectly within its functioning range, as its accuracy widely overtakes that offered by pH indicator strips. For this purpose, additionally, cheap hardware has been used, making the future product a feasible alternative to classic pH measuring devices.

A complete embedding of such circuit has been conceived in theory, lacking only time to manufacture it. In a similar way and for the same reasons, the programming has not been completed, although a working algorithm has been created to match with the needs of the device and the working conditions of the sensor.

Overall, this project has proved as a high potential tool as pH sensors go, and even it has not been manufactured, it has shown itself as a fast, inexpensive, low power automatic monitoring option for such parameter. Still, there is a lot of scope for improvement, as more environmental parameters can be added to create an even more resourceful device. On the writer side, it has come as a great learning experience, and it has turned out to be a both personal and professional involvement with research, facing challenges and seeking solutions as the project kept moving on.

Chapter X
References

[1] http://www.chemheritage.org/discover/online-resources/chemistry-in-history/themes/electrochemistry/beckman.aspxAdsf

[2] http://www.physik.uni-siegen.de/quantenoptik/lehre/fpraktikum/fabry-perot.pdf

[3] All components bought from Digikey (www.digikey.ca)

[4] http://encyclobeamia.solarbotics.net/articles/bip_junct_trans.htmlAsdf

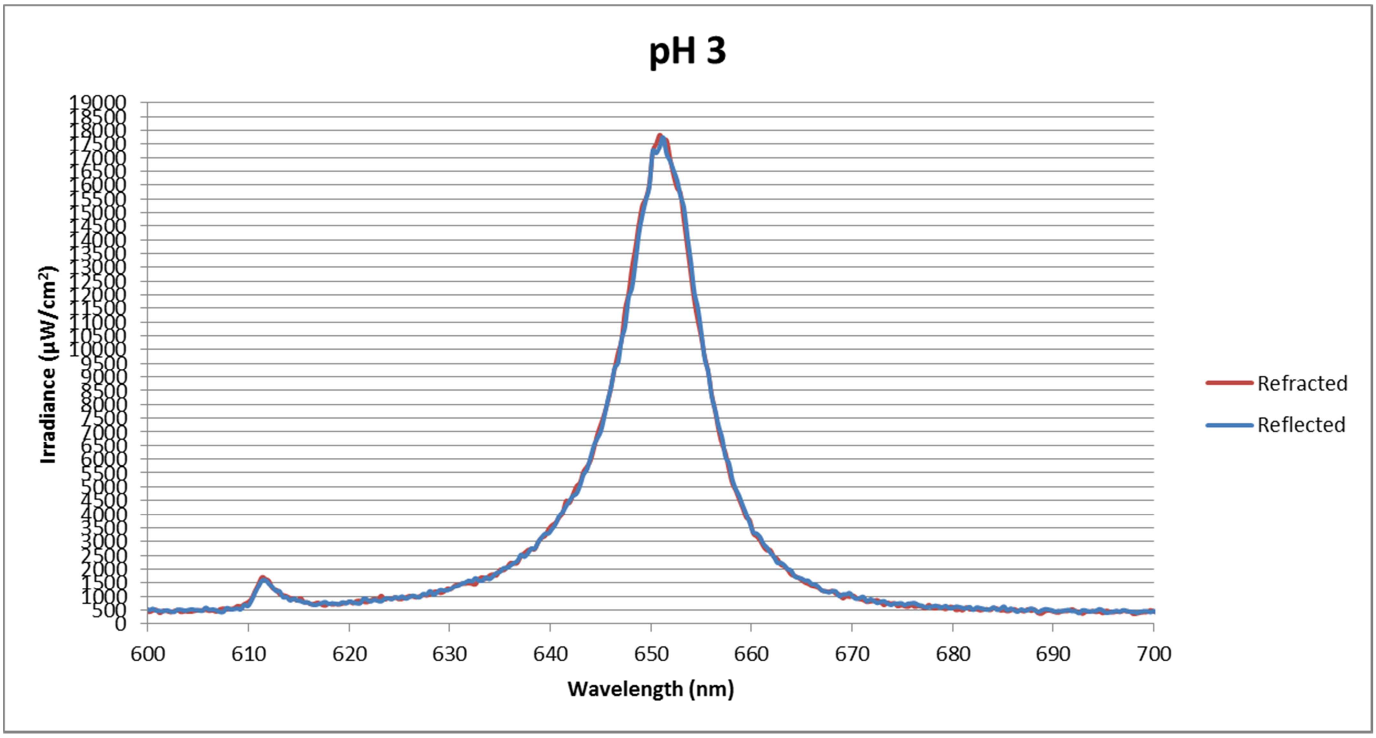
[5] The OPA2350PA comes with two amplifiers in the same package, thus only needing to buy one to use two.

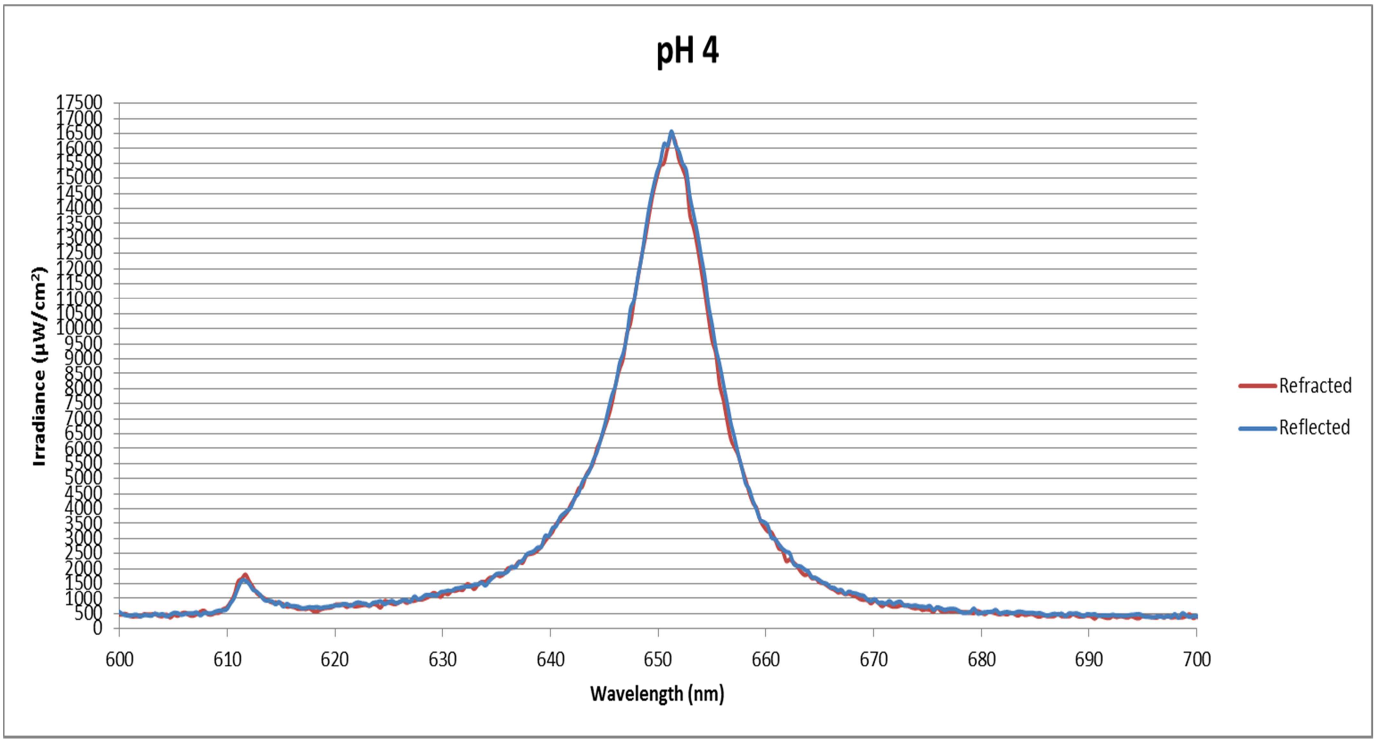
[6] https://www.sparkfun.com/products/13006

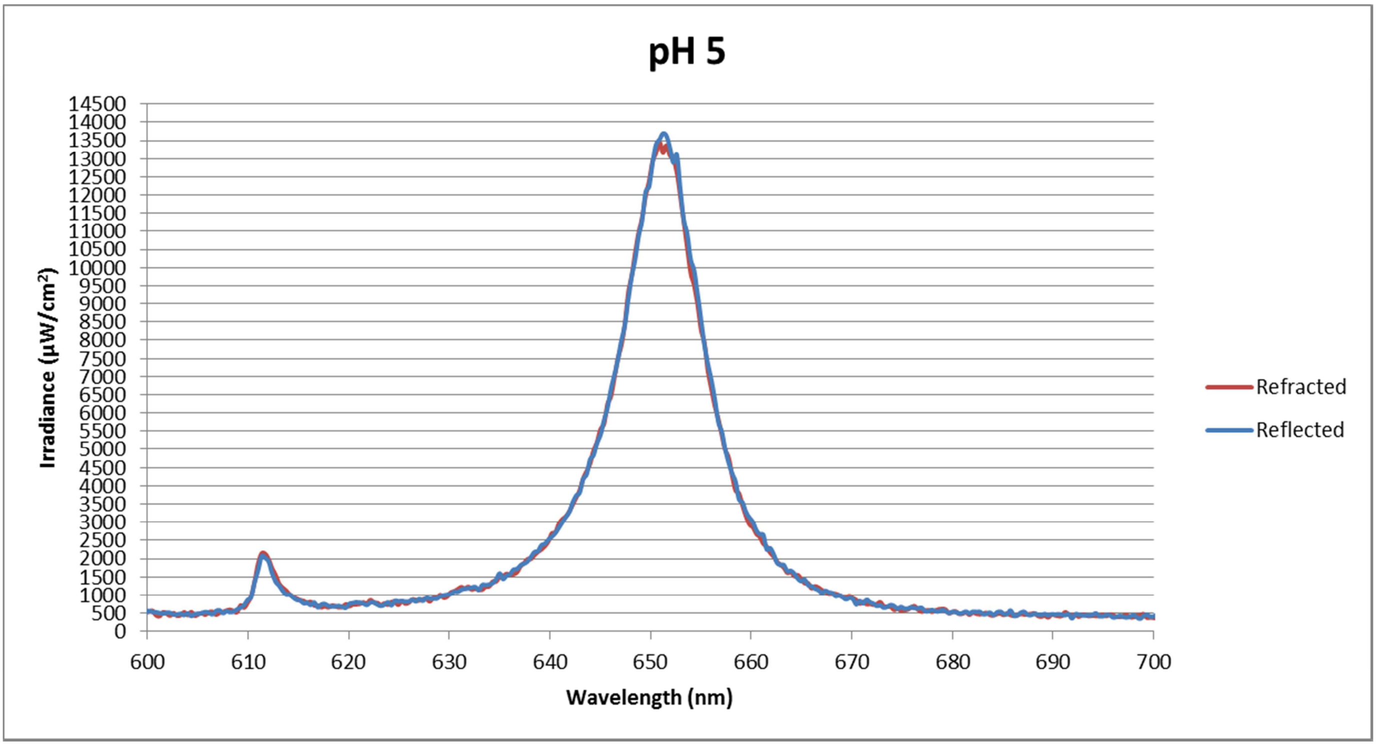
[7] Design with the aid of Michal Prauzek, whose help sped the PCB design process up, among other steps.

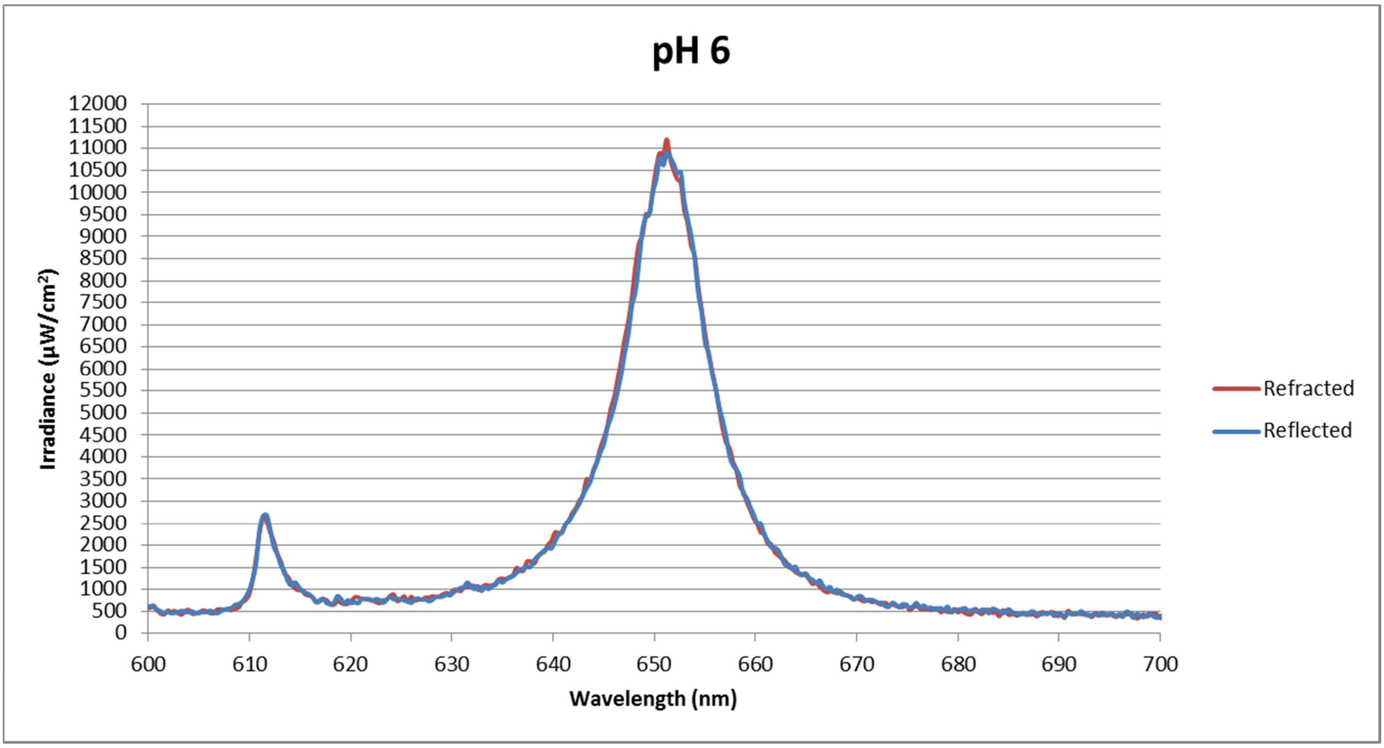
APPENDIX A:

SPECTROMETER DATA FROM DEVELOPMENT TESTS






pH 5
14500
14000
13500
13000
12500
12000
11500
11000
10500
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Irradiance (μW/cm²)
600
610
620
630
640
650
660
670
680
690
700
Wavelength (nm)
Refracted
Reflected


pH 6
12000
11500
11000
10500
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Irradiance (μW/cm²)
600
610
620
630
640
650
660
670
680
690
700
Wavelength (nm)
Refracted
Reflected

APPENDIX B:

WIRELESS GAS MONITOR AND DATA LOGGER

1. Executive Summary

The CO_2 Wireless Sensor platform is a low power solution for gas detection. The device runs on 4xAA batteries and provides four analog and one digital sensor channels along with a Zigbee radio. The default configuration of the device is a single, digital CO_2 gas sensor which captures relative humidity, temperature, and two carbon dioxide signals. All sensory information is stored on an SD Card and can be transmitted by Zigbee if configured to do so. The sensor is initially set to wake up every 15 minutes to take measurements, but this can be changed to any time period greater than 30 seconds and less than 24 hours. In addition, by default, the device looks for user intervention, indicated by a green LED, for 3 seconds after being switched on or waking up from sleep mode. This is too energy intensive for regular operation, so this can be disabled before the device is deployed.

A basic Configuration Utility (CU) has been provided to help test the device and facilitate deployment. Sending any value to the Zigbee radio will cause the platform to enter the utility. The Zigbee loggers are currently all part of the “0x434F” (PANID: 'CO') channel and operate at maximum power. The loggers are not currently designed to be part of a network. If clustered, ensure that only one is awake at a time or they will wake each other up. From this utility, both the Zigbee radio and the CO_2 sensor can be programmed. This is necessary to change Zigbee settings or configure/calibrate the CO_2 sensor. The utility can also be used to find files on the SD card remotely and read them over the network. The real time clock requires the CU to get the time and date. The internal memory of the logger can be accessed and edited to set how the device operates. Additionally, all sensors can be accessed and run independently for error checking and troubleshooting. Please note that most of the entries to these options are not thoroughly error checked. Do not deploy the device with erroneous values in the settings.

The internal memory saves the operational state of the device. Upon waking up from sleep, microcontroller must reboot. To ensure that the user's settings are kept, the state is saved to EEPROM inside of the device. The Zigbee radio is controlled by Digital State 0: when set to 0, periodic Zigbee transmission is disabled to save power. The CO_2 sensor is controlled by Digital State 1. When set to 0, the sensor is disabled. If the state is set to 1, the sensor is periodically power cycled with platform sleep and wake-up, and if state is 2, the CO_2 sensor is put to sleep but never actually powered off. State 2 may be necessary to prevent the CO_2 sensor from losing detailed calibration information. If the sensor is left uncalibrated, then state 1 should be sufficient; consult the appropriate data sheet for detailed information. The “deployed” state allows the device to determine whether it is supposed to be in the field or not. If this is set to 1, the platform stops looking for an external user and the CU is disabled. This is important for power saving.

In the event of a fault serious enough to reset the real time clock, the platform will look for external intervention for one hour. It will continue to save data to the SD card under a default file name. This can indicate how many times the device has failed, and approximately how often. This can also be used to unlock the device; if the Zigbee radio is disabled, and the user cannot connect to the device, remove the watch battery and power cycle the device. Any failures related to the SD card are indicated by a red LED. This LED will turn off before the device returns to sleep. If the LED turns on, assume that data point has not been logged. Do not deploy the device if the red LED continues to light.

2. Hardware Overview

2.1. Main Board

2.1.1. Microcontroller Unit (MCU) Module

2.1.1.1. ATMega324PA

Data Sheet: “ATMEL ATMega324PA Microcontroller.pdf”

The low power microcontroller is responsible for all computations on the sensor platform. It is programmed by the 2x5pin header beside the power switch. This component enters a low power sleep mode when not in use and receives a wake-up interrupt from the Real Time Clock (RTC). Non-volatile memory within the MCU stores the operational mode of the device because every sleep cycle completely restarts the MCU.

2.1.1.2. Indicator LEDs

Two indicator LEDs are attached directly to the microcontroller outputs. The green LED indicates when the device is available to the user for wireless communication. The red LED indicates file system failure. If either of these LEDs is lit repeatedly, do not deploy the device.

2.1.1.3. Oscillator

The MCU is attached to an 8MHz crystal oscillator.

2.1.2. Real Time Clock (RTC) Module

2.1.2.1. DS3231

Data Sheet: "MAXIM DS3231 I2C Real Time Clock.pdf"

The DS3231 RTC stores time and date information for the platform. The memory of the DS3231 requires backup power to operate when the rest of the device is sleeping. If the platform has locked the user out of wireless communication, resetting the RTC by removing watch battery will unlock the device for one hour (from the RTC's perspective). This will allow the user to change the settings in the MCU's non-volatile memory and unlock the device.

Additionally, the DS3231 is responsible for generating the wake-up interrupt for the microcontroller when measurements are required. The third pin of the DS3231 is tied to the "INT" pin of the expansion port via a 30 gauge wire. Inspect this connection for damage before deploying the device; if severed, the hardware will not wake up from sleep mode.

2.1.2.2. Watch Battery

The battery which powers the device is 3V Lithium 1216 watch battery. It is housed underneath the conditioning board of the platform. It is inserted positive side up. The battery may be difficult to insert because a small raised platform has been added to the bottom plate to ensure good connection between the battery and the circuit. The battery is easiest to remove using a pen tip and a gentle push from behind. Removing the watch battery while the device is switched off will reset the RTC timer and the device will need to be reconfigured using the CU.

2.1.3. Non-Volatile Storage

2.1.3.1. Secure Digital Card (SD Card)

The SD Card stores all data collected by the wireless platform. The SD Card must be formatted in FAT32. The unit size has worked at both 1024 and 4096 bytes, but the microcontroller grabs clusters in 512bytes segments. A failure of the file system will light up the red LED. If this happens repeatedly, try reformatting the SD card, or power cycling the device.

Files from the SD card can be accessed over the network if the user can access to the platform wirelessly upon wake-up. Please note that this is very energy intensive and assumes the user has not set the “deployed” state to '1'. The SD Card can also be removed to retrieve the data manually, it is stored in “.CSV” format padded with leading zeroes.

2.1.3.2. Card Holder

The SD Card holder has two interesting parts: the signal connectors, and the top latch. The signal connectors are flexible and bent upwards to hold themselves against the SD Card terminals. They must remain clean and clear of debris. The top latch is locked by pulling it towards the back to the SD Card (away from the SD Card terminals). Ensure that the SD Card is correctly aligned in the card holder before locking, as the signal connectors try to push it out of the correct position. The top latch is unlocked by sliding it down the SD Card (towards the terminals) and then gently lifting it to release the SD Card.

2.1.4. Wireless Communication Module

2.1.4.1. Zigbee Radio

Datasheet: “MAXSTREAM XBeepro 4214A Product Manual.pdf”

Wireless communication is provided by Zigbee Radio. While Zigbee radio is a “Low Power” solution, it is the most energy intensive part of the device when on. Long term deployments should minimize or eliminate the use of Zigbee Radio. The radio is put to sleep between operational periods to eliminate waste energy consumption, making it acceptable for short term deployments. The Zigbee radio is presently in “transparent” mode and passes any information sent to it at 9600baud to the UART channel of the MCU. This is the default setting for Zigbee devices out of the box, which makes these parts easily replaceable if damaged.

The devices have their sleep mode set to “1” which allows them to be put to sleep by setting the sleep pin high. They consume very little power when asleep, however, they take several seconds to enter sleep mode. The PanID of the devices is set to “CO” in ASCII; only devices with the same PanID can signal each other (except on the broadcast channel). That said, the devices are currently programmed to act individually, not as a network. Placing them within range of each other will cause them to enter the configuration utility (CU) and then fail due to excessive power consumption. This might be solved by changing them all to different networks (PanIDs) or adding a sort of log in to the CU which would time out. Additionally, they could be deployed in a way which multiplexes their wake-up periods on the network so they never have the opportunity to talk to each other. The Zigbee radios can be reprogrammed using the CU.

2.1.4.2. Whip Antena

The Zigbee Radios have a small coaxial port to attach a whip antenna. This antenna needs to be attached to the case. Zigbee radios have a very limited range without the antenna, but can still transmit and receive accurately within a meter or two. Please note that there is no error checking on the communication channel. When deployed the platform does not accept Zigbee transmissions, so that is not an issue, but when configuring the device, always ensure it reports the correct values before leaving it in the field.

2.1.5. Battery Pack

2.1.5.1. Batteries

The battery pack holds 4xAA 1.5V Lithium batteries which nominally power the device at 6.0V. The battery pack is presently loose inside the case; if the platform will not be stationary, secure the battery pack to the case to ensure that it does not damage other components (or its own connection to the platform). If the platform will be exposed to temperature variations or shock, secure the batteries within the battery pack. Losing a battery will result in device failure. Removing the batteries will not affect non-volatile memory in the MCU or the SD Card. If the watch battery is in place, it also should not affect the RTC.

2.1.5.2. Switch

The battery switch is in the off position when it is closest to the edge of the board with the JTAG port (for programming). It is on when it is closest to the centre of the board. When the switch is off, the battery voltage is still connected to the battery monitor circuitry and the "VBAT" terminals if the expansion port. While engaged, the switch passes the battery voltage directly to a buck converter which provides power for the rest of the circuitry.

2.1.6. CO2 Sensor Module

Data Sheets: "SST CO2S-PPM-1 AN0049 Quick Start Guide.pdf"
"SST CO2S-PPM-1 AN0114 User Guide.pdf"
"SST CO2S-PPM-1 AN0117 Auto Calibration Note.pdf"
"SST CO2S-PPM-1 Ultra Low Power Carbon Dioxide Sensor.pdf".

The CO2 Sensor Module is attached to the platform via the Digital Sensor Port. The CO2 Sensor Module MUST be attached or the platform will lock up and need to be power cycled. Additionally, if the CO2 Sensor module is ever detached during deployment (due to damage for example) the module will also lock up, inevitably resulting in device failure after battery depletion. The CO2 Sensor Module can be programmed using the CU. This programming will be lost if the CO2 Module loses power.

To maintain power to the device, ensure "D1 State = 2" in the memory management section of the CU. "D1 State = 1" will power the device periodically, but may result in decalibration. "D1 State = 0" will prevent the Sensor Module from being used at all – select this option if only analog sensors are used – any other selection will result in the platform locking up (it will wait forever to talk to the sensor). Do not deploy a locked up device. "D1 State" may be renamed to "CO2 Chan" or something similar.

2.2. Conditioning Board

2.2.1. Expansion Port

The Expansion Port is a set of 16 terminals which have been labelled for convenience. These additional ports provide access to various device functions and power sources. The I2C and SPI digital channels are available for additional devices provided the firmware is available. The "VBAT" and GND terminals on the expansion port can be used to allow an external battery pack to be implemented through one of the extra sensor ports; this connection puts it in parallel with the AA battery pack. Do not simultaneously use multiple battery sources – only attach an external battery if the AA battery holder is completely empty.

2.2.2. Digital Sensor Port

The Digital Sensor Port is an attachment for the external CO2 Sensor Module. The port is labelled "DIGITAL1" on the conditioning board. The terminal closest to the label (left-most) is ground, followed by the two central terminals which are receive and transmit respectively. The terminal furthest away from the label (right-most) is sensor power and can be switched off to save power. To use the port with a different type of sensor, the firmware of the platform must be modified.

2.2.3. Analog Sensor Ports

There are four Analog Sensor Ports above the Digital Sensor Port. These are labelled "ANALOG<1:4>". The two terminals closest to the labels (left-most) are both ground; one is intended to be signal ground, while the other is for cable shielding. The analog signal is the third port (from the left) which accepts DC voltage signals. Finally, the terminal furthest away from the label (right-most) provides power to the sensor. Power to the analog channels is switched in pairs: 1 and 2 share a power switch as do 3 and 4. If only one of the two channels is used and both are powered, the second channel will slowly "charge up". This does not appear to affect the functionality of the channel in use, but it is important to ignore the undesirable channel.

2.2.3.1. Jumper Pins

The jumper pins increase the gain of the Analog Channels from x1V/V voltage followers (voltage in = voltage out) to x3 voltage amplifiers. This is helpful for measuring small DC values. This also changes the configuration of the analog circuitry, making it more stable.

2.2.3.2. Noise and Accuracy

Please note that the microcontroller uses an internal 2.56V reference; any signals above this value will clip, and be registered as maximum. Note that if the jumper is in, the maximum voltage that can be applied to the input is 0.853V. If a larger range is required, resistors will need to be changed to modify the gain of the device.

The analog channels are not completely accurate. The CU can be used to test variations in signal measurements for accuracy. So far, they appear to be accurate to <+/-1% of the range. Any floating channels (turned on but not driven by a sensor) will gradually accumulate charge and provide stable, but false data. Do not use data from lines which are powered but undriven.

3. Software Overview

3.1. Software Description

The software written to the microcontroller is inaccessible to the user without a programmer. Either the ATMEL JTAGICE3 or the ATMEL JTAGICE mkII are recommended for this purpose. There is a small, primitive, CU written for user convenience in the field. This has proven to be very useful and at this point, the devices could be deployed in a limited sense for configuration/calibration and experimental purposes for short time periods. The software is functional but not “industrial strength”; it is also quite specialized. Some C experience is recommended to modify the firmware of the device.

3.2. File List

co2_adc Functions to operate the ADC and capture analog sensor values.
co2_battery Functions to interface with the battery monitor circuit. Relies on co2_adc.
co2_config Functions for the CU. Sizable, but simple.
co2_fat32 Function for the SD Card file system - unstable, black box of doom.
co2_i2c Functions for I2C/TWI communication with RTC. Helpful and direct.
co2_led Functions for operating the indicator LEDs
co2_main Main function for system operation. Not Real Time Loop.
co2_rtc Functions for interacting with RTC. Also contains internal timer functions.
co2_sd Functions for interacting with the SD Card (on a sort of raw level)
co2_sensor Functions for interfacing with CO2 Sensor and computing analog values
co2_sleep Small file with a few sleep options
co2_spi SPI drivers for talking to SD Card. co2_SD and co2_fat32 rely on this.
co2_uart UART functions. Required for all Zigbee and CO2 Sensor operation.
co2_zigbee Zigbee related functions.

3.3. Zigbee Settings

The following settings should be written to any Zigbee radio before it is soldered into the sensor platform.

1. PAN ID: 0x4345 (This is ASCII for 'CO')
2. Destination Address Low (DL): 0xFFFF
3. Coordinator Enable (CE): 0 (Unless it is the computer one)
4. Power Level (PL): 0 (Lowest transmit power level)
5. Sleep Mode (SM): 1 (Required to sleep: if SM: 0 device fails)
6. Guard Time (GT): 64 (Set for 100ms GT: failure if >100ms)

*** Write (WR) NOTE: Not a setting.

*** If configuring one command at a time over CU Zigbee interface, be sure to save options to non-volatile memory before powering off or sleeping. Any unsaved variables will be reset when power is returned. Use 'ATWR' in "Modem Parameter and Firmware" after using the "Read" button. The "Write" button executes this for you.

4. <u>Operational Summary</u>

4.1. Operational Modes

The platform has a few pre-programmed operational modes to allow for limited experimental deployments. The operational mode information is saved to non-volatile memory and is preserved though power cycling. The different modes are described below.

4.1.1. The Configuration Utility (CU) (State: "Deployed = '0'")

If the platform receives any Zigbee communication while the green LED is on, it will enter the CU. This is an energy intensive mode intended to be used to program the platforms for deployment or used to find and repair hardware problems quickly. This mode is intended as a convenience, and does not error check user inputs. Do not deploy devices with inappropriate user inputs in any field. This utility is detailed further in a later section. Do not deploy the device without thoroughly exploring this operational mode.

4.1.2. Seek User Mode (Default) (State: "Deployed = '0'" and "D0 State = '1'")

This is the default setting upon powering on the device. The device makes the CU available for 3 seconds after waking up from sleep mode and performing its regular tasks. Any transmission to the platform will cause it to enter the CU if the green LED is on. The default measurement period is 15 minutes and the platform is programmed to capture measurements from the CO2 Sensor Module and the battery monitor. After these measurements are taken, the Zigbee radio will transmit the data string and the platform will sleep until the next wake-up interrupt from the RTC. This mode is useful, and less power intensive than the previous one, but it is unsuitable for even short term deployments. It is the most useful for calibration and testing as the user has an opportunity to play with the CU every measurement cycle. The CU is unavailable while sleeping.

4.1.3. Deployed Wireless Node (State: “Deployed = '1'” and “D0 State = '1'”)

This mode is the first mode useful for wireless monitoring. The “Deployed = '1'” variable indicates to the platform that a user is unlikely to be present and that it should not looks for user input. This disables the CU. To reenable it, remove the watch battery and power cycle the device. The sensor platform will always seek user input after a major power fault (which the device notices when the RTC is reset). The “D0 State = '1'” indicates that the user still wants wireless updates on measurements, so the platform will send the measurement string over Zigbee radio after collecting it. This is energy intensive, but is suitable for short term deployments.

4.1.4. Deployed Low Power Mode (State: “Deployed = '1'” and “D0 State = '0'”)

In this mode, the Zigbee radio is completely disabled. This is the lowest possible power mode, but completely isolates the device from the user. To allow the user to access the device, the watch battery must be removed and the platform power cycled. Measurements are saved to the SD Card and can be retrieved wirelessly once the device is unlocked, or taken from the SD Card manually. This mode is dependent upon the SD Card for data storage, so do not deploy the device is the red LED is lit at any time. The red LED indicates a file system error, and means no data will be saved to the SD Card. This operational mode is suitable for long deployment periods as it consumes very little power and is on for very short periods of time.

4.2. User Interface

This is a brief walk through of the Configuration Utility (CU) user interface. It is entirely text based and the sample is copied from the X-CTU Terminal for Zigbee devices. Notice the three text colors: red text is platform transmission to the user, blue text is a user response via the terminal, and black text is used to explain the interaction.

1. When “Deployed = 0” and the device has woke from sleep mode:
   Hello Human.

2. After receiving a transmission over Zigbee Radio:
   <Any character>
   We hear you.

3. Upon entering the CU:
   Config. Utils.
   - 'h' for help.

   Menu Selection:

4. MENU: “h+Enter” - selects “help”
   Menu Selection:
   h
   HELP OPTIONS:

<d> - TERMINATE	End the CU
<f> - FILES	Interact with files on the SD Card
<m> - MEMORY	Check and reset the EEPROM of the MCU
<h> - HELP	See a list of Menu Options for the CU
<s> - SENSOR TEST	Access the Conditioning board sensor ports
<t> - TIME & DATE	Read or update the RTC time
<c> - DIG. CONFIG	Send command to the CO_2 Sensor Module
<z> - ZIG. CONFIG.	Send commands to the platform's Zigbee Module

5. MENU: “f + Enter” - selects “file”
   Menu Selection:
   f
   FILE MENU:

r – Read	Read a file from SD Card over Zigbee connection
f – Find	Determine if a specific file is present
l – List	Show a list of all files on SD Card

   Selection:

5.1. FILE: “r + Enter” - selects “read”:
   Selection: r

Enter File Name (8.3): CONFIG.TXT — All Caps or numbers for file name. 8 characters max. followed by '.' then 3 character for file type.

User Input: CONFIG.TXT
File System: CONFIG TXT — Ensure that the file name is correct

OK (y/n)? y — Any character other than 'y' prompts another name input

No file data is present.
END OF FILE — Displayed after every file

5.2. FILE: “f + Enter” - selects “find”:
Selection: f
Enter File Name (8.3): CONFIG.TXT

User Input: CONFIG.TXT
File System: CONFIG TXT

OK (y/n)? y

Find: No File — That file could not be located

5.3. FILE: “l+Enter” - selects “list”:
Selection: l

.Kingston ROOT
.CO000101 CSV FILE 46 Bytes — These are presently on the SD Card.
.CO131125 CSV FILE 255 Bytes

6. MENU: “t + Enter” - RTC “time”:
Menu Selection:
t
TIME & DATE:
r - Read Time — Find what time the RTC and MCU have stored/
u - Update Time — Update the RTC time and date

Selection:

6.1. TIME: “r + Enter” - Read RTC Time:

Selection: r

PRESENT TIME:

.Time:00:04:11 It is 4:11 since the device lost power

.Date:01/01/2000 This is the default initial date

6.2. TIME “u + Enter” - Update RTC Time:

Selection: u

UPDATE TIME:

.Enter Time in 24h format (hh:mm:ss): 19:34:00 Key inputs are instantly read

.Time Updated successfully! Use 24hr time.

.Enter Date (dd/mm/yy): 26/11/13 Do not press enter after inputs.

.Enter Week Day (0 Sun., 1 Mon.): 2

.Date Updated successfully!

7. The “m + Enter” Memory options:

Menu Selection:

m

MEMORY OPERATIONS:

Modify Config. Info:

r – Read Read the internal EEPROM settings

w – Write Change the internal EEPROM settings

Selection:

7.1. MEMORY: “r + Enter” - Read EEPROM

Selection: r — Below are the default settings for EEPROM
Read Config:

Deployed: 0 — The platform seeks user input (Not Deployed)
Timer H: 0 — The platform wakes up at least once an hour
Timer M: 15 — The platform wakes up every 15 minutes
Timer S: 0
A0 State: 1 Scale: 53 — The battery voltage is measured and saved in mV (53 due to hardware)
A1 State: 0 Scale: 10 — The Analog sensors 1 – 4 are disabled by “State = 0” (default);
A2 State: 0 Scale: 10 — however, Scale = 10 is required
A3 State: 0 Scale: 10 — for their readings to be in mV.
A4 State: 0 Scale: 10
D0 State: 1 CMDs: 0 — Zigbee Channel. Set = 0 to disable. Name changed to “Zigbee State:”.
D1 State: 2 CMDs: 0 — CO2 Sensor Channel. Set = 0 to disable. Name changed to “CO2 State:”.

7.2. MEMORY: “W + Enter” - Write EEPROM

Selection: w
Write Config:
WARNING: MAXVAL = 65535

Deployed:0 — Valid Inputs: <'0' or '1'> + Enter
Period (hh): 0 — Valid Inputs: <'0' to '24'> + Enter
Period (mm): 1 — Valid Inputs: <'0' to '59'> + Enter — Wake up every 1 Minute.
Period (ss): 0 — Valid Inputs: <'30' to '59'> + Enter
A0 State:1 — Valid Inputs: <'0' or '1'> + Enter — Value of '0' sets Scale: 10” and skips scale input.
Scale:53 — Valid Inputs: <'0' to '65534'> + Enter
A1 State:0 — Valid Inputs: <'0' or '1'> + Enter
Scale:0 — Valid Inputs: <'0' to '65534'> + Enter
A2 State:0 — Valid Inputs: <'0' or '1'> + Enter
Scale:0 — Valid Inputs: <'0' to '65534'> + Enter

A3 State:0	Valid Inputs: <'0' or '1'> + Enter
Scale:0	Valid Inputs: <'0' to '65534'> + Enter
A4 State:0	Valid Inputs: <'0' or '1'> + Enter
Scale:0	Valid Inputs: <'0' to '65534'> + Enter
D0 State:1	Valid Inputs: <'0' or '1'> + Enter
CMDs: 0	Valid Inputs: <'0'> + Enter
D1 State:2	Valid Inputs: <'0', '1', or '2'> + Enter
CMDs: 0	Valid Inputs: <'0'> + Enter

8. MENU: "z + Enter" - Zigbee options:

Menu Selection:
z
ZIGBEE COMMANDS:

Enter XBee CMD: ATSM 1 — Enter exact Zigbee Command
XBee RPY: OK — Exact Zigbee Reply

9. MENU: "c + Enter" - Digital Sensor options:

Menu Selection:
c
DIGITAL CONFIG.:

Digital Command: K 0 — Enter exact CO2 Command, terminate with '\r'
. — In this case it is "K 0\r\n"
Command Received: K 0 — Confirm Command.
.
Digital Reply: K 00000 — Exact CO2 Reply

.

10. MENU: "s+ Enter" - Sensor options:

Menu Selection:
s
SENSOR TEST:

Select Channel, then Return:
0 - Battery
1:4 - Analog
5 - Digital
d - Terminate

10.1. SENSOR: "s + Enter" Scan, then "<number + Enter>" to select sensors.

Select Channel, then Return:
0 - Battery
1:4 - Analog
5 - Digital

d - Terminate
0 Select sensor by pressing <Number
+ Enter>
1 Continue until all desired sensors
are selected
3 Terminate with 'd' + Enter
d

Selection Complete.
Selected: 0 1 3

Mode:
w – Sweep Sweep option repeatedly streams sensor
data
c – Scan Scan option takes a single set of
measurements
c
Mode: c
0 1 3 Sensor Labels

05021,00862,00875, Scanned sensor Data (post scaling, zero
padded)

10.2. SENSOR: “s + Enter” Sweep, then “<number + Enter>” to select sensors.

Select Channel, then Return:
0 - Battery
1:4 - Analog
5 - Digital
d - Terminate
0
2
5
d

Selection Complete.
Selected: 0 2 5

Mode:
w - Sweep
c - Scan
w
Mode: w
0 2 HHHHH,TTTTT,CCCCC,ccccc Letters indicate
Digital Parameters

05048,00862,00000,01000,00191,00136,
05048,00837,00000,01000,00188,00155,
05021,00830,00000,01000,00183,00134,
05048,00812,00000,01000,00182,00156,
05048,00812,00000,01000,00179,00131,
05035,00820,00000,01000,00173,00082,
04995,00800,00000,01000,00170,00122,
05008,00812,00000,01000,00167,00137,
05061,0d0800,00000,01000,00166,00156, Terminate Sweep by pressing 'd'
05048,00802,00000,01000,00170,00205, Note the 'd' in the line above.

11. MENU: “d + Enter” - exit the CU:
    Menu Selection:
    d
    CMD UTL TERMINATED

12. When the platform disables user intervention:
    Goodbye Human.

13. The sensor data string sent when “D1 State = '1'”
    00,01,01,00,03,48,2,00000,01000,00228,00228,1,05021,0,00000,0,00000,0,00000,0,00000,
    The sensor parameters are:
    <Year>,<Month>,<Day>,<Hour>,<Minute>,<Second>,<Digital Sensor D1 State>,<Relative Humidity>,<Temperature>,<Digital CO2>,<Instantaneous Digital CO2>,<Analog Channel 1 State>,<Analog Channel 1 Value>,<CH A2 State>,<CH A2 Value>,<CH A3 State>,<CH A3 Value>,<CH A4 State>,<CH A4 Value>,

5. <u>SD Card Data File</u> (This should be available on the SD Card)

The data files are saved in FAT32 format as “.csv” files with “8.3” names. The file name is eight characters, numbers and capital letters only, followed by a ".", followed by three capital letters for the file type (hence “8.3”). For example “NFOFILE.TXT” is: "NFOFILE" "." "TXT". File names under 8 characters are padded with spaces and all files are saved as 11 character entries. Thus, the example file would appear as "NFOFILE.TXT" but in the SD card memory it is "NFOFILE TXT".

Formatting is important, because the file system is troublesome. The actual data files are saved as "COYYMMDD.CSV", where the "CO" stands for Carbon dioxide (the 2 didn't fit) and then "YYMMDD" is the year, month, and day the file was created according to the RTC. "CO000101.CSV" holds data which was captured after the RTC failed and the clock was reset to "January 1, 2000". Data is appended the end of the file, so it is possible to tell how many times the clock has failed. Missing data lines are likely do to SD Card boot failure.

The SD Card CSV file has a number of unlabelled columns. The column information is provided below:

Acronyms:

RTC - Real Time Clock. External time keeping microchip backed up by a watch battery.

DS1 - Digital Sensor 1. A CO2 Sensor module. Has multiple power states.
0 - "OFF". No power consumption.
1 - "Low Power". Powers off every cycle, but may lose calibration - sensor is off unless needed.
2 - "ON". Enters low power idle, but preserves calibration data – sensor module does not power off.

OVF - Overflow. This is a possibility for analog sensor values which are scaled too high (As in at or near MAXINT, which indicates a serious math error).

Format:

Column #	Designator	Description
1	YY	Two digit Year value from RTC. (Ex: 2013 -> "13")
2	MM	Two digit Month value from RTC (Ex: January -> "01")
3	DD	Two digit Day value from RTC (Ex: Jan. 1 -> "01")
4	hh	Two digit Hour value from RTC in 24hr time (Ex: Noon -> "12", Midnight -> "00")
5	mm	Two digit Minute value from RTC (Ex: Half Past -> "30")
6	ss	Two digit Second value from RTC.
7	d	One digit state information on DS1. 0 - OFF, 1 - ON (low power,

		uncalibrated), 2 - ON (Holds calibration)
8	HHHHH	Five digit zero padded relative humidity data from DS1. Interpret from Data Sheet.
9	TTTTT	Five digit zero padded temperature data from DS1. Interpret from Data Sheet.
10	DDDDD	Five digit zero padded Digital CO2 measurement (?). Interpret from Data Sheet.
11	ddddd	Five digit zero padded Instantaneous CO2 measurement (?). Interpret from Datasheet.
12	b	Battery monitor state. Default is 1. Enabled Battery monitoring.
13	BBbbb	Five digit, zero padded value from Analog Sensor ADC0. Multiplied by "A0_Scale" value. MAXVAL 65535. Watch for OVF. The resistor configuration on the device makes the default value "53"; when scale is "53" result is in mV.
14	a	Analog Sensor Channel 1 state. 0 - OFF. Data invalid, 1 - ON, Data Valid.
15	AAaaa	Five digit zero padded, Analog Sensor Channel 1 value. Default value is "10". This should provide the result in mV. NOTE: This neglects the effect of the 3xJumper! This is the raw voltage value captured by the device.
16	a	Analog Sensor Channel 1 state. 0 - OFF. Data invalid, 1 - ON, Data Valid.
17	AAaaa	Five digit zero padded, Analog Sensor Channel 2 value. Default value is "10". This should provide the result in mV. NOTE: This neglects the effect of the 3xJumper! This is the raw voltage value captured by the device.
18	a	Analog Sensor Channel 1 state. 0 - OFF. Data invalid, 1 - ON, Data Valid.
19	AAaaa	Five digit zero padded, Analog Sensor Channel 3 value. Default value is "10". This should provide the result in mV. NOTE: This neglects the effect of the 3xJumper! This is the raw voltage value captured by the device.
20	a	Analog Sensor Channel 1 state. 0 - OFF. Data invalid, 1 - ON, Data Valid.
21	AAaaa	Five digit zero padded, Analog Sensor Channel 4 value. Default value is "10".This should provide the result in mV. NOTE: This neglects the effect of the 3xJumper! This is the raw voltage value captured by the device

6. Future Work

There is still some hardware and software work to be done. Software improvements are listed at the bottom, hardware improvements near the top. Subpoints attempt to provide additional detail on the issue.

1. Trim the conditioning board shield headers

    1.1. Headers hold the conditioning board too far away from the MCU board and interfere with though-case connector placement

    1.2. Large exposed headers are vulnerable to shorts and damage

2. Realign the conditioning board shield headers

    2.1. Some headers are not very straight and make attachment to MCU board difficult

3. Select a new location for through-case connectors to avoid conditioning board

    3.1. The height of the conditioning board and depth of connectors make them incompatible

    3.2. Presently, it is impossible to add cables to the connectors without interfering with conditioning board when case is closed

    3.3. Relocate through-case connectors to prevent issues with conditioning board or battery pack

4. Modify or reinforce battery pack attachment to MCU board

    4.1. The wires connecting the battery pack are vulnerable to stress and are easily ripped off or broken

    4.2. Either reinforce the joints with hot glue to prevent stress failures or install detachable connectors

5. Cut holes for through-case connectors

    5.1. Four holes are required: 3xAnalog (4 Pin) and 1xDigital (7Pin)

6. Install and weather proof through-case connectors

    6.1. Through-case connectors must seal the case from the environment

7. Wire through-case connectors to conditioning board

7.1. Pins from through-case connectors must be wired to appropriate Conditioning Board ports

7.2. Wires must withstand continual case opening and closing

7.3. Wire attachments to Conditioning Board must be reinforced or modified to withstand case opening and closing and prevent stress related failure

8. Optional: Allow external power through one set of sensor wires

8.1. Select one sensor channel. Allow a space for a wire splice so that wires could later be soldered to “VBAT” and “GND” connections on expansion port (open left side terminals). This idea requires approval by project lead (it's just a proposal)

9. Attach Zigbee antenna to Zigbee Module

9.1. Attach Zigbee whip antenna to small coaxial port on Zigbee Radio

10. Attach Zigbee antenna to case

10.1. Adhere Zigbee whip antenna to case so that it can withstand repeated opening and closing and resist stress related failure

11. Construct sensor cables

11.1. Sensor wires need to be attached to tips compatible with through-case connectors.

11.2. Sensor wire orientation in connector must match case-side connection

12. Attach a Zigbee radio to Board #9

12.1. MCU Board #9 appears fully functional aside from a missing Zigbee Radio.

12.2. Pre-program the Zigbee Radio to PanID “CO” and Sleep Mode '1'

13. Remove capacitors on Conditioning Board #1

13.1. Conditioning Board #1 (Short connectors) has 4.7nF capacitors which interfere with input amplifier stability

13.2. Remote capacitors from operational amplifier output to prevent instability

13.3. This will provide one spare board unless MCU Board #5 is repaired

14. Determine how to securely attach MCU Board to case for versatility and to prevent potential stress failure

    14.1. During transport or deployment in a mobile environment, movement of the circuitry may damage components

    14.2. Anchoring device to case, or case liner, may mitigate failure related to this

    14.3. The interrupt wire which jumps the RTC to the “INT” pin of the conditioning board, along with the battery connector wires, is particularly vulnerable

15. Determine how to securely attach battery pack inside of case to prevent movement and damage to other components during deployments

    15.1. The battery back is smaller than the inside of the case and heavy relative to the other modules
    15.2. Impact to the case could cause the battery pack to damage its own connection to the board, or the board itself. This will inevitably result in device failure

16. Determine how to securely hold batteries inside of battery case to prevent power failure

    16.1. Impact may dislodge batteries, resulting in device failure

    16.2. If the batteries are not secured, size changes (thermal expansion) relative to the battery holder could cause them to fall out

    16.3. A zip-tie or elastic band may be sufficient for this task

17. Modify the case for the appropriate anchoring modifications

    17.1. For example, small holes may need to be cut into the case liner for zip-ties, or a section remove to glue something to the case

    17.2. Modifications dependent upon test conditions

18. Optional: Find electrical fault on MCU Board #5

    18.1. MCU Board #5 was inspected, but appears to have an electrical fault somewhere when board peripherals are powered up

    18.2. This appeared as a short somewhere on the board – its cause and location are unknown

18.3. The buck converter is probably the place to start; however, the problem only appeared after the peripherals were added to the firmware (the buck convert worked successfully at least once)

19. Repair electrical fault on MCU Board #5

19.1. If electrical fault is easily located and repaired (read: cheap and quick to find and fix)

20. Calibrate CO2 Sensors

20.1. The CO2 Sensors come somewhat calibrated out of the box, but there has been no attempt to calibrate them accurately or permanently

20.2. It may be possibly to avoid hardware calibration and use data from known gas concentrations to compute more accurate results – consult datasheets

21. Modify Zigbee Software settings

21.1. Zigbee module is mostly unmodified – changing some settings should be able to reduce its power consumption

21.2. For example, the lockout time to program the device is set at human usable speeds (1.5seconds), this can be decreased to significantly reduce energy consumption

21.2.1. Zigbee lockout reduced to 100ms. (150ms in code for safety)

21.3. Power levels are programmable and the time it takes to sleep after receiving the sleep command may also be reduced for massive power savings

21.3.1. Power Level reduced to “PL 0”. This should be 10dBm for PRO modules

21.3.2. Idle-to-sleep transition time does not appear easily modified

22. Add error checking to CU

22.1. Presently the CU accepts all inputs and malfunctions or crashes if they are invalid

22.2. This should be changed to prevent invalid inputs in the first place

23. Add CMD functionality in CU

    23.1. Presently only '0' is valid for CMD part of CU Memory section. This should be modified to accept commands which are needed by the device

    23.2. The commands are presently written directly into the software which makes the platform less versatile than it should be

24. Modify or replace file system software

    24.1. While functional, the file system software has been written as a "black box" and is very difficult to work with

    24.2. Sufficient C programming talent should allow this to be swapped for a more stable, readable set of code

25. Customize low level drivers for "Real Time Loop"

    25.1. Code for low level drivers was written for polling

    25.2. While functional, this can result in devices locking up; for robustness this should be changed

7. Sample CU Session

Hello Human.
h
We hear you.

Config. Utils.
- 'h' for help.

Menu Selection:
h
HELP OPTIONS:
<d> - TERMINATE
<f> - FILES
<m> - MEMORY
<h> - HELP
<s> - SENSOR TEST
<t> - TIME & DATE
<c> - DIG. CONFIG
<z> - ZIG. CONFIG.

Menu Selection:

```
f
FILE MENU:
  r - Read
  f - Find
  l - List

 Selection: r

Enter File Name (8.3): CONFIG.TXT

User Input: CONFIG.TXT
File System: CONFIG  TXT

OK (y/n)? y


END OF FILE

Menu Selection:
f
FILE MENU:
  r - Read
  f - Find
  l - List

 Selection: f

Enter File Name (8.3): CONFIG.TXT

User Input: CONFIG.TXT
File System: CONFIG  TXT

OK (y/n)? y

Find: No File

Menu Selection:
f
FILE MENU:
  r - Read
  f - Find
  l - List

 Selection: l

.Kingston       ROOT
```

```
.CO000101 CSV   FILE         46  Bytes
.CO131125 CSV   FILE        255  Bytes

Menu Selection:
t
TIME & DATE:
  r - Read Time
  u - Update Time

Selection: r

PRESENT TIME:

.Time:00:04:11
.Date:01/01/2000

Menu Selection:
t
TIME & DATE:
  r - Read Time
  u - Update Time

Selection: u

UPDATE TIME:

.Enter Time in 24h format (hh:mm:ss): 19:34:00
.Time Updated successfully!

.Enter Date (dd/mm/yy): 26/11/13
.Enter Week Day (0 Sun., 1 Mon.): 2
.Date Updated successfully!

Menu Selection:
m
MEMORY OPERATIONS:

 Modify Config. Info:
  r - Read
  w - Write

Selection: r
Read Config:

Deployed: 0
Timer H:  0
```

Timer M: 1
Timer S: 0
A0 State: 1 Scale: 53
A1 State: 0 Scale: 0
A2 State: 0 Scale: 0
A3 State: 0 Scale: 0
A4 State: 0 Scale: 0
D0 State: 1 CMDs: 0
D1 State: 2 CMDs: 0

Menu Selection:
m
MEMORY OPERATIONS:

 Modify Config. Info:
  r - Read
  w - Write

Selection: w
Write Config:
  WARNING: MAXVAL = 65535

Deployed:0
Period (hh): 0
Period (mm): 1
Period (ss): 0
A0 State:1
   Scale:53
A1 State:0
   Scale:0
A2 State:0
   Scale:0
A3 State:0
   Scale:0
A4 State:0
   Scale:0
D0 State:1
   CMDs: 0
D1 State:2
   CMDs: 0

Menu Selection:
z
ZIGBEE COMMANDS:

Enter XBee CMD: ATSM 1

XBee RPY: OK

Menu Selection:
c
DIGITAL CONFIG.:

Digital Command: K 0
.
Command Received: K 0
.
Digital Reply: K 00000
.

Menu Selection:
s
SENSOR TEST:
Select Channel, then Return:
  0   - Battery
  1:4 - Analog
  5   - Digital
  d   - Terminate
0
1
3
d

Selection Complete.
Selected: 0 1 3

Mode:
  w - Sweep
  c - Scan
c
Mode: c
0   1   3

05021,00862,00875,

Menu Selection:
s
SENSOR TEST:

Select Channel, then Return:
  0   - Battery
  1:4 - Analog
  5   - Digital

```
  d   - Terminate
0
2
5
d

Selection Complete.
Selected: 0 2 5

Mode:
  w - Sweep
  c - Scan
w
Mode: w
0     2    HHHHH,TTTTT,CCCCC,ccccc

05048,00862,00000,01000,00191,00136,
05048,00837,00000,01000,00188,00155,
05021,00830,00000,01000,00183,00134,
05048,00812,00000,01000,00182,00156,
05048,00812,00000,01000,00179,00131,
05035,00820,00000,01000,00173,00082,
04995,00800,00000,01000,00170,00122,
05008,00812,00000,01000,00167,00137,
05061,0d0800,00000,01000,00166,00156,
05048,00802,00000,01000,00170,00205,
Menu Selection:
d
CMD UTL TERMINATED

Goodbye Human.

00,01,01,00,03,48,2,00000,01000,00228,00228,1,05021,0,00000,0,00000,0,00000,
0,00000,
```

APPENDIX C:

LIGHT SOURCE DEVICES AND COMPONENTS DATASHEETS

Ultra high bright circular LED lamps (φ5.0mm)

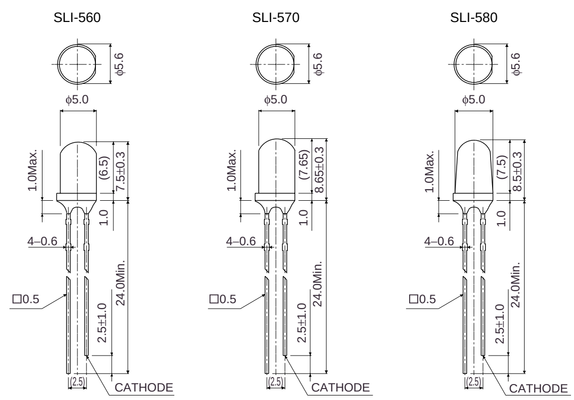
SLI-560 / SLI-570 / SLI-580 Series

The SLI-560, SLI-570 and SLI-580 series are high luminance LEDs which give you a choice of narrow to wide viewing angles. One red type, one orange type and yellow type are available in three packages for a total of nine different types, and they suitable for use in a wide variety of applications.

●Features

1) Super high brightness using AlInGaP.
2) 3 types of viewing angle is available.
3) High reliability.
4) Suitable for information board application.

●External dimensions (Units : mm)



Tolerances are ±0.2 unless otherwise noted:

●Selection guide

Lens \ Emitting color	Red	Orange	Yellow
Narrow tupe	SLI-580UT3F	SLI-580DT3F	SLI-580YT3F
Medium tupe	SLI-570UT3F	SLI-570DT3F	SLI-570YT3F
Wide viewng tupe	SLI-560UT3F	SLI-560DT3F	SLI-560YT3F

●Absolute maximum ratings (Ta=25°C)

Parameter	Symbol	Maximum ratings	Unit
Power dissipation	P_D	125	mW
Forward current	I_F	50	mA
Peak forward current	I_{FP}	200	mA
Reverse voltage	V_R	9	V
Operating temperature	Topr	–30~+85	°C
Storage temperature	Tstg	–40~+100	°C
Soldering temperature	–	260°C 5 seconds maximum	–

●Electrical and optical characteristics (Ta=25°C)

Parameter		Symbol	Conditions	Red			Orange			Yellow			Unit
				Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	
Forward voltage		V_F	I_F=20mA	–	1.9	2.5	–	1.9	2.5	–	1.9	2.5	V
Reverse current		I_R	V_R=9V	–	–	100	–	–	100	–	–	100	μA
Peak wavelength		λ_P	I_F=20mA	–	630	–	–	611	–	–	591	–	nm
Spectral line half width		$\Delta\lambda$	I_F=20mA	–	20	–	–	17	–	–	15	–	nm
Viewing angle	SLI-560	$2\theta_{1/2}$	–	–	40	–	–	40	–	–	40	–	deg
	SLI-570				25			25			25		
	SLI-580				10			10			10		

●Luminous intensity vs. wavelength

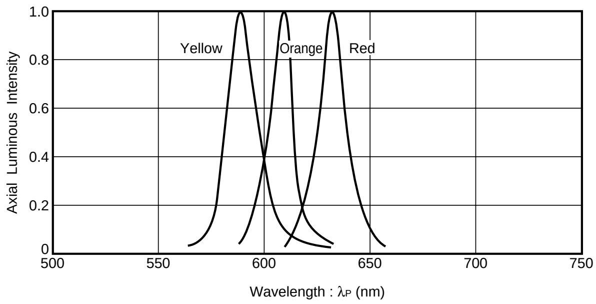


Fig.1

●Luminous intensity

Color	λP	Type	Min.	Typ.	Max.	Unit
Red	630	SLI-560UT3F	300	1000	–	mcd
		SLI-570UT3F	900	3000	–	
		SLI-580UT3F	1350	5000	–	
Orange	611	SLI-560DT3F	300	1000	–	
		SLI-570DT3F	900	3000	–	
		SLI-580DT3F	1350	5000	–	
Yellow	591	SLI-560YT3F	300	1000	–	
		SLI-570YT3F	610	2500	–	
		SLI-580YT3F	1350	5000	–	

Note : 1. Measured at I_F=20mA
2. The specification is subject to be without notice.
We would like you to refer to the latest specification in use.

●**Directional pattern**

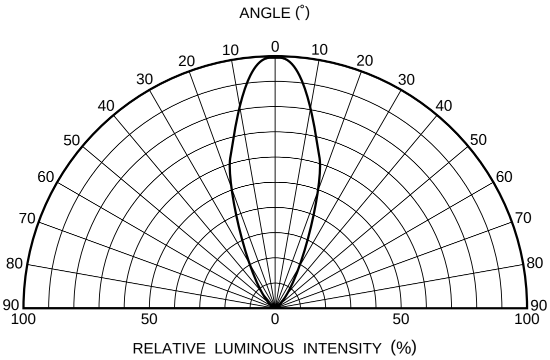


Fig.2 SLI-560 Directional patterm

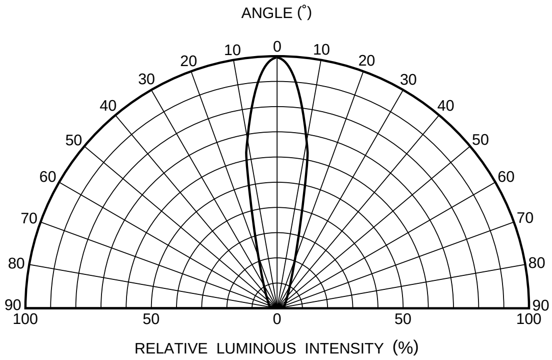


Fig.3 SLI-570 Directional patterm

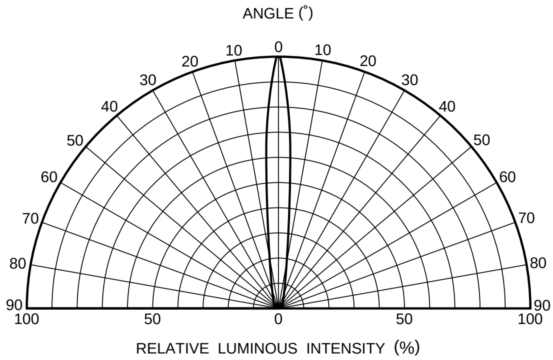


Fig.4 SLI-580 Directional patterm

●**Electrical characteristic curves**

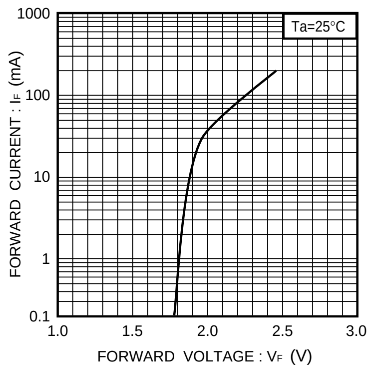


Fig.5 Forward current vs. forward voltage

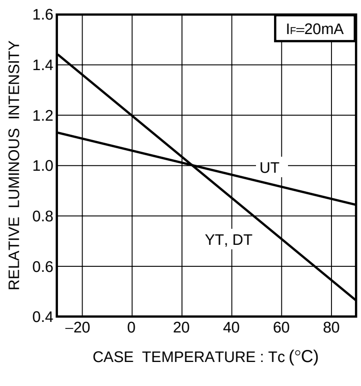


Fig.6 Luminous intensity vs. case temperature

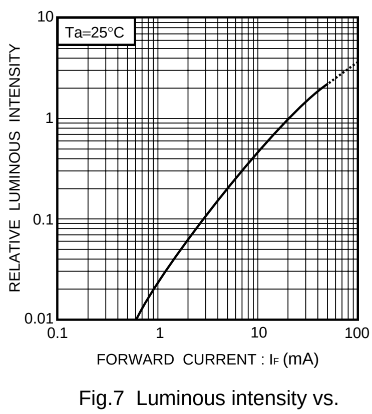


Fig.7 Luminous intensity vs. forward current

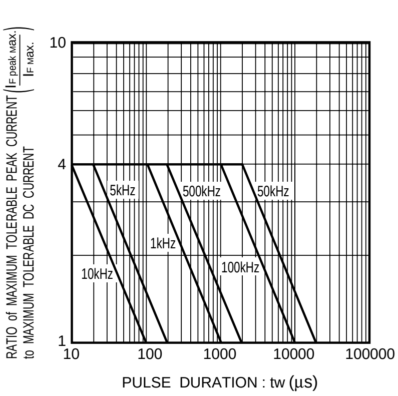


Fig.8 Ratio maximum tolerable peak vs. pulse duration

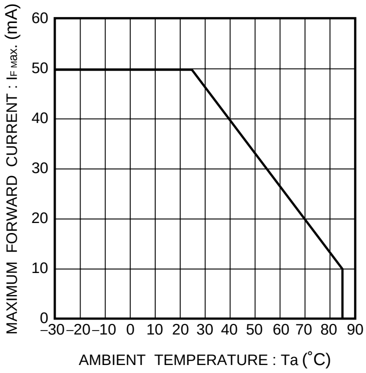
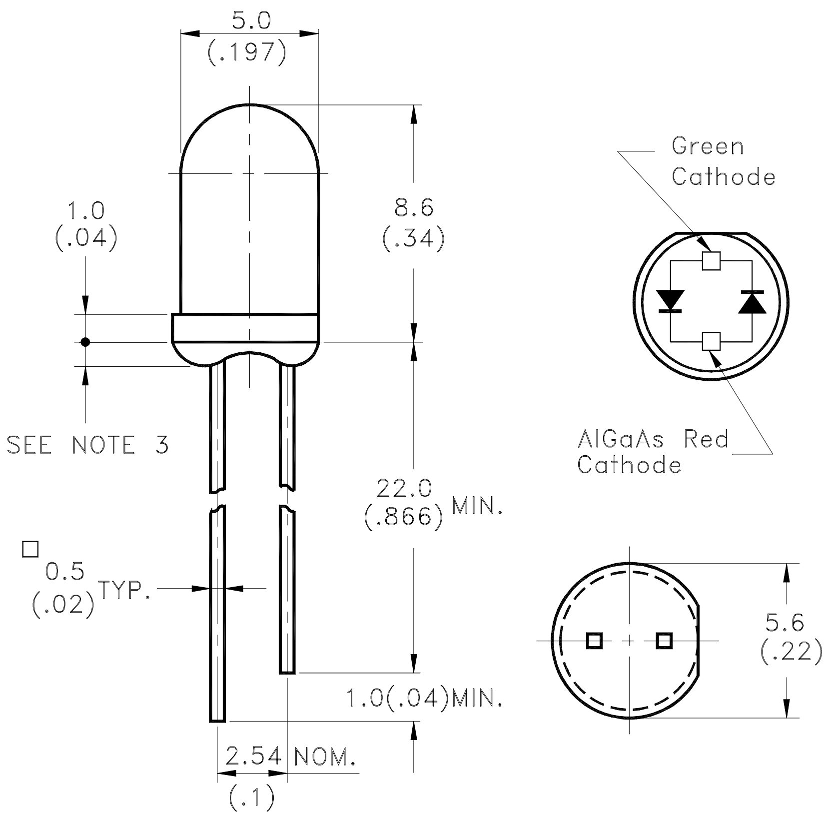


Fig.9 Maximum forward current vs. ambient temperature (Derating)

Features

* AlGaAs Red and Green chips are matched for uniform. light output.
* T-13/4 type package.
* Long life solid state reliability.
* Low power consumption.
* I.C compatible.

Package Dimensions



Part No.	Lens	Source Color
LTL-293SJW	White Diffused	AlGaAs Red / Green

NOTES:

1. All dimensions are in millimeters (inches).
2. Tolerance is ± 0.25mm(.010") unless otherwise noted.
3. Protruded resin under flange is 1.0mm (.04”) max.
4. Lead spacing is measured where the leads emerge from the package.
5. Specifications are subject to change without notice.

Absolute Maximum Ratings at T_A=25℃

Parameter	AlGaAs Red	Green	Unit
Power Dissipation	100	100	mW
Peak Forward Current (1/10 Duty Cycle, 0.1ms Pulse Width)	200	120	mA
Continuous Forward Current	40	30	mA
Derating Linear From 50℃	0.5	0.4	mA/℃
Operating Temperature Range	-55℃ to + 100℃		
Storage Temperature Range	-55℃ to + 100℃		
Lead Soldering Temperature [1.6mm(.063") From Body]	260℃ for 5 Seconds		

Electrical Optical Characteristics at T_A=25℃

Parameter	Symbol	Color	Min.	Typ.	Max.	Unit	Test Condition
Luminous Intensity	Iv	AlGaAs Red Green	29 12.6	90 40		mcd	I_F = 20mA I_F = 20mA Note 1,4
Viewing Angle	$2\theta_{1/2}$	AlGaAs Red Green		60 60		deg	Note 2 (Fig.6)
Peak Emission Wavelength	λp	AlGaAs Red Green		660 565		nm	Measurement @Peak (Fig.1)
Dominant Wavelength	λd	AlGaAs Red Green		638 569		nm	Note 3
Spectral Line Half-Width	$\Delta\lambda$	AlGaAs Red Green		20 30		nm	
Forward Voltage	V_F	AlGaAs Red Green		1.8 2.1	2.4 2.6	V	I_F = 20mA I_F = 20mA
Reverse Current	I_R	AlGaAs Red Green			100 100	μA	V_R = 4V V_R = 5V Note 5
Capacitance	C	AlGaAs Red Green		30 35		pF	V_F = 0 , f = 1MHz

Note: 1. Luminous intensity is measured with a light sensor and filter combination that approximates the CIE (Commission International De L'Eclairage) eye-response curve.

2. $\theta_{1/2}$ is the off-axis angle at which the luminous intensity is half the axial luminous intensity.

3. The dominant wavelength, λ_d is derived from the CIE chromaticity diagram and represents the single wavelength which defines the color of the device.

4. The Iv guarantee should be added ± 15%.

5. Reverse current is controlled by dice source.

Typical Electrical / Optical Characteristics Curves

(25℃ Ambient Temperature Unless Otherwise Noted)

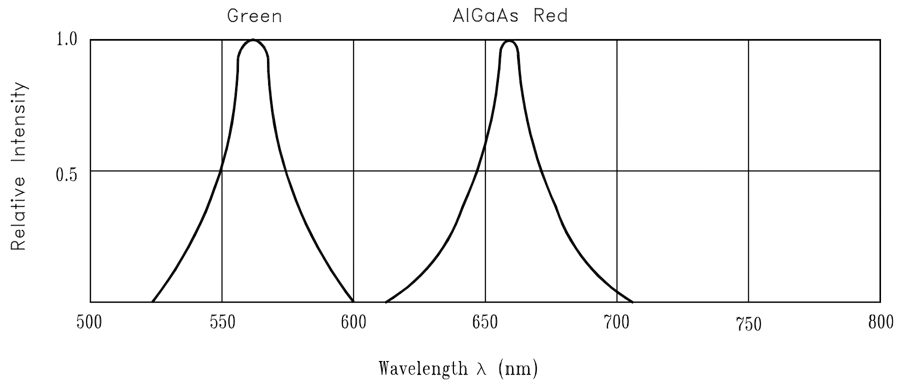


Fig.1 Relative Intensity vs. Wavelength

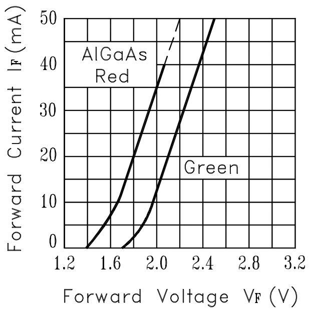


Fig.2 Forward Current vs. Forward Voltage

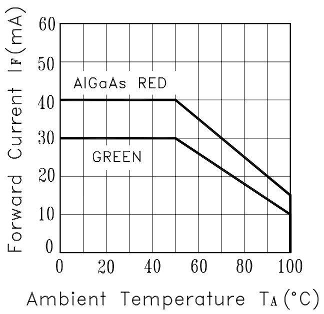


Fig.3 Forward Current Derating Curve

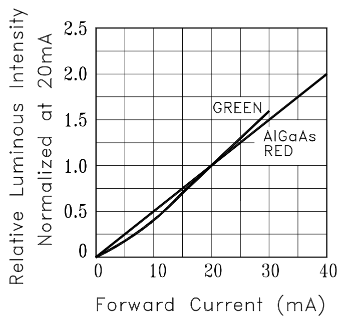


Fig.4 Relative Luminous Intensity vs. Forward Current

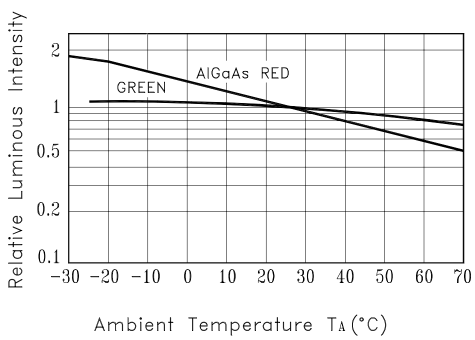


Fig.5 Luminous Intensity vs. Ambient Temperature

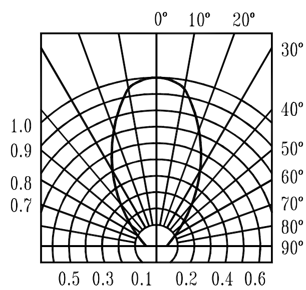
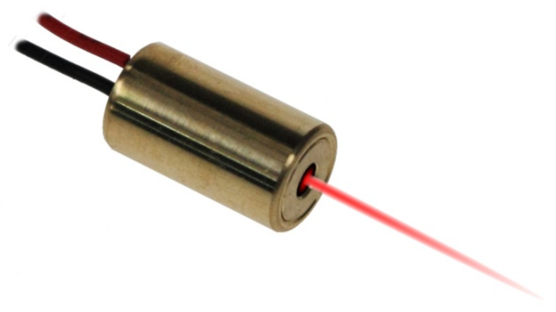


Fig.6 Spatial Distribution

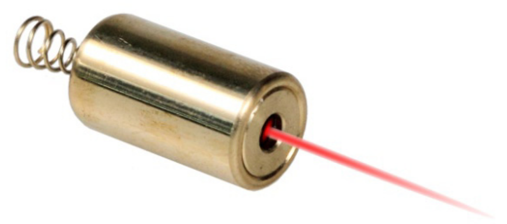
INFINITER®

Industrial Use Laser

VLM-635/650-01 Series



Lead Wire type



Spring type

FEATURES:

- Industrial Red Dot Laser.
- Basic module, compact size with APC Driver Circuit inside, ideal for industrial Laser application.
- This module has integrated optic, laser diode, and APC driver circuit.
- APC Driver Circuit enables the Laser output power safe and constant.
- Includes patented solid brass structure for the best shock resistance and better heat transfer consideration.
- Aspherical plastic lens provides Dot Laser.
- Dimensions : Φ10.4 x 18.4 mm (Φ0.409" x 0.724")
- Wavelength : 635 / 650 nm
- Output power : Class II – less than 1mW / Class IIIa – less than 5mW.
- Beam Divergence (Half Angle) : 0.5 mRad
- 2.6~5 VDC operation.
- Connection type : Lead wire / Spring.

APPLICATIONS:

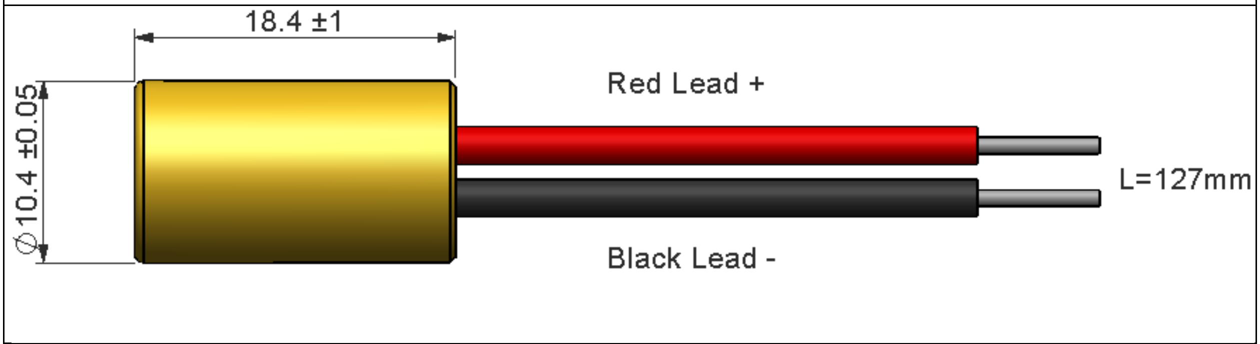
- Industrial Red Dot Laser - for positioning, measuring, pointing and laser sighting device.
- Wood processing.
- Metal processing.
- Stone processing.
- Textile industry.
- Food industry.
- Automotive industry.
- Medical science

INFINITER®

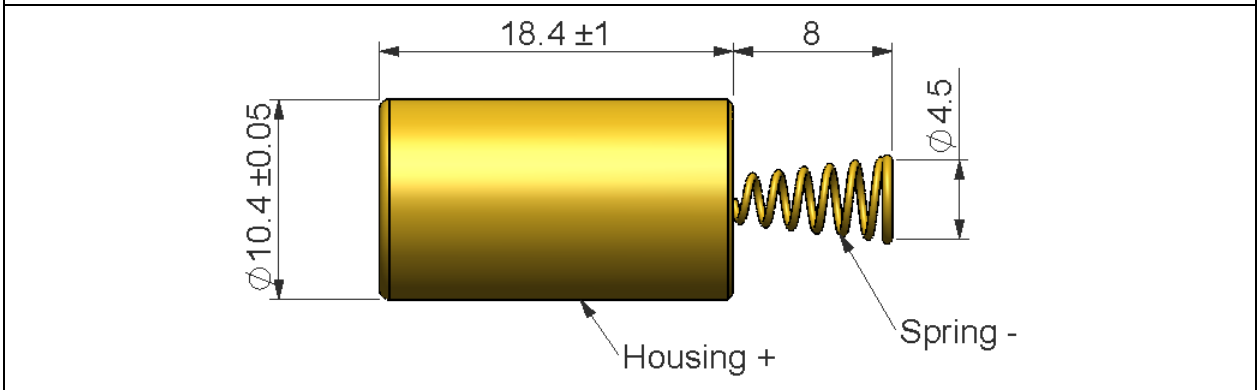
VLM-635/650-01 Series

OUTLINE DIMENSIONS (UNITS: mm)

Outline (Lead Wire type)



Outline (Spring type)



SPECIFICATIONS

SPECIFICATIONS		635-01	650-01
1	Dimensions	Φ10.4 x 18.4 mm (Φ0.409" x 0.724")	
2	Operating voltage (Vop)	2.6~5 VDC	
3	Operating current (Iop)	< 50mA	< 35mA
4	Continuous wave output power (Po)	LPT<1mW / LPA≦3mW	
5	Wavelength at peak emission (λp)	630~645nm	645~665nm
6	Collimating lens	Aspherical plastic lens(ø7)	
7	Spot size at 5M	5±1 mm	
8	Divergence (Half Angle)	0.5 mRad	
9	Operating temp. range	+10°C ~+40°C	
10	Storage temp. range	-20°C ~+65°C	
11	Housing	Brass	
12	Mean time to failure (MTTF) 25℃	5000hrs	10000hrs

Note : Laser module housing is an electrical positive surface, it is imperative that contact between the laser module and the machine be avoided. This is to prevent damage from the machine electrical leakage. Surge protected power supply to the laser module is strongly recommended

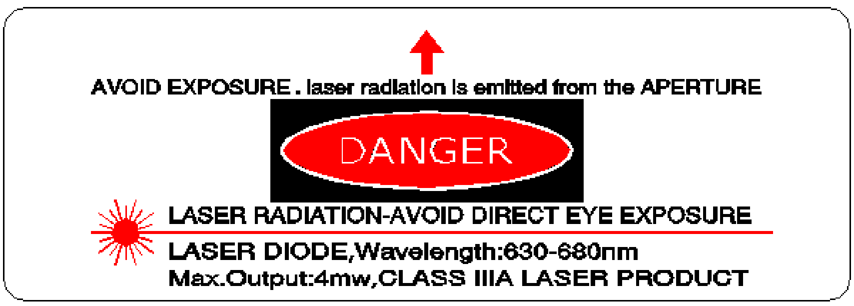
INFINITER®

VLM-635/650-01 Series

ORDER CODE

Order Code	Wavelength	Output Power	Connection Type
VLM-635-01 LPA	635 nm	≦3mW	Lead Wire
VLM-635-01 LPT	635 nm	＜1mW	Lead Wire
VLM-635-01 SPA	635 nm	≦3mW	Spring
VLM-635-01 SPT	635 nm	＜1mW	Spring
VLM-650-01 LPA	650 nm	≦3mW	Lead Wire
VLM-650-01 LPT	650 nm	＜1mW	Lead Wire
VLM-650-01 SPA	650 nm	≦3mW	Spring
VLM-650-01 SPT	650 nm	＜1mW	Spring

SAFETY LABEL



Advanced Small Signal MOSFET 2N7000BU/2N7000TA

FEATURES

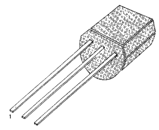
- Fast Switching Times
- Improved Inductive Ruggedness
- Lower Input Capacitance
- Extended Safe Operating Area
- Improved High Temperature Reliability

BV_{DSS} = 60 V

$R_{DS(on)}$ = 5.0 Ω

I_D = 200 mA

TO-92



1.Source 2. Gate 3. Drain

Absolute Maximum Ratings

Symbol	Characteristic	Value	Units
V_{DSS}	Drain-to-Source Voltage	60	V
I_D	Continuous Drain Current (T_C=25℃)	200	mA
	Continuous Drain Current (T_C=100℃)	110	
I_{DM}	Drain Current-Pulsed ①	1000	mA
V_{GS}	Gate-to-Source Voltage	±30	V
P_D	Total Power Dissipation (T_C=25℃) Linear Derating Factor	400 3.2	mW mW/℃
T_J , T_{STG}	Operating Junction and Storage Temperature Range	- 55 to +150	℃
T_L	Maximum Lead Temp. for Soldering Purposes, 1/8? from case for 5-seconds	300	

Thermal Resistance

Symbol	Characteristic	Typ.	Max.	Units
$R_{\theta JA}$	Junction-to-Ambient	--	312.5	℃/W

Electrical Characteristics (T_C=25℃ unless otherwise specified)

Symbol	Characteristic	Min.	Typ.	Max.	Units	Test Condition
BV_{DSS}	Drain-Source Breakdown Voltage	60	--	--	V	V_{GS}=0V,I_D=250μA
$V_{GS(th)}$	Gate Threshold Voltage	0.3	--	3.9	V	V_{DS}= V_{GS},I_D=250μA
		0.4	--	2.2		V_{DS}= V_{GS},I_D=1mA
I_{GSS}	Gate-Source Leakage , Forward	--	--	100	nA	V_{GS}=15V
	Gate-Source Leakage , Reverse	--	--	-100		V_{GS}=-15V
I_{DSS}	Drain-to-Source Leakage Current	--	--	1	μA	V_{DS}=60V
		--	--	1000		V_{DS}=45V,T_C=125℃
$R_{DS(on)}$	Static Drain-Source On-State Resistance ②	--	--	5.0	Ω	V_{GS}=10V,I_D=0.5A
g_{fs}	Forward Transconductance ②	0.1	0.3	--	S	V_{DS}=15V,I_D=0.5A
C_{iss}	Input Capacitance	--	30	--	pF	V_{GS}=0V,V_{DS}=25V, f =1MHz
C_{oss}	Output Capacitance	--	12	--		
C_{rss}	Reverse Transfer Capacitance	--	3.0	--		
$t_{d(on)}$	Turn-On Delay Time	--	--	10	ns	V_{DD}=30V,I_D=0.5A, R_G=15Ω ②③
t_r	Rise Time	--	--	10		
$t_{d(off)}$	Turn-Off Delay Time	--	--	10		
t_f	Fall Time	--	--	10		

Notes ;

① Repetitive Rating : Pulse Width Limited by Maximum Junction Temperature
② Pulse Test : Pulse Width = 250μs, Duty Cycle ≤ 2%
③ Essentially Independent of Operating Temperature

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ImpliedDisconnect™
ISOPLANAR™
LittleFET™
MicroFET™
MicroPak™
MICROWIRE™
MSX™
MSXPro™
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OPTOPLANAR™
PACMAN™
POP™
Power247™
PowerTrench®
QFET™
QS™
QT Optoelectronics™
Quiet Series™
RapidConfigure™
RapidConnect™
SILENT SWITCHER®
SMART START™
SPM™
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SuperSOT™-8
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TruTranslation™
UHC™
UltraFET®
VCX™

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2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

PRODUCT STATUS DEFINITIONS

Definition of Terms

Datasheet Identification	Product Status	Definition
Advance Information	Formative or In Design	This datasheet contains the design specifications for product development. Specifications may change in any manner without notice.
Preliminary	First Production	This datasheet contains preliminary data, and supplementary data will be published at a later date. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
No Identification Needed	Full Production	This datasheet contains final specifications. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
Obsolete	Not In Production	This datasheet contains specifications on a product that has been discontinued by Fairchild semiconductor. The datasheet is printed for reference information only.

APPENDIX D:

MEASURING CIRCUIT AND LIGHT DETECTORS DEVICES AND COMPONENTS DATASHEETS

USB2000+ Spectrometer

The USB2000+ is a versatile, general-purpose UV-Vis spectrometer for absorption, transmission, reflectance, emission, color and other applications between 200-1100 nm. Its compact size, robust optoelectronics and easy modularity make it one of the most popular spectrometers in the world, supporting thousands of applications.

Ocean Optics

At a Glance

Size: 89.1 mm x 63.3 mm x 34.4 mm

Weight: 190 g

Wavelength range: Grating dependent within 200-1100 nm

Signal-to-noise ratio: 250:1 (at full signal)

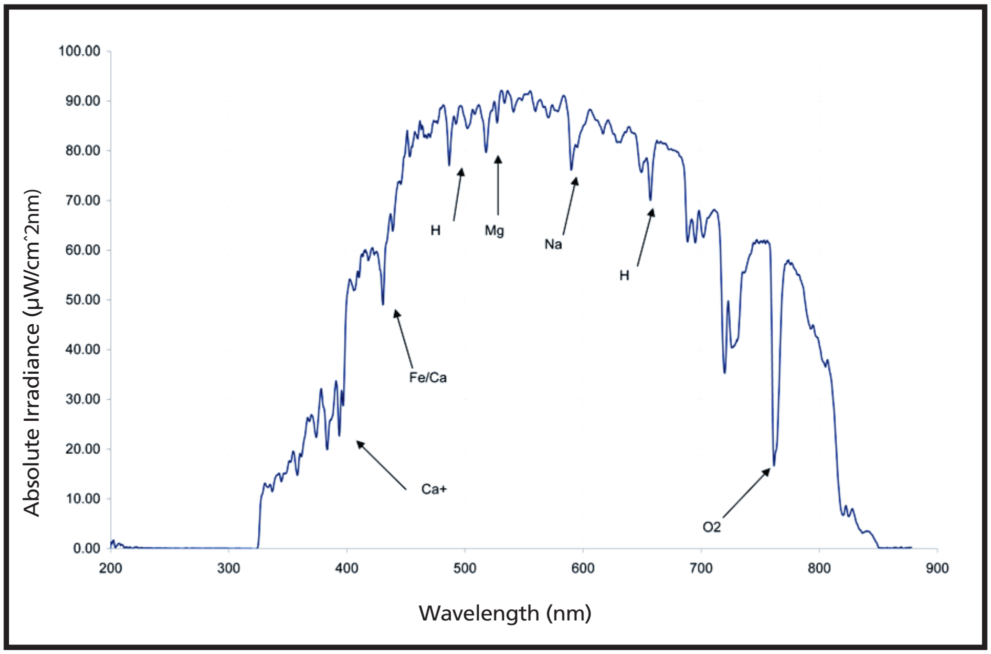
Dynamic range: 8.5 x 10^7 (system); 1300:1 for a single acquisition

Integration time: 1 ms - 65 s (20 s typical)

Flexible Design, Great Performance

The USB2000+ is a modular spectrometer. You can select a model that is preconfigured for a particular application or you can build your own. Our Application Sales Engineers help you with selection of grating, slits and optical bench accessories, as well as sampling accessories such as fibers, light sources, sampling holders, filter holders, flow cells, fiber optic probes and integrating spheres.

At the heart of the USB2000+ is a 2048-element CCD array detector in a robust, high-speed optoelectronic design that provides remarkable performance for a spectrometer its size. Depending on configuration, sub-nanometer optical resolution is possible, and rapid acquisition rates allow users to capture and store up to 1,000 full spectra every second. Also, the spectrometer's detector has a UV-sensitive coating that makes the system versatile enough for UV-Vis and Vis-NIR performance.



Absorption bands of atmospheric elements are easily identifiable in this solar irradiance spectrum measured with a USB2000+ spectrometer and cosine corrector.

Features

- Great response across the 200-1100 nm wavelength range
- Hundreds of configurations possible with modular design
- Built-to-suit wavelength range and optical resolution performance
- High-speed electronics for capturing and storing up to a thousand spectra per second

Learn more online at www.oceanoptics.com

Contact an Ocean Optics Application Scientist for details and pricing

www.oceanoptics.com | info@oceanoptics.com
US +1 727-733-2447 **EUROPE** +31 26-3190500 **ASIA** +86 21-6295-6600

5mm DIP
Ambient Light Sensor

ALS-PT243-3C/L177

Features

- Close responsively to the human eye spectrum
- Light to Current, analog output
- Good output linearity across wide illumination range
- Low sensitivity variation across various light sources
- Operation temperature performance, -40^{o}C to 85^{o}C
- Wide supply voltage range, 2.5V to 5.5V
- Size : 5mm Lamp (Flat lens)
- RoHS compliant and Pb Free package

Description

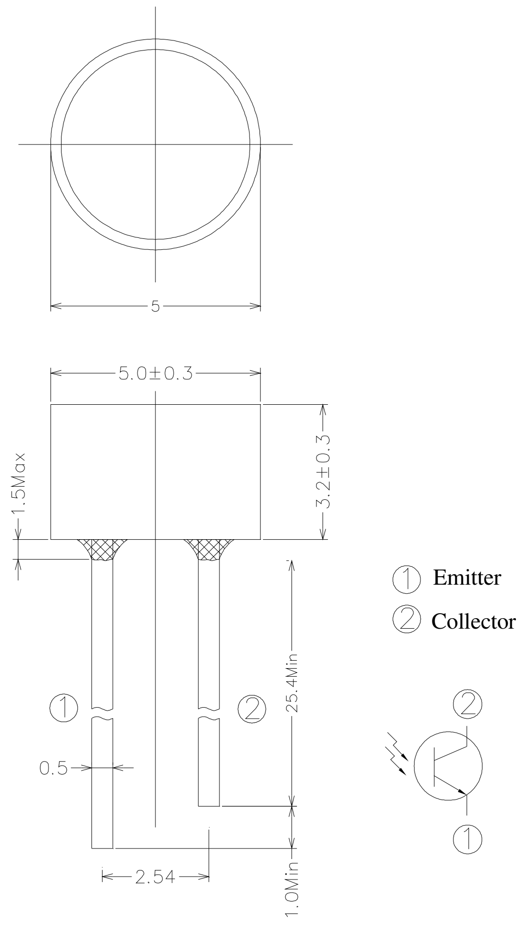
The ALS-PT243-3C/L177 is consisting of phototransistor in DIP package. EVERLIGHT ALS series product are a good effective solution to the power saving of display backlighting of mobile appliances, such as the mobile phones, NB and PDAs. Due to the high rejection ratio of infrared radiation, the spectral response of the ambient light sensor is close to human eyes.

Applications

- Detection of ambient light to control display backlighting
  - Mobile devices – mobile phones, PDAs
  - Computing device – TFT LCD monitor for Notebook computer
  - Consumer device – TFT LCD TV, video camera, digital camera, toys

- Automatic residential and commercial management
- Automatic contrast enhancement for electronic signboard
- Ambient light monitoring device for daylight and artificial light
  – Street light, CCD/CCTV

Package Dimensions



Notes: 1.All dimensions are in millimeters
2.Tolerances unless dimensions ±0.1mm

Absolute Maximum Ratings (Ta=25℃)

Parameter	Symbol	Rating	Unit
Supply Voltage	Vcc	-0.5~6.0	V
Operating Temperature Range	Topr	-40 ~ +85	°C
Storage Temperature Range	Tstg	-40 ~ +100	°C
Soldering Temperature Range [Note1]	T_{sol}	260 ± 10	°C

Note1: For detail reflow time and the recommended temperature profile, please refer to page 8.

Recommended Operating Conditions (Ta=25℃)

Parameter	Symbol	Min.	Max.	Unit
Operating Temperature	Topr	-40	+85	°C
Supply Voltage	Vcc	2.5	5.5	V

Rankings

Bin	Symbol	Min	Max	Unit	Test Condition
1	$I_{C(ON)}$	5	12	μA	V_{CE}=5V Ee=100Lux
2		12	17		
3		17	23		

Electrical and Optical Characteristics (Ta=25℃)

Parameter	Symbol	MIN	TYP	MAX.	Unit	Test Condition
Dark Current	I_{CEO}	---	---	0.1	uA	V_{CE}=10V, Ev= 0Lux
Collector-Emitter Saturation Voltage	$V_{CE(sat)}$	---	---	0.4	V	I_C=2mA, Ev= 1000Lux
Light Current	I_{PH1}	7	10	---	uA	V_{CE}=5V, Ev= 100Lux [Note1]
	I_{PH2}	200	230	---	uA	V_{CE}=5V, Ev= 1000Lux [Note1]
	I_{PH3}	950	1100	---	uA	V_{CE}=5V, Ev= 1000Lux [Note2]
Photocurrent Ratio	I_{PH3} / I_{PH2}	---	4.8	---	---	V_{CE}=5V, Ev= 1000Lux
Saturation Output Voltage	Vo	4.5	4.6	---	V	Vcc=5V, Ev= 1000Lux R_L=75K [Note2]
Peak Sensitivity Wavelength	λ_p	---	630	---	nm	
Sensitivity Wavelength Range	λ	390	---	700	nm	
Rise time	tr	---	0.11	---	ms	V_{CC} = 5 V R_L = 7.5KΩ
Fall time	tf	---	0.22	---	ms	
Angle of half Sensitivity	$2\theta_{1/2}$	---	143	---	Deg.	I_F = 20 mA

Note:
1. White Fluorescent light (Color Temperature = 6500K) is used as light source. However, White LED is substituted in mass production.
2. Illuminance by CIE standard illuminant-A / 2856K, incandescent lamp.

Typical Electrical and Optical Characteristics Curves

Fig.1 Light Current vs. Illuminance

(typ.)

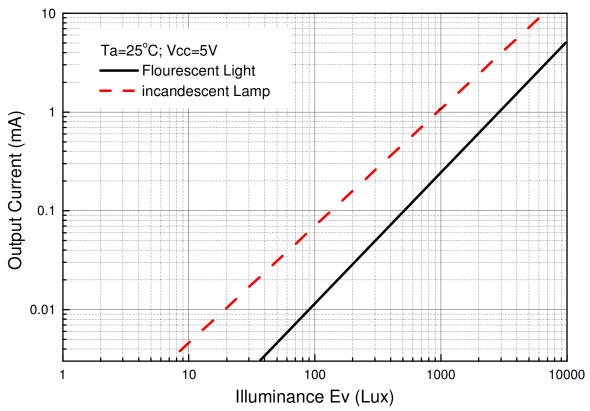


Fig.2 Output Voltage vs. Illuminance

(typ.)

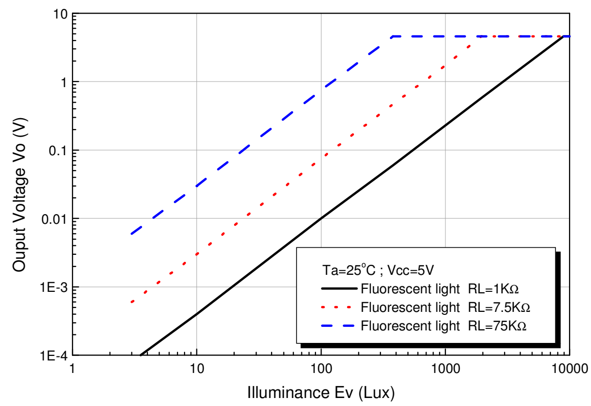


Fig.3 Spectral Response

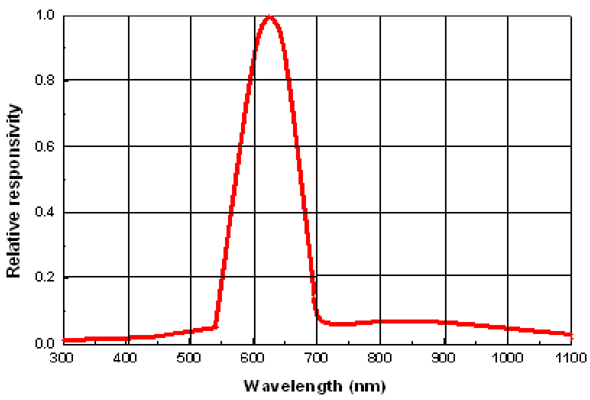


Fig.4 Light current vs. Supply Voltage

(typ.)

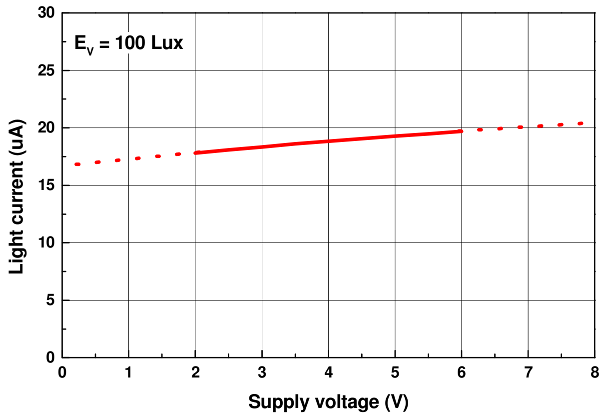


Fig.5 Light Current vs. Temperature

(typ.)

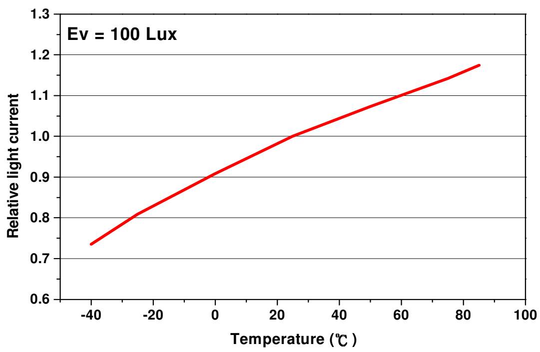
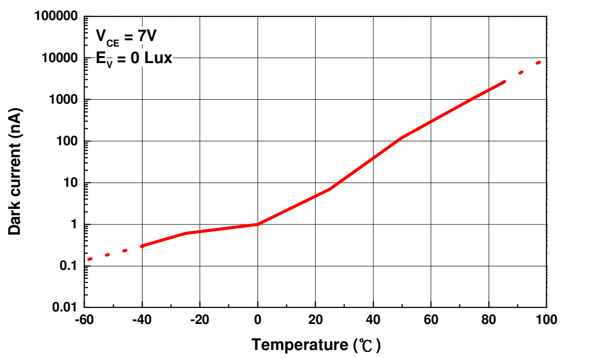
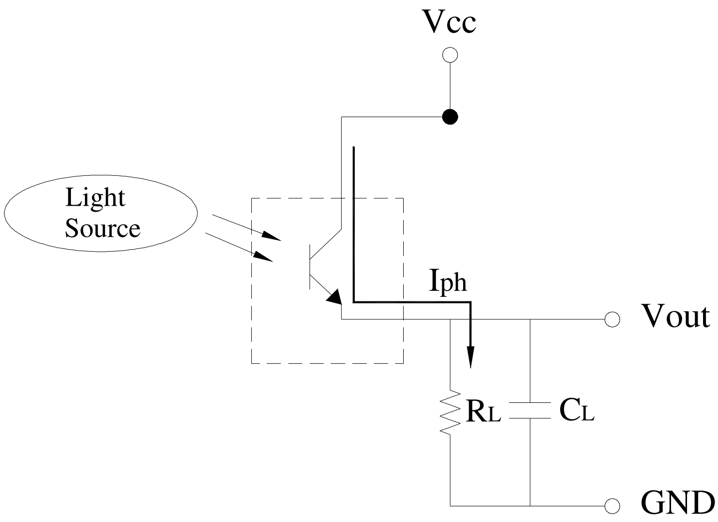


Fig.6 Dark Current vs. Temperature

(typ.)



Converting Photocurrent to Voltage



Note:

1. The output voltage (Vout) is the product of photocurrent (IPH) and loading resistor (RL)
2. A right loading resistor shall be chosen to meet the requirement of maximum ambient light, and output saturation voltage:

$$V_{out}(max.) = I_{out}(max.) \times R_L \leqq V_{out}(saturation) = V_{cc} - 0.4V$$

Recommended method of storage

Reflow Terms: JEDEC Level 4 Specification

Dry box storage is recommended as soon as the aluminum bag has been opened prevent

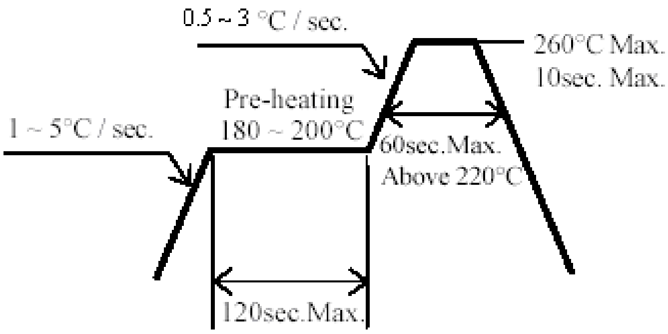
1. Over-current-proof
   Customer must apply resistors for protection, otherwise slight voltage shift might cause big current happen. (Burned-out might happen).

2. Storage
   (1) Do not open moisture proof bag before components are ready to use.
   (2) Before opening moisture proof bag, components should be kept at 30℃ or less and 90%RH or less.
   (3) Components should be used within a year.
   (4) After opened moisture proof bag, components should be kept at 30℃ or less and 70%RH or less.
   (5) Components should be used within 168 hours after opened moisture proof bag.
   (6) If the moisture absorbent material (silica gel) has faded away or the components have exceeded the storage time, baking treatment should be performed using the following conditions. (Baking treatment: 60±5℃ for 24 hours)

ESD Precaution:

Proper storage and handing procedures should be followed to prevent ESD damage to the devices especially when they are removed from the Anti-static bag. Electro-Static Sensitive Devices warning labels are on the packing.

Recommended Solder Profile



Notice:

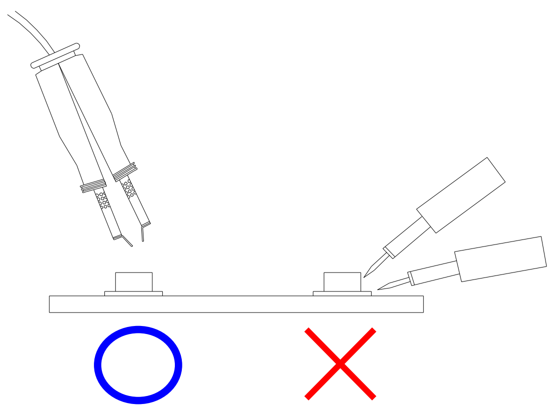
(1) Reflow soldering should not be done more than two times.
(2) When soldering, do not put stress on the devices during heating.
(3) After soldering, do not warp the circuit board.

Soldering Iron

Each terminal is to go to the tip of soldering iron temperature less than 350℃ for 3 seconds within once in less than the soldering iron capacity 25W. Leave two seconds and more intervals, and do soldering of each terminal. Be careful because the damage of the product is often started at the time of the hand solder.

Repairing

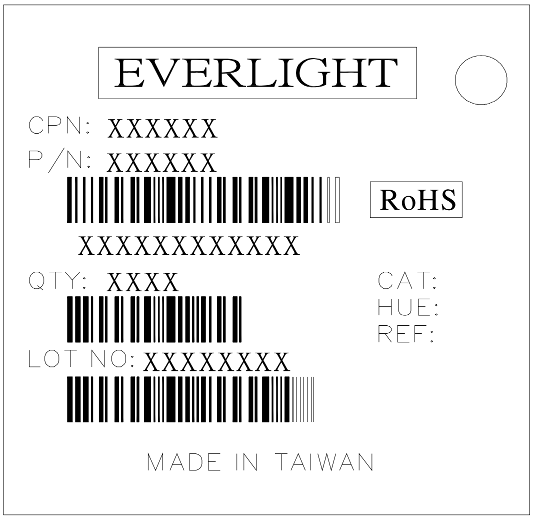
Repair should not be done after the device have been soldered. When repairing is unavoidable, a double-head soldering iron should be used (as below figure). It should be confirmed beforehand whether the characteristics of the device will or will not be damaged by repairing.



Packing Quantity Specification

1.500PCS/1Bag，5Bags/1Box
2.10Boxes/1Carton

Label Format



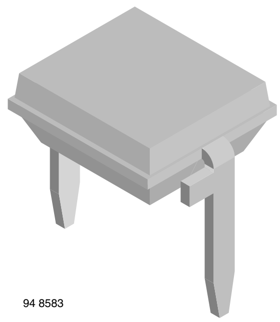
Notes

1. Above specification may be changed without notice. EVERLIGHT will reserve authority on material change for above specification.

2. When using this product, please observe the absolute maximum ratings and the instructions for using outlined in these specification sheets. EVERLIGHT assumes no responsibility for any damage resulting from use of the product which does not comply with the absolute maximum ratings and instructions included in these specification sheets.

3. These specification sheets include materials protected under copyright of EVERLIGHT corporation. Please don't reproduce or cause anyone to reproduce them without EVERLIGHT's consent.

Silicon PIN Photodiode



FEATURES

- Package type: leaded
- Package form: top view
- Dimensions (L x W x H in mm): 5.4 x 4.3 x 3.2
- Radiant sensitive area (in mm^2): 7.5
- High photo sensitivity
- High radiant sensitivity
- Suitable for visible and near infrared radiation
- Fast response times
- Angle of half sensitivity: $\varphi = \pm 65°$
- Compliant to RoHS Directive 2002/95/EC and in accordance to WEEE 2002/96/EC

Pb-free
e3
RoHS COMPLIANT
GREEN (5-2008)**

Note

** Please see document "Vishay Material Category Policy": www.vishay.com/doc?99902

DESCRIPTION

BPW34 is a PIN photodiode with high speed and high radiant sensitivity in miniature, flat, top view, clear plastic package. It is sensitive to visible and near infrared radiation. BPW34S is packed in tubes, specifications like BPW34.

APPLICATIONS

- High speed photo detector

PRODUCT SUMMARY			
COMPONENT	**I_{ra} (μA)**	**φ (deg)**	**$\lambda_{0.1}$ (nm)**
BPW34	50	± 65	430 to 1100
BPW34S	50	± 65	430 to 1100

Note

- Test condition see table "Basic Characteristics"

ORDERING INFORMATION			
ORDERING CODE	**PACKAGING**	**REMARKS**	**PACKAGE FORM**
BPW34	Bulk	MOQ: 3000 pcs, 3000 pcs/bulk	Top view
BPW34S	Tube	MOQ: 1800 pcs, 45 pcs/tube	Top view

Note

- MOQ: minimum order quantity

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)				
PARAMETER	**TEST CONDITION**	**SYMBOL**	**VALUE**	**UNIT**
Reverse voltage		V_R	60	V
Power dissipation	$T_{amb} \leq 25$ °C	P_V	215	mW
Junction temperature		T_j	100	°C
Operating temperature range		T_{amb}	- 40 to + 100	°C
Storage temperature range		T_{stg}	- 40 to + 100	°C
Soldering temperature	$t \leq 3$ s	T_{sd}	260	°C
Thermal resistance junction/ambient	Connected with Cu wire, 0.14 mm^2	R_{thJA}	350	K/W

BASIC CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	**TEST CONDITION**	**SYMBOL**	**MIN.**	**TYP.**	**MAX.**	**UNIT**
Breakdown voltage	I_R = 100 μA, E = 0	$V_{(BR)}$	60			V
Reverse dark current	V_R = 10 V, E = 0	I_{ro}		2	30	nA
Diode capacitance	V_R = 0 V, f = 1 MHz, E = 0	C_D		70		pF
	V_R = 3 V, f = 1 MHz, E = 0	C_D		25	40	pF
Open circuit voltage	E_e = 1 mW/cm², λ = 950 nm	V_o		350		mV
Temperature coefficient of V_o	E_e = 1 mW/cm², λ = 950 nm	TK_{Vo}		- 2.6		mV/K
Short circuit current	E_A = 1 klx	I_k		70		μA
	E_e = 1 mW/cm², λ = 950 nm	I_k		47		μA
Temperature coefficient of I_k	E_e = 1 mW/cm², λ = 950 nm	TK_{Ik}		0.1		%/K
Reverse light current	E_A = 1 klx, V_R = 5 V	I_{ra}		75		μA
	E_e = 1 mW/cm², λ = 950 nm, V_R = 5 V	I_{ra}	40	50		μA
Angle of half sensitivity		φ		± 65		deg
Wavelength of peak sensitivity		$λ_p$		900		nm
Range of spectral bandwidth		$λ_{0.1}$		430 to 1100		nm
Noise equivalent power	V_R = 10 V, λ = 950 nm	NEP		4 x 10^{-14}		W/√Hz
Rise time	V_R = 10 V, R_L = 1 kΩ, λ = 820 nm	t_r		100		ns
Fall time	V_R = 10 V, R_L = 1 kΩ, λ = 820 nm	t_f		100		ns

BASIC CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)

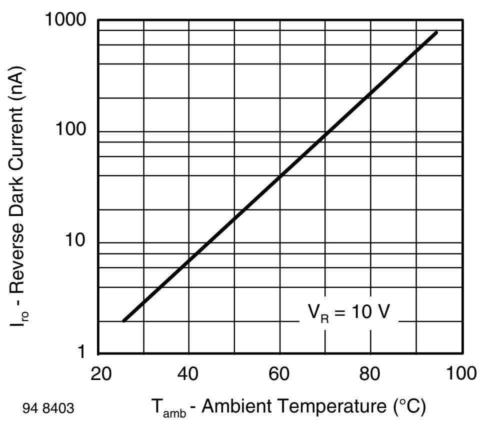


Fig. 1 - Reverse Dark Current vs. Ambient Temperature

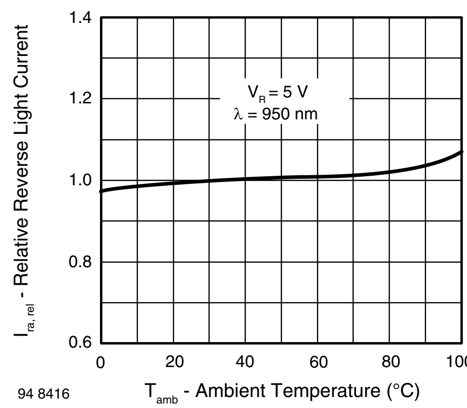


Fig. 2 - Relative Reverse Light Current vs. Ambient Temperature

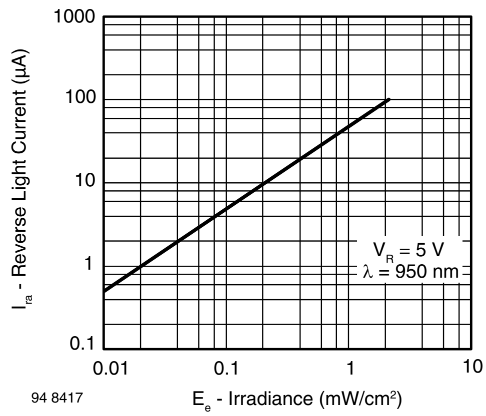


Fig. 3 - Reverse Light Current vs. Irradiance

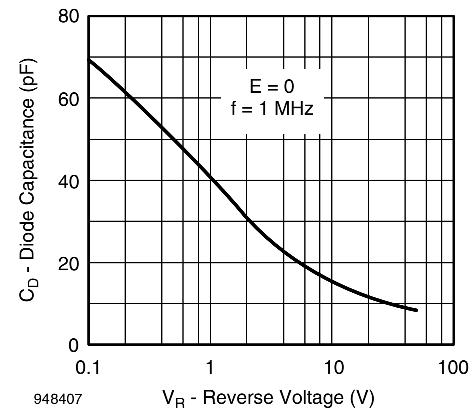


Fig. 6 - Diode Capacitance vs. Reverse Voltage

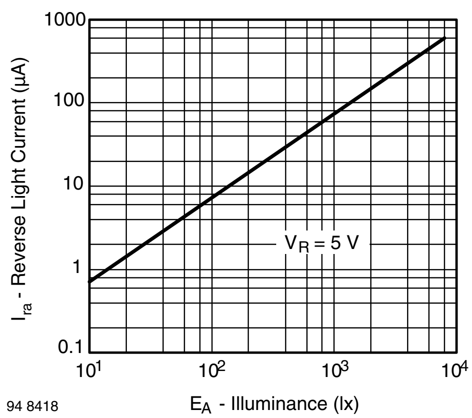


Fig. 4 - Reverse Light Current vs. Illuminance

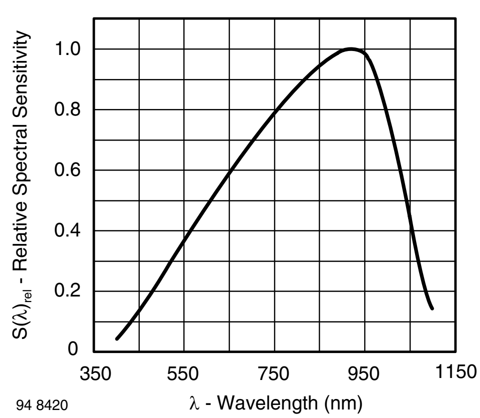


Fig. 7 - Relative Spectral Sensitivity vs. Wavelength

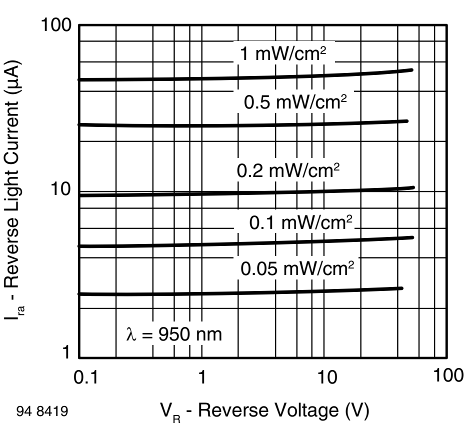


Fig. 5 - Reverse Light Current vs. Reverse Voltage

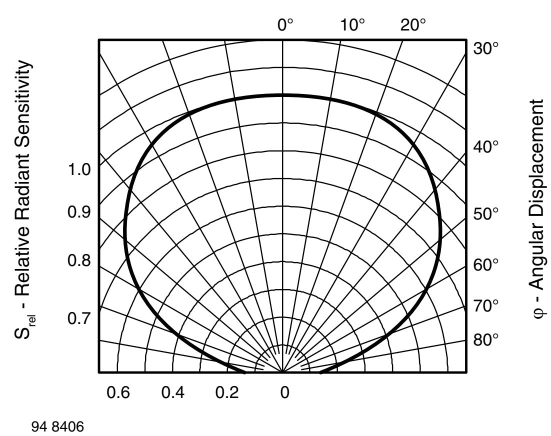
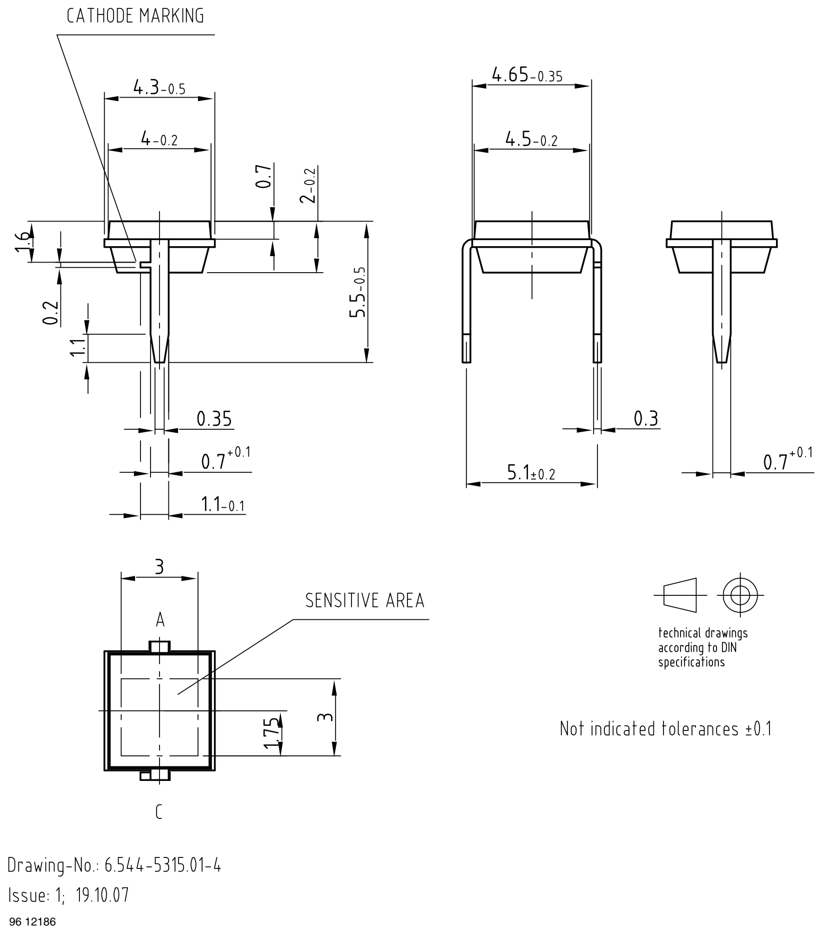


Fig. 8 - Relative Radiant Sensitivity vs. Angular Displacement

PACKAGE DIMENSIONS in millimeters



TUBE PACKAGING DIMENSIONS in millimeters

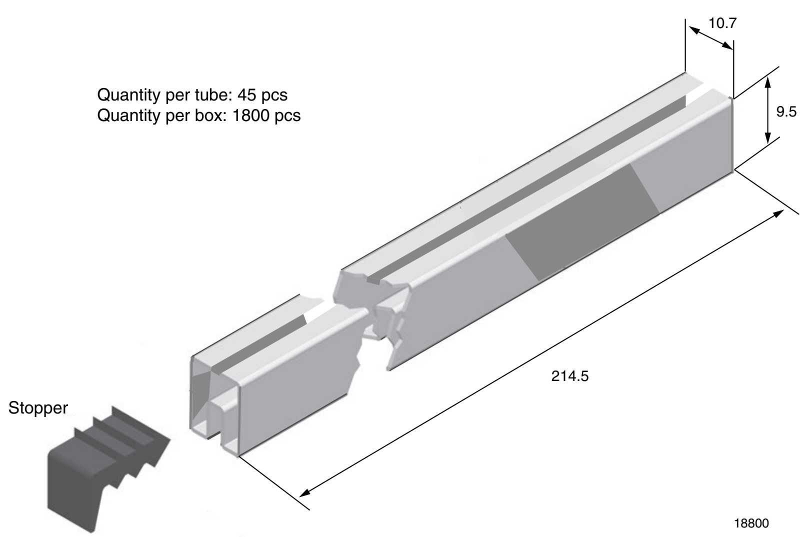


Fig. 9 - Drawing Proportions not scaled

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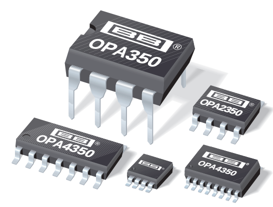
Vishay Intertechnology, Inc. hereby certifies that all its products that are identified as RoHS-Compliant fulfill the definitions and restrictions defined under Directive 2011/65/EU of The European Parliament and of the Council of June 8, 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (EEE) - recast, unless otherwise specified as non-compliant.

Please note that some Vishay documentation may still make reference to RoHS Directive 2002/95/EC. We confirm that all the products identified as being compliant to Directive 2002/95/EC conform to Directive 2011/65/EU.

Vishay Intertechnology, Inc. hereby certifies that all its products that are identified as Halogen-Free follow Halogen-Free requirements as per JEDEC JS709A standards. Please note that some Vishay documentation may still make reference to the IEC 61249-2-21 definition. We confirm that all the products identified as being compliant to IEC 61249-2-21 conform to JEDEC JS709A standards.

BURR - BROWN®



For most current data sheet and other product information, visit www.burr-brown.com

OPA350
OPA2350
OPA4350

High-Speed, Single-Supply, Rail-to-Rail OPERATIONAL AMPLIFIERS
*Micro**Amplifier*™ Series

FEATURES

- RAIL-TO-RAIL INPUT
- RAIL-TO-RAIL OUTPUT (within 10mV)
- WIDE BANDWIDTH: 38MHz
- HIGH SLEW RATE: 22V/µs
- LOW NOISE: 5nV/√Hz
- LOW THD+NOISE: 0.0006%
- UNITY-GAIN STABLE
- *Micro*SIZE PACKAGES
- SINGLE, DUAL, AND QUAD

APPLICATIONS

- CELL PHONE PA CONTROL LOOPS
- DRIVING A/D CONVERTERS
- VIDEO PROCESSING
- DATA ACQUISITION
- PROCESS CONTROL
- AUDIO PROCESSING
- COMMUNICATIONS
- ACTIVE FILTERS
- TEST EQUIPMENT

DESCRIPTION

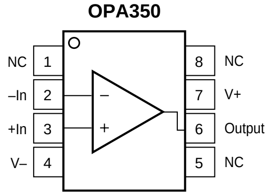
OPA350 series rail-to-rail CMOS operational amplifiers are optimized for low voltage, single-supply operation. Rail-to-rail input/output, low noise (5nV/√Hz), and high speed operation (38MHz, 22V/µs) make them ideal for driving sampling analog-to-digital converters. They are also well suited for cell phone PA control loops and video processing (75Ω drive capability) as well as audio and general purpose applications. Single, dual, and quad versions have identical specifications for maximum design flexibility.

The OPA350 series operates on a single supply as low as 2.5V with an input common-mode voltage range that extends 300mV below ground and 300mV above the positive supply. Output voltage swing is to within 10mV of the supply rails with a 10kΩ load. Dual and quad designs feature completely independent circuitry for lowest crosstalk and freedom from interaction.

The single (OPA350) and dual (OPA2350) come in the miniature MSOP-8 surface mount, SO-8 surface mount, and 8-pin DIP packages. The quad (OPA4350) packages are the space-saving SSOP-16 surface mount and SO-14 surface mount. All are specified from –40°C to +85°C and operate from –55°C to +125°C.

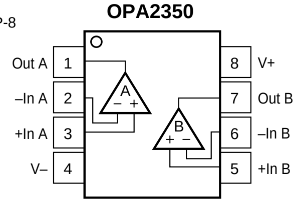
SPICE Model available at www.burr-brown.com

OPA350



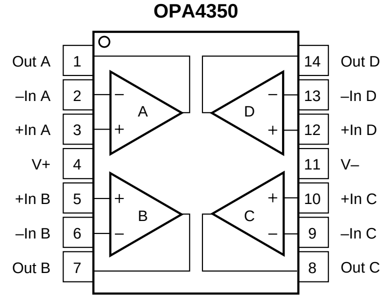
8-Pin DIP, SO-8, MSOP-8

OPA2350



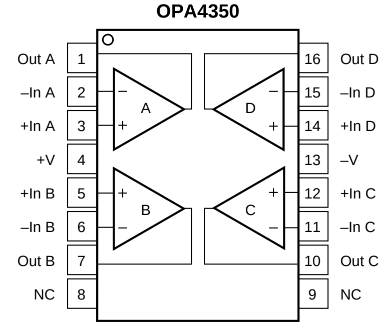
8-Pin DIP, SO-8, MSOP-8

OPA4350



SO-14

OPA4350



SSOP-16

International Airport Industrial Park • Mailing Address: PO Box 11400, Tucson, AZ 85734 • Street Address: 6730 S. Tucson Blvd., Tucson, AZ 85706 • Tel: (520) 746-1111
Twx: 910-952-1111 • Internet: http://www.burr-brown.com/ • Cable: BBRCORP • Telex: 066-6491 • FAX: (520) 889-1510 • Immediate Product Info: (800) 548-6132

PDS-1470B

Printed in U.S.A. March, 1999

SPECIFICATIONS: V_S = 2.7V to 5.5V

At T_A = +25°C, R_L = 1kΩ connected to $V_S/2$ and V_{OUT} = $V_S/2$, unless otherwise noted.
Boldface limits apply over the specified temperature range, T_A = –40°C to +85°C. V_S = 5V.

PARAMETER		CONDITION	OPA350EA, UA, PA OPA2350EA, UA, PA OPA4350EA, UA			UNITS
			MIN	TYP(1)	MAX	
OFFSET VOLTAGE						
Input Offset Voltage	V_{OS}	V_S = 5V		±150	±500	µV
T_A = –40°C to +85°C					**±1**	mV
vs Temperature		**T_A = –40°C to +85°C**		**±4**		µV/°C
vs Power Supply Rejection Ratio	PSRR	V_S = 2.7V to 5.5V, V_{CM} = 0V		40	150	µV/V
T_A = –40°C to +85°C		**V_S = 2.7V to 5.5V, V_{CM} = 0V**			**175**	µV/V
Channel Separation (dual, quad)		dc		0.15		µV/V
INPUT BIAS CURRENT						
Input Bias Current	I_B			±0.5	±10	pA
vs Temperature			See Typical Performance Curve			
Input Offset Current	I_{OS}			±0.5	±10	pA
NOISE						
Input Voltage Noise, f = 100Hz to 400kHz				4		µVrms
Input Voltage Noise Density, f = 10kHz	e_n			7		nV/√Hz
f = 100kHz				5		nV/√Hz
Current Noise Density, f = 10kHz	i_n			4		fA/√Hz
INPUT VOLTAGE RANGE						
Common-Mode Voltage Range	V_{CM}	**T_A = –40°C to +85°C**	**–0.1**		**(V+)+0.1**	V
Common-Mode Rejection Ratio	CMRR	V_S = 2.7V, –0.1V < V_{CM} < 2.8V	66	84		dB
		V_S = 5.5V, –0.1V < V_{CM} < 5.6V	76	90		dB
T_A = –40°C to +85°C		**V_S = 5.5V, –0.1V < V_{CM} < 5.6V**	**74**			dB
INPUT IMPEDANCE						
Differential				10^{13} || 2.5		Ω || pF
Common-Mode				10^{13} || 6.5		Ω || pF
OPEN-LOOP GAIN						
Open-Loop Voltage Gain	A_{OL}	R_L = 10kΩ, 50mV < V_O < (V+) –50mV	100	122		dB
T_A = –40°C to +85°C		**R_L = 10kΩ, 50mV < V_O < (V+) –50mV**	**100**			dB
		R_L = 1kΩ, 200mV < V_O < (V+) –200mV	100	120		dB
T_A = –40°C to +85°C		**R_L = 1kΩ, 200mV < V_O < (V+) –200mV**	**100**			dB
FREQUENCY RESPONSE		C_L = 100pF				
Gain-Bandwidth Product	GBW	G = 1		38		MHz
Slew Rate	SR	G = 1		22		V/µs
Settling Time, 0.1%		G = ±1, 2V Step		0.22		µs
0.01%		G = ±1, 2V Step		0.5		µs
Overload Recovery Time		V_{IN} • G = V_S		0.1		µs
Total Harmonic Distortion + Noise	THD+N	R_L = 600Ω, V_O = 2.5Vp-p(2), G = 1, f = 1kHz		0.0006		%
Differential Gain Error		G = 2, R_L = 600Ω, V_O = 1.4V(3)		0.17		%
Differential Phase Error		G = 2, R_L = 600Ω, V_O = 1.4V(3)		0.17		deg
OUTPUT						
Voltage Output Swing from Rail(4)	V_{OUT}	R_L = 10kΩ, A_{OL} ≥ 100dB		10	50	mV
T_A = –40°C to +85°C		**R_L = 10kΩ, A_{OL} ≥ 100dB**			**50**	mV
		R_L = 1kΩ, A_{OL} ≥ 100dB		25	200	mV
T_A = –40°C to +85°C		**R_L = 1kΩ, A_{OL} ≥ 100dB**			**200**	mV
Output Current	I_{OUT}			±40(5)		mA
Short-Circuit Current	I_{SC}			±80		mA
Capacitive Load Drive	C_{LOAD}		See Typical Curve			
POWER SUPPLY						
Operating Voltage Range	V_S	**T_A = –40°C to +85°C**	**2.7**		**5.5**	V
Minimum Operating Voltage				2.5		V
Quiescent Current (per amplifier)	I_Q	I_O = 0		5.2	7.5	mA
T_A = –40°C to +85°C		I_O = 0			**8.5**	mA
TEMPERATURE RANGE						
Specified Range			–40		+85	°C
Operating Range			–55		+125	°C
Storage Range			–55		+125	°C
Thermal Resistance	θ_{JA}					
MSOP-8 Surface Mount				150		°C/W
SO-8 Surface Mount				150		°C/W
8-Pin DIP				100		°C/W
SO-14 Surface Mount				100		°C/W
SSOP-16 Surface Mount				100		°C/W

NOTES: (1) V_S = +5V. (2) V_{OUT} = 0.25V to 2.75V. (3) NTSC signal generator used. See Figure 6 for test circuit. (4) Output voltage swings are measured between the output and power supply rails. (5) See typical performance curve, “Output Voltage Swing vs Output Current.”

ABSOLUTE MAXIMUM RATINGS[1]

Supply Voltage	5.5V
Signal Input Terminals, Voltage[2]	(V–) – 0.3V to (V+) + 0.3V
Current[2]	10mA
Output Short Circuit[3]	Continuous
Operating Temperature	–55°C to +125°C
Storage Temperature	–55°C to +125°C
Junction Temperature	150°C
Lead Temperature (soldering, 10s)	300°C

NOTES: (1) Stresses above these ratings may cause permanent damage. Exposure to absolute maximum conditions for extended periods may degrade device reliability. (2) Input terminals are diode-clamped to the power supply rails. Input signals that can swing more than 0.3V beyond the supply rails should be current-limited to 10mA or less. (3) Short circuit to ground, one amplifier per package.

ELECTROSTATIC DISCHARGE SENSITIVITY

This integrated circuit can be damaged by ESD. Burr-Brown recommends that all integrated circuits be handled with appropriate precautions. Failure to observe proper handling and installation procedures can cause damage.

ESD damage can range from subtle performance degradation to complete device failure. Precision integrated circuits may be more susceptible to damage because very small parametric changes could cause the device not to meet its published specifications.

PACKAGE/ORDERING INFORMATION

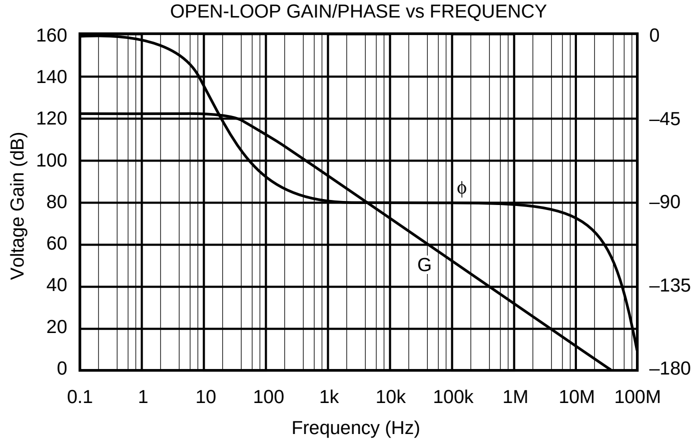
PRODUCT	PACKAGE	PACKAGE DRAWING NUMBER[1]	SPECIFIED TEMPERATURE RANGE	PACKAGE MARKING	ORDERING NUMBER[2]	TRANSPORT MEDIA
Single						
OPA350EA	MSOP-8 Surface Mount	337	–40°C to +85°C	C50	OPA350EA/250	Tape and Reel
"	"	"	"	"	OPA350EA/2K5	Tape and Reel
OPA350UA	SO-8 Surface-Mount	182	–40°C to +85°C	OPA350UA	OPA350UA	Rails
"	"	"	"	"	OPA350UA/2K5	Tape and Reel
OPA350PA	8-Pin DIP	006	–40°C to +85°C	OPA350PA	OPA350PA	Rails
Dual						
OPA2350EA	MSOP-8 Surface-Mount	337	–40°C to +85°C	D50	OPA2350EA/250	Tape and Reel
"	"	"	"	"	OPA2350EA/2K5	Tape and Reel
OPA2350UA	SO-8 Surface-Mount	182	–40°C to +85°C	OPA2350UA	OPA2350UA	Rails
"	"	"	"	"	OPA2350UA/2K5	Tape and Reel
OPA2350PA	8-Pin DIP	006	–40°C to +85°C	OPA2350PA	OPA2350PA	Rails
Quad						
OPA4350EA	SSOP-16 Surface-Mount	322	–40°C to +85°C	OPA4350EA	OPA4350EA/250	Tape and Reel
"	"	"	"	"	OPA4350EA/2K5	Tape and Reel
OPA4350UA	SO-14 Surface Mount	235	–40°C to +85°C	OPA4350UA	OPA4350UA	Rails
"	"	"	"	"	OPA4350UA/2K5	Tape and Reel

NOTES: (1) For detailed drawing and dimension table, please see end of data sheet, or Appendix C of Burr-Brown IC Data Book. (2) Models with a slash (/) are available only in Tape and Reel in the quantities indicated (e.g., /2K5 indicates 2500 devices per reel). Ordering 2500 pieces of “OPA2350EA/2K5” will get a single 2500-piece Tape and Reel. For detailed Tape and Reel mechanical information, refer to Appendix B of Burr-Brown IC Data Book.

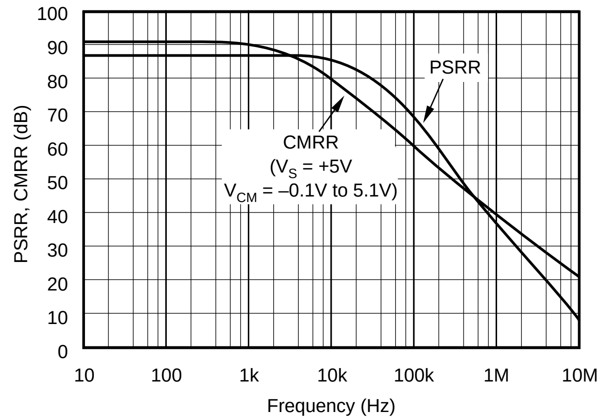
TYPICAL PERFORMANCE CURVES

At $T_A = +25°C$, $V_S = +5V$, and $R_L = 1k\Omega$ connected to $V_S/2$, unless otherwise noted.

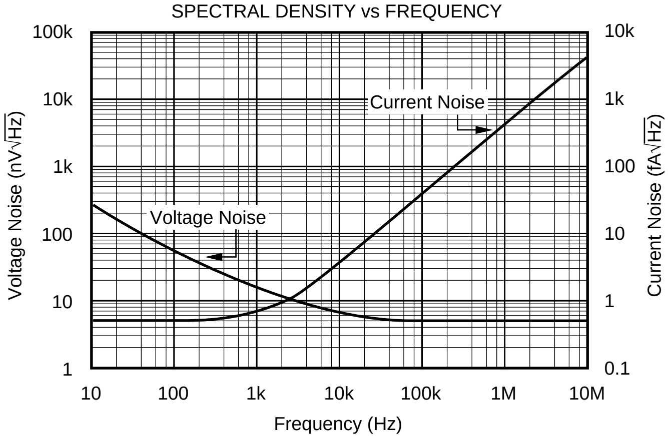
OPEN-LOOP GAIN/PHASE vs FREQUENCY



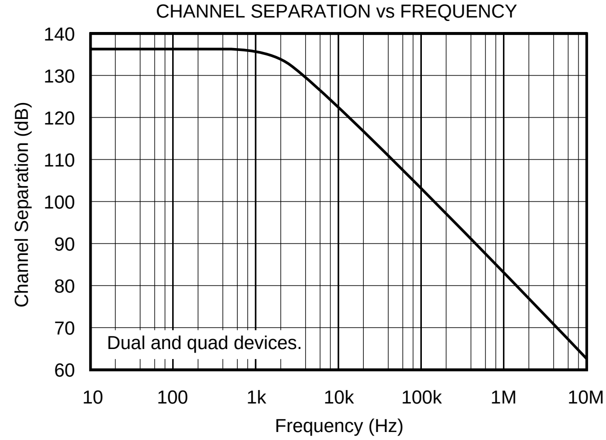
POWER SUPPLY AND COMMON-MODE REJECTION RATIO vs FREQUENCY



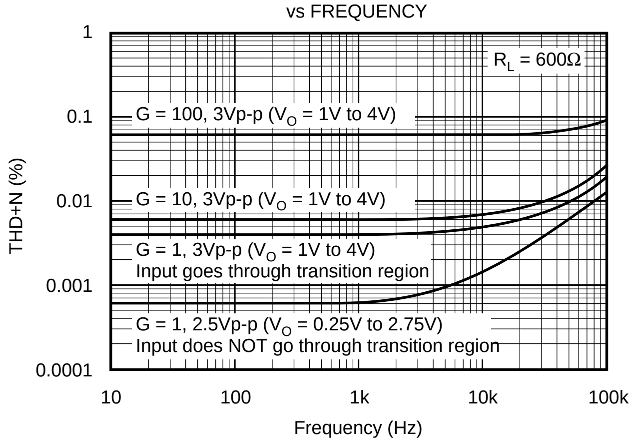
INPUT VOLTAGE AND CURRENT NOISE SPECTRAL DENSITY vs FREQUENCY



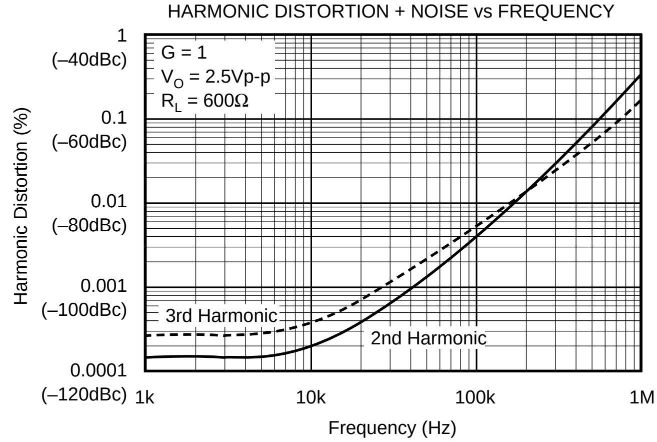
CHANNEL SEPARATION vs FREQUENCY



TOTAL HARMONIC DISTORTION + NOISE vs FREQUENCY



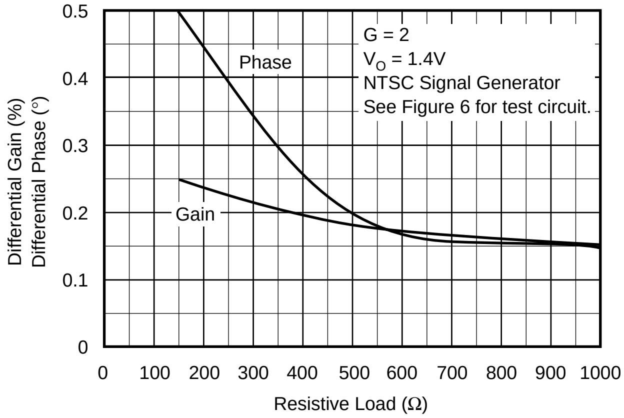
HARMONIC DISTORTION + NOISE vs FREQUENCY



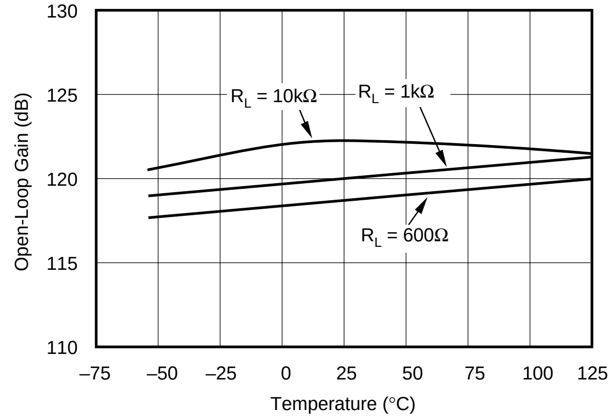
TYPICAL PERFORMANCE CURVES (CONT)

At $T_A = +25°C$, $V_S = +5V$, and $R_L = 1k\Omega$ connected to $V_S/2$, unless otherwise noted.

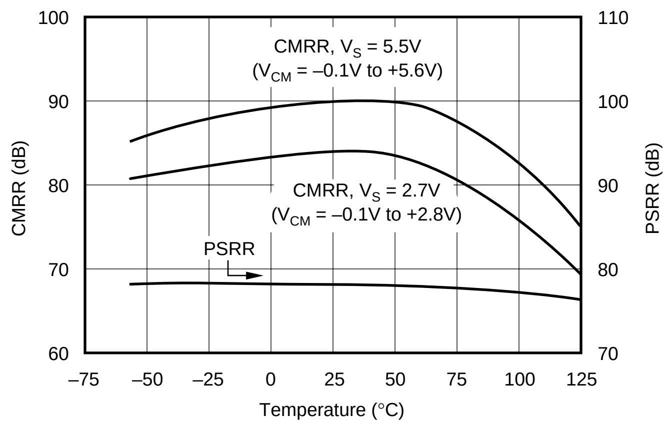
DIFFERENTIAL GAIN/PHASE vs RESISTIVE LOAD



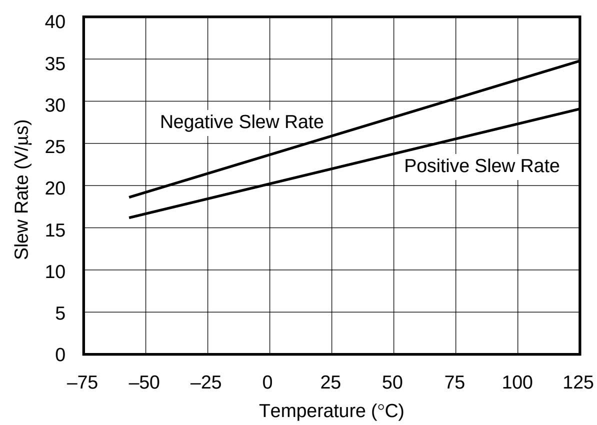
OPEN-LOOP GAIN vs TEMPERATURE



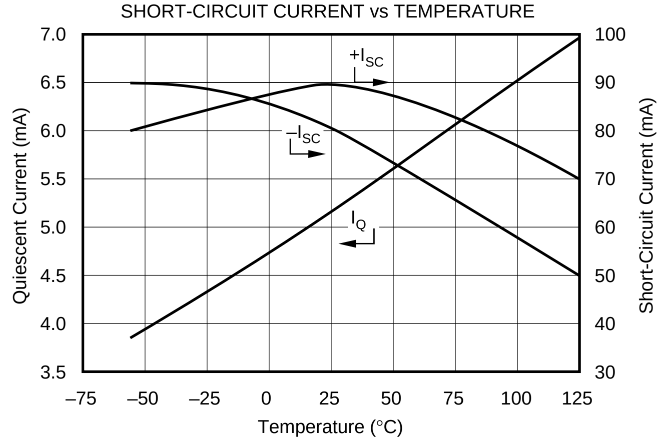
COMMON-MODE AND POWER SUPPLY REJECTION RATIO vs TEMPERATURE



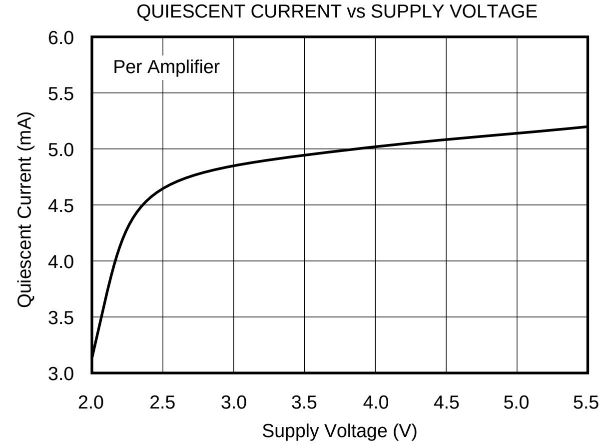
SLEW RATE vs TEMPERATURE



QUIESCENT CURRENT AND SHORT-CIRCUIT CURRENT vs TEMPERATURE

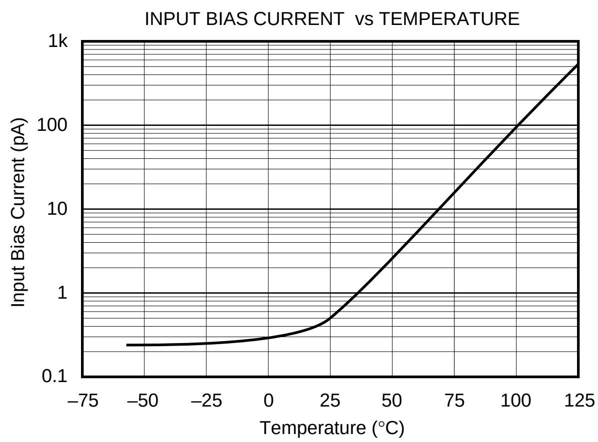


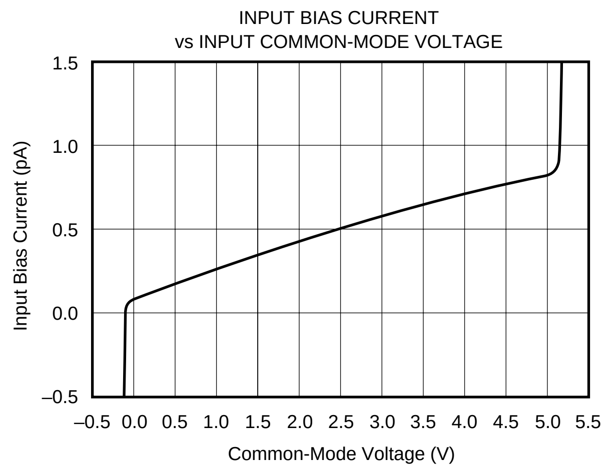
QUIESCENT CURRENT vs SUPPLY VOLTAGE

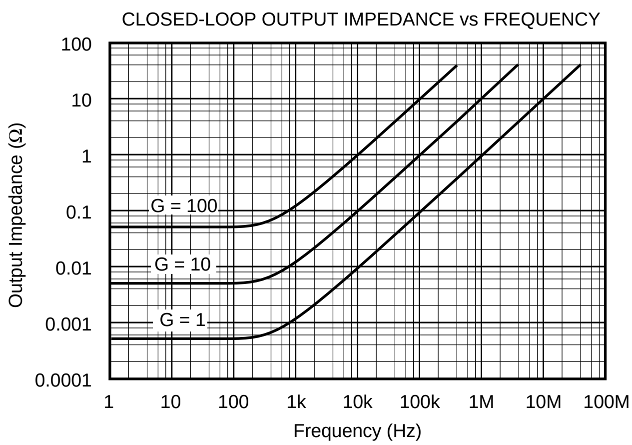


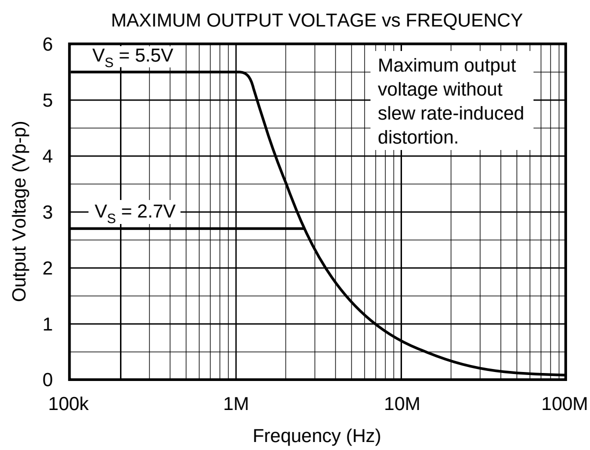
TYPICAL PERFORMANCE CURVES (CONT)

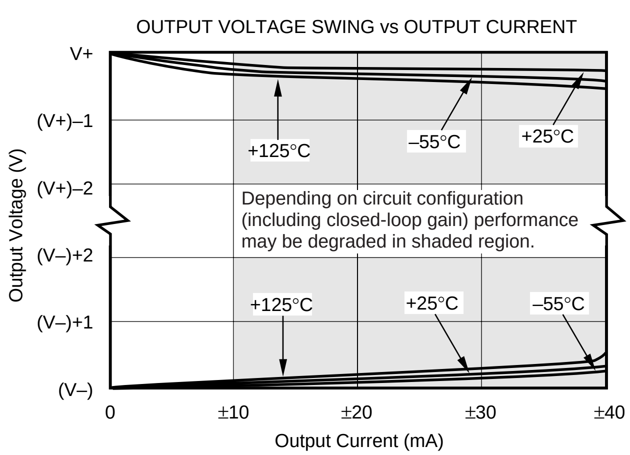
At T_A = +25°C, V_S = +5V, and R_L = 1kΩ connected to V_S/2, unless otherwise noted.

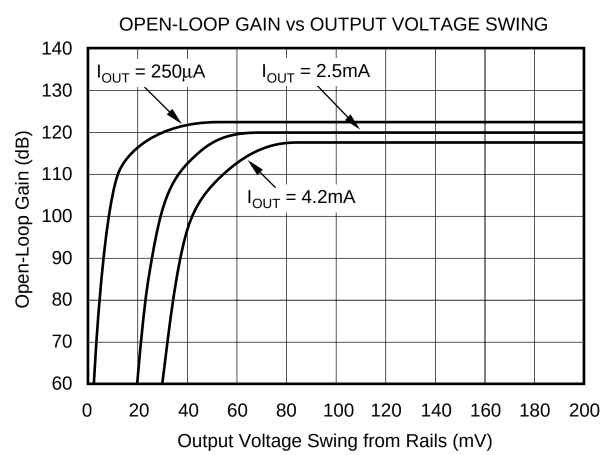








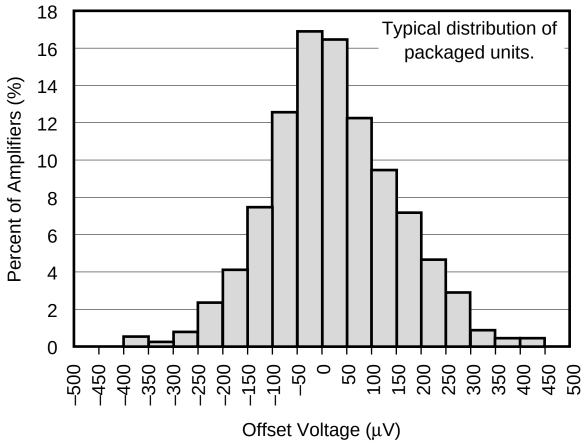




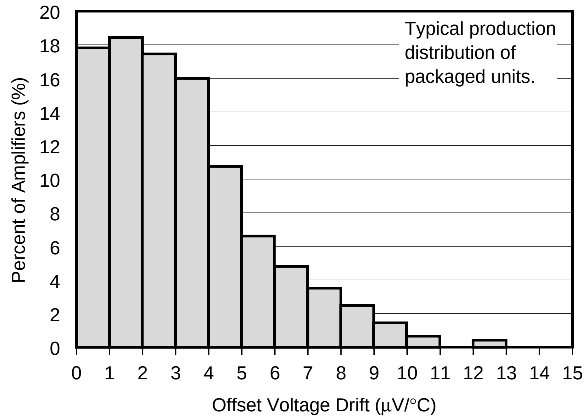
TYPICAL PERFORMANCE CURVES (CONT)

At T_A = +25°C, V_S = +5V, and R_L = 1kΩ connected to $V_S/2$, unless otherwise noted.

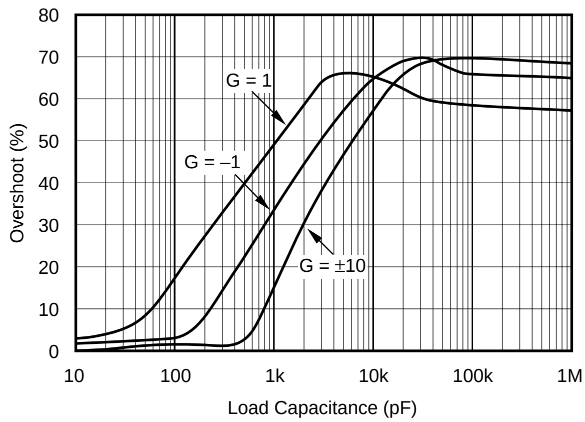
OFFSET VOLTAGE PRODUCTION DISTRIBUTION



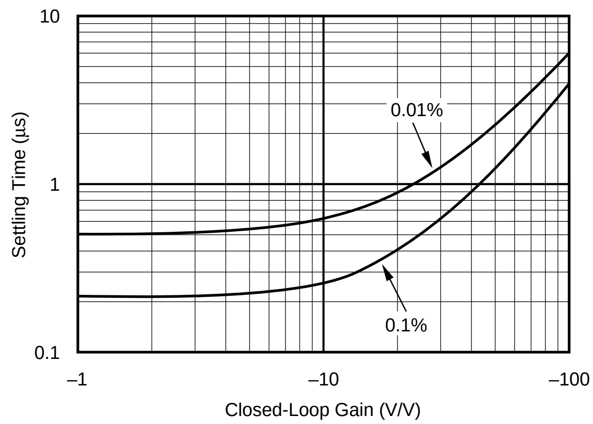
OFFSET VOLTAGE DRIFT PRODUCTION DISTRIBUTION



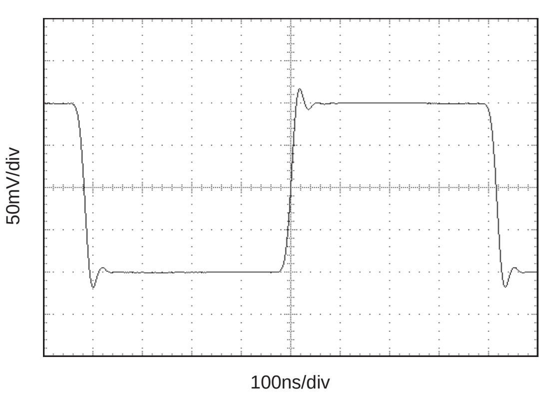
SMALL-SIGNAL OVERSHOOT vs LOAD CAPACITANCE



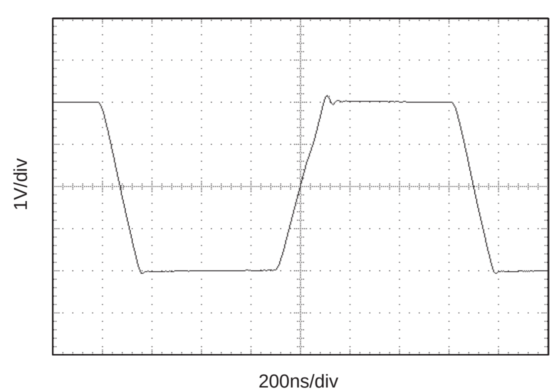
SETTLING TIME vs CLOSED-LOOP GAIN



SMALL-SIGNAL STEP RESPONSE
C_L = 100pF



LARGE-SIGNAL STEP RESPONSE
C_L = 100pF



APPLICATIONS INFORMATION

OPA350 series op amps are fabricated on a state-of-the-art 0.6 micron CMOS process. They are unity-gain stable and suitable for a wide range of general purpose applications. Rail-to-rail input/output make them ideal for driving sampling A/D converters. They are also well suited for controlling the output power in cell phones. These applications often require high speed and low noise. In addition, the OPA350 series offers a low cost solution for general purpose and consumer video applications (75Ω drive capability).

Excellent ac performance makes the OPA350 series well suited for audio applications. Their bandwidth, slew rate, low noise ($5nV/\sqrt{Hz}$), low THD (0.0006%), and small package options are ideal for these applications. The class AB output stage is capable of driving 600Ω loads connected to any point between V+ and ground.

Rail-to-rail input and output swing significantly increases dynamic range, especially in low voltage supply applications. Figure 1 shows the input and output waveforms for the OPA350 in unity-gain configuration. Operation is from a single +5V supply with a 1kΩ load connected to $V_S/2$. The input is a 5Vp-p sinusoid. Output voltage swing is approximately 4.95Vp-p.

Power supply pins should be bypassed with 0.01µF ceramic capacitors.

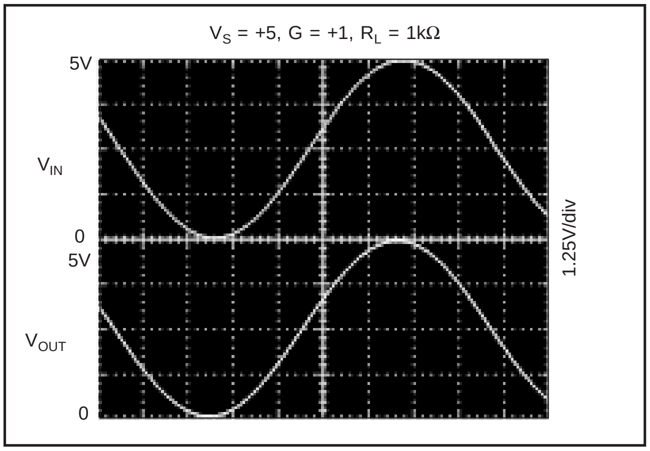


FIGURE 1. Rail-to-Rail Input and Output.

OPERATING VOLTAGE

OPA350 series op amps are fully specified from +2.7V to +5.5V. However, supply voltage may range from +2.5V to +5.5V. Parameters are guaranteed over the specified supply range—a unique feature of the OPA350 series. In addition, many specifications apply from –40°C to +85°C. Most behavior remains virtually unchanged throughout the full operating voltage range. Parameters which vary significantly with operating voltage or temperature are shown in the typical performance curves.

RAIL-TO-RAIL INPUT

The guaranteed input common-mode voltage range of the OPA350 series extends 100mV beyond the supply rails. This is achieved with a complementary input stage—an N-channel input differential pair in parallel with a P-channel differential pair (see Figure 2). The N-channel pair is active for input voltages close to the positive rail, typically (V+) – 1.8V to 100mV above the positive supply, while the P-channel pair is on for inputs from 100mV below the negative supply to approximately (V+) – 1.8V. There is a small transition region, typically (V+) – 2V to (V+) – 1.6V, in which both pairs are on. This 400mV transition region can vary ±400mV with process variation. Thus, the transition region (both input stages on) can range from (V+) – 2.4V to (V+) – 2.0V on the low end, up to (V+) – 1.6V to (V+) – 1.2V on the high end.

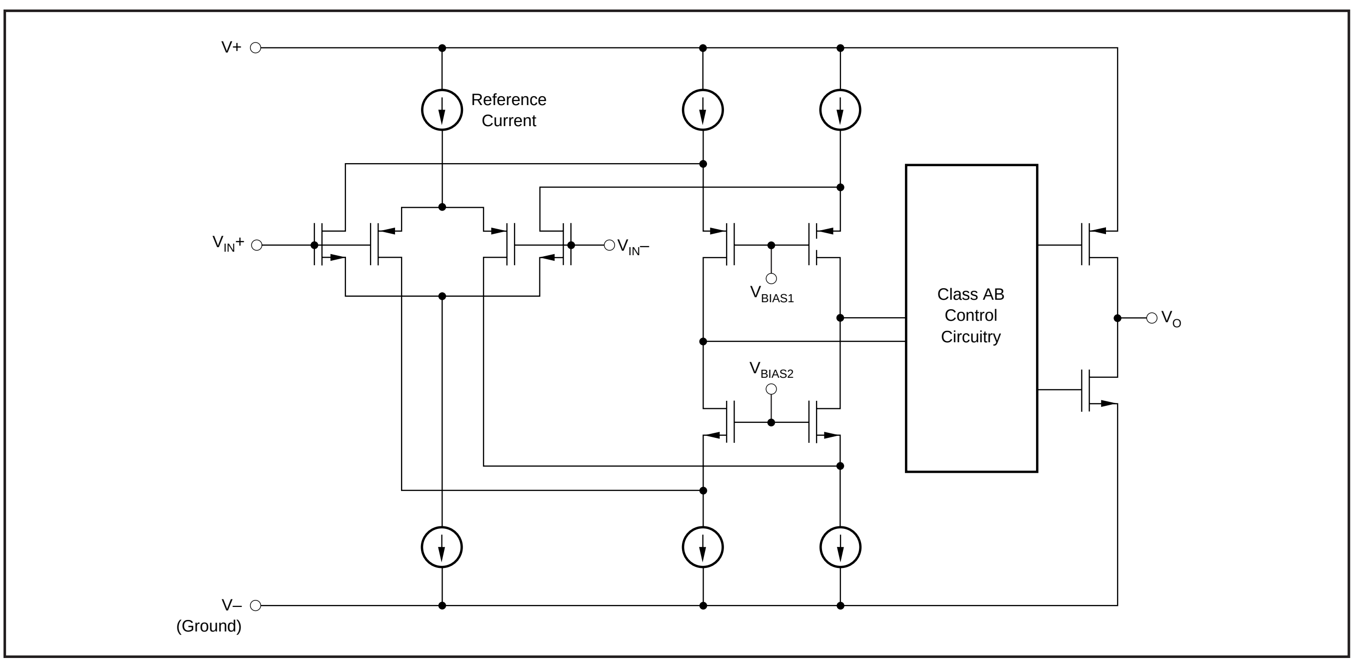


FIGURE 2. Simplified Schematic.

OPA350 series op amps are laser-trimmed to reduce offset voltage difference between the N-channel and P-channel input stages, resulting in improved common-mode rejection and a smooth transition between the N-channel pair and the P-channel pair. However, within the 400mV transition region PSRR, CMRR, offset voltage, offset drift, and THD may be degraded compared to operation outside this region.

A double-folded cascode adds the signal from the two input pairs and presents a differential signal to the class AB output stage. Normally, input bias current is approximately 500fA. However, large inputs (greater than 300mV beyond the supply rails) can turn on the OPA350's input protection diodes, causing excessive current to flow in or out of the input pins. Momentary voltages greater than 300mV beyond the power supply can be tolerated if the current on the input pins is limited to 10mA. This is easily accomplished with an input resistor as shown in Figure 3. Many input signals are inherently current-limited to less than 10mA, therefore, a limiting resistor is not required.

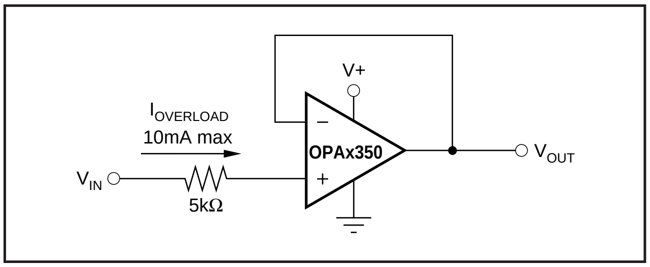


FIGURE 3. Input Current Protection for Voltages Exceeding the Supply Voltage.

RAIL-TO-RAIL OUTPUT

A class AB output stage with common-source transistors is used to achieve rail-to-rail output. For light resistive loads (>10kΩ), the output voltage swing is typically a ten millivolts from the supply rails. With heavier resistive loads (600Ω to 10kΩ), the output can swing to within a few tens of millivolts from the supply rails and maintain high open-loop gain. See the typical performance curves "Output Voltage Swing vs Output Current" and "Open-Loop Gain vs Output Voltage."

CAPACITIVE LOAD AND STABILITY

OPA350 series op amps can drive a wide range of capacitive loads. However, all op amps under certain conditions may become unstable. Op amp configuration, gain, and load value are just a few of the factors to consider when determining stability. An op amp in unity gain configuration is the most susceptible to the effects of capacitive load. The capacitive load reacts with the op amp's output impedance, along with any additional load resistance, to create a pole in the small-signal response which degrades the phase margin.

In unity gain, OPA350 series op amps perform well with very large capacitive loads. Increasing gain enhances the amplifier's ability to drive more capacitance. The typical performance curve "Small-Signal Overshoot vs Capacitive Load" shows performance with a 1kΩ resistive load. Increasing load resistance improves capacitive load drive capability.

FEEDBACK CAPACITOR IMPROVES RESPONSE

For optimum settling time and stability with high-impedance feedback networks, it may be necessary to add a feedback capacitor across the feedback resistor, R_F, as shown in Figure 4. This capacitor compensates for the zero created by the feedback network impedance and the OPA350's input capacitance (and any parasitic layout capacitance). The effect becomes more significant with higher impedance networks.

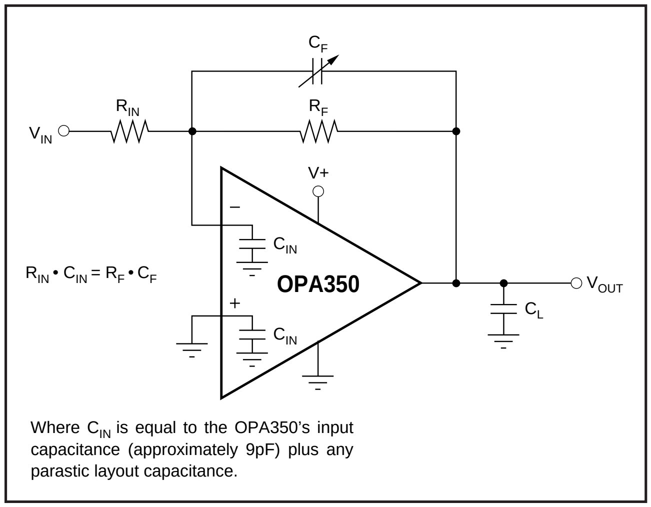


FIGURE 4. Feedback Capacitor Improves Dynamic Performance.

It is suggested that a variable capacitor be used for the feedback capacitor since input capacitance may vary between op amps and layout capacitance is difficult to determine. For the circuit shown in Figure 4, the value of the variable feedback capacitor should be chosen so that the input resistance times the input capacitance of the OPA350 (typically 9pF) plus the estimated parasitic layout capacitance equals the feedback capacitor times the feedback resistor:

$$R_{IN} \cdot C_{IN} = R_F \cdot C_F$$

where C_{IN} is equal to the OPA350's input capacitance (sum of differential and common-mode) plus the layout capacitance. The capacitor can be varied until optimum performance is obtained.

DRIVING A/D CONVERTERS

OPA350 series op amps are optimized for driving medium speed (up to 500kHz) sampling A/D converters. However, they also offer excellent performance for higher speed converters. The OPA350 series provides an effective means of buffering the A/D's input capacitance and resulting charge injection while providing signal gain.

Figure 5 shows the OPA350 driving an ADS7861. The ADS7861 is a dual, 500kHz 12-bit sampling converter in the tiny SSOP-24 package. When used with the miniature package options of the OPA350 series, the combination is ideal for space-limited applications. For further information, consult the ADS7861 data sheet.

OUTPUT IMPEDANCE

The low frequency open-loop output impedance of the OPA350's common-source output stage is approximately 1kΩ. When the op amp is connected with feedback, this value is reduced significantly by the loop gain of the op amp. For example, with 122dB of open-loop gain, the output impedance is reduced in unity-gain to less than 0.001Ω. For each decade rise in the closed-loop gain, the loop gain is reduced by the same amount which results in a ten-fold increase in effective output impedance (see the typical performance curve, "Output Impedance vs Frequency").

At higher frequencies, the output impedance will rise as the open-loop gain of the op amp drops. However, at these frequencies the output also becomes capacitive due to parasitic capacitance. This prevents the output impedance from becoming too high, which can cause stability problems when driving capacitive loads. As mentioned previously, the OPA350 has excellent capacitive load drive capability for an op amp with its bandwidth.

VIDEO LINE DRIVER

Figure 6 shows a circuit for a single supply, G = 2 composite video line driver. The synchronized outputs of a composite video line driver extend below ground. As shown, the input to the op amp should be ac-coupled and shifted positively to provide adequate signal swing to account for these negative signals in a single-supply configuration.

The input is terminated with a 75Ω resistor and ac-coupled with a 47µF capacitor to a voltage divider that provides the dc bias point to the input. In Figure 6, this point is approximately (V–) + 1.7V. Setting the optimal bias point requires some understanding of the nature of composite video signals. For best performance, one should be careful to avoid the distortion caused by the transition region of the OPA350's complementary input stage. Refer to the discussion of rail-to-rail input.

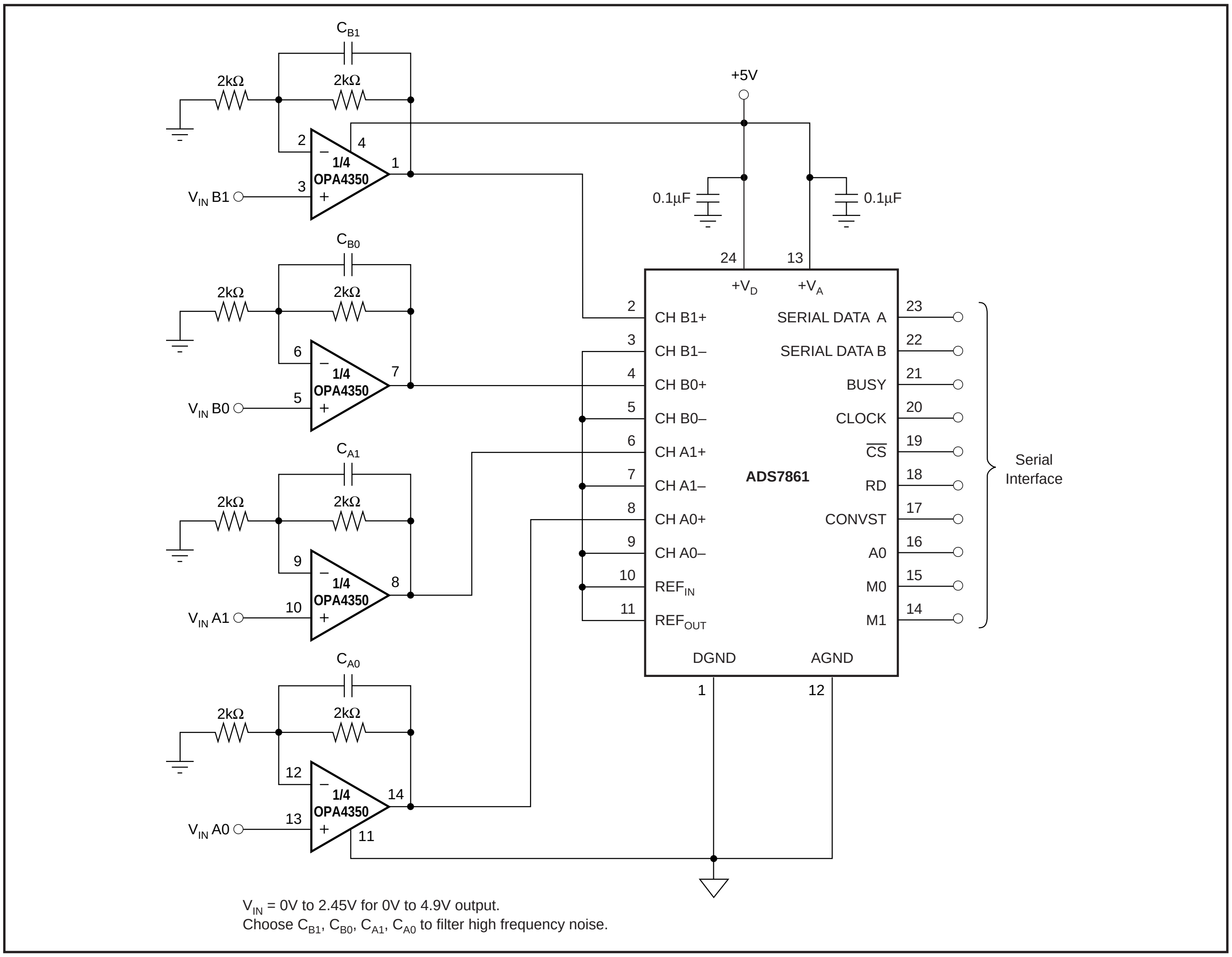


FIGURE 5. OPA4350 Driving Sampling A/D Converter.

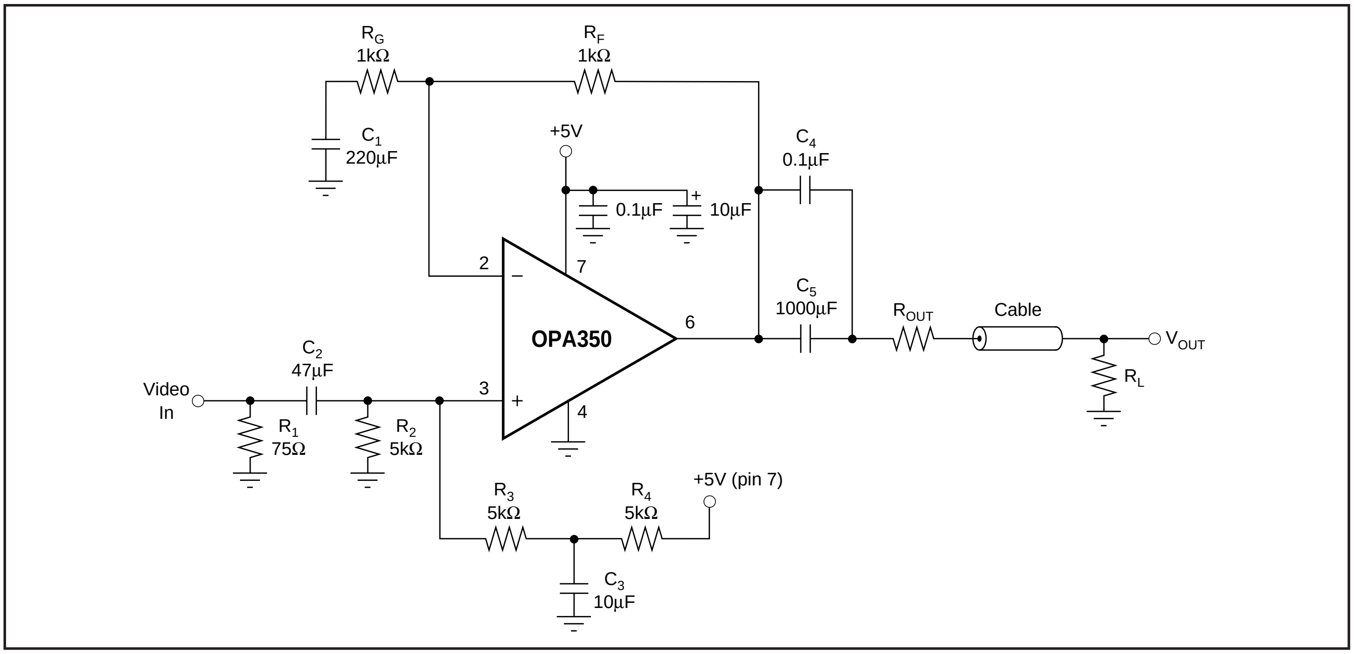


FIGURE 6. Single-Supply Video Line Driver.

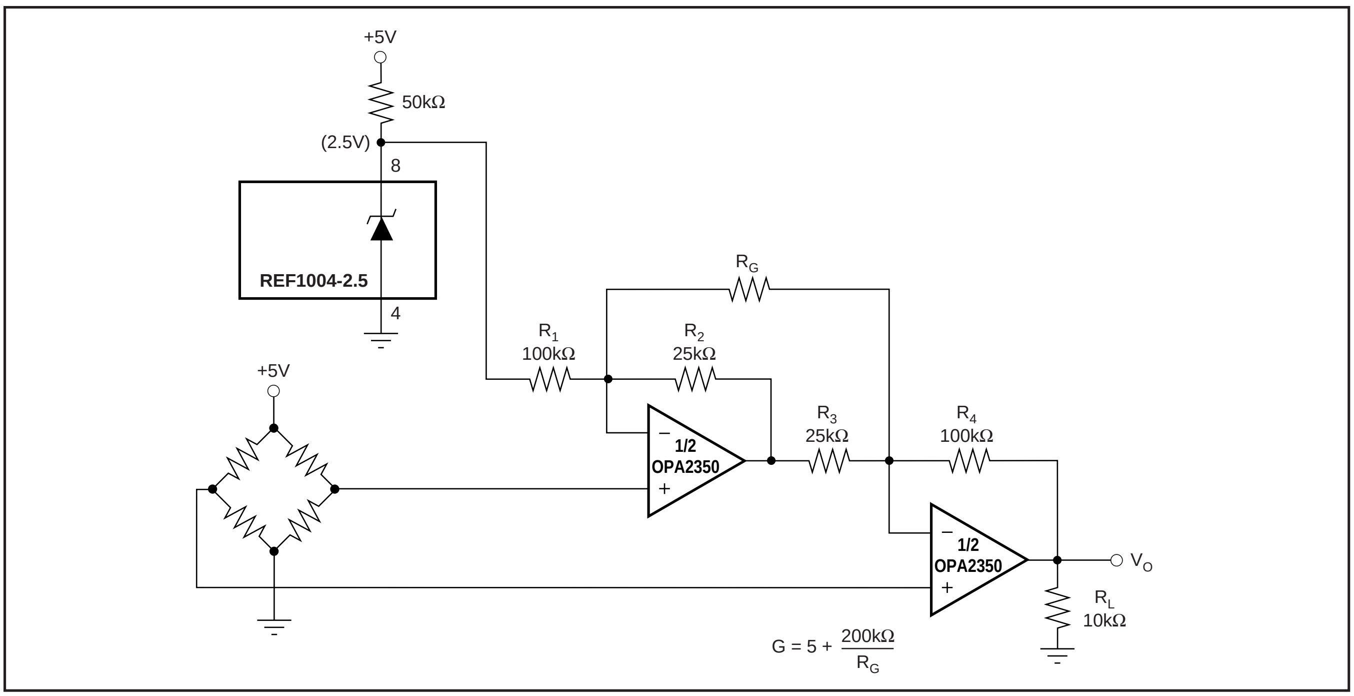


FIGURE 7. Two Op-Amp Instrumentation Amplifier With Improved High Frequency Common-Mode Rejection.

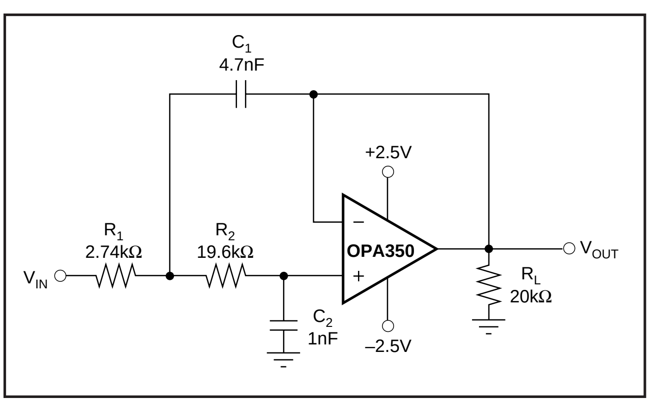


FIGURE 8. 10kHz Low-Pass Filter.

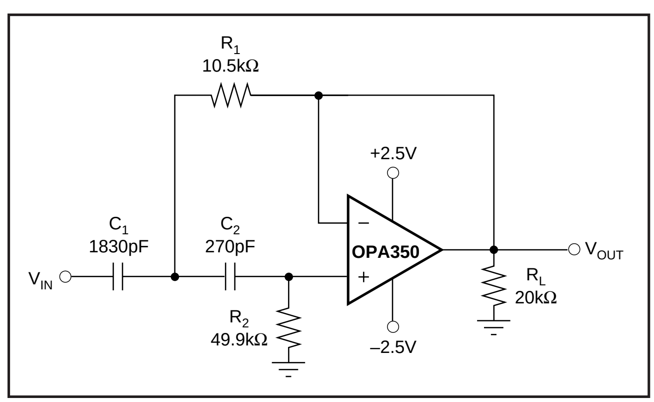


FIGURE 9. 10kHz High-Pass Filter.

Radial Leaded Multilayer Ceramic Capacitors for General Purpose Class 1, Class 2 and Class 3, 50 V_{DC}, 100 V_{DC}, 200 V_{DC}, 500 V_{DC}

FEATURES

- High capacitance with small size
- High reliability
- Crimp and straight leadstyles
- Material categorization: For definitions of compliance please see www.vishay.com/doc?99912

RoHS COMPLIANT

APPLICATIONS

- Temperature compensation
- Coupling and decoupling

QUICK REFERENCE DATA										
DESCRIPTION	VALUE									
Ceramic Class	1				2				3	
Ceramic Dielectric	C0G				X7R				Y5V	
Voltage (V_{DC})	50	100	200	500	50	100	200	500	50	100
Min. Capacitance (pF)	10	10	33	33	100	100	100	100	10 000	10 000
Max. Capacitance (pF)	10 000	5600	3900	1800	1 000 000	560 000	220 000	47 000	1 000 000	220 000
Mounting	Radial									

MARKING

Marking indicates capacitance value and tolerance in accordance with “EIA 198” and voltage marks.

OPERATING TEMPERATURE RANGE

C0G, X7R: - 55 °C to + 125 °C

Y5V: - 30 °C to + 85 °C

TEMPERATURE CHARACTERISTICS

Class 1: C0G

Class 2: X7R

Class 3: Y5V

SECTIONAL SPECIFICATIONS

Climatic category (acc. to EN 60058-1)

Class 1 and 2: 55/125/21

Class 3: 30/85/21

APPROVALS

EIA 198

IEC 60384-9

DESIGN

- The capacitors consist of a general purpose MLCC
- The lead wires are 0.5 mm and are made of 100 % tinned copper clad steel wire
- The capacitors may be supplied with straight or kinked leads having a lead spacing of 2.5 mm and 5.0 mm
- Coating is made of yellow colored flame retardant epoxy resin in accordance with UL 94 V-0

CAPACITANCE RANGE

10 pF to 1 µF

TOLERANCE ON CAPACITANCE

± 5 %, ± 10 %, ± 20 %, + 80 %/- 20 %

RATED VOLTAGE

50 V_{DC}, 100 V_{DC}, 200 V_{DC}, 500 V_{DC}

TEST VOLTAGE

- 50 V_{DC} and 100 V_{DC}: 250 % of rated voltage
- 200 V_{DC}: 150 % of rated voltage + 100 V_{DC}
- 500 V_{DC}: 130 % of rated voltage + 100 V_{DC}

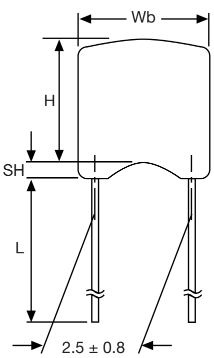
INSULATION RESISTANCE AT 500 V_{DC}

- 50 V_{DC} and 100 V_{DC}: 100 GΩ or 1000 ΩF whichever is less at rated voltage within 2 min of charging
- 200 V_{DC} and 500 V_{DC}: 10 GΩ or 100 ΩF whichever is less at rated voltage within 2 min of charging

DISSIPATION FACTOR

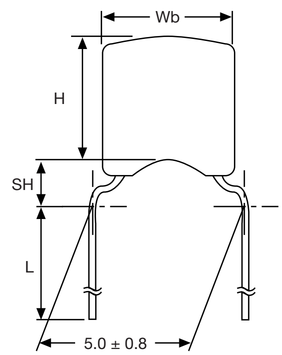
Class 1	0.1 % max. when $C \geq 30$ pF (at 1 MHz; 1 V where $C \leq 1000$ pF, and at 1 kHz; 1 V where $C > 1000$ pF) For $C < 30$ pF: $DF = 100/(400 + 20 \times C)$ DF = Dissipation factor in %; C = Capacitance value in pF
Class 2	2.5 % max. (at 1 kHz; 1 V)
Class 3	5 % max. (at 1 kHz; 1 V)

LEAD CONFIGURATION AND DIMENSIONS (in millimeters)



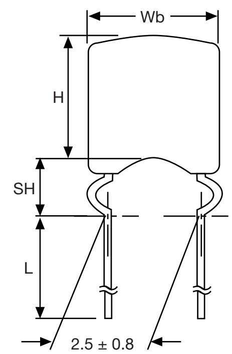
L2

Component outline for lead spacing 2.5 mm ± 0.8 mm (straight leads)



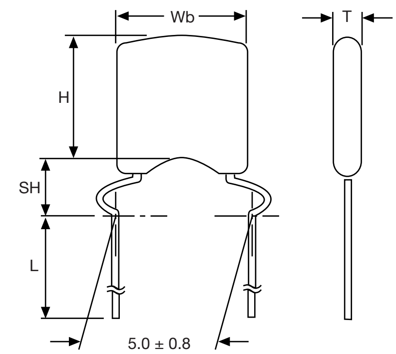
H5

Component outline for lead spacing 5.0 mm ± 0.8 mm (flat bent leads)



K2

Component outline for lead spacing 2.5 mm ± 0.8 mm (outside kink)



K5

Component outline for lead spacing 5.0 mm ± 0.8 mm (outside kink)

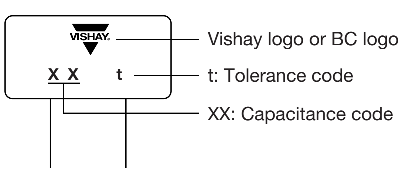
SIZE CODE	$Wb_{MAX.}$	$H_{MAX.}$	$T_{MAX.}$	MAXIMUM SEATING HEIGHT (SH)			
				L2	H5	K2	K5
10	3.6	3.6	2.3	1.6	2.6	3.5	-
15	4.0	4.0	2.6	1.6	2.6	3.5	3.5
20	5.0	5.0	3.2	1.6	2.6	3.5	3.5

Notes

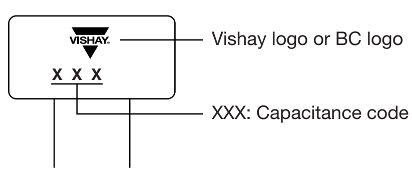
- Bulk packed types have a standard lead length L = 30 mm ± 5 mm.
- The K5 lead style is not available for size 10.
- L2 and H5 are preferred styles.

MARKING

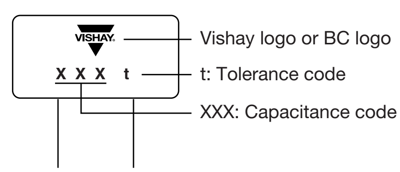
SIZE 10 AND 15 CAPACITANCE VALUE < 100 pF



SIZE 10 AND 15 CAPACITANCE VALUE ≥ 100 pF



SIZE 20



Notes

- The capacitance code indicates actual capacitance in pF when capacitance value < 100 pF.
- Two significant digits followed by one digit for the multiplier as given following: 1 = * 10, 2 = * 100, 3 = * 1000, 4 = * 10 000, 5 = * 100 000.
- The tolerance codes are J = 5 %, K = 10 %, M = 20 % and Z = + 80 %/- 20 %.

ORDERING CODE INFORMATION

K	104	K	15	X7R	F	5	3	H	5
1	2 3 4	5	6 7	8 9 10	11	12	13	14	15
Product Type	**Capacitance (pF)**	**Capacitance Tolerance**	**Size Code**	**T.C. Code**	**Rated Voltage**	**Lead Diameter**	**Packaging/ Lead Length**	**Lead Style**	**Lead Spacing**
K = Radial leaded MLCC	The first two digits are the significant figures of capacitance and the last digit is a multiplier as follows: 0 = * 1 1 = * 10 2 = * 100 3 = * 1000 4 = * 10 000 5 = * 100 000	J = ± 5 % K = ± 10 % M = ± 20 % Z = + 80 %/ - 20 %	Please refer to relevant datasheet	Please refer to relevant datasheet	F = 50 V_{DC} H = 100 V_{DC} K = 200 V_{DC} L = 500 V_{DC}	5 = 0.50 mm ± 0.05 mm	3 = Bulk T = Tape and reel U = Ammo	H = Flat crimp L = Straight K = Outside crimp	2 = 2.5 mm 5 = 5.0 mm

ORDERING CODES

DIELECTRIC C0G						
CAP. (pF)	50 V_{DC}		100 V_{DC}		200 V_{DC}	500 V_{DC}
	SMALLER SIZE	NORMAL SIZE	SMALLER SIZE	NORMAL SIZE	NORMAL SIZE	NORMAL SIZE
10	K100#10C0GF5###	K100#15C0GF5###	K100#10C0GH5###	K100#15C0GH5###	-	-
12	K120#10C0GF5###	K120#15C0GF5###	K120#10C0GH5###	K120#15C0GH5###	-	-
15	K150#10C0GF5###	K150#15C0GF5###	K150#10C0GH5###	K150#15C0GH5###	-	-
18	K180#10C0GF5###	K180#15C0GF5###	K180#10C0GH5###	K180#15C0GH5###	-	-
22	K220#10C0GF5###	K220#15C0GF5###	K220#10C0GH5###	K220#15C0GH5###	-	-
27	K270#10C0GF5###	K270#15C0GF5###	K270#10C0GH5###	K270#15C0GH5###	-	-
33	K330#10C0GF5###	K330#15C0GF5###	K330#10C0GH5###	K330#15C0GH5###	K330#15C0GK5###	K330#15C0GL5##5
39	K390#10C0GF5###	K390#15C0GF5###	K390#10C0GH5###	K390#15C0GH5###	K390#15C0GK5###	K390#15C0GL5##5
47	K470#10C0GF5###	K470#15C0GF5###	K470#10C0GH5###	K470#15C0GH5###	K470#15C0GK5###	K470#15C0GL5##5
56	K560#10C0GF5###	K560#15C0GF5###	K560#10C0GH5###	K560#15C0GH5###	K560#15C0GK5###	K560#15C0GL5##5
68	K680#10C0GF5###	K680#15C0GF5###	K680#10C0GH5###	K680#15C0GH5###	K680#15C0GK5###	K680#15C0GL5##5
82	K820#10C0GF5###	K820#15C0GF5###	K820#10C0GH5###	K820#15C0GH5###	K820#15C0GK5###	K820#15C0GL5##5
100	K101#10C0GF5###	K101#15C0GF5###	K101#10C0GH5###	K101#15C0GH5###	K101#15C0GK5###	K101#15C0GL5##5
120	K121#10C0GF5###	K121#15C0GF5###	K121#10C0GH5###	K121#15C0GH5###	K121#15C0GK5###	K121#15C0GL5##5
150	K151#10C0GF5###	K151#15C0GF5###	K151#10C0GH5###	K151#15C0GH5###	K151#15C0GK5###	K151#15C0GL5##5
180	K181#10C0GF5###	K181#15C0GF5###	K181#10C0GH5###	K181#15C0GH5###	K181#15C0GK5###	K181#15C0GL5##5
220	K221#10C0GF5###	K221#15C0GF5###	K221#10C0GH5###	K221#15C0GH5###	K221#15C0GK5###	K221#15C0GL5##5
270	K271#10C0GF5###	K271#15C0GF5###	K271#10C0GH5###	K271#15C0GH5###	K271#15C0GK5###	K271#15C0GL5##5
330	K331#10C0GF5###	K331#15C0GF5###	K331#10C0GH5###	K331#15C0GH5###	K331#15C0GK5###	K331#15C0GL5##5
390	K391#10C0GF5###	K391#15C0GF5###	K391#10C0GH5###	K391#15C0GH5###	K391#15C0GK5###	K391#15C0GL5##5
470	K471#10C0GF5###	K471#15C0GF5###	K471#10C0GH5###	K471#15C0GH5###	K471#15C0GK5###	K471#20C0GL5##5
560	K561#10C0GF5###	K561#15C0GF5###	K561#10C0GH5###	K561#15C0GH5###	K561#15C0GK5###	K561#20C0GL5##5
680	K681#10C0GF5###	K681#15C0GF5###	-	K681#15C0GH5###	K681#15C0GK5###	K681#20C0GL5##5
820	K821#10C0GF5###	K821#15C0GF5###	-	K821#15C0GH5###	K821#15C0GK5###	K821#20C0GL5##5
1000	K102#10C0GF5###	K102#15C0GF5###	-	K102#20C0GH5###	K102#20C0GK5###	K102#20C0GL5##5
1200	-	K122#15C0GF5###	-	K122#20C0GH5###	K122#20C0GK5###	K122#20C0GL5##5
1500	-	K152#15C0GF5###	-	K152#20C0GH5###	K152#20C0GK5###	K152#20C0GL5##5
1800	-	K182#15C0GF5###	-	K182#20C0GH5###	K182#20C0GK5###	K182#20C0GL5##5
2200	-	K222#15C0GF5###	-	K222#20C0GH5###	K222#20C0GK5###	-
2700	-	K272#20C0GF5###	-	K272#20C0GH5###	K272#20C0GK5###	-
3300	-	K332#20C0GF5###	-	K332#20C0GH5###	K332#20C0GK5###	-
3900	-	K392#20C0GF5###	-	K392#20C0GH5###	K392#20C0GK5###	-
4700	-	K472#20C0GF5###	-	K472#20C0GH5###	-	-
5600	-	K562#20C0GF5###	-	K562#20C0GH5###	-	-
6800	-	K682#20C0GF5###	-	-	-	-
8200	-	K822#20C0GF5###	-	-	-	-
10 000	-	K103#20C0GF5###	-	-	-	-

Notes

- Lead diameter is 0.5 mm
- # 5th digit is capacitance tolerance code: ± 5 % = J; ± 10 % = K
- # 13th digit is packaging code: Bulk = 3; Reel = T; Ammo = U
- # 14th digit is lead style code: L; H; K (L and H are preferred lead configuration)
- # 15th digit is lead spacing code: 2.5 mm = 2; 5.0 mm = 5

DIELECTRIC X7R

CAP. (pF)	50 V_{DC}		100 V_{DC}		200 V_{DC}	500 V_{DC}
	SMALLER SIZE	NORMAL SIZE	SMALLER SIZE	NORMAL SIZE	NORMAL SIZE	NORMAL SIZE
100	K101#10X7RF5###	K101#15X7RF5###	K101#10X7RH5###	K101#15X7RH5###	K101#15X7RK5###	K101#15X7RL5##5
120	K121#10X7RF5###	K121#15X7RF5###	K121#10X7RH5###	K121#15X7RH5###	K121#15X7RK5###	K121#15X7RL5##5
150	K151#10X7RF5###	K151#15X7RF5###	K151#10X7RH5###	K151#15X7RH5###	K151#15X7RK5###	K151#15X7RL5##5
180	K181#10X7RF5###	K181#15X7RF5###	K181#10X7RH5###	K181#15X7RH5###	K181#15X7RK5###	K181#15X7RL5##5
220	K221#10X7RF5###	K221#15X7RF5###	K221#10X7RH5###	K221#15X7RH5###	K221#15X7RK5###	K221#15X7RL5##5
270	K271#10X7RF5###	K271#15X7RF5###	K271#10X7RH5###	K271#15X7RH5###	K271#15X7RK5###	K271#15X7RL5##5
330	K331#10X7RF5###	K331#15X7RF5###	K331#10X7RH5###	K331#15X7RH5###	K331#15X7RK5###	K331#15X7RL5##5
390	K391#10X7RF5###	K391#15X7RF5###	K391#10X7RH5###	K391#15X7RH5###	K391#15X7RK5###	K391#15X7RL5##5
470	K471#10X7RF5###	K471#15X7RF5###	K471#10X7RH5###	K471#15X7RH5###	K471#15X7RK5###	K471#15X7RL5##5
560	K561#10X7RF5###	K561#15X7RF5###	K561#10X7RH5###	K561#15X7RH5###	K561#15X7RK5###	K561#15X7RL5##5
680	K681#10X7RF5###	K681#15X7RF5###	K681#10X7RH5###	K681#15X7RH5###	K681#15X7RK5###	K681#15X7RL5##5
820	K821#10X7RF5###	K821#15X7RF5###	K821#10X7RH5###	K821#15X7RH5###	K821#15X7RK5###	K821#15X7RL5##5
1000	K102#10X7RF5###	K102#15X7RF5###	K102#10X7RH5###	K102#15X7RH5###	K102#15X7RK5###	K102#15X7RL5##5
1200	K122#10X7RF5###	K122#15X7RF5###	K122#10X7RH5###	K122#15X7RH5###	K122#15X7RK5###	K122#15X7RL5##5
1500	K152#10X7RF5###	K152#15X7RF5###	K152#10X7RH5###	K152#15X7RH5###	K152#15X7RK5###	K152#15X7RL5##5
1800	K182#10X7RF5###	K182#15X7RF5###	K182#10X7RH5###	K182#15X7RH5###	K182#15X7RK5###	K182#15X7RL5##5
2200	K222#10X7RF5###	K222#15X7RF5###	K222#10X7RH5###	K222#15X7RH5###	K222#15X7RK5###	K222#15X7RL5##5
2700	K272#10X7RF5###	K272#15X7RF5###	K272#10X7RH5###	K272#15X7RH5###	K272#15X7RK5###	K272#15X7RL5##5
3300	K332#10X7RF5###	K332#15X7RF5###	K332#10X7RH5###	K332#15X7RH5###	K332#15X7RK5###	K332#20X7RL5##5
3900	K392#10X7RF5###	K392#15X7RF5###	K392#10X7RH5###	K392#15X7RH5###	K392#15X7RK5###	K392#20X7RL5##5
4700	K472#10X7RF5###	K472#15X7RF5###	K472#10X7RH5###	K472#15X7RH5###	K472#15X7RK5###	K472#20X7RL5##5
5600	K562#10X7RF5###	K562#15X7RF5###	K562#10X7RH5###	K562#15X7RH5###	K562#15X7RK5###	K562#20X7RL5##5
6800	K682#10X7RF5###	K682#15X7RF5###	K682#10X7RH5###	K682#15X7RH5###	K682#15X7RK5###	K682#20X7RL5##5
8200	K822#10X7RF5###	K822#15X7RF5###	K822#10X7RH5###	K822#15X7RH5###	K822#15X7RK5###	K822#20X7RL5##5
10 000	K103#10X7RF5###	K103#15X7RF5###	K103#10X7RH5###	K103#15X7RH5###	K103#15X7RK5###	K103#20X7RL5##5
12 000	K123#10X7RF5###	K123#15X7RF5###	-	K123#15X7RH5###	K123#15X7RK5###	K123#20X7RL5##5
15 000	K153#10X7RF5###	K153#15X7RF5###	-	K153#15X7RH5###	K153#15X7RK5###	K153#20X7RL5##5
18 000	K183#10X7RF5###	K183#15X7RF5###	-	K183#15X7RH5###	K183#15X7RK5###	K183#20X7RL5##5
22 000	K223#10X7RF5###	K223#15X7RF5###	-	K223#15X7RH5###	K223#15X7RK5###	K223#20X7RL5##5
27 000	K273#10X7RF5###	K273#15X7RF5###	-	K273#20X7RH5###	K273#20X7RK5###	K273#20X7RL5##5
33 000	K333#10X7RF5###	K333#15X7RF5###	-	K333#20X7RH5###	K333#20X7RK5###	K333#20X7RL5##5
39 000	K393#10X7RF5###	K393#15X7RF5###	-	K393#20X7RH5###	K393#20X7RK5###	K393#20X7RL5##5
47 000	K473#10X7RF5###	K473#15X7RF5###	-	K473#20X7RH5###	K473#20X7RK5###	K473#20X7RL5##5
56 000	K563#10X7RF5###	K563#15X7RF5###	-	K563#20X7RH5###	K563#20X7RK5###	-
68 000	K683#10X7RF5###	K683#15X7RF5###	-	K683#20X7RH5###	K683#20X7RK5###	-
82 000	K823#10X7RF5###	K823#15X7RF5###	-	K823#20X7RH5###	K823#20X7RK5###	-
100 000	K104#10X7RF5###	K104#15X7RF5###	-	K104#20X7RH5###	K104#20X7RK5###	-
150 000	-	K154#20X7RF5###	-	K154#20X7RH5###	K154#20X7RK5###	-
220 000	-	K224#20X7RF5###	-	K224#20X7RH5###	K224#20X7RK5###	-
330 000	-	K334#20X7RF5###	-	K334#20X7RH5###	-	-
470 000	-	K474#20X7RF5###	-	K474#20X7RH5###	-	-
560 000	-	K564#20X7RF5###	-	K564#20X7RH5###	-	-
680 000	-	K684#20X7RF5###	-	-	-	-
1 000 000	-	K105#20X7RF5###	-	-	-	-

Notes
- Lead diameter is 0.5 mm
- # 5th digit is capacitance tolerance code: ± 10 % = K; ± 20 % = M
- # 13th digit is packaging code: Bulk = 3; Reel = T; Ammo = U
- # 14th digit is lead style code: L; H; K (L and H are preferred lead configuration)
- # 15th digit is lead spacing code: 2.5 mm = 2; 5.0 mm = 5

DIELECTRIC Y5V			
CAP. (pF)	50 V_{DC}		100 V_{DC}
	SMALLER SIZE	NORMAL SIZE	NORMAL SIZE
10 000	K103Z10Y5VF5###	K103Z15Y5VF5###	K103Z15Y5VH5###
15 000	K153Z10Y5VF5###	K153Z15Y5VF5###	K153Z15Y5VH5###
22 000	K223Z10Y5VF5###	K223Z15Y5VF5###	K223Z15Y5VH5###
33 000	K333Z10Y5VF5###	K333Z15Y5VF5###	K333Z15Y5VH5###
47 000	K473Z10Y5VF5###	K473Z15Y5VF5###	K473Z15Y5VH5###
68 000	K683Z10Y5VF5###	K683Z15Y5VF5###	K683Z15Y5VH5###
100 000	K104Z10Y5VF5###	K104Z15Y5VF5###	K104Z15Y5VH5###
150 000	K154Z10Y5VF5###	K154Z15Y5VF5###	K154Z20Y5VH5###
220 000	-	K224Z15Y5VF5###	K224Z20Y5VH5###
330 000	-	K334Z20Y5VF5###	-
470 000	-	K474Z20Y5VF5###	-
680 000	-	K684Z20Y5VF5###	-
1 000 000	-	K105Z20Y5VF5###	-

Notes

- Lead diameter is 0.5 mm
- Tolerance is + 80 %/- 20 %
- # 13th digit is packaging code: Bulk = 3; Reel = T; Ammo = U
- # 14th digit is lead style code: L; H; K (L and H are preferred lead configuration)
- # 15th digit is lead spacing code: 2.5 mm = 2; 5.0 mm = 5

TAPING AND PACKAGING

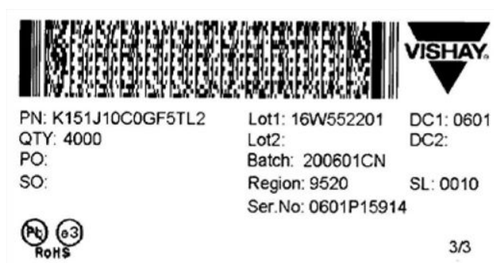
LABELLING

Each reel is provided with a label showing the following details:

Manufacturer, K style, capacitance, tolerance, batch number, quantity of components, rated voltage, dielectric.

On special request other designations can be shown.

For example:

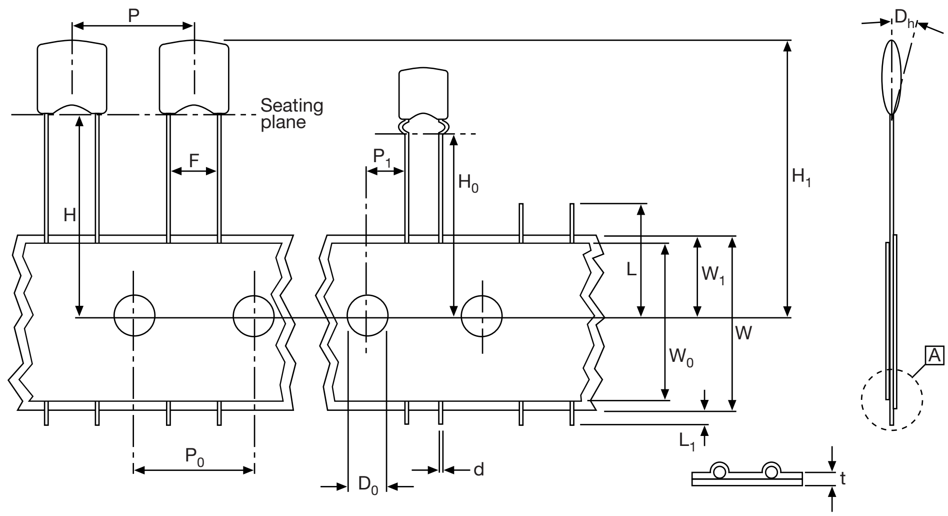


PACKAGING QUANTITIES AND BOX DIMENSIONS			
PACKAGING	SIZE CODE	SMALLEST PACKAGING QUANTITY (SPQ)	BOX DIMENSIONS L x W x H (mm)
Tape on reel	10, 15	4000	370 x 370 x 60
	20	3000	
Ammopack	10, 15, 20	2500	335 x 290 x 50
Bulk [(1)]	10, 15, 20	5000	245 x 120 x 65

Note

[(1)] SPQ contains one or a multiple of poly-bags, 1000 units per bag.

CAPACITORS ON TAPE



PARAMETER	SYMBOL	DIMENSIONS	
		mm	INCH
Cut-off length	L	≤ 11.0	≤ 0.443
Lead end protrusion	L_1	≤ 1.0	≤ 0.039
Height to seating plane (straight leads)	H	≥ 18.0	≥ 0.709
Height to seating plane (crimp leads)	H_0	16.0 ± 0.5	0.630 ± 0.020
Top of component height	H_1	≤ 32	≤ 1.26
Body inclination	Δh	0.0 ± 1.0	0.000 ± 0.039
Carrier tape width	W	18.0 + 1.0/- 0.5	0.709 + 0.039/- 0.020
Hold down tape width	W_0	15.0 REF.	0.591 REF.
Sprocket hole position	W_1	9.00 + 0.075/- 0.50	0.354 + 0.030/- 0.020
Lead space	F	2.50 + 0.60/- 0.40	0.100 + 0.024/- 0.016
		5.00 + 0.60/- 0.40	0.200 + 0.024/- 0.016
Sprocket hole pitch	P_0	12.70 ± 0.3	0.500 ± 0.012
Sprocket hole center to lead center at F = 2.5 mm	P_1	5.08 ± 0.7	0.200 ± 0.028
Sprocket hole center to lead center at F = 5 mm		3.85 ± 0.7	0.150 ± 0.028
Sprocket hole diameter	D_0	4.00 ± 0.30	0.157 ± 0.012
Overall tape thickness	t	≤ 0.90	≤ 0.035
Wire lead diameter	d	0.50 ± 0.05	0.020 ± 0.002
Taping pitch	P	12.7 REF.	0.50 REF.

REEL DATA

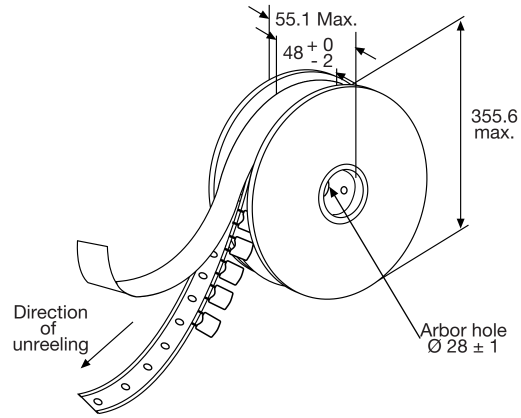
A maximum of 0.5 % of the total number of capacitors per reel may be missing.

A maximum of 1 consecutive vacant positions is followed by 6 consecutive components.

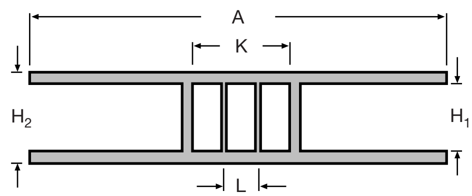
Tape begins and ends with a minimum of 4 empty positions (50 mm tape).

Maximum of 5 splicers per reel.

REEL



REEL DIMENSIONS



REEL SIZE		(mm)
A	Outer diameter	355.6 max.
L	Hole diameter	28 ± 1.5
K	Core diameter	90
H_1	Internal width	48 + 0/- 2
H_2	External width	55 max.

AMMOPACK DATA

A maximum of 0.5 % of the total number of capacitors per box may be missing.

A maximum of 2 consecutive vacant positions is followed by 6 consecutive components.

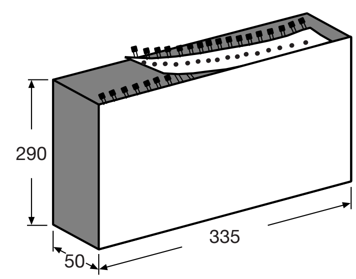
Tape begins and ends with a minimum of 4 empty positions (50 mm tape).

Maximum of 5 splicers per reel.

The cumulative pitch tolerance over 20 consecutive units is not to exceed ± 1.0 mm.

Lead space (F) shall be measured at (3.6 ± 0.5) mm from the capacitor seating plane.

AMMOPACK



RELATED DOCUMENTS

General Information	www.vishay.com/doc?45163

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Please note that some Vishay documentation may still make reference to RoHS Directive 2002/95/EC. We confirm that all the products identified as being compliant to Directive 2002/95/EC conform to Directive 2011/65/EU.

Vishay Intertechnology, Inc. hereby certifies that all its products that are identified as Halogen-Free follow Halogen-Free requirements as per JEDEC JS709A standards. Please note that some Vishay documentation may still make reference to the IEC 61249-2-21 definition. We confirm that all the products identified as being compliant to IEC 61249-2-21 conform to JEDEC JS709A standards.

Type HOLCO Series

Key Features

- Ultra Precision - Down To 0.05%
- Matched Sets Available To 2ppm/°C
- High Pulse Withstand
- Low Reactance
- Low TCR - Down To 5ppm/°C
- Long Term Stability
- Up To 1 Watt At 70°C
- Released To CECC 40101 004, 030 And 804

The Holco range of Precision Metal Film Resistors meets the requirement for economically priced components for industrial and military applications. The manufacturing facility utilises closely controlled production processes including the sputter coating of metal alloy films to ceramic substrates, and laser spiralling to achieve close tolerance and high stability resistors. An epoxy coating is applied for environmental and mechanical protection. Commercially the Series is available in two case sizes, from 1 ohm to 4M ohms, tolerances from 0.05% to 1% and TCR's from 5ppm/°C to 100ppm/°C. Offered with release to BS CECC 40101 004, 030 and 804 the H8 is available via distribution.

Characteristics - Electrical

	H4P	H4	H8	
BS CECC 40101 004				
Style:		K	H	J
Power Rating at 70°C:		0.25W	0.063W	0.125W
Temperature Rise (max):		32°C	14°C	28°C
Limiting Element Voltage:		250V	200V	200V
BS CECC 40101 030				
Style:		J	H	
Power Rating at 125°C:		0.125W	0.1W	
Temperature Rise (max):		30°C	30°C	
Limiting Element Voltage:		250V	200V	
BS CECC 40101 804				
Style:		B	A	
Power Rating at 125°C:		0.25W	0.125W	
Limiting Element Voltage:		250V	200V	
Commercial Ratings				
Power Rating at 70°C:	1.0W	0.5W	0.25W	
Temperature Rise:	70°C	55°C	40°C	
Limiting Element Voltage:	500V	350V	350V	

General Data

Lead Material:	Solderability to BS CECC 40101 004 Para 4.15.1
Encapsulation:	Conformal Epoxy Coating
Resistor Marking:	Legend printed in accordance with CECC 40000 Para 2.4
Solvent Resistance:	The epoxy coating and print will withstand the action of all commonly used industrial cleansing solvents

Dimensions are in millimeters and inches unless otherwise specified. Values in brackets are standard equivalents.

Dimensions are shown for reference purposes only. Specifications subject to change.

Type HOLCO Series

Temperature Coefficient / Tolerance Ranges

TCR	H4P			H4			H8		
ppm/°C	0.05%	0.1%-0.25%	0.5%-1.0%	0.05%	0.1%-0.25%	0.5%-1.0%	0.05%	0.1%-0.25%	0.5%-1.0%
5	10R-500K	10R-500K	10R-500K	10R-500K	10R-500K	10R-500K	10R-500K	10R-500K	10R-500K
10	10R-1M0	10R-1M0	10R-1M0	10R-1M0	10R-1M0	10R-1M0	10R-1M0	10R-1M0	10R-1M0
15	10R-1M0	10R-1M0	10R-1M0	10R-1M0	10R-1M0	10R-1M0	10R-1M0	10R-1M0	10R-1M0
25	10R-1M0	10R-2M0	10R-2M0	10R-1M0	10R-2M0	10R-2M0	10R-1M0	10R-2M0	10R-2M0
50	10R-1M0	10R-2M0	10R-4M0	10R-1M0	10R-2M0	10R-4M0	10R-1M0	10R-2M0	10R-4M0
100	10R-1M0	1R0-2M0	1R0-4M0	10R-1M0	1R0-2M0	1R0-4M0	10R-1M0	1R0-2M0	1R0-4M0

Approved Value Ranges
40101-004, 40101-030

Type	Style 004	Style 030	Z 100ppm	C 50ppm	D 25ppm	Y 15ppm
H4	K	J	10R-1M0	49R9-1M0	49R9-1M0	49R9-1M0
H8	HJ	H	10R-1M0	49R9-1M0	49R9-1M0	49R9-1M0

Tolerances 0.1%, 0.25%, 0.5%, 1%

40101-804

Type	Style	C 50ppm	D 25ppm	T 15ppm
H4	B	49R9-1M0	49R9-1M0	49R9-1M0
H8	A	49R9-1M0	49R9-1M0	49R9-1M0

Tolerances 0.1%, 0.25%, 0.5%, 1%

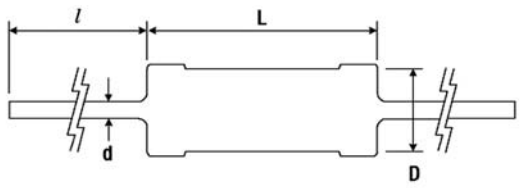
Characteristics - Electrical

	Typical Data	Reference
Voltage Coefficient of Resistance (Between 10% and Full Rated Voltage)	Less Than 5ppm/Volt Applied	n/a
Insulation Resistance at 500 Volts	Greater Than 10^{12} Ohms	n/a
Resistance to Soldering Heat (260°C for 10 Secs.)	Less Than 0.05%	BS CECC 40101 004 Para 4.15.2
Short Term Overload (6.25 Times Rated BS CECC Wattage for 5 Seconds)	Less Than 0.06%	BS CECC 40101 004 Para 4.11
Ambient Temperature Range	-55°C to +155°C	BS CECC 40101 004, BS CECC 40101 030 & Commercial
Rapid Change of Temperature (-55°C to +155°C, 5 cycles)	Less Than 0.04%	BS CECC 40101 004 Para 4.16
Shelf Life (at Normal Room Temp.)	Less Than 0.05% Per Annum	n/a
Vibration (10-500 HZ,Amplitude 0.75mm, or Acceleration 98m/s2 which is less severe, sweep duration 6 hours)	Less Than 0.04%	BS CECC 40101 004 Para 4.19
Vibration (55-2000 Hz Simple Harmonic Motion, Max.Acceleration 98m/s2, Duration 35±5 Minutes)	Less Than 0.04%	MIL STD 202 METHOD 204-C
Bump (390m/s2, 4000 Bumps)	Less Than 0.03%	BS 2011 Part 2.1 Eb 1977 (1984)
Load Stability	See Graphs	n/a
Damp Heat Steady State	See Graph	BS CECC 40101 004 Para 4.21

Type HOLCO Series

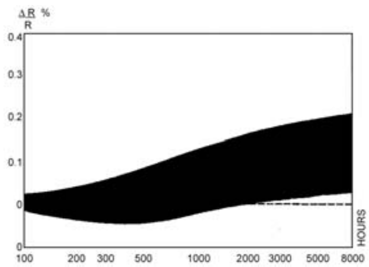
Dimensions

To prevent damage to the components conformal coating, the leads should be adequately supported during the forming process

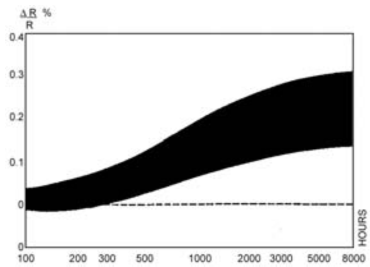


	H4P	H4	H8
Body Length (L) maximum:	10.0 mm	10.0 mm	7.20 mm
Body Diameter (D) maximum:	3.70 mm	3.70 mm	2.50 mm
Lead Diameter (d) maximum:	0.60 mm	0.60 mm	0.60 mm
Lead Length (l) nominal:	30.0 mm	30.0 mm	30.0 mm
Recommended Mounting Pitch:	12.7 mm	12.7 mm	10.2 mm
Weight (g/100 resistors)	40	40	24

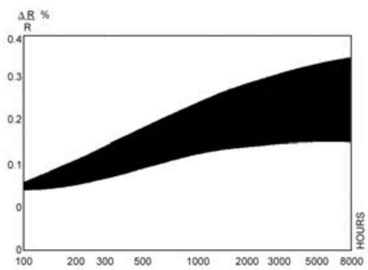
Characteristics - Long Term Stability



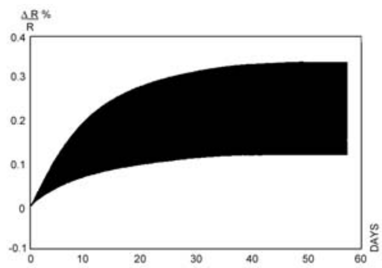
Long Term Stability
BS CECC 40101 004
Ratings at 70°C
H4 - 0.25 W
H8 - 0.125 W



Long Term Stability
BS CECC 40101 030
Ratings at 125°C
H4 - 0.125 W
H8 - 0.1 W



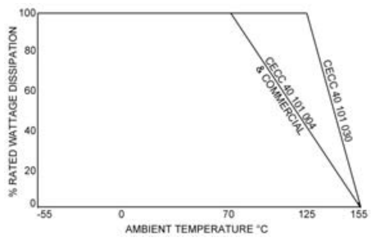
Long Term Stability
Commercial
Ratings at 125°C
H4P - 1W
H4 - 0.5 W
H8 - 0.25 W



Damp Heat Steady State
93% RH at 40°C

Type HOLCO Series

Derating Graph - Approved and Commercial Ratings



How to Order

H8	100R	B	Y	B
Common Part	**Resistance Value**	**Tolerance**	**T.C.R. Code**	**Release**
H4P H4 H8	1.0 ohm (1000 milli ohms) 1R0 10 ohm (10 ohms) 10R 100 ohm (100 ohms) 100R 1K 0hm (1000 ohms) 1K0 10K ohm (10000 ohms) 10K 100K ohm (100000 ohms) 100K 1M ohm (1000000 ohms) 1M0	A - 0.05% B - 0.1% C - 0.25% D - 0.5% F - 1.0%	A - 5ppm B - 10ppm Y - 15ppm D - 25ppm C - 50ppm Z - 100ppm	A - Part can only be sold with Commercial or C of C release. B - Part can be sold to BS CECC 40101 004, BS CECC 40101 030 D - Part can be sold to BS CECC 40101 804