Laboratory #3

OPAMP Basics and Applications

I. Objectives

1. Familiarize with the fundamental OPAMP circuits.
2. Understand the non-ideality of OPAMP.
3. Implement some OPAMP application circuits.

II. Components and Instruments

1. Components
   (1) OPAMP IC : LM324 ×1
   (2) Resistor : 1kΩ ×1, 10kΩ ×1, 100kΩ ×2
   (3) Capacitor : 0.1μF ×1
2. Instruments
   (1) DC power supply (Keysight E36311A)
   (2) Digital multimeter (Keysight 34450A)
   (3) Oscilloscope (Agilent MSOX 2014A)

III. Reading

1. Chapter 2 and chapter 10 of the Textbook “Microelectronic Circuits, 6th edition, Sedra/Smith”.

IV. Preparation

1. Overview of OPAMP

The schematic of a typical OPAMP is shown in Figure 3.1.

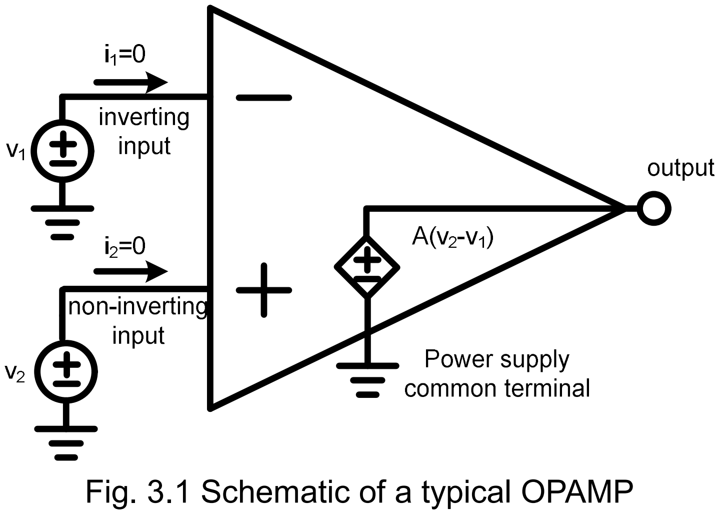

Fig. 3.1 Schematic of a typical OPAMP

An ideal OPAMP has the characteristics of infinite input impedance, zero output impedance, infinite gain, etc. But, in practical, the physical limitation leads to imperfections of OPAMP. Table 3.1 compares the difference between ideal and practical OPAMP.

Table 3.1 Comparison between ideal and practical OPAMP

	Ideal	Practical (i.e. uA741)
input impedance	∞	2 MΩ
output impedance	0	75 Ω
voltage gain	∞	> 100dB
bandwidth	∞	Dominant pole < 10 Hz
CMRR (common-mode rejection ration)	∞	90 dB
temperature shift	0	< 15 μV/℃

2. Non-ideal effect of OPAMP

(1) Input offset：

Connect the OPAMP with the power supply and short the input nodes to ground, there will be a non-zero voltage at output terminal. This voltage can be canceled out by adding a proper small voltage at the input terminal; this small voltage is called input offset voltage. The offset voltage results from the non-symmetric differential input stage of a practical OPAMP. Because of unavoidable process variation, although symmetry is demanded during the design process, the transistors on the both sides of the amplifier might not be perfectly symmetrical. Besides, the magnitude of input offset voltage is dependent on temperature and modes of operation.

(2) Input bias current：

There will be no current flow into the input terminal of an ideal OPAMP. However, to a practical OPAMP, it is unlikely to avoid current from flowing into the input terminal. The average current value is called input bias current. Input bias current leads to a small voltage difference between V_+ and V_-, it is then appeared on the output terminal after the amplification of the OPAMP.

(3) PSRR(Power Supply Rejection Ratio)：

Once the power supply connected to the OPAMP has noise or ripple, the energy of power supply will affect the output signal of OPAMP. This phenomenon might also lead an input bias current.

(4) Slew rate：

The maximum changing rate of OPAMP output is called slew rate. Under the large-swing signal operational condition, due to the limit current of output stage, it is possible to charge or discharge without enough time and results that the output signal cannot keep up with the input signal.

3. Application circuits of OPAMP

(1) Inverting OPAMP

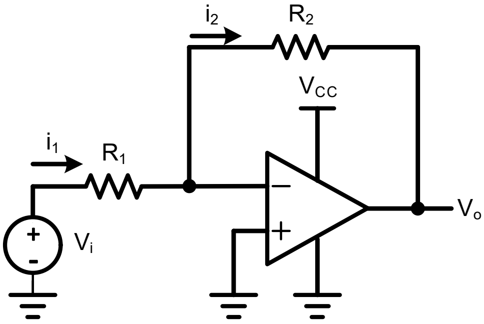

Fig. 3.2 Inverting OPAMP

Close-loop gain of ideal inverting OPAMP

(Open-loop gain is infinite):

Because of the virtual short at input terminals, the input nodes have same voltage potential, V+≒V-. By KCL, we can derive the output voltage as below.

$$i_1 = \frac{V_i - 0}{R_1}, V_O = -i_1 \cdot R_2 = \frac{-V_i}{R_1} \cdot R_2 \ldots (3.1)$$

Divide both sides of (3.1) by V_i, we can derive the close-loop gain as below.

$$A_V = \frac{V_o}{V_i} = -\frac{R_2}{R_1} \ldots (3.2)$$

Close-loop gain of non-ideal inverting OPAMP

(Open-loop gain is finite):

Let the open-loop gain be A and the $Z_{in} = \infty$：

$$V_O = A(V_+ - V_-) = -AV_- \Rightarrow V_- = -\frac{V_O}{A} \ldots (3.3)$$

$$i_1 = \frac{V_i - V_-}{R_1} = \frac{V_i - \left(-\frac{V_O}{A}\right)}{R_1} = \frac{V_i + \frac{V_O}{A}}{R_1} = i_2 \ldots (3.4)$$

$$V_o = (V_-) - i_2 \cdot R_2 = -\frac{V_o}{A} - \frac{V_i + \frac{V_o}{A}}{R_1} \cdot R_2 \ldots (3.5)$$

Combining equations (3.3-5), the close-loop gain could be derived as the equation (3.6).

$$A_V = \frac{V_o}{V_i} = \frac{-R_2/R_1}{1 + (1 + R_2/R_1)/A} \ldots (3.6)$$

(2) Non-inverting OPAMP

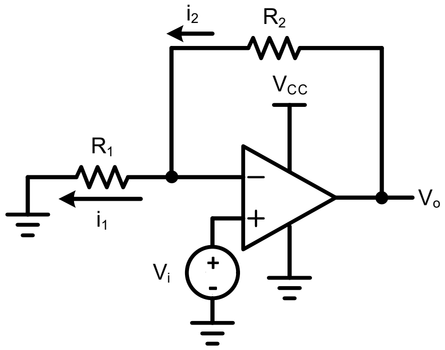

Fig. 3.3 Non-inverting OPAMP

Close-loop gain of ideal non-inverting OPAMP

(Open-loop gain is infinite):

Because of the virtual short at input terminals, the input nodes have same voltage potential, $V_+ \fallingdotseq V_-$. By KCL, we can derive the output voltage as below.

$$i_1 = \frac{V_i - 0}{R_1}, V_O = V_i + i_2 \cdot R_2 = V_i \cdot \left(1 + \frac{R_2}{R_1}\right) \ldots (3.7)$$

Divide both sides of (3.7) by V_i, we can derive the close-loop gain as below.

$$A_V = \frac{V_o}{V_i} = 1 + \frac{R_2}{R_1} \ldots (3.8)$$

Close-loop gain of non-ideal non-inverting OPAMP

(Open-loop gain is finite):

Let the open-loop gain be A and the $Z_{in} = \infty$：

$$V_O = \left(V_i - \frac{R_1}{R_1 + R_2} V_o\right) \cdot A \Rightarrow V_o \cdot \left(1 + \frac{R_1}{R_1 + R_2}\right) \cdot A = V_i \cdot A \ldots (3.9)$$

With (3.7)、(3.8)、(3.9), the close-loop gain becomes,

$$A_V = \frac{V_o}{V_i} = \frac{1+R_2/R_1}{1+\left(1+R_2/R_1\right)/A} \ldots (3.10)$$

(3) The OPAMP Inverting integrator

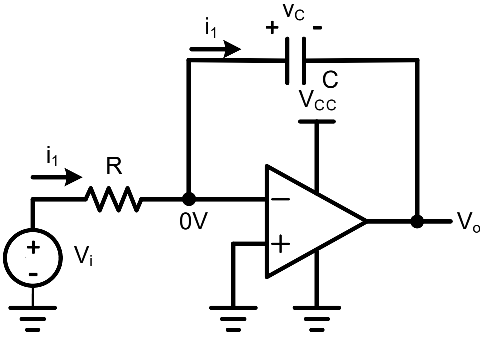

Fig. 3.4 Inverting integrator

Inverting integrator operation in time domain expression

Let the input be a time-varying function $V_i(t)$. The virtual ground at the negative input of the op-amp causes the current $i_1(t)$ to be $V_i(t)/R$. This current flows through the capacitor C, which then causes charge to accumulate on C. if we assume that the circuit begins operation at t = 0, and the initial voltage on capacitor is Vc. The voltage drop on C is

$$v_c(t) = Vc + \frac{1}{C}\int_0^t i_1(t)dt \ldots (3.11)$$

The output voltage can be expressed as $v_O(t) = -v_c(t)$

$$v_o(t) = -\frac{1}{RC}\int_0^t v_i(t)dt - Vc \ldots (3.12)$$

Inverting integrator operation in frequency domain expression

From the eq.3.2, we can further obtain the transfer function of the inverting integrator, which can be expressed as below.

$$A_V = \frac{V_o(\mathrm{s})}{V_i(s)} = -\frac{\mathrm{Z_C}}{\mathrm{Z_R}} = -\frac{1}{\mathrm{sCR}} \ldots (3.13)$$

$$\left|\frac{V_o(\mathrm{s})}{V_i(s)}\right| = \frac{1}{\omega\mathrm{CR}} \ldots (3.14)$$

And phase $\phi = 90^\circ \ldots (3.15)$

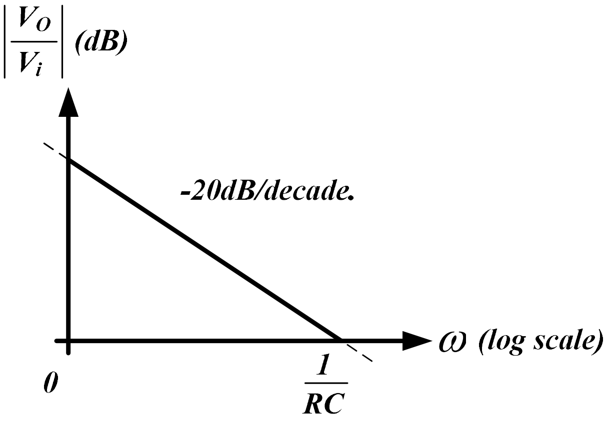

Fig. 3.5 Frequency response of the integrator

(4) The OPAMP differentiator

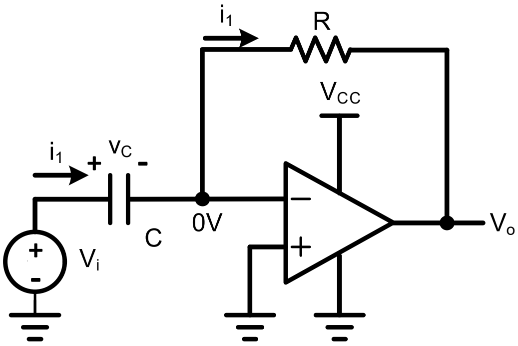

Fig. 3.6 Differentiator

Differentiator operation in time domain expression

Let the input be a time-varying function $V_i(t)$. The virtual ground at the negative input of the op-amp causes the voltage across the capacitor to be $V_i(t)$. The output voltage is

$$V_O(t) = -i_1 R = -CR\frac{dV_i(t)}{dt} \ldots (3.16)$$

Differentiator operation in frequency domain expression

From the eq.3.2, we can further obtain the transfer function of the differentiator, which can be expressed as below.

$$A_V = \frac{V_o(s)}{V_i(s)} = -\frac{Z_R}{Z_C} = -sCR \ldots (3.17)$$

$$\left|\frac{V_o(\mathrm{s})}{V_i(s)}\right| = \omega \mathrm{CR} \ldots (3.18)$$

And phase

$$\phi = -90^\circ \ldots (3.19)$$

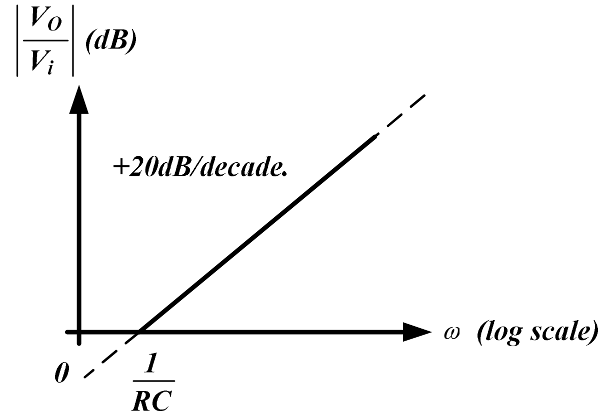

Fig. 3.7 Frequency response of the differentiator

V. Explorations

The layout and connections of LM324 OPAMPs is shown in Fig. 3.8. As what it shows, LM324 consists of four independent, high gain, internal frequency compensated OPAMPs in a DIP package. LM324 uses single supply instead of dual supplies.

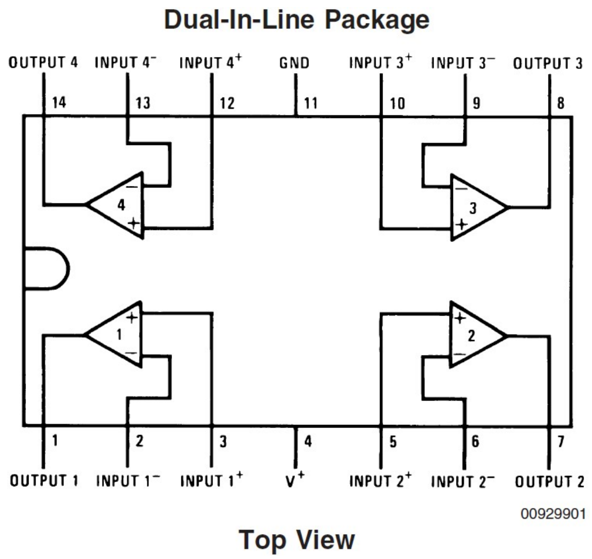

Fig. 3.8 Pin diagram of LM324 OPAMP

Table 3.2 Absolute maximum ratings of LM324 OPAMP

Supply voltage	32	V
Differential input voltage	32	V
Input voltage	-0.3 to +32	V
Operating Temperature Range	0 to +70	°C

NOTE: Pin 4 must be connected to the most positive voltage (**+15V** in this Lab), and pin 11 to the **ground**. For the sake of safety, maintain the voltage between pin 4 and pin 11 at or below 15V to avoid internal voltage breakdown. **Make sure you turn off the power supply before changing any circuit connection**.

1. Inverting OPAMP

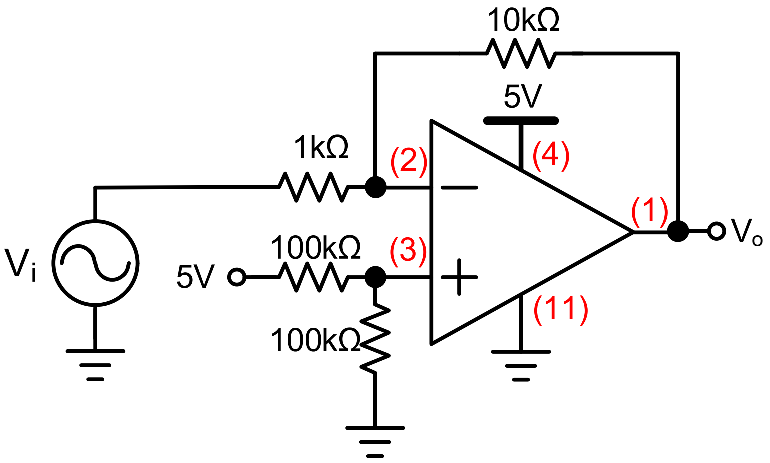

Fig. 3.9 Inverting OPAMP

(1) Assemble the circuit as shown in Fig. 3.9.

(2) Use R_1=1kΩ, R_2=10kΩ.

(3) Measure the voltage of pin 1, 2, 3, 4, 11, and record down the values in Table 3.3.

(4) Provide the small signal sine wave v_i with 200m$V_{p\text{-}p}$, 1kHz with 2.5V offset as input by using function generator.

(5) Record the voltage gain $A_V=V_o/V_i$ (V/V) by observing the differentiation of input and output voltage value in Table 3.4.

(6) Change the frequency of input signal and repeat step (4).

2. Non-inverting OPAMP

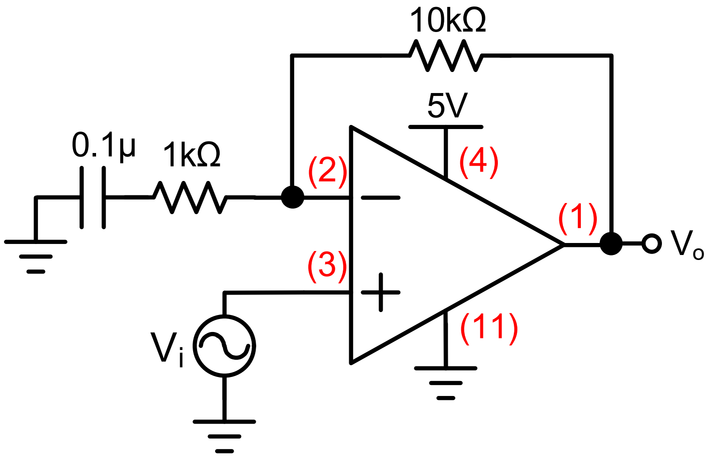

Fig. 3.10 Non-inverting OPAMP

(1) Assemble the circuit as shown in Fig. 3.10.

(2) Use R_1=1kΩ, R_2=10kΩ.

(3) Measure the voltage of pin 1, 2, 3, 4, 11, and record down the values in Table 3.5.

(4) Provide the small signal sine wave v_i with 200m$V_{p\text{-}p}$, 1kHz with 2.5V offset as input by using function generator.

(5) Record the voltage gain $A_V=V_o/V_i$ (V/V) by observing the differentiation of input and output voltage value in Table 3.6.

(6) Change the frequency of input signal, and repeat step (4).

3. OPAMP inverting integrator

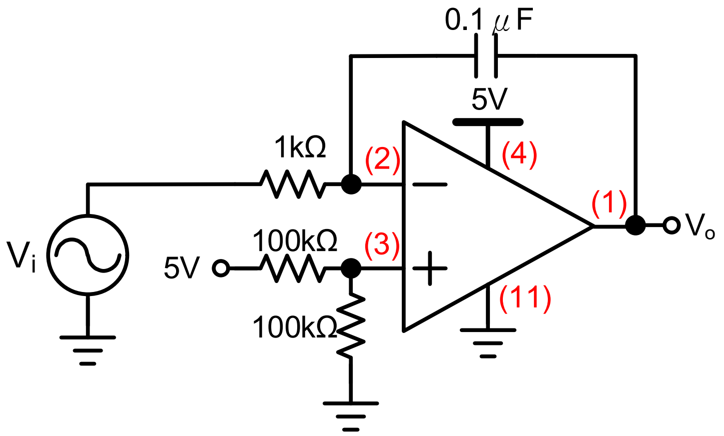

Fig. 3.11 OPAMP inverting integrator

(1) Assemble the circuit as shown in Fig. 3.11.

(2) Use R=1kΩ, C=0.1μF.

(3) Measure the voltage of pin 1, 2, 3, 4, 11, and record down the values in Table 3.7.

(4) Provide V_i with a 200m$V_{p\text{-}p}$, 2.5V offset, 1kHz square wave signal and observe the output waveform and the input signal.

(5) Provide V_i with a 200m$V_{p\text{-}p}$, 2.5V offset, sine wave signal with respective frequency in Table 3.8 and fill up the Table.

4. OPAMP differentiator

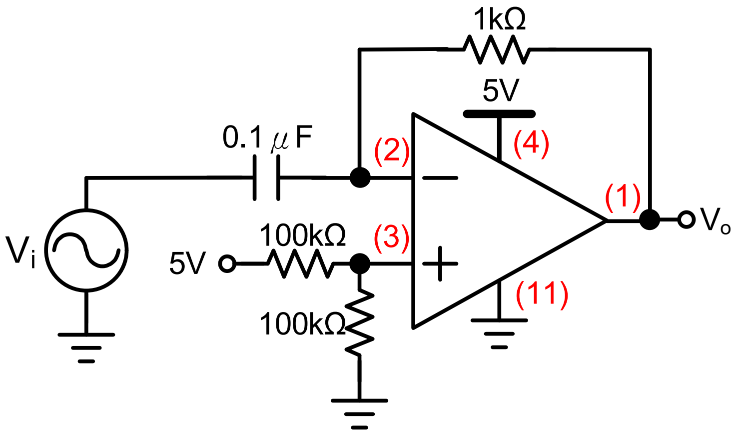

Fig. 3.12 OPAMP differentiator

(1) Assemble the circuit as shown in Figure 3.12.
(2) Use R=1kΩ, C=0.1μF.
(3) Measure the voltage of pin 1, 2, 3, 4, 11, and record down the values in Table 3.9.
(4) Provide V_i with a 200m$V_{p\text{-}p}$, 2.5V offset, 1kHz, 50% symmetry ramp wave signal and observe the output waveform and the input signal.
(5) Provide V_i with a 200m$V_{p\text{-}p}$, 2.5V offset, sine wave signal with respective frequency in Table 3.10 and fill up the Table.

VI. Reference

1. “Laboratory manual for microelectronic circuits”, third edition.
2. “Microelectronic circuit”, sixth edition.
3. “HA17741/PS” datasheet, HITACHI.

Class:

Name: Student ID:

1. Problem 1 (PSPICE simulation) Inverting OPAMP

Assemble the circuit as shown in Fig. 3.13 using LM324 OPAMP. The resistance values are $R_1=1\text{k}\Omega$, $R_2=10\text{k}\Omega$. Then, apply a sine wave at input node with 200mV_{pp} amplitude and 1 kHz frequency. Plot the waveforms at input and output terminals and explain the result.

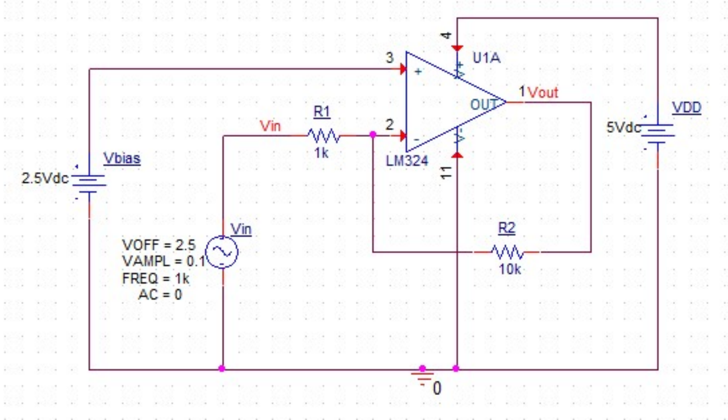

Fig. 3.13 Inverting OPAMP

2. Problem 2 (PSPICE simulation) Non-inverting OPAMP

Assemble the circuit as shown in Fig. 3.14 using LM324 OPAMP. The resistance values are $R_1=1\text{k}\Omega$, $R_2=10\text{k}\Omega$. Then apply a sine wave at input node with 200m V_{pp} amplitude and 1 kHz frequency. Plot the waveforms at input and output terminals and explain the result.

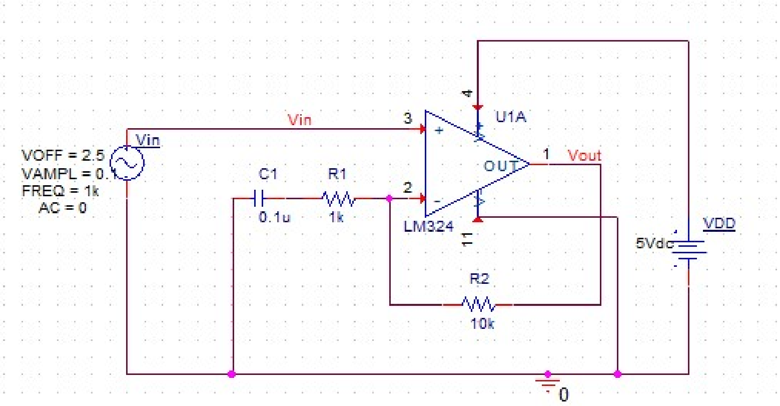

Fig. 3.14 Non-inverting OPAMP

3. Problem 3 (PSPICE simulation) OPAMP Integrator

Assemble the circuit as shown in Fig. 3.15 using LM324 OPAMP. The resistance values are $R=1k\Omega$, $C=0.1\mu F$. Then apply sine wave at input node with $200mV_{pp}$ amplitude and 1 kHz frequency. Plot the waveforms at input and output terminals and explain the result.

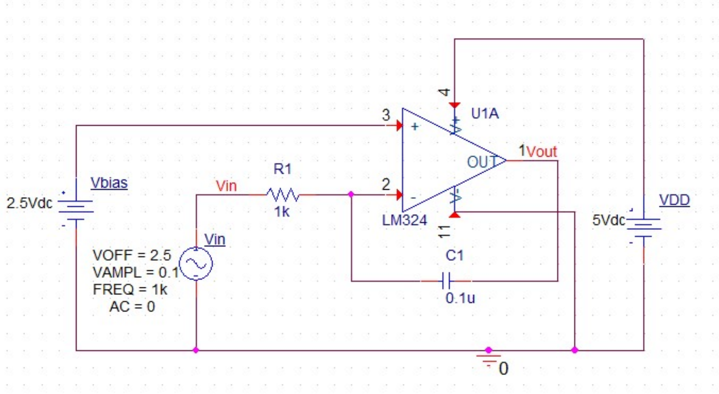

Fig. 3.15 OPAMP integrator

4. Problem 4 (PSPICE simulation) OPAMP differentiator

Assemble the circuit as shown in Fig. 3.16 using LM324 OPAMP. The resistance values are $R=1k\Omega$, $C=0.1\mu F$. Then apply sine wave at input node with $200mV_{pp}$ amplitude and 1 kHz frequency. Plot the waveforms at input and output terminals and explain the result.

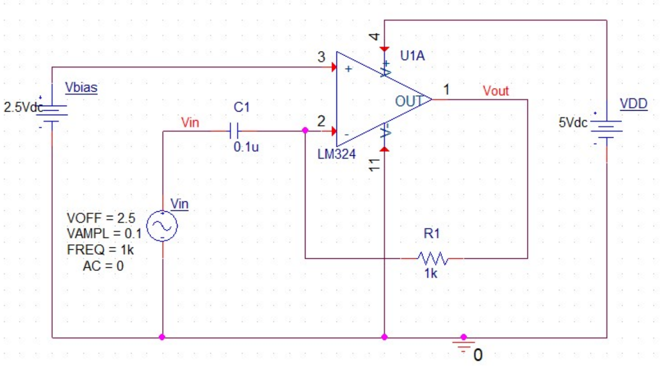

Fig. 3.16 OPAMP differentiator

5. Problem 5 (Term explanation)

Explain the following terminologies:

(1) 3-dB bandwidth

(2) Gain margin

(3) Phase margin

(4) CMRR

(5) PSRR

Laboratory #3 Report

Class:
Name: Student ID:

1. Exploration 1

(1) Voltage measurements of pin 1, 2, 3, 4, 11

Table 3.3

Pin			Measured value		
11					
4					
1	2	3			

(2) Voltage gain measurements of the inverting OPAMP

Table 3.4

f (Hz)	$V_{i(p-p)}$ (V)	$V_{o(p-p)}$ (V)	A_V (dB)	f (Hz)	$V_{i(p-p)}$ (V)	$V_{o(p-p)}$ (V)	A_V (dB)
100				20k			
500				50k			
1k				100k			
5k				200k			
10k				500k			

2. Exploration 2

(1) Voltage measurements of pin 1, 2, 3, 4, 11

Table 3.5

Pin			Measured value		
11					
4					
1	2	3			

(2) Voltage gain measurements of the non-inverting OPAMP

Table 3.6

f (Hz)	$V_{i(p-p)}$ (V)	$V_{o(p-p)}$ (V)	A_V (dB)	f (Hz)	$V_{i(p-p)}$ (V)	$V_{o(p-p)}$ (V)	A_V (dB)
100				20k			
500				50k			
1k				100k			
5k				200k			
10k				500k			

3. Exploration 3

(1) Voltage measurements of pin 1, 2, 3, 4, 11

Table 3.7

<table>
<tr><th colspan="3">Pin</th><th colspan="3">Measured value</th></tr>
<tr><td colspan="3">11</td><td colspan="3"></td></tr>
<tr><td colspan="3">4</td><td colspan="3"></td></tr>
<tr><td>1</td><td>2</td><td>3</td><td></td><td></td><td></td></tr>
</table>

(2) V_i and V_O graph with square wave input

(3) Voltage gain measurements of the OPAMP inverting integrator

Table 3.8

f (Hz)	$V_{i(p-p)}$ (V)	$V_{o(p-p)}$ (V)	A_V (dB)	f (Hz)	$V_{i(p-p)}$ (V)	$V_{o(p-p)}$ (V)	A_V (dB)
100				600			
200				700			
300				800			
400				900			
500				1000			

4. Exploration 4

(1) Voltage measurements of pin 1, 2, 3, 4, 11

Table 3.9

<table>
<tr><th colspan="3">Pin</th><th colspan="3">Measured value</th></tr>
<tr><td colspan="3">11</td><td colspan="3"></td></tr>
<tr><td colspan="3">4</td><td colspan="3"></td></tr>
<tr><td>1</td><td>2</td><td>3</td><td></td><td></td><td></td></tr>
</table>

(2) V_i and V_O graph with ramp wave input

(3) Voltage gain measurements of the OPAMP differentiator

Table 3.10

f (Hz)	$V_{i(p-p)}$ (V)	$V_{o(p-p)}$ (V)	A_V (dB)	f (Hz)	$V_{i(p-p)}$ (V)	$V_{o(p-p)}$ (V)	A_V (dB)
1k				6k			
2k				7k			
3k				8k			
4k				9k			
5k				10k			

5. Problem 1

What's the importance of CMRR in the amplifier circuits?

6. Problem 2

Use MATLAB or Excel to plot the frequency vs. gain figures according to your measurement and explain the results.

7. Problem 3

The applied small signal input in exploration 1 and 2 is 200mV_{pp}. Is it possible to apply a 3 V_{pp} signal? Why?

8. Conclusion