The Effect of Correlated Level Shifting on Noise Performance in Switched Capacitor Circuits

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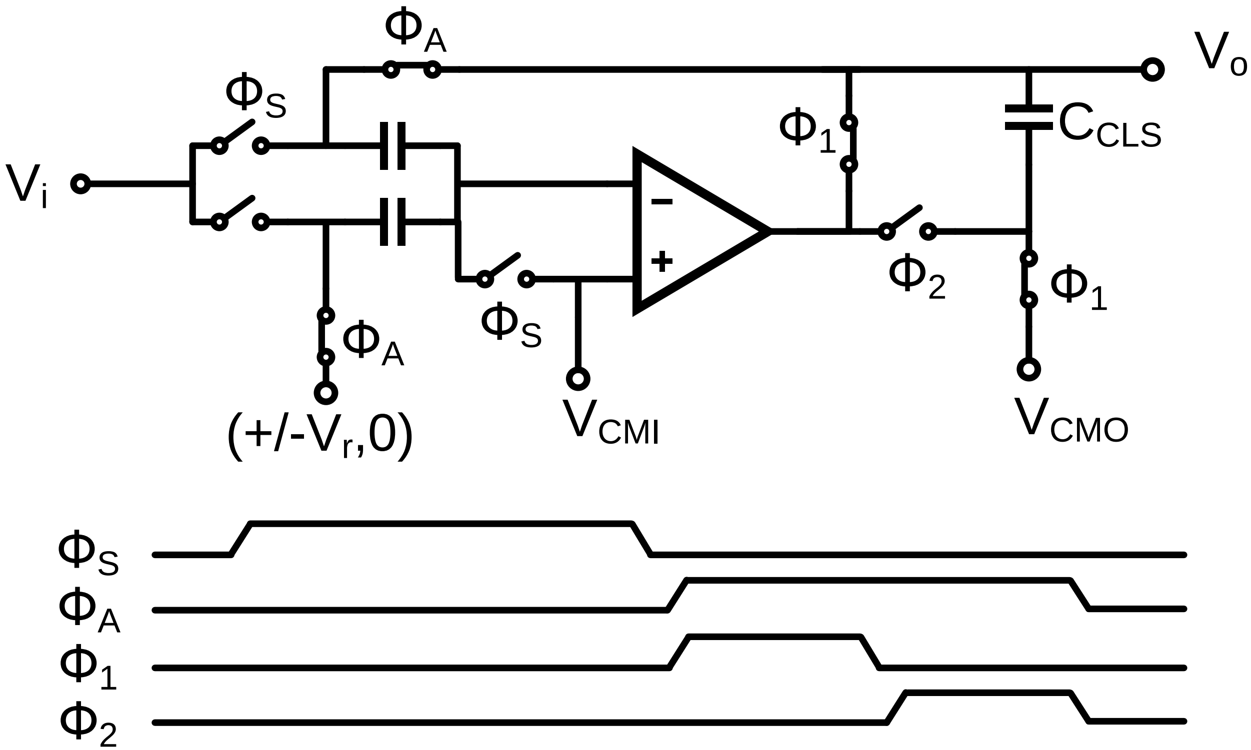
Presentation Outline

- Background
  - CLS (Correlated Level-Shifting)
  - Split-CLS
- Theoretical Noise Analysis
- Numerical and Simulation Results
- Conclusion

Background

Correlated Level Shifting (CLS)



- Finite opamp gain error becomes $1/A^2$
- Opamp output tied to different nodes in Φ_1 and Φ_2

[Gregoire, JSSC 2008]

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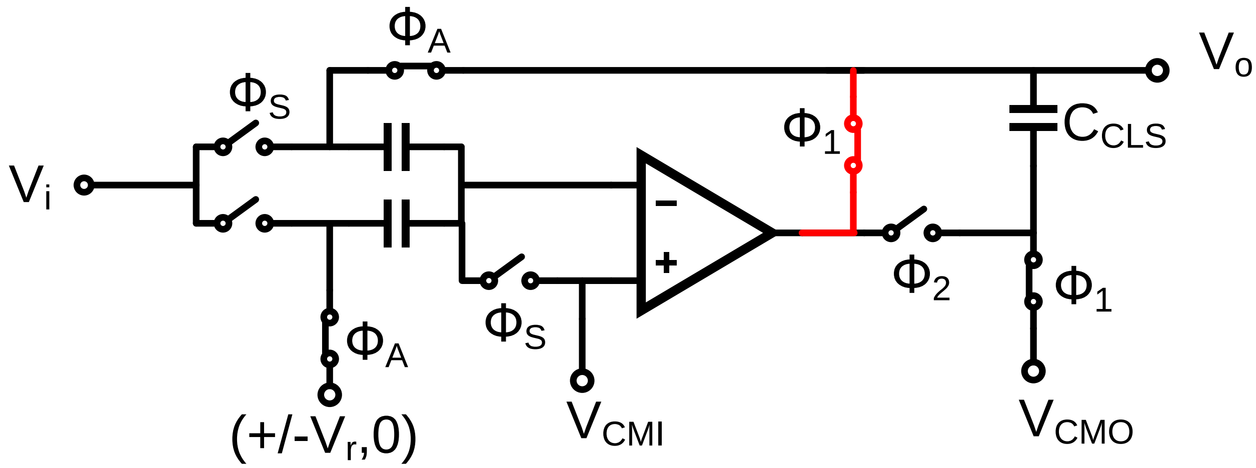
CLS Basic Operation



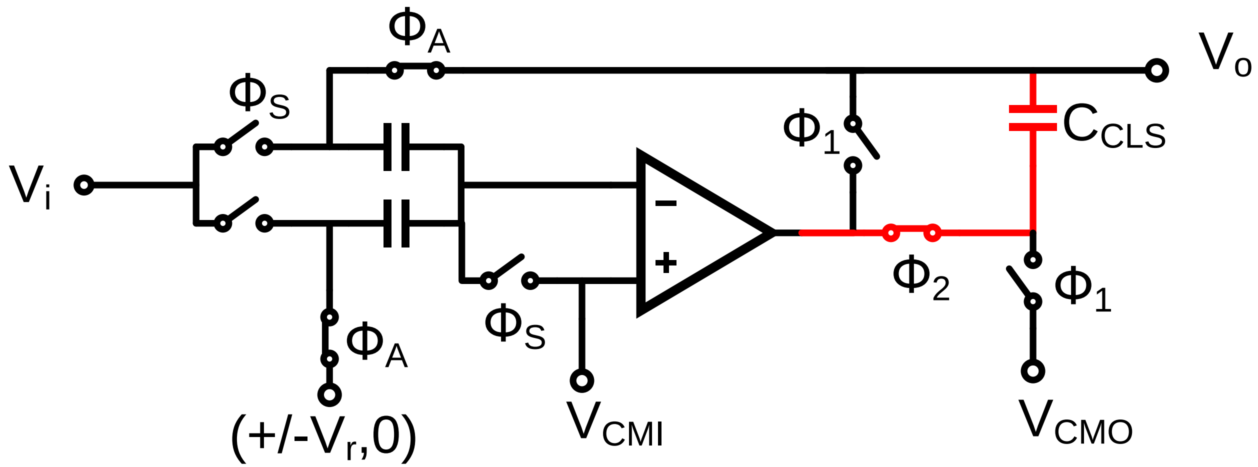
Φ_1 :

- opamp charges output directly
- processes full signal

Opamp Design Requirements

	Φ_1	Φ_2
Output Swing	**Large**	**Small**
Slew Rate	**Large**	**Small**

CLS Basic Operation



Φ_2 :

- opamp is level shifted to mid-rail
- processes error only

Opamp Design Requirements

	Φ_1	Φ_2
Output Swing	**Large**	**Small**
Slew Rate	**Large**	**Small**

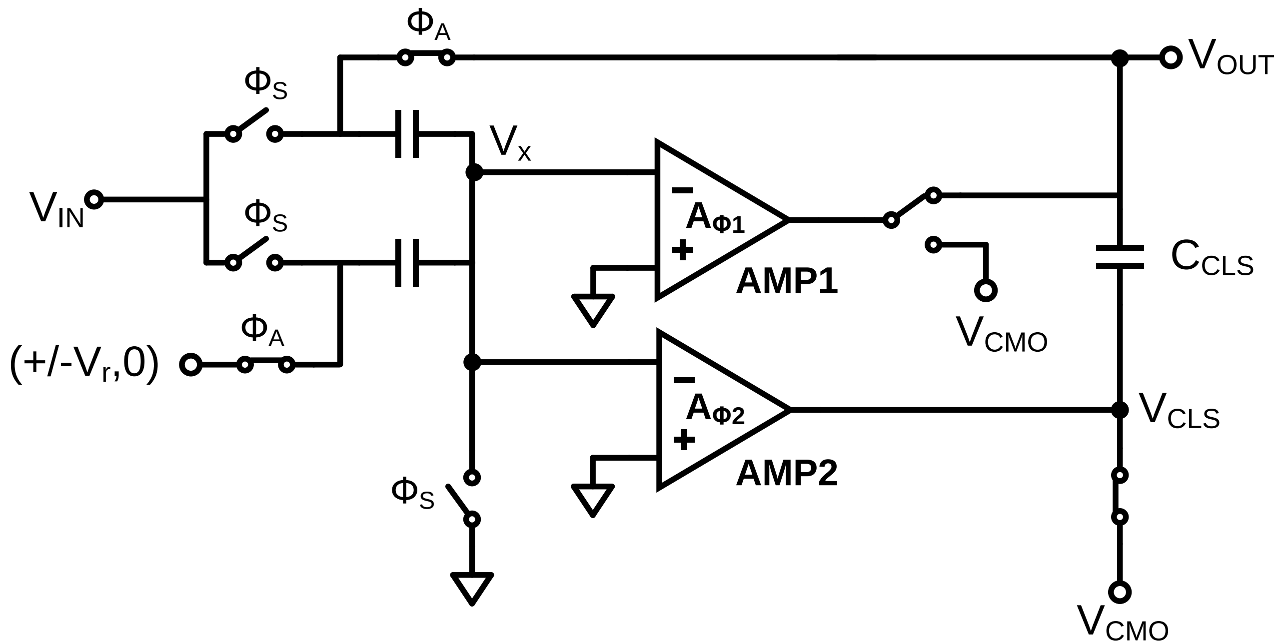
Observation: Split-CLS

- Use separate charging devices for Φ_1 and Φ_2
- Optimized design for each phase
  - Increase overall accuracy & efficiency

Opamp Design Requirements

	Φ_1	Φ_2
Output Swing	**Large**	**Small**
Slew Rate	**Large**	**Small**

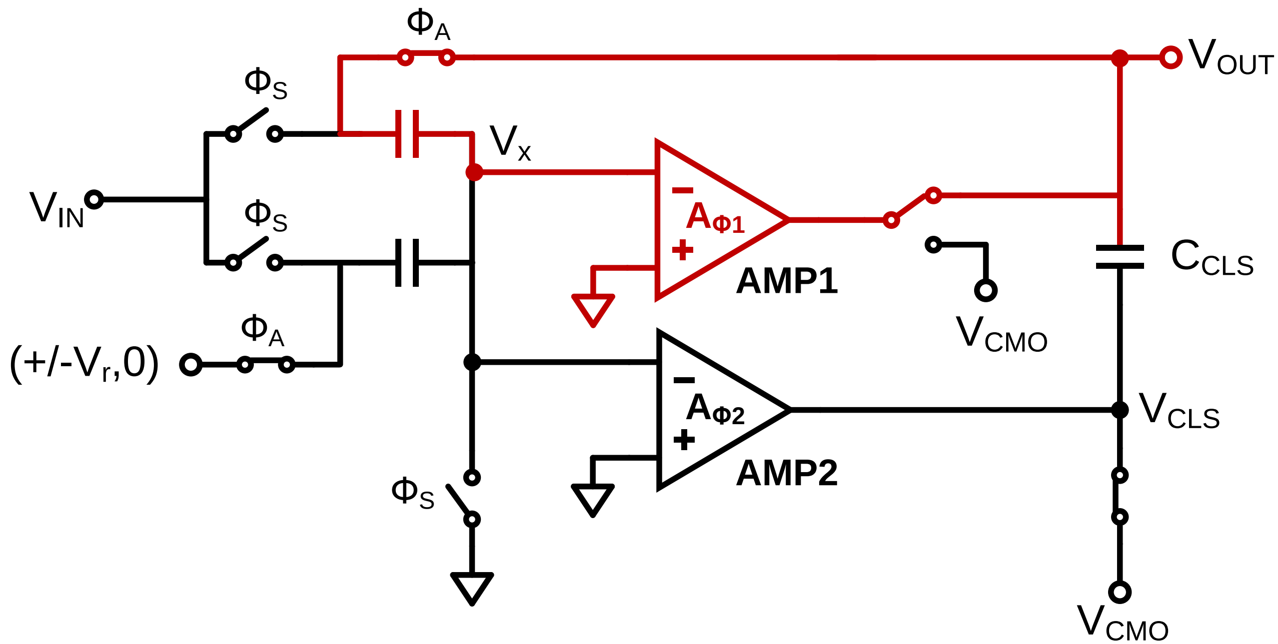
Split-CLS (Correlated Level Shifting)



- Split-CLS
  - Generalized form of Correlated Level Shifting (CLS)
  - Finite opamp gain error approx. $1 / (A_1 * A_2)$

[Hershberg, JSSC 2010]

Split-CLS (Correlated Level Shifting)



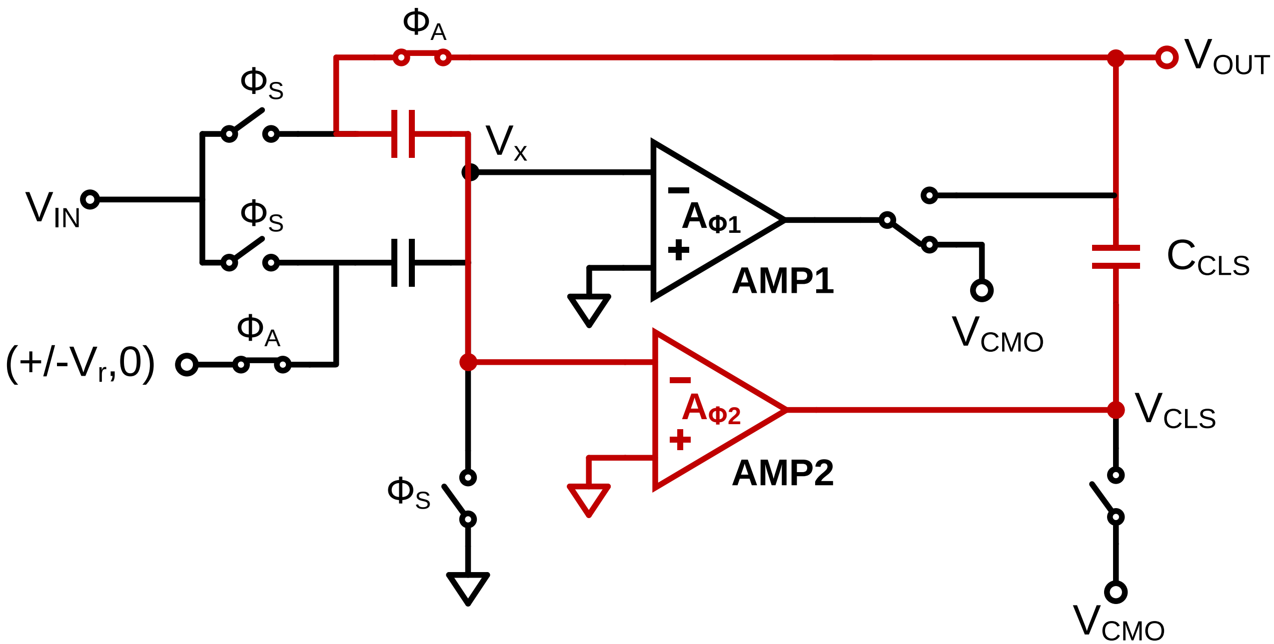
Φ_1:

- amp charges output directly
- processes full signal

Amplifier Design Requirements

	Φ_1	Φ_2
Output Swing	**Large**	**Small**
Slew Rate	**Large**	**Small**

Split-CLS (Correlated Level Shifting)



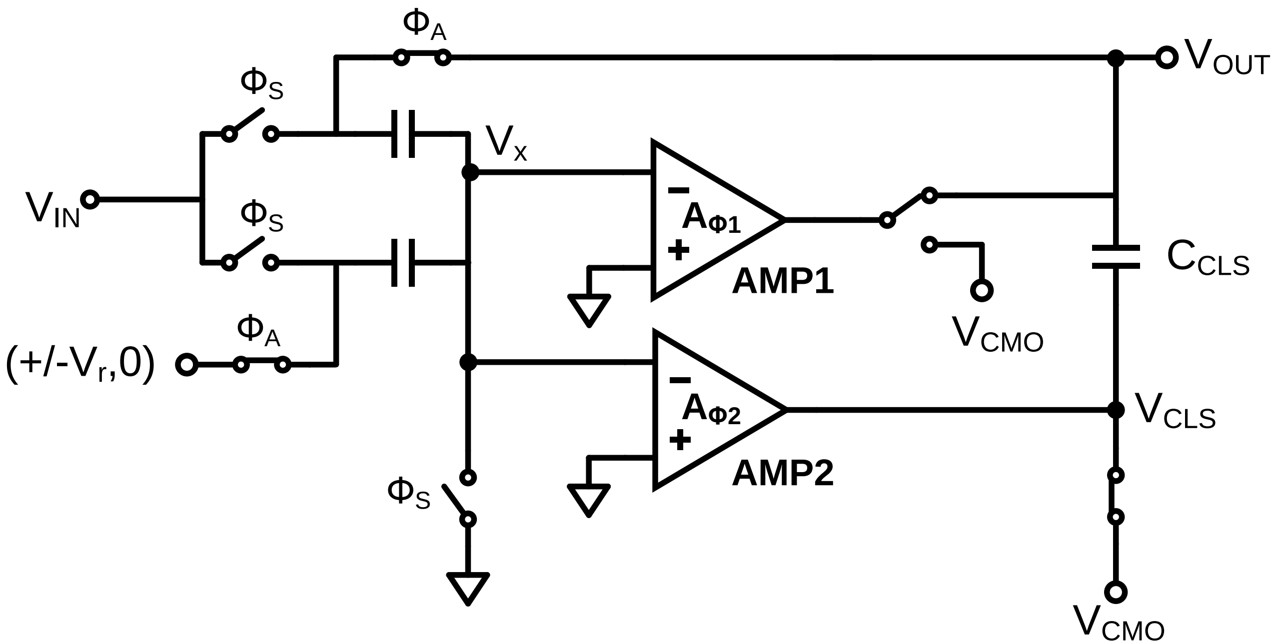
Φ_2:

- opamp is level-shifted to mid-rail
- processes error only

Amplifier Design Requirements

	Φ_1	Φ_2
Output Swing	**Large**	**Small**
Slew Rate	**Large**	**Small**

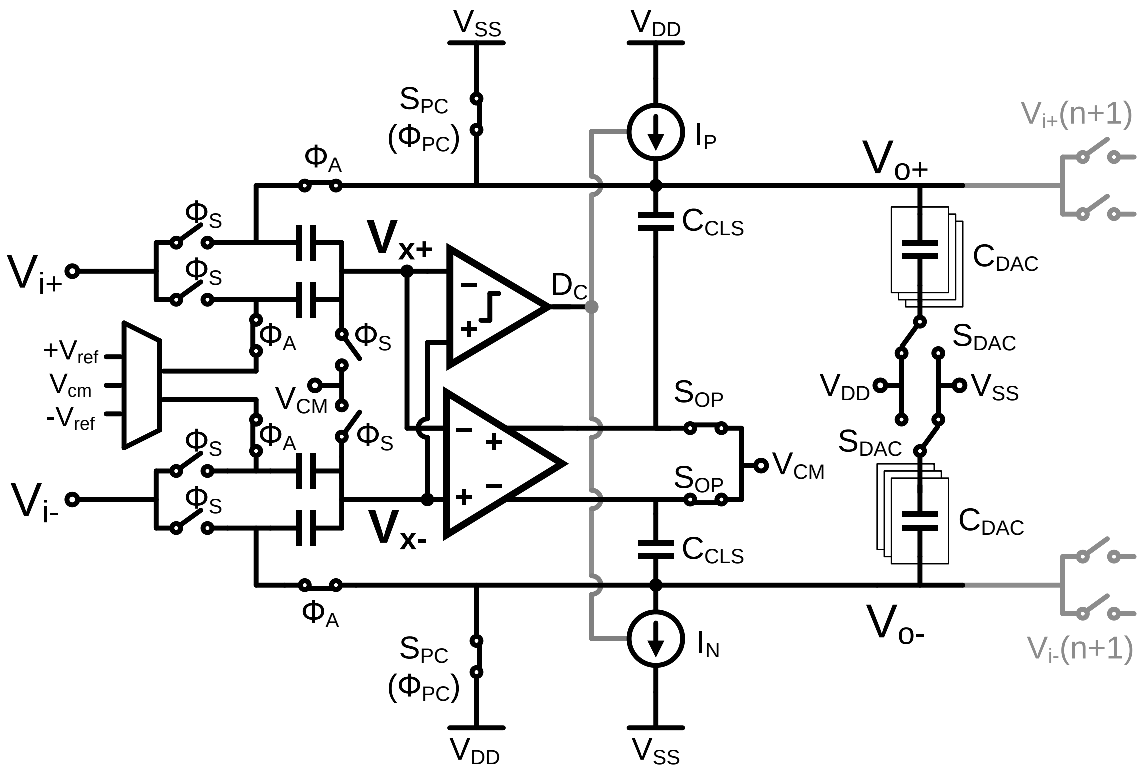
Split-CLS (Correlated Level Shifting)



- Many options for coarse amp / fine amp…
  - ISSCC 2010: ZCBC (coarse) + Telescopic opamp (fine)
  - ISSCC 2012: Ring Amplifier (coarse) + Telescopic opamp (fine)

[Hershberg, ISSCC 2010] ,[Hershberg, ISSCC 2012]

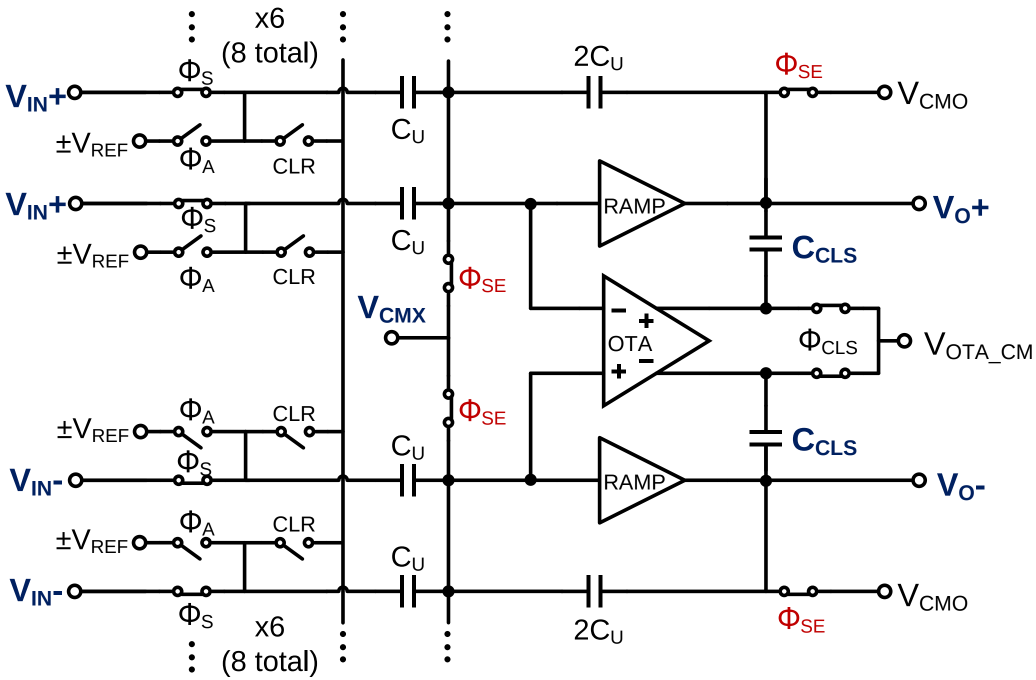
Split-CLS: ISSCC 2010



- Coarse Amp: Zero-crossing based circuit (ZCBC)
- Fine Amp: Double-cascoded telescopic opamp

[Hershberg, ISSCC 2010]

Split-CLS: ISSCC 2012



- Coarse Amp: Pseudo-differential Ring Amplifier (ringamp)
- Fine Amp: Double-cascoded telescopic opamp
- Best FoM of any high-resolution ADC ever reported
  - 76.8dB SNDR, 95.4dB SFDR, 5.1mW, 20Msps, 45fJ/c-step FoM

[Hershberg, ISSCC 2012]

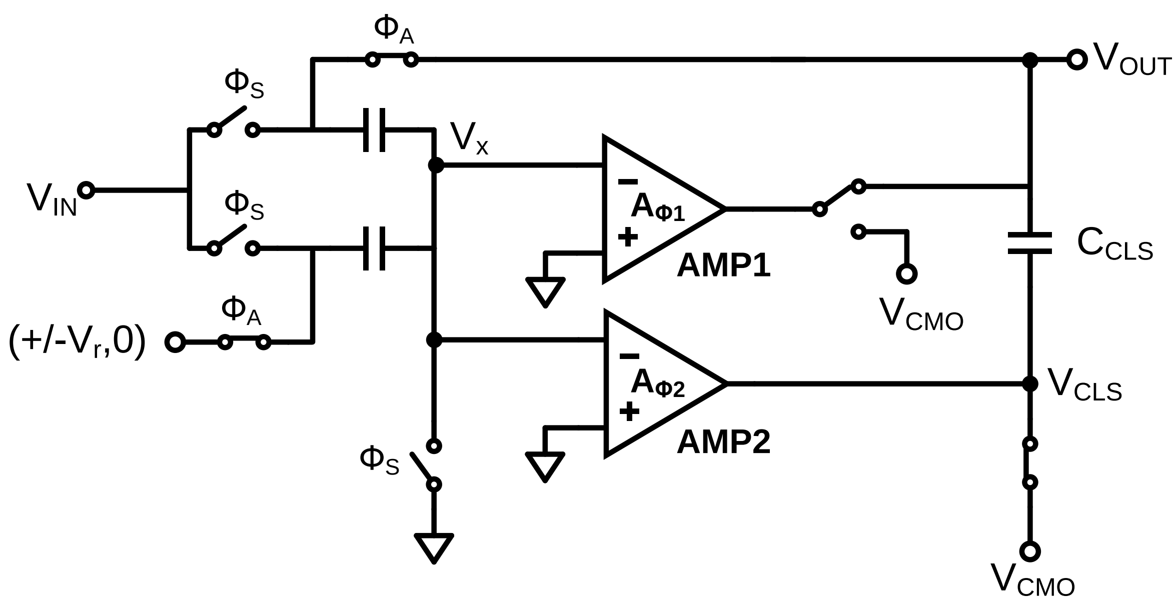
Noise Analysis

Noise Analysis: Split-CLS

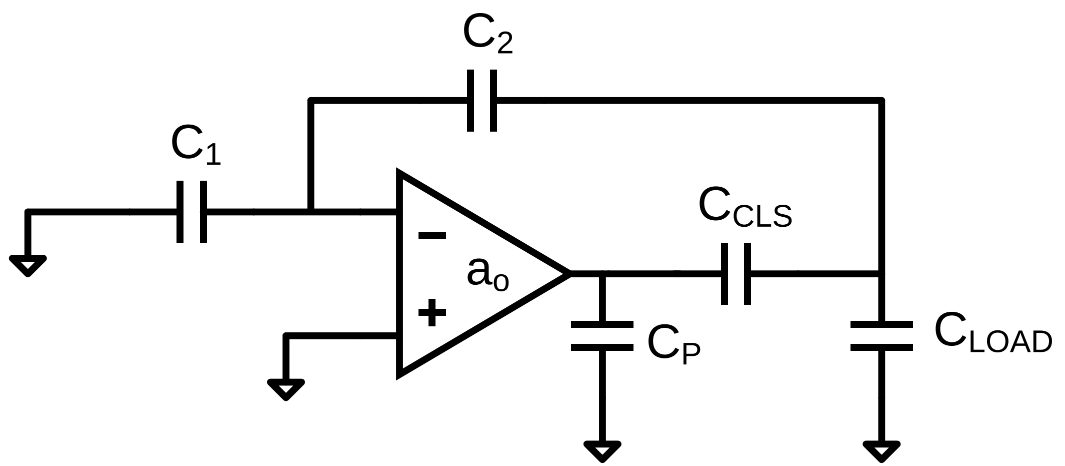
- The size of C_{CLS} affects:
  - Accuracy - feedback factor
  - Speed - total load capacitance seem by fine amp
  - Opamp requirements - fine amp output swing requirement
- How does level-shifting affect noise performance
  - Help? Hurt?

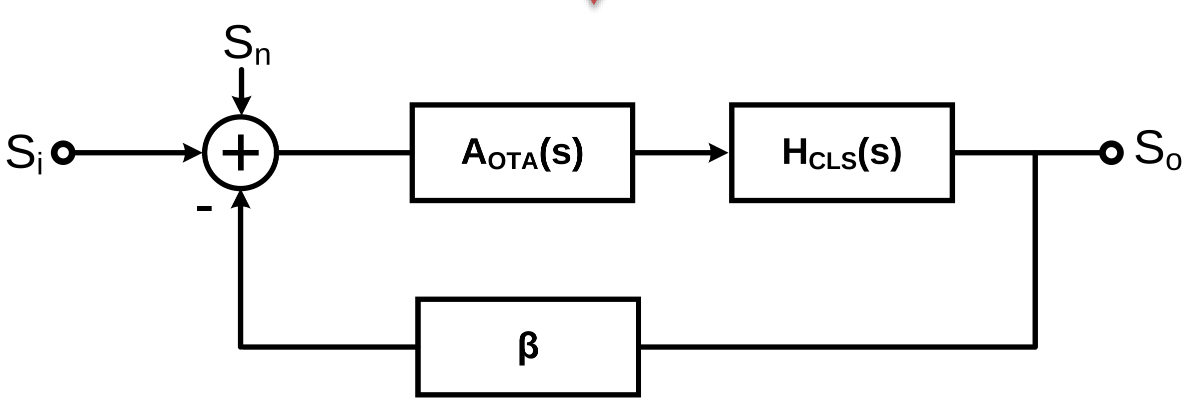
Noise Analysis: Split-CLS

- Noise due to AMP1 is suppressed by gain of AMP2
  - Final noise determined by AMP2
- Only fine phase configuration must be considered

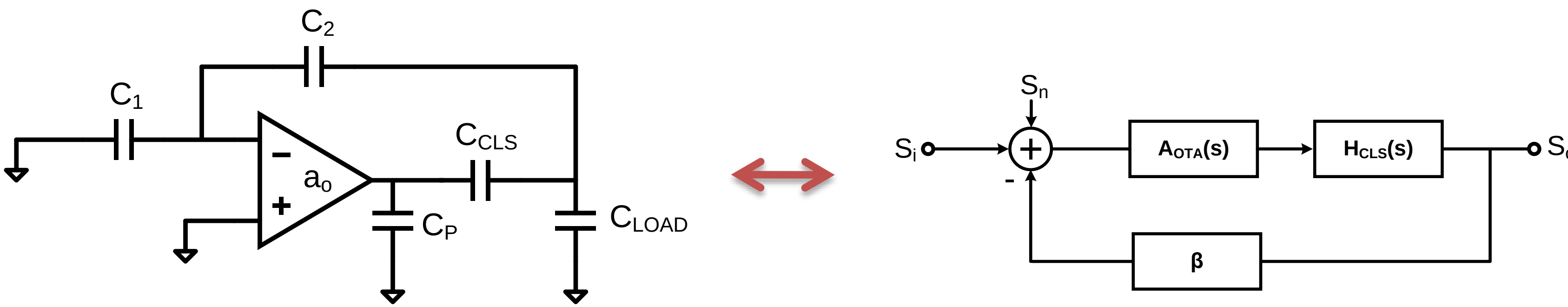


Noise Analysis: Split-CLS





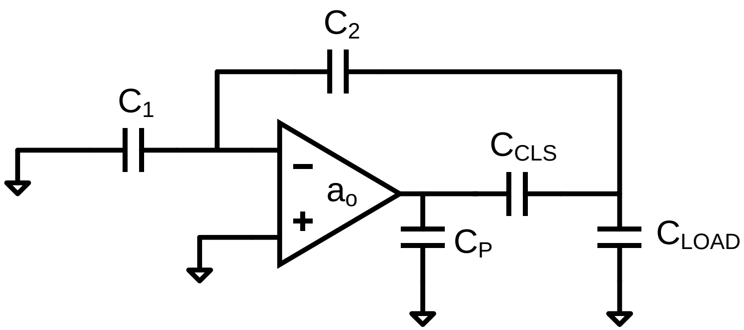
Noise Analysis: Split-CLS

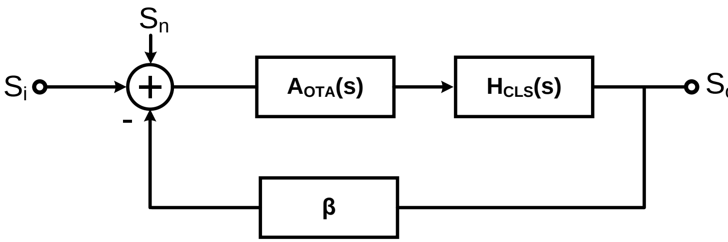


$$C_{LOAD} = \alpha(C_1 + C_2) \quad (1)$$

$$\beta = \frac{C_2}{C_1 + C_2}. \quad (2)$$

Noise Analysis: Split-CLS

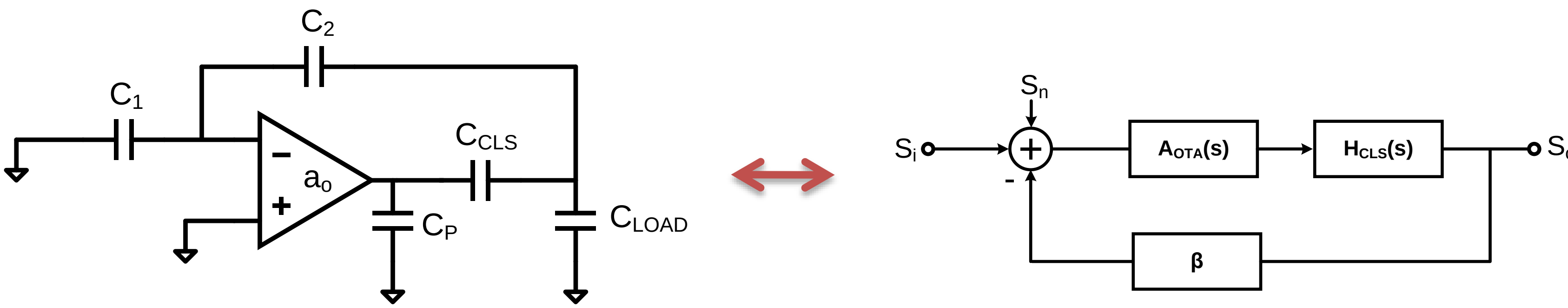




$$H_{CLS}(s) = \frac{C_{CLS}}{C_{CLS} + C_{LD}} \quad (3)$$

$$C_{LD} = C_{LOAD} + \frac{C_1 \cdot C_2}{C_1 + C_2}. \quad (4)$$

Noise Analysis: Split-CLS

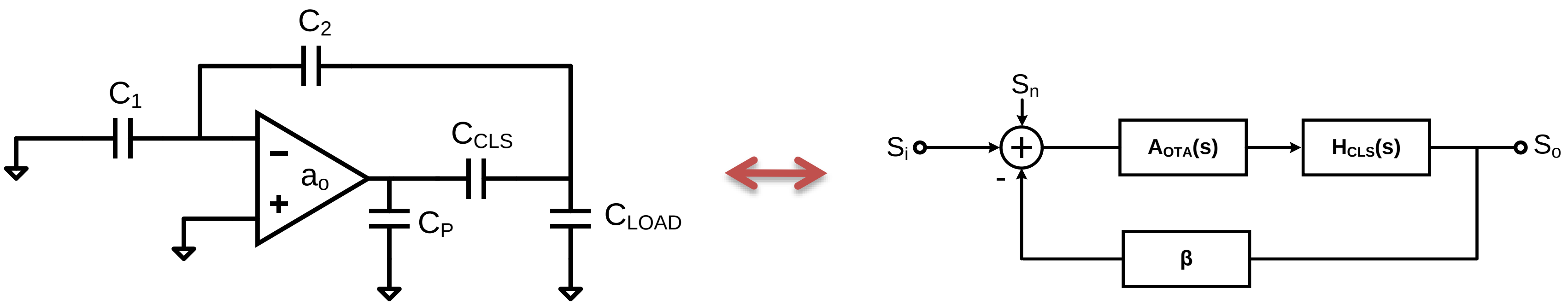


Single-stage opamp (as is commonly used in Split-CLS) has one dominant pole:

$$C_{OTA} = C_P + \frac{C_{CLS} \cdot C_{LD}}{C_{CLS} + C_{LD}} \tag{5}$$

$$A_{OTA}(s) = \frac{a_o}{1 + \frac{s}{p_1}} \Bigg|_{p_1 = \frac{1}{R_O C_{OTA}}} \tag{6}$$

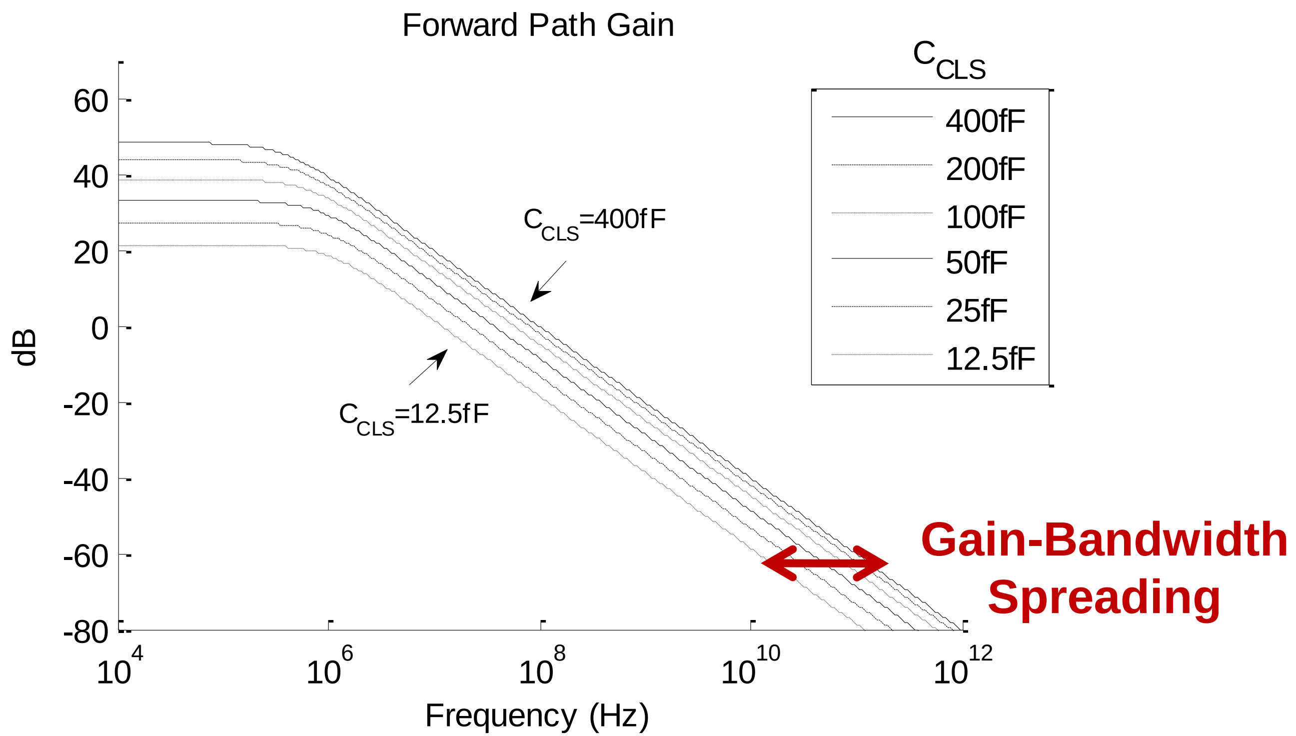
Noise Analysis: Split-CLS

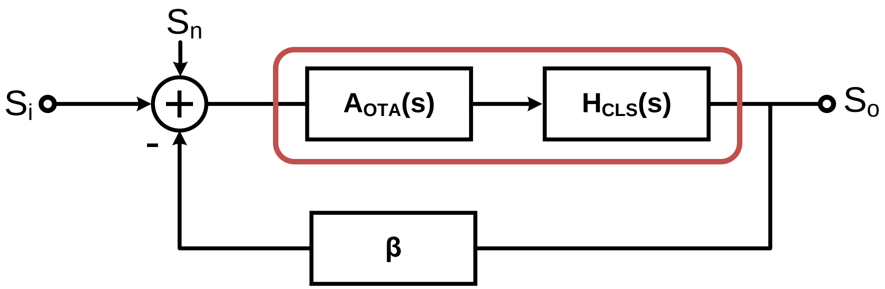


$$A_{fp}(s) = A_{OTA}(s) \cdot H_{CLS}(s) \quad (7)$$

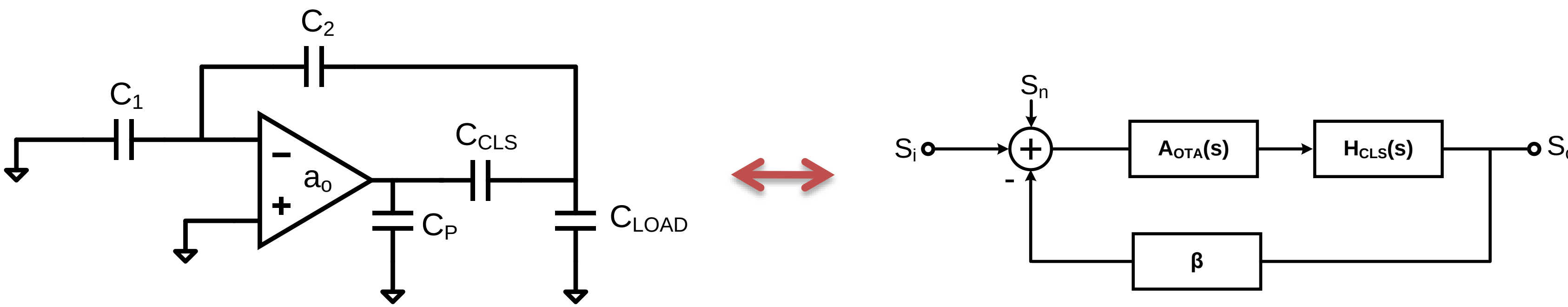
$$H_n(s) = \frac{A_{OTA}(s) \cdot H_{CLS}(s)}{1 + \beta \cdot A_{OTA}(s) \cdot H_{CLS}(s)}. \quad (8)$$

Noise Analysis: Split-CLS





Noise Analysis: Split-CLS

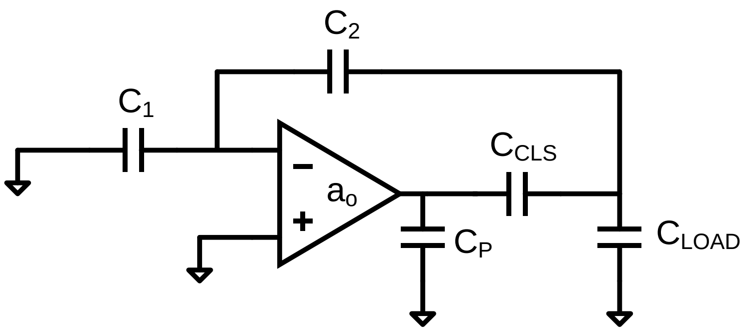


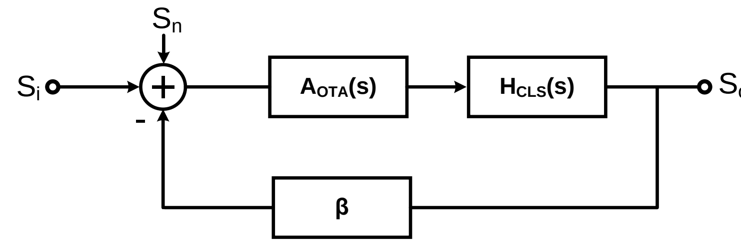
$$A_{fp}(s) = A_{OTA}(s) \cdot H_{CLS}(s)$$

$$C_{OTA} = C_P + \frac{C_{CLS} \cdot C_{LD}}{C_{CLS} + C_{LD}} \qquad H_{CLS}(s) = \frac{C_{CLS}}{C_{CLS} + C_{LD}}$$

Normally, factors cancel & gain-bandwidth product is constant

Noise Analysis: Split-CLS



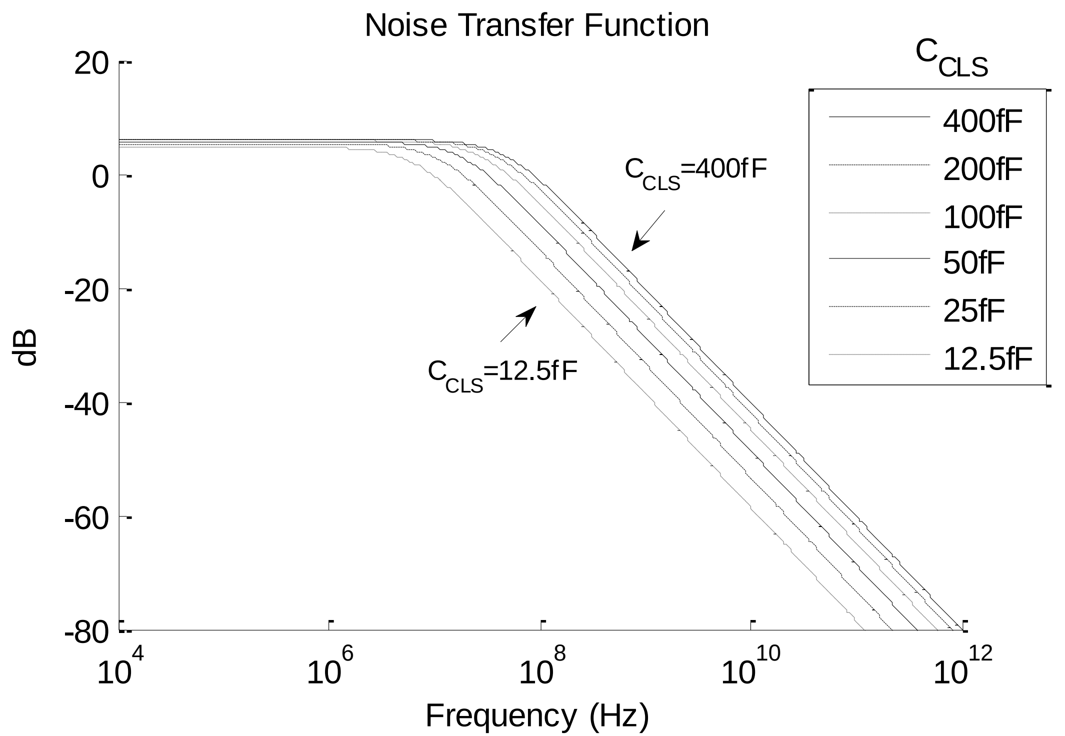


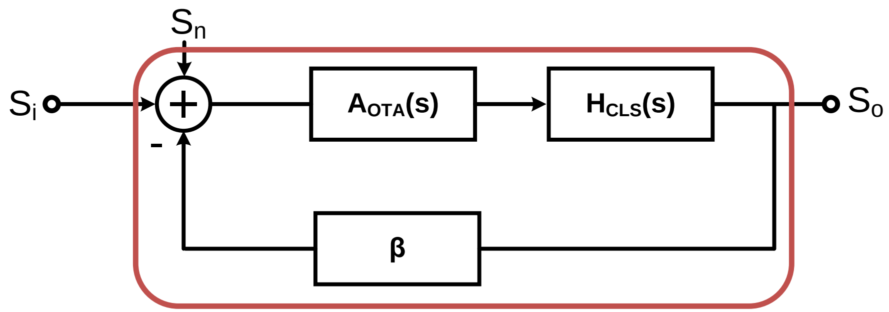
$$A_{fp}(s) = A_{OTA}(s) \cdot H_{CLS}(s)$$

$$C_{OTA} = C_P + \frac{C_{CLS} \cdot C_{LD}}{C_{CLS} + C_{LD}} \qquad H_{CLS}(s) = \frac{C_{CLS}}{C_{CLS} + C_{LD}}$$

Presence of C_P causes gain-bandwidth spreading when C_{CLS} is varied

Noise Analysis: Split-CLS





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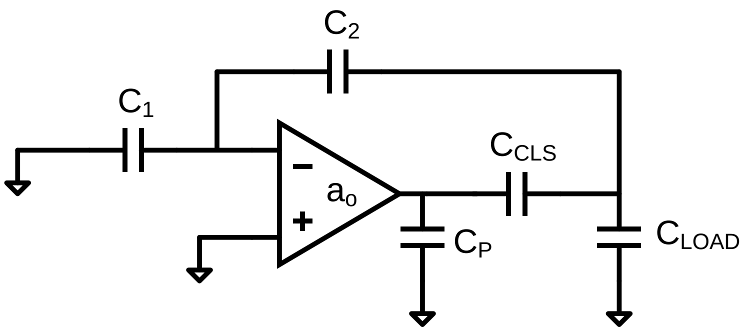
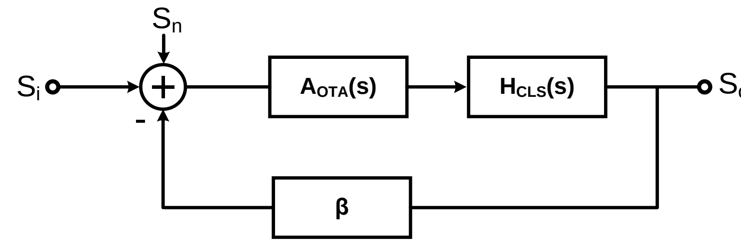
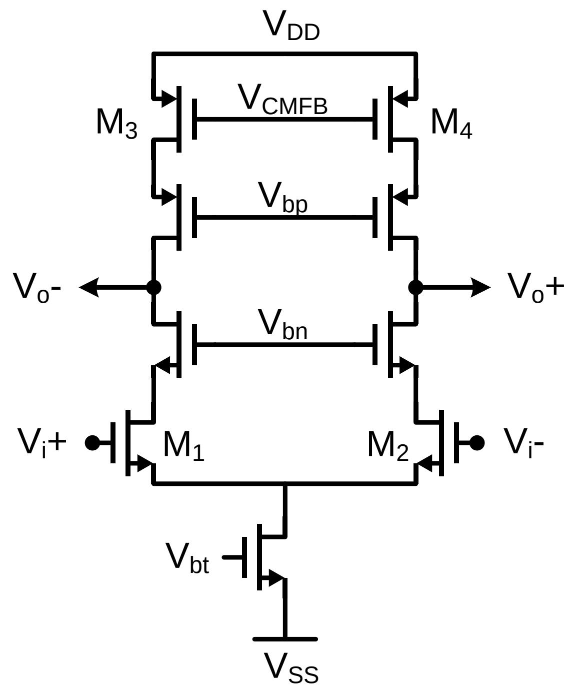




Total integrated noise power for noise source $S_n(f)$:

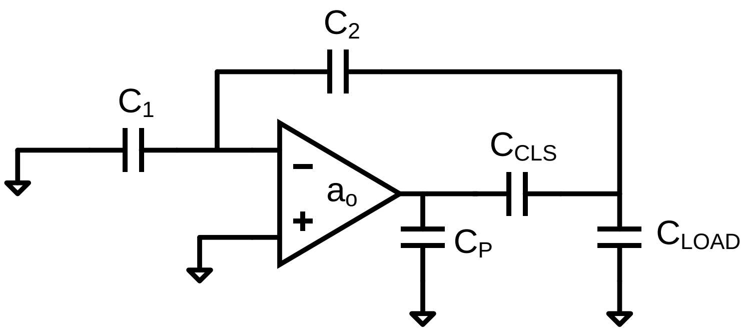
$$\tilde{v}_{no}^2 = \int_0^\infty S_n(f) \cdot |H_n(2\pi f)|^2 \, df. \qquad (10)$$

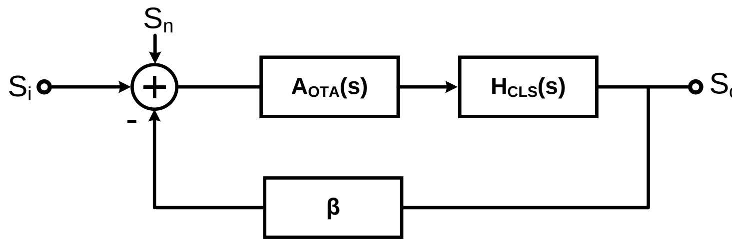
Noise Analysis: Split-CLS



- Telescopic opamp used as noise source
- M_1, M_2, M_3, M_4 are the dominant noise contributors
  - Can be modeled as single input-referred noise contributor

Noise Analysis: Split-CLS

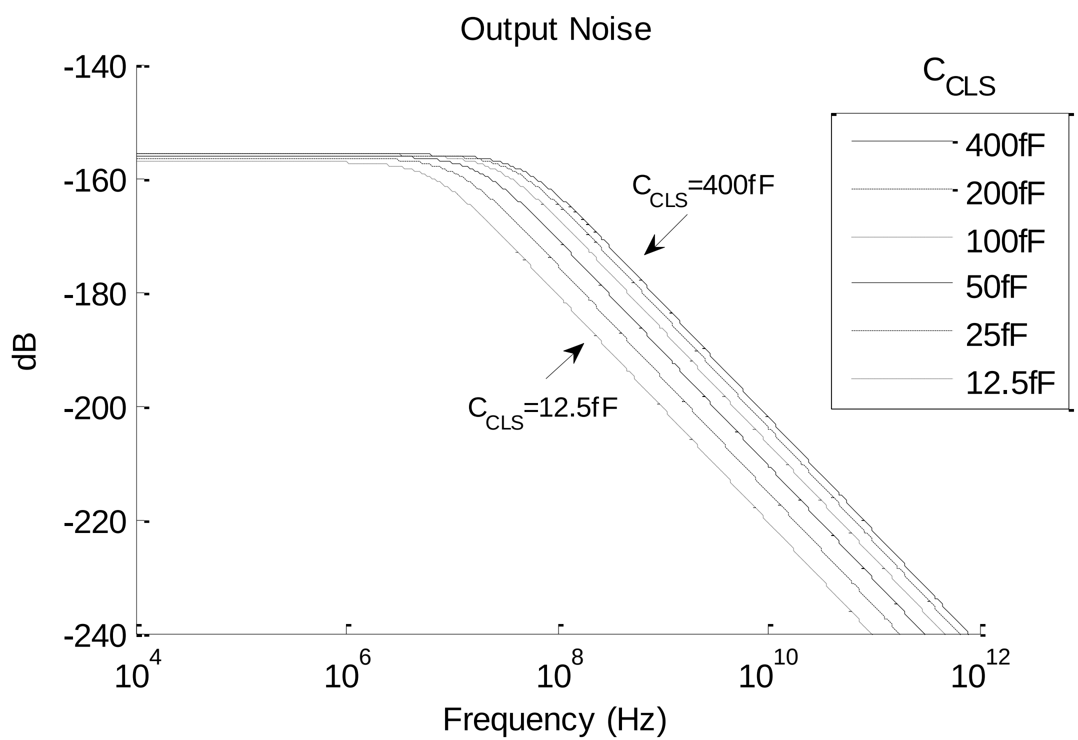


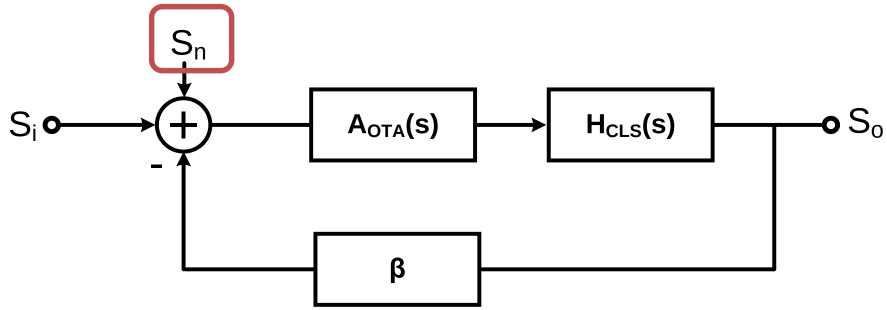


When 1/f noise is entirely in passband of $A_{OTA}(s)$, noise sources can be treated as frequency-independent constants:

$$\tilde{v}_{no}^2 = v_{n(1/f)}^2 + \int_0^{\infty} S_{n(white)} \cdot |H_n(2\pi f)|^2 \, df \qquad (11)$$

Noise Analysis: Split-CLS





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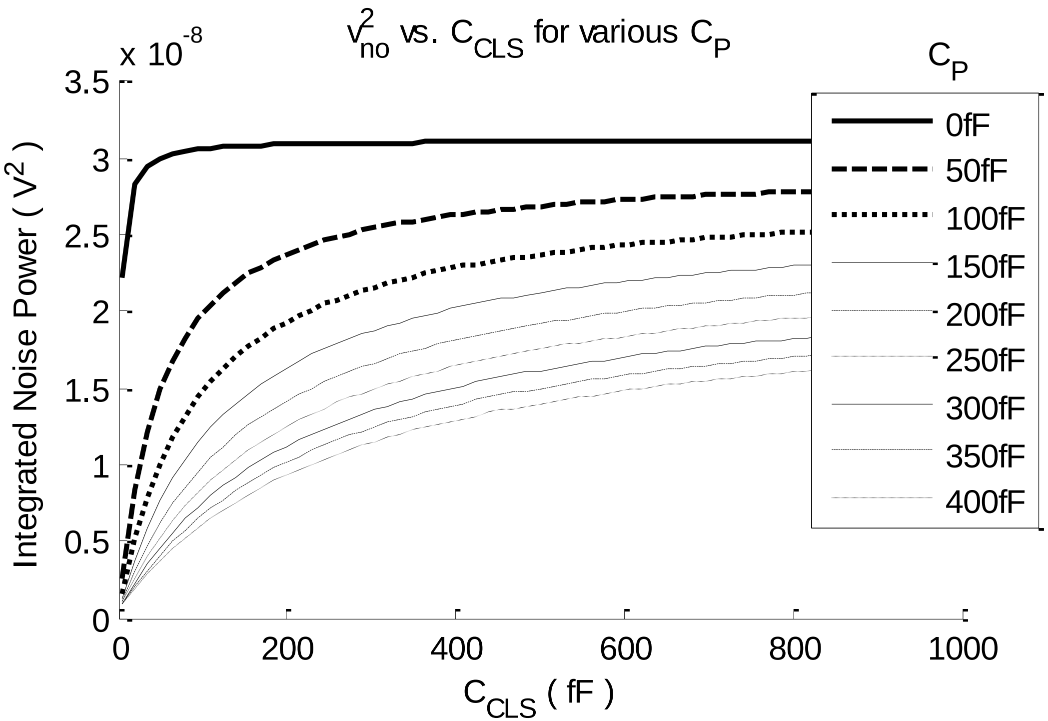


$$C_P >> \frac{C_{CLS} \cdot C_{LD}}{C_{CLS} + C_{LD}}$$ → C_{CLS} and noise are heavily correlated.

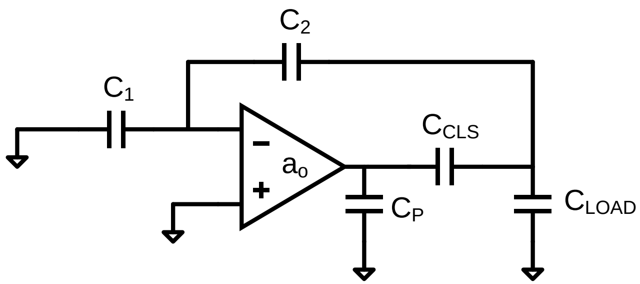
$$C_P << \frac{C_{CLS} \cdot C_{LD}}{C_{CLS} + C_{LD}}$$ → C_{CLS} and noise are weakly correlated.

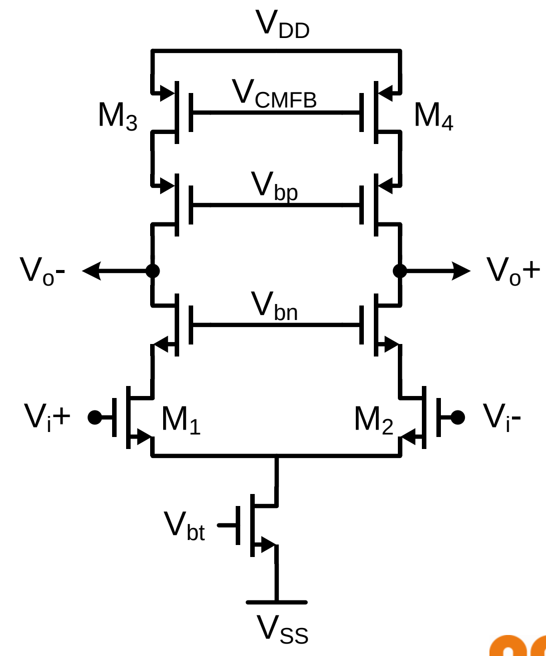
(Mostly likely case in practical designs.)

Comparison with Simulation

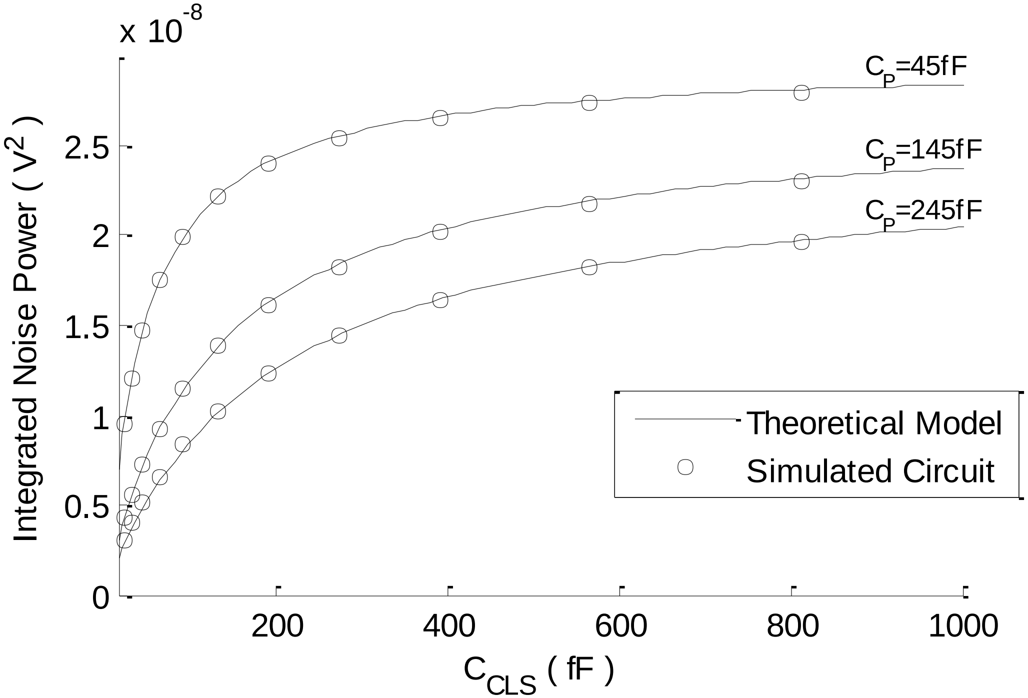
Comparison with Simulation

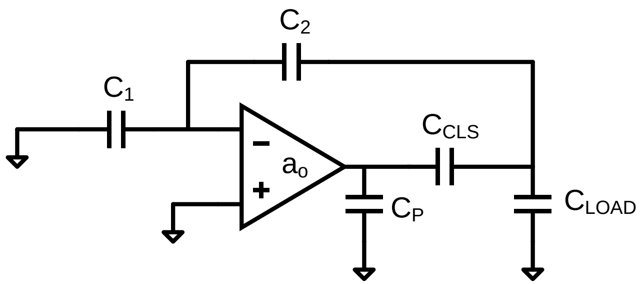
- Extracted values
  - $C_P = 45fF$
  - $a_o = 58.4dB$
  - $C_1 = C_2 = 400fF$
  - $C_{LOAD} = 640fF$
  - $v^2_{n(1/f)} = 6.31 \times 10^{-10}\ V^2$
  - $S_{n(white)} = 6.17 \times 10^{-17}\ V^2/Hz$

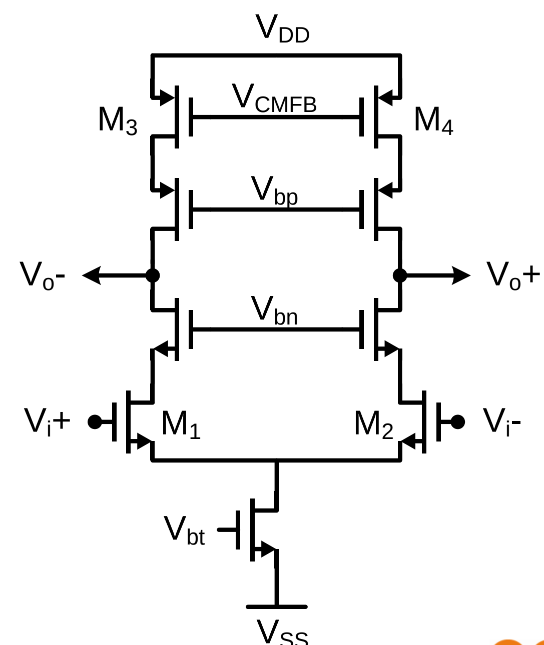




Comparison with Simulation

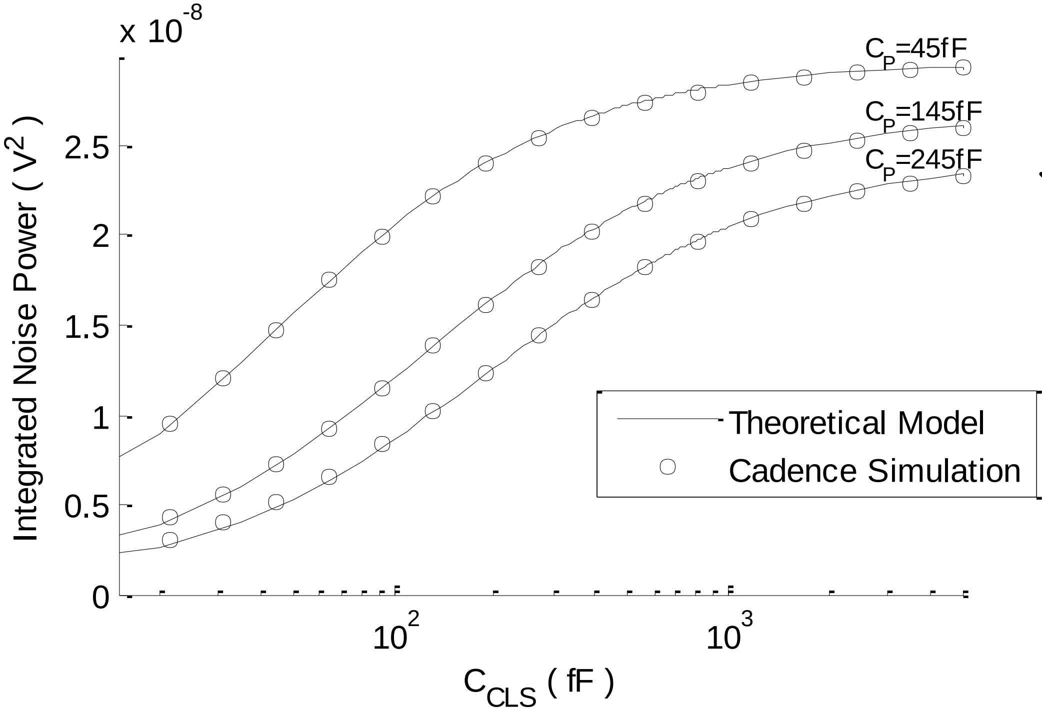






- Simulation and Theoretical model found to be in good agreement.

Comparison with Simulation



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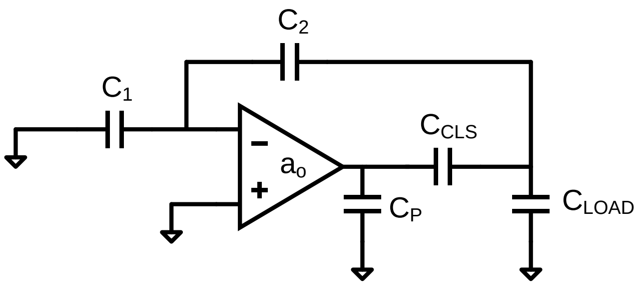

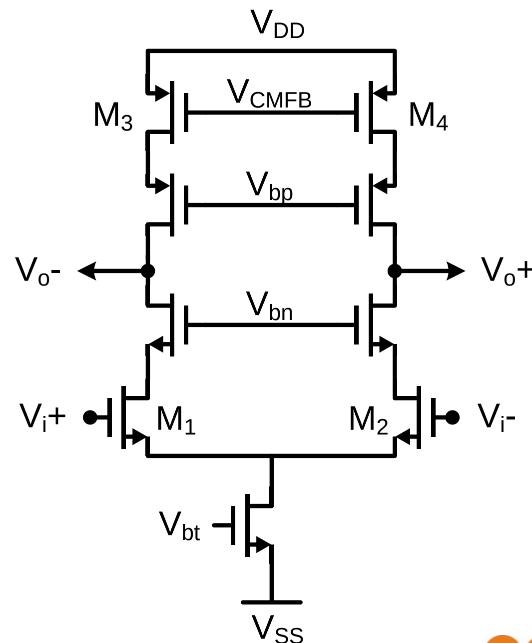

Conclusion

Conclusion

- CLS and Split-CLS reduce finite-opamp gain error by approximately $1/A^2$
- Addition of C_{CLS} network to MDAC structure introduces bandwidth spreading dependent on $C_{CLS} \leftrightarrow C_P$ relation.
- For most practical Split-CLS designs, $C_{CLS} >> C_P$
  - C_{CLS} should be large enough to minimize swing requirement, maintain sufficient loop gain.
  - C_P is only intrinsic parasitic capacitances of opamp
- In practical cases, total integrated opamp noise is not significantly affected by Split-CLS.

Thank You For Your Attention