VLSI Engineering Lab (Analog)

Experiment 4 – Operational Amplifier

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Objective

Designing inverting and non-inverting operational amplifiers, observing the gain of the circuit and using them to design voltage follower and comparator.

Circuit Diagram

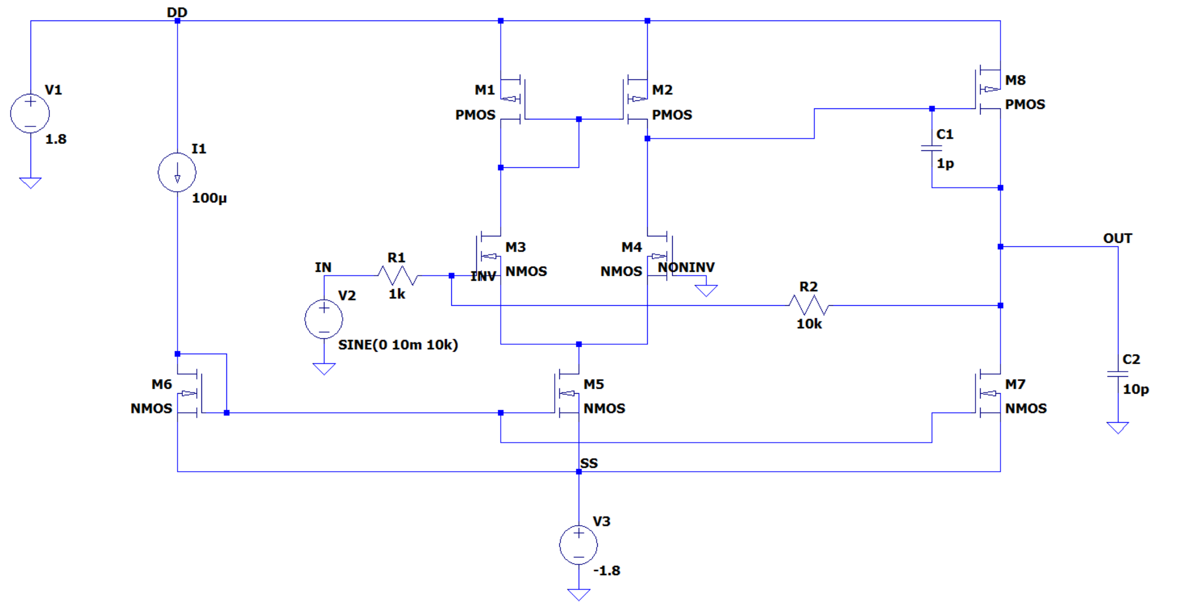

Fig. 1. Schematic of inverting operational amplifier

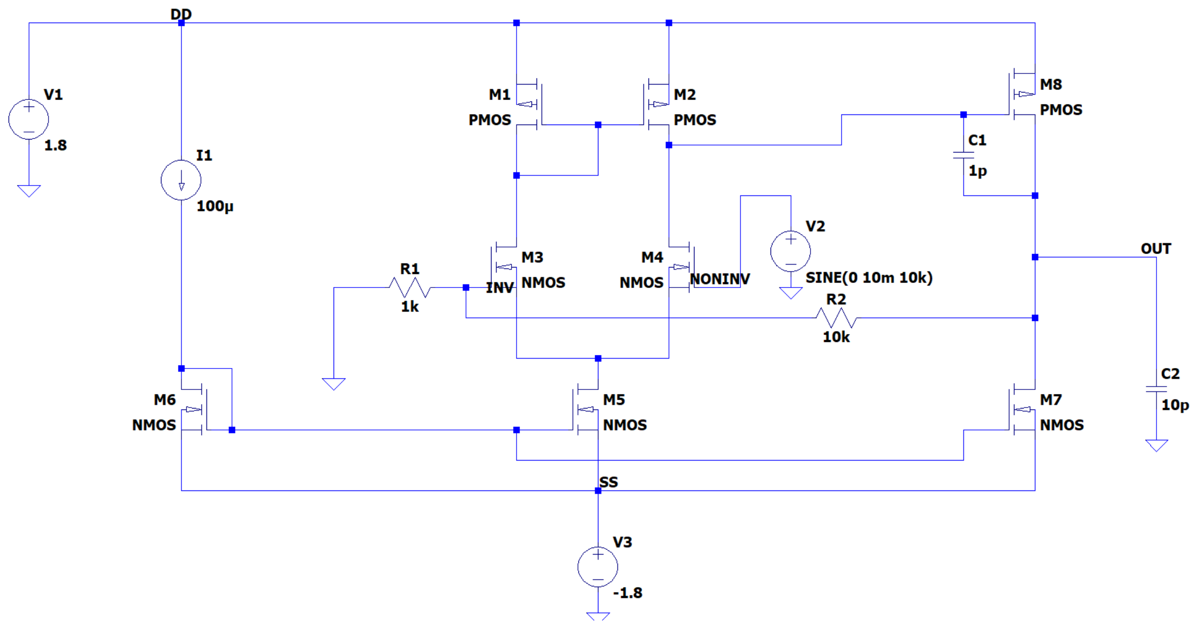

Fig. 2. Schematic of non-inverting operational amplifier

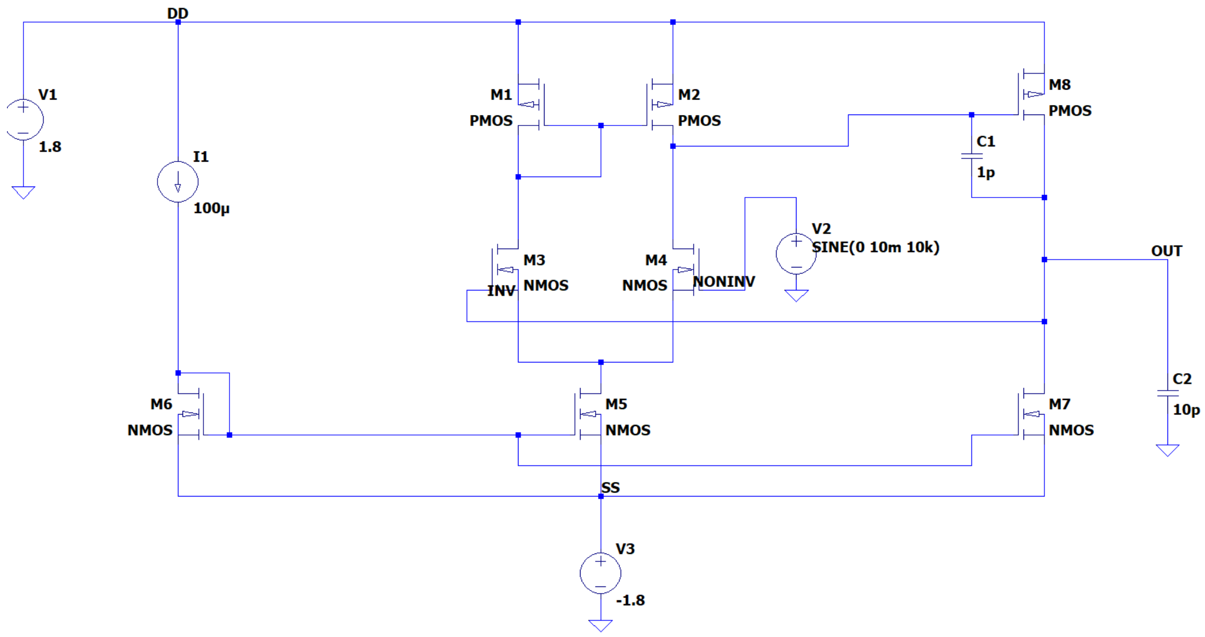

Fig. 3. Schematic of voltage follower

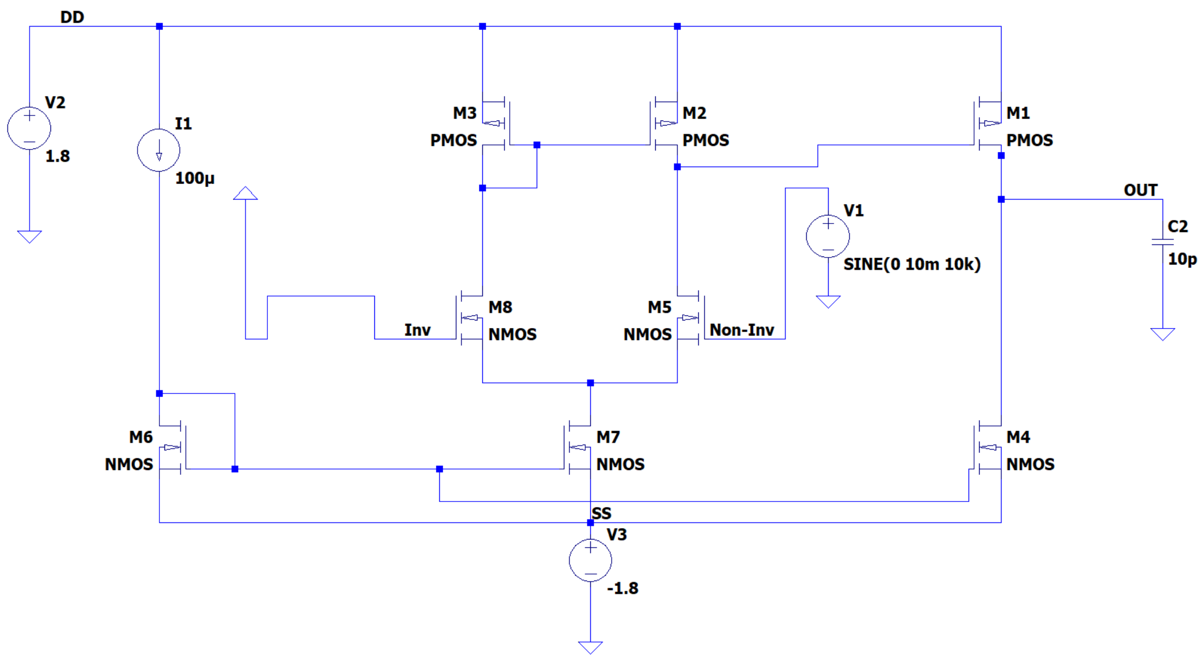

Fig. 4. Schematic of comparator

Theory

Fig. 1. and Fig. 2. depicts the schematic for inverting and non-inverting op-amp respectively. The two-stage circuit architecture has historically been the most popular approach to op-amp design. It can provide high gain and high output swing. The two-stage refers to the number of gain stages in the op-amp. The output buffer is normally present only when resistive loads need to be driver.

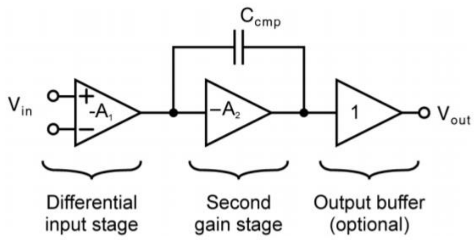

Fig. 5. Stage-wise decomposition

The first stage is a NMOS differential pair with NMOS current mirrors. Second stage is a common-source amplifier. The differential gain stage consists of M1, M2, M3 and M4. Transistors M3 and M4 are standard NMOS which form the basic input stage of the differential amplifier. The gate of M3 and M4 are the inverting and non-inverting inputs with respect to transistors. The two main resistances that contribute to the output resistance are that of the input transistors and also the output resistance of active load transistors, M1 and M2. The gain of differential stage is given as

$$A_v^{(1)} = g_{m,3}\left(r_{o,2}||r_{o,4}\right)$$

where

$$g_{m,3} = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right)_3 \frac{I_{SS}}{2}}$$

The second stage is PMOS common source amplifier with NMOS as the active load. It should be noted that second stage doesn't load the first stage as the input resistance (which is equal to gate resistance of M8) is infinity. The gain of this stage is given as

$$A_v^{(2)} = g_{m,8}\left(r_{o,8}||r_{o,7}\right)$$

The open loop gain of this operational amplifier is thus given as

$$A_v = A_v^{(1)} A_v^{(2)} = g_{m,3} g_{m,8}\left(r_{o,2}||r_{o,4}\right)\left(r_{o,8}||r_{o,7}\right)$$

Compensating Capacitor

The op-amp at high frequencies has a problem that because of its internal multistage connection, it has a phase shift added at each stage and at high frequencies, the phase shift, depending on the frequency, increases to such an extent that 180 degree negative feedback at the inverting input turns to 360 = 0 degrees. So, now we have positive feedback to the amplifier, unfortunately converting it into an oscillator. To avoid such problem, a compensating capacitor is added in the circuit. It forces a pole on the transfer function of op-amp, thus bringing down the bandwidth by fixing a low-pass filter.

Inverting amplifier

The open loop gain A_v of op-amp as given by previous equation can be as high as 120 dB. However, this very high gain is of no real use to us as it makes the amplifier both unstable and hard to control as the smallest of input signals, just a few micro-volts, (μV) would be enough to cause the output voltage to saturate and swing towards one or the other of the voltage supply rails losing complete control of the output. As the open loop DC gain of an operational amplifier is extremely high we can therefore afford to lose some of this high gain by connecting a suitable resistor across the amplifier from the output terminal back to the inverting input terminal to both reduce and control the overall gain of the amplifier. This then produces and effect known commonly as Negative Feedback, and thus produces a very stable Operational Amplifier based system. Negative Feedback is the process of "feeding back" a fraction of the output signal back to the input, but to make the feedback negative, we must feed it back to the negative or "inverting input" terminal of the op-amp using an external Feedback Resistor called Rf. This feedback connection between the output and the inverting input terminal forces the differential input voltage towards zero.

This effect produces a closed loop circuit to the amplifier resulting in the gain of the amplifier now being called its Closed-loop Gain. Then a closed-loop inverting amplifier uses negative feedback to accurately control the overall gain of the amplifier, but at a cost in the reduction of the amplifiers gain. This negative feedback results in the inverting input terminal having a different signal on it than the actual input voltage as it will be the sum of the input voltage plus the negative feedback voltage giving it the label or term of a Summing Point. We must therefore separate the real input signal from the inverting input by using an Input Resistor, Rin.

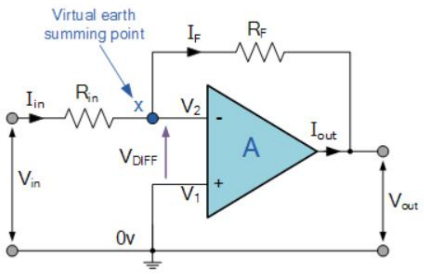

Fig. 6. Inverting op-amp configuration

The closed loop gain with this configuration is given as

$$A_{v,inv} = -\frac{R_f}{R_{in}}$$

Non-inverting amplifier

In this configuration, the input voltage signal, (Vin) is applied directly to the non-inverting (+) input terminal which means that the output gain of the amplifier becomes "Positive" in value in contrast to the "Inverting Amplifier" circuit. Feedback control of the non-inverting operational amplifier is achieved by applying a small part of the output voltage signal back to the inverting (–) input terminal via a Rf – R2 voltage divider network, again producing negative feedback. This closed-loop configuration produces a non-inverting amplifier circuit with very good stability, a very high input impedance, Rin approaching infinity, as no current flows into the positive input terminal, (ideal conditions) and a low output impedance, Rout.

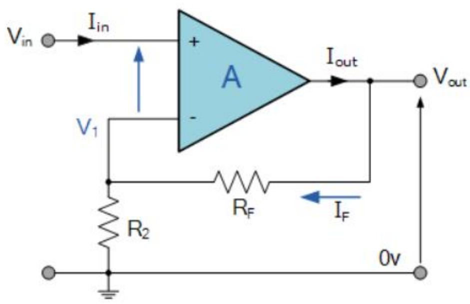

Fig. 7. Non-inverting op-amp configuration

The closed loop gain with this configuration is given as

$$A_{v,inv} = 1 + \frac{R_f}{R_2}$$

Voltage follower

Voltage follower is a special case of non-inverting amplifier with Rf = 0 and R2 = infinity, thus unity-gain. In this configuration, the output voltage signal exactly follows the input voltage signal.

Comparator

The Op-amp comparator compares one analogue voltage level with another analogue voltage level, or some present reference voltage, VREF and produces an output signal based on this voltage comparison. In other words, the op-amp voltage comparator compares the magnitudes of two voltage inputs and determines which is the largest of the two. The open-loop op-amp comparator is an analogue circuit that operates in its non-linear region as changes in the two analogue inputs, V+ and V- causes it to behave like a digital bistable device as triggering causes it to have two possible output states, +Vcc or -Vcc. Then we can say that the voltage comparator is essentially a 1-bit analogue to digital converter, as the input signal is analogue but the output behaves digitally.

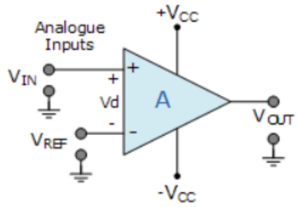

Fig. 8. Comparator op-amp configuration

Plots

All the NMOS and PMOS devices used while in schematic have length 180 nm and width 4 um.

1 Inverting amplifier

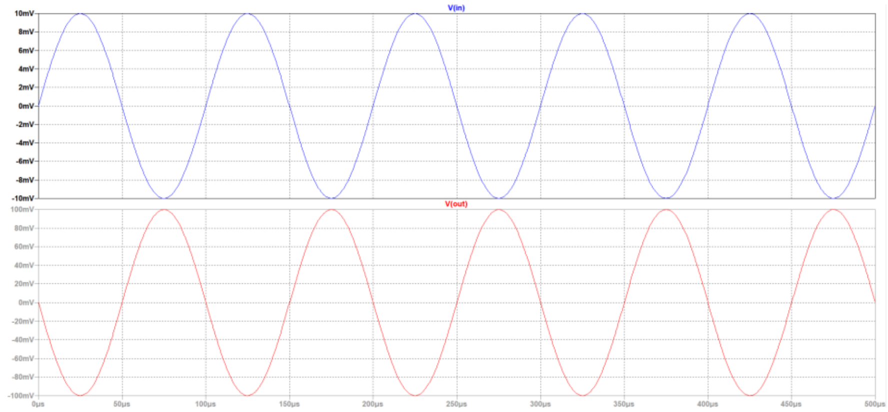

Fig. 9. ***Input and output voltage waveform for inverting op-amp:*** We can observe that the output voltage is inverted with respect to input voltage and a gain of -10 can be observed as well, which is same as that given by the gain equation of inverting op-amp.

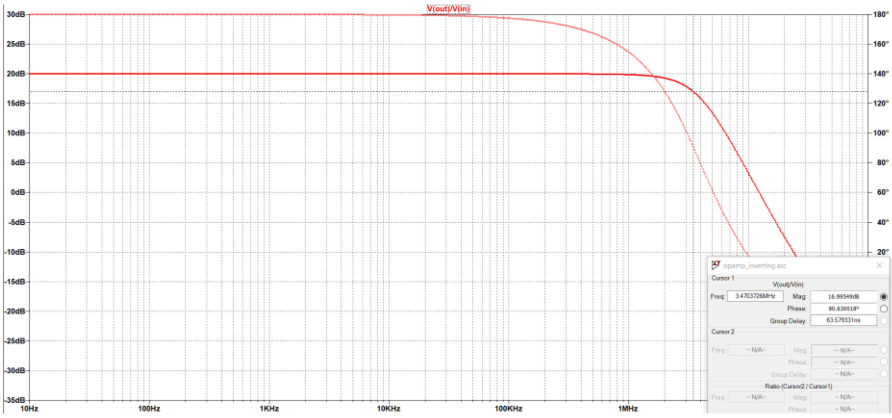

Fig. 10. ***Bode plot for inverting op-amp:*** As given in the theory, op-amp circuits are used with compensating capacitors which acts as a low-pass filter. However, due to absence of coupling capacitors, there is no high-pass type characteristics at low frequencies. The gain is observed to be 20 dB with upper cut-off frequency being 3.47 MHz.

2 Non-inverting amplifier

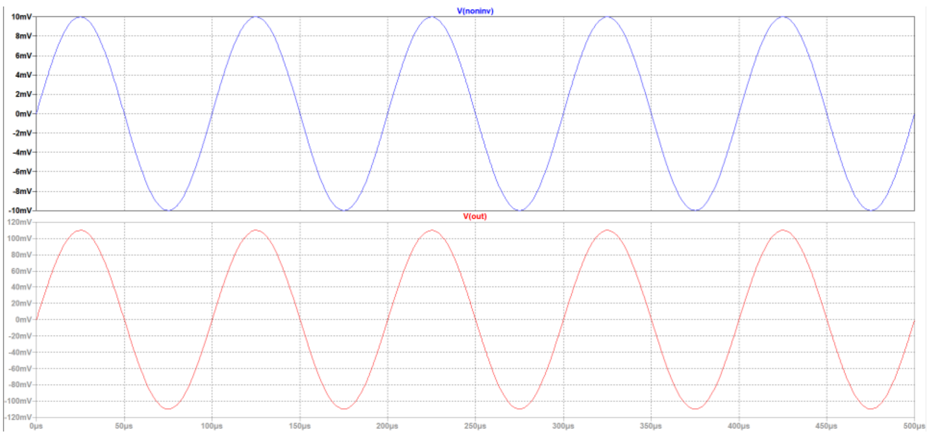

Fig. 11. ***Input and output voltage waveform for non-inverting op-amp:*** We can observe that the output voltage is in phase with respect to input voltage and a gain of 11 can be observed as well, which is same as that given by the gain equation of non-inverting op-amp.

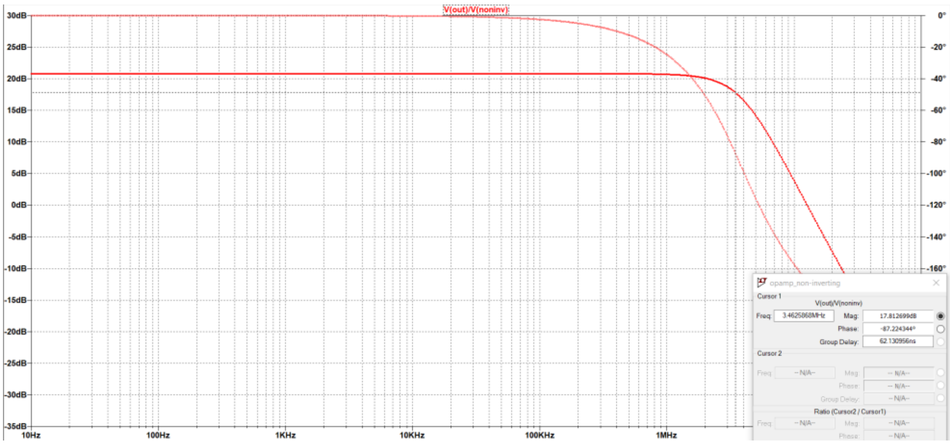

Fig. 12. ***Bode plot for non-inverting op-amp:*** As given in the theory, op-amp circuits are used with compensating capacitors which acts as a low-pass filter. However, due to absence of coupling capacitors, there is no high-pass type characteristics at low frequencies. The gain is observed to be 20.82 dB with upper cut-off frequency being 3.46 MHz.

3 Voltage follower (buffer)

Voltage follower is a special case of non-inverting op-amp with R2 = 0 and R1 = infinity (see Fig. 2). Due to this, the output is expected to follow the input.

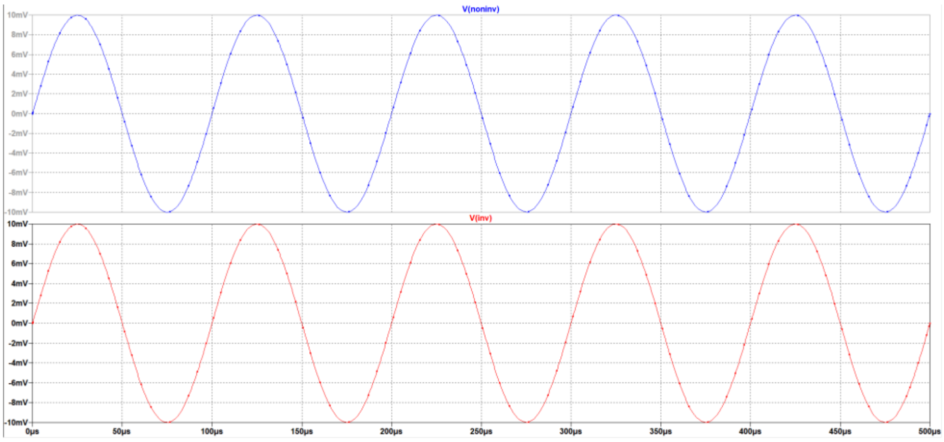

Fig. 13. ***Input and output voltage waveform for voltage follower:*** We can observe that the output voltage follows the input voltage as expected. In this case, the label **INV** and **OUT** (Fig. 2) become shorted.

4 Comparator

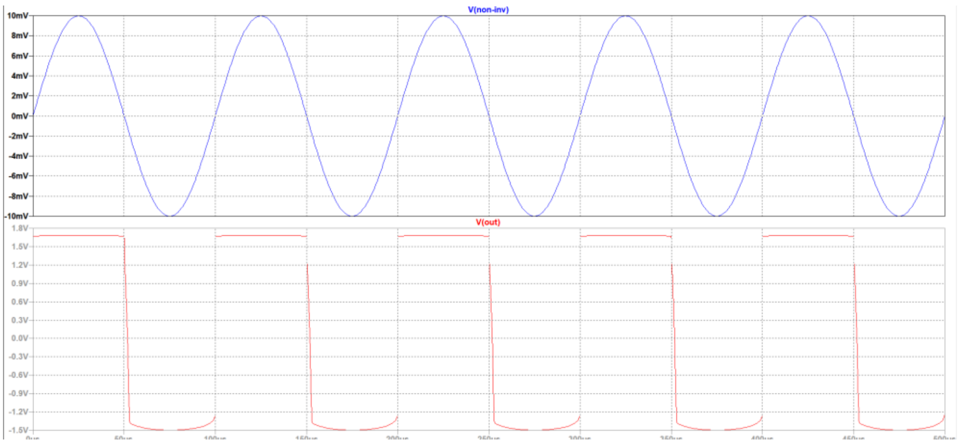

Fig. 14. ***Input and output voltage waveform for comparator:*** We can observe that when Vin is positive, Vout = 1.8 V (high) and when Vin is negative, Vout = -1.8 V (low)

Discussion

1. Op-amp is generally designed in two-stage circuit architecture, for high gain and high swing.
2. First stage comprises of a differential pair, and the second stage is a common-source amplifier.
3. Op-amp at high frequencies has a problem that because of its internal multistage connection, it has a phase shift added at each stage, and at high frequencies, this is a huge problem. To avoid this, a compensating capacitor is added in the circuit. It helps by forcing a pole in the transfer function of op-amp, thus bringing down the bandwidth by acting as a low-pass filter.
4. The open-loop gain of op-amp is very high (up to 120 dB). This very high gain is of no real use as it makes the amplifier both unstable and hard to control. Negative feedback is used to control the gain and make the op-amp stable.
5. Inverting amplifier is designed by adding an input resistance at the inverting terminal of op-amp, and a feedback resistance, input is provided at the other end of input resistance and the non-inverting terminal is grounded.
6. From Fig. 9 and Fig. 10, it can be observed that the output signal is inverted with respect to input signal and the gain observed matches with that calculated with the formula. A bandwidth of 3.47 MHz is observed for inverting amplifier.
7. Non-inverting amplifier is designed by adding a resistance to the inverting terminal with the other end grounded, a feedback resistance from output terminal to inverting terminal and the input is provided at the non-inverting terminal.
8. From Fig. 11 and Fig. 12, it can be observed that the output signal is in phase with respect to the input signal and gain observed matches with that computed with the formula. A bandwidth of 3.46 MHz is observed for non-inverting amplifier.
9. Voltage follower is special configuration of non-inverting amplifier which has unity gain.
10. From Fig. 13, it can be observed that the output signal follows the input signal precisely.
11. Comparator compares the input analog signal with the provided reference. If input signal is greater than reference at any time, then output is logic high, otherwise logic low.
12. From Fig. 14, the same is observed while simulation.

Conclusion

In this experiment, op-amp design with two-stage circuit architecture was simulated for inverting and non-inverting amplifier configuration. It was observed that bandwidth of inverting and non-inverting amplifier was same (3.46 MHz), and the observations are as per with the theory.