OPERATIONAL AMPLIFIERS

OPERATIONAL AMPLIFIERS

- Dc coupled amplifiers and can amplify both Ac and Dc
- Differential Amplifiers: Amplifies input voltages between inverting and non-inverting terminals.
- High input impedance
- Low output impedance
- Vout = A *[Vin(+) - Vin(-)]
- Ideally gain is infinity. In reality it's around 10e6
- So for even small difference in input voltage the output voltage saturates to the supply voltages. (~5V)
- Gain and frequency are inversely related
- Feedback (negative) is most of the time applied to inverting terminal to control the open loop voltage gain.

ASSUMPTIONS:

1. Vin(-) and Vin(+) should always have the same voltage.
2. There is no input currents

OPERATIONAL AMPLIFIERS: REAL WORLD COMPLICATIONS

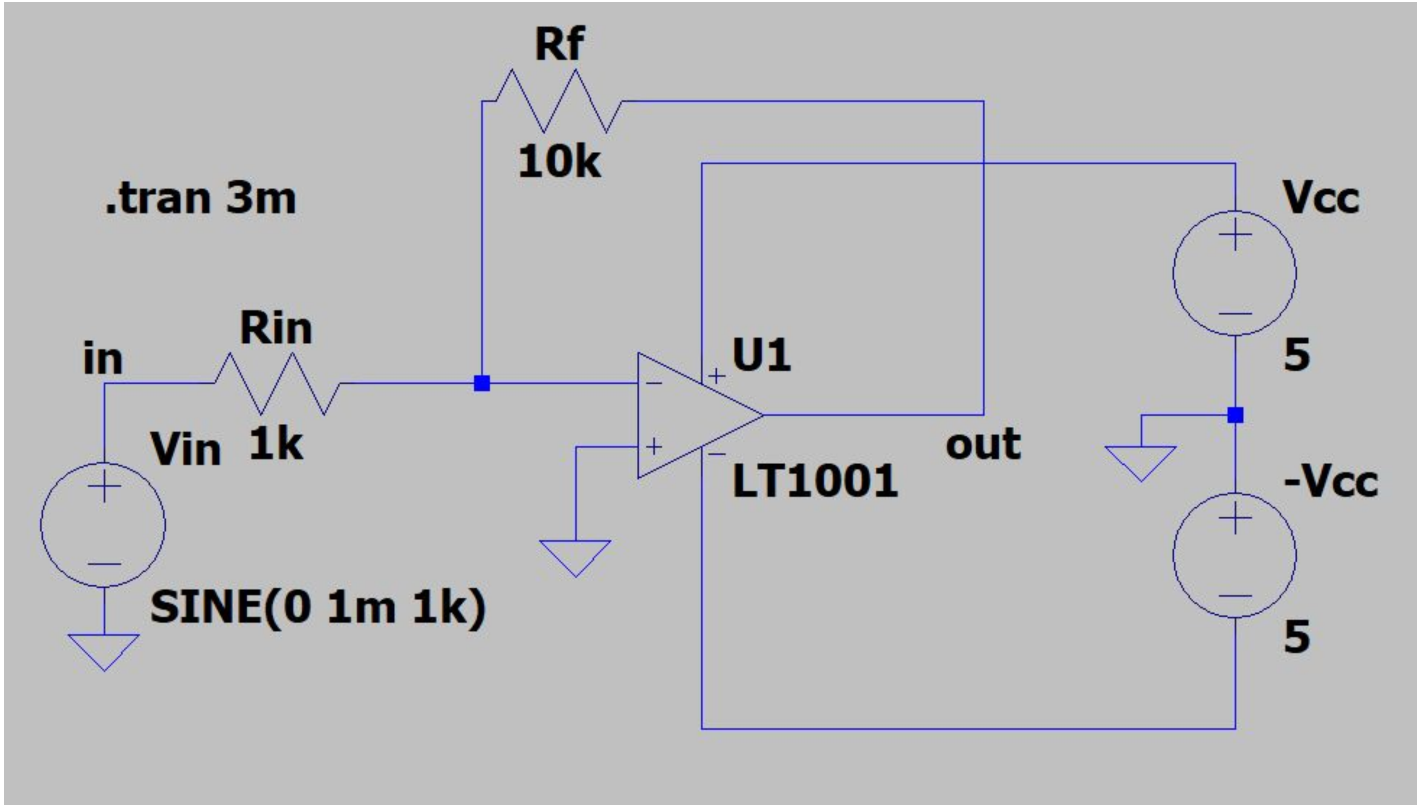
- **Rail to Rail amplifiers** -> swing is bound by supply voltages V(+) and V(-). For higher voltage op amps there is a headroom above an below these bounds.
- **Offset Voltage:** Minute difference Vin(+) and Vin(-).
- **Input bias current:** Current into terminals.
- **Slew Rate**: Rate at which voltage changes in a non instantaneous manner.
  - Slew rate = 2*π*Vpeak*fmax (usually in V/us)
- **Bandwidth**: points beyond where op amp is not fast enough to reproduce singal, i.e. slew rate is not fast enough

BASIC CIRCUITS

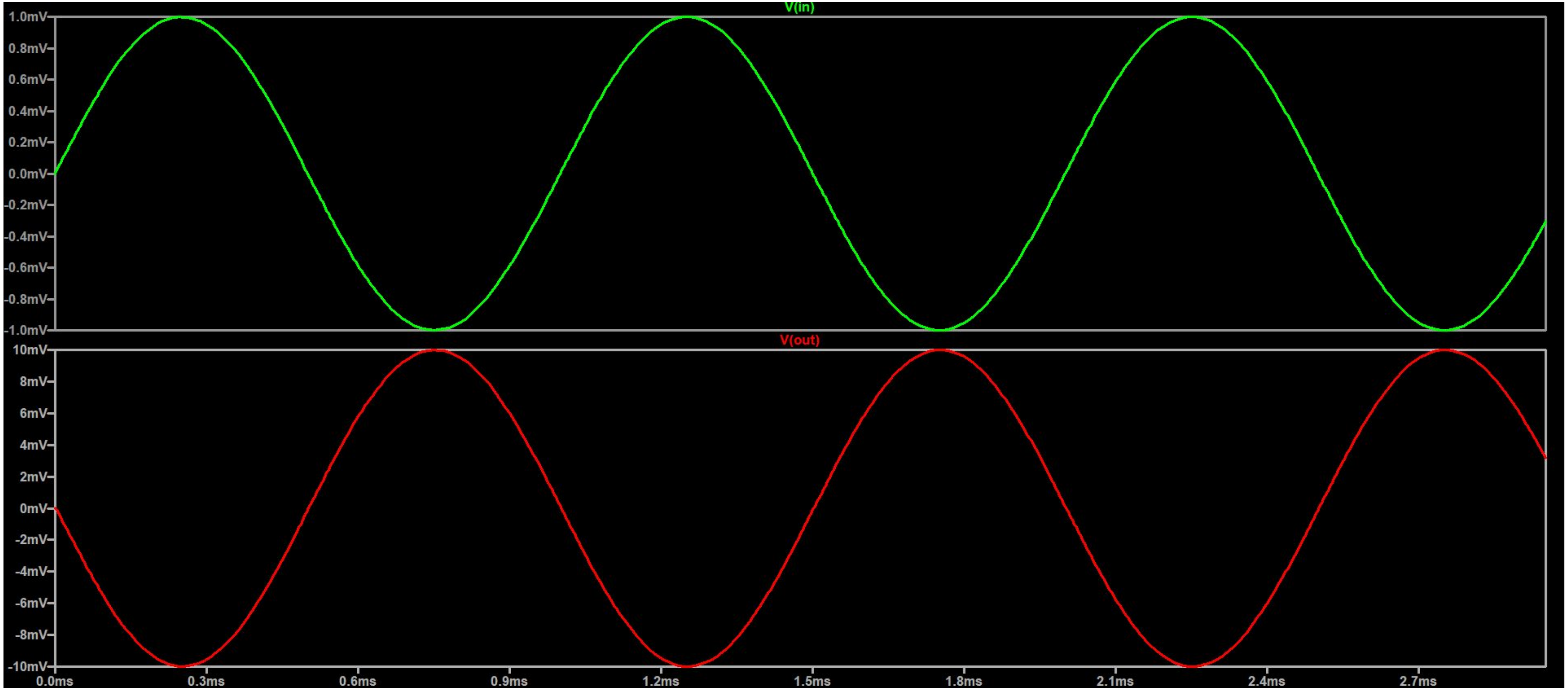
INVERTING AMPLIFIER

G = -Rf / Ri =
10e3 / 1e3 = -10

Input impedance
= R1



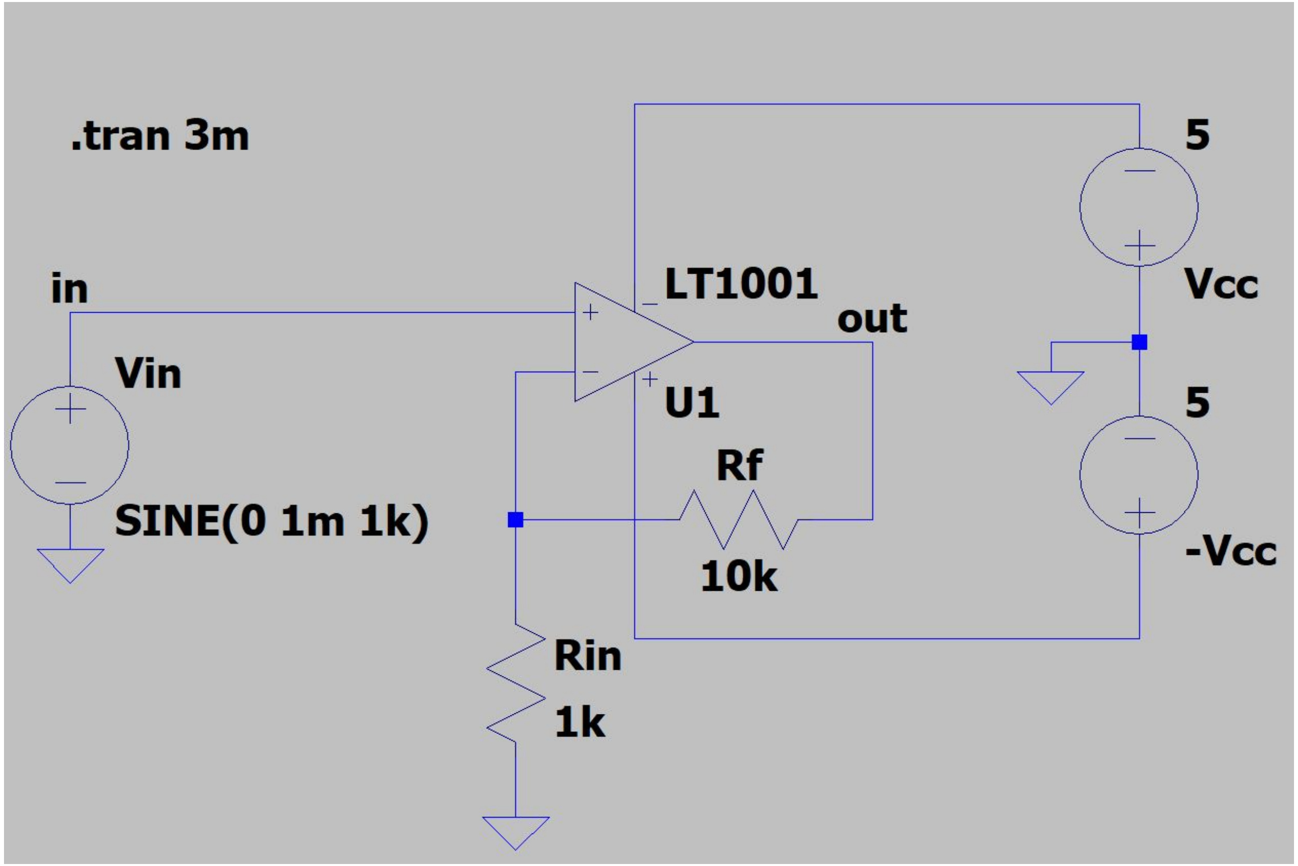
INVERTING AMPLIFIER



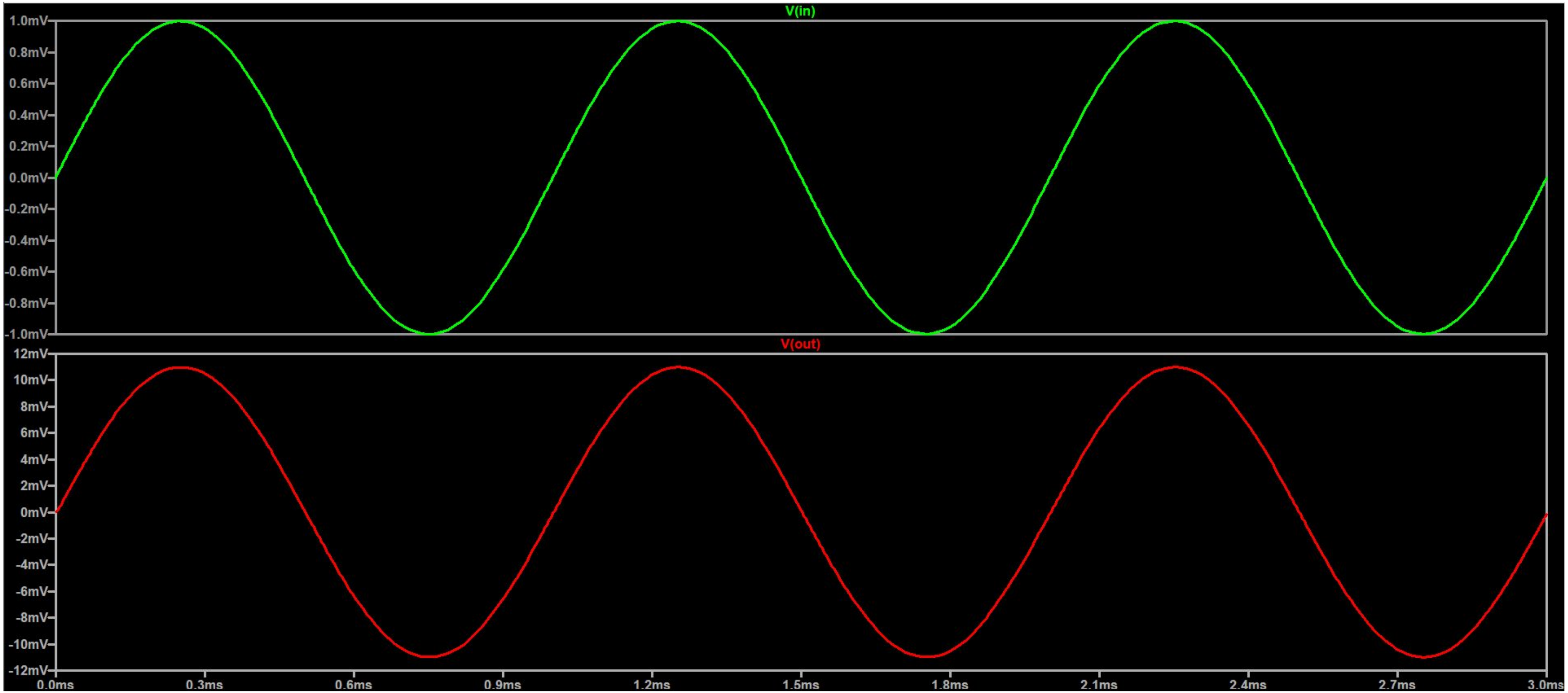
NON-INVERTING AMPLIFIER

G = 1+ Rf / Ri =
1 + 10e3 / 1e3 =
11

Input impedance is high equal to op amp impeadance

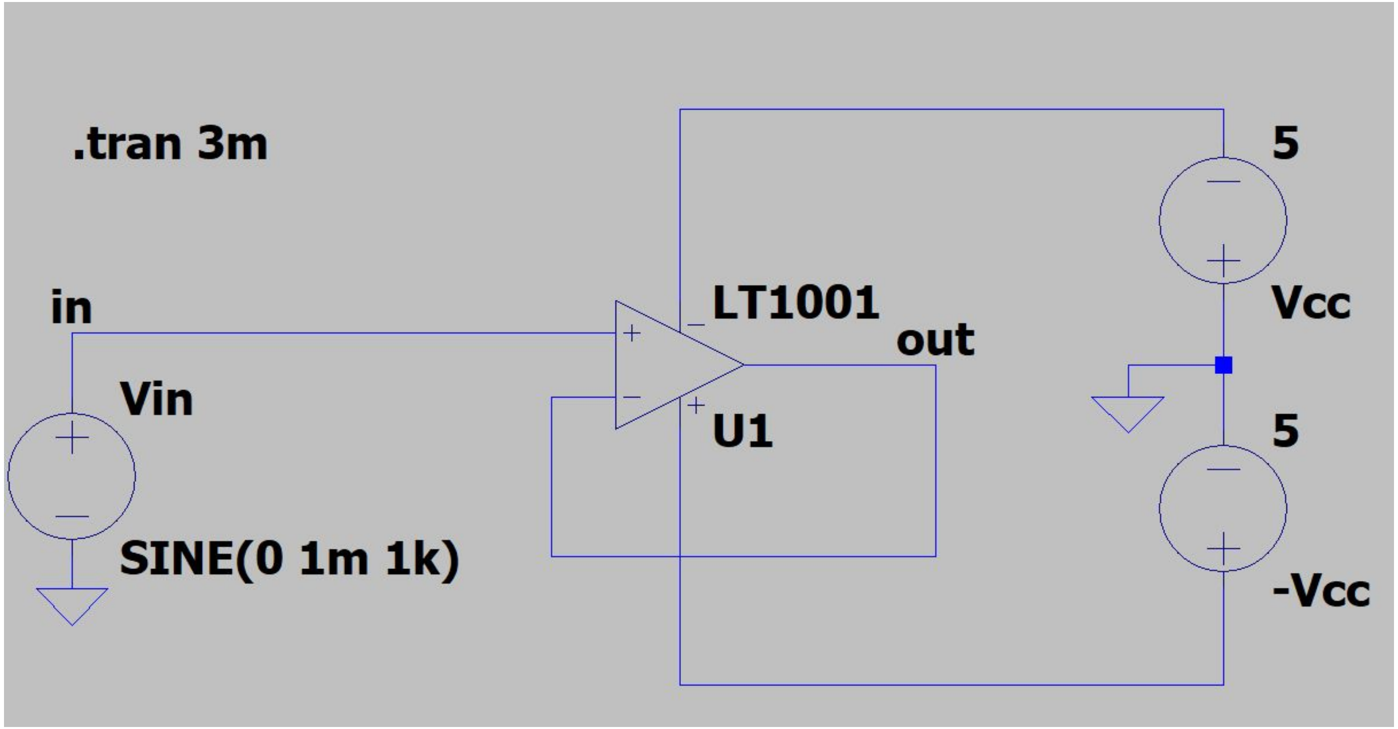


NON-INVERTING AMPLIFIER



VOLTAGE FOLLOWER / BUFFER

Ri=infinity
Rf = 0
Gain = 1

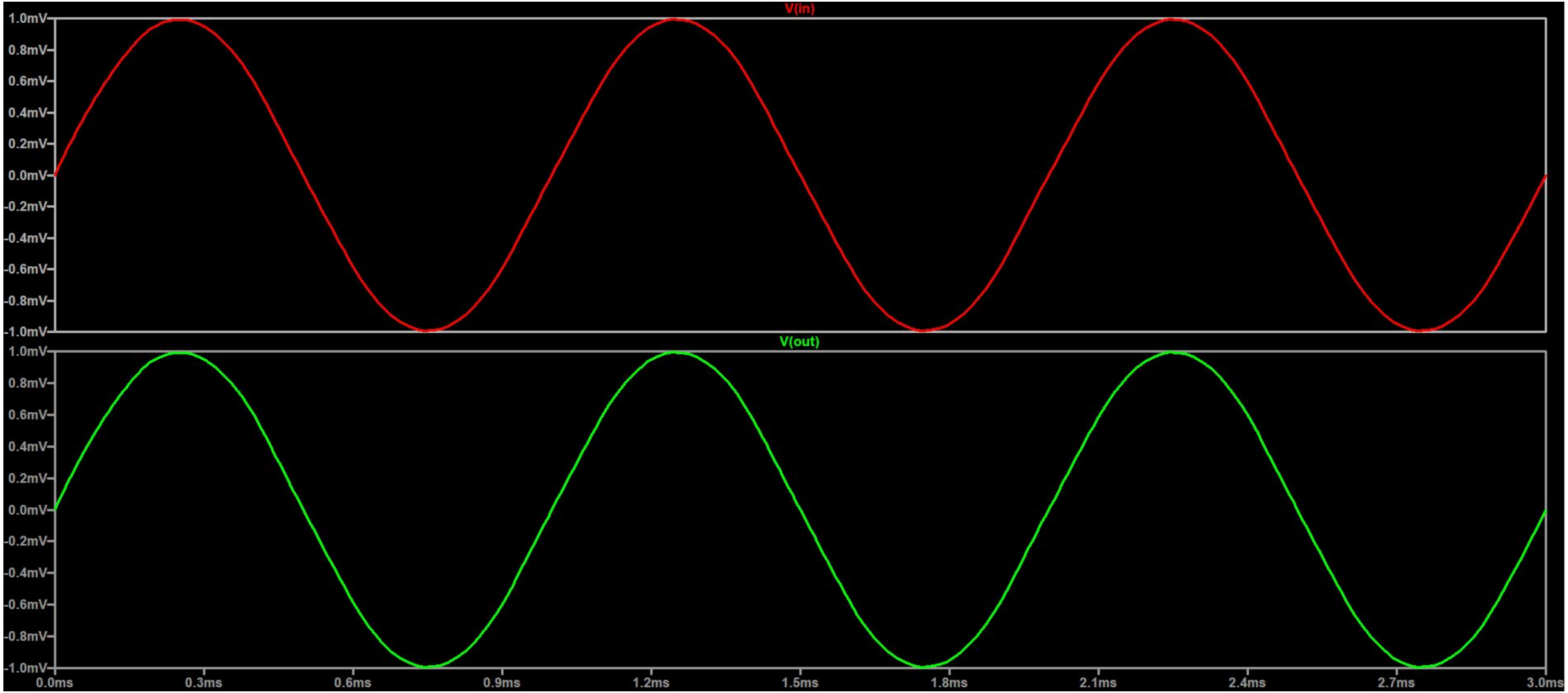


Output voltage follows input voltage.

Input impedance is equal to op amp gain.

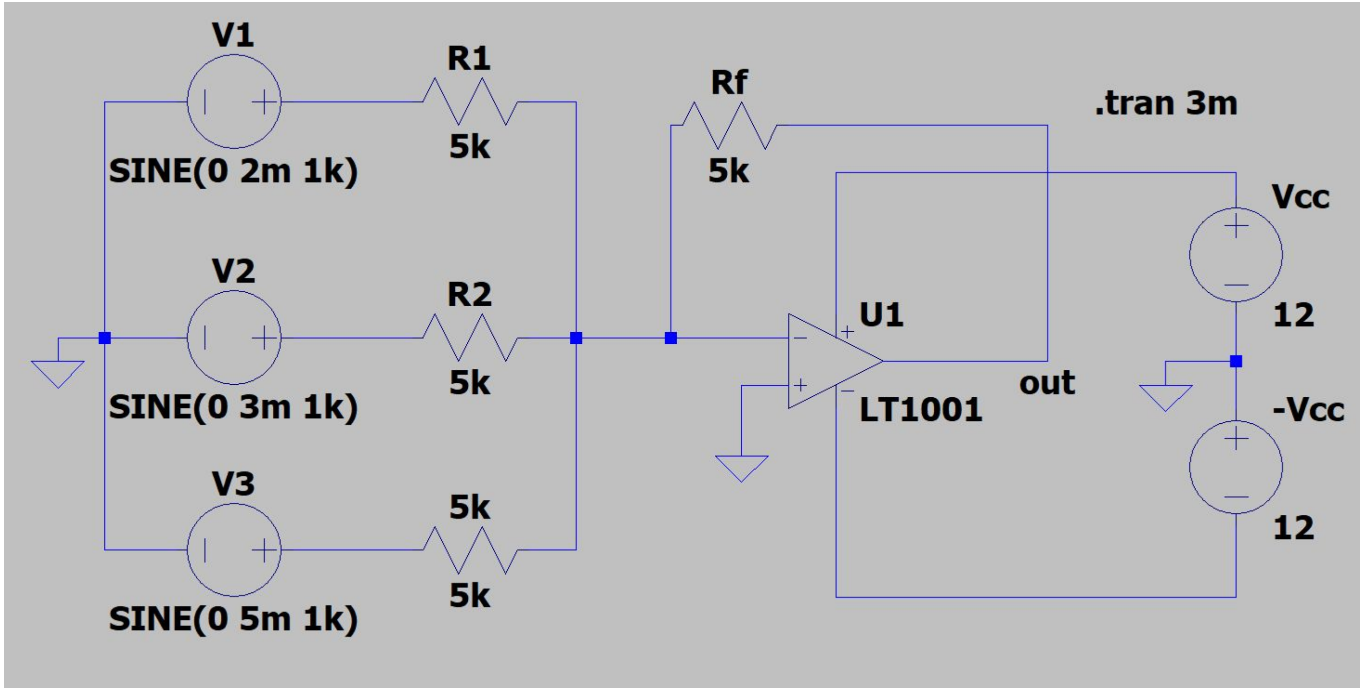
So it acts as buffer, i.e.separating input and output circuits with high impedance but with same voltage.

VOLTAGE FOLLOWER / BUFFER

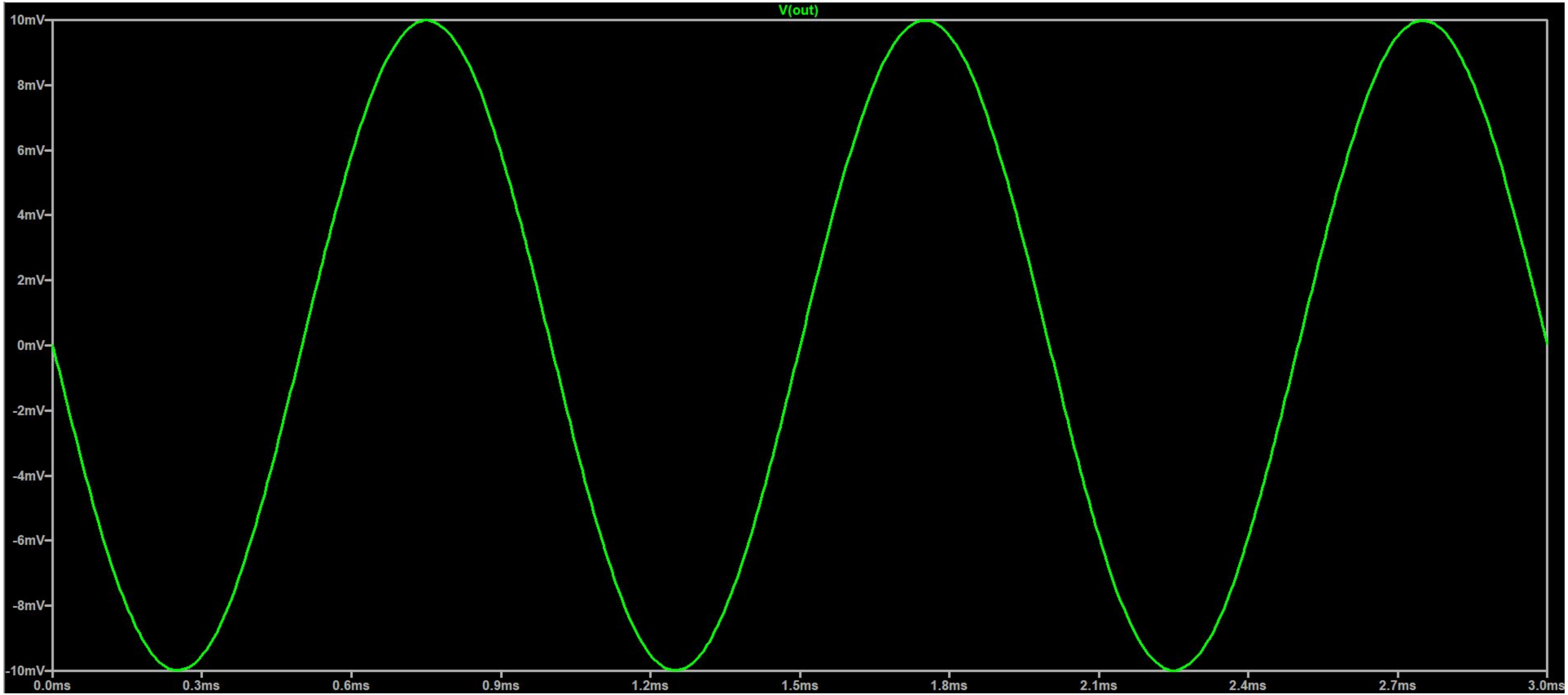


SUMMING AMPLIFIER (INVERTING)

Vout = -Rf[V1/R1 + V2/R2 + V3/R3]
= 5k*[2m/5k + 3m/5k + 5m/5k]
=10mV



SUMMING AMPLIFIER (INVERTING)



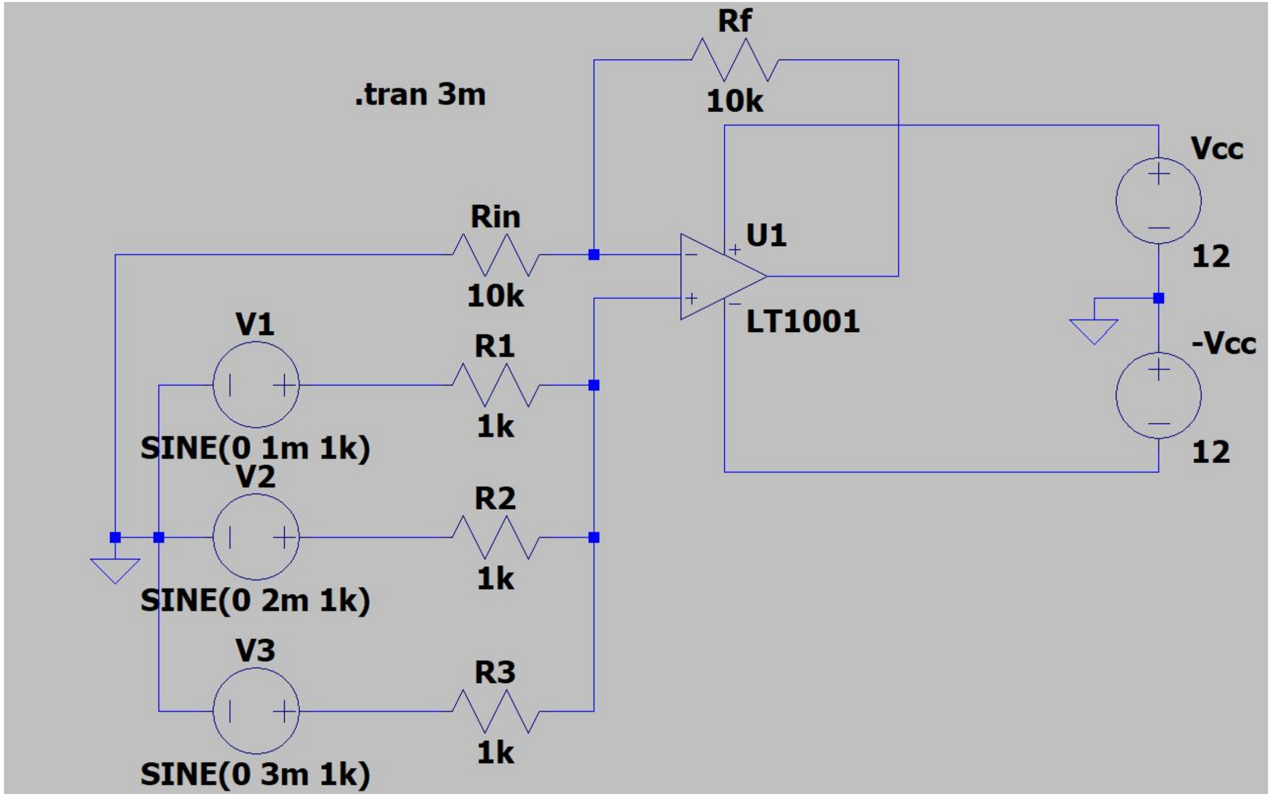
SUMMING AMPLIFIER (NON-INVERTING)

Vout = (1 + Rf/Rin)*[(R2||R3)*V1/ (R1 + (R2||R3) + (R1||R3)*V2/ (R2 + (R1 || R3) + (R1||R2)*V3 / (R3 + (R1 || R2))

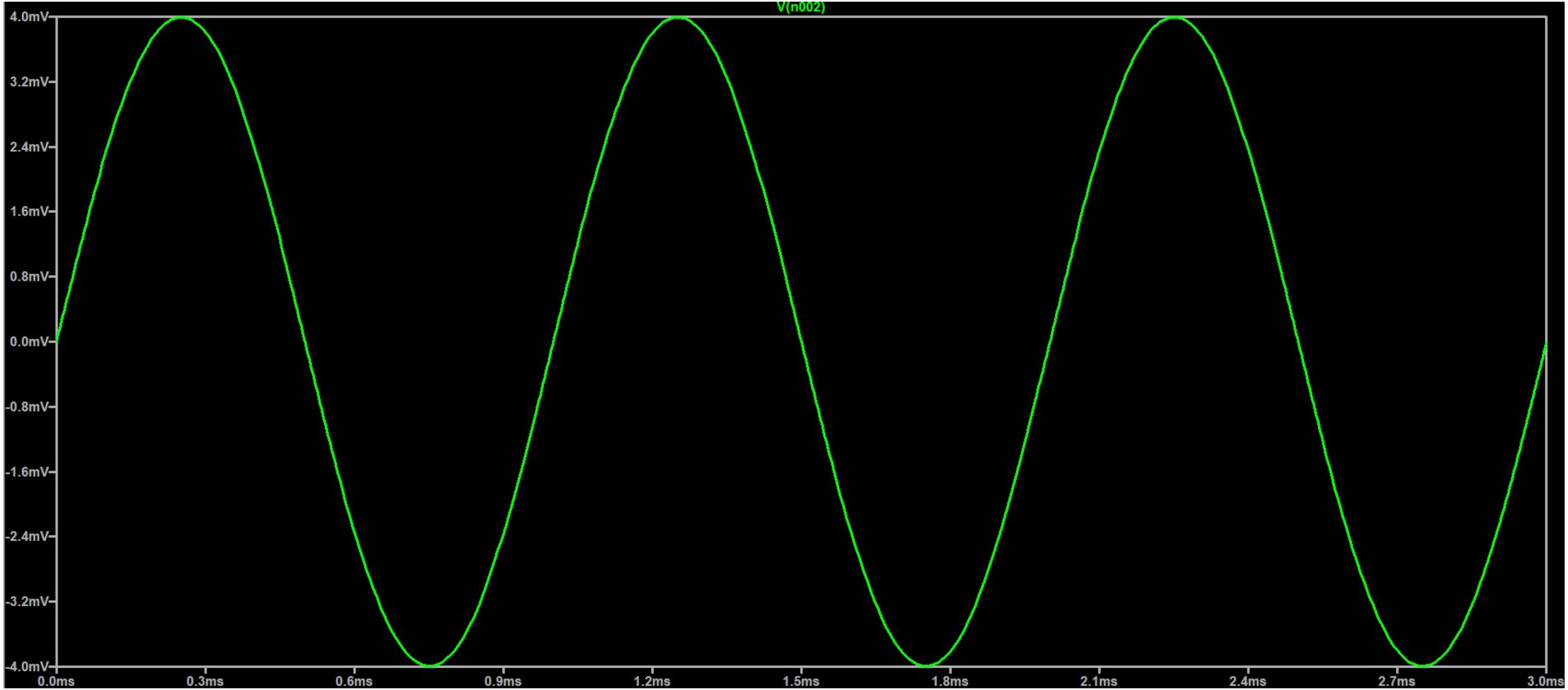
Since R1=R2=R3 and Rin = Rf
Vout = 2 * (V1 + V2 + V3)/3
= 2 * (1+2+3)m / 3
= 4mV

Since voltage contribution for each source at non-inverting terminal depends upon parallel resistances in opposite branches,
Voltage sources **are not isolated**,

So inverting configuration is preferred for summing.



SUMMING AMPLIFIER (NON-INVERTING)



DIFFERENTIAL AMPLIFIERS

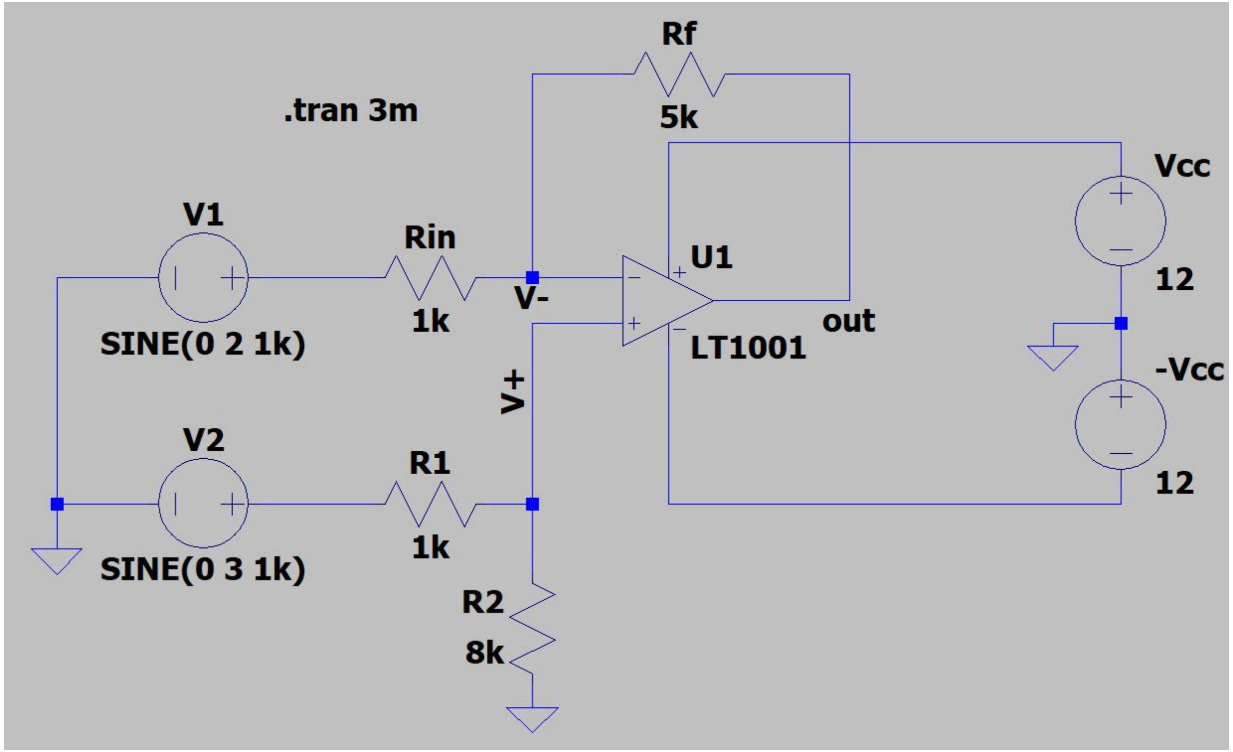
At inverting terminal: Vo1 = -Rf/Rin * V1= -5*2 = -10V

At non-inverting terminal: Vo2 = (1+Rf/Rin)*V(+) = (1+Rf/Rin)*R2/(R2+R1)*V(+) =6*8/9*3 = 16V

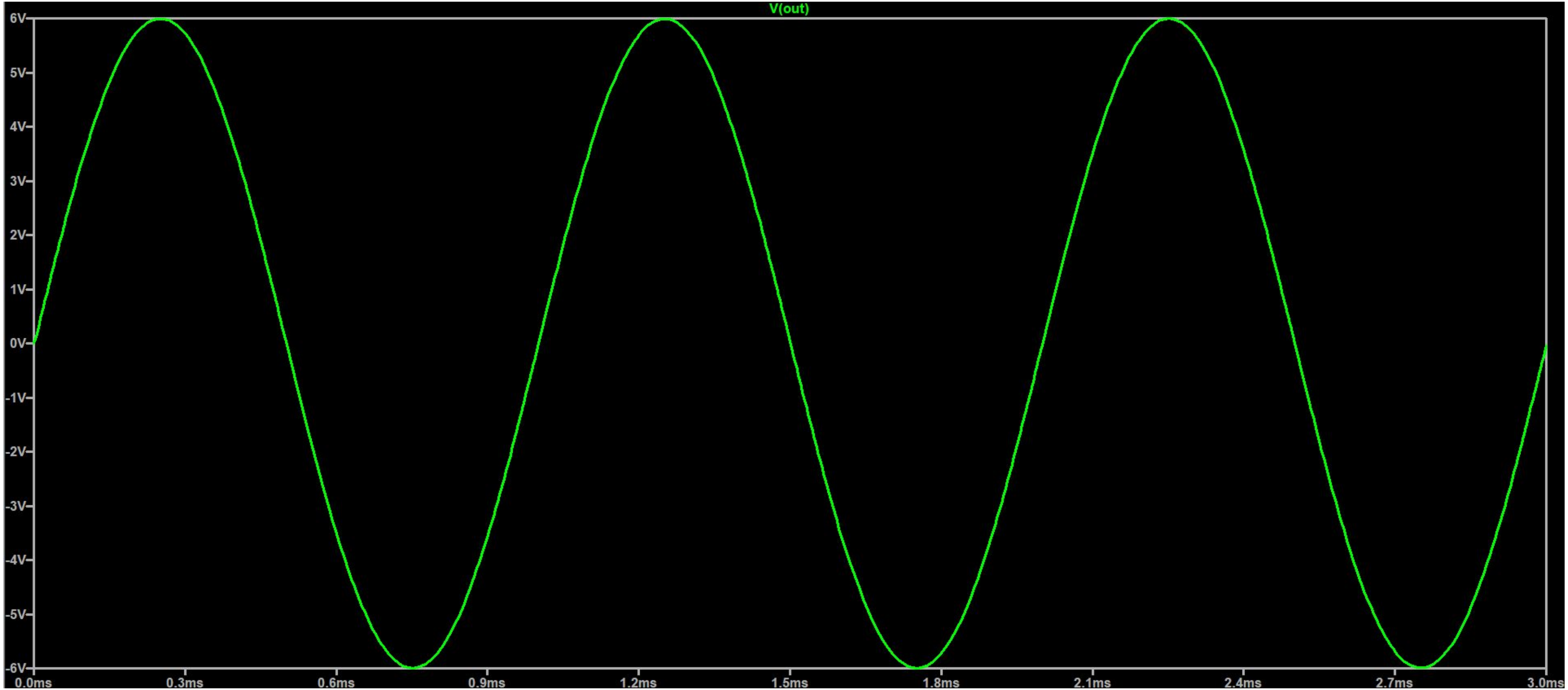
Vout = Vo1 + Vo2 = 6V (should be lower than Vcc)

Issues: **Input impedance** is Rin + R1, is quite **low** and can load the input sources.

Usually buffers are connected to inputs before supplying to amplifier.



DIFFERENTIAL AMPLIFIERS



INTEGRATOR

Mathematical expression

$$V_{out} = -\frac{1}{RC}\int V_{in}dt$$

Inverting op amp configuration

$$V_{out} = -\frac{X_C}{R_{in}}V_{in}$$

Gain formula

$$A_v = -\frac{1}{2\pi f R_{in} C_F}$$

.

So for low frequencies, gain is very high and limited by open loop gain of op amp (capacitor has infinite reactance as Xc = 1/2pi f C).

Practical op amp will have input offset voltage on terminals, which leads to even small voltage gets multiplied by open gain leading to Vout hitting saturation value.

A resistor is added in parallel to capacitor can be added which ensures at low frequency the gain is

$$A_v = -\frac{R_f}{R_{in}}$$

Cutoff frequency

$$f_L = \frac{1}{2\pi R_f C_f}$$

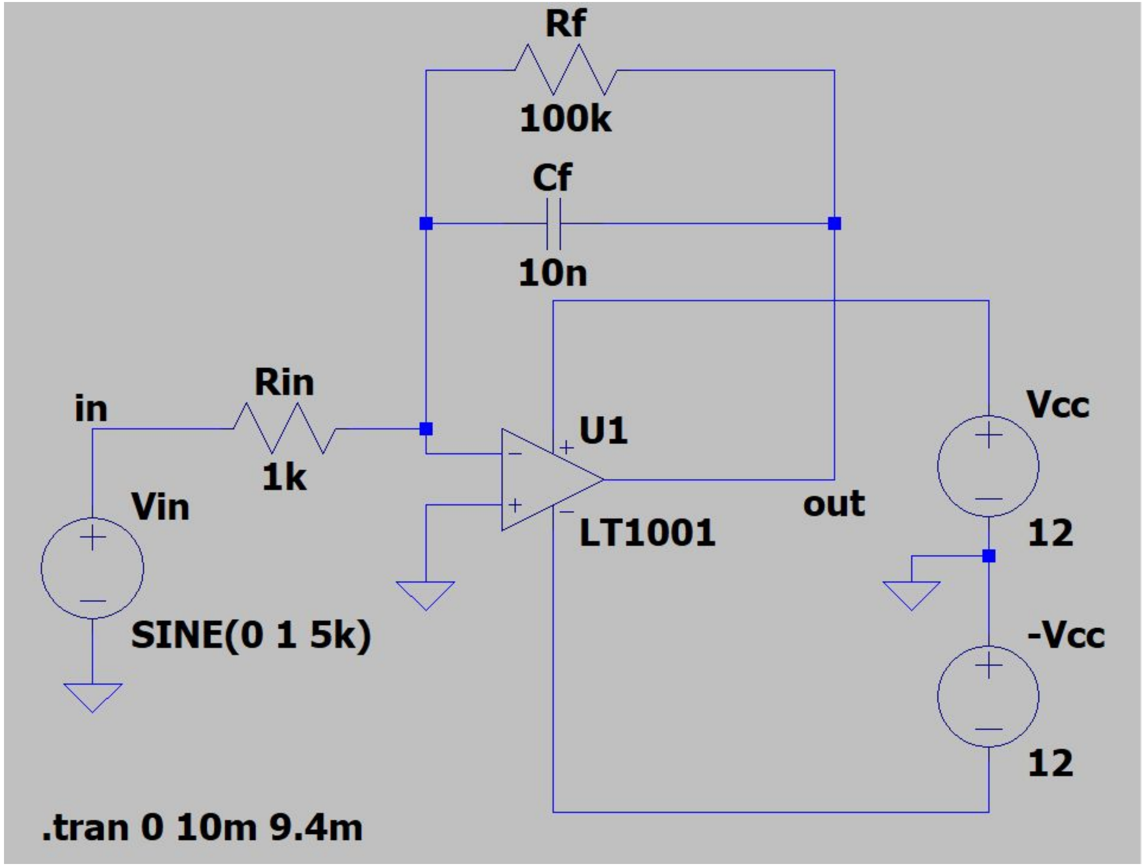
For safe operation

$$f_s = 10 \times f_L$$

INTEGRATOR

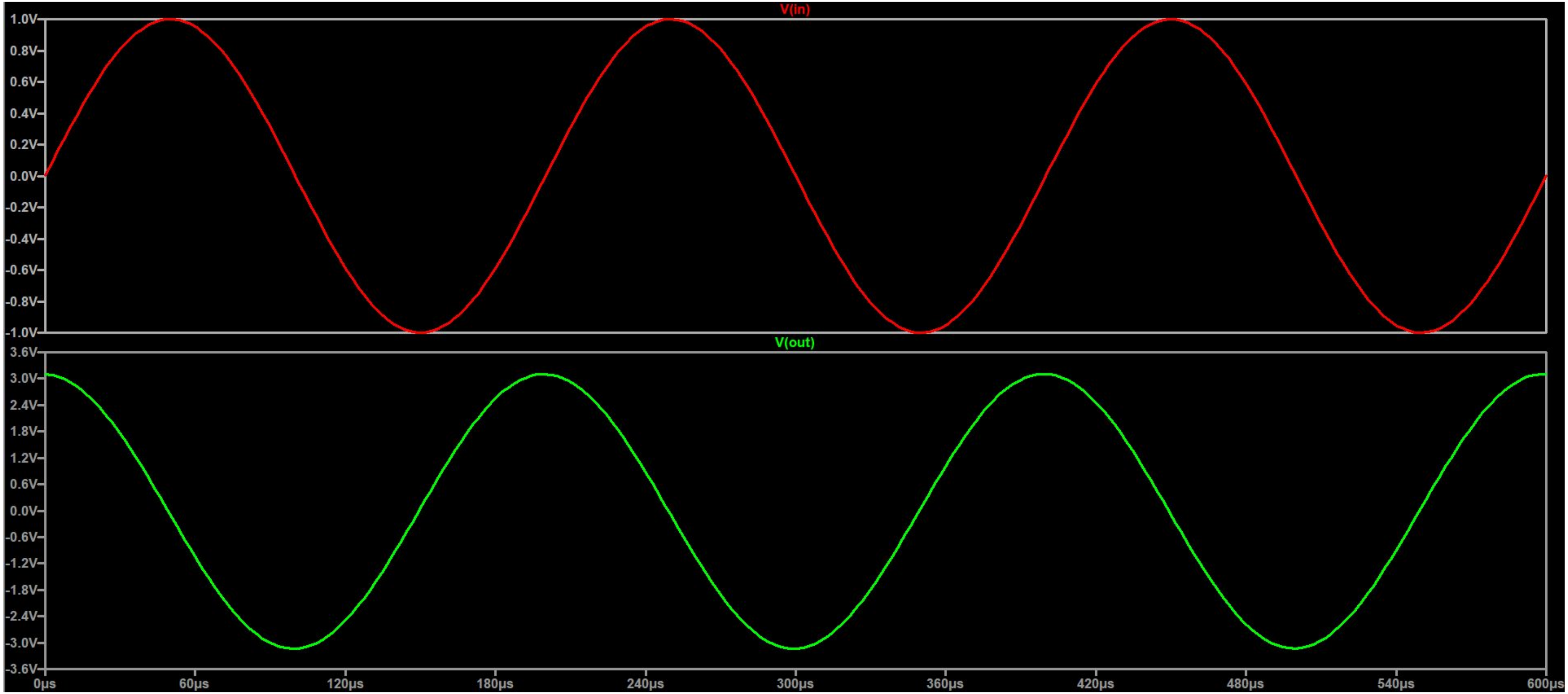
fL = 1 / (2*pi*Rf*Cf) = 159.15 Hz
fs = 10 * fL = 1591.55 Hz

Vout = -1/(Rin*Cf) * ∫sin(2π*5k*t)dt
Vout= -1/(2π*5k*1k*10n)*cos(2π*5k*t)
Vout = -3.18*cos(2π*5k*t)



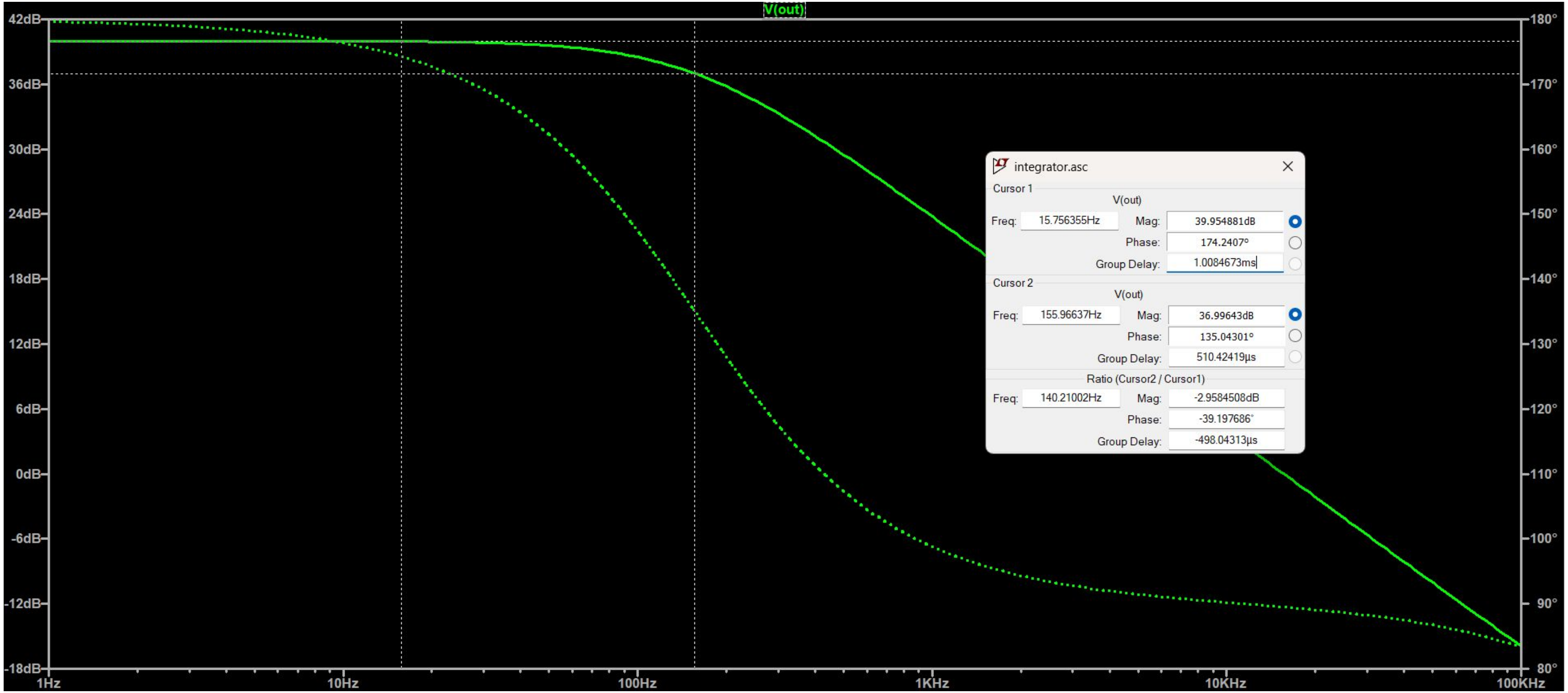
Note: Integrator takes time to settle, due to slew rate, small bandwidth etc.
Therefore reading are taken after 9.4ms

INTEGRATOR



Vout = -3.18cos(2π*5k*t), that is a cosine wave with 180° phase shift

INTEGRATOR



Theoretical: $A_v(\text{dB}) = 20\log_{10}\left(\left|\frac{-R_f}{Ri}\right|\right) = 40\ \text{dB} \quad f_L = 159.15\ \text{Hz}$

DIFFERENTIATOR

Mathematical expression

$$V_{out} = -R_f C_{in} \frac{dV_{in}}{dt}$$

Voltage gain using inverting amplifier gain

$$A_v = -\frac{R_f}{X_C} = -2\pi f_s R_F C_{in}$$

Issues:

1. As frequency increases input impedance decreases.
2. Sensitive high frequency noise

Solution:

1. Add resistor in series with input capacitor.
2. Adding a parallel feedback resistor.

Cutoff frequencies:

$$f_1 = \frac{1}{2\pi R_{in} C_{in}} \quad f_2 = \frac{1}{2\pi R_f C_f}$$

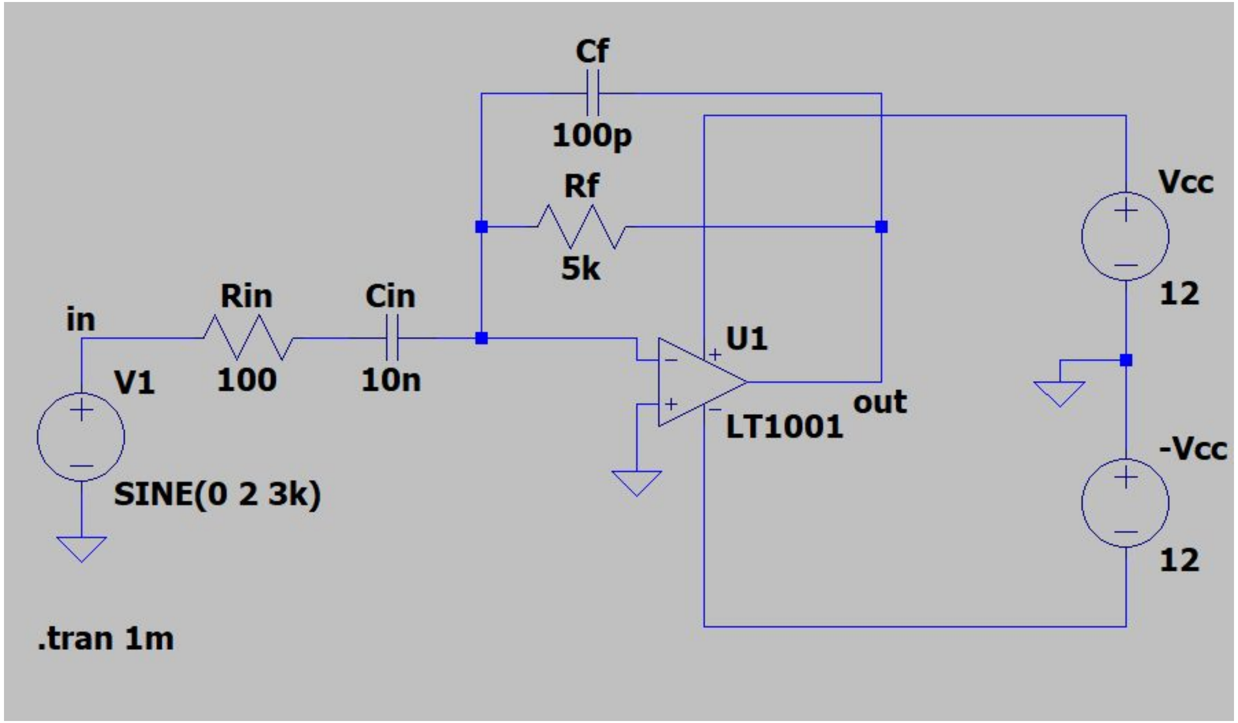
Operating frequency limit

$$f_s = \frac{\min(f_1, f_2)}{10}$$

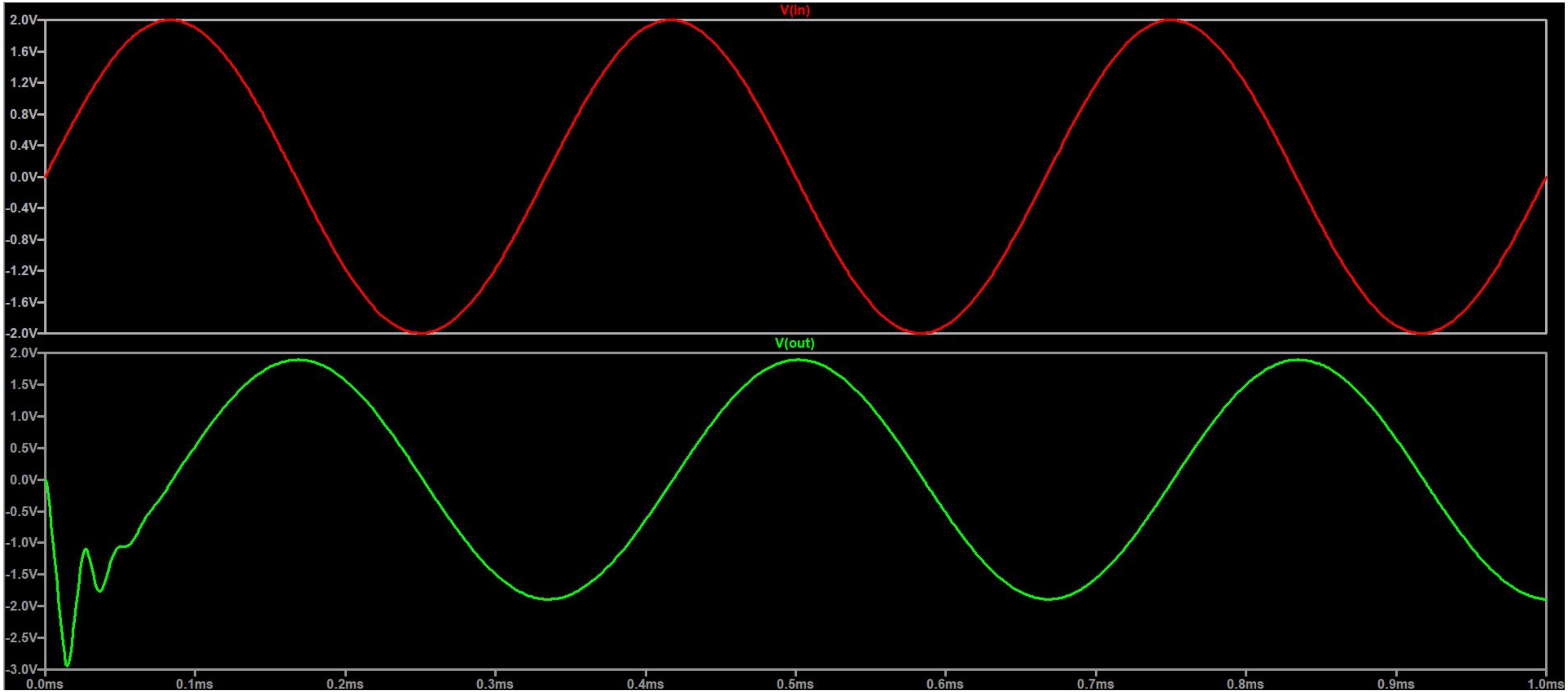
DIFFERENTIATOR

f1 = 159.15kHz
f2 = 318.31kHz
fs = 15.92kHz

Vin = 2*sin(2π*3000t)
Vout = -Rf * Cin *
d [2*sin(2π*3000t)] / dt
= -10e-4 * 2π*3000 * cos(2π*3000t)
= -1.88*cos(2π*3000t)

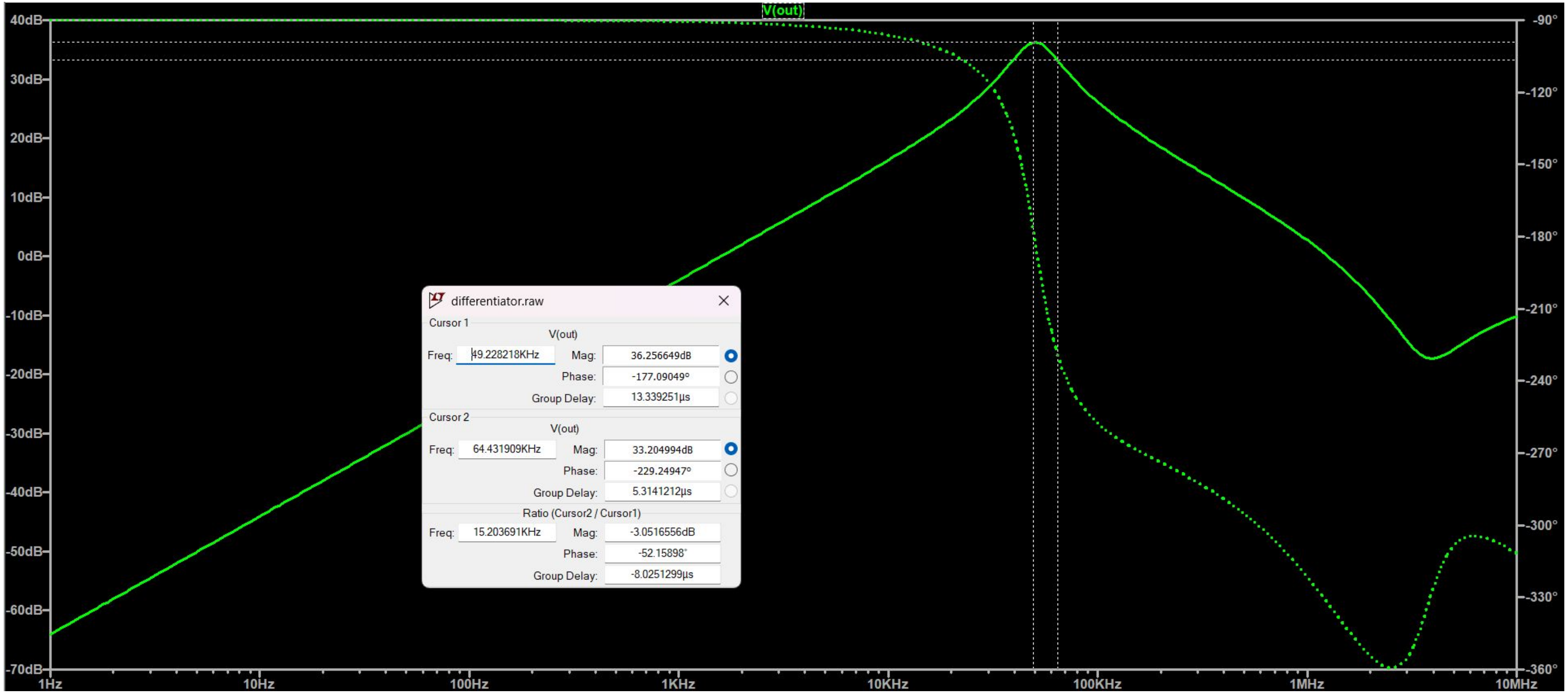


DIFFERENTIATOR



Vout = -1.88*cos(2π*3000t), that is a cosine wave with 1.88 magnitude and 180° phase shift.

DIFFERENTIATOR



Theoretical: Gain: 20*log10(5k/100) = 33.98 dB, fH = 159.15kHz

BANDWIDTH

- **Internal compensating capacitor** -> ensures op amp to have high voltage gain at high frequencies Also it helps remove multiple break frequencies
- Gain bandwidth product:
  - Non-inverting: Unity gain frequency (fu) = Acl * fcl
  - Inverting: Unity gain frequency (fu) = [| Acl | + 1] * fcl
  - Therefore whenever gain of op amp of closed is low, non-inverting configuration is preferred
- Gain is constant upto cutoff frequency
- Cascaded op amp gain bandwidth: $f_{CL} = f_C \times \sqrt{2^{1/n} - 1}$, where n is number of identical op amps.

SLEW RATE

- The rate at which the op amp changes the output voltage.
- Measure in V/us, usually in range of 1V/us to 1000V/us
- Caused by the compensator capacitor. $\frac{dV_C}{dt} = \frac{i_C}{C}$
- For a input sine wave: $V(t) = V_m \sin(\omega t)$ $\frac{dV(t)}{dt} = V_m \omega \cos(\omega t)$ $|\frac{dV(t)}{dt}|_{max} = V_m \omega$
- For signal to be undistorted slew rate (fs) > Vm*2*π*f
- Power Bandwidth of op amp: $f_{max} = \frac{SR}{2\pi V_m}$, beyond which we see distortion.

COMMON MODE REJECTION

- Common voltage is applied to both inverting and non-inverting terminals.
- Ideally the output should be 0, but there is small output voltage present Vocm. $A_{CM} = \frac{V_{OCM}}{V_{CM}} < 1$
- Sources of common mode inputs are
  - 50-60Hz noise signals.
  - Circuit operated in high electromagnetic field.
- If differential voltage is applied to op amp,

$$V_{out} = A_d \times V_{id} + A_{CM} \times V_{CM}$$

$$\mathrm{CMMR} = \frac{A_d}{A_{CM}}$$

- Cmmr depends on frequency and signals on high frequency are not able to

OFFSET VOLTAGE

- Imperfection which causes op amp to have a dc voltage component, causing offset in output voltage.
- That is we need to apply this offset voltage to a terminal to make output zero.
- Caused by non-identical transistors in op amps.
- Its issue in cases where vout should be ideally 0 and same inputs like differential amplifiers
- Can be reduced using Dc offset nulling circuits.

COMPARATOR

- Vin(+) > Vin(-) -> Vout is high
- Vin(-) < Vin(+) -> Vout is low
- We can see it acts as analog (continuous voltage values) to digital (discrete high-low values) converter.
- As we have seen op amps can be used as comparators in open loop configuration (out putting saturation supply voltage depending on input differential voltage), they are designed to be used linear operations.
- Comparators (specially designed) have higher slew rates than general op amps.