Fully Differential Amplifiers - 2

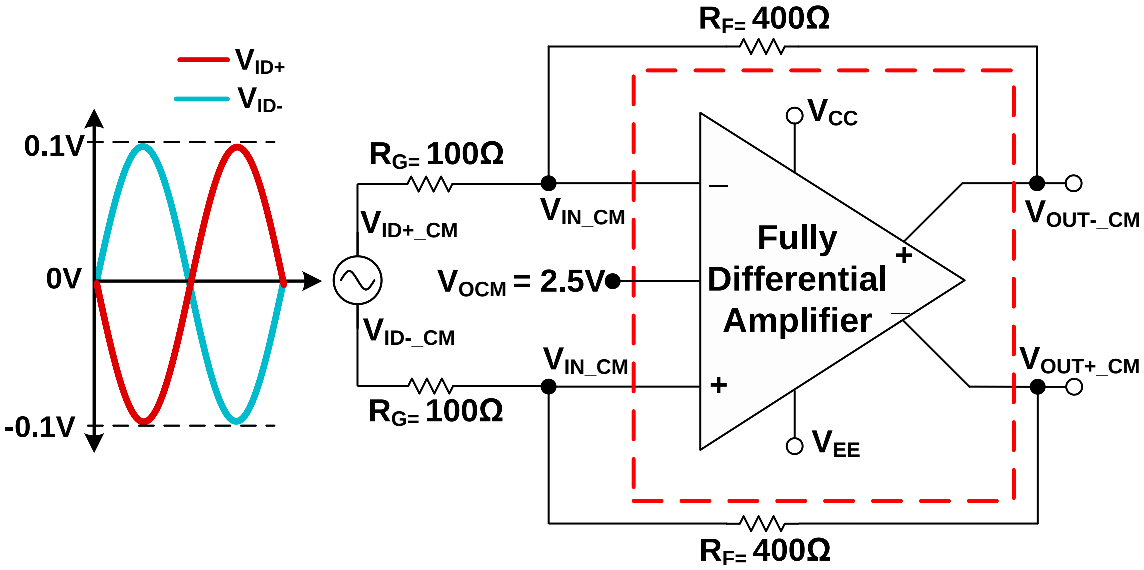
TIPL 2022

TI Precision Labs: Op Amps

Prepared and Presented by Samir Cherian

Diff-In to Diff-Out: Common-mode Analysis

Assume $V_{ID-} = -V_{ID+} = 0.2V_{PP}$,
$V_{ID\pm\_CM} = 0V$, & $V_{OCM} = 2.5V$



At the FDA Output

$$V_{OUT+\_CM} = V_{OUT-\_CM} = V_{OCM} = 2.5V$$

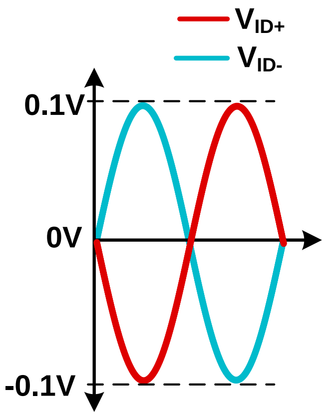
At the FDA Input, use KCL

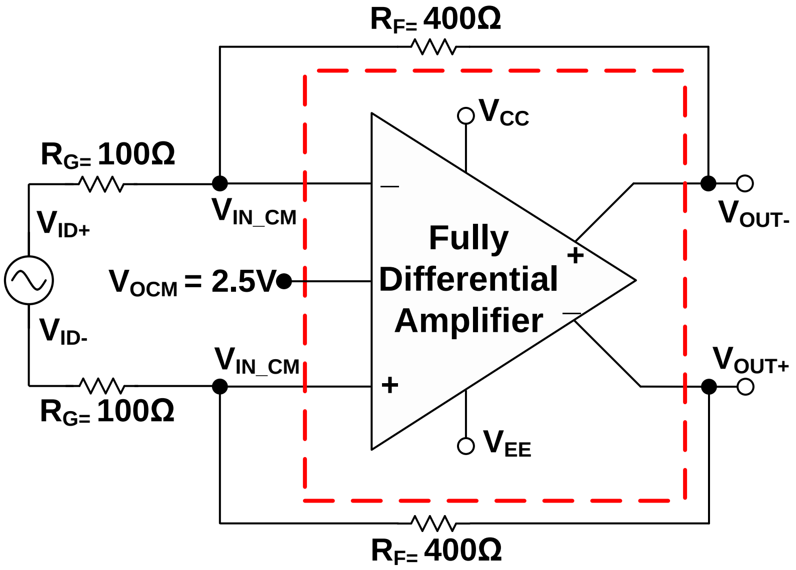
$$\frac{(V_{ID\mp\_CM} - V_{IN\_CM})}{R_G} = \frac{(V_{IN\_CM} - V_{OUT\pm\_CM})}{R_F}$$

$$V_{IN\_CM} = 2.5V \cdot \frac{100\Omega}{(400\Omega + 100\Omega)} = 0.5V$$

Diff-In to Diff-Out: Differential Analysis

Assume $V_{ID-} = -V_{ID+} = 0.2V_{PP}$,
$V_{ID\pm\_CM} = 0V$, & $V_{OCM} = 2.5V$





Taking each half of the FDA separately and applying KCL,

$$V_{IN\_CM} = \frac{V_{OUT-} + V_{ID+}\left(\frac{R_F}{R_G}\right)}{\left(1+\frac{R_F}{R_G}\right)}, \text{ and} \quad (1)$$

$$V_{IN\_CM} = \frac{V_{OUT+} + V_{ID-}\left(\frac{R_F}{R_G}\right)}{\left(1+\frac{R_F}{R_G}\right)} \quad (2)$$

Equating (1) & (2)

$$\left(V_{OUT-} - V_{OUT+}\right) = -\left(\frac{R_F}{R_G}\right).\left(V_{ID+} - V_{ID-}\right) \quad (3)$$

$$\frac{\Delta V_{OUT}}{\Delta V_{ID}} = -\left(\frac{R_F}{R_G}\right)$$

Diff-In to Diff-Out: Differential + CM Analysis

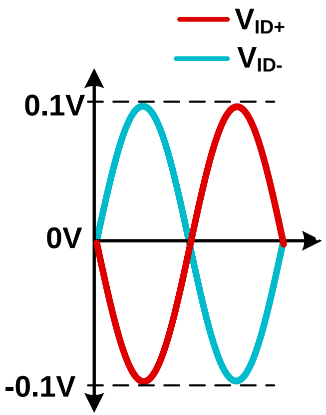
At the FDA Output

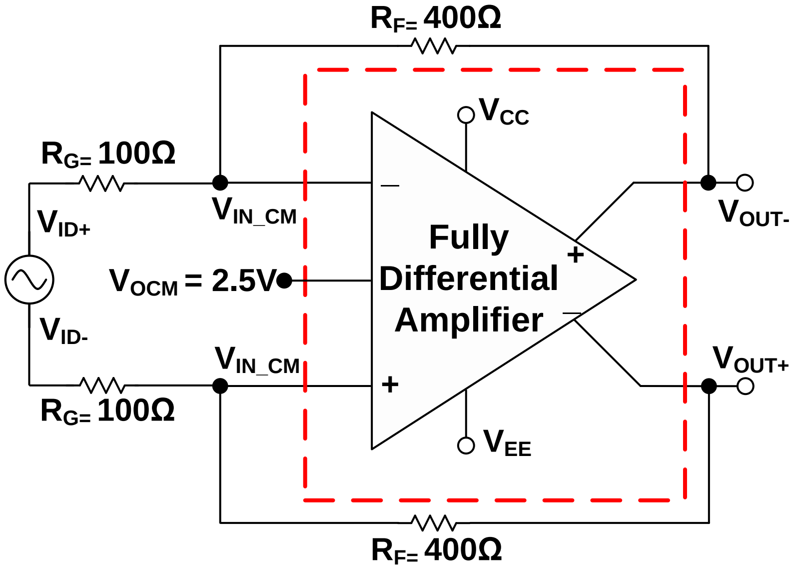
Differential V_{OUT},

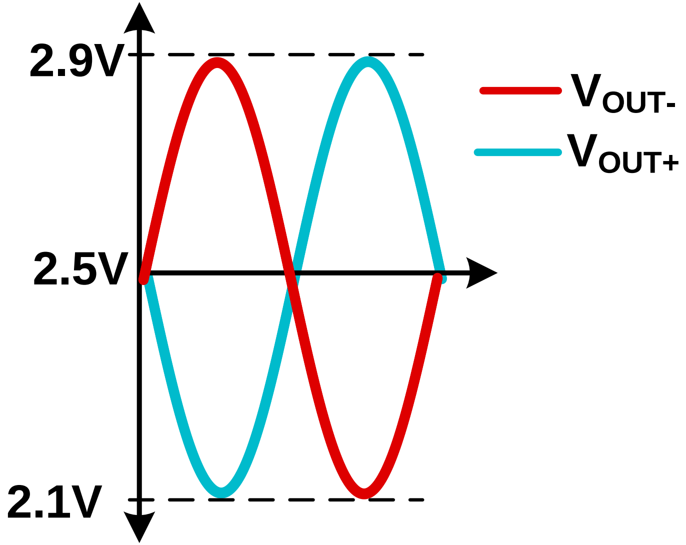
$$V_{OUT-} = -V_{OUT+} = 4 \times 0.2V_{PP} = 0.8V_{PP}$$

$(Differential + CM)$ V_{OUT},

$$V_{OUT-} = 2.5V \pm 0.8V, \text{ and, } V_{OUT+} = 2.5V \mp 0.8V$$





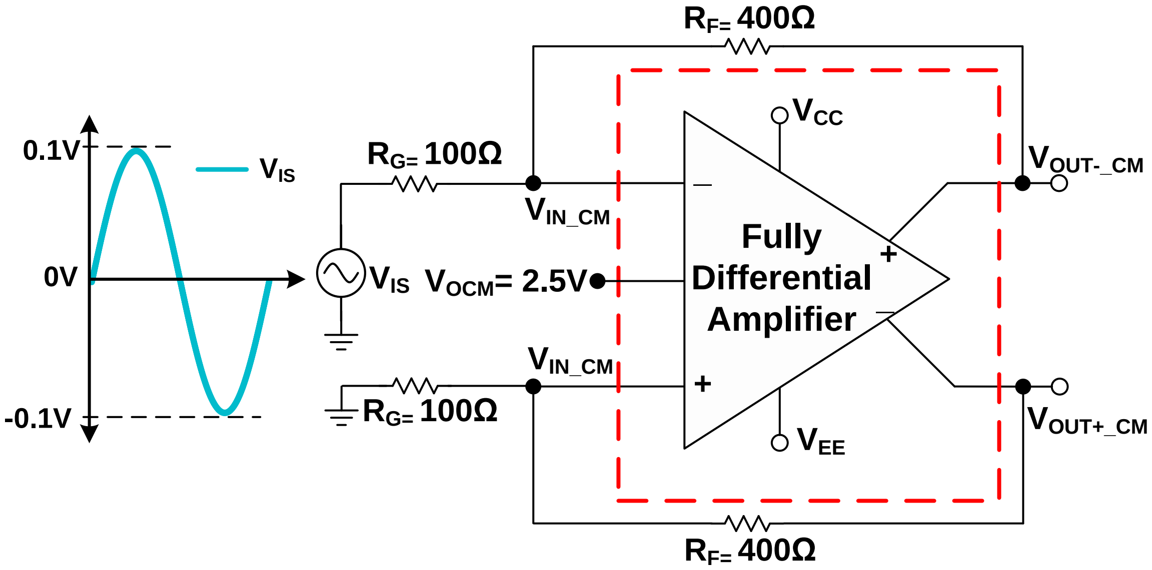


Single-ended-In to Diff-Out: Common-Mode Analysis

Assume $V_{IS} = 0.2V_{PP}$, $V_{IS\_CM} = 0V$, & $V_{OCM} = 2.5V$

At the FDA Output

$$V_{OUT+\_CM} = V_{OUT-\_CM} = V_{OCM} = 2.5V$$



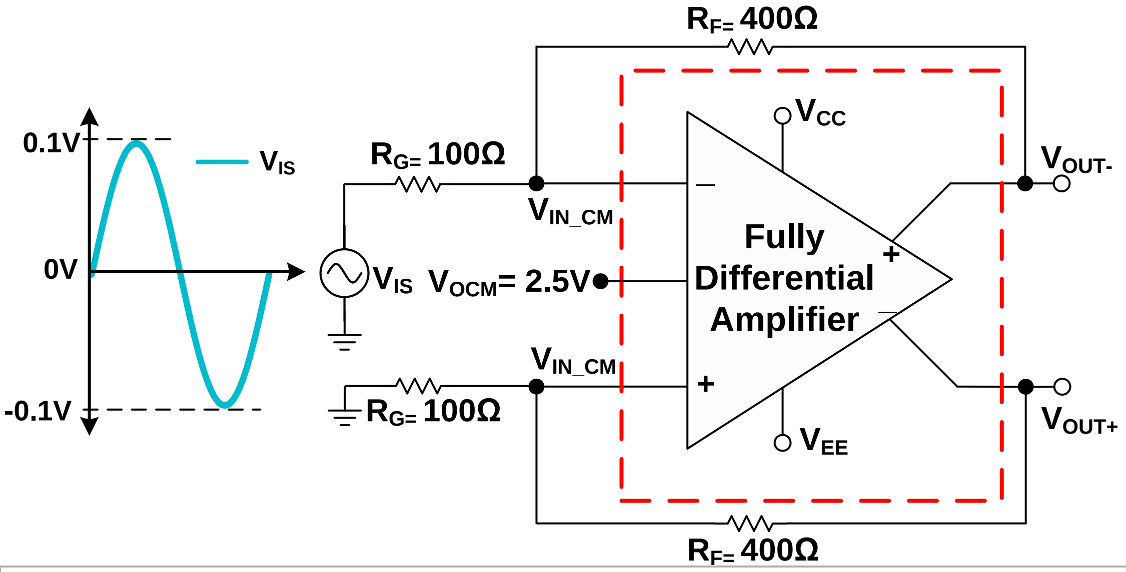
At the FDA Input, use KCL on non-driven input

$$\frac{(V_{OUT+\_CM} - V_{IN\_CM})}{R_F} = \frac{(V_{IS\_CM} - V_{IN\_CM})}{R_G}$$

$$V_{IN\_CM} = 2.5V \cdot \frac{100\Omega}{(400\Omega + 100\Omega)} = 0.5V$$

Single-ended-In to Diff-Out: Differential Analysis

Assume $V_{IS} = 0.2V_{PP}$, $V_{IS\_CM} = 0V$, & $V_{OCM} = 2.5V$



First find the Input Common-mode,

$$V_{IN\_CM} = \frac{V_{OUT+}}{\left(1+\frac{R_F}{R_G}\right)} \qquad (1)$$

Use KCL on the driven half,

$$\frac{V_{IS} - V_{IN\_CM}}{R_G} = \frac{V_{IN\_CM} - V_{OUT-}}{R_F}$$

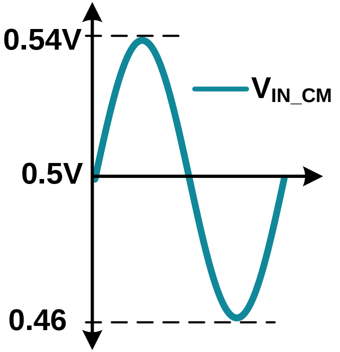
$$V_{IS}\left(\frac{R_F}{R_G}\right) = V_{IN\_CM}\left(1+\frac{R_F}{R_G}\right) - V_{OUT-} \qquad (2)$$

From (1) & (2)

$$V_{IS}\left(\frac{R_F}{R_G}\right) = \frac{V_{OUT+}}{\left(1+\frac{R_F}{R_G}\right)}\left(1+\frac{R_F}{R_G}\right) - V_{OUT-}$$

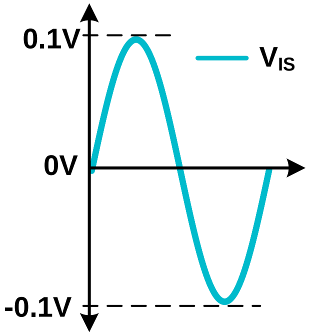
$$\frac{V_{OUT-} - V_{OUT+}}{V_{IS}} = \frac{\Delta V_{OUT}}{V_{IS}} = -\left(\frac{R_F}{R_G}\right)$$

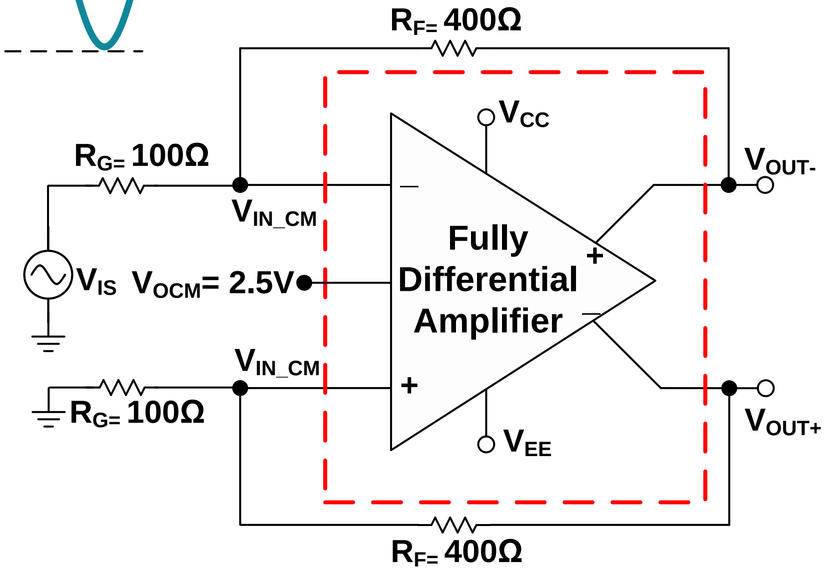
Single-ended-In to Diff-Out: Differential + CM analysis

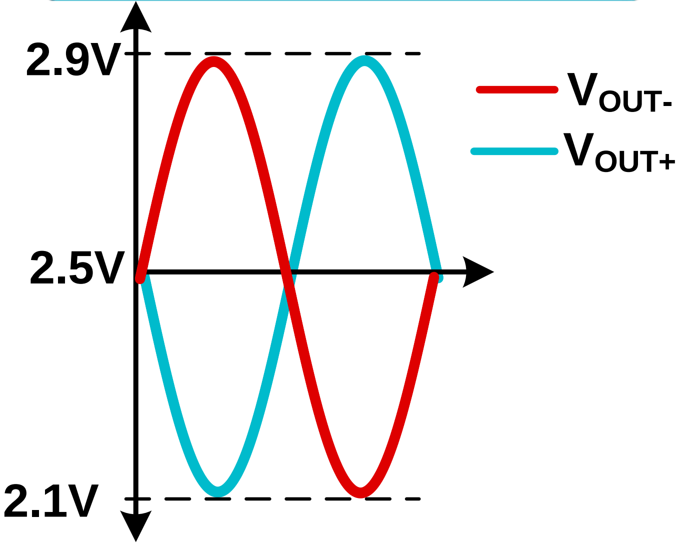


$$V_{IN\_CM}(DC) = \frac{V_{OCM}}{\left(1+\frac{R_F}{R_G}\right)} = \frac{2.5V}{5} = 0.5V$$

$$V_{IN\_CM}(AC) = \frac{V_{OUT\pm}}{\left(1+\frac{R_F}{R_G}\right)} = \frac{400mV_{PP}}{5} = 80mV_{PP}$$

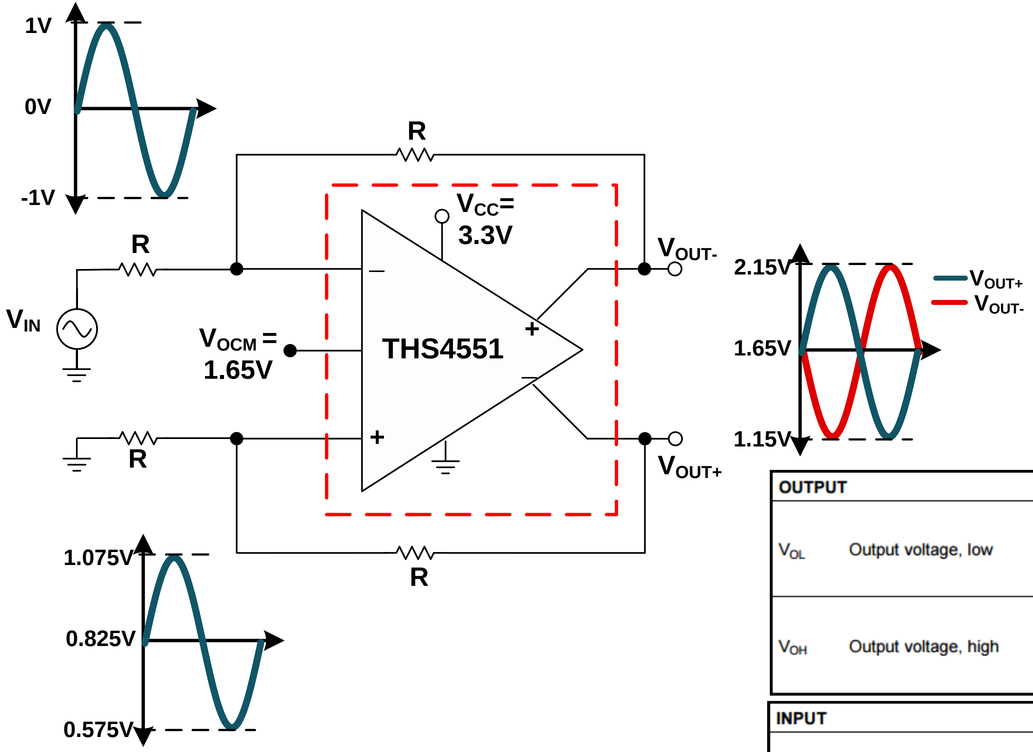






Bipolar Input Signals with Single-sided Supply Voltage

- A_V = 1V/V, V_{OCM} = 1.65V, V_S = 3.3V
- Input = $2V_{PP}$ around GND



OUTPUT						
V_{OL}	Output voltage, low	T_A = 25°C		$(V_{S-}) + 0.2$	$(V_{S-}) + 0.21$	V
		T_A = –40°C to +125°C		$(V_{S-}) + 0.2$	$(V_{S-}) + 0.22$	
V_{OH}	Output voltage, high	T_A = 25°C	$(V_{S+}) - 0.21$	$(V_{S+}) - 0.2$		V
		T_A = –40°C to +125°C	$(V_{S+}) - 0.22$	$(V_{S+}) - 0.2$		

INPUT						
Common-mode input, low	> 87-dB CMRR at input range limits	T_A = 25°C		$(V_{S-}) - 0.2$	$(V_{S-}) - 0.1$	V
		T_A = –40°C to +125°C		$(V_{S-}) - 0.1$	V_{S-}	
Common-mode input, high	> 87-dB CMRR at input range limits	T_A = 25°C	$(V_{S+}) - 1.2$	$(V_{S+}) - 1.1$		V
		T_A = –40°C to +125°C	$(V_{S+}) - 1.3$	$(V_{S+}) - 1.2$		

Fully Differential Amplifiers - 2

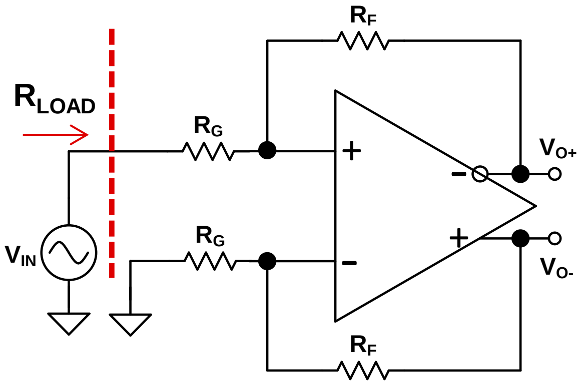
Exercises

TI Precision Labs: Op Amps

Questions

1. How would you AC couple a single-ended input source to an FDA?

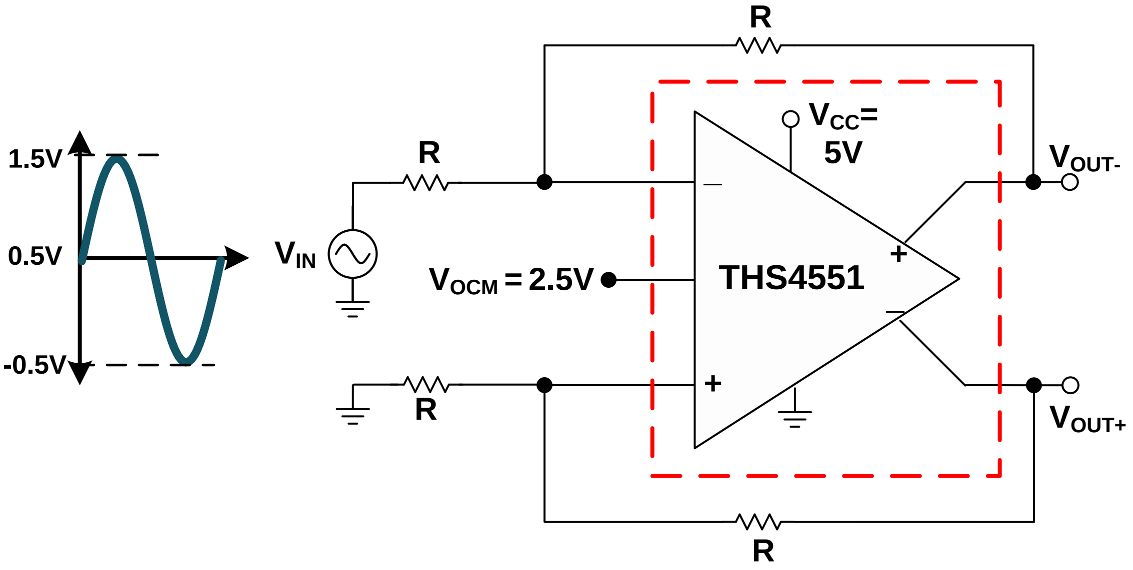
2. What is the load seen by the single-ended input source? (HINT: It is not R_G). Assume that both the VOCM = 0V and the input signal common-mode is 0V.



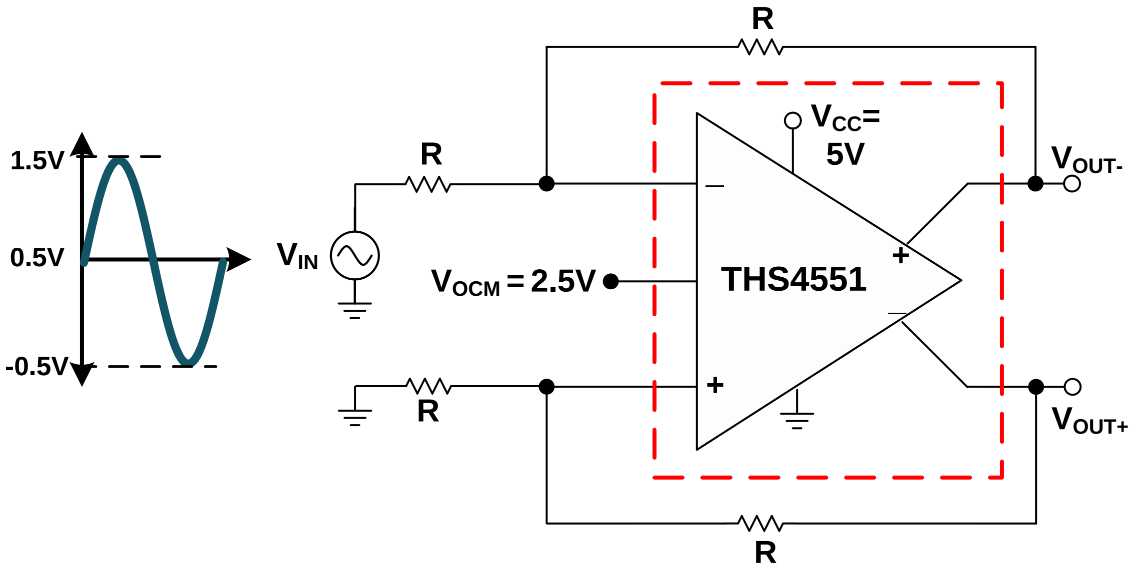
3. For the circuit shown below what is the,

- Output signal (differential and common-mode), and
- Input signal (differential and common-mode)

(HINT: The signal input common-mode is 0.5V while the non-driven input is at GND.)



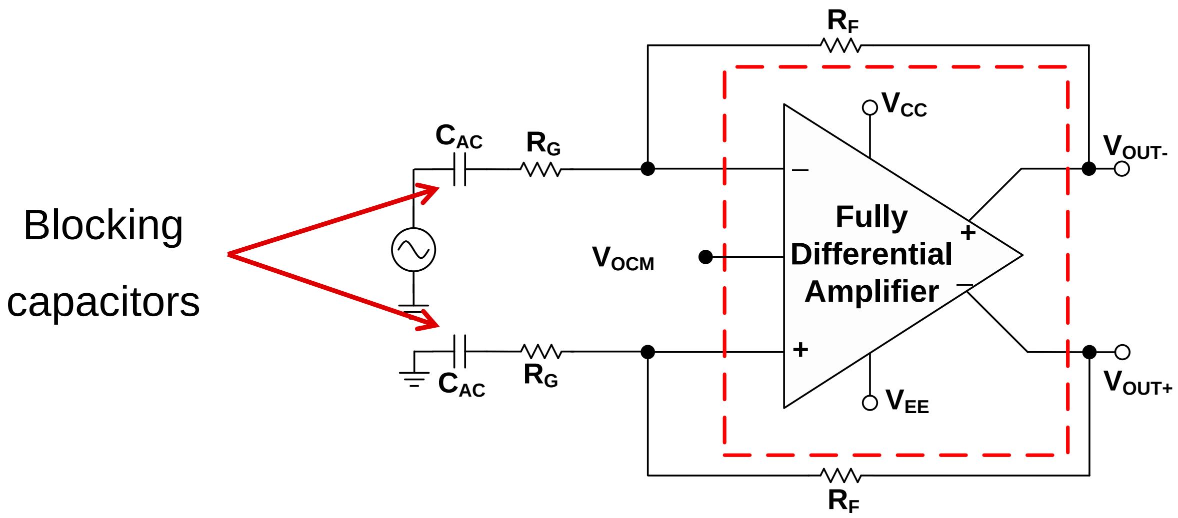
4. In the previous question how would you solve the problem of each output having a different common-mode (2.75V and 2.25V)



Answers

1. How would you AC couple a single-ended input source to an FDA?

Answer: This circuit configuration is useful when the DC and low-frequency signal content can be ignored. If the single-ended input common-mode is not GND, then using this circuit configuration precludes the need for a 2nd opamp on the un-driven FDA side, to match the common-mode of the input signal.



2. What is the load seen by the single-ended input source? (HINT: It is not R_G). Assume that both the VOCM = 0V and the input signal common-mode is 0V.

Answer: The load is not R_G because the amplifiers input common-mode is not fixed but is a function of the signal input and the feedback network.

$$V_{CM} = V_{O-}\left(\frac{R_G}{R_G + R_F}\right) \rightarrow$$ (1) Using KCL on the bottom half of FDA

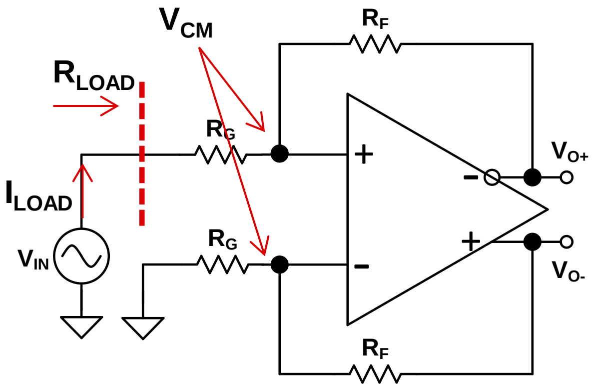
$$\frac{V_{O-}}{V_{IN}} = \frac{1}{2}(\text{SignalGain}) = \frac{1}{2}\left(\frac{R_F}{R_G}\right) \rightarrow \text{By definition}$$

$$\Rightarrow V_{O-} = \frac{1}{2}\left(\frac{R_F}{R_G}\right)V_{IN} \rightarrow (2)$$

$$I_{LOAD} = \frac{V_{IN} - V_{CM}}{R_G} = \frac{V_{IN} - \frac{1}{2}\left(\frac{R_F}{R_G}\right)V_{IN}\left(\frac{R_G}{R_G + R_F}\right)}{R_G}$$

$$R_{LOAD} = \frac{V_{IN}}{I_{LOAD}} = \frac{R_G}{\left(1 - \frac{1}{2}\left(\frac{R_F}{R_G + R_F}\right)\right)}$$

Divide R_G by this factor to find the load seen by the signal source



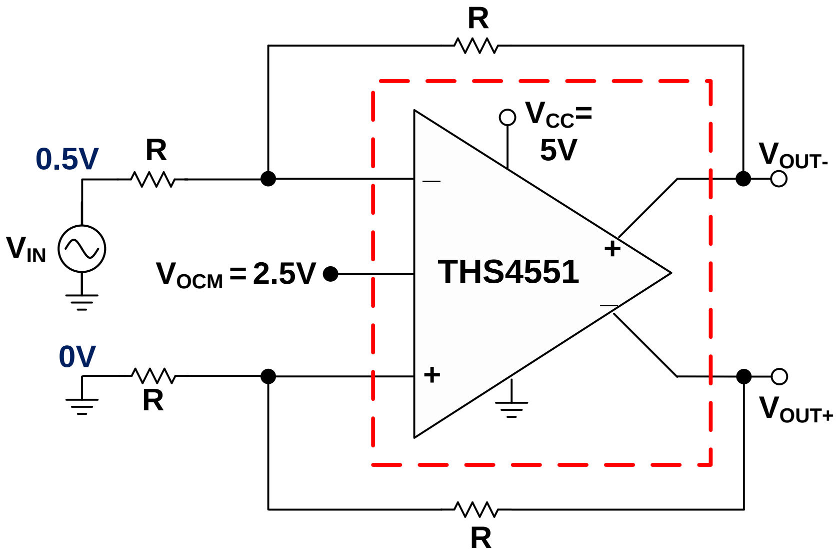
3. For the circuit shown below what is the,

- Output signal (differential and common-mode), and
- Input signal (differential and common-mode)

<u>Intuitive derivation of input and output common-mode</u>

<u>Answer:</u> **First lets start with the common-mode analysis**

- The input common-mode is 0.5V and 0V respectively.
- The difference in common-mode is amplified by the signal gain and manifests itself as a differential signal centered on the output common-mode of 2.5V.
- The common-mode for V_{OUT-} is therefore equal to 2.25V and V_{OUT+} = 2.75V
- Also the input common-mode, V_{CM} = ½ V_{OUT+} = 1.375V
- The mathematical derivation for this is shown on the next slide.



$$V_{CM} = \frac{1}{2}(V_{OUT+}) \rightarrow$$ Simple resistive divider on un-driven side (1)

$$V_{OCM} = 2.5V = \left(\frac{V_{OUT+} + V_{OUT-}}{2}\right) \rightarrow$$ By definition $\Rightarrow V_{OUT-} = (2V_{OCM} - V_{OUT+})$ (2)

$$\frac{0.5 - V_{CM}}{R} = \frac{V_{CM} - V_{OUT-}}{R} \rightarrow$$ Using KCL on the driven side

$$\Rightarrow \frac{0.5V - \frac{1}{2}(V_{OUT+})}{R} = \frac{\frac{1}{2}(V_{OUT+}) - (2V_{OCM} - V_{OUT+})}{R}$$

$$\Rightarrow \left(\frac{1}{2}\right)V_{OUT+} + \left(\frac{1}{2}\right)V_{OUT+} + V_{OUT+} = 0.5V + 5V$$

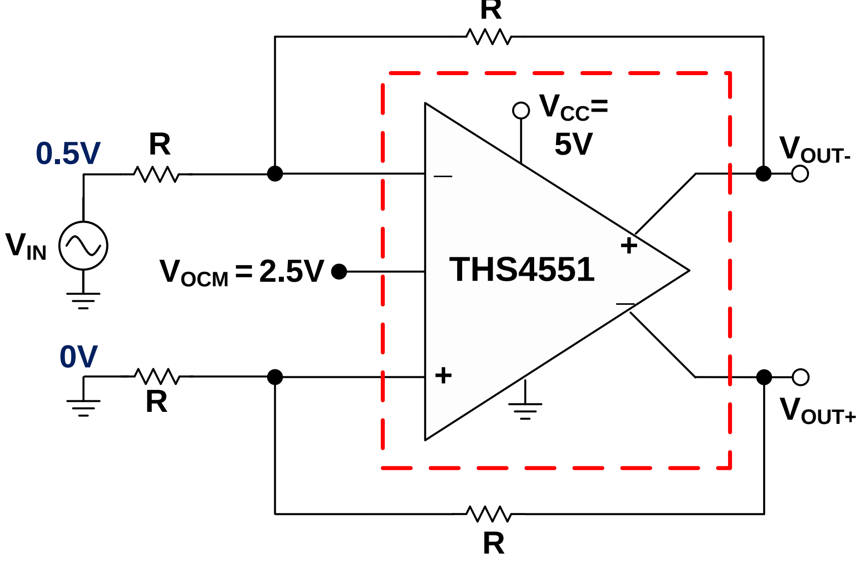
$$\Rightarrow 2V_{OUT+} = 5.5V \Rightarrow V_{OUT+} = 2.75V$$

From (2) and (1) respectively -

$$V_{OUT-} = (2V_{OCM} - V_{OUT+}) = (5V - 2.75V) = 2.25V$$

$$V_{CM} = \frac{1}{2}(V_{OUT+}) = \frac{1}{2}(2.75) = 1.375V$$

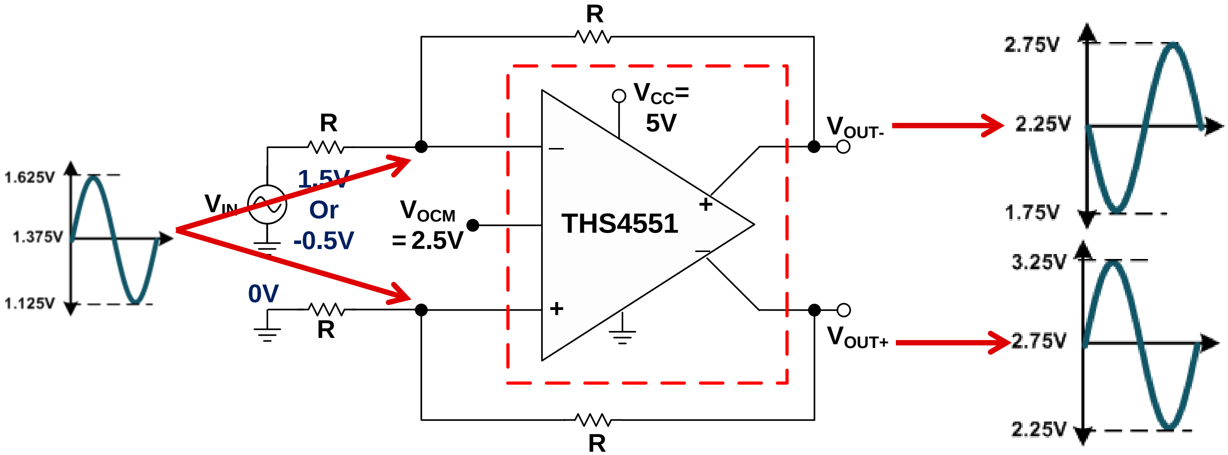
Mathematical derivation of input and output common-mode



Answer: Now on to differential analysis

- Input sine-wave is $2V_{PP}$. FDA gain is 1V/V. So each output will swing $1V_{PP}$ on each outputs common-mode of 2.75V and 2.25V.
- The input common-mode will swing $0.5V_{PP}$ on the common-mode of 1.375V.
- The results are shown below. Mathematical derivation is left as an exercise. Use similar concepts as shown for the common-mode.

Intuitive derivation of input and output differential-mode



4. In the previous question how would you solve the problem of each output having a different common-mode (2.75V and 2.25V)

Answer: Use a 2nd single-ended opamp to drive 0.5V into the un-driven side. It is important to use a wideband amplifier that has a bandwidth on par with the FDA used. (Try the OPA836)