Operational Amplifiers

Qingmu “Josh” Deng

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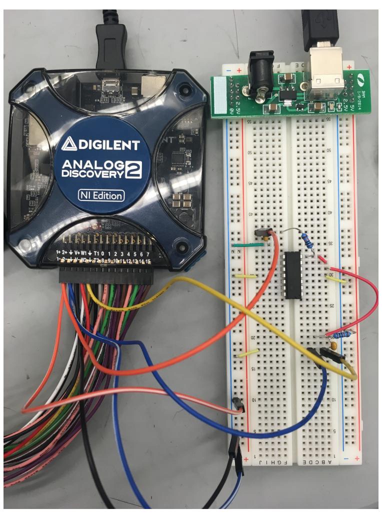
Abstract

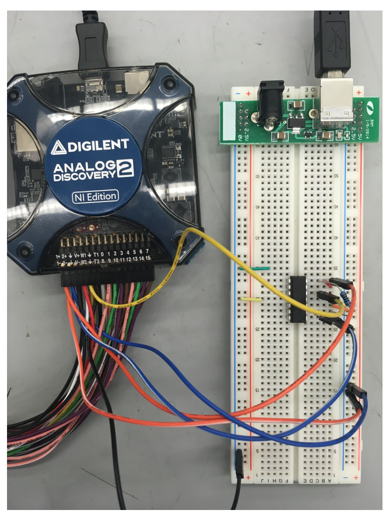
The purpose of this lab is to familiarize students with behaviors of a typical operational amplifier and basic usage of it in real world applications.

1 Description

In this lab, various circuits were constructed to understand the applications of an operational amplifiers. First of all, the voltage across one of the two 1 $M\Omega$ was measured directly with Analog Discovery and then with an added op-amp follower. The idea of op-amp follower was subsequently used again in a multi-filter circuit. The first configuration was a high pass filter immediately followed by a low pass filter; the other configuration included an op-amp follower between the high pass filter and the low pass filter. The voltage measurements were taken cross the capacitor in the low pass filter. The third general circuit is a non-inverting amplifier that is referenced at 2.5V or 0V while the supply voltage of the op-amp was kept to be 5V and 0V, and the output of op-amp was recorded. The fourth and final circuit consisted of 2 op-amps, a resistor, and a “black box”, which could be any analog components. The current flowing in the circuit can be easily changed or determined with the resistor placed in the circuit.



(a) The multi-filter circuit that took advantage of an op-amp follower.



(b) The “black box” circuit with a diode.

Figure 1: Lab setups

2 Evidence

2.1 Op-amp Follower

With the input voltage measured to be 5.121V, the voltage measured across one of the two 1 $M\Omega$ resistors was 1.732V. With an op-amp follower added to the circuit, in contrast, the measurement became 2.545V.

The idea of an op-amp follower was also applied to a low-pass and a high-pass filter in series. Figure 2 shows the resulting Bode plot with the blue line denoting the measurement without the op-amp, the red line denoting that with the op-amp, and the green line denoting the ideal model.

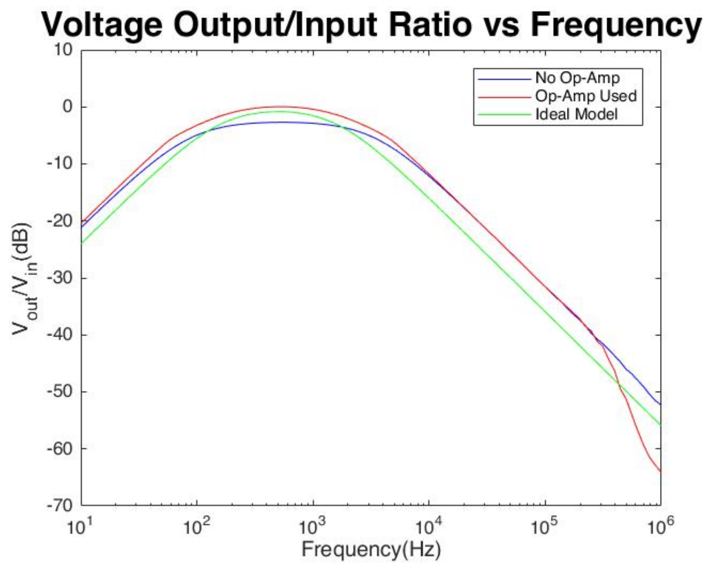
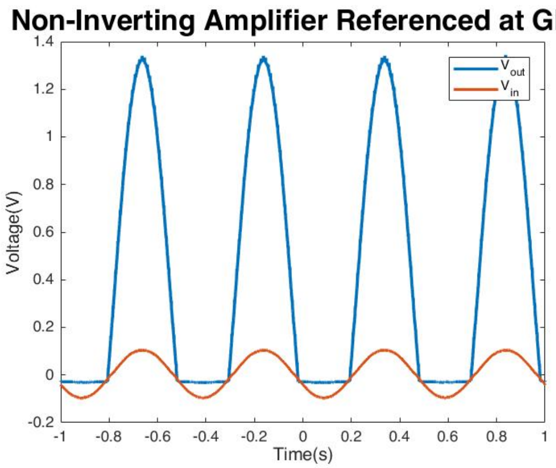


Figure 2: A combined Bode Plot of the multi-filter circuit with and without the op-amp and its ideal curve.

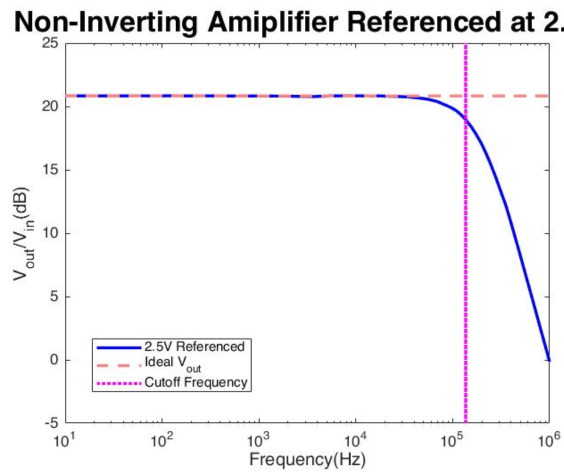
2.2 Amplifier

In this section, measurements were taken at the output voltage of a non-inverting amplifier that was either referenced at 2.5V or at 0V. For the former, a 100mV amplitude sinusoidal signal with an offset of 2.5 volts would ultimately give a measured input with an amplitude of 97.4mV and a measured output with an amplitude of 1.0984V. The same voltage supplied to an op-amp reference at ground would constantly peak out at 5V which was the top rail of the op-amp. When the offset was changed back to 0V, the output would be cut off for anything below 0V as shown in Figure 3(a). At this time, the amplitude at the input was 59.5mV, and that at the output was 644.2mV.

To also test the limit of the op-amp, a Bode plot ranging from 10Hz to 1 MHz was generated with 100mV amplitude signal with an offset of 2.5 V with the op-amp referenced at 2.5V. The Bode plot is shown in Figure 3(b).



(a) A combined Bode Plot of the multi-filter circuit with and without the op-amp and its ideal curve.



(b) Bode Plot of a non-inverting amplifier referenced at 2.5V.

Figure 3: Section Amplifier

2.3 Set current, measure Voltage

The first set of measurement in this section was taken with one 1 $M\Omega$ resistor and .1 μF capacitor. Five different voltages were used for input that would generate different currents flowing through the resistor and the capacitor. The table below sums up all the values.

Table 1: $\frac{dV}{dt}$ versus Amplitude

Amplitude(mV)	100	200	500	1000	2000
$\frac{dV}{dt}$**(rising)(V/s)**	.6085	1.586	4.445	9.145	18.45
$\frac{dV}{dt}$**(falling)(V/s)**	-1.387	-2.346	-5.226	9.920	-19.150

The current flowing through the circuit was calculated using Ohm's law for all five voltages.

$$I = \frac{V_{in} - 2.5V}{1M\Omega} \tag{1}$$

Table 2 shown below provides the calculated results.

Table 2: Current versus Amplitude

Amplitude(mV)	100	200	500	1000	2000
Current(rising)$(10^{-7}$**A)**	.504	2.00	5.04	10.12	20.03
Current(falling)$(10^{-7}$**A)**	-1.504	-2.00	-5.04	-10.12	-20.03

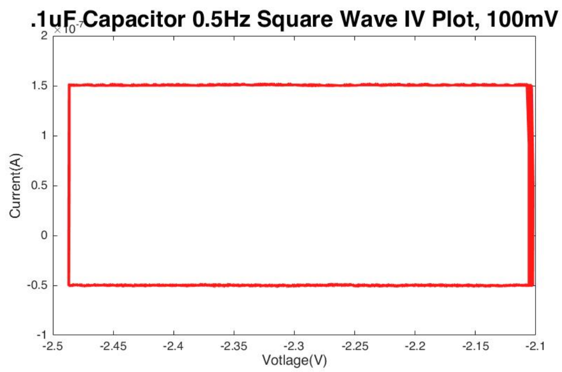


Figure 4: I-V plot of $.1\mu F$ capacitor with 100mV amplitude square wave.

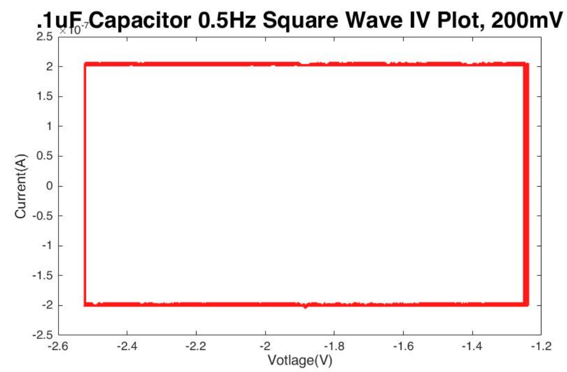


Figure 5: I-V plot of $.1\mu F$ capacitor with 200mV amplitude square wave.

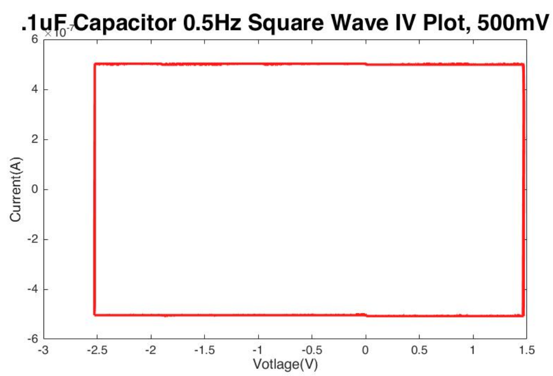


Figure 6: I-V plot of $.1\mu F$ capacitor with 500mV amplitude square wave.

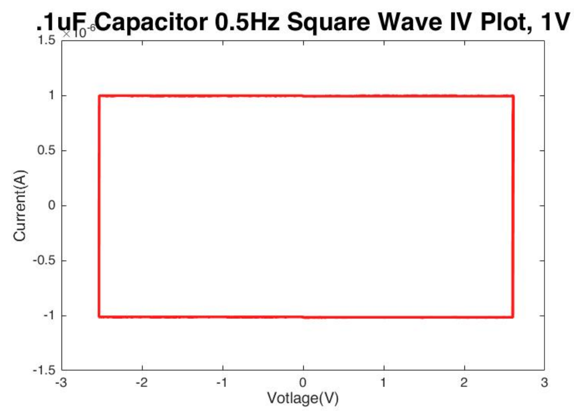


Figure 7: I-V plot of $.1\mu F$ capacitor with 1V amplitude square wave.

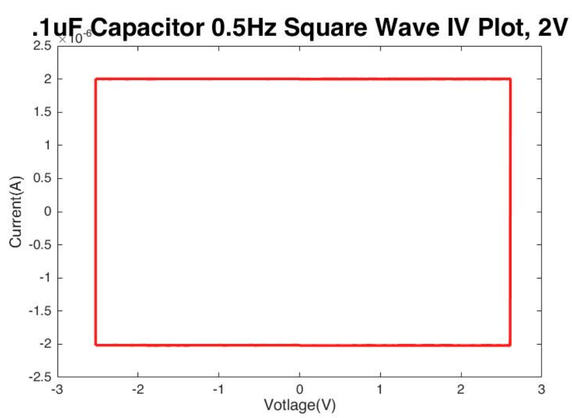


Figure 8: I-V plot of $.1\mu F$ capacitor with 2V amplitude square wave.

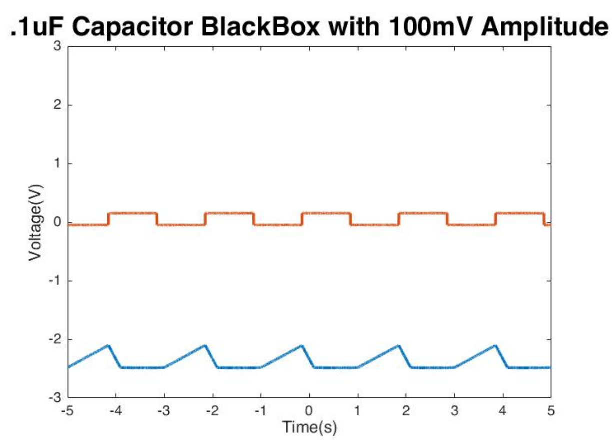


Figure 9: $.1\mu F$ capacitor with 100mV amplitude square wave and output over time.

Finally, the 1 $M\Omega$ resistor was replaced with a 100 Ω resistor, and a LED was in place of the black box. An I-V plot, shown on the next page, was provided for the diode. The current was also calculated with Equation (1).

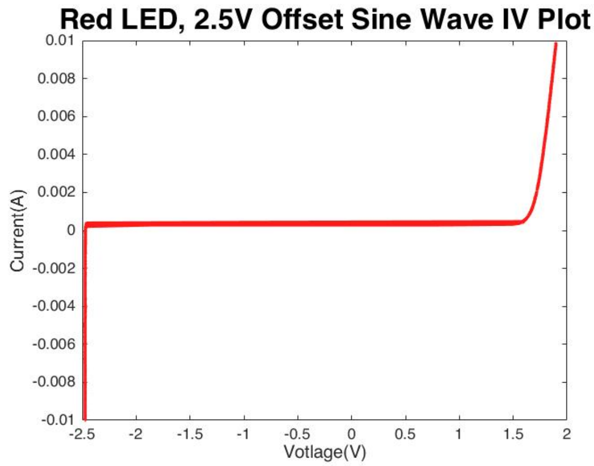


Figure 10: I-V plot of a red light emitting diode with 1V amplitude, 2.5V offset, 10Hz sine wave

3 Interpretation

3.1 Op-amp follower

For measuring the voltage across one of the two 1 $M\Omega$ resistors in series without an op-amp, V_{out} turned out to be 1.732V which is about only $\frac{1}{3}V_{in}$ due to the internal resistance of Analog Discovery. However, with the op-amp follower, V_{out} was measured to be 2.545V, which was what we would be expecting from the theoretically calculated $\frac{1}{2}V_{in}$. The reason behind the correct measurement with an op-amp was that, first, it was built to have negative feedback so that the positive input and the negative input can be treated to have the same voltage, and since the output of the op-amp is wired to the negative input, the output voltage is also equal to the positive input which is $\frac{1}{2}V_{in}$. As the inputs of an op-amp draws almost no current, $\frac{1}{2}V_{in}$ would not be disturbed, and voltage measurement can be taken at the op-amp's output where as much current as Analog Discovery would need to measure the circuit can be supply.

The same reason applies to the multi-filter system as the op-amp follower created isolation between the two filters and eliminate the coupling effect that would otherwise happen when the two filters were in series. As shown in Figure 2, the circuit without the op-amp follower never reaches 0 dB and is slightly below the curve with the op-amp follower used. Nevertheless, the use of an om-amp was not without setbacks. At around 3×10^5 Hz, the voltage output/input ratio in decibel started to drop off significantly due to the involvement of an op-amp.

To model the ideal behavior of the filters, the following equation for high pass and low pass filters are used:

$$A_{HP} = \frac{2\pi RC\omega}{\sqrt{1 + (2\pi RC\omega).^2}} \tag{2}$$

$$A_{LP} = \frac{1}{\sqrt{1 + (2\pi RC\omega).^2}} \tag{3}$$

The product of A_{HP} and A_{LP} is the resulting ideal model. Unfortunately, the model fits neither measurement very well. It might be due to the fact that the measurement were taken with 2.5V offset and 1V amplitude.

3.2 Amplifier

For a non-inverting amplifier, the relationship between the op-amp output and input is given by:

$$V_{out} = \frac{R1 + R2}{R2} V_{in} \tag{4}$$

Since we are using $10k\Omega$ for R1 and $1k\Omega$ for R2, the equation becomes:

$$V_{out} = 11Vin \tag{5}$$

This holds true for both the non-inverting amplifier referenced at 2.5V and that at 0V.

$$2.5V : \frac{V_{out}}{V_{in}} = \frac{1.0984V}{97.4mV} \approx 11.3 \tag{6}$$

$$0V : \frac{V_{out}}{V_{in}} = \frac{644.2mV}{59.5mV} \approx 10.8 \tag{7}$$

An interesting experiment was carries out on the circuit referenced at 2.5V. As shown in Figure 3(b), when the frequency of the input increases from 10 to 10^6, the ratio start dropping significantly at around 10^5Hz, just like what a low pass filter Bode plot would look like. According to my research online, the "cutoff frequency" of a op-amp is equal to its Gain Bandwidth Product divided by the voltage gain. The Gain Bandwidth Product of LMC6484 can be found in its datasheet to be 1.5MHz.

$$f_c = \frac{Gain\ Bandwidth\ Product}{Gain} = \frac{1.5MHz}{11} \approx 1.36 \times 10^5 Hz \tag{8}$$

The cutoff frequency is shown in Figure 3(b) in purple, and the line looks to be fitting the overall data well.

The benefit of referencing the circuit at 2.5V rather than 0V was also explored in this section. With an input offset of 2.5V and the circuit referenced at ground, the output peaked out at 5V constantly. When the offset was dialed back to 0V, the negative half of the input were simply cut out from the output as shown in Figure 3(a). The limitation mainly coming from the power supply whose highest output is 5V and whose lowest output is 0V. What referencing the circuit at 2.5V does is to allow for the measurement to go both up and down 2.5V with respect to +2.5V so that we won't be hitting either 5V or 0V rail the whole time.

3.3 Set current, measure voltage

As provided before, the current flowing through the resistor, or essentially the current flowing through the black box because of KCL and the op-amp property that it draws nearly 0 current, is calculated through Equation (1). However, since Channel1 was measuring the voltage across the resistor, the current can be easily calculated by dividing Channel 1 data by the resistance.

To check the circuit's conformity to the capacitor law,

$$\frac{dV}{dt} = \frac{I}{C} \tag{9}$$

the above equation is applied to the data collected. The results are shown as follows:

Table 3: Measured and Calculated $\frac{dV}{dt}$

Amplitude(mV)	100	200	500	1000	2000
$\frac{dV}{dt}$**(rising)(V/s)**	.6085	1.586	4.445	9.145	18.45
$\frac{dV}{dt}$**(cal)(V/s)**	.504	2.00	5.04	10.12	20.03
$\frac{dV}{dt}$**(falling)(V/s)**	-1.387	-2.346	-5.226	-9.920	-19.150
$\frac{dV}{dt}$**(cal)(V/s)**	-1.504	-2.00	-5.04	-10.12	-20.03

For the measurements, a general pattern that can be observed is that the charging up of the capacitors is not as steep as the discharging. That pattern is the most obvious with 100mV amplitude input and becomes less and less some as the amplitude rises higher. Even though the error between the calculated and the actual values of $\frac{dV}{dt}$ is often quite easy to spot in the table, the two still sticks to the same trend quite well. The error may simply come from measurement error because measuring $\frac{dV}{dt}$ at different points would return slightly different results.

An I-V plot was also generated for the red light emitting diode in Figure 10. For a diode, light emitting diodes included, there is usually a forward voltage and a reverse breakdown voltage. A diode would only allow current to flowing from its anode to its cathode but not vice versa, and current only starts to flow provided enough forward voltage is present. For a red light emitting diode, that forward voltage is usually around 1.65V. As we can see in the plot, the current is pretty much 0 until the voltage supplied goes beyond roughly 1.65V. Often, when a reverse voltage is applied to a diode, very limited current will be allowed through the diode. Given that the reverse voltage is large enough, however, the current will start to flow backwards just like in a normal wire. In Figure 10, as the reverse voltage reaches 2.5V, the amount of current spikes sharply.