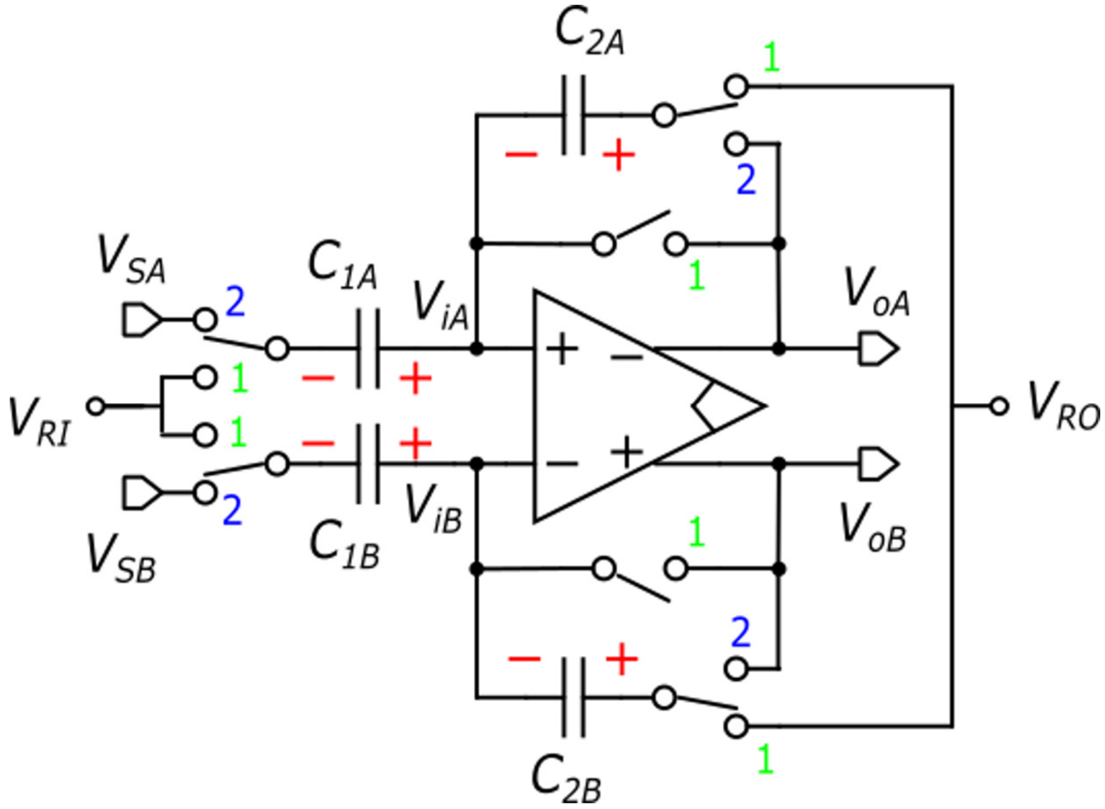
Fully-differential switched capacitor amplifier



V_{RO} and V_{RI} are constant voltages used to periodically discharge capacitor pairs. They substitute *gnd* in a single-supply circuit

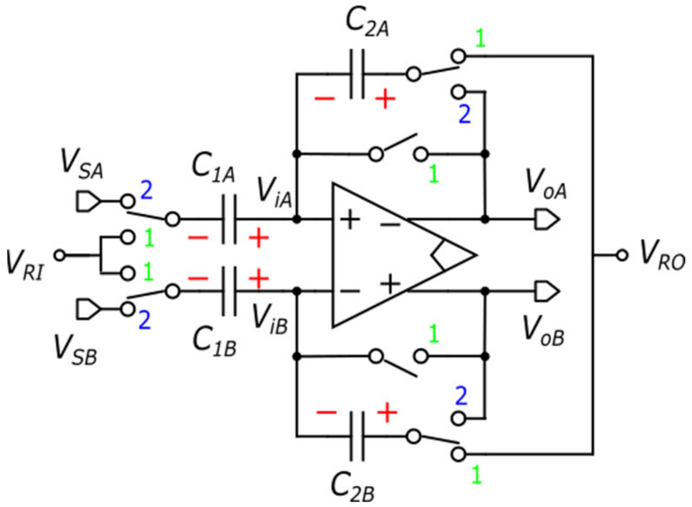
$$V_{Sd} = V_{SA} - V_{SB}$$ Input. diff. voltage

$$V_{od} = V_{oB} - V_{oA}$$ Output. diff. voltage

We will consider the nominal case for the capacitors:

$$\begin{cases} C_{1A} = C_{1B} \equiv C_1 \\ C_{2A} = C_{2B} \equiv C_2 \end{cases}$$

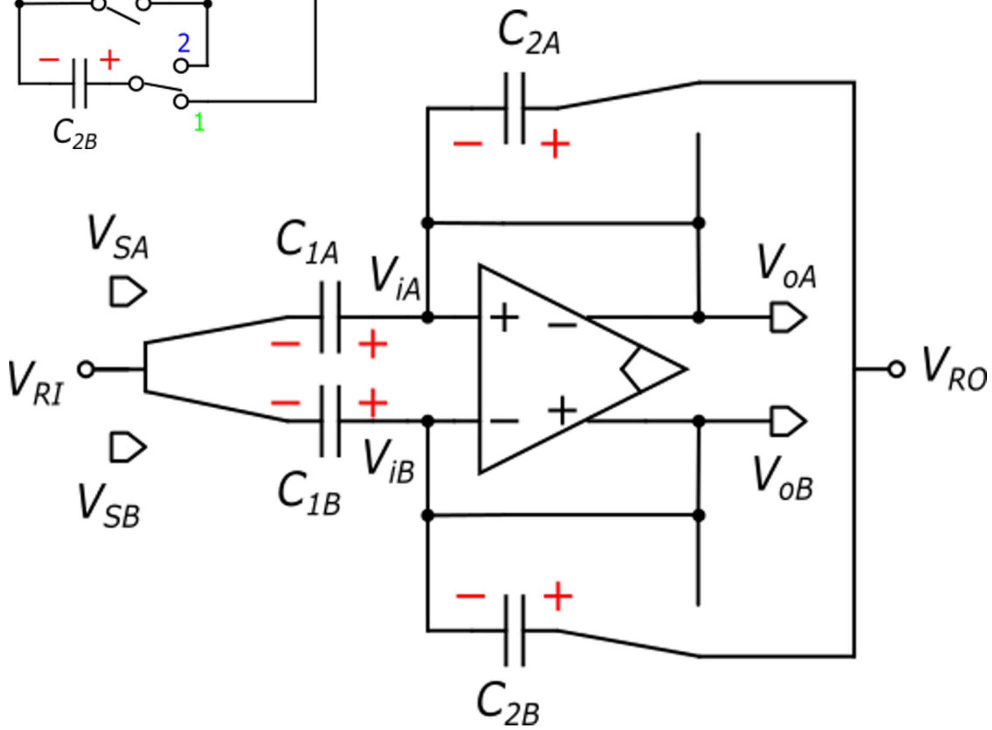
Phase 1



$$v_{iA}^{(1)} = V_{CMO} + \frac{v_n^{(1)}}{2}; \qquad v_{iB}^{(1)} = V_{CMO} - \frac{v_n^{(1)}}{2}$$

Due to the unity-gain connection

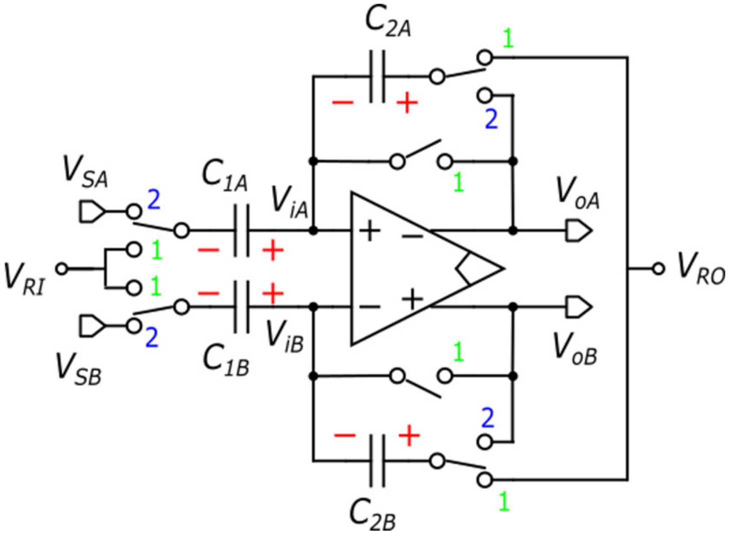
Let us write the voltages across each capacitor

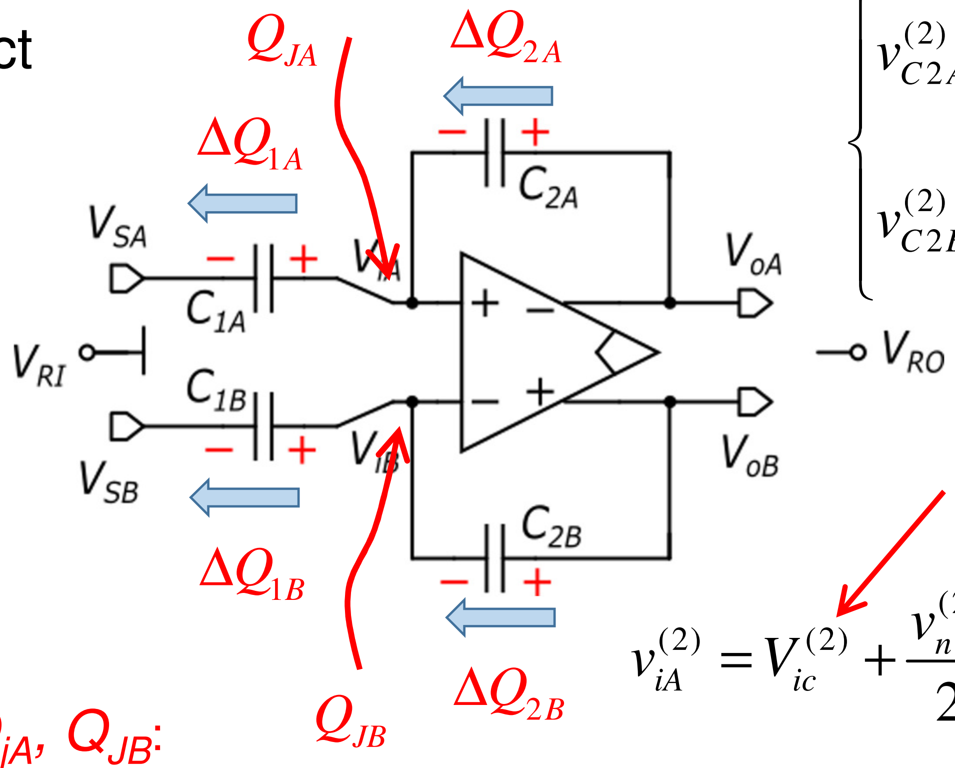


$$\begin{cases} v_{C1A}^{(1)} = V_{CMO} + \frac{v_n^{(1)}}{2} - V_{RI} \\ v_{C1B}^{(1)} = V_{CMO} - \frac{v_n^{(1)}}{2} - V_{RI} \\ v_{C2A}^{(1)} = V_{RO} - V_{CMO} - \frac{v_n^{(1)}}{2} \\ v_{C2B}^{(1)} = V_{RO} - V_{CMO} + \frac{v_n^{(1)}}{2} \end{cases}$$

Transition to phase 2

In this analysis we will neglect the kT/C noise, for simplicity





$$\begin{cases} v_{C2A}^{(2)} = v_{C2A}^{(1)} + \dfrac{\Delta Q_{2A}}{C_2} \\ v_{C2B}^{(2)} = v_{C2B}^{(1)} + \dfrac{\Delta Q_{2B}}{C_2} \end{cases}$$

unknown

$$v_{iA}^{(2)} = V_{ic}^{(2)} + \frac{v_n^{(2)}}{2}; \qquad v_{iB}^{(2)} = V_{ic}^{(2)} - \frac{v_n^{(2)}}{2}$$

$$v_{C1A}^{(2)} = V_{ic}^{(2)} + \frac{v_n^{(2)}}{2} - V_{SA}$$

$$v_{C1B}^{(2)} = V_{ic}^{(2)} - \frac{v_n^{(2)}}{2} - V_{SB}$$

Q_{jA}, Q_{JB}: caused by charge-injection and other mechanisms

$$\begin{cases} \Delta Q_{2A} = \Delta Q_{1A} - Q_{JA} = C_1\left(v_{C1A}^{(2)} - v_{C1A}^{(1)}\right) - Q_{JA} \\ \Delta Q_{2B} = \Delta Q_{1B} - Q_{JB} = C_1\left(v_{C1B}^{(2)} - v_{C1B}^{(1)}\right) - Q_{JB} \end{cases}$$

$$\begin{cases} v_{C2A}^{(2)} = v_{C2A}^{(1)} + \dfrac{\Delta Q_{2A}}{C_2} \\ v_{C2B}^{(2)} = v_{C2B}^{(1)} + \dfrac{\Delta Q_{2B}}{C_2} \end{cases}$$

$$\Delta Q_{2A} = C_1\left(v_{C1A}^{(2)} - v_{C1A}^{(1)}\right) - Q_{JA}$$

$$\Delta Q_{2B} = C_1\left(v_{C1B}^{(2)} - v_{C1B}^{(1)}\right) - Q_{JB}$$

Phase 2

$$v_{C1A}^{(2)} = V_{ic}^{(2)} + \frac{v_n^{(2)}}{2} - V_{SA}$$

$$v_{C1B}^{(2)} = V_{ic}^{(2)} - \frac{v_n^{(2)}}{2} - V_{SB}$$

Phase 1

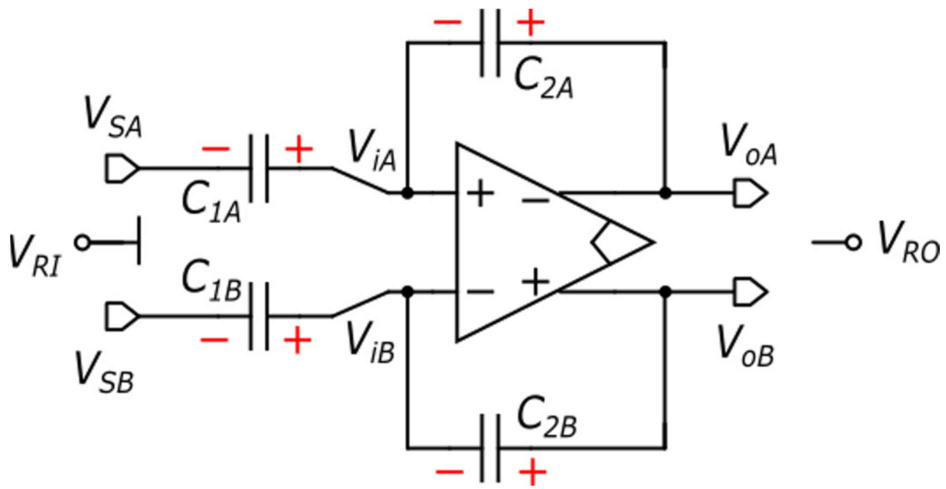
$$\begin{cases} v_{C1A}^{(1)} = V_{CMO} + \dfrac{v_n^{(1)}}{2} - V_{RI} \\ v_{C1B}^{(1)} = V_{CMO} - \dfrac{v_n^{(1)}}{2} - V_{RI} \\ v_{C2A}^{(1)} = V_{RO} - V_{CMO} - \dfrac{v_n^{(1)}}{2} \\ v_{C2B}^{(1)} = V_{RO} - V_{CMO} + \dfrac{v_n^{(1)}}{2} \end{cases}$$

$$v_{C2A}^{(2)} = V_{RO} - V_{CMO} - \frac{v_n^{(1)}}{2} + \frac{C_1}{C_2}\left(V_{ic}^{(2)} + \frac{v_n^{(2)}}{2} - V_{SA} - V_{CMO} - \frac{v_n^{(1)}}{2} + V_{RI}\right) - \frac{Q_{JA}}{C_2}$$

$$v_{C2B}^{(2)} = V_{RO} - V_{CMO} + \frac{v_n^{(1)}}{2} + \frac{C_1}{C_2}\left(V_{ic}^{(2)} - \frac{v_n^{(2)}}{2} - V_{SB} - V_{CMO} + \frac{v_n^{(1)}}{2} + V_{RI}\right) - \frac{Q_{JB}}{C_2}$$

$$v_{C2A}^{(2)} = V_{RO} - V_{CMO} - \frac{v_n^{(1)}}{2} + \frac{C_1}{C_2}\left(V_{ic}^{(2)} + \frac{v_n^{(2)}}{2} - V_{SA} - V_{CMO} - \frac{v_n^{(1)}}{2} + V_{RI}\right) - \frac{Q_{JA}}{C_2}$$

$$v_{C2B}^{(2)} = V_{RO} - V_{CMO} + \frac{v_n^{(1)}}{2} + \frac{C_1}{C_2}\left(V_{ic}^{(2)} - \frac{v_n^{(2)}}{2} - V_{SB} - V_{CMO} + \frac{v_n^{(1)}}{2} + V_{RI}\right) - \frac{Q_{JB}}{C_2}$$



$$\begin{cases} v_{oA}^{(2)} = v_{iA}^{(2)} + v_{C2A}^{(2)} \\ v_{oB}^{(2)} = v_{iB}^{(2)} + v_{C2B}^{(2)} \end{cases}$$

$$v_{iA}^{(2)} = V_{ic}^{(2)} + \frac{v_n^{(2)}}{2}; \qquad v_{iB}^{(2)} = V_{ic}^{(2)} - \frac{v_n^{(2)}}{2}$$

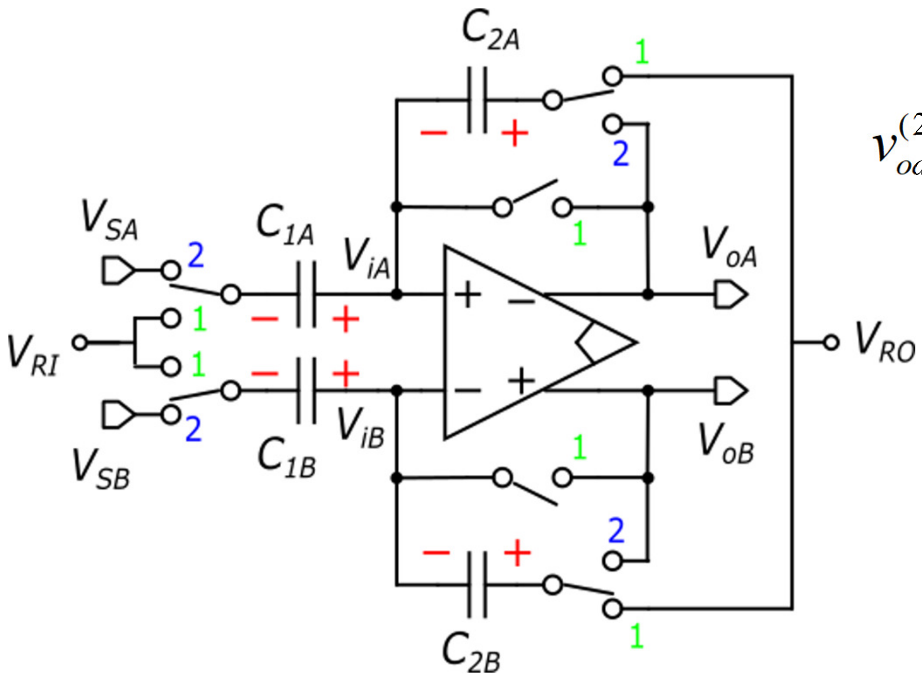
$$\begin{cases} v_{oA}^{(2)} = V_{ic}^{(2)} + \dfrac{v_n^{(2)}}{2} + V_{RO} - V_{CMO} - \dfrac{v_n^{(1)}}{2} + \dfrac{C_1}{C_2}\left(V_{ic}^{(2)} + \dfrac{v_n^{(2)}}{2} - V_{SA} - V_{CMO} - \dfrac{v_n^{(1)}}{2} + V_{RI}\right) - \dfrac{Q_{JA}}{C_2} & - \\ v_{oB}^{(2)} = V_{ic}^{(2)} - \dfrac{v_n^{(2)}}{2} + V_{RO} - V_{CMO} + \dfrac{v_n^{(1)}}{2} + \dfrac{C_1}{C_2}\left(V_{ic}^{(2)} - \dfrac{v_n^{(2)}}{2} - V_{SB} - V_{CMO} + \dfrac{v_n^{(1)}}{2} + V_{RI}\right) - \dfrac{Q_{JB}}{C_2} & + \end{cases}$$

$$v_{od}^{(2)} = v_{oB}^{(2)} - v_{oA}^{(2)}$$

Differential mode analysis

$$v_{od}^{(2)} = -v_n^{(2)} + v_n^{(1)} + \frac{C_1}{C_2}\left(-v_n^{(2)} + V_{SA} - V_{SB} + v_n^{(1)}\right) - \frac{Q_{JB} - Q_{JA}}{C_2}$$

$$v_{od}^{(2)} = \frac{C_1}{C_2}\left(V_{SA} - V_{SB}\right) - \left(v_n^{(2)} - v_n^{(1)}\right)\left(\frac{C_1}{C_2} + 1\right) - \frac{Q_{JB} - Q_{JA}}{C_2}$$



$$v_{od}^{(2)} = \frac{C_1}{C_2}\left(V_{SA} - V_{SB}\right) - \left(v_n^{(2)} - v_n^{(1)}\right)\left(\frac{C_1}{C_2} + 1\right) - \frac{Q_{JB} - Q_{JA}}{C_2}$$

V_{Sd}

output noise due to the amplifier

output error due to charge injection

$$A_{dd} = \frac{C_1}{C_2} \equiv A$$

Errors referred to the input $-\left(v_n^{(2)} - v_n^{(1)}\right)\left(\frac{A+1}{A}\right) \quad -\frac{Q_{JB} - Q_{JA}}{C_1}$

Note that CDS is applied to the amplifier noise

Common mode components

$$\begin{cases} v_{oA}^{(2)} = V_{ic}^{(2)} + \dfrac{v_n^{(2)}}{2} + V_{RO} - V_{CMO} - \dfrac{v_n^{(1)}}{2} + \dfrac{C_1}{C_2}\left(V_{ic}^{(2)} + \dfrac{v_n^{(2)}}{2} - V_{SA} - V_{CMO} - \dfrac{v_n^{(1)}}{2} + V_{RI}\right) - \dfrac{Q_{JA}}{C_2} & \times\dfrac{1}{2} \\ v_{oB}^{(2)} = V_{ic}^{(2)} - \dfrac{v_n^{(2)}}{2} + V_{RO} - V_{CMO} + \dfrac{v_n^{(1)}}{2} + \dfrac{C_1}{C_2}\left(V_{ic}^{(2)} - \dfrac{v_n^{(2)}}{2} - V_{SB} - V_{CMO} + \dfrac{v_n^{(1)}}{2} + V_{RI}\right) - \dfrac{Q_{JB}}{C_2} & \times\dfrac{1}{2} \end{cases}$$

Neglecting the charge injection (calculation of the CM components require less accuracy)

$$V_{CMO} = V_{ic}^{(2)} + V_{RO} - V_{CMO} + \frac{C_1}{C_2}\left(V_{ic}^{(2)} - \frac{V_{SA} + V_{SB}}{2} - V_{CMO} + V_{RI}\right)$$

$$V_{CMO} = V_{ic}^{(2)}\left(1 + A\right) + V_{RO} - V_{CMO}\left(1 + A\right) + \frac{C_1}{C_2}\left(-V_{SC} + V_{RI}\right)$$

Common mode components

$$V_{CMO} = V_{ic}^{(2)}(1+A) + V_{RO} - V_{CMO}(1+A) + \frac{C_1}{C_2}(-V_{SC} + V_{RI})$$

$$V_{CMO} - V_{RO} + V_{CMO}(1+A) - \frac{C_1}{C_2}(-V_{SC} + V_{RI}) = V_{ic}^{(2)}(1+A)$$

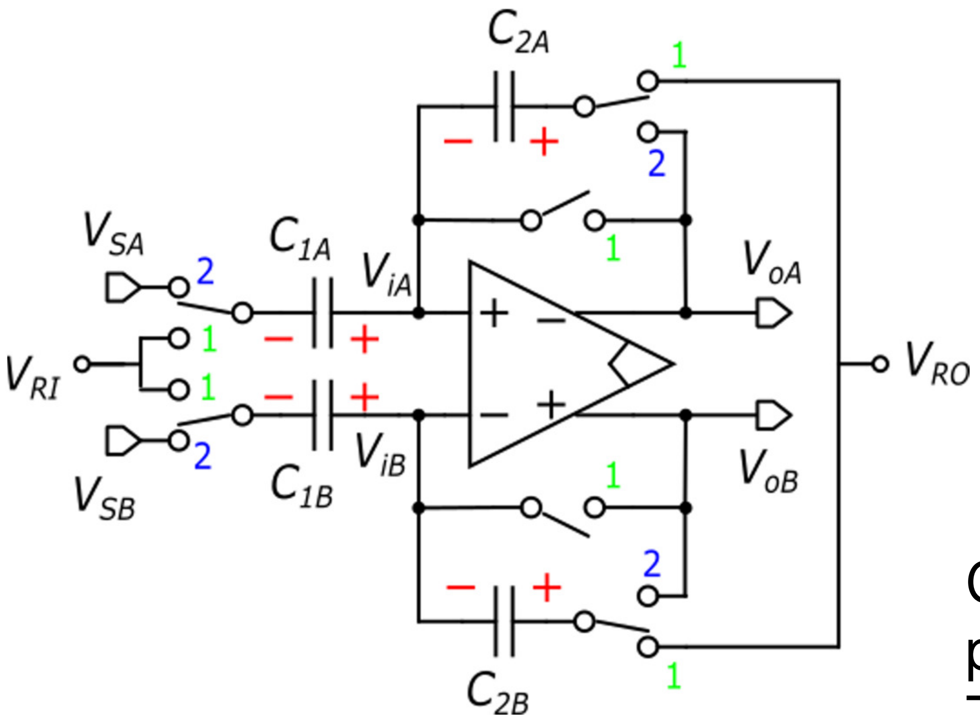
$$V_{ic}^{(2)} = V_{CMO} + \frac{V_{CMO} - V_{RO}}{A+1} + \frac{A}{A+1}(V_{SC} - V_{RI})$$

Since in phase 1 V_{ic} is equal to V_{CMO}, it is desirable that it does not change passing into phase 2.

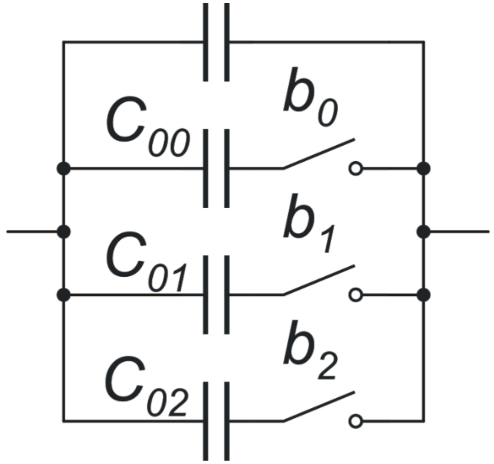
To obtain this, we set: $V_{RO} = V_{CMO}$

$V_{RI} = V_{SC}$ ⇐ This is not always possible to guarantee, since the common mode of the source may be not predictable

Programmable gain amplifier (PGA)



$$A_L = \frac{C_1}{C_2}$$



Capacitors can be made easily programmable.
The advantage with respect of resistive feedback amplifier is that the switch resistance does not affect accuracy (it affects only speed)

Additional charge injection from non-constant V_{ic}

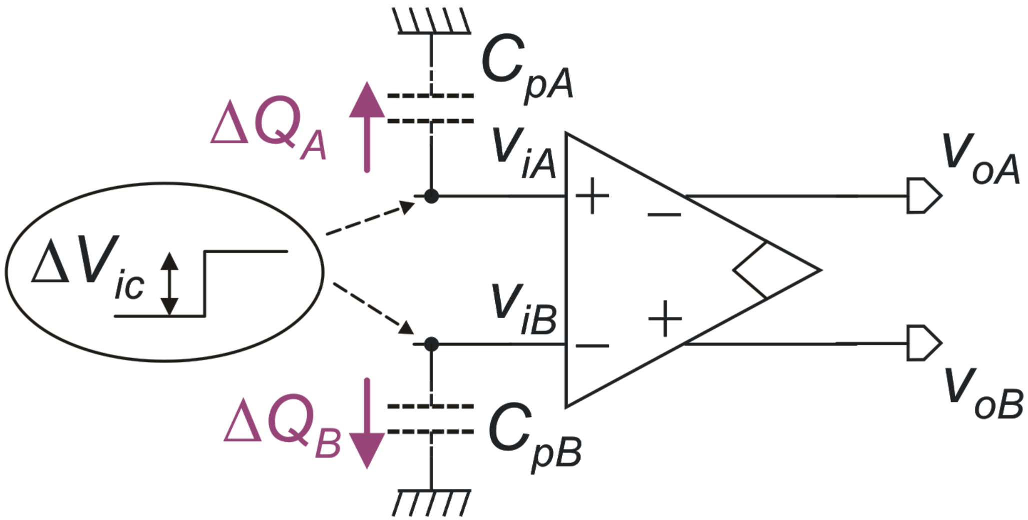
$$V_{ic}^{(1)} = V_{CMO}$$

$$V_{ic}^{(2)} = V_{CMO} + \frac{V_{CMO} - V_{RO}}{A+1} + \frac{A}{A+1}\left(V_{SC} - V_{RI}\right)$$

$$\Delta Q_A = \Delta V_{ic} C_{pA}$$

$$\Delta Q_B = \Delta V_{ic} C_{pB}$$

In this simplified picture, switches and feedback capacitors are not represented



These charges contribute to Q_{JA} and Q_{JB} together with charge injection from the switches

Since parasitic capacitance may have some mismatch, a differential voltage may result.