SU QuarkNet Workshop 2012 — Lab Activity 4 ELECTRONICS I: OP AMPs & SI DETs

Laboratory Goals

- 1. Learn about basic circuits and how to use an oscilloscope.
- 2. Understand the key properties of operational amplifiers.
- 3. Investigate how the response of an operational amplifier configured with negative feedback changes with the amplitude and frequency of the input.
- 4. Understand the operation of a silicon photodiode and how to amplify its output to give an observable output signal.

1. INTRODUCTION

Most modern high energy physics experiments read out detectors using an electronics arrangement substantially like that shown in a simplified manner in Figure 1.



Figure 1. Simplified schematic showing the elements in a detector readout chain used in a typical high energy physics experiment.

The detector D (or sensor or transducer) takes a physical quantity (like position or temperature) and translates it into charge (or current or voltage), either directly or indirectly. This may be something simple like a thermistor or something more complex, like a channel in a silicon vertex detector.

Following is the amplifier A, which takes the signal from the detector and boosts it by some factor, called gain. This stage also shapes and stretches the signal, as necessary for subsequent processing. This is known as the "front-end" electronics, and often is required to be very fast. In the LHCb experiment, there is a potential event of interest every 25 ns (a 40 MHz rate).

Next, the data converter C takes the analog signal and converts it into some digitized quantity that a computer (or equivalent) can manipulate or process. This converter may be an ADC (amplitude) or TDC (time) or another device, whose output is a digital signal which following some standard definition. The signal information is now encoded into bits, and may be manipulated fairly easily and reliably: the digital signal may then be added or subtracted or stored temporarily or rearranged in some other way, as needed, by fast devices like DSPs or FPGAs. This stage can be considered the "back-end" electronics.

Lastly, the data acquisition system Q, is the system that takes the processed digitized signal and transfers it to a storage medium. This so-called DAQ may also processes the information further if needed. (In practice, the boundary line between the final two stages is a matter for technical debate.) An on-line computer, or more often, a farm of such CPUs, is typically used for this task. The digitized information for each event of interest is then available for sophisticated analysis, off-line, by the physicist.

Overall, one tries to design the electronics chain to be linear and proportional to the physical quantity measured. This is more often true in breach, however, and much additional work involving monitoring and calibration is needed to assure the measurement's fidelity to the physics.

In this lab activity (Op Amp + Si Det), the focus will be on the first two elements in Figure 1. In the second electronics lab activity (ADC + DAQ), it will be on the last two elements.

2. TUTORIAL ON THE OPERATIONAL AMPLIFIER

The operational amplifier is a crucial building block in several operations involving analog signals, namely signals whose amplitude carries some relevant physical information. This characteristic is opposed to the quantized nature of digital signals where one distinguishes between two states corresponding to the logical 1 or 0 respectively. Analog signals need frequently to be amplified, to reach the sensitivity of the measuring apparatus. For example, a sensor that monitors a physical quantity such as light, temperature, pressure, may produce a signal that is too low to be digitized with sufficient accuracy by your data acquisition system. Now you have two examples at your disposal, the digital oscilloscope and your LabVIEW set-up.

Additional manipulations that we may want to perform on signals are mathematical ones. We may want to sum or subtract two signals, or even to differentiate or integrated them.

The operational amplifier takes its name by the fact that it can be configured through a suitable combination of passive components connected between its terminals to perform operations and scale analog signals to reach the desired sensitivity.



Figure 2. LF356, a typical operational amplifier.

The op amp (operational amplifier) is represented by the circuit symbol shown in Figure 2. It derives its DC power from two supply rails (the voltages called V^+ and V^-). The amplifier has two input terminals: one inverting and the other non inverting. This terminology refers to the relative sign of the relative direction in which a voltage change at each terminal drives v_{out} . For example, and increase of vin+ produces an increase in v_{out} , while an increase in vin- produces a decrease in v_{out} .

In particular, we can say that the output is controlled only by the difference between the two inputs: the operational amplifier is sensitive to the difference dV=vin+-vin-. For a very small range of dV, the gain A (called also open loop gain) is large and linear in dV. However, there is a maximum absolute value of v_{out} for any given value of V⁺ and V⁻, so when AdV>Vomax+ orAdV<Vomax-, the output is constant (saturated) at its extreme value. You can see this behavior depicted in Figure 3.



Figure 3. Static characteristic of the operational amplifier.

Modern operational amplifiers are complicated devices containing many different transistor stages. Perhaps you will be motivated in learning more about these extremely useful and versatile devices, however for this laboratory it is important that you learn to understand some very simple properties that relate differential input and output voltages.

3. TUTORIAL ON SILICON PHOTODIODES

Experimental physics, biology, chemistry, diagnostic medicine, and several other aspects of modern technology take advantage of the unique properties of solid-state detectors as fast, accurate and efficient position sensitive devices. In particular, silicon detectors are the foundation of precision tracking system, such as micro-strip or pixel devices used in particle physics. Photodiodes are widely used to convert light signals into electrical signals. We will use photodiodes to illustrate the main properties of silicon detectors.

In general, modern silicon detectors are based on the p-n junction that you may have encountered in previous electronics courses as a rectifying element, conducting almost perfectly current in one direction and being an almost open circuit for DC currents in the opposite direction.

Detector grade silicon is generally a high purity crystal. It has high resistivity, implying that most of the crystal electrons are in the valence band. Thermal motion may promote 1 e⁻ to the conduction band, leaving a "hole" [absence of an electron, behaving from the electrical point of view as a positive charge] in the valence band. Thus intrinsic Si is a device that carries current through 2 different carriers, electrons and holes. The key technology that allows the production of silicon detector is controlled doping of the intrinsic Si device. Si is a group 4 element. Fig 1 shows a schematic view of an n-type silicon, where a substitutional P atom has replaced a Si atom and a negative-charge electron is "donated" to the conduction band. This produces an excess of electrons in the conduction band: the electrons become the majority current carriers in this device.

An interesting process happens when p-type and n-type silicon share a boundary surface (pn junction). The majority carriers from the two regions flow across the boundary and "annihilate each other". Thus a "space charge region" is formed, deplete of charge carriers:



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The space charge produces a potential difference that is called **built-in potential** that prevents further flow of majority carriers from one region to the area. An external potential modulates this intrinsic potential barrier: if the sign of the external voltage across the junction is opposite to the one of the built in potential, current is resumed [positively biased diode], if the sign of the external voltage is the same as the built-in potential, the potential barrier increases and the size of the space charge region is increased.

The reverse-biased diode is the key element of modern photon detectors such as photodiodes or silicon strip detectors. The space charge region is a region of non-zero electric field [remember the electric field inside a capacitor]. Now we have all the elements to build a silicon detector, whose behavior is illustrated in Fig. 3. For simplicity, the bulk of the detector is assumed fully depleted [the space-charge region touches the bottom electrode]. Generally, silicon detectors are built with a very asymmetric junction, so that the space charge region occupies mostly the n-type component of the junction.



4. CIRCUITS USING OP AMPS

Following is a series of op amp circuits to build and perform experiments upon. Each is to be built on the solderless breadboard using circuit components and jumper wires. If you need a refresher on the use of an oscilloscope, refer to the online material provided on the activities webpage.

Experiment 1. The Operational Amplifier in Inverting Configuration



Measurement I: Use the digital scope to measure the response to a square wave for this circuit. Observe the gain, and the rise time [time it takes to v_{out} to go between 10% and 90% of its full swing.

Measurement II: Use an input signal of sinusoidal shape, and use the digital scope to measure the gain [ratio between V_{out} and V_1] and the phase between V_{out} and V_1 at different frequencies. In particular, measure the region close to the frequency at which you would expect to see the effects of the frequency dependence of the response of the operational amplifier.

Measurement III and IV: Repeat measurement I and II changing RF to 10 K. Which changes do you see in the key properties of the gain as a function of time or frequency?

Analysis: Discuss the results that you obtained in the context of deviations from ideal behavior in an operational amplifier.

Experiment 2. A Summing Amplifier

Now you are in a position of designing a circuit that performs the analog sum between two waveforms and a circuit which performs the analog difference between two waveforms. Draw the circuit diagram and calculate the resistors that you would be using to assemble one such circuit. You can then build a circuit which makes the sum of the original waveform and the output of an operational amplifier circuit which has the original waveform as input and is configured with gain -2. Construct a VI which samples the input waveform and the output one using a TTL signal synchronous with the input signal as a digital trigger and display the input and output waveforms with a waveform graph. Note: for this VI use a 1 KHz sine wave as the signal. Specify the source that you choose.

If you need a reference for this, use the circuit collection by Bob Pease, linked on the activities webpage.

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Experiment 3. The Transimpedance Amplifier
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A very nice way to measure current exploits some properties of the ideal operational amplifier, namely the very high input impedance seen at the inverting and non inverting inputs and the very low output impedance at the output node.



Figure 4. An op amp configured as a transimpedance amplifier.

See if you can convince yourself that the circuit shown in Figure 4 has the "transimpedance gain" given by: $V_{\text{out}} = -R1 I1$. If V_{out} is very small, you will have to subtract the offset voltage [Vout without any input current].



Figure 5. Transimpedance amplifier circuit (to build).

Experimental set-up: Build the circuit shown in Figure 5. Proceeds in two steps: first build the transimpedance amplifier and measure the offset voltage [V_{out} in this configuration]. Then attach the photodiode and its biasing circuit. Make sure that V_2 has a positive polarity: if you bias the photodiode with a high forward voltage, too much current will flow and you may burn the device! To provide V_2 , use the variable 2-20 V power supply.

Measurement: Measure the dark current as a function of the applied reverse bias. In order to make a precise measurement, start by building the transimpendance amplifier and measure the offset [vout without the photodiode attached to the transimpedance to the inverting input].

Analysis: Plot I_{dark} versus V2 [the reverse bias]. What can you say about the dependence of the dark current upon the reverse bias?

Experiment 4. The Photodiode Response to a Light Signal from an LED

Now, all elements from this lab will be combined.



Experimental set-up: Position an LED to face the photodiode. You should bias it with the pulse generator configured to produce a positive square pulse of about 1.5 V. Use a big series resistance to provide some current limit. If you are not provided with the set-up in the black box you should try to shield the LED-photodiode pair from the light.

Measurement: Observe the output when the LED is pulsed. Increase the amplitude of the LED biasing pulse and observe its effects.

Analysis: Relate your observations to your expectations on the basis of the properties of this photon detector. Describe the signal and any additional noise that you may observe.

Can you explain your observations? If you see noise, you may try to guess the source and how you would improve on this apparatus.

5. REFERENCES

[1] Horowitz and Hill, The Art of Electronics, 2nd ed., McGraw-Hill (1995).

[2] Bob Pease, Op Amp Circuit Collection, Texas Instruments (2005).

This document is based on the laboratory write-ups by M. Artuso, for the SU course PHY351 Modern Instrumentation (2010). Additional contributions to this write-up by: R. Mountain and Dylan Hsu, for the SU QuarkNet Workshop (2012).