

**EE320L Electronics I**

**Laboratory**

**Laboratory Exercise #2**

**Basic Op-Amp Circuits**

**By**

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**Objective:**

The purpose of this lab is to understand the basics of operational amplifiers, their use as inverting and noninverting amplifiers and gain-bandwidth trade-offs.

**Equipment Used:**

Power Supply

Oscilloscope

Function Generator

Breadboard

Jumper Wires

TL082 or LF412 Dual JFET Input Operational Amplifiers

10x Scope Probes

Various Resistors and Capacitors

## Background:

### Basic Op-Amp Circuits

The operational amplifier or “op-amp” is perhaps the most important electronic component ever invented. With a minimal of understanding of its inner workings, anyone can use an op-amp for common electronic engineering tasks such as amplification and filtering. The name operational amplifier comes from the fact that historically they were used to perform mathematical operations particularly integration and differentiation. Many real world problems modeled by differential equations were solved using op-amps. This role has completely been superseded by digital computers in the modern era. The first op-amps appeared in the late 1940s and were based on vacuum tubes crammed into a brick sized module. With the invention of transistors these modules became smaller bricks. Finally, the invention of the low-cost monolithic (fabricated on a single chip) op-amp resulted in op-amps being incorporated in almost all electronic devices. The availability of low-cost, high performance op-amps allows the design of sophisticated electronic circuits with a minimal of math equations and dispenses with the complicated biasing schemes of discrete transistor circuitry.

A modern op-amp has dozens to hundreds of transistors integrated on a single chip. It is not necessary to understand how the internal circuitry works in order to use the op-amp; it can be treated as a “black-box” device. The symbol for an op-amp is shown in fig. 1. This is the most basic op-amp symbol with five terminals comprised of positive (non-inverting) and negative (inverting) inputs;  $V+$  and  $V-$  supply terminals; and one output. All equations that describe the behavior of op-amp circuits rely on certain assumptions about the op-amp. These assumptions about an ideal op-amp are summarized in table 1 and compared to the real op-amp used in this lab, the TL082. A modern op-amp approaches an ideal op-amp when used within its bandwidth and output limitations. For non-critical applications the ideal op-amp assumptions are valid. In the case of the TL082 as long as the device is operated at low frequencies and does not exceed its rated output voltage and current limits the ideal assumptions are valid.

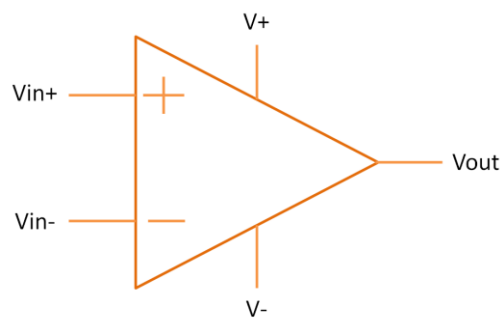


Figure 1 Basic Op-Amp Symbol

Parameter	Ideal Op-Amp	TL082
Input Resistance looking Into Vin+ and Vin- Terminals	Infinite	1 Tera-ohm
Open Loop Gain	Infinite	200,000
Bandwidth	Infinite	3 MHz
Voltage Output	Infinite	+/- 13.5V
Current Output	Infinite	20mA
Output Resistance	Zero	80 ohm (open-loop)
Input Offset Voltage	Zero	3 mV
Input Bias Current	Zero	30 pA

Table 1 Comparison of Ideal Op-Amp and TL082

The behavior of an op-amp can be described by two rules. These rules are:

1. *An op-amp will attempt to make the voltage at both its inputs equal through the use of a feedback path.*
2. *If rule one cannot be followed, then the output takes the polarity of the input with higher magnitude.*

The function of most op-amp circuits is based on these two rules. An example of op-amp behavior that can be explained by rule 1 is the case of the simple inverting amplifier. This circuit configuration is shown in fig. 2. With nothing applied to the input, the op-amp's output follows the voltage at the positive input which is grounded. Both inputs and the output are at 0V. Rule #1 is satisfied. If a 1V positive step is applied to "Vin", then this equilibrium is disturbed. A current flows through the "Rin" resistor equal to  $I_{in} = \frac{V_{in}-0}{R_{in}}$  the zero comes from the fact that the inverting input was at zero volts. This current cannot flow into the inverting input of the op-amp because of the infinite input resistance. When current is injected into a node the voltage at that node rises. Conversely when current is taken out of a node the voltage at that node falls. The voltage at the inverting input begins to rise, which causes the output voltage to drop. This is because of the nature of the inverting input; the output does the opposite of what is applied to the inverting input. As the output voltage drops, a current begins to flow because of the imbalance in voltage between the inverting input and the output. This current flow, being of opposite sign, cancels out the input current. This current cancellation is what maintains the inverting input at zero volts. The current flowing through the feedback resistor causes a "voltage drop" which is the output voltage. The most important thing to remember is that the currents flowing in Rin and Rf are equal. If Rf is larger than Rin, to maintain an equal current the voltage at Vout must be of larger magnitude than the voltage at Vin. This is what causes this circuit to operate as a voltage amplifier. This explanation may seem more complicated than the traditional explanation seen in textbooks; however it is more intellectually satisfying.

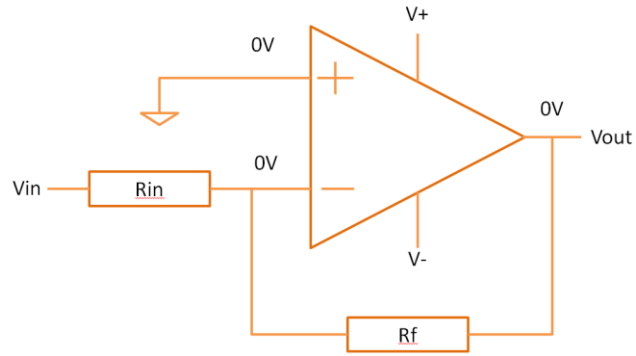


Figure 2 Inverting Amplifier with All Inputs and Outputs in Equilibrium

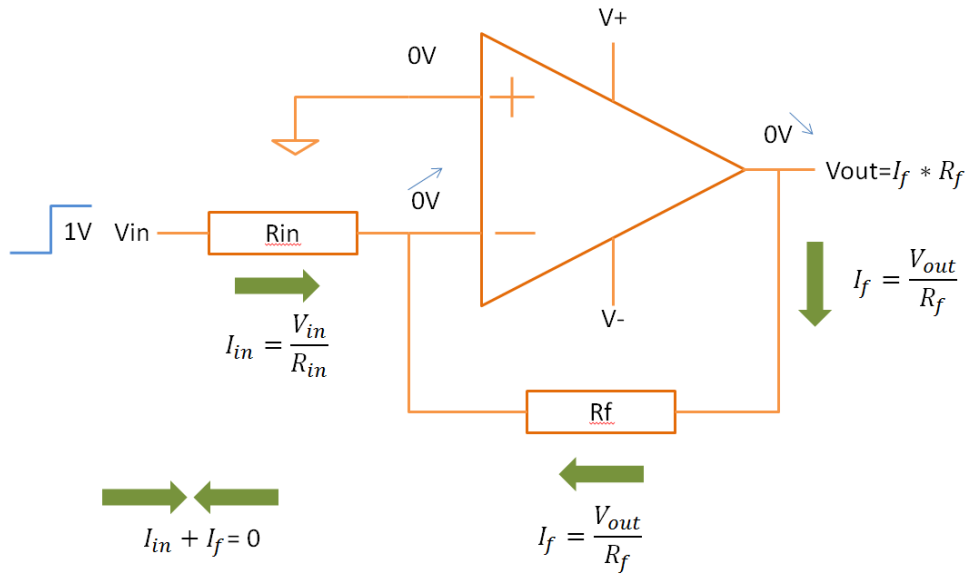


Figure 3 Current Flow in Inverting Amplifier

The traditional explanation of the inverting amplifier uses only one current as shown in fig. 4. The input current that flows into the input resistor cannot flow into the inverting input. It must flow through the feedback resistor  $R_f$  since this is the only path. However since current flows from positive to negative, the voltage at the output must be negative since the voltage at the inverting input is zero. In this case zero is the higher voltage. There is nothing wrong with this explanation, however it isn't clear what exactly the op-amp is doing. It fades into the background when it should be portrayed as the main actor.

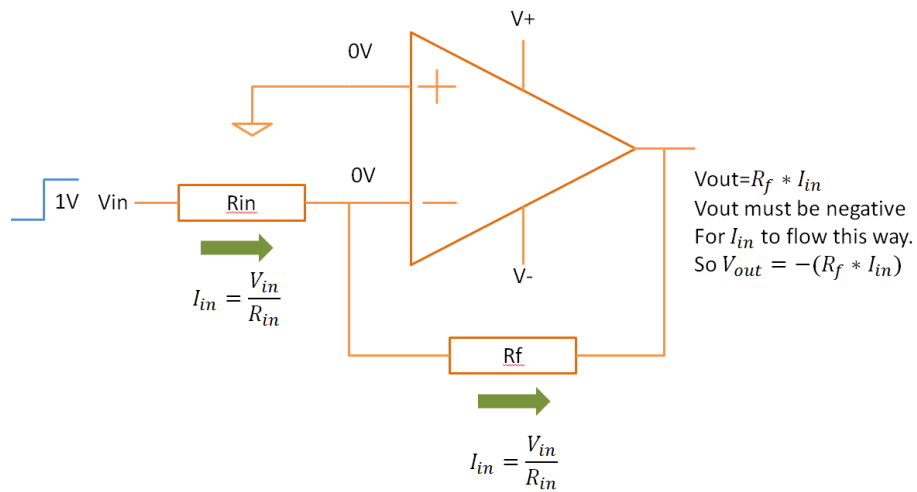


Figure 4 Traditional Analysis of Inverting Amplifier

The analysis of the non-inverting amplifier is considerably simpler. A schematic of the non-inverting amplifier is shown below in fig. 5. If a voltage is applied to the noninverting input then the output voltage will become whatever value is necessary to maintain the inverting input at the same value as the non-inverting input. The two resistors  $R_f$  and  $R_g$  form a voltage divider between the output of the op-amp and the inverting input. This means that there will always be a fixed relationship between the voltage at the inverting input and the output. This is what causes amplification. The relationship is clearly seen in the given equation for the inverting node voltage in fig. 5. For an example with numbers, assume that a 1V input is applied into the non-inverting input and assume that  $R_f$  has a value of 10k and  $R_g$  has a value of 1k. For 1V to appear at the inverting input, the output needs to be at 11V. This 11V is divided down by the voltage divider to 1V. Finally, from the formula it is clear that omitting  $R_g$  completely created an amplifier with a gain of 1. This topology is called a unity gain buffer. The feedback resistor can be removed and the output directly shorted to the inverting terminal but it is good practice to use a small feedback resistor (1-10 ohm) to prevent oscillation.

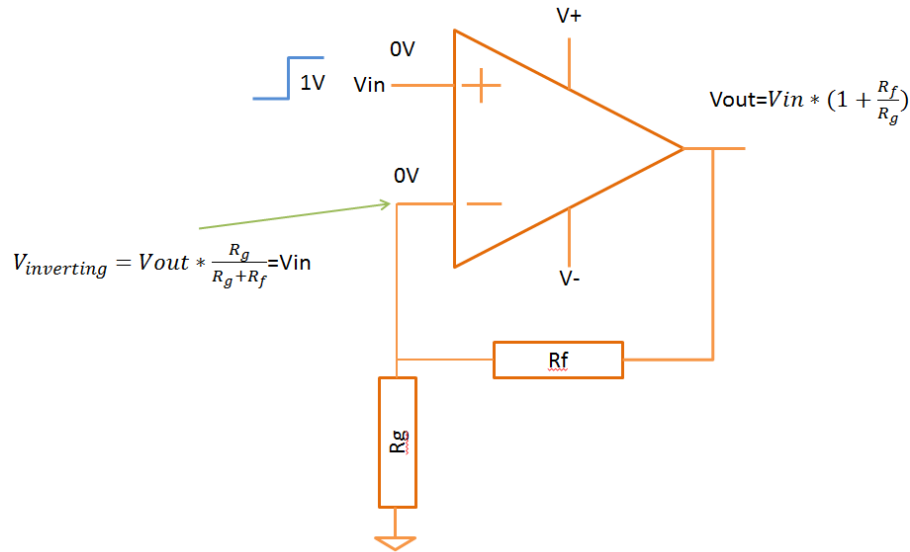


Figure 5 Non-inverting Amplifier

One of the most important parameters when selecting an op-amp is the gain-bandwidth product. The gain-bandwidth product, as implied by the name, is simply the product of the maximum open-loop gain at DC with the bandwidth of the amplifier at a gain of one. There is a trade-off between the gain of an op-amp and its bandwidth. This is illustrated in fig. 6 below. The maximum gain of 110dB or 200,000 is only possible for input signals which are at a very low frequency, typically under a few dozen Hz. After this point, the gain falls as frequency increases. The gain-bandwidth product appears as a straight line when plotted on a graph with X and Y logarithmic axes. Fig. 7 shows how to use the gain-bandwidth plot to characterize the bandwidth of an amplifier. The frequency response is constant until the green line hits the orange line, after which there is steady 10dB attenuation per decade.

Since most manufacturers don't provide this graph on their datasheets it is important to learn how to calculate the bandwidth for an amplifier with a certain gain. For example let's say that a gain of 100 with a bandwidth of 100 KHz is desired. The product of these two numbers is 10 million. This requires an op-amp with a specified GBW product of 10 million or a unity-gain bandwidth of 10 MHz. For most general purpose op-amps it is appropriate to use the unity-gain bandwidth specified on the datasheet as the GBW product.

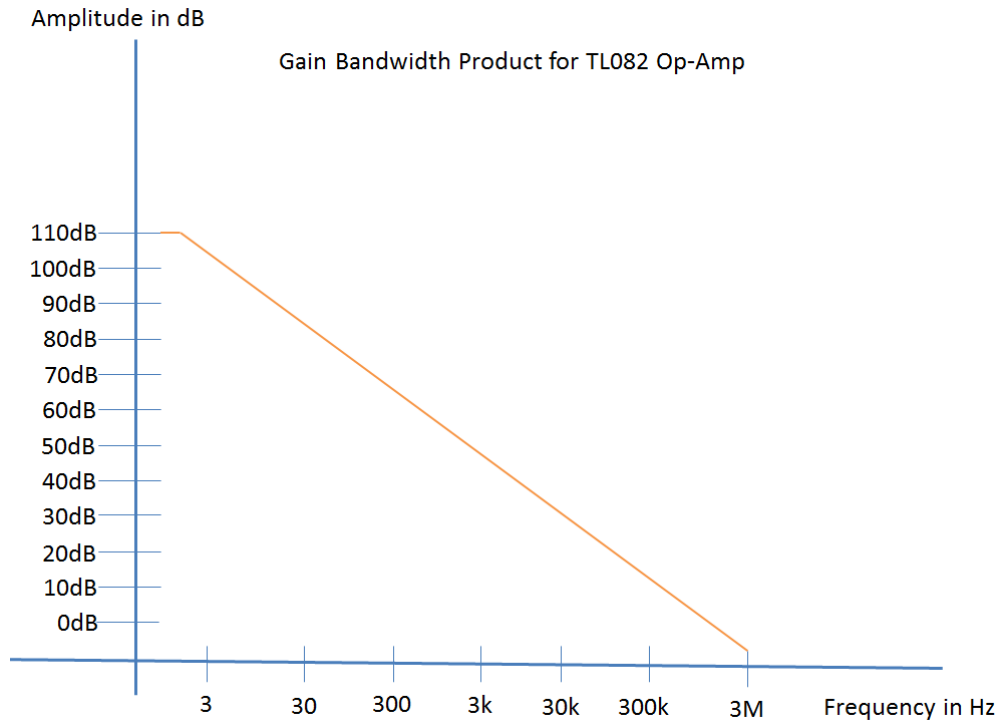


Figure 6 Gain Bandwidth Product for TL082 Op-Amp

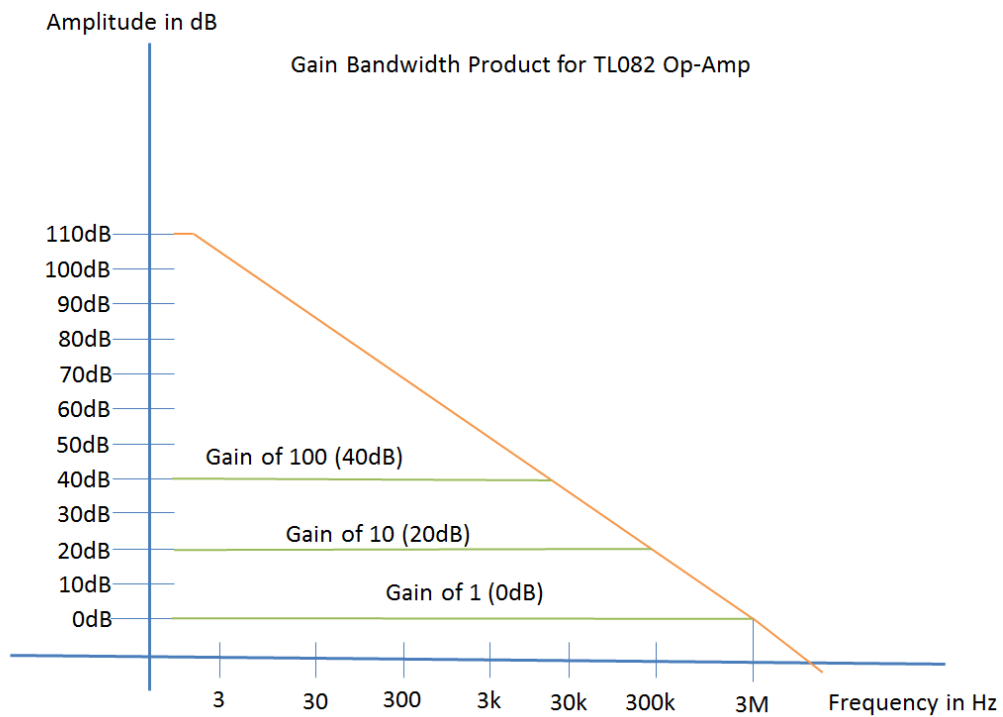


Figure 7 Bandwidth for Different Amplifier Gains

## Prelab:

### **Analysis 1: Transient Simulation of Inverting Amplifier**

Simulate an inverting amplifier with a gain of -10 as shown in fig. 8 below. The op-amp is the “UniversalOpamp2” component found in the “Opamps” directory of LTSpice. Fig. 9 shows the selection of this component. The parameters of this part need to be edited to accurately match the parameters of the desired op-amp. Right-clicking on the op-amp symbol brings up the attribute editor in fig. 10. Change the default values to the ones seen in fig. 10. These values are taken from the datasheet of the LF412CN op-amp. These values are reproduced from the datasheet in fig. 11. Next, edit the voltage source’s parameters at the input of the op-amp by right-clicking on it. Match the values to be the same as fig. 12. The reason for using a series resistance of 50 ohm is to accurately model the function generator in the lab which has a 50 ohm output impedance. For our frequencies it is unlikely that this parameter has much influence but it is good to include it for the sake of completeness. Also the AC value of 1V is not needed for a transient simulation but it will be used in the next simulation. Next, edit the simulation command to run a transient analysis for 10m seconds as shown in fig. 13. The input and output waveforms should look like fig. 14. The output is 10 times larger in amplitude and inverted compared to the input.

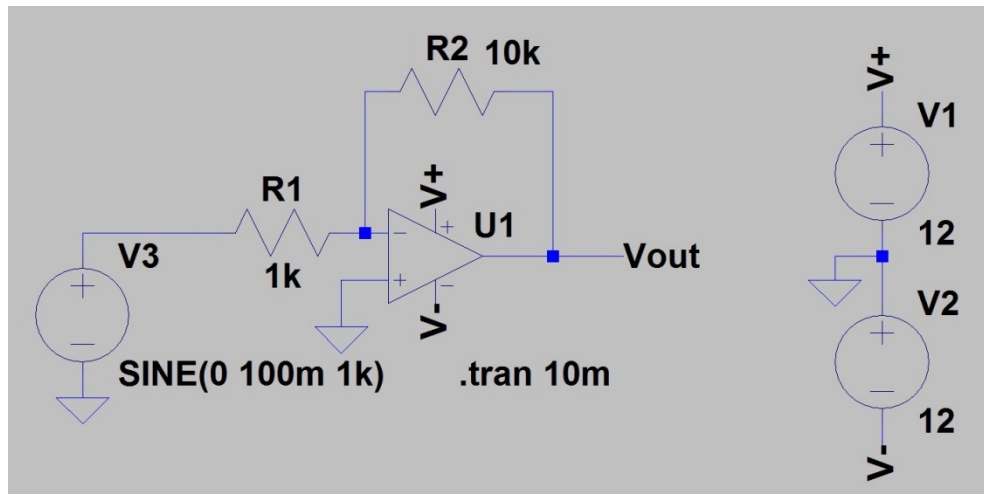


Figure 8 Inverting Amplifier with a Gain of -10



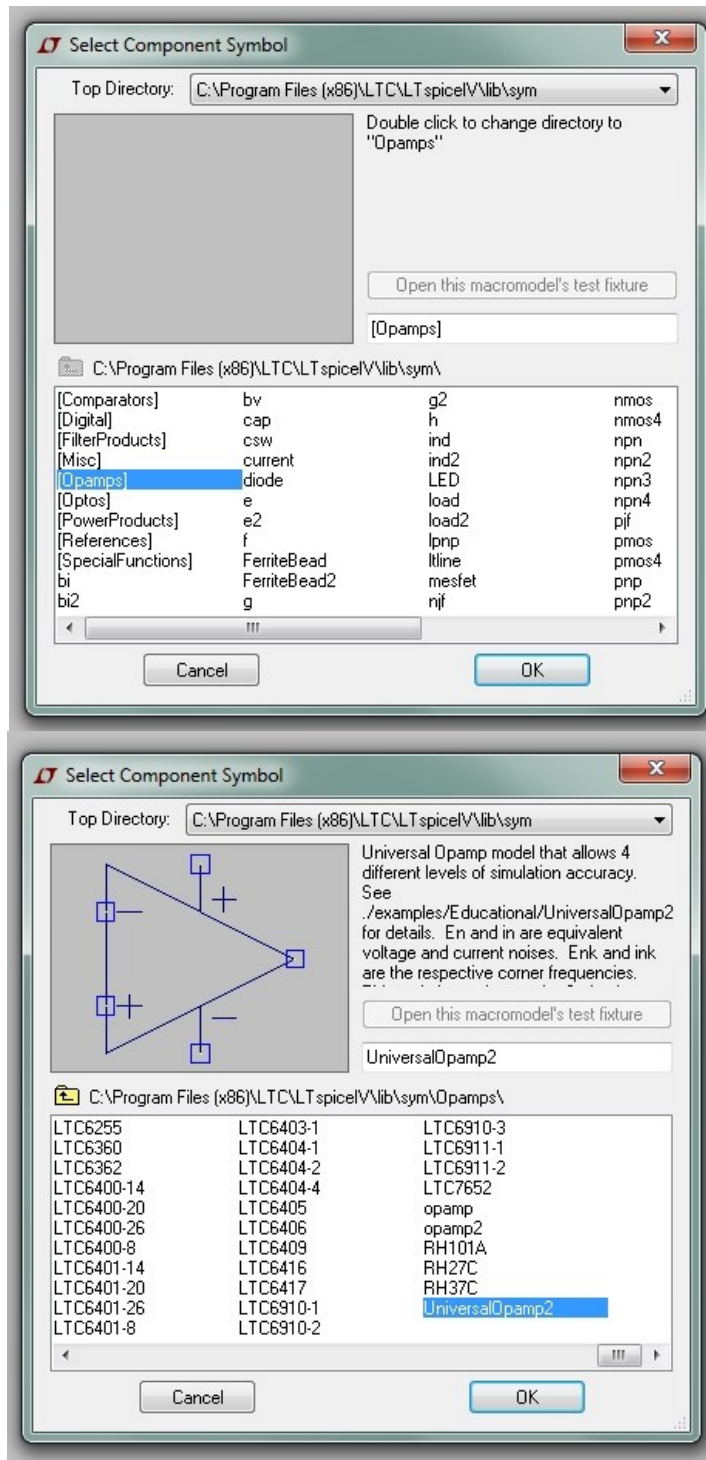


Figure 9 "UniversalOpamp2"

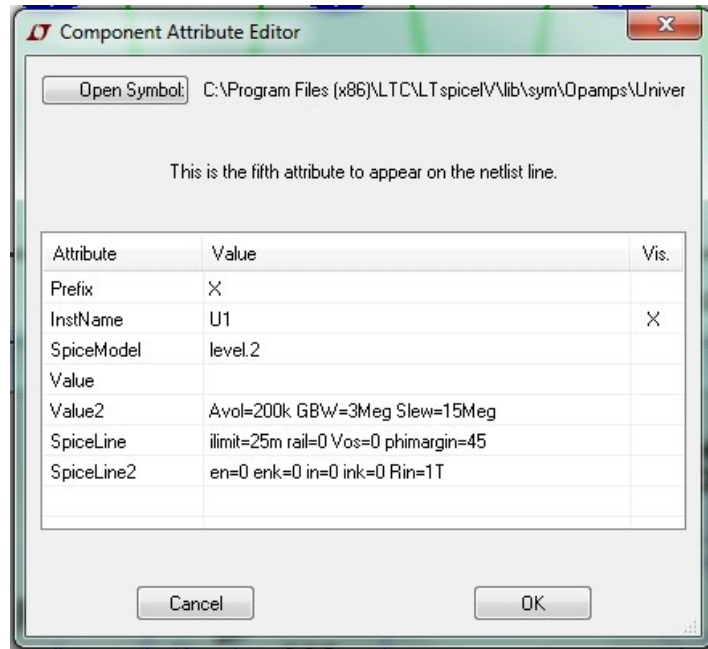


Figure 10 Attribute Editor for “UniversalOpamp2”

### DC Electrical Characteristics

Symbol	Parameter	Conditions	LF412A <sup>(1)</sup>			LF412 <sup>(1)</sup>			Units
			Min	Typ	Max	Min	Typ	Max	
V <sub>OS</sub>	Input Offset Voltage	R <sub>S</sub> =10 kΩ, T <sub>A</sub> =25°C		0.5	1.0		1.0	3.0	mV
ΔV <sub>OS</sub> /ΔT	Average TC of Input Offset Voltage	R <sub>S</sub> =10 kΩ <sup>(2)</sup>		7	10		7	20	μV/°C
I <sub>OS</sub>	Input Offset Current	V <sub>S</sub> =±15V <sup>(1)</sup> (3)	T <sub>J</sub> =25°C	25	100		25	100	pA
			T <sub>J</sub> =70°C					2	nA
			T <sub>J</sub> =125°C					25	nA
I <sub>B</sub>	Input Bias Current	V <sub>S</sub> =±15V <sup>(1)</sup> (3)	T <sub>J</sub> =25°C	50	200		50	200	pA
			T <sub>J</sub> =70°C					4	nA
			T <sub>J</sub> =125°C					50	nA
R <sub>IN</sub>	Input Resistance	T <sub>J</sub> =25°C		10 <sup>12</sup>		10 <sup>12</sup>		Ω	
A <sub>VOL</sub>	Large Signal Voltage Gain	R <sub>L</sub> =2k, T <sub>A</sub> =25°C	50	200		25	200		V/mV
		V <sub>S</sub> =±15V, V <sub>O</sub> =±10V, Over Temperature	25	200		15	200		V/mV
V <sub>O</sub>	Output Voltage Swing	V <sub>S</sub> =±15V, R <sub>L</sub> =10k	±12	±13.5		±12	±13.5		V
V <sub>CM</sub>	Input Common-Mode Voltage Range		±16	+19.5		±11	+14.5		V
				-16.5			-11.5		V
CMRR	Common-Mode Rejection Ratio	R <sub>S</sub> ≤10k	80	100		70	100		dB
PSRR	Supply Voltage Rejection Ratio		(4)80	100		70	100		dB
I <sub>S</sub>	Supply Current	V <sub>O</sub> = 0V, R <sub>L</sub> = ∞		3.6	5.6		3.6	6.5	mA

### AC Electrical Characteristics

Symbol	Parameter	Conditions	LF412A <sup>(1)</sup>			LF412 <sup>(1)</sup>			Units
			Min	Typ	Max	Min	Typ	Max	
	Amplifier to Amplifier Coupling	T <sub>A</sub> =25°C, f=1 Hz-20 kHz (Input Referred)		-120			-120		dB
SR	Slew Rate	V <sub>S</sub> =±15V, T <sub>A</sub> =25°C	10	15		8	15		V/μs
GBW	Gain-Bandwidth Product	V <sub>S</sub> =±15V, T <sub>A</sub> =25°C	3	4		2.7	4		MHz
THD	Total Harmonic Dist	A <sub>V</sub> =+10, R <sub>L</sub> =10k, V <sub>O</sub> =20 Vp-p, BW=20 Hz-20 kHz		≤0.02			≤0.02		%
e <sub>n</sub>	Equivalent Input Noise Voltage	T <sub>A</sub> =25°C, R <sub>S</sub> =100Ω, f=1 kHz		25			25		nV / √Hz
i <sub>n</sub>	Equivalent Input Noise Current	T <sub>A</sub> =25°C, f=1 kHz		0.01			0.01		pA / √Hz

Figure 11 LF412CN Datasheet Excerpt

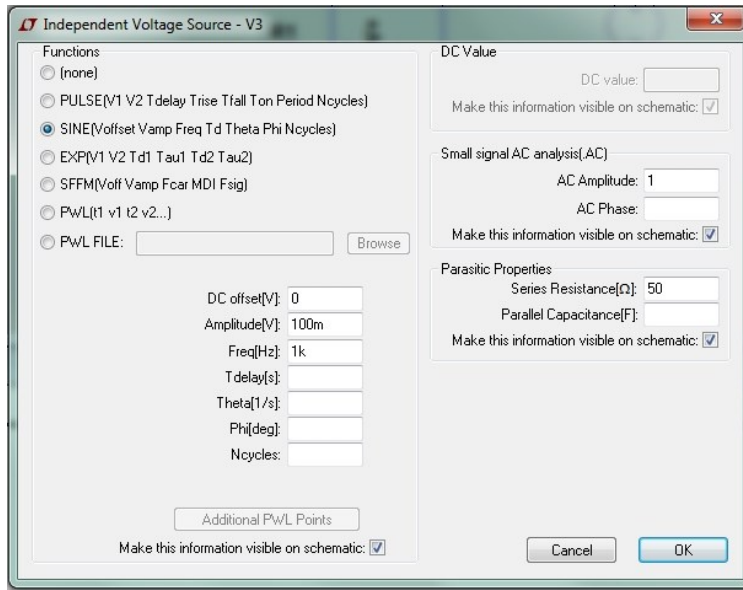


Figure 12 Voltage Source Parameters

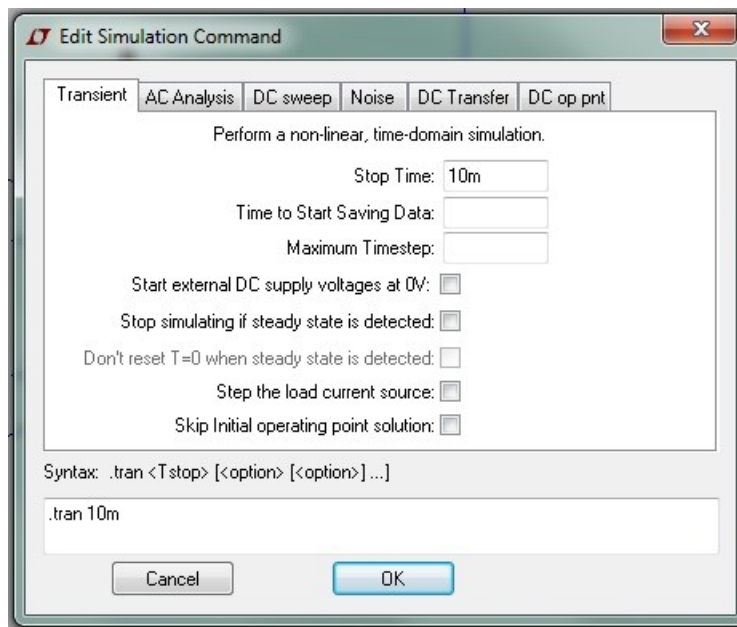


Figure 13 Simulation Command

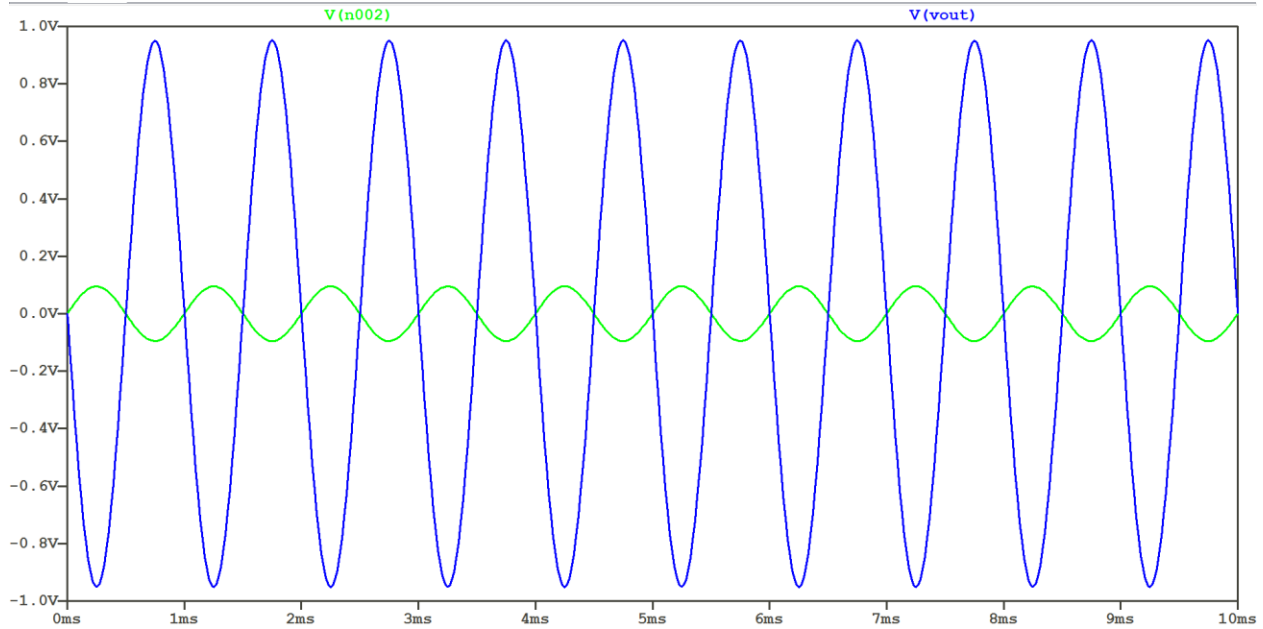


Figure 14 Input and Output for an Inverting Amplifier with a Gain of 10

### Analysis 2: Gain vs. Bandwidth (inverting)

A good way to illustrate the gain-bandwidth trade-off of an op-amp is to run an AC analysis in SPICE for different gains. Create the schematic shown below in fig. 15. A big difference between this schematic and the previous one is the value for “R2”. The value should be entered as “{R}” as shown in fig. 16. Entering a letter within curly brackets in SPICE for any parameter tells the simulator that this value can be varied. The reason we are doing this is so we can run the simulation three times for three different values of R2 and graph it all on the same plot. As shown in fig. 15, enter a SPICE directive exactly as shown “.step param R list 1k 10k 100k”. This line of code tells SPICE to vary the parameter R’s value to 1k, 10k and 100k. The list command steps through the discrete values entered. There are other commands that can linearly vary a variable’s value too. Next, edit the simulation command to an AC analysis with the values shown in fig. 17. Probing the output should result in the plot displayed in fig. 18.

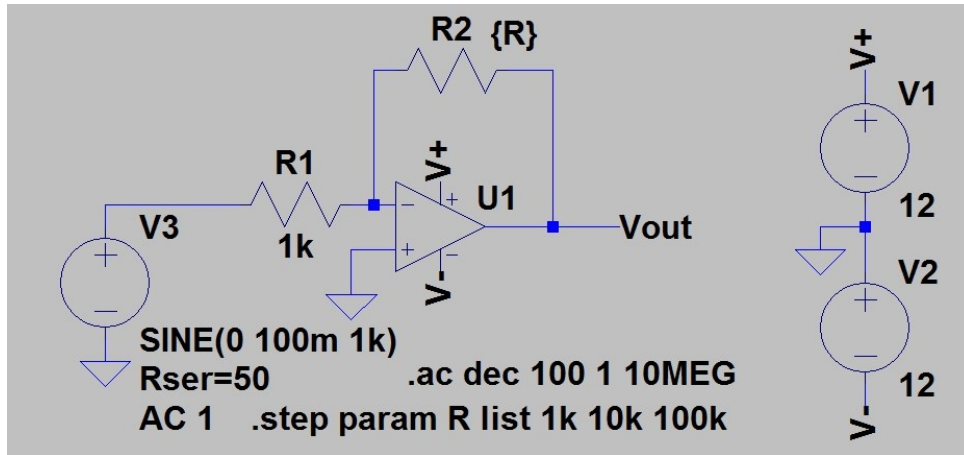


Figure 15 AC Analysis for Inverting Amplifier



Figure 16 Value for R2

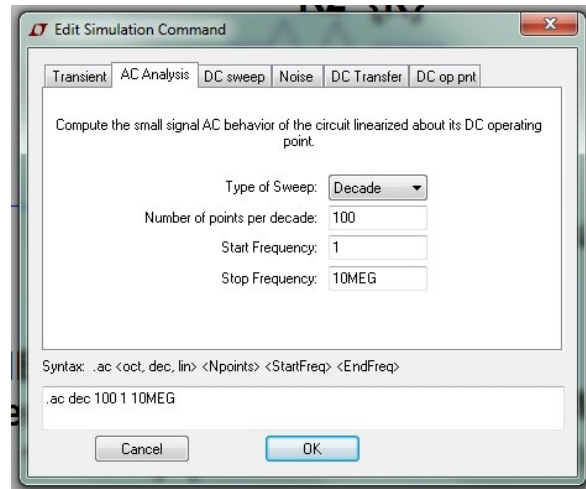


Figure 17 AC Analysis

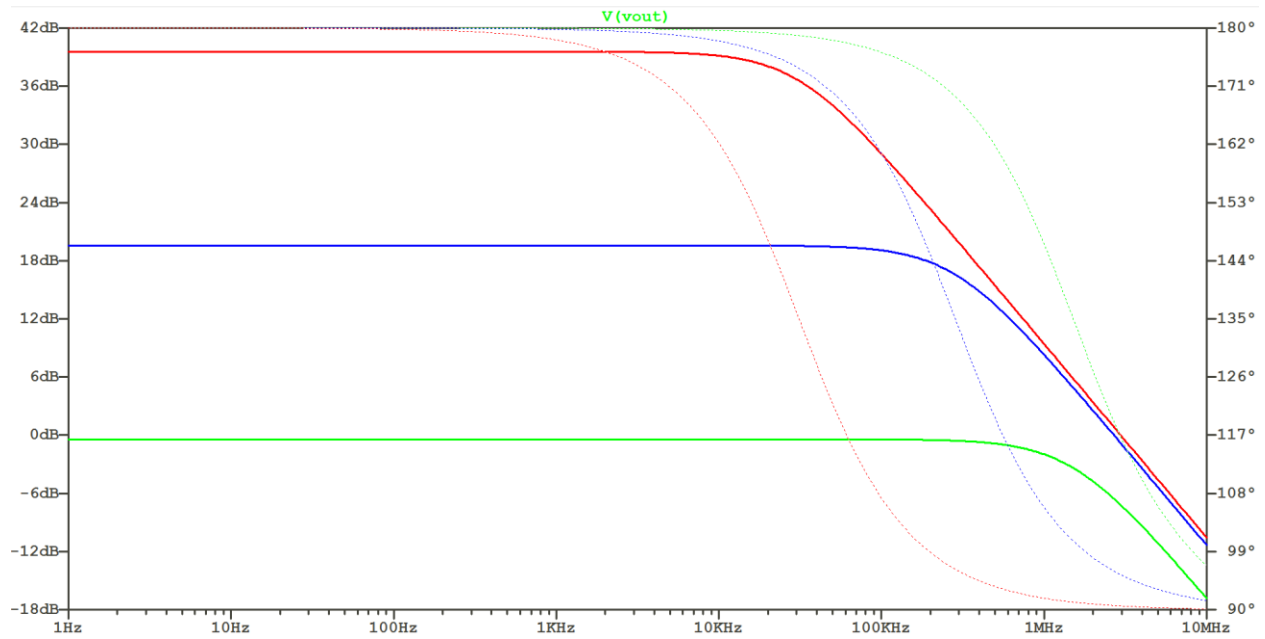


Figure 18 Frequency Response for Gains of -100, -10, -1

### Analysis 3: Gain vs. Bandwidth (noninverting)

Repeat exercise 2 but using the circuit shown in fig. 19. Be sure to note the change in values for the R parameter. This simulation only shows the frequency response for gains of 10 and 100.

This is because in order to show the frequency response for a gain of 1, we need to delete the resistor R1. This will be done in the next exercise. The result of this simulation is shown in fig. 20.

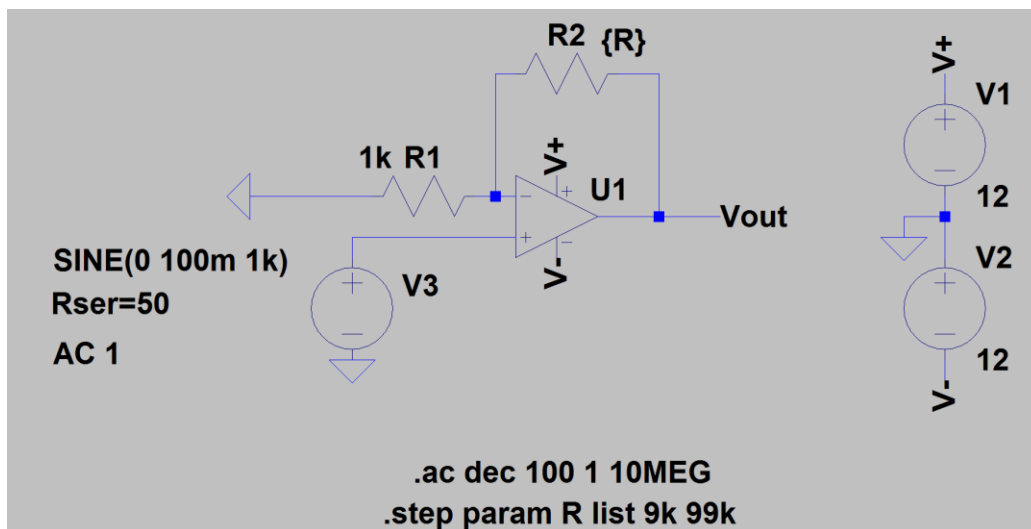


Figure 19 AC Analysis for Non-Inverting Amplifier

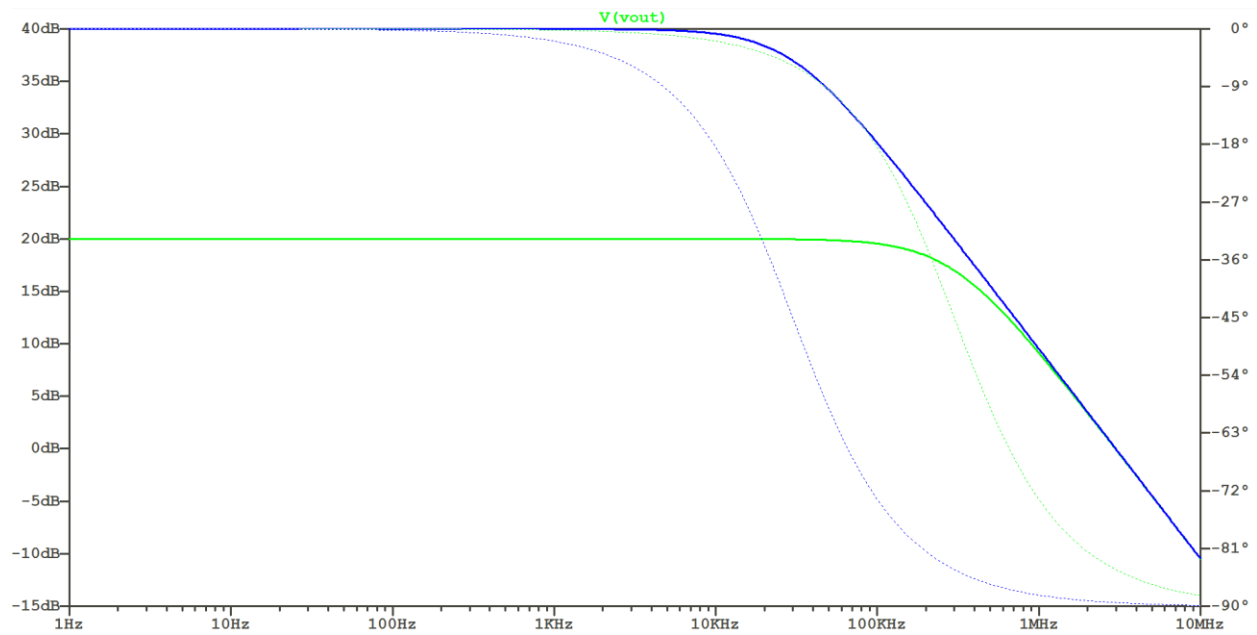


Figure 20 Frequency Response for Gains of 100 and 10

#### Analysis 4: Unity Gain Bandwidth

Finally, run an AC analysis for a non-inverting amplifier with a gain of 1 as seen in the schematic below in fig. 21. Notice that R1 has been completely removed. R2 isn't necessary and the inverting input can be directly shorted to the output but it is good practice to use a small resistor for R2 for stability. The frequency response is shown in fig. 22.



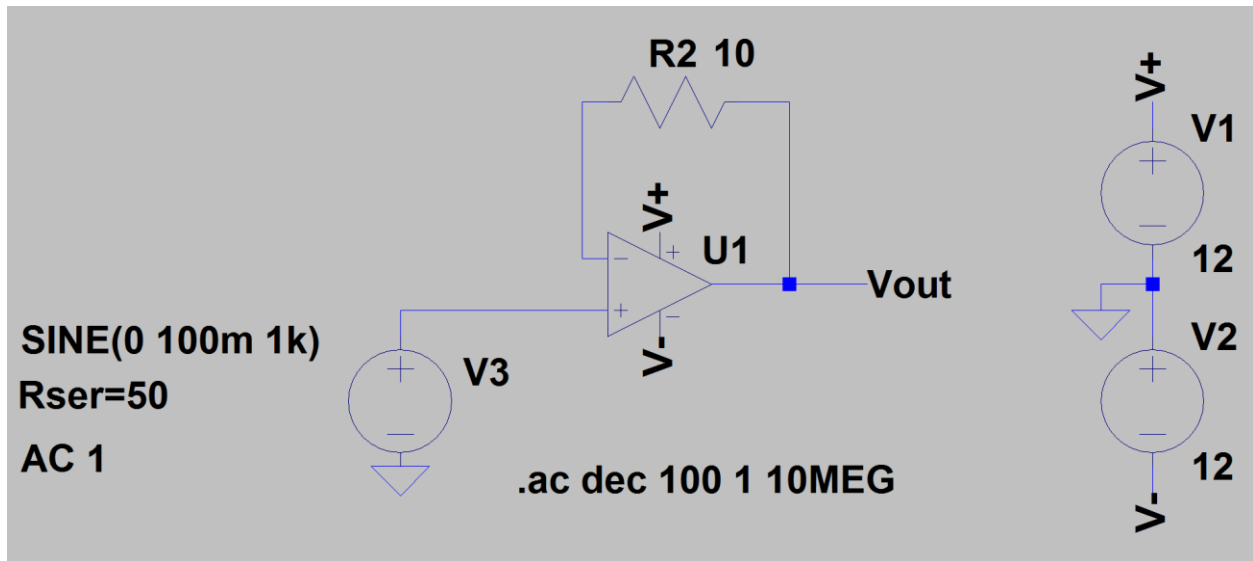


Figure 21 Non-Inverting Amplifier with a Gain of 1

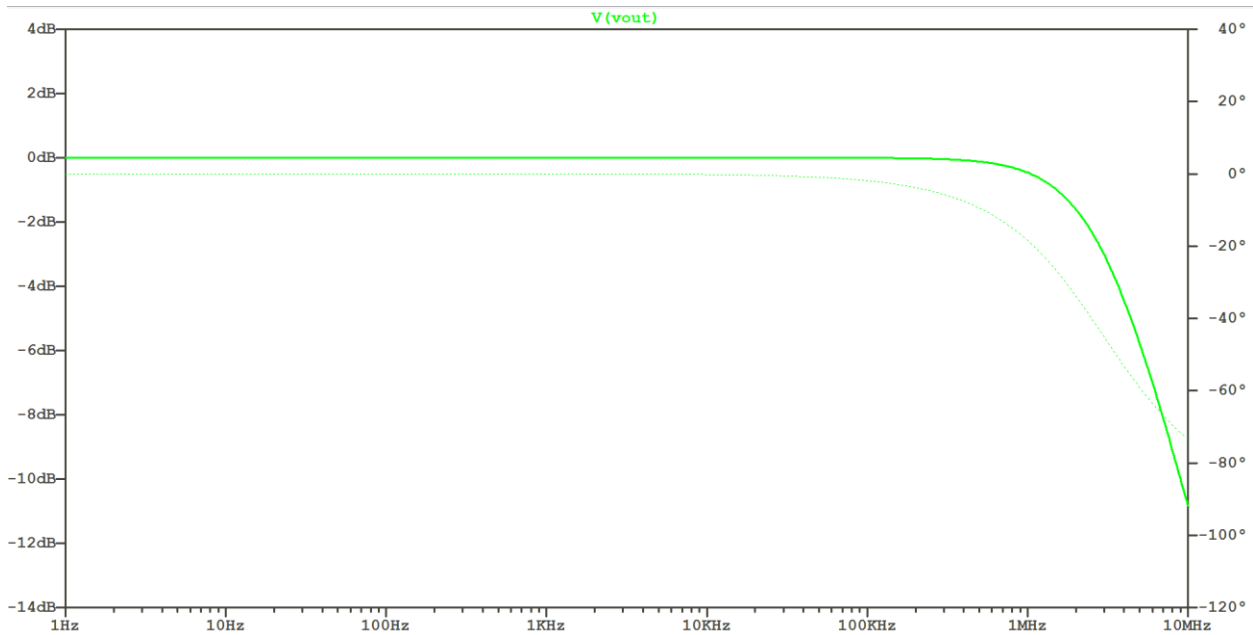


Figure 22 Frequency Response for a gain of 1

### **Prelab Deliverables:**

1. Screen captures of schematics and outputs for each prelab exercise.
2. You must also include an Altium schematic, Altium netlist, and PCB layout for the circuits in prelabs 1 through 5. Each PCB layout must include footprints for all components used and can be auto routed or manually routed. You may use either thru-hole footprints or surface mount footprints for each component. (For the voltage and current sources just put a two pin header and label them VCC and GND.) Also include a grounding plane and make sure your traces are wide enough for the increase in current. To determine the trace width use a PCB trace calculator. If you are unsure how to use Altium please click on the Lab Equipment, Learning, Tutorials, Manuals, Downloads link on the UNLV EE Labs homepage and read the Altium tutorial or watch the videos.  
[https://faculty.unlv.edu/eelabs/index.html?navi=main\\_labequipment](https://faculty.unlv.edu/eelabs/index.html?navi=main_labequipment)

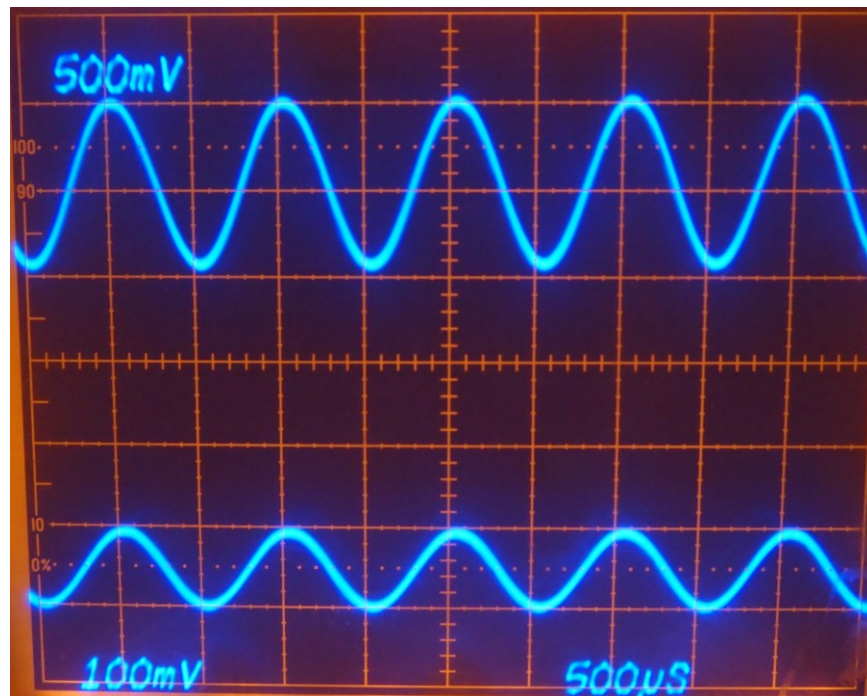
## Laboratory Experiments:

### Experiment 1: Inverting Amplifier with Gains of 1, 10 and 100.

Construct the circuit shown in fig. 15. Connect a function generator to the input of the circuit. Apply a low frequency, low amplitude signal (such as 100 mV and 1 KHz). Attach 10x probes to both the input and output of the amplifier. Verify that the gain is correct. Next, increase the frequency until the output of the amplifier drops 3dB. (Hint: this occurs at 0.707 of the original voltage level). The frequency at which this occurs is the bandwidth of the amplifier. Record this value. Repeat this experiment for all gain values. You may have to vary the amplitude of the input signal in order to prevent the op-amp from saturating. For a gain of 100, the function generator may not output the low amplitude needed to prevent saturation. This can be solved by using either a voltage divider or terminating the function generator with a 50 ohm resistor which will halve the voltage output at the input of the op-amp.

### Experiment 2: Non-inverting Amplifier with Gains of 1, 10 and 100.

Construct the circuit shown in figure 19. Repeat everything that was done in experiment 1. For the unity gain buffer construct the circuit shown in fig. 21.



An example scope trace showing output (top) and input (bottom) for a non-inverting amplifier with a gain of 10.

### Postlab Deliverables and Questions:

1. Submit a picture of your breadboard with your circuit on it.
2. Submit a picture of both input and output on the scope for each circuit topology and gain e.g. inverting 1X, inverting 10X, inverting 100X etc.
3. Create a table summarizing bandwidth and gain for each topology.
4. From the table create a rudimentary gain-bandwidth plot.
5. Questions:
  - a. What striking difference in bandwidth do you notice about the inverting and non-inverting amplifiers? If you needed to use an op-amp for a high bandwidth application which topology would you likely use?
  - b. Can an op-amp be used as an attenuator? An attenuator has a gain of less than one. Which topology needs to be used? Design an attenuator that will output  $1/10^{\text{th}}$  of the voltage applied to the input.
  - c. Go to an IC manufacturer's website such as Linear Technology, Texas Instruments, Analog Devices or other manufacturer; select an op-amp that appeals to you; and write down the part number, its GBW product and its open-loop gain.

## **Additional Resources**

**1. Op Amps for Everyone**

**<http://www.ti.com/lit/an/slod006b/slod006b.pdf>**

**The best reference on how to use Op-Amps with qualitative analysis and quantitative design equations, a must read.**

**2. <http://sound.westhost.com/dwopa.htm>**

**This website has a clear practical guide to designing with op-amps.**

**3. Microelectronic Circuits by Sedra/Smith 6<sup>th</sup> Edition**

**This is a very large textbook that describes a wide variety of useful circuits.**