Vrije Universiteit Brussel

# Design and Analysis of an On-Chip Programmable Op-Amp based Filter

Adam Cooman

Vrije Universiteit Brussel

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**Promotor** Prof. Dr. ir. Gerd Vandersteen

# eSYSID

**electronic SYStem IDentification test-bench**

Programmable chip to simulate a wide class of systems.

- Experimental verification of system identification techniques
- Useful for labs on system identification

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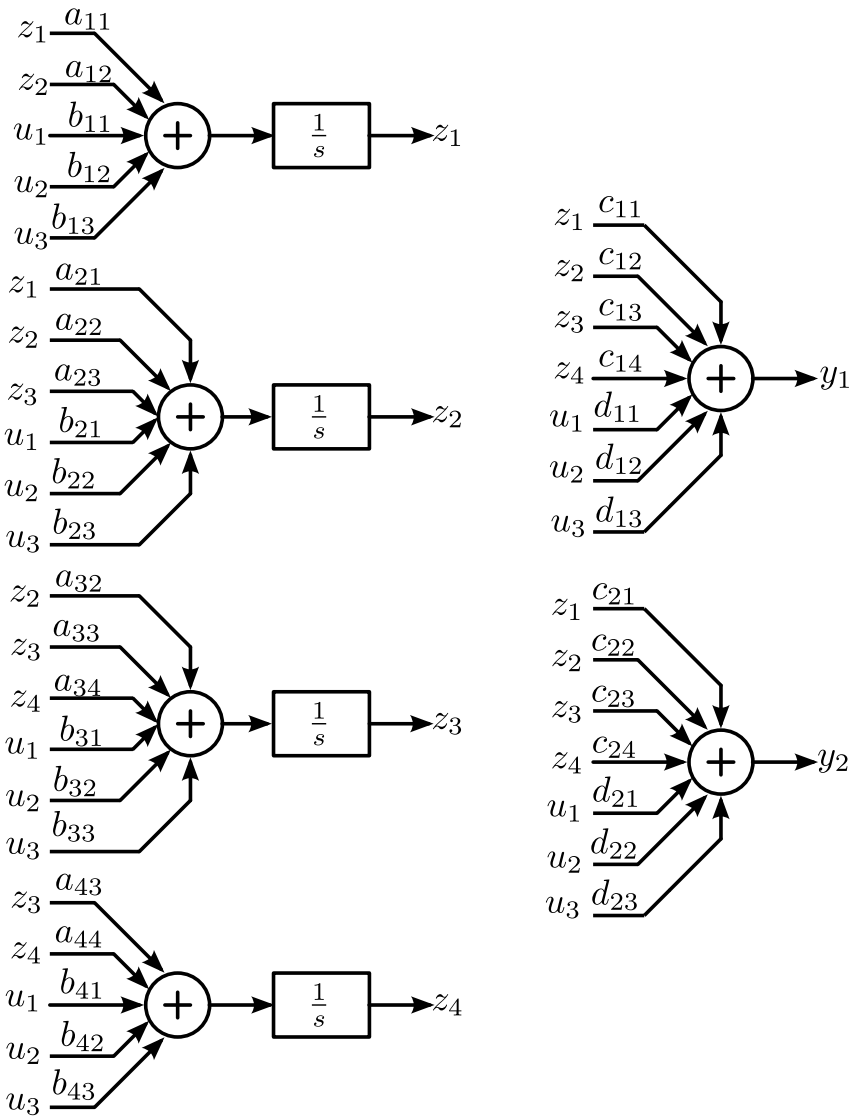
- High-level architecture
- Op-amp design
- Nonlinear analysis

# Architecture

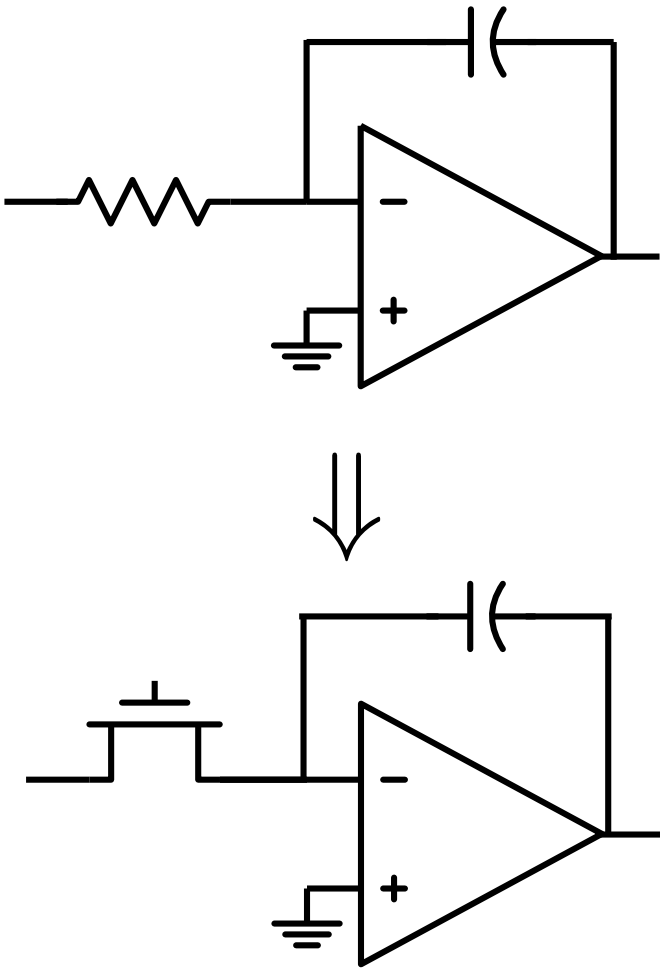
- State-Space

$$\begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A}(p,q)\mathbf{x}(t) + \mathbf{B}(p,q)\mathbf{u}(t) \\ \mathbf{y}(t) = \mathbf{C}(p,q)\mathbf{x}(t) + \mathbf{D}(p,q)\mathbf{u}(t) \end{cases}$$



# MOSFET-C

- Continuous time filter
- Low bandwidth
- High SNDR
- Better tune-ability than RC integrators

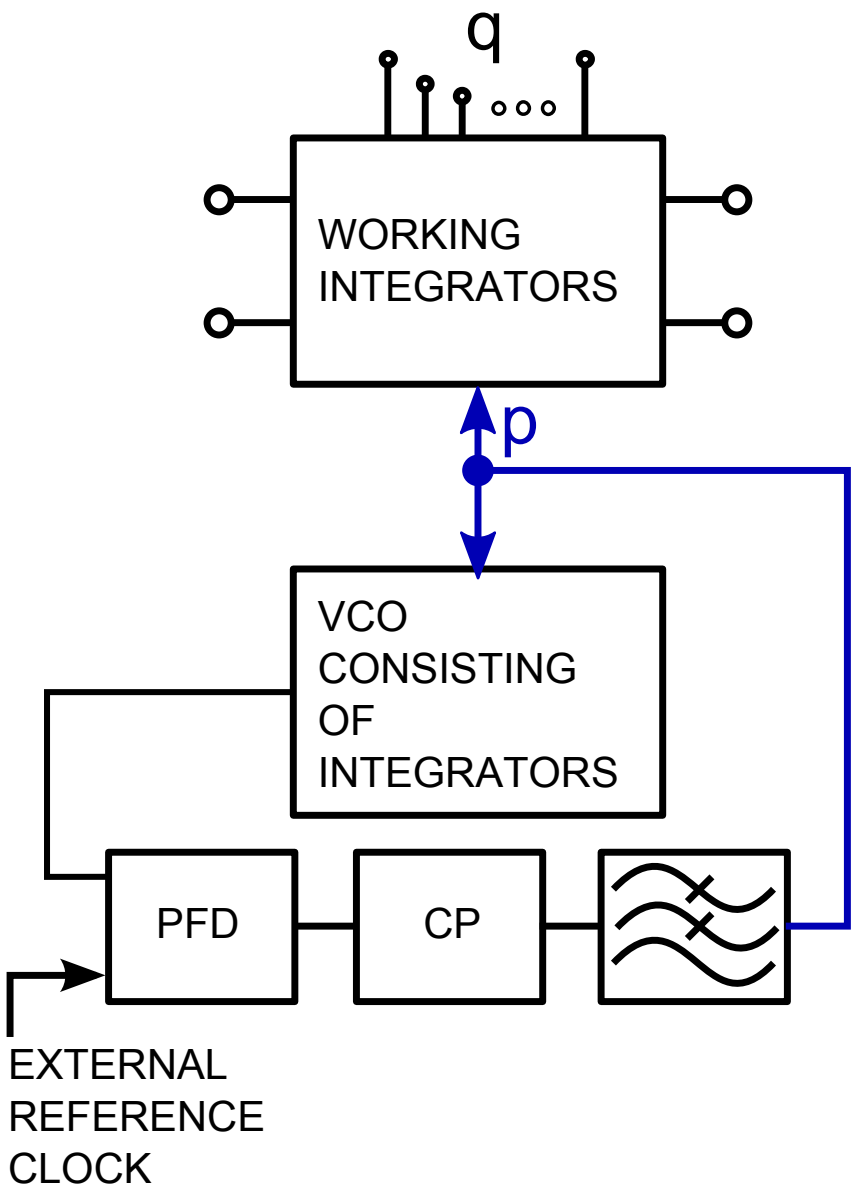


# Tuning scheme

PLL-based tuning network

- Build VCO with two integrators
- Set oscillation frequency to precisely known external reference

⇒High precision + repeatability



# Op-Amp

Op-amp is critical to the performance of the MOSFET-C integrator

- High gain needed: $\pm 80$dB
- $GBW$ of about 100MHz
- load capacitance $C_L$ of 10pF.

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- 2 stage op-amp
- Miller compensation
- Ahuja compensation
- Fully Differential op-amp
- Final Design

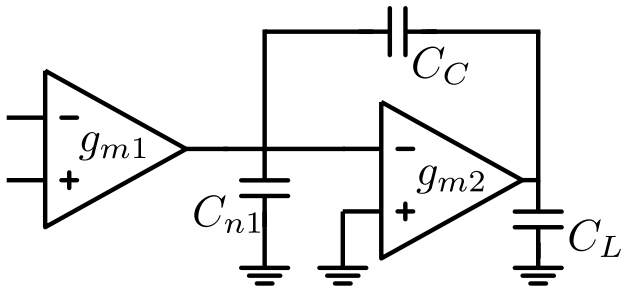
# Design Plan Sansen

Two equations

$$GBW = \frac{g_{m1}}{2\pi C_C}$$

$$f_{nd} = \frac{g_{m2}}{2\pi C_L(1 + C_{n,1}/C_C)}$$

Design parameters:




$$\alpha = C_L/C_C = 3$$
$$\beta = C_C/C_{n1} = 3$$
$$\gamma = f_{nd}/GBW = 3$$

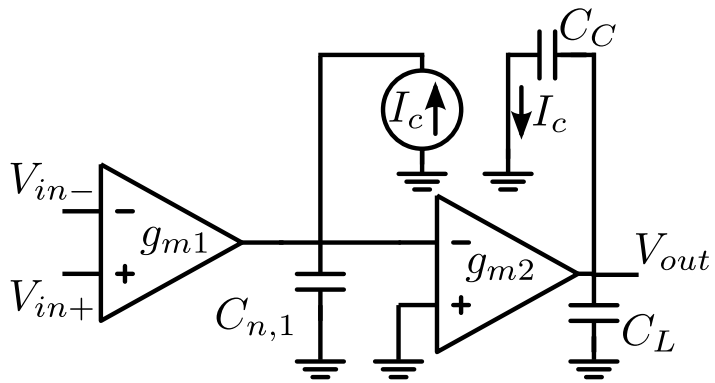
# Ahuja Compensation

Improvement over Miller compensated op-amp

- RHP zero compensation
- Lower current consumption

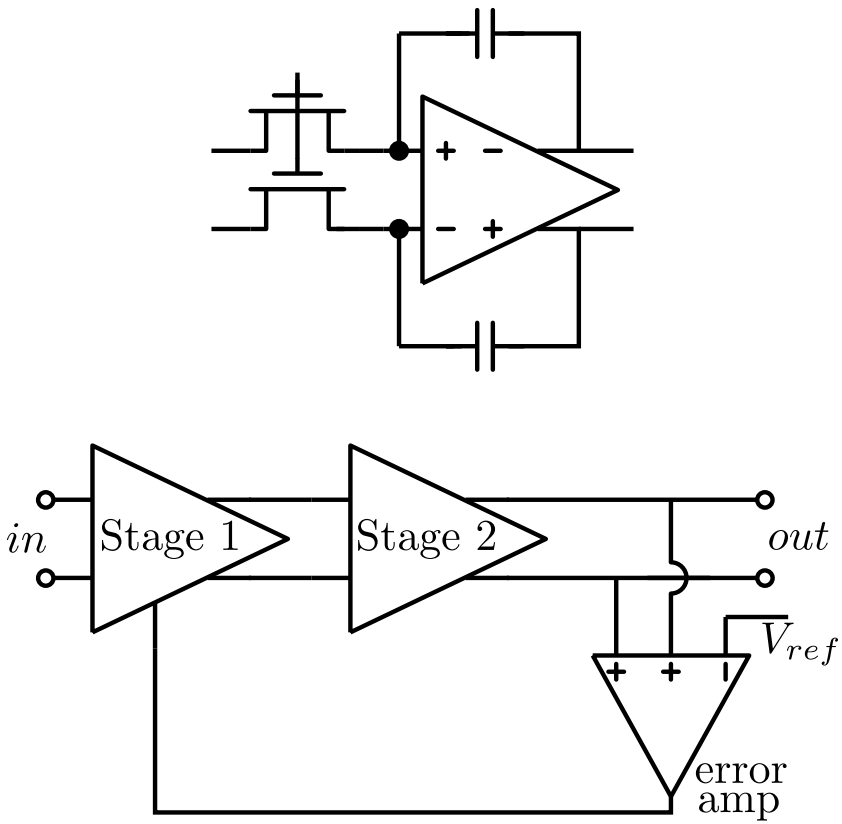
$$GBW = \frac{g_{m1}}{2\pi C_C}$$

$$f_{nd} = \frac{g_{m2}}{2\pi(C_C + C_L)} \frac{C_C}{C_{n1}}$$

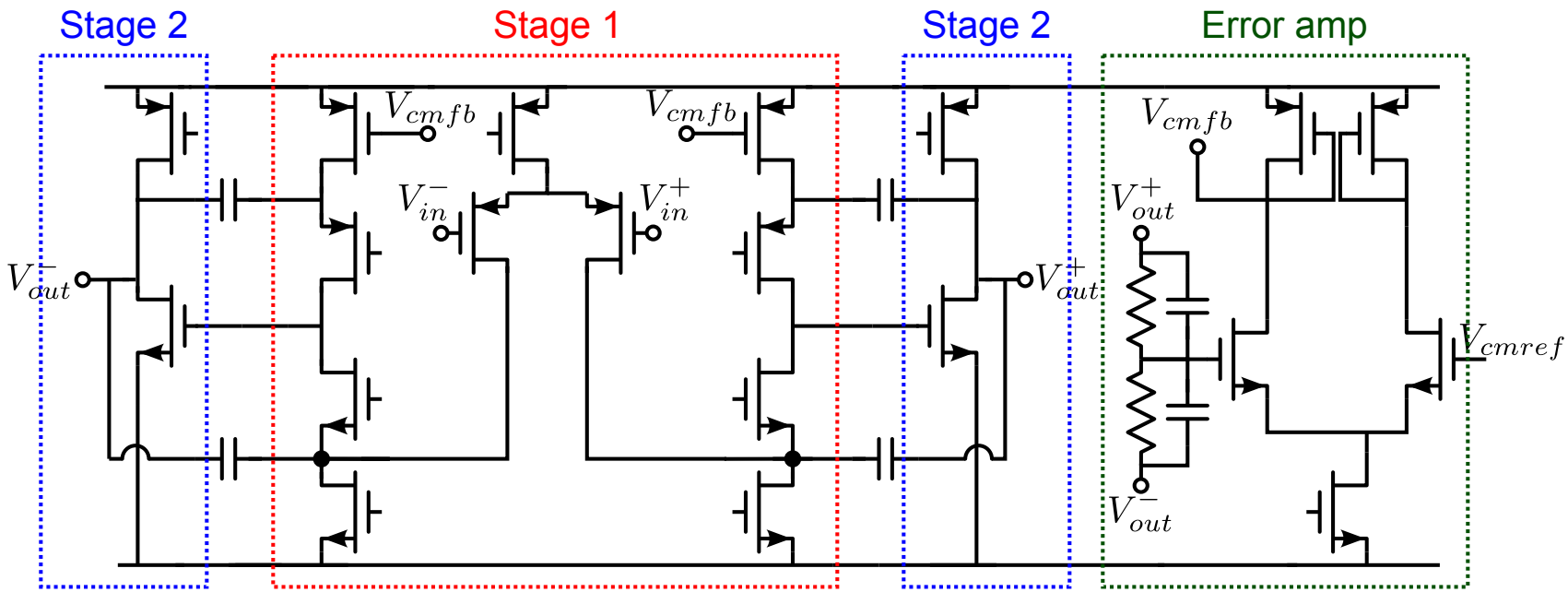



Design plan can be recycled

# Fully Differential



# Design results



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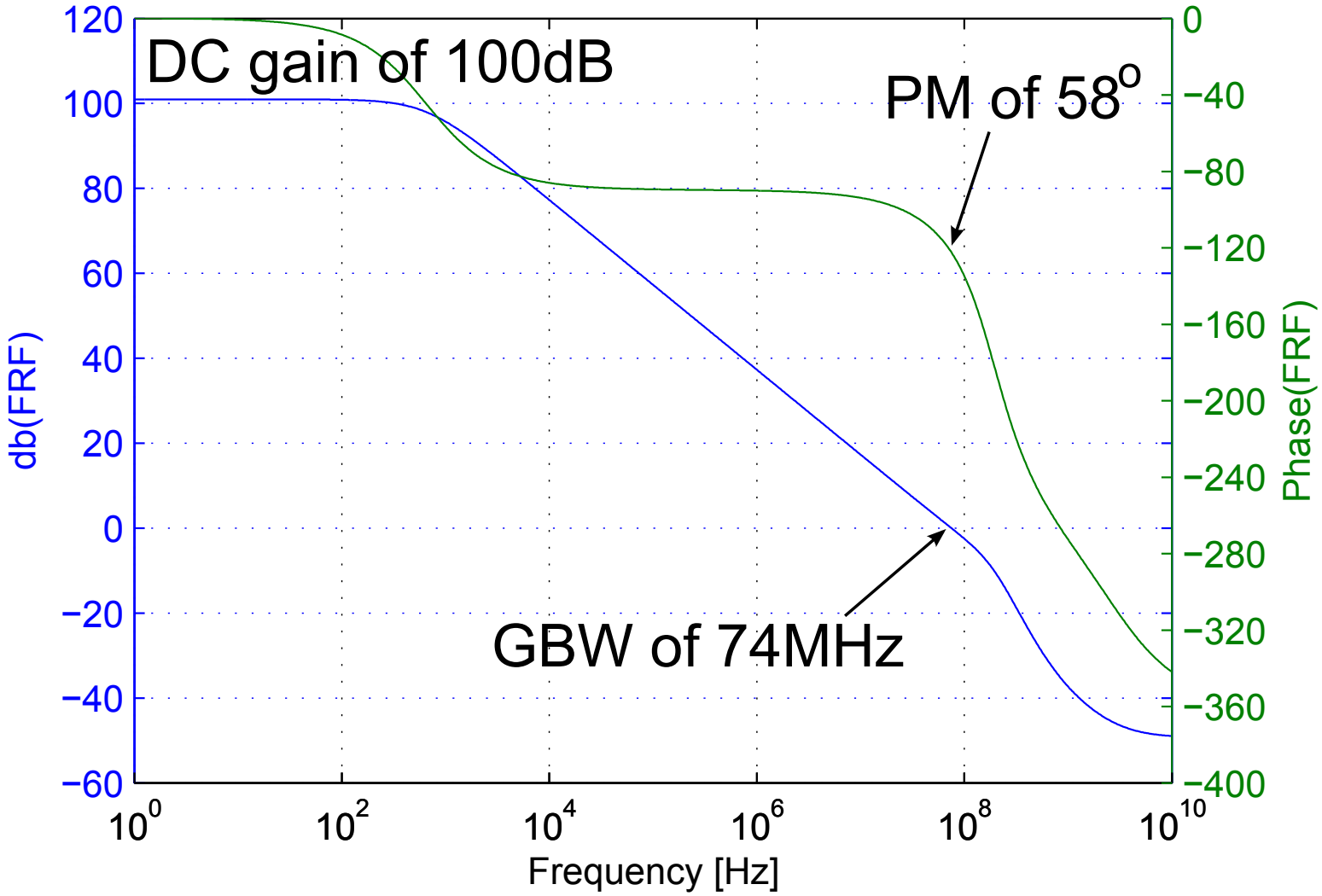

# Nonlinear Analysis

We have the op-amp, How to improve its performance?

- Noise performance $\rightarrow$ Noise analysis
- Nonlinear performance $\rightarrow$ ???

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Overview

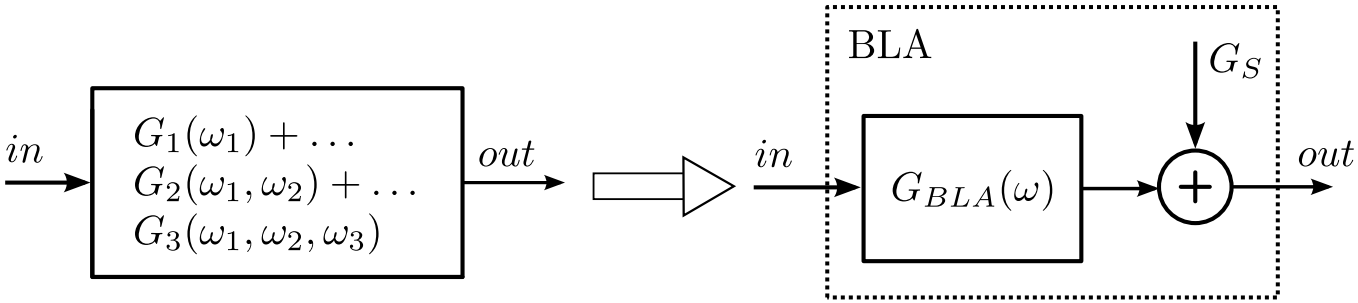
- Method
- Single-ended op-amp

} Published in conference paper

- Fully differential op-amp

# Idea Behind the Analysis

- Best Linear Approximation



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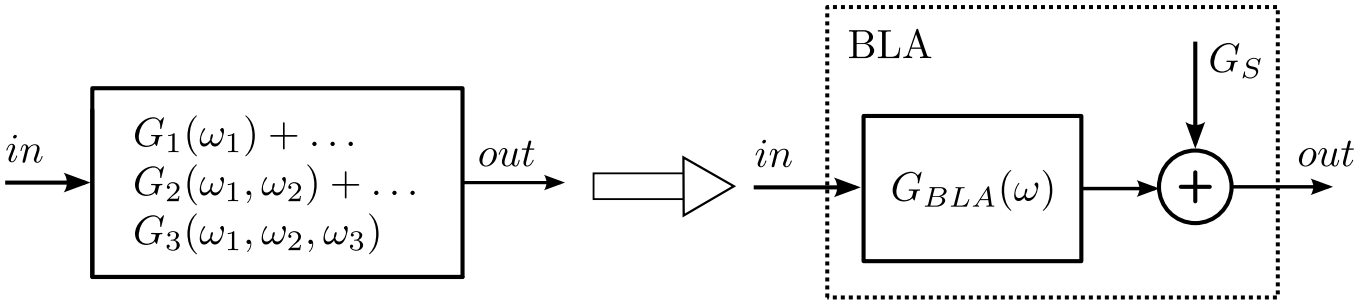


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$$G_S(\omega) = out(\omega) - in(\omega) \cdot G_{BLA}(\omega)$$

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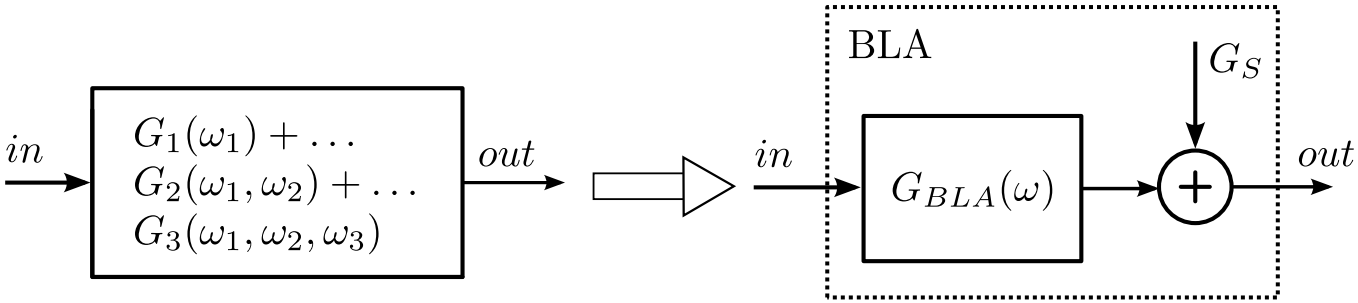


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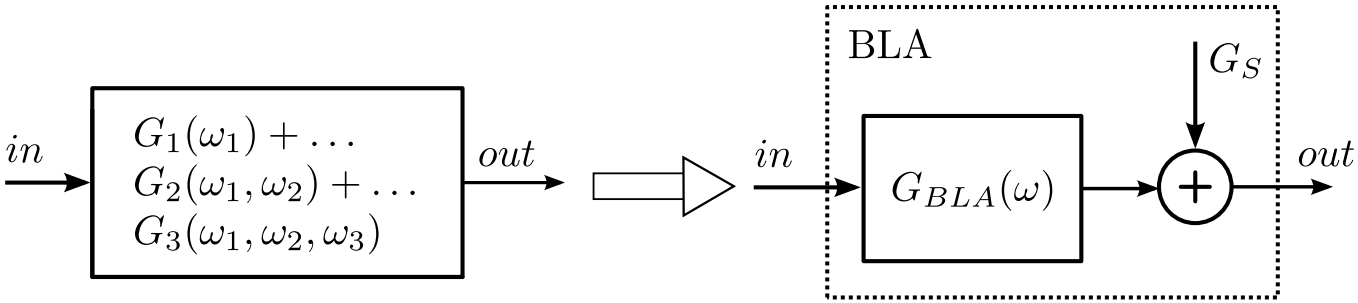


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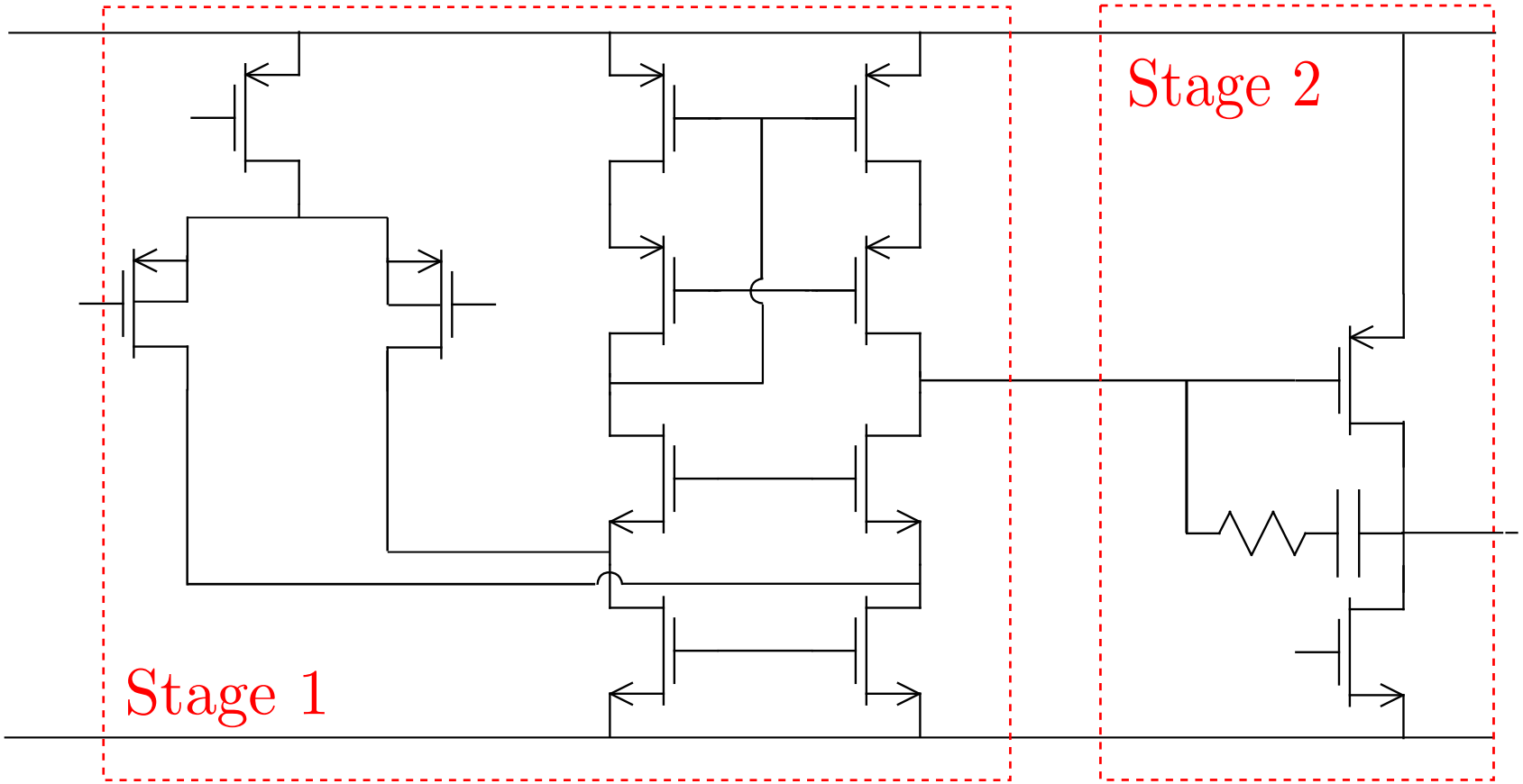
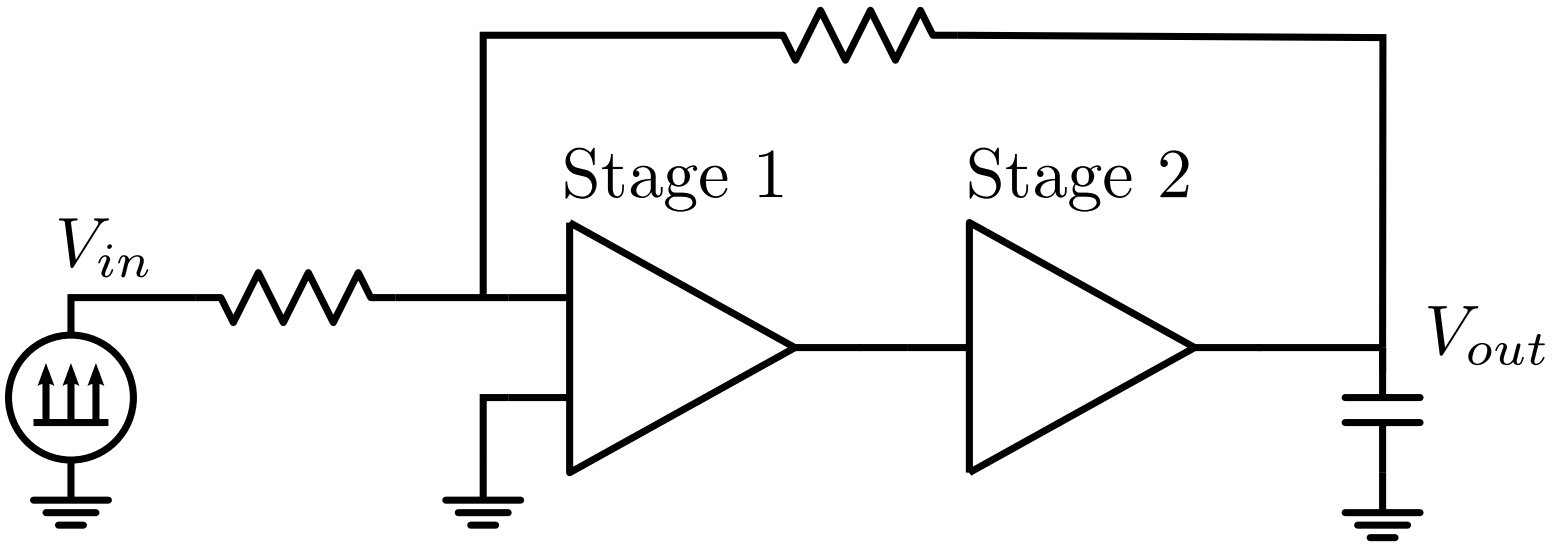
- Noise Analysis

Refer nonlinear contributions to the output to compare them

# Single-Ended Op-Amp



# Step 1: Transient Analysis



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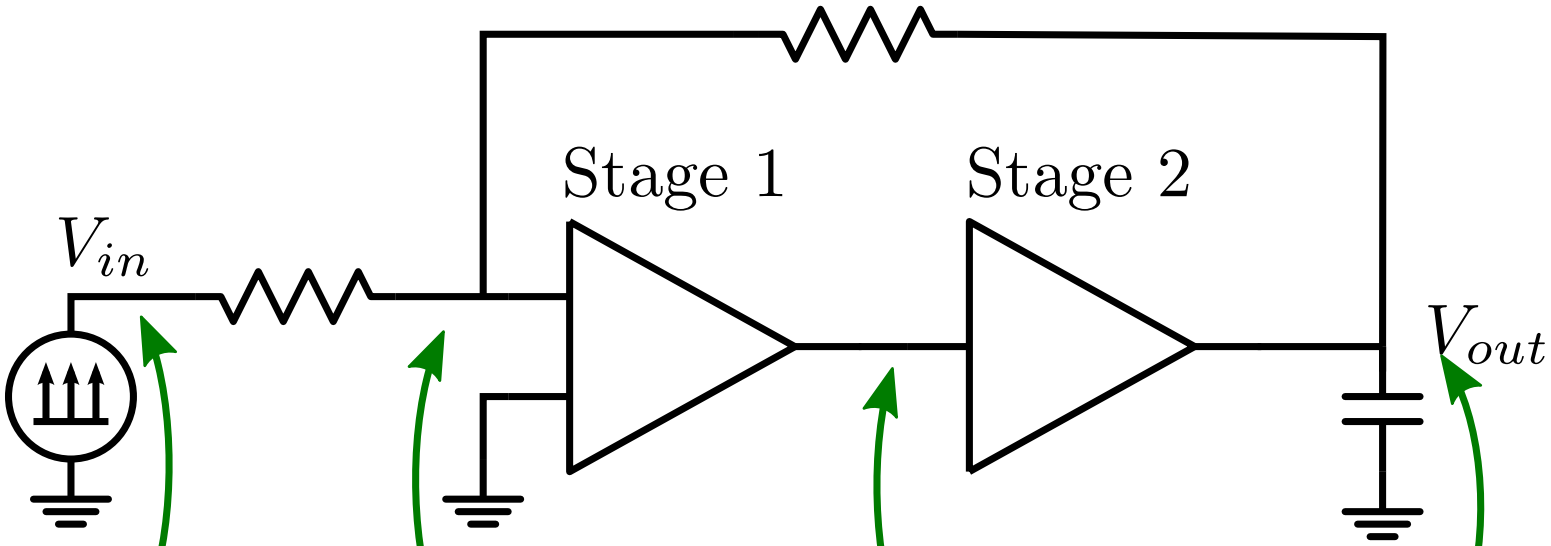
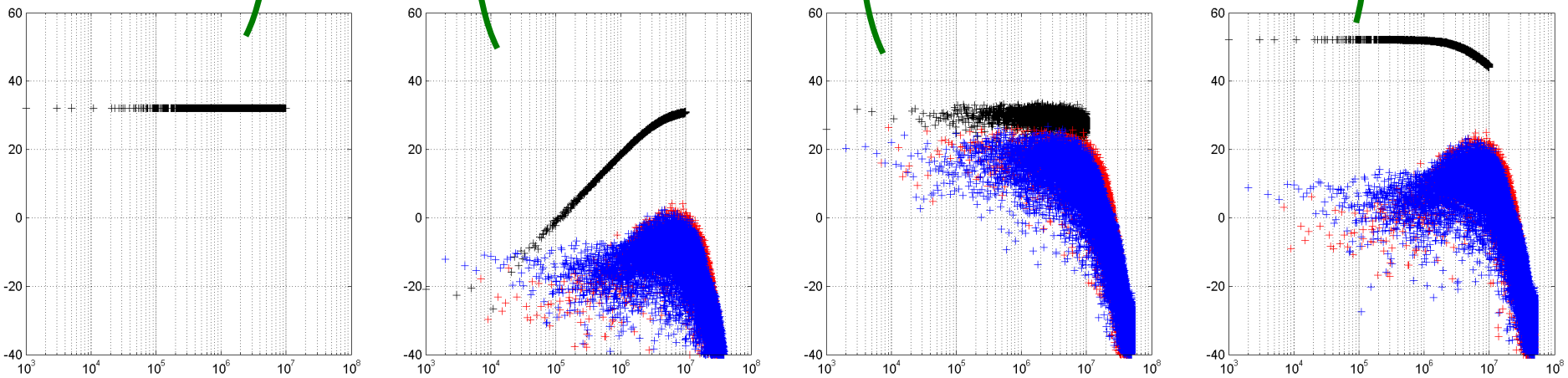
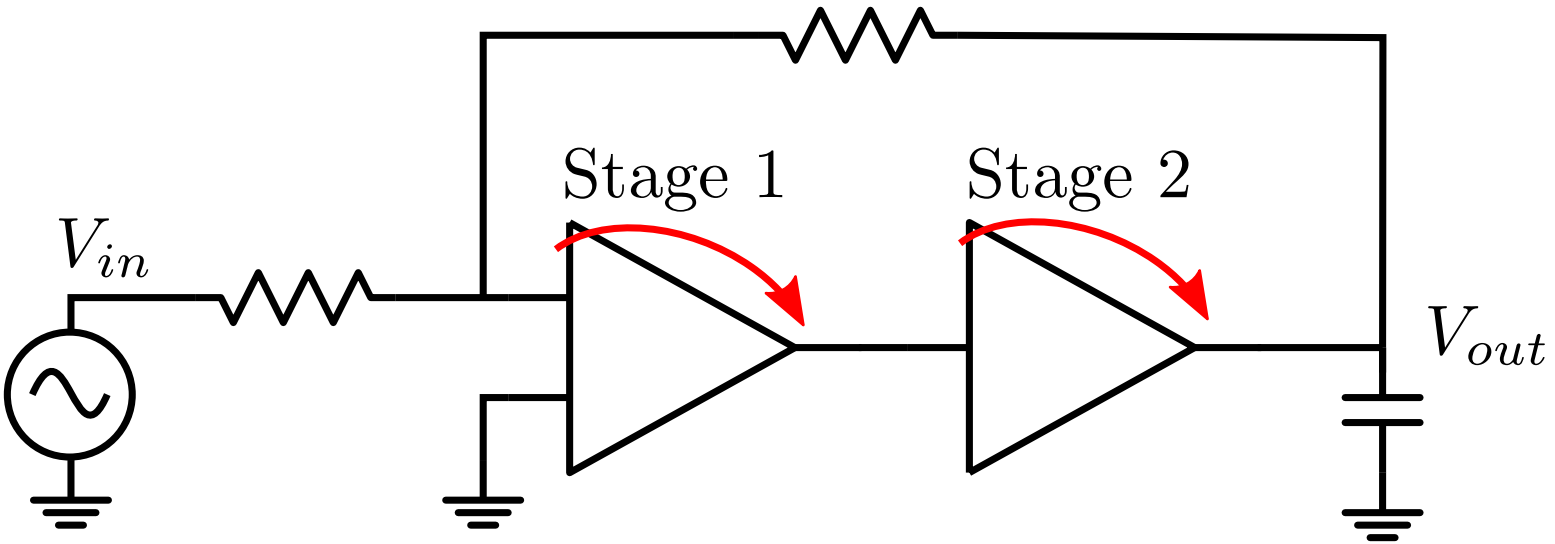


# Step 2: Spectral correction



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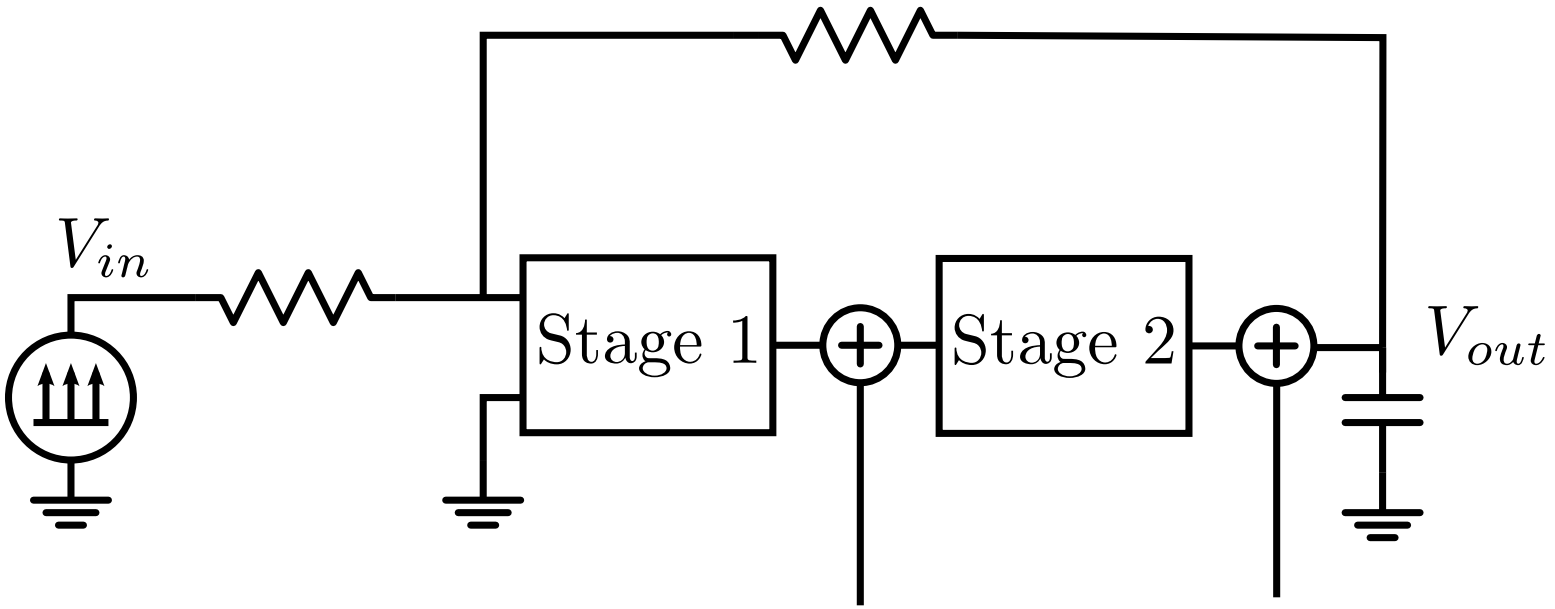

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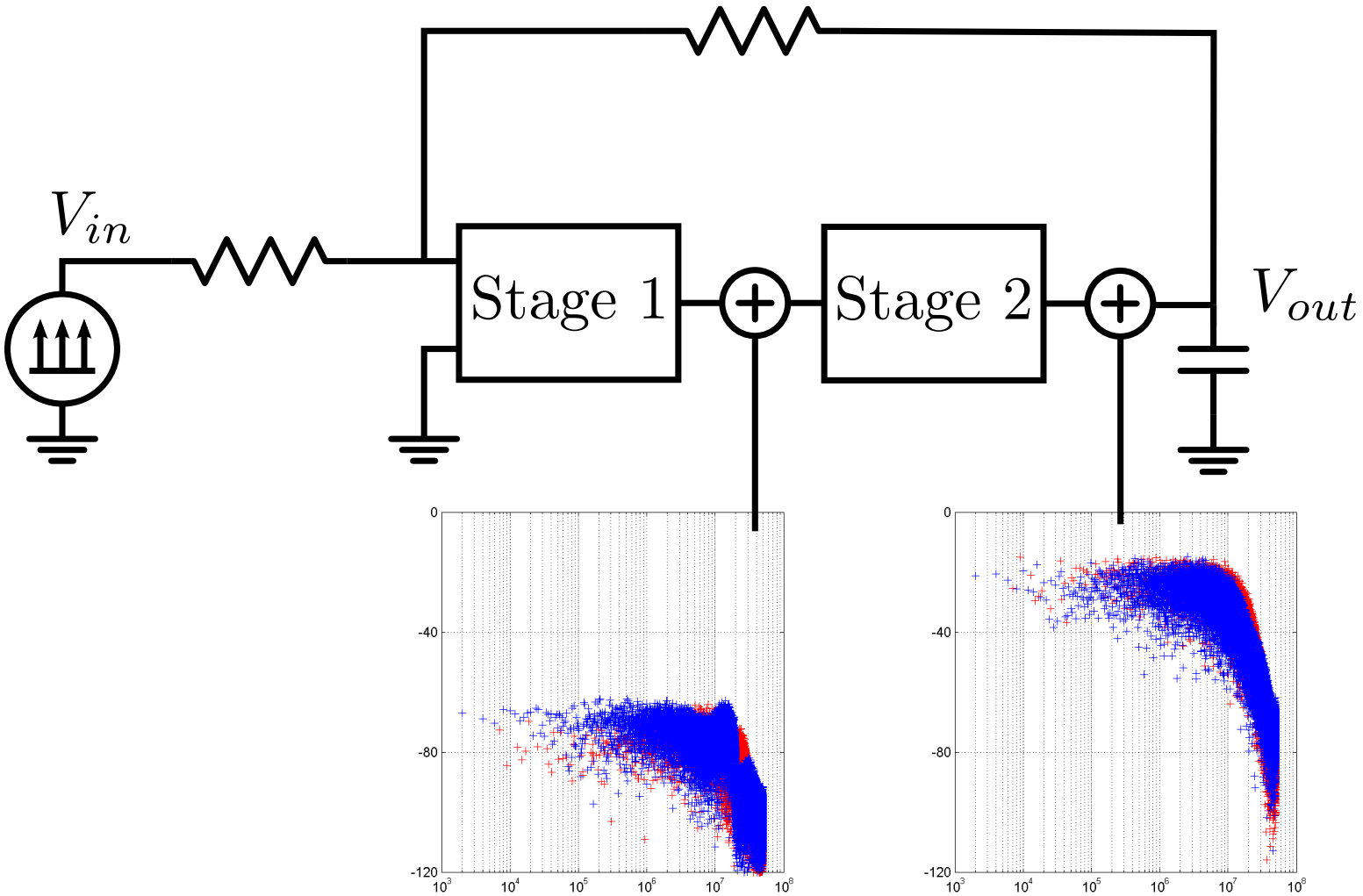
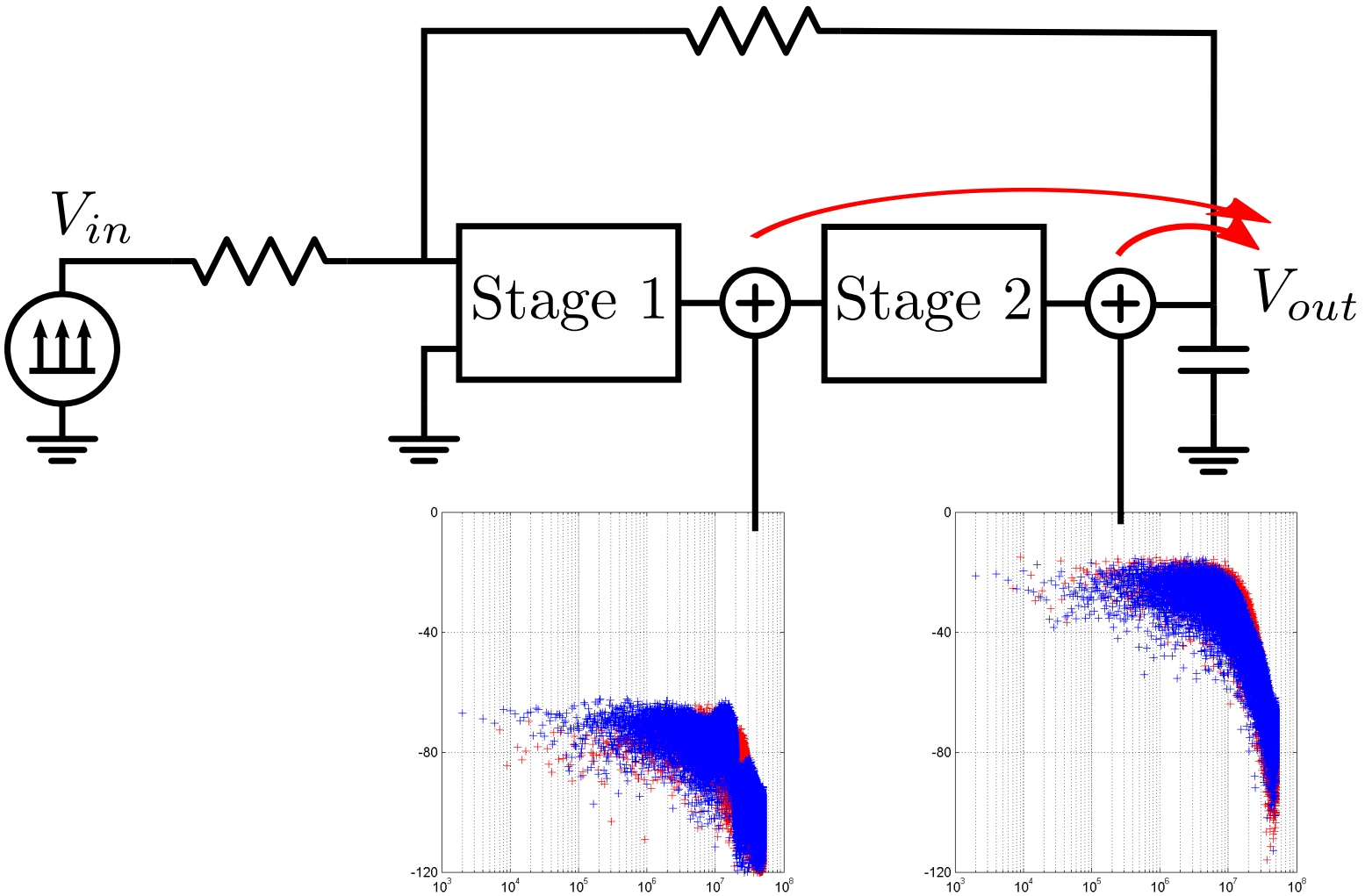
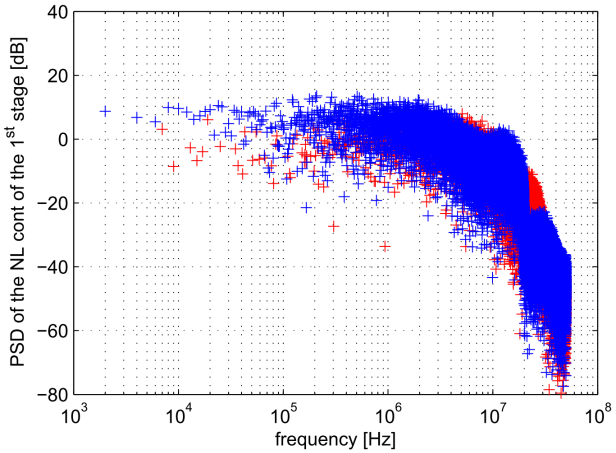


# Step 3: Refer to the output

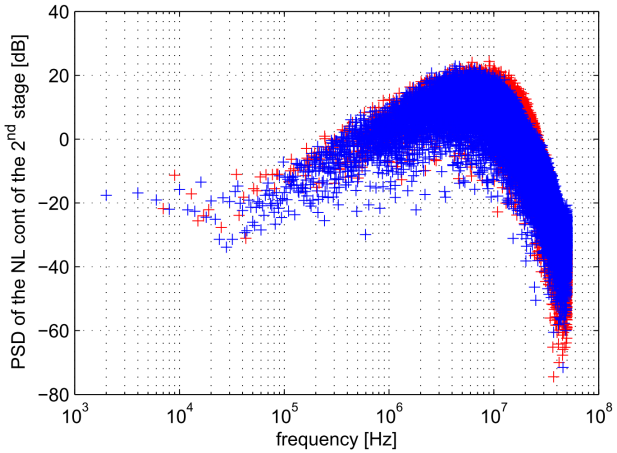


# Results

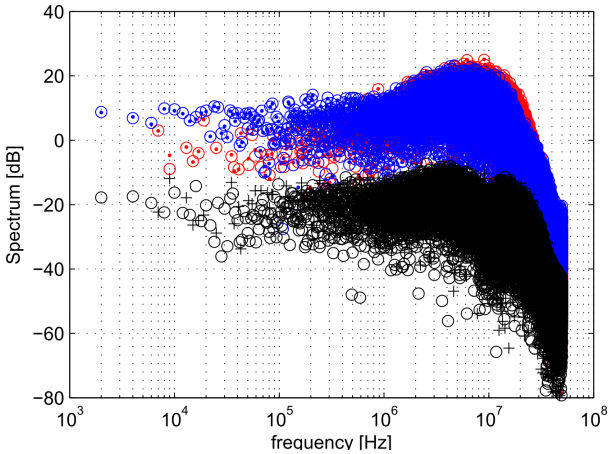
## Stage 1 at output



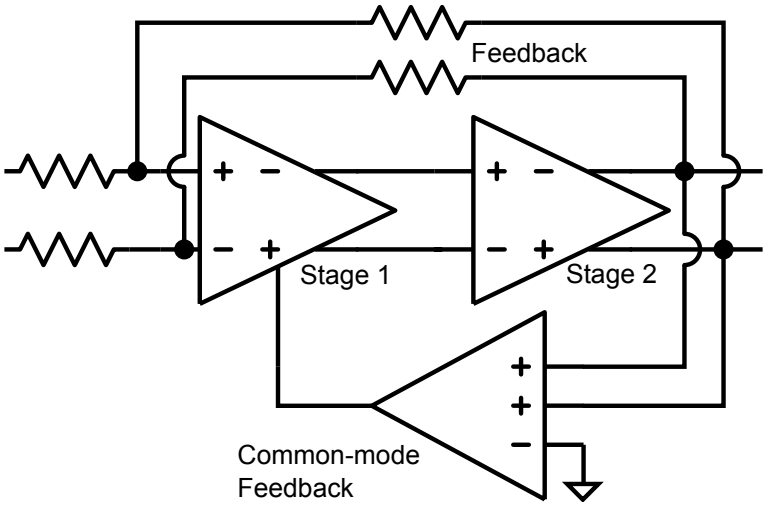

## Stage 2 at output




## Sum of contributions vs simulated output



# Extension to Fully-Differential Op-Amps




The method remains the same, but:

- MIMO
- Differential and Common mode
- Extra stage (Error amp)
- Assume symmetry

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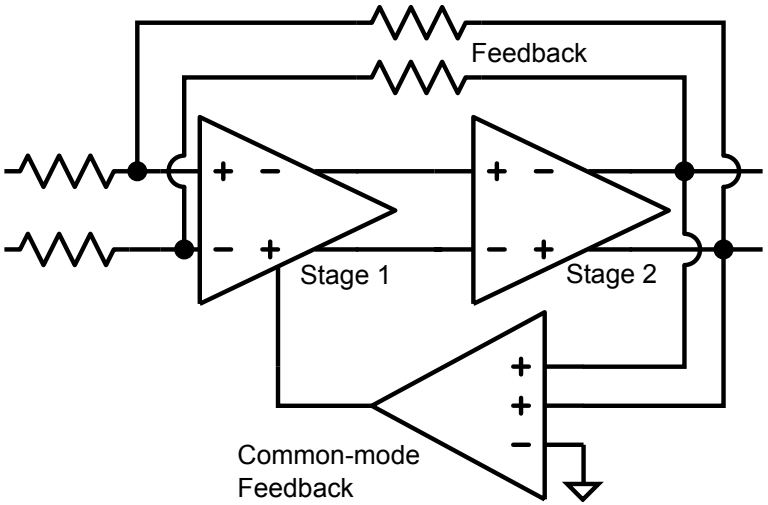


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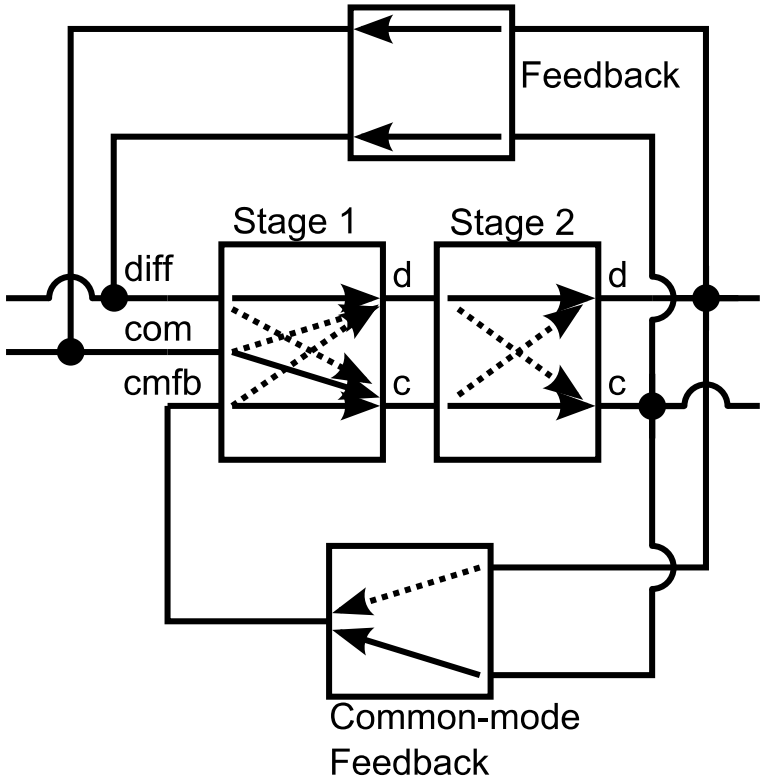
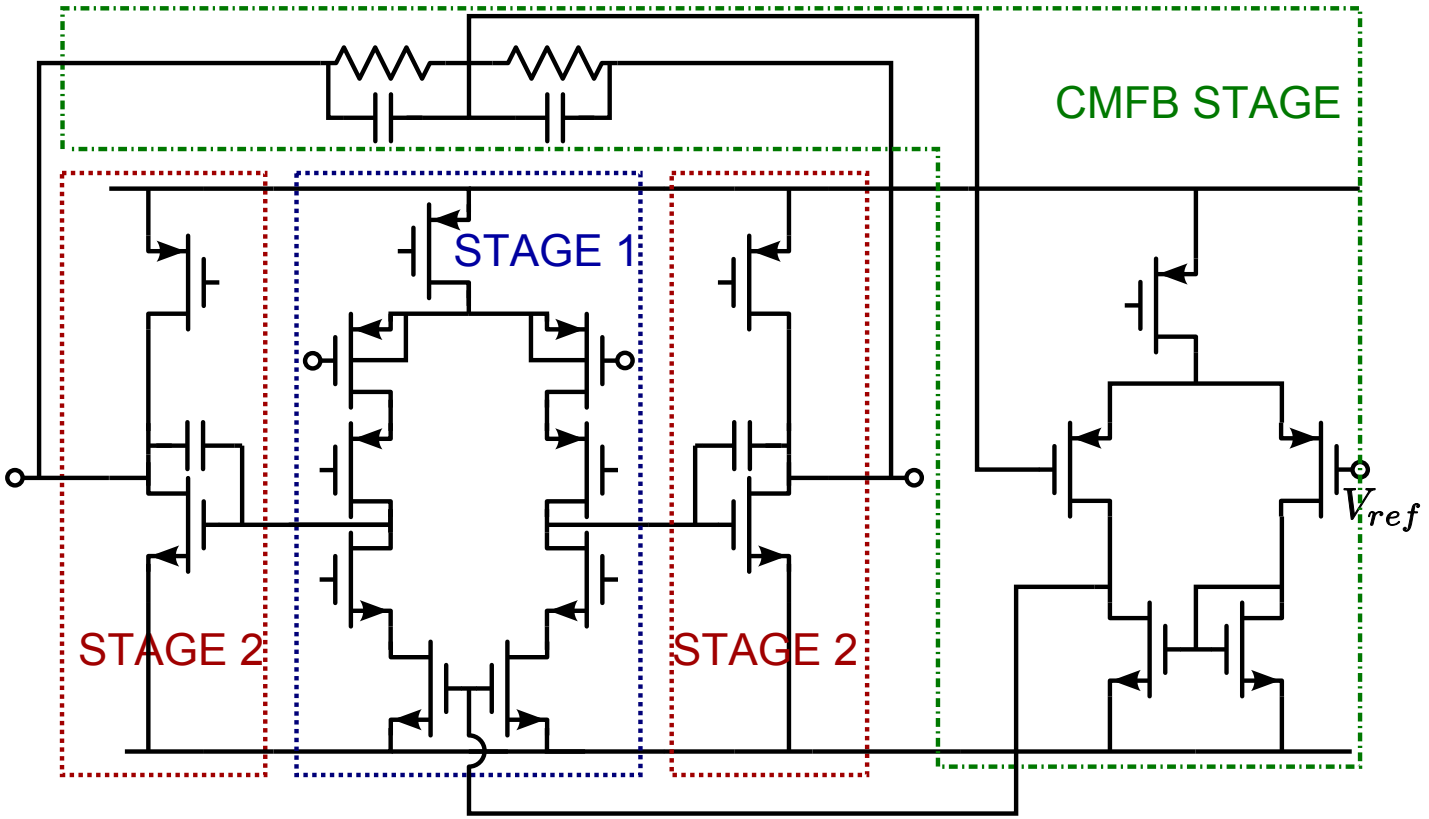
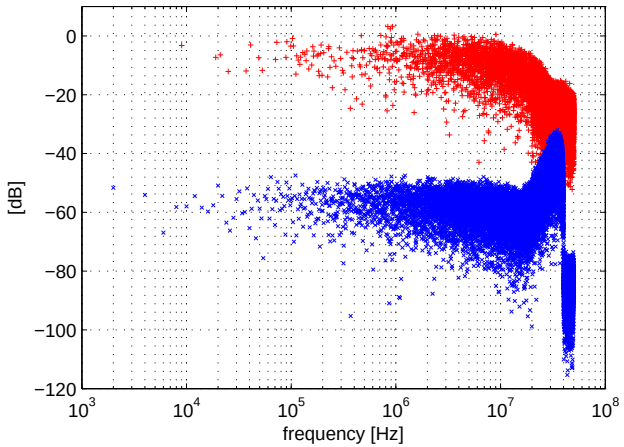


# Fully-Differential Op-Amp under test

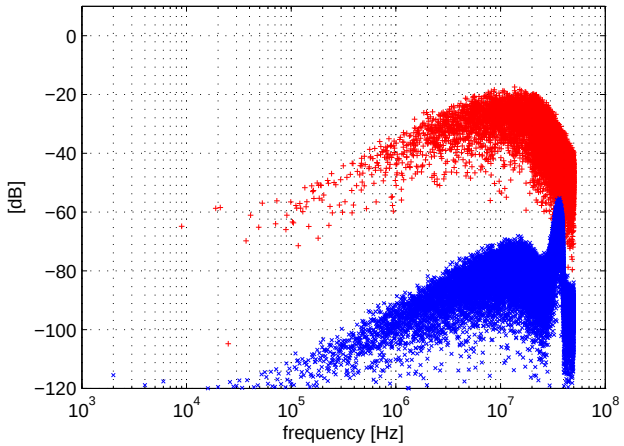


# Results Differential Analysis

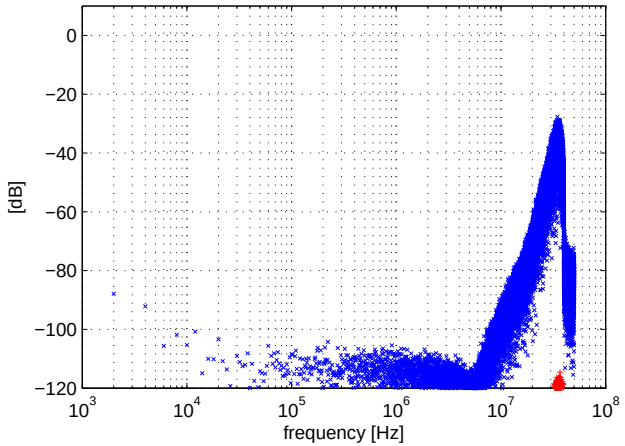
## stage 1 at output



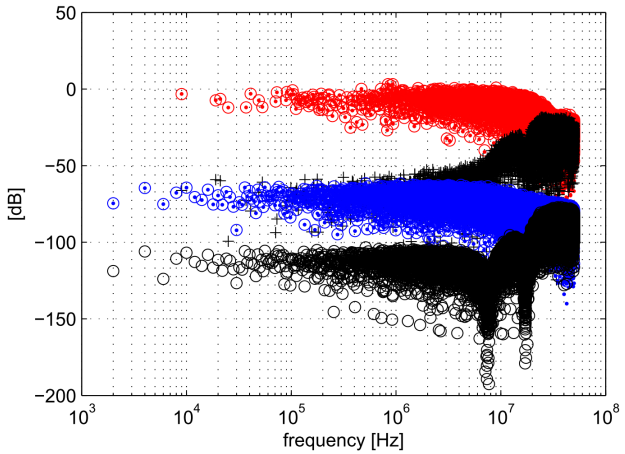

## stage 2 at output




## CMFB stage at out




## error made on the differential mode



# Future Research

- Simplify analysis
- Quicken analysis
- Improve accuracy

# Overview

- System-Level architecture
- Op-Amp Design
- Nonlinear Analysis

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- Design of the tuning network
- ESD, Yield, Lay-out