Magnetic Sensor and Interface Circuit (2)

林宗賢

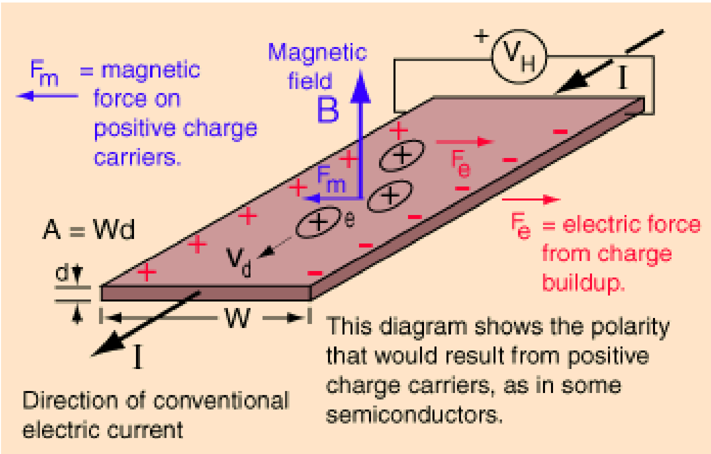
GIEE/NTU

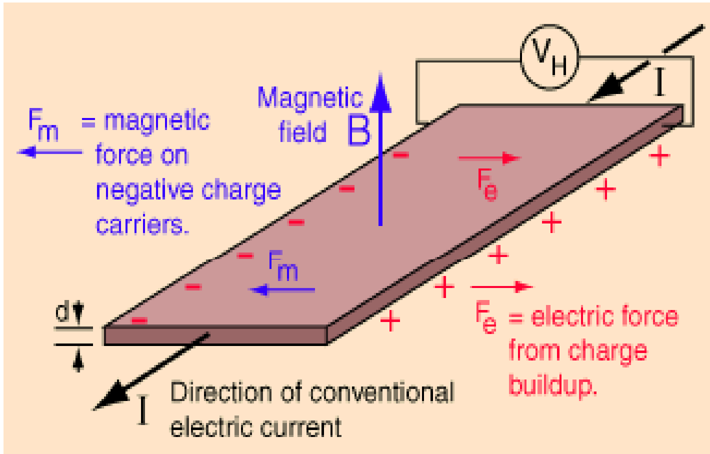
Outlines

- More on Hall sensors
  - Review
  - Hall sensor array
  - Integrated magnetic concentrator
  - Three-axis application

Review: Hall Sensor

- Based on the interaction between moving electric carriers and an external magnetic field.





$$\boxed{F_m = qv_d B} \qquad I = qnAv_d; \quad n: density\ of\ the\ charge\ carriers$$

$$\Rightarrow F_m = IB/nA$$

At equilibrium: $F_m = F_e = qV_H/W$

$$\Rightarrow V_H = IB/qnd$$

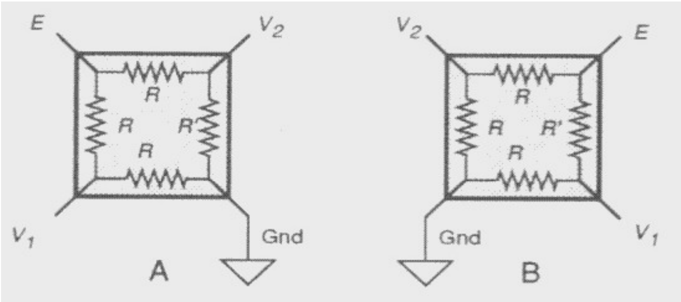
$$I = \frac{E}{R_H} = \frac{E}{\rho(L/Wd)}; \quad \rho = \frac{1}{qn\mu_H}$$

$$\boxed{\Rightarrow V_H = \mu_H \frac{W}{L} EB}$$

μ_H : mobility of the carriers (*E*: driving voltage)

Review: Hall Sensor Offset

- Major design issue: offset
  - Modeled as resistor mismatch in a Wheatstone bridge
  - Use multiple Hall plates with rotated connections
    - Limited by Hall plate mismatch
  - Spinning current techniques
    - Modulate either the Hall voltage or offset

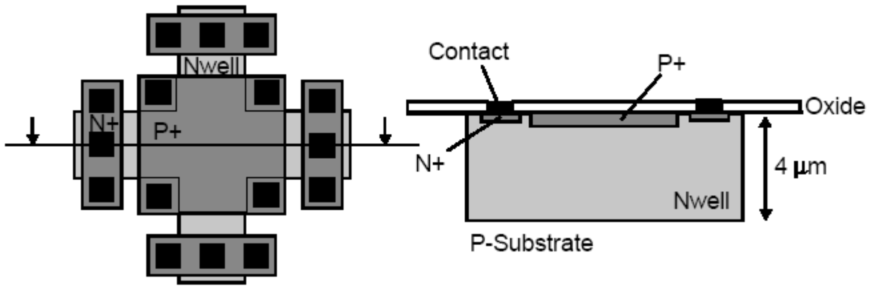


$$V_a = V_2 - V_1 = V_H + \frac{R' - R}{2(R' + R)} E$$

$$V_b = V_2 - V_1 = -V_H + \frac{R' - R}{2(R' + R)} E$$

$$\Rightarrow V_{out} = V_a - V_b = 2V_H$$

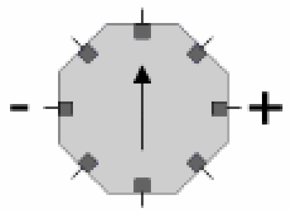
  - Inherent chopping
  - Temperature compensation



Hall Sensor Array

- Single plate vs. array

Spinning-Current Hall Plate

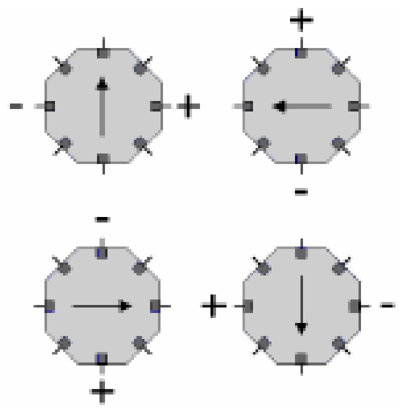


- Current is rotated, while the Hall voltage is summed
- Symmetrical offsets are canceled out
- Spinning-current Hall sensor offset 10-100μT

- Compensation over time

⇒Varying offset sources remain a problem

Hall Sensor Offset Reduction

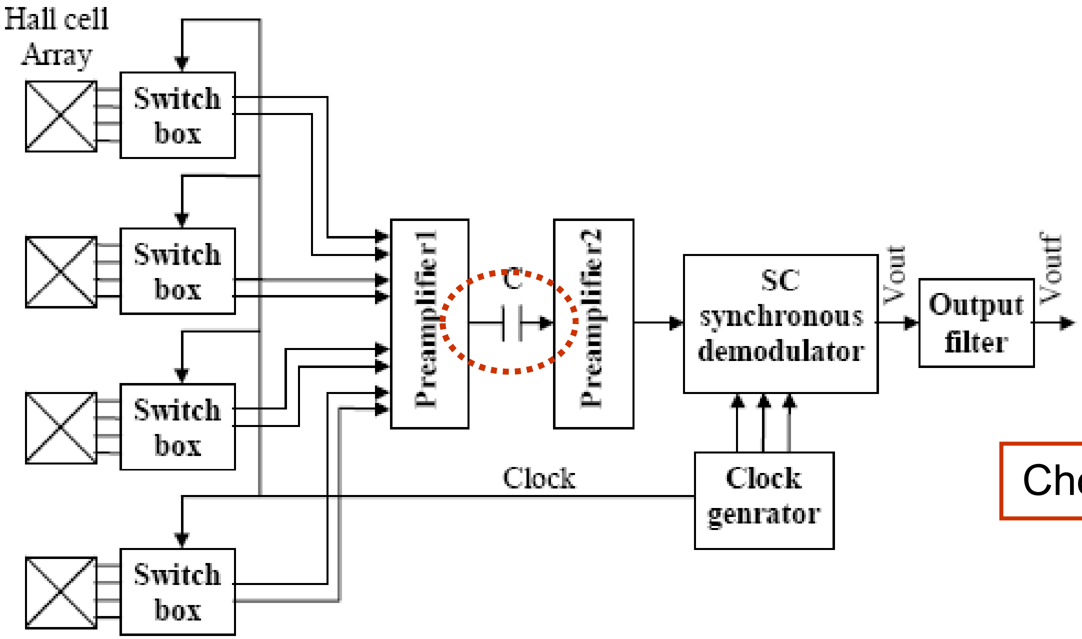


- Orthogonal coupling
  - Quad layout
  - Instantaneous compensation
- Time-varying offset is also compensated
  - Ambient temperature
  - Packaging stress
  - Intermodulation of Hall sensor & electronics

✓ SNR improvement
✓ Offset reduction
× Increased current consumption
× Area increased

Hall Sensor Array & Interface

- Spinning current technique with array of Hall sensors
  - Use smaller sensor
- Hall voltages change polarity in each state, whereas the offset voltages appear as DC at output nodes.

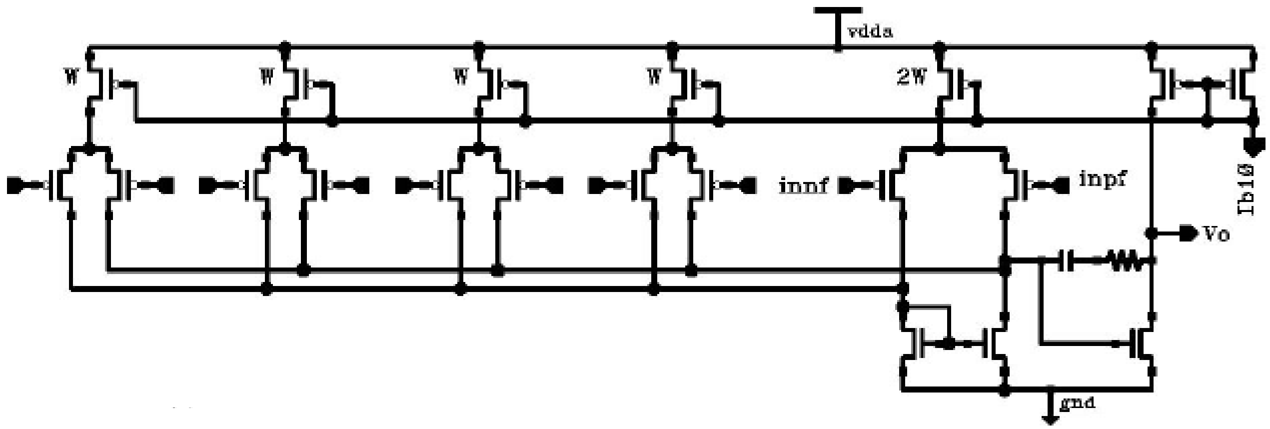


Chopper + CDS

- J. Frounchi et al., "Integrated Hall Sensor Array Microsystem", *ISSCC*, pp.218-219, Feb. 2001.

Hall Sensor Array & Interface

- Preamplifier 1: 5-input Differential-Difference Amplifier (DDA)

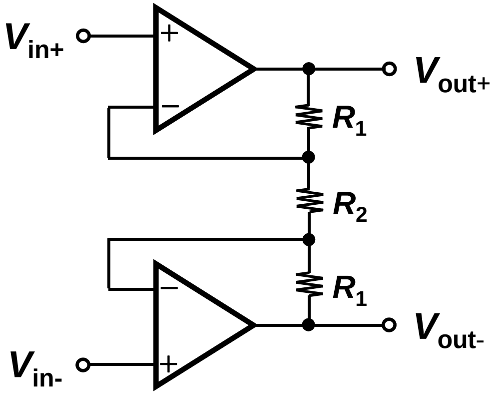


Design issues:

- Input offset voltage of each input pair
- Transconductance (g_m) of each pair
- Stability

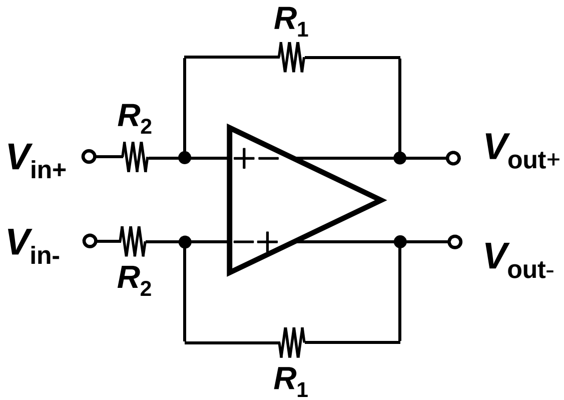
Differential-Difference Amplifier (DDA)

- Comparison



$$A_V = 1 + 2 \cdot \frac{R_1}{R_2}$$

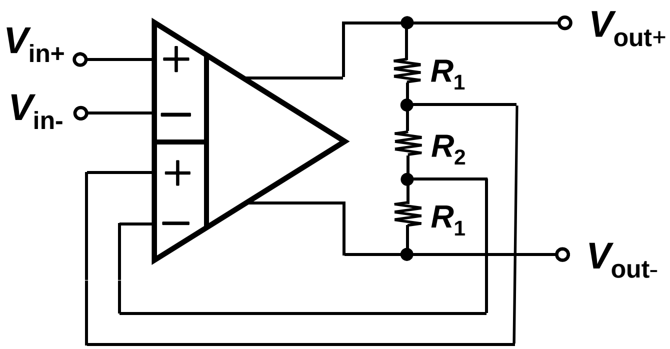
Consume more power!



$$A_V = \frac{R_1}{R_2}$$

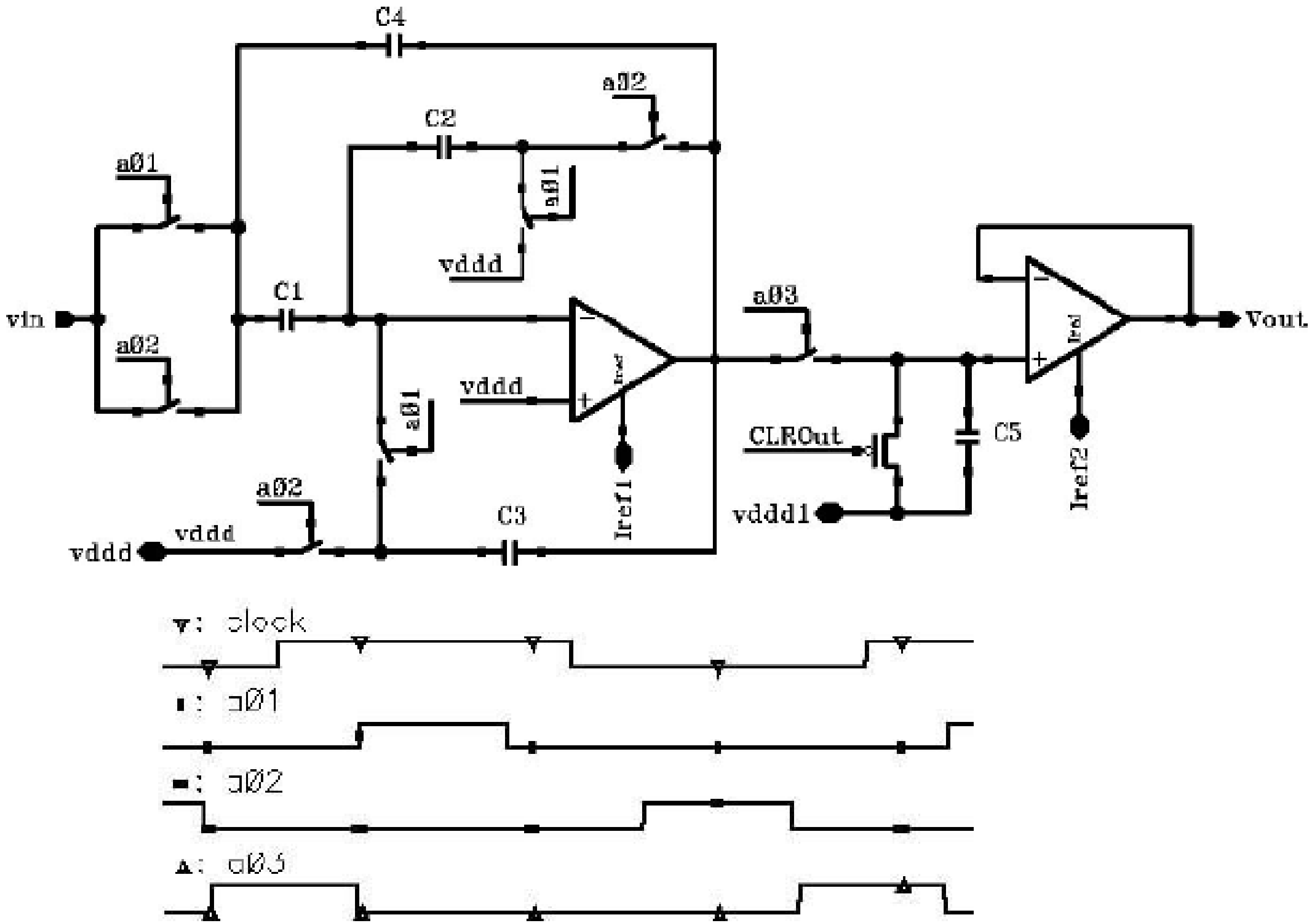
Finite input impedance!

Differential-Difference Amplifier (DDA)



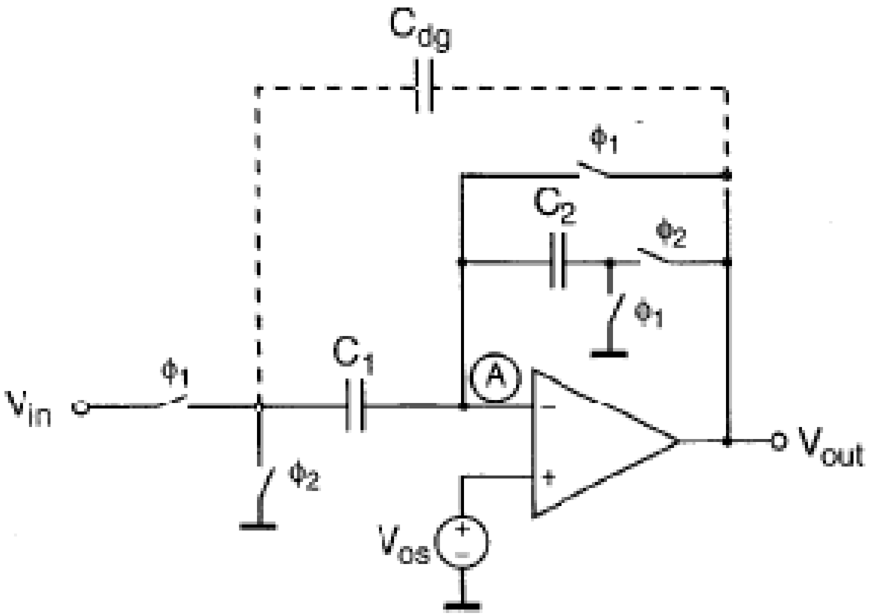
$$A_V = 1 + 2 \cdot \frac{R_1}{R_2}$$

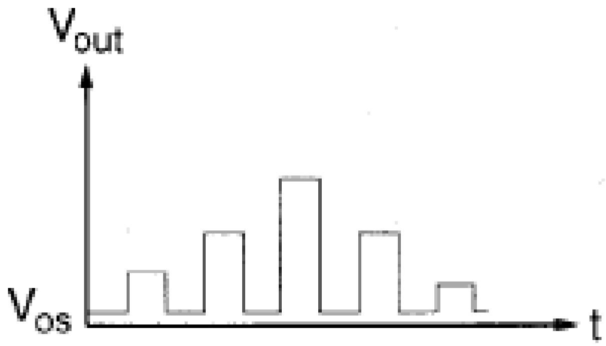
SC Synchronous Demodulator



Offset-Compensated SC Amplifier

- V_{out} is pulled to V_{os} during ϕ1.



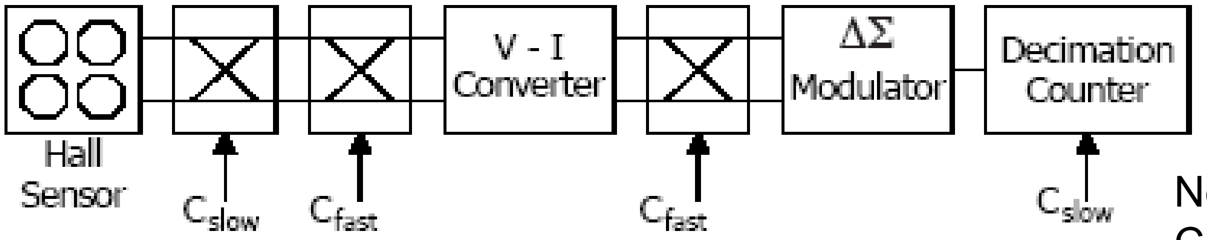


What is the purpose of C_{dg}?

- C. C. Enz and G. C. Temes, “Circuit Techniques for Reducing the Effects of Op-Amp Imperfections: Autozeroing, Correlated Double Sampling, and Chopper Stabilization”, *Proceedings of the IEEE*, pp.1584-1614, Nov. 1996

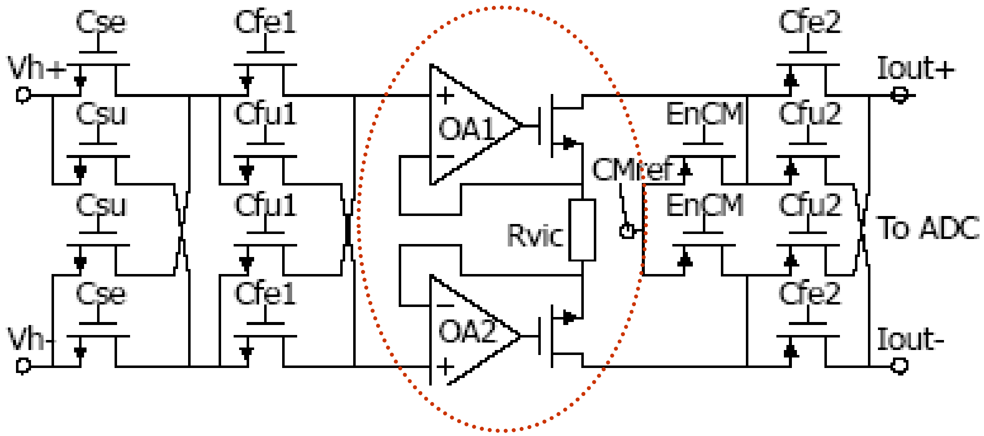
Hall Sensor Array & Interface

- Apply nested-chopper technique



Nested chopper
Charge injection deadband

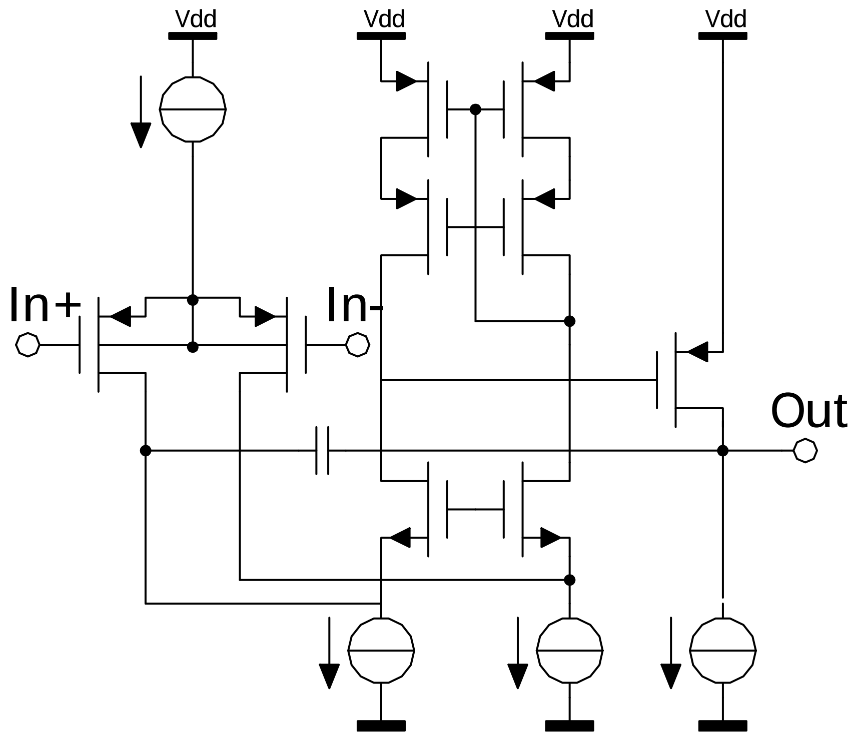
- Chopper implementation with the high-linearity V-I converter



- J. C. van der Meer et al., “A Fully Integrated CMOS Hall Sensor with a 3.65μT 3σ Offset for Compass Applications”, *IEEE ISSCC*, pp. 246-247, Feb. 2005.

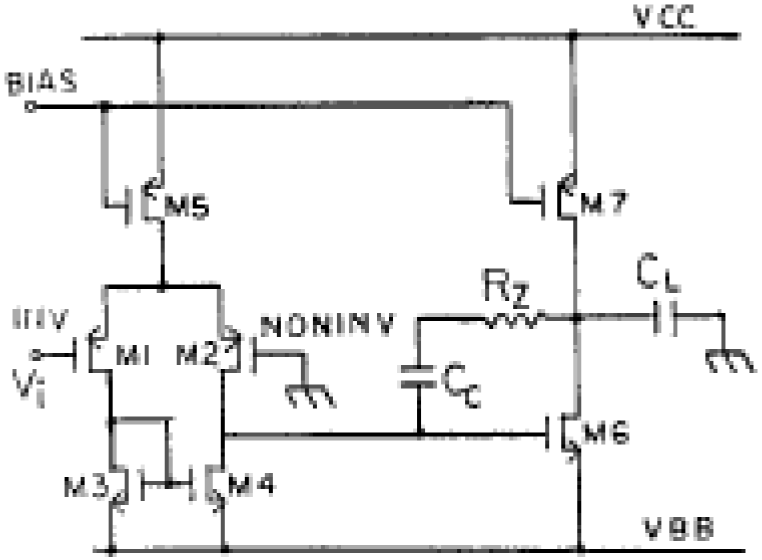
Design of OA1

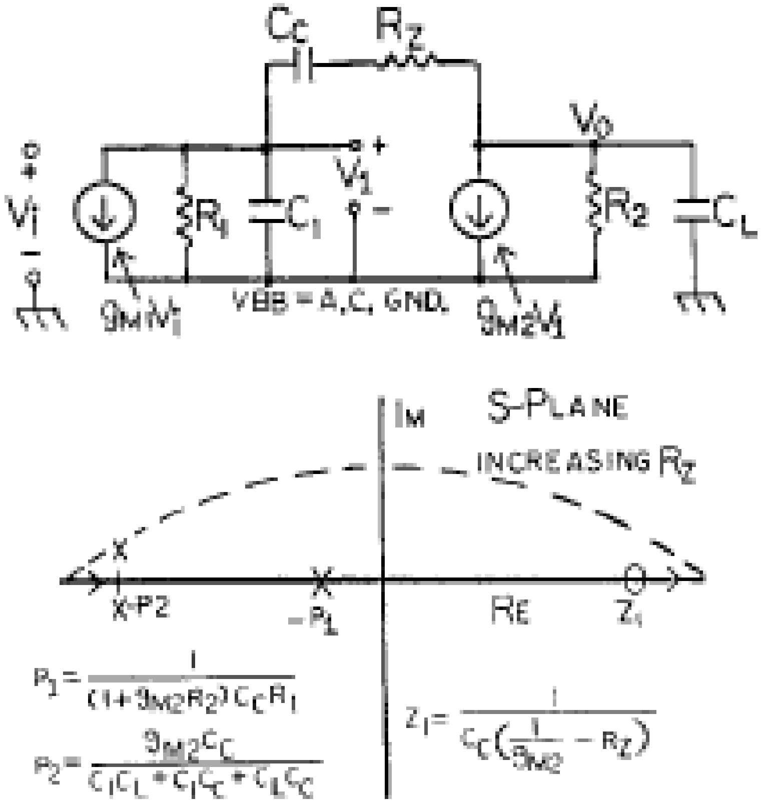
- Folded cascode input stage
- Large gain for high linearity



Frequency Compensation

- Miller compensation



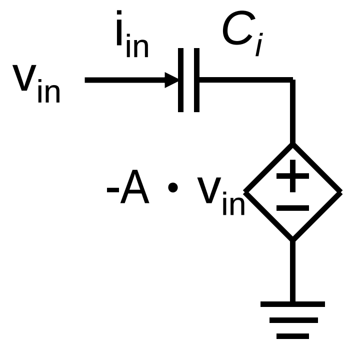


- B. K. Ahuja, "An Improved frequency compensation technique for CMOS operational amplifiers", *IEEE JSSC*, vol. SC-18. no. 6, pp. 629-633, Dec. 1983.

Capacitor Multiplier

- Manipulate the terminal voltage or current

Control the terminal voltage

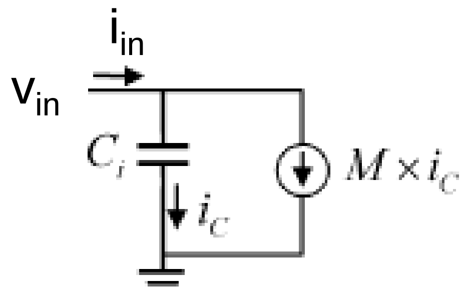


$$i_{in} = (v_{in} + A \cdot v_{in}) sC_i$$

$$\frac{v_{in}}{i_{in}} = \frac{1}{s(1+A)C_i}$$

$$C_{eq} = (1+A)C_i$$

Control the terminal current

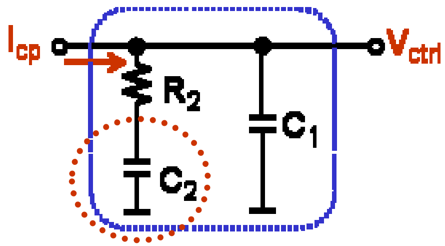


$$i_{in} = v_{in} \cdot sC_i + M \cdot v_{in} \cdot sC_i$$

$$\frac{v_{in}}{i_{in}} = \frac{1}{s(1+M)C_i}$$

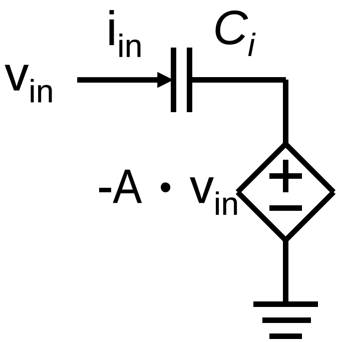
$$C_{eq} = (1+M)C_i$$

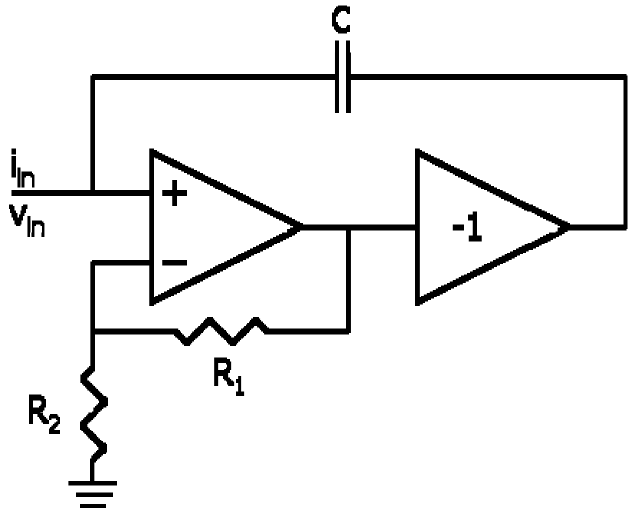
- Application: PLL loop filter



Capacitor Multiplier

- Control the terminal voltage
  - Increase the amount of current flowing through a capacitor for a given V_{in}





$$i_{in} = (v_{in} + A \cdot v_{in}) sC_i$$

$$\frac{v_{in}}{i_{in}} = \frac{1}{s(1+A)C_i}$$

$$C_{eq} = (1+A)C_i$$

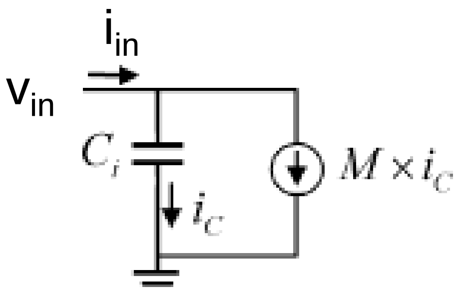
$$i_{in} = [v_{in} + v_{in}(1+\frac{R_1}{R_2})]sC$$

$$\frac{v_{in}}{i_{in}} = \frac{1}{s(1+A)C} \qquad A = 1 + \frac{R_1}{R_2}$$

$$C_{eq} = (1+A)C$$

Capacitor Multiplier

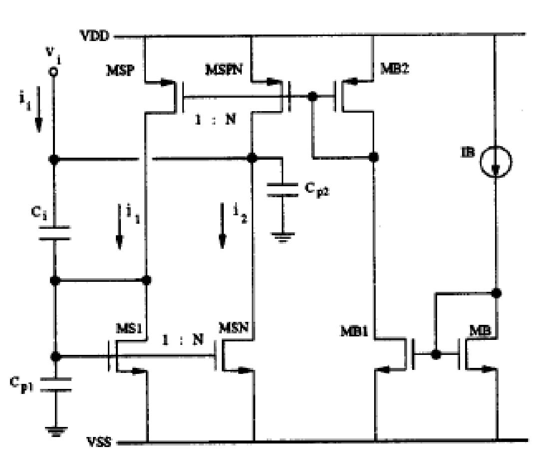
- Control the terminal current
  - Produce a larger input current for a given input voltage



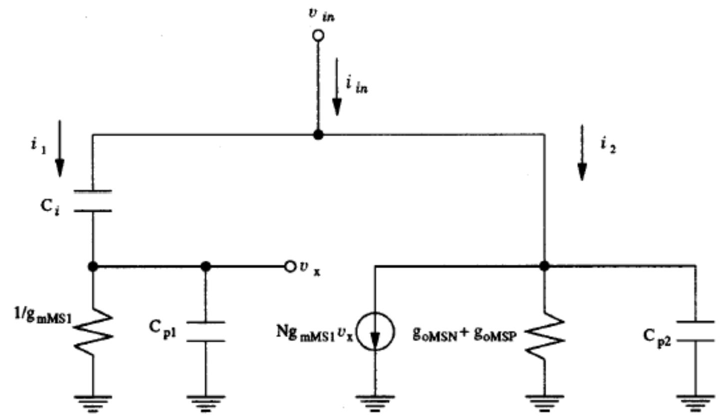
$$i_{in} = v_{in} \cdot sC_i + M \cdot v_{in} \cdot sC_i$$

$$\frac{v_{in}}{i_{in}} = \frac{1}{s(1+M)C_i}$$

$$C_{eq} = (1+M)C_i$$



Basic circuit

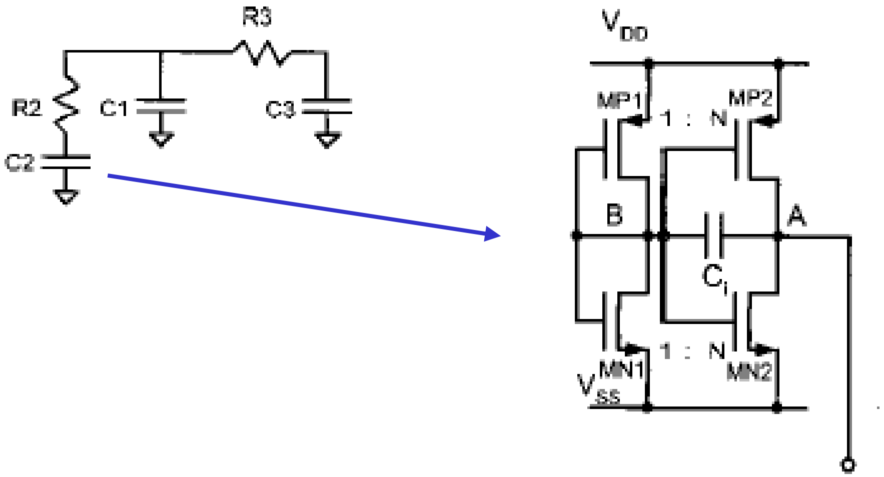


Small-signal circuit model

- S. Solis-Bustos et al., “A 60-dB Dynamic-Range CMOS Sixth-Order 2.4-Hz Low-Pass Filter for Medical Applications,” *IEEE Tran. On Circuits and Systems-II*, vol. 47, pp. 1391-1398, Dec. 2000.

Capacitor Multiplier

- Self-biased capacitance multiplier



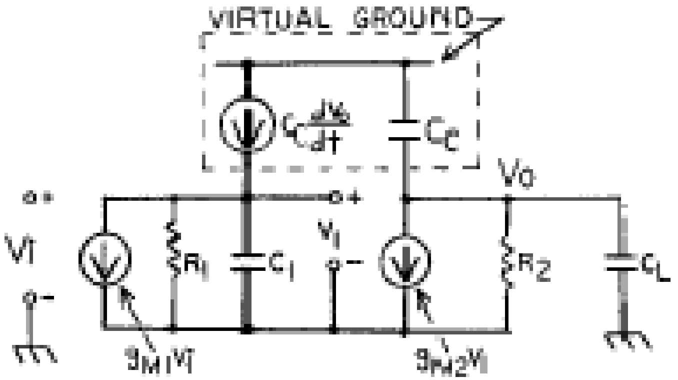
$$G_{in} = (1+N)\cdot\frac{sC_i}{1+sC_i/(g_{mn}+g_{mp})}$$

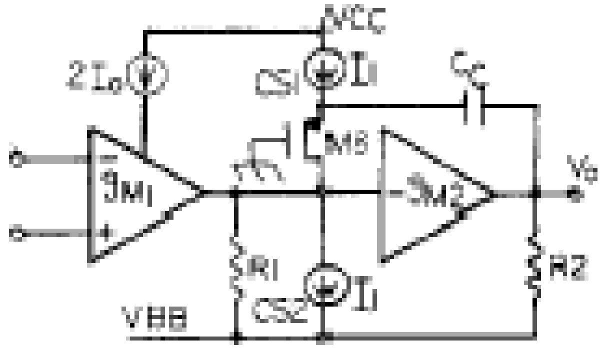
- Upper frequency operation range: $\omega=(g_{mn}+g_{mp})/C_i$
- Lower limit of frequency is affected by DC impedance seen at node A
  - Cascode design

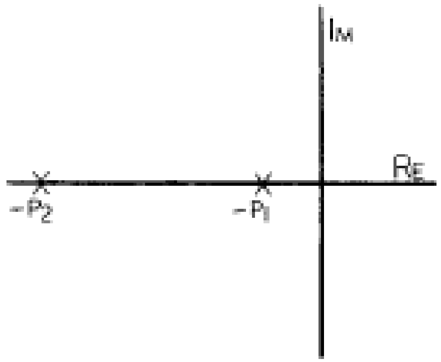
- I.-C. Hwang et al., “A Σ-Δ Fractional-N Synthesizer with a Fully-Integrated Loop Filter for a GSM/GPRS Direct-Conversion Transceiver,” *IEEE VLSI Symposium*, pp. 42-45, 2004.

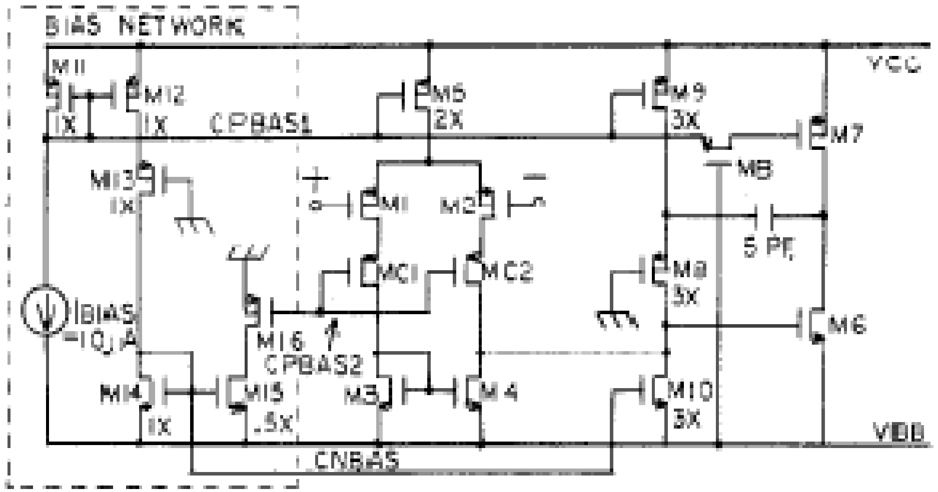
Frequency Compensation

- Modified Miller compensation



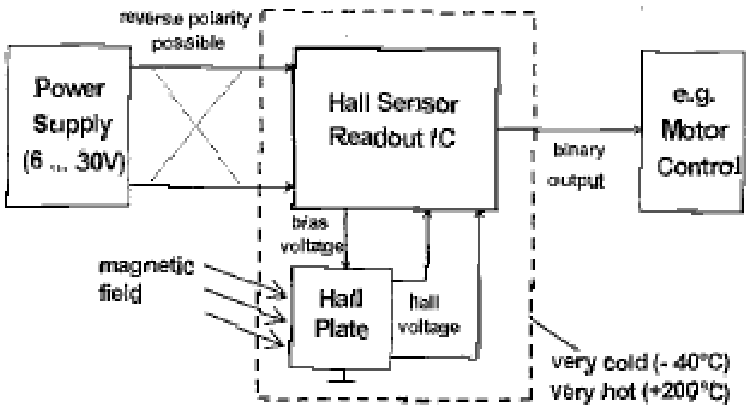


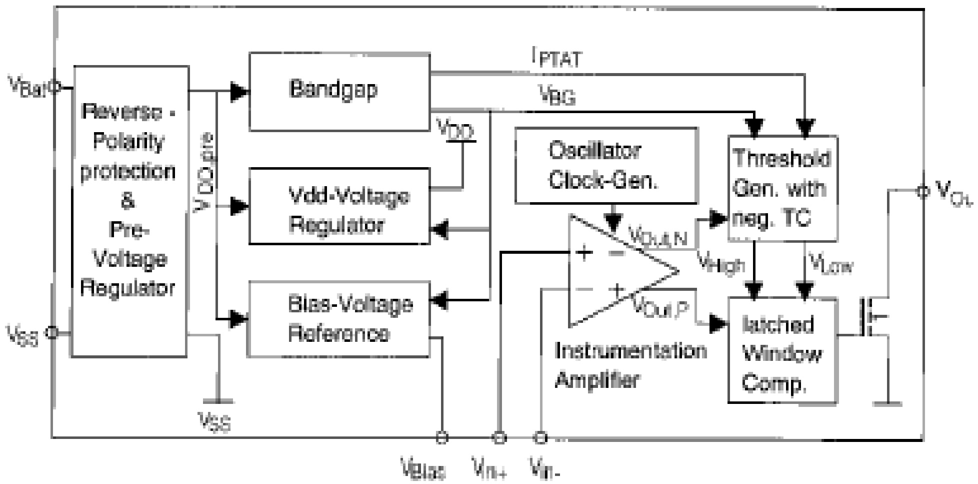




Hall Sensor: Interface (1)

- Design considerations:
  - Offset and noise (Hall sensor and electronics)
  - Temperature compensation
  - Stable (BG) reference voltages (Vdd and bias voltage for Hall plate)





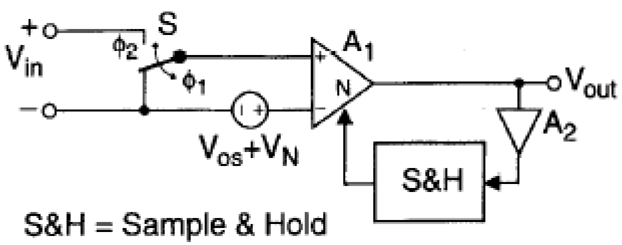
Switch-type application

- N. Kordas et al., "An SOI 0.6mV Offset Temperature-Compensated Hall Sensor Readout IC for Automotive Applications up to 200°C", *ISSCC*, pp.134-135, Feb. 1999.

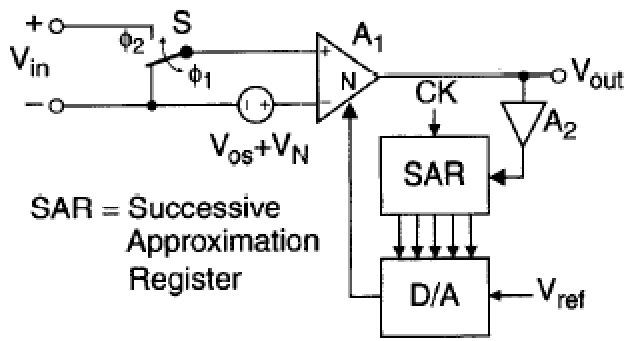
Review: Auto-zeroing

- Sampling the unwanted offset and then subtracting from the output
- Two-phase operation:
  - Sampling phase
  - Signal-processing (amplification) phase

- Analog method



- Digital method

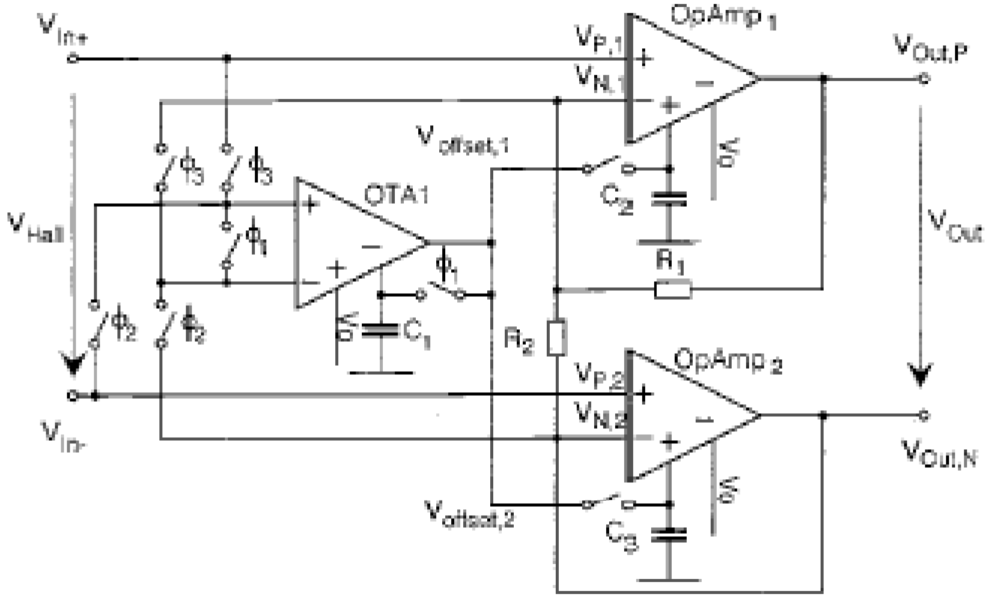


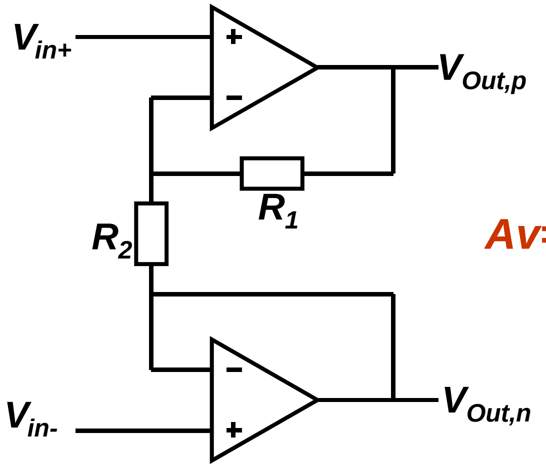
- A ***sampling*** process – sub-sampling the noise spectrum, noise folding occurs

- C. C. Enz and G. C. Temes, "Circuit Techniques for Reducing the Effects of Op-Amp Imperfections: Autozeroing, Correlated Double Sampling, and Chopper Stabilization", *Proceedings of the IEEE*, pp.1584-1614, Nov. 1996

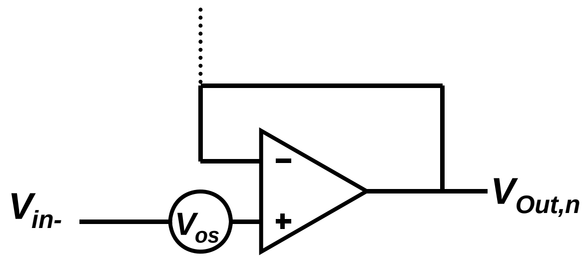
Hall Sensor: Interface (2)

- Instrumentation Amplifier
  - Offset in the first amplification stage (IA) is the most important one.



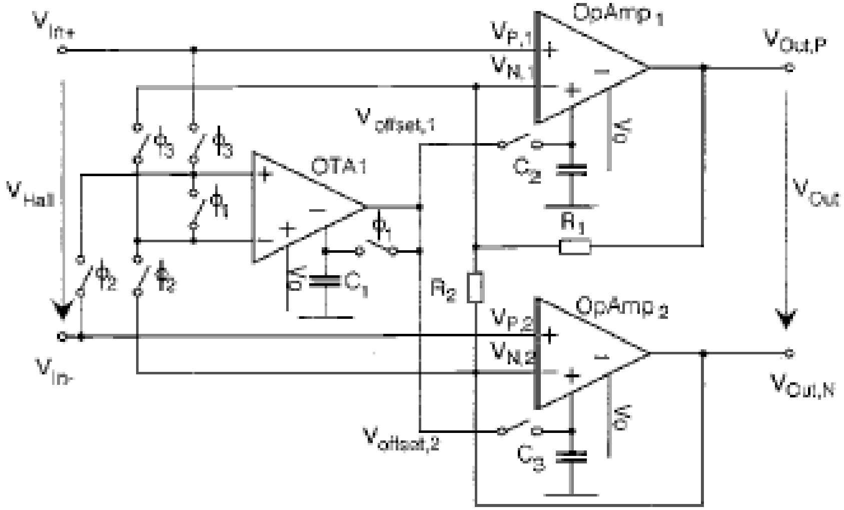


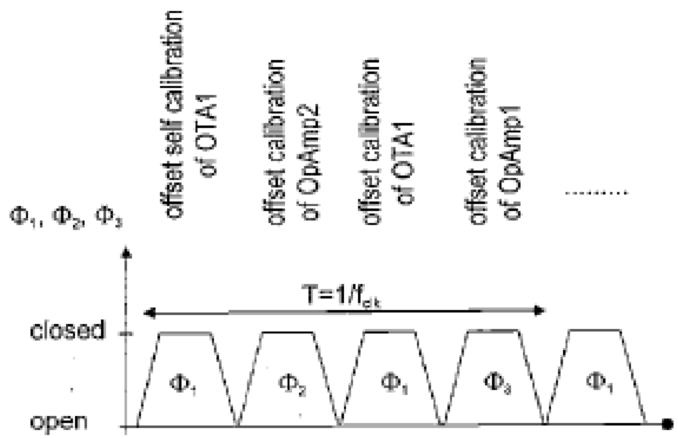
Av=?



Hall Sensor: Interface (3)

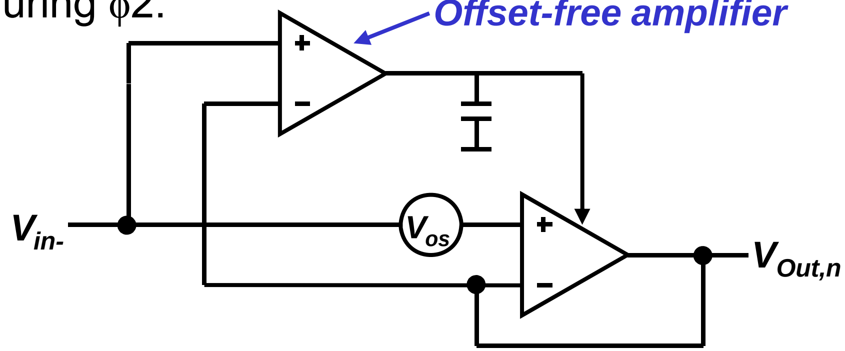
- ***Time continuous*** offset cancellation





During ϕ1, the offset of OTA1 is cancelled

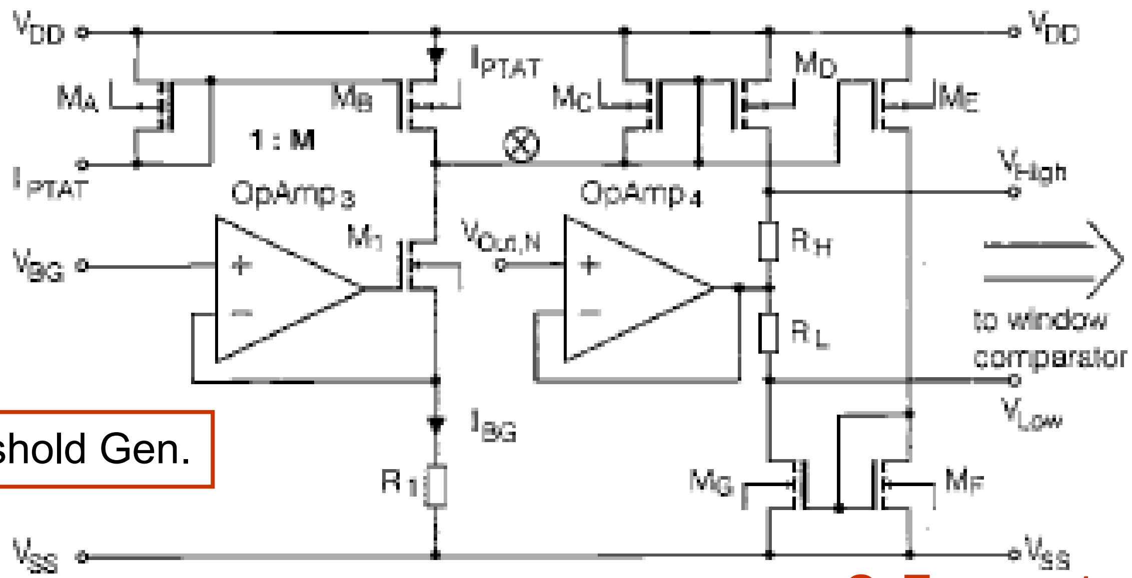
During ϕ2:



Q: Does the bandwidth of the signal path depend on the offset cancellation frequency?

Hall Sensor: Interface (4)

- In this application, Hall sensor is a switch type sensor.
- Temperature dependent reference voltage generation
  - Why two reference voltages?
  - What is the temperature dependence of the reference voltage (V_{High} & V_{Low})?
  - What is the possible reason that the temperature dependence is designed this way?

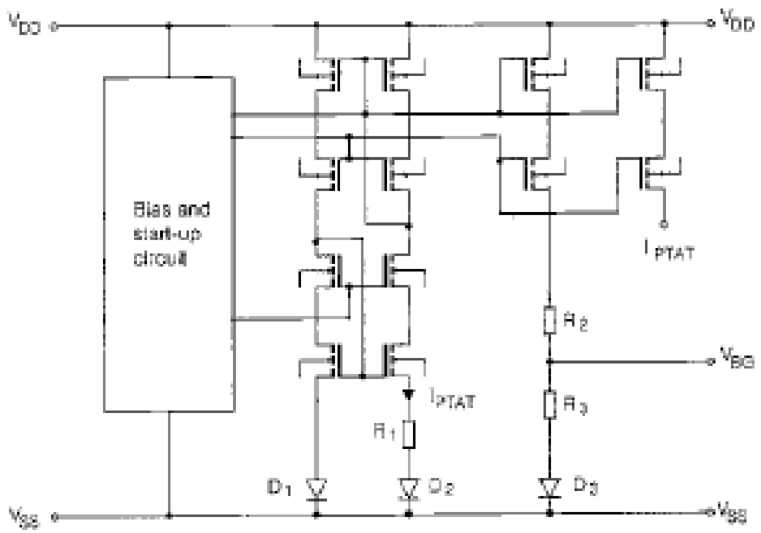


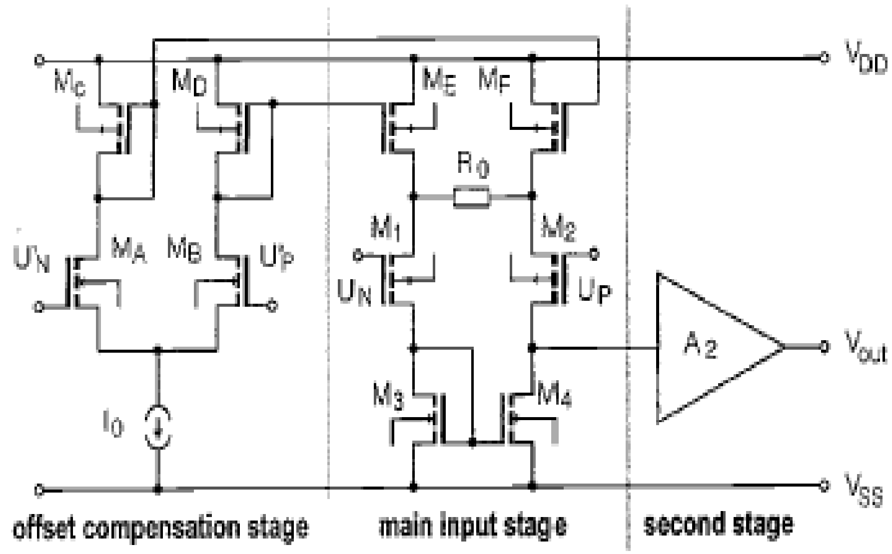
Threshold Gen.

Q: Temperature effect of R1?

Hall Sensor: Interface (5)

- Bandgap circuit & Amplifier with auxiliary input

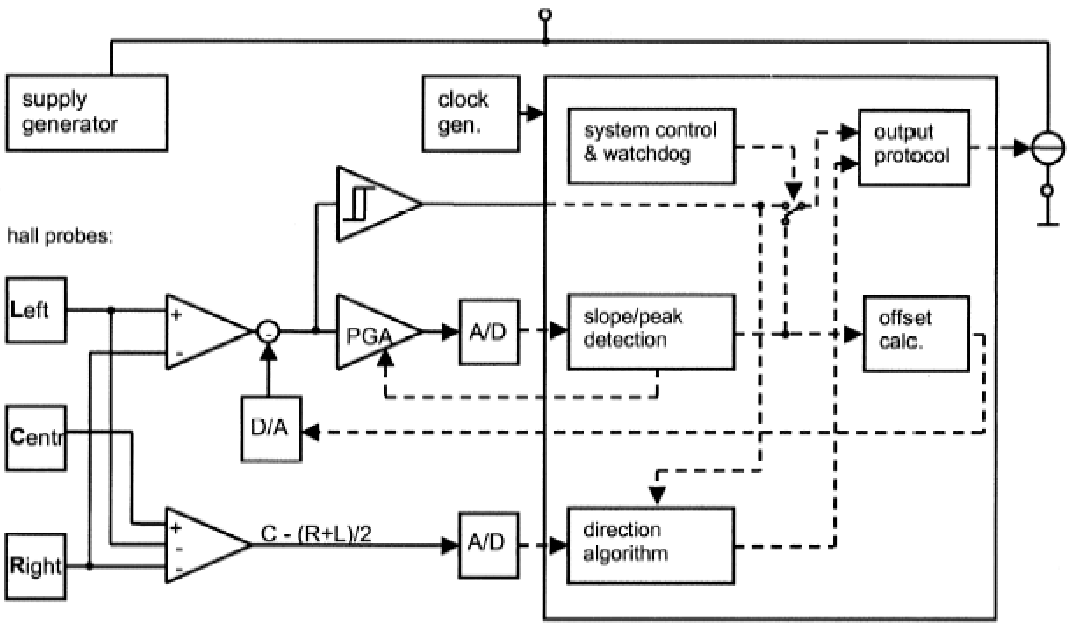




$$V_{BG} = V_{D3} + \frac{R_3}{R_1} m \frac{kT}{q} \ln(\frac{A_2}{A_1}), \quad I_{PTAT} = \frac{m}{R_1} \frac{kT}{q} \ln(\frac{A_2}{A_1})$$

Hall Sensor: Interface (6)

- Another offset cancellation topology
  - Estimate the offset in digital domain, then apply the correction in analog domain (similar to a wireless transceiver)
  - Noise and offset are particularly important in the front-end stage



- D. Draxelmayr, et al., “A Self-Calibrating Hall Sensor IC with Direction Detection”, *IEEE JSSC*, pp.1207-1212, July 2003.

Hall Sensor: Interface (7)

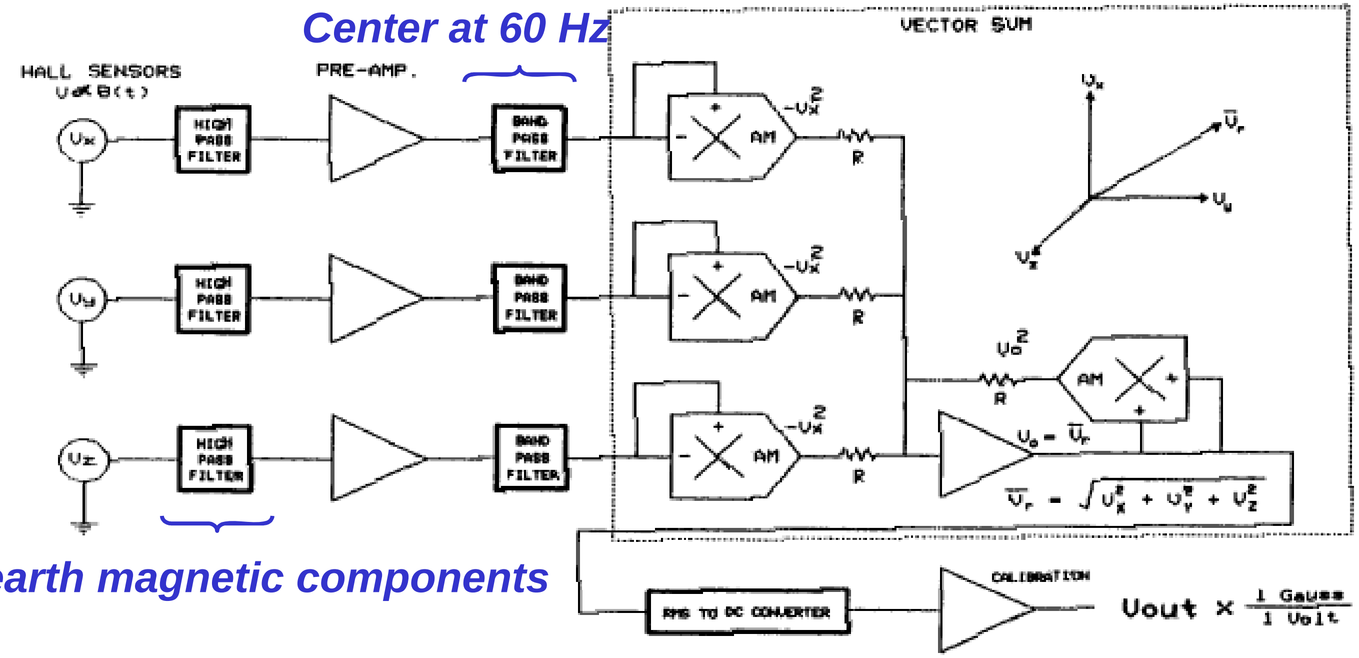
- Offset cancellation approach: high-pass filtering
  - Low corner frequency
    - Large time constant
    - Off-chip components
  - Long start-up time
  - Sensitive to leakage current

- D. Draxelmayr, et al., “A Dynamic Differential Hall IC with Current Interface for Automotive Sensor Applications”, *IEEE ISSCC*, pp. 204-205, 1997.

Hall Sensor: Total-Field Magnetometer

- Measuring magnetic field from electrical appliance, power line, etc.
  - Not orientation dependent
- Tai power < 10m Gauss

Center at 60 Hz

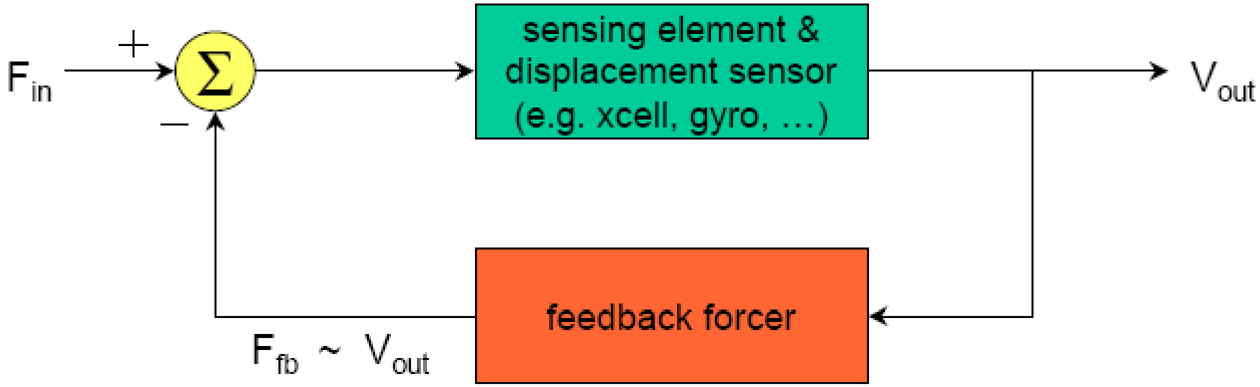


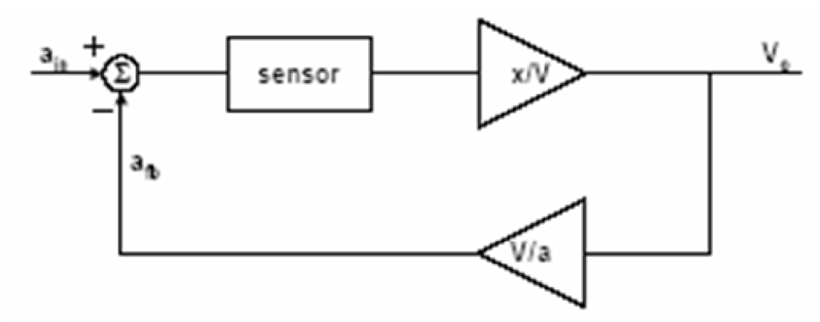
Remove earth magnetic components

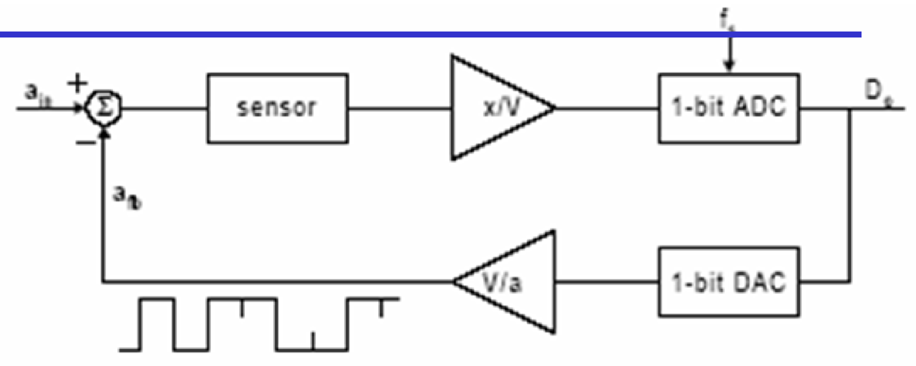
- F. A. Phan, "A Hall-Effect Magnetic Field Detector", *IEEE Northeast Bioengineering Conf.*, pp.255-256, April 1991.

Interface Technique: Closed-Loop

- Feedback to maintain zero influence
  - When stable, $F_{in} = F_{fb} \Rightarrow V_{out}$ represents the sensed output signal



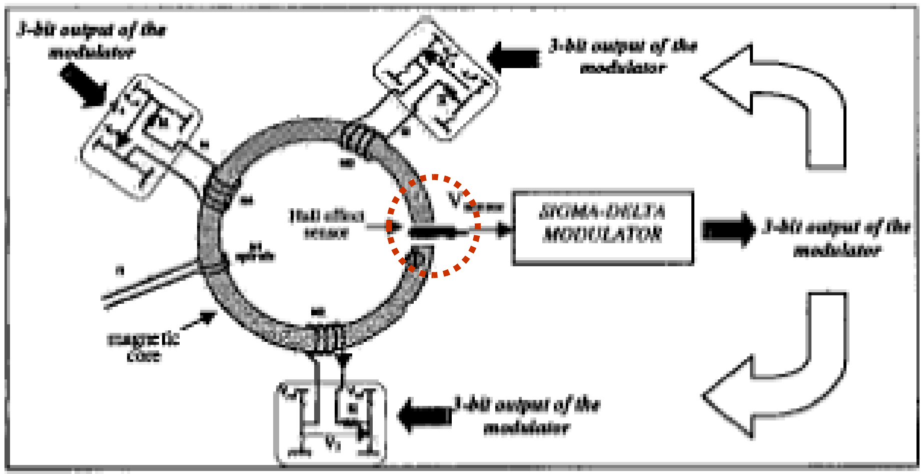




How to apply the closed-loop method?

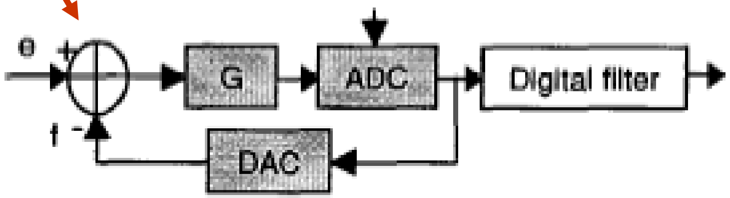
Current Sensor

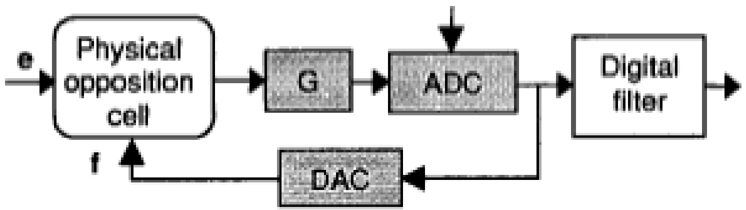
- Applying Hall effect for current sensing
  - Hall sensor placed in the air gap to measure the net magnetic flux



- Average of ***f*** tracks ***e***.
- Hall sensor measures an average of zero flux.

"sensor"

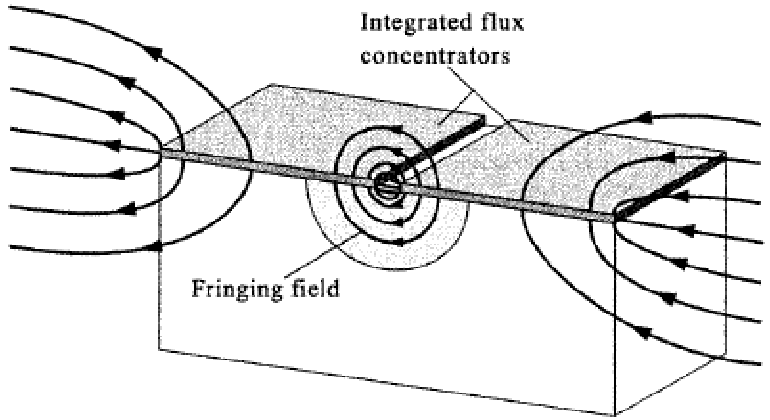


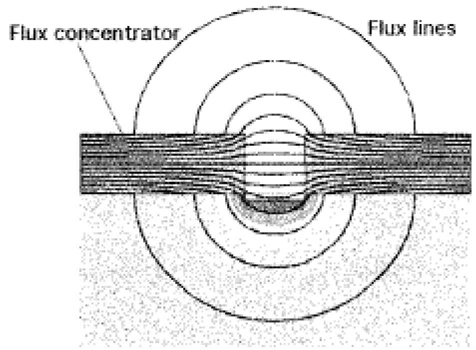


- M. Jouini, et al., "High-Level Design of a Digital Current Sensor Using Multi-bit Sigma-Delta modulation", *IEEE Sensors for Industry Conf.*, pp.23-28, Nov. 2001.

Integrated Magnetic Concentrator (IMC)

- A high-permeability ferromagnetic layer is deposited
- Etched a gap in the middle and split into two pieces
- External magnetic field parallel to the chip surface is captured by IMC
- In the vicinity of the gap, the magnetic flux splits into two parts: horizontal and fringing parts





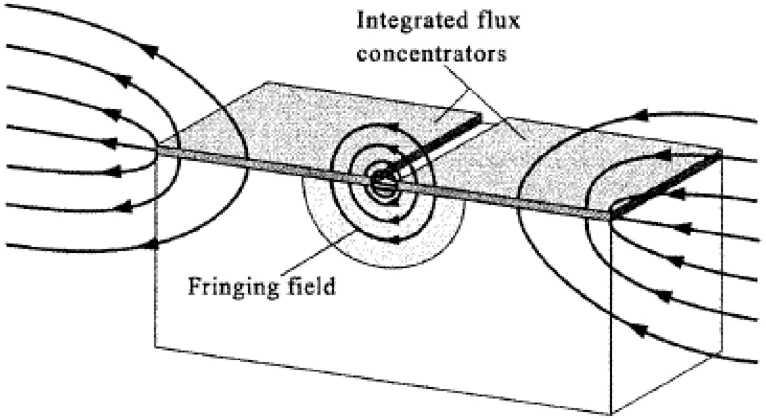
- Integrated magnetic concentrator
  - Change the direction
  - Focus the magnetic flux

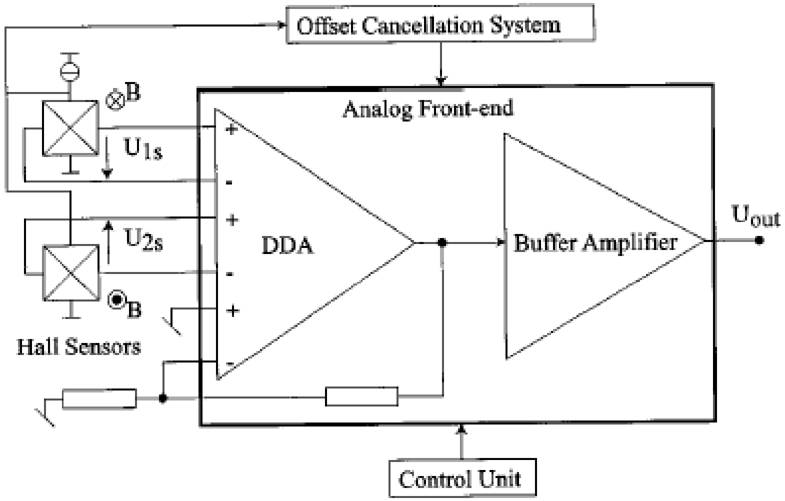
Produce vertical flux from a horizontal field

- Z. B. Randjelvoic, et al., "Highly Sensitivity Hall Magnetic Sensor Microsystem in CMOS Technology", *IEEE JSSC*, vol. 37, pp. 151-159, Feb. 2002.

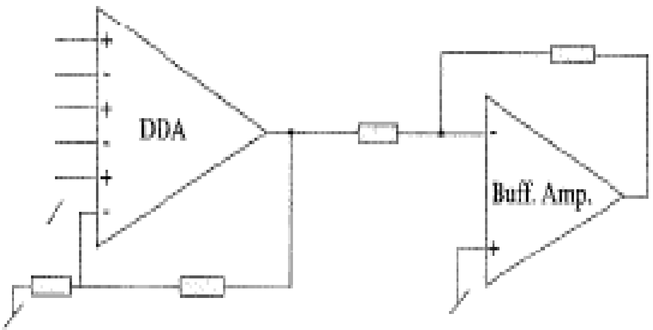
Interface Circuitry

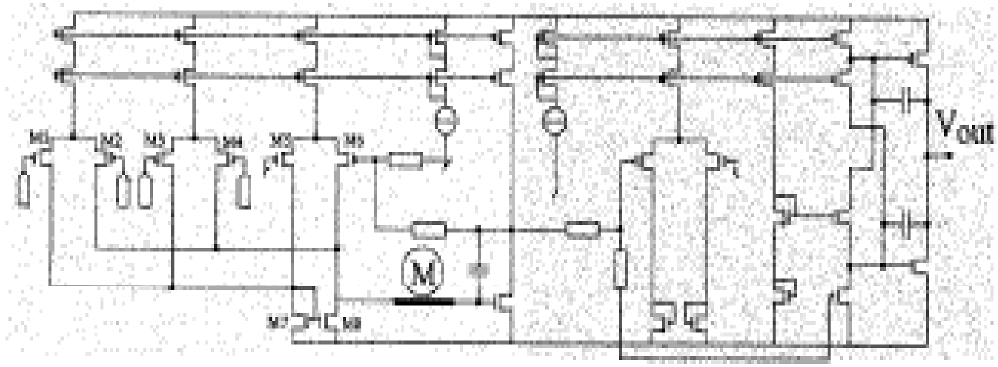
- The hall plates are placed just below the edges of the IMC near the gap





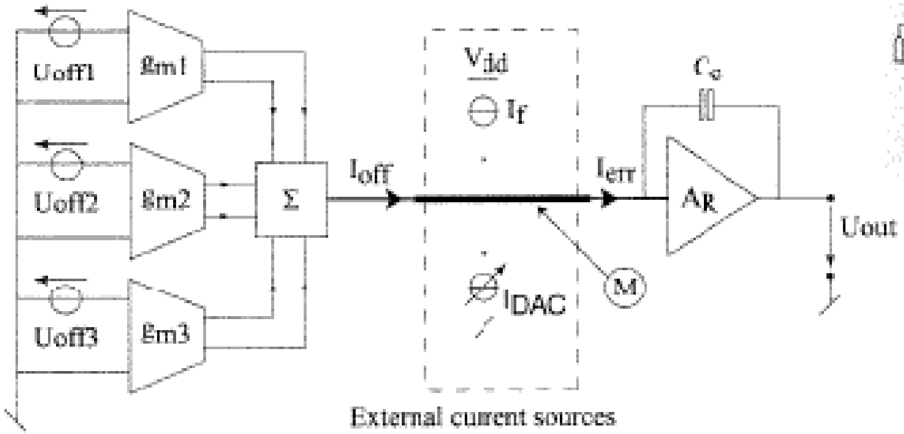
- Amplifier schematic

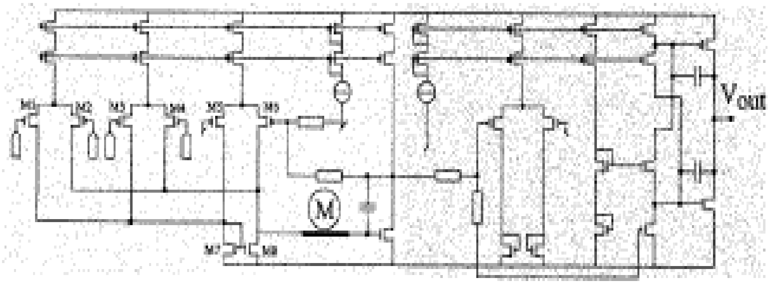


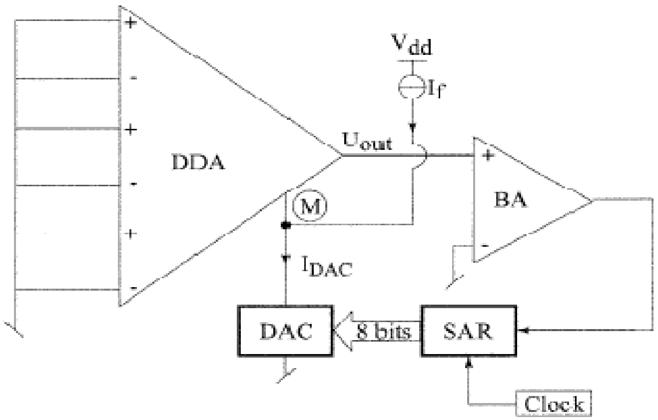


DDA Offset Cancellation

- DDA offset cancellation scheme

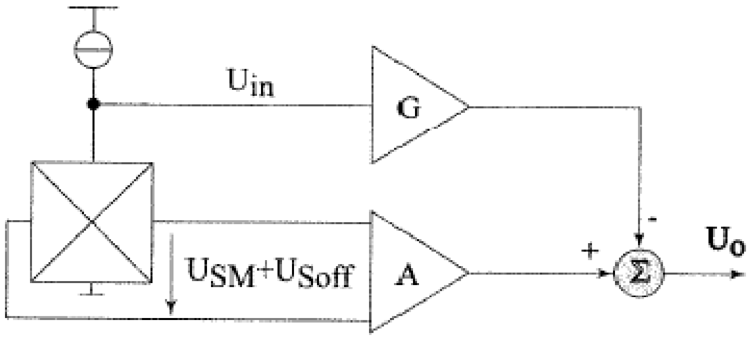




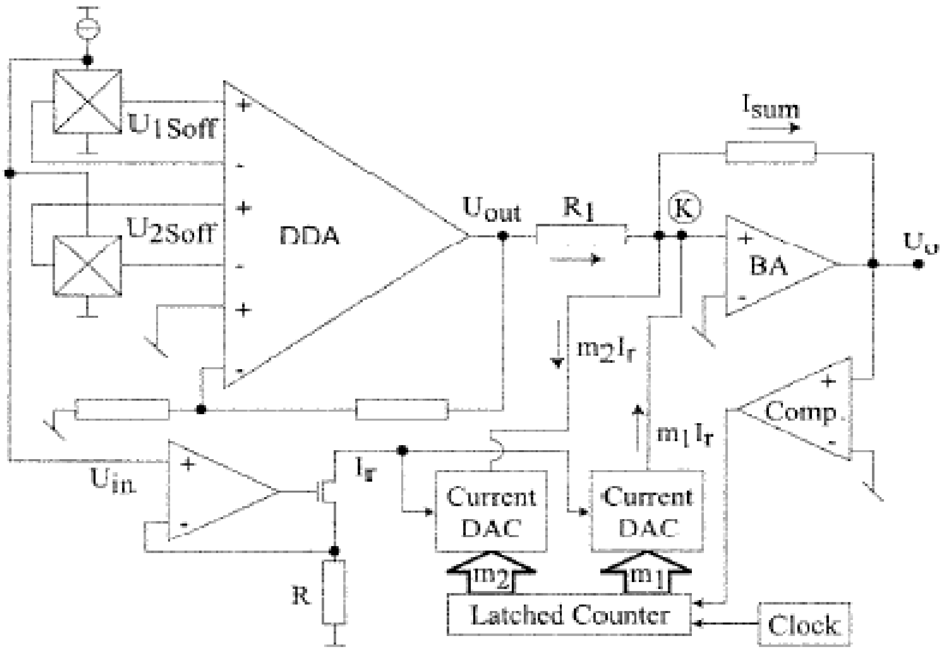


Sensor Offset Cancellation

- Did not rely on dynamic spinning-current technique

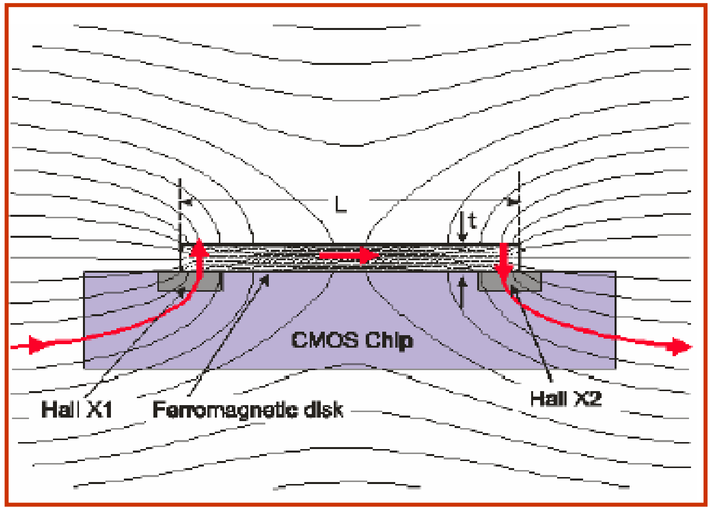


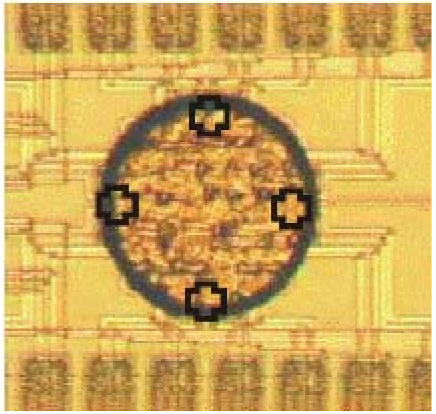
$$U_{Soff} = KU_{in}.$$



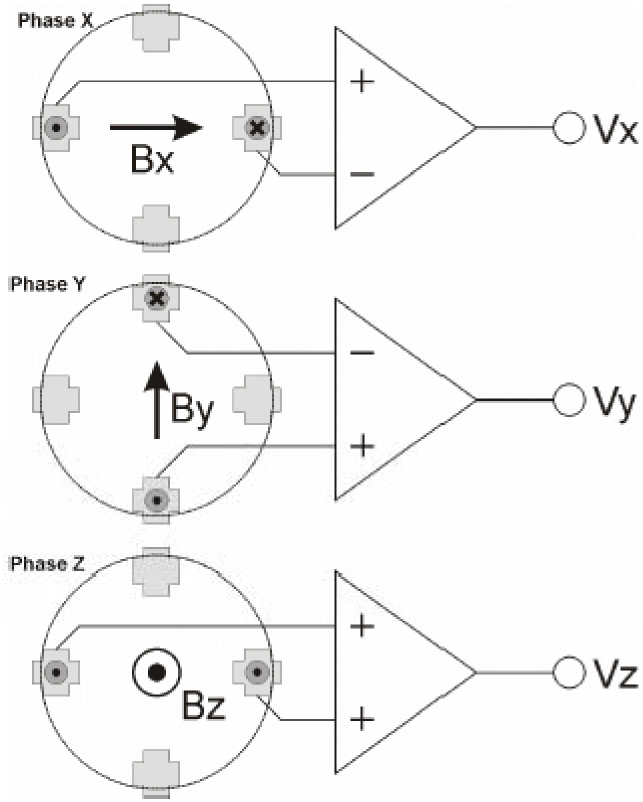
Three-Axis Hall Sensor (1)

- Based on the **IMC** technology instead of assembling 3 Hall sensors





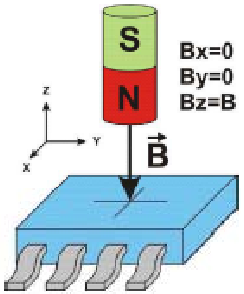
Disk shape



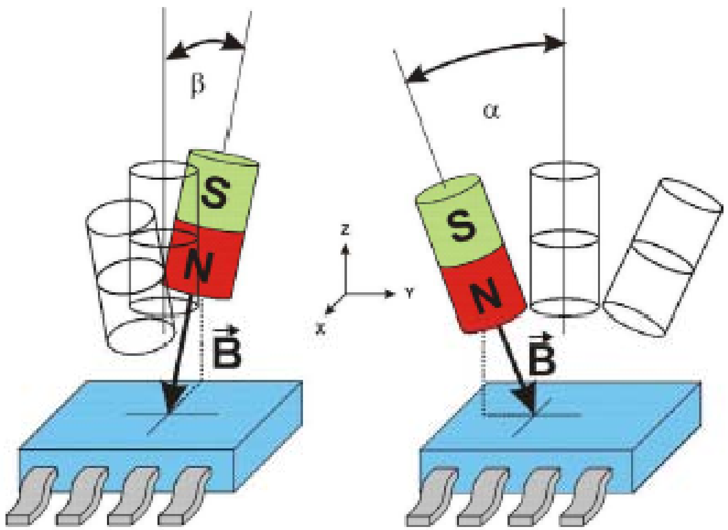
Three-Axis Hall Sensor (2)

- Joystick application

Figure 8: Gimbaled Mount Type Joystick



In center position all the field is perpendicular to the chip



Bx=B*sinβ
By=0
Bz=-B*cosβ
->β = Atan(Bx/Bz)

Bx=0
By=B*sinα
Bz=-B*cosα
->α=Atan(By/Bz)

Figure 10: The horizontal field components depend on the total field strenght B, whereas the ratios Bx/Bz and By/Bz are indpendent of B.

- C. Schott, et al., "CMOS Three Axis Hall Sensor and Joystick Application", *IEEE Sensors*, pp. 977-980, Oct. 2004.

Three-Axis Hall Sensor (3)

- Ratio measurement

Why 3-axis?

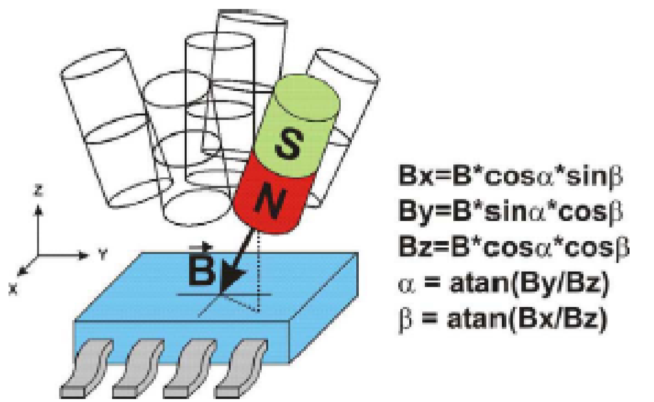


Figure 11: All three magnetic field components depend on both inclination angles α and β.

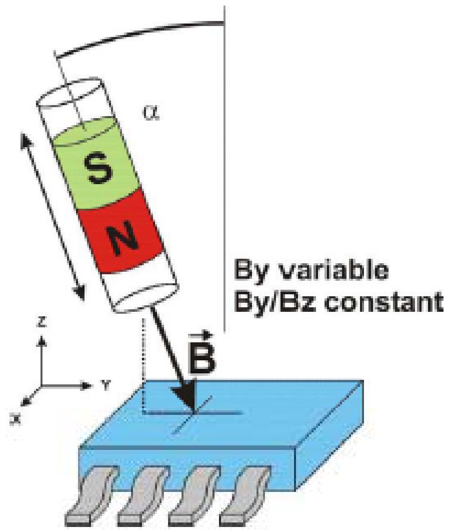


Figure 12: By changing the distance magnet to sensor the total field strength and the one of the components changes, whereas the ratios Bx/Bz and By/Bz remain constant.

Why about the temperature dependency?

Magnetic Sensor Interface Summary

- Offset cancellation (Hall cell and circuit)
  - Array of Hall sensors
  - Spinning current
    - Either the offset voltage or the Hall voltage can be chopped
  - Continuous-time auto-zeroing
  - Digital approach
  - High-pass filtering (AC couple)
- Temperature compensation
- Insensitive to supply
- Employing sigma-delta modulation for direct digital output
- Magnetic concentrator
- Three-axis Hall sensor