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Digitally-Controlled Gm-C Band-pass Filter

G .Jin, H. Chen, C. Gao, Y. Zhang
H. Kobayashi, N. Takai, K. Niitsu
（Gunma University）
K. Hadidi (Urmia University)

Supported by STARC

Presented by Guanglei Jin (靳　光磊)

Outline

- *Research Objective*
- *Switched Gm-C Band-pass Filter*
- *Center Frequency Tuning*
- *Q-Value Tuning*
- *Conclusion*

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- ***Research Objective***
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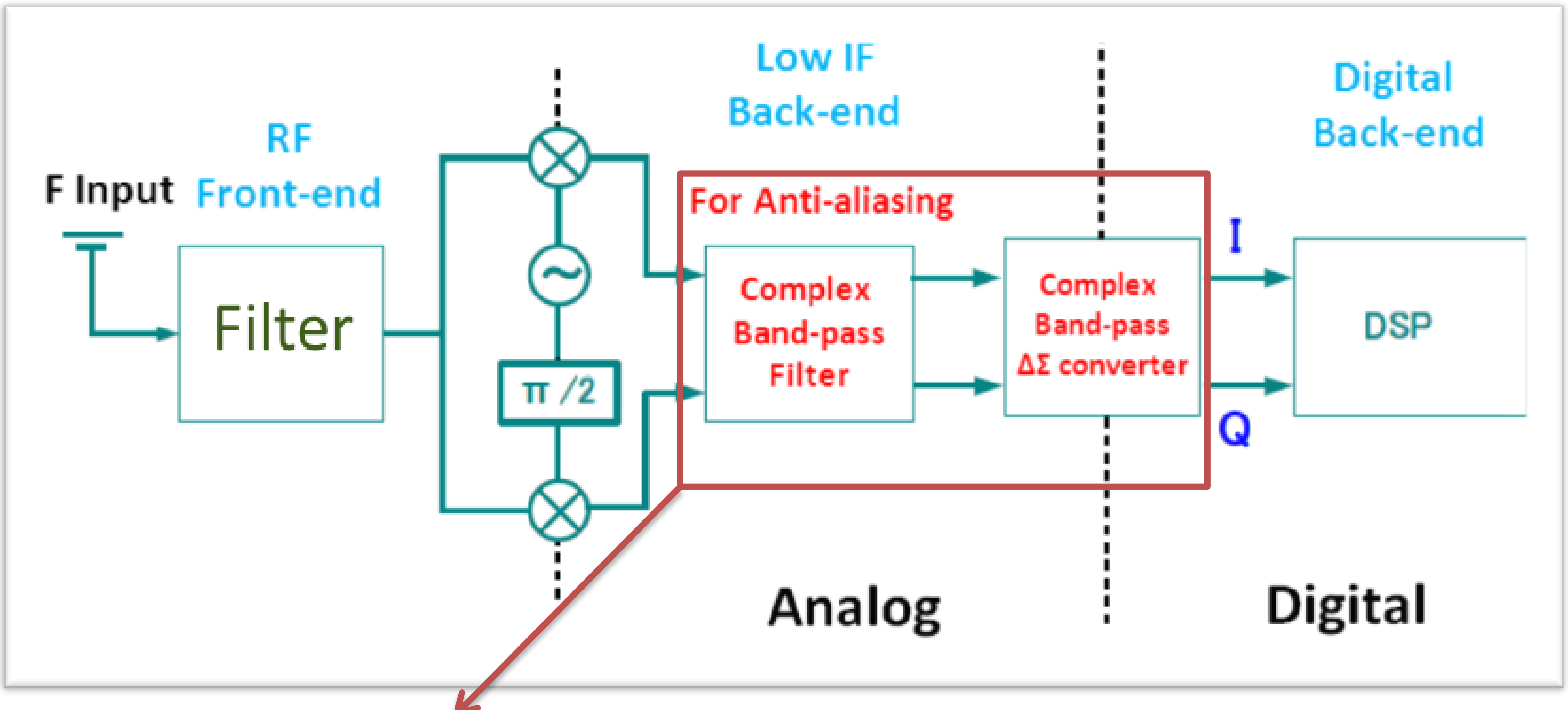
Wireless LAN, Bluetooth, etc.
IF Receiver



Gm-C filters are needed → Center frequency & Q-value adjustment is a challenge

Research Objective

Fine CMOS process → Low voltage

↓

Analog band-pass filter

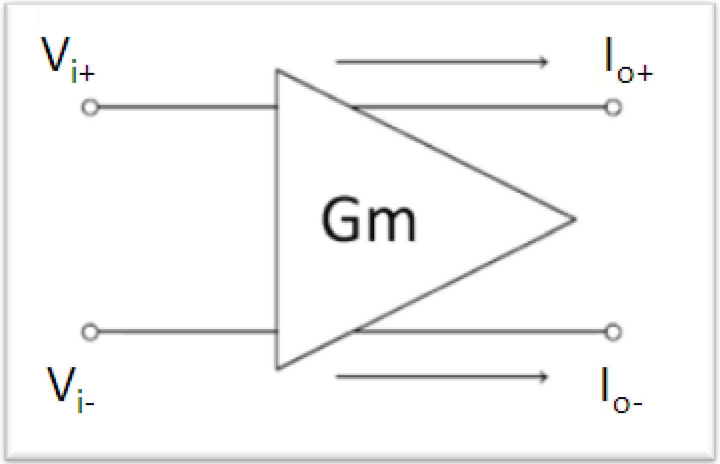
- Switched Gm-C integrator
- Digital schemes
  - Center Frequency
  - Q-value

Outline

- *Research Objective*
- ***Switched Gm-C Band-pass Filter***
- *Center Frequency Tuning*
- *Q-Value Tuning*
- *Conclusion*

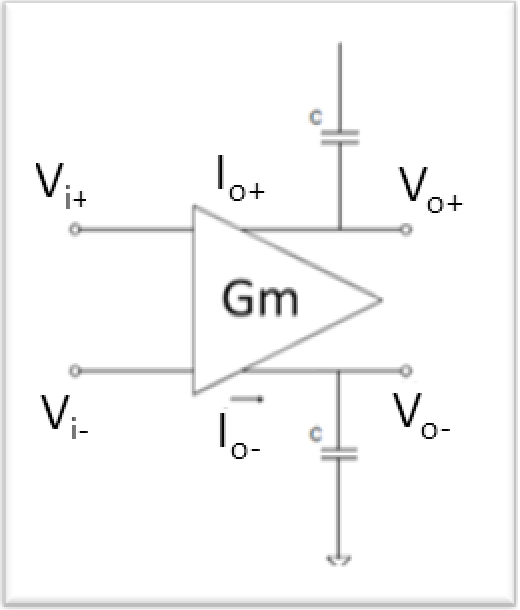
Proposed Switched Gm-C Integrator

Input Voltage Output Current



Gm Cell (OTA)

$$I_o = I_{o+} - I_{o-} = gm(V_{i+} - V_{i-})$$



Gm-C Integrator

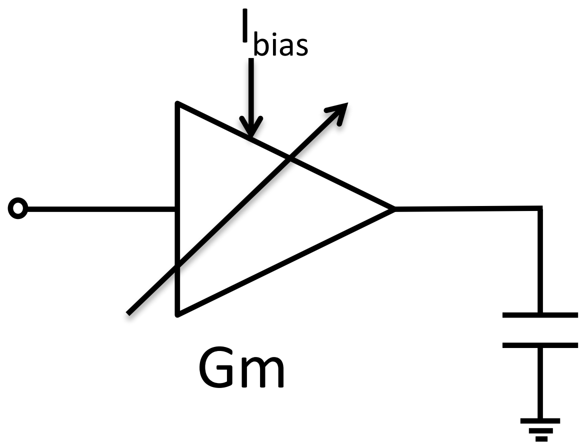
$$V_{o+} = \frac{I_{o+}}{sC} = \frac{gm}{2sC}(V_{i+} - V_{i-})$$

$$V_{o-} = \frac{I_{o-}}{sC} = -\frac{gm}{2sC}(V_{i+} - V_{i-})$$

$$V_o = V_{o+} - V_{o-} = \frac{gm}{sC}V_i$$

Proposed Switched Gm-C Integrator

Conventional approach

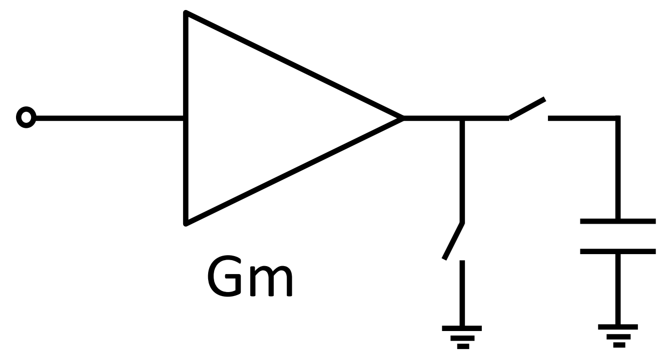


Analog adjustment of Gm using I_{bias}

Difficult for fine CMOS with low voltage

☹

Proposed method



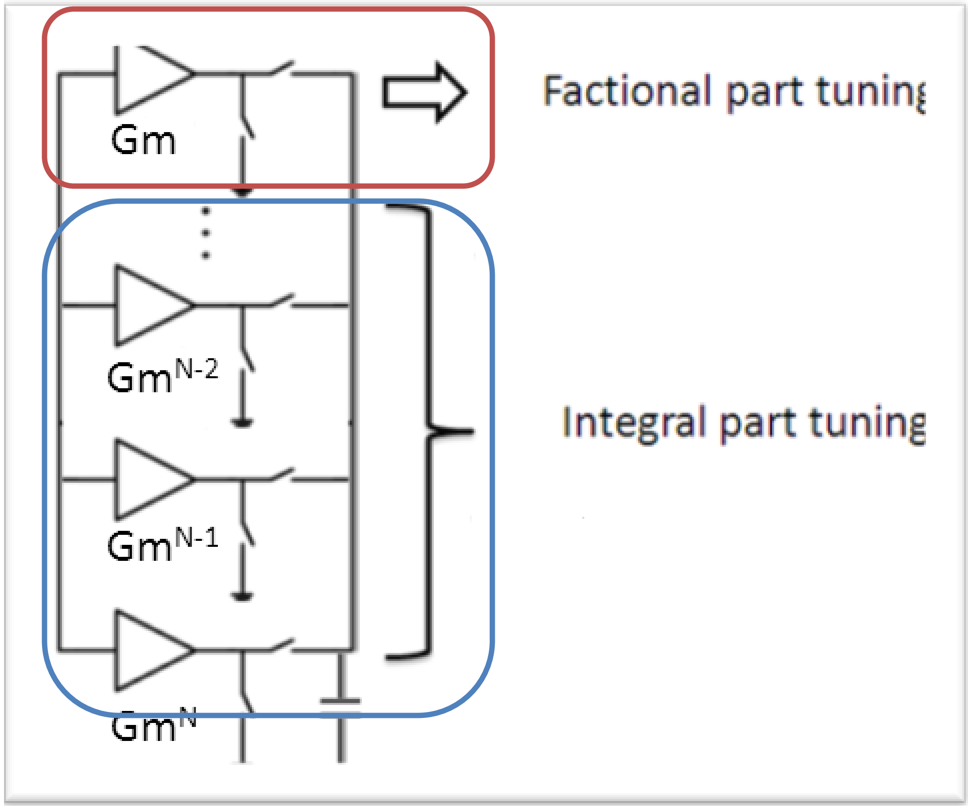
Digital adjustment of Gm by switch

low voltage control

☺

Continuous Adjustment of Switched Gm-C Integrator

Noise characteristics → C → Constant; Gm → Adjustable

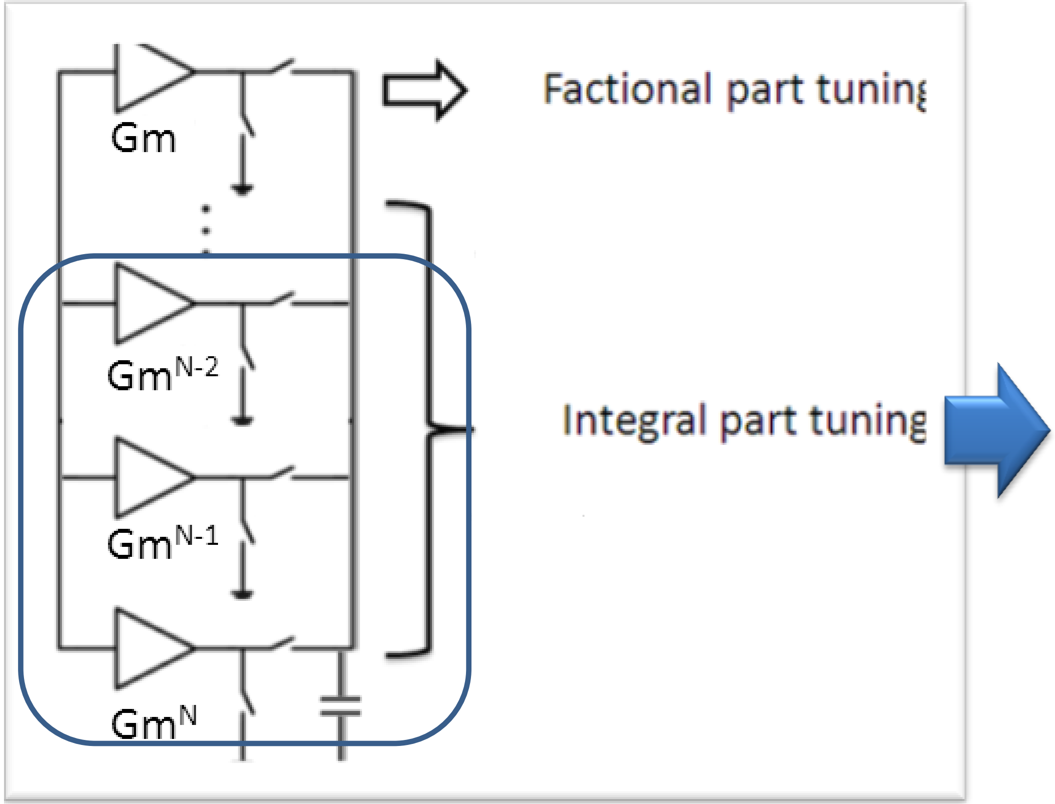


→ Continuous Adjustment

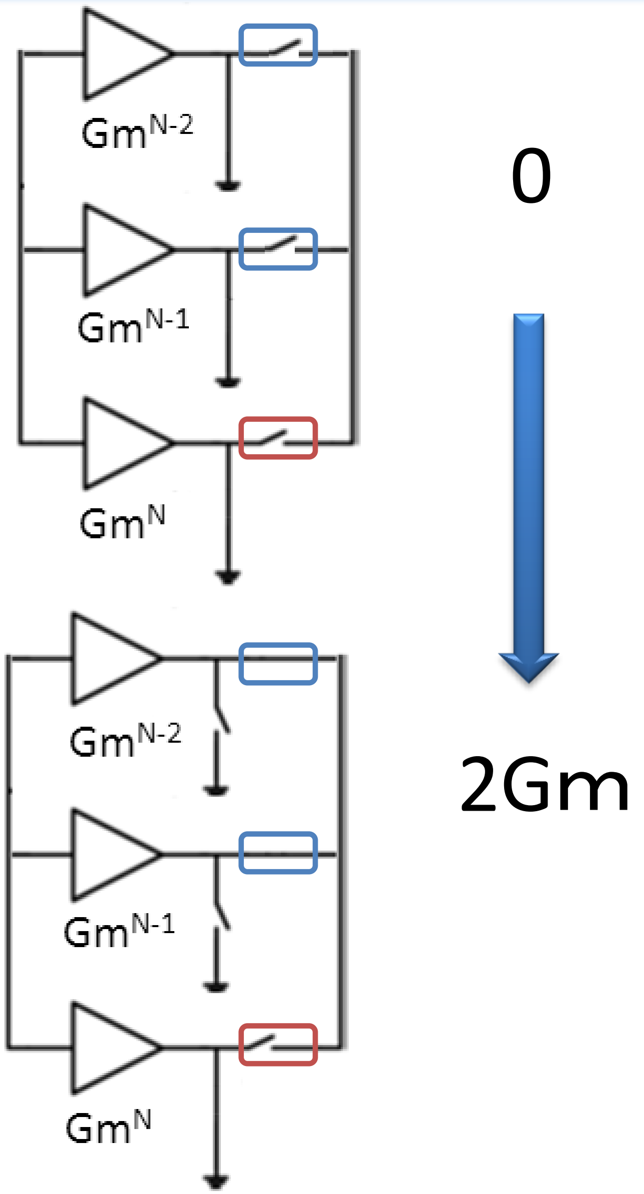
Switched Gm-C Integrator →

- Low-voltage
- Digital control

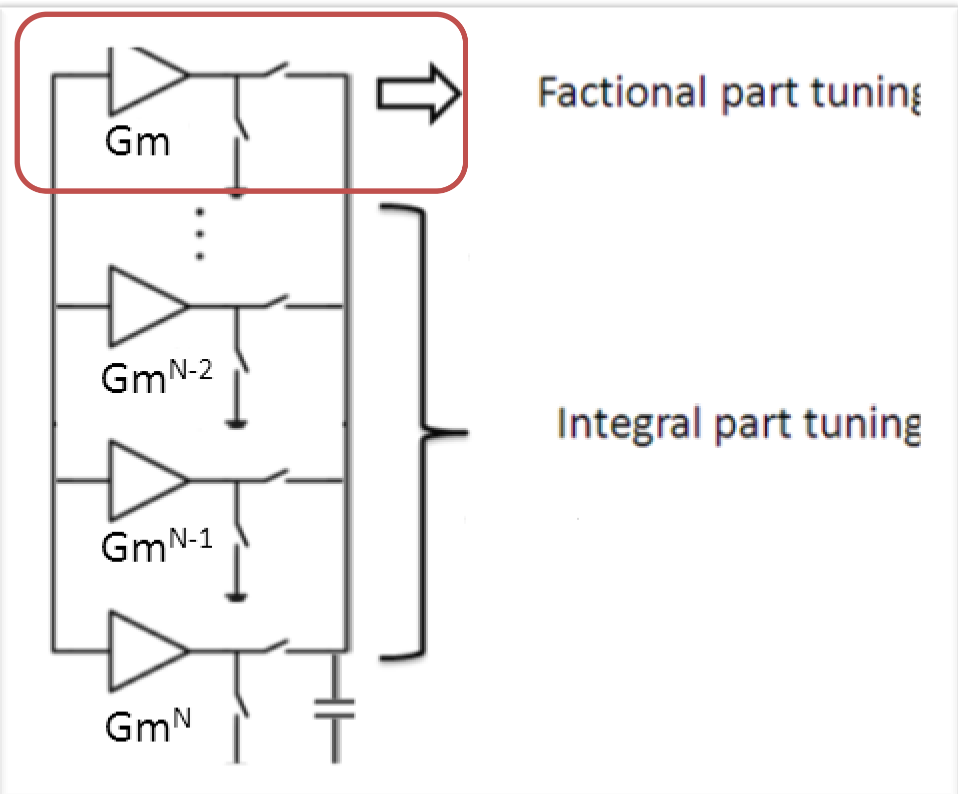
Integral Part Adjusting



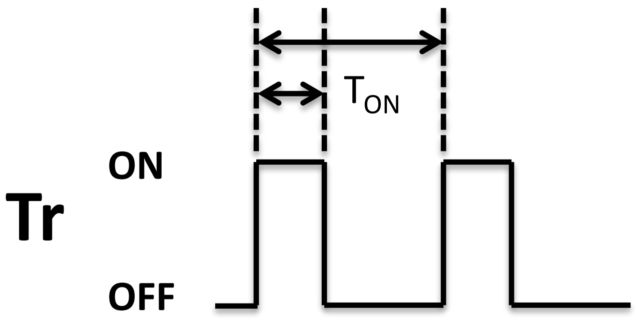
Switched Gm-C Integrator



Adjust Fractional Part by PWM



Switched Gm-C Integrator

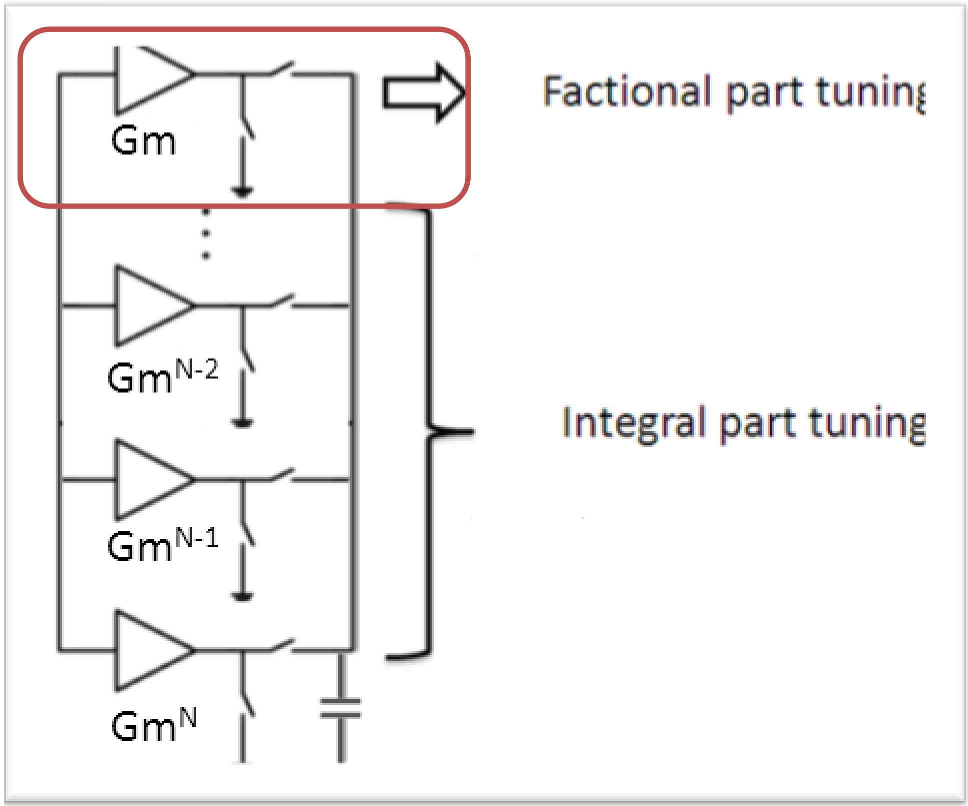


$$\frac{I_{out}}{Vin} = D \cdot Gm$$

$$D = \frac{T_{on}}{T_{on} + T_{off}}$$

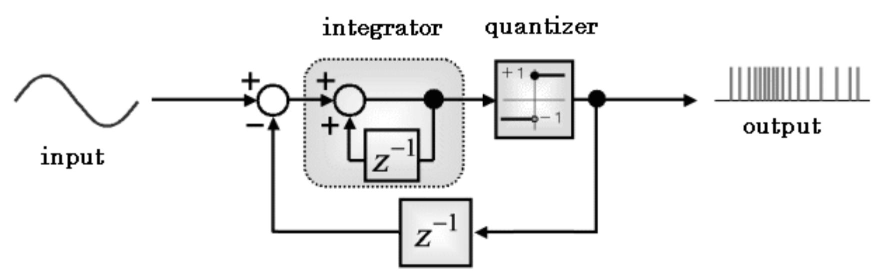
PWM control

Adjust Fractional Part by ΔΣ



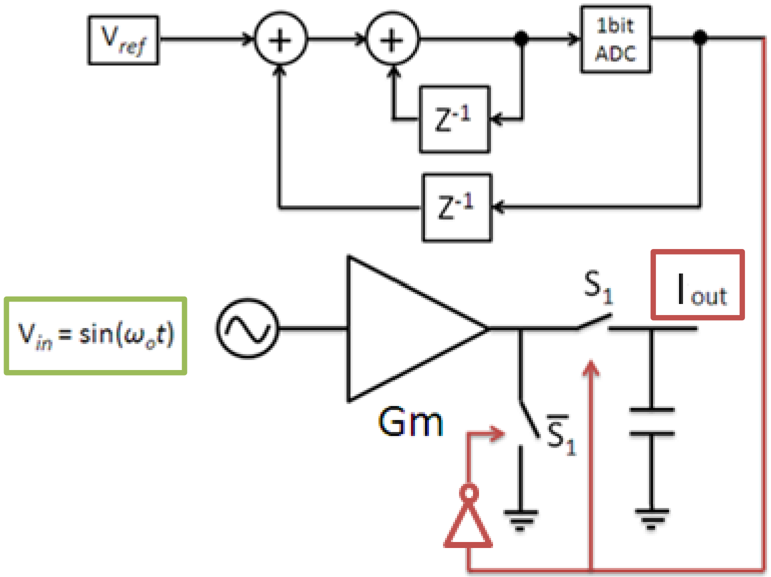
Switched Gm-C Integrator

1bit ΔΣ converter for high accuracy



1bit ΔΣ converter

Input and Output Waveforms of Switched Gm-C Integrator

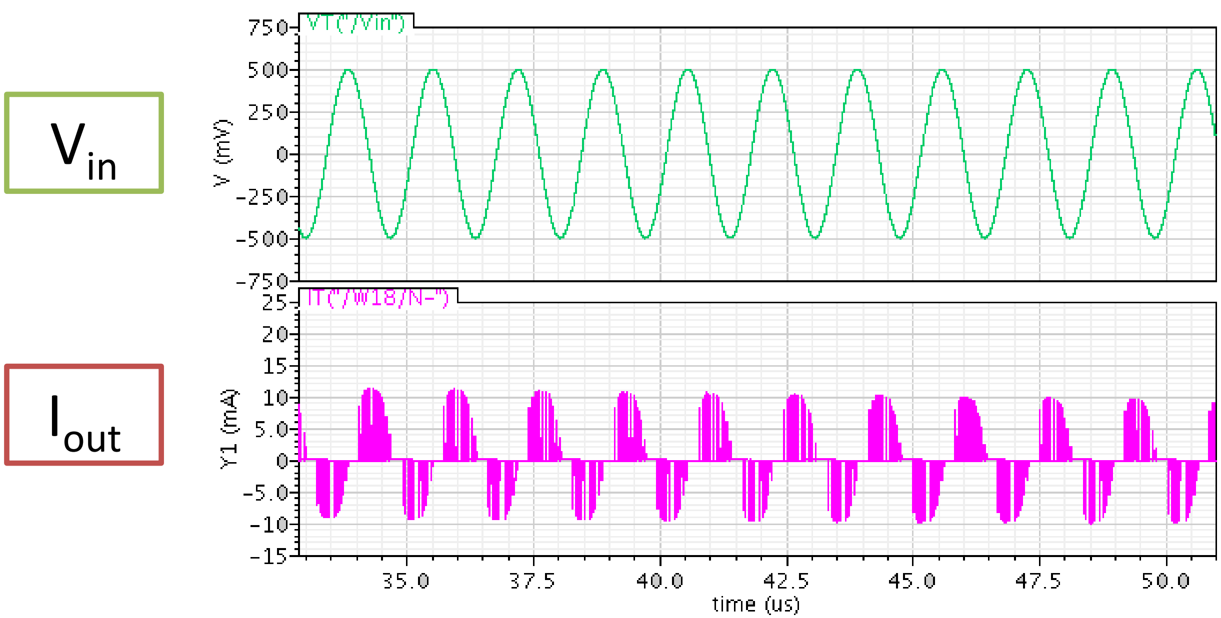


$$V_{in} = 500mV$$

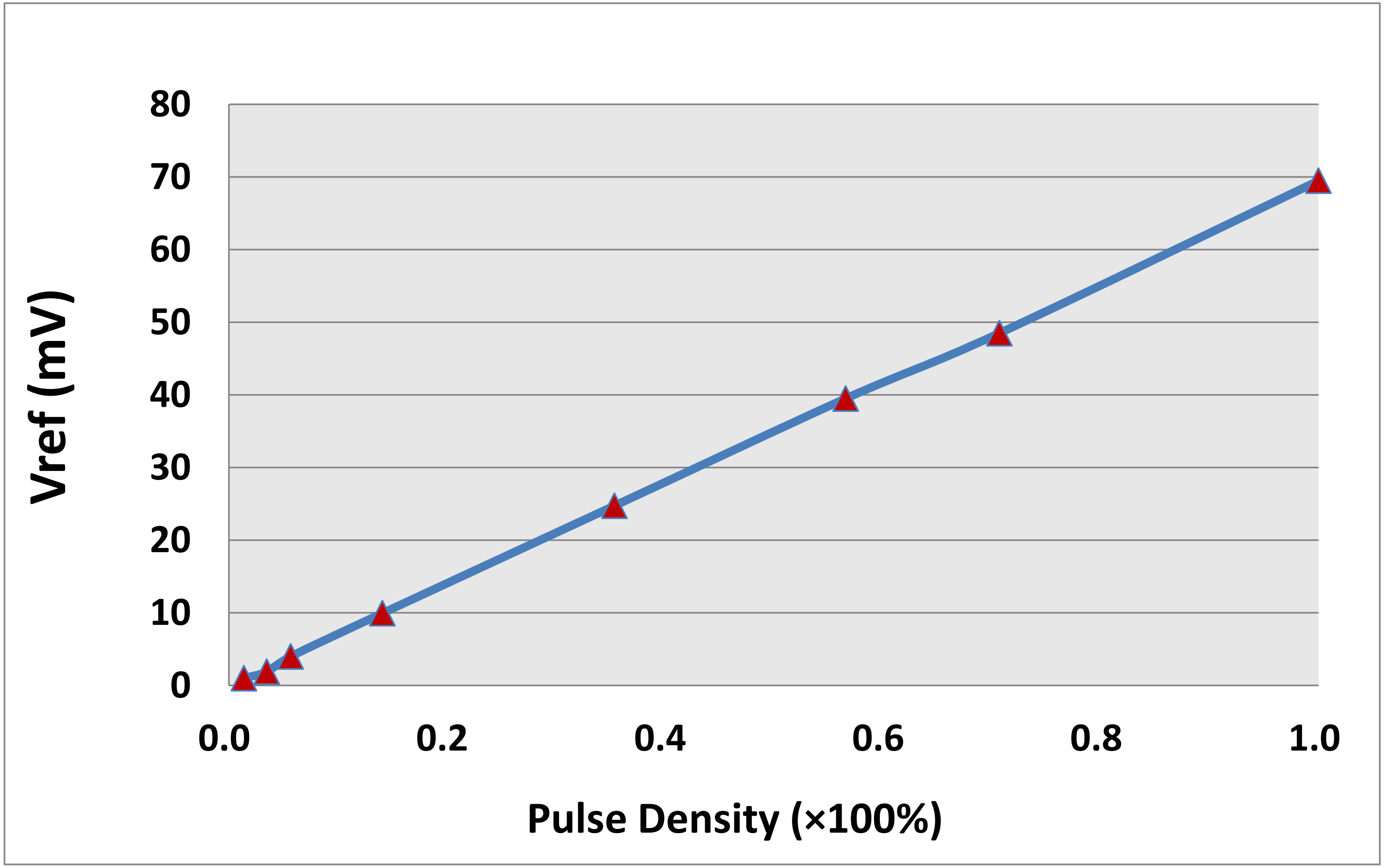
$$f = 598kHz$$

$$C = 1pF$$

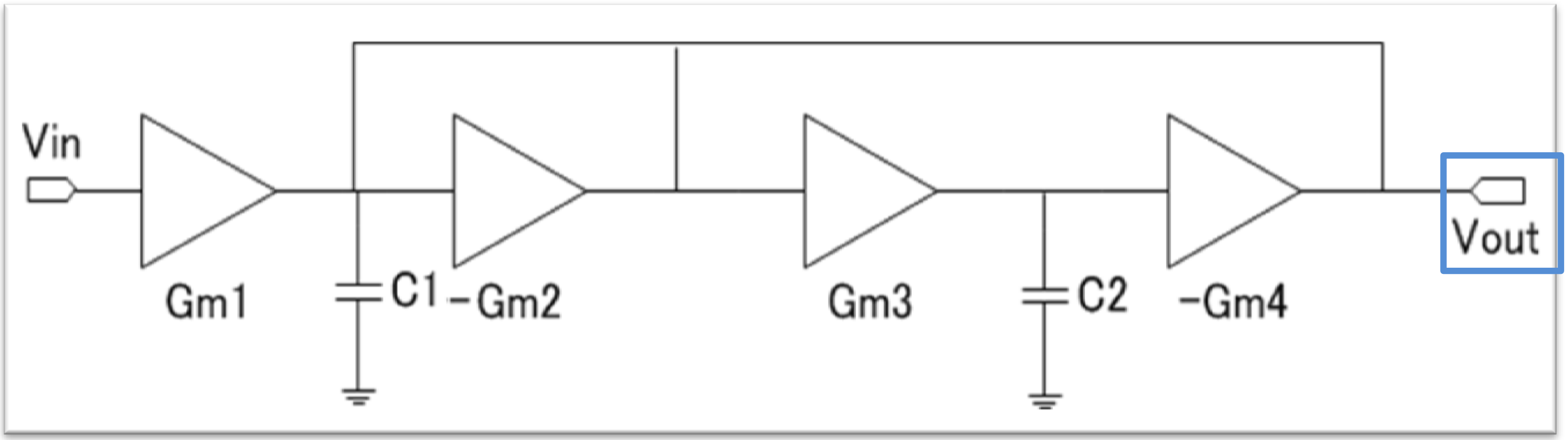
$$1/Gm = 2\times10^{6}S$$



Input Voltage Amplitude and Pulse Density with ΔΣ Adjustment



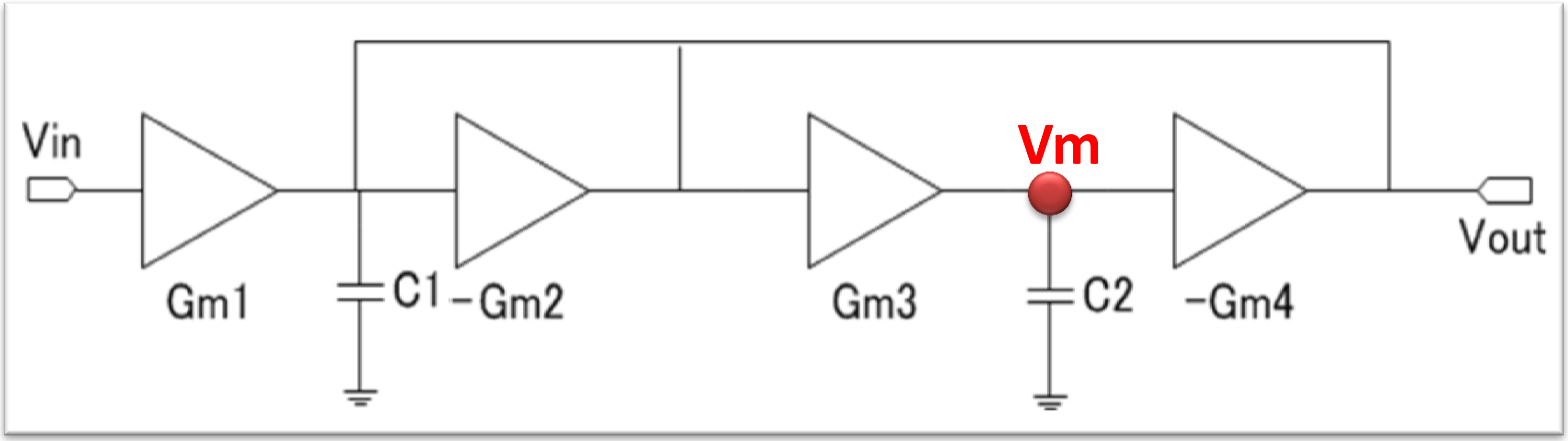
Gm-C Second-order BPF



$$H(s)=\frac{Gm_1C_2s}{s^2C_1C_2+sC_2Gm_2+Gm_3Gm_4} \Rightarrow H(s)=\frac{K\omega_0 s}{s^2+\frac{\omega_0}{Q}s+\omega_0^2}$$

$$\omega_0=\sqrt{\frac{Gm_3Gm_4}{C_1C_2}} \qquad Q=\sqrt{\frac{C_1Gm_3Gm_4}{C_2Gm_2^2}} \qquad K=\sqrt{\frac{C_2Gm_1^2}{C_1Gm_3Gm_4}}$$

Gm-C Second-order LPF

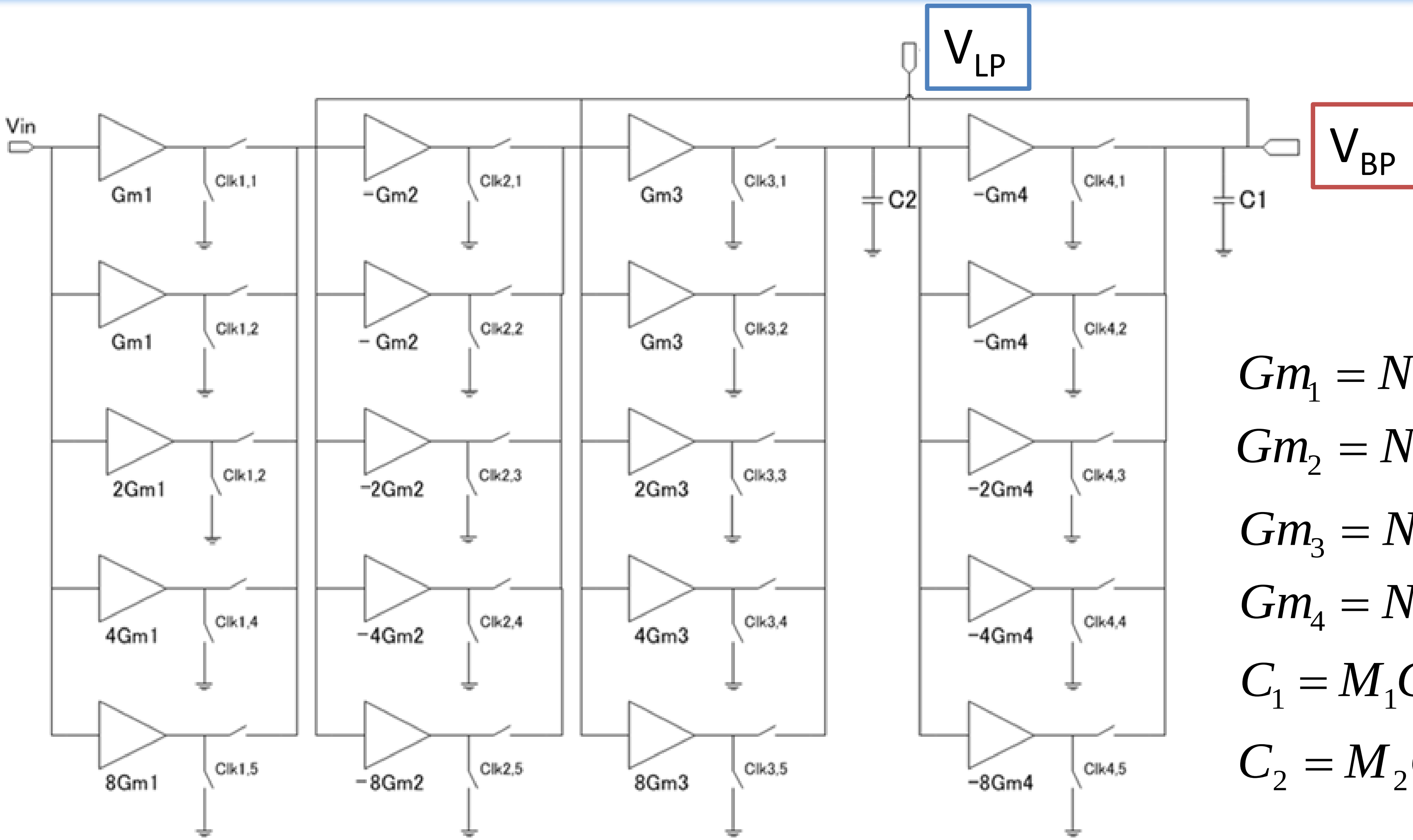


Another node of the filter

$$H''(s) = \frac{V_m}{V_{in}} = \frac{Gm_1 Gm_3}{s^2 C_1 C_2 + s C_2 Gm_2 + Gm_3 Gm_4} \Rightarrow H(s) = \frac{K\omega_0}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

$$\omega_0 = \sqrt{\frac{Gm_3 Gm_4}{C_1 C_2}} \qquad Q = \sqrt{\frac{C_1 Gm_3 Gm_4}{C_2 Gm_2^2}} \qquad K = \sqrt{\frac{Gm_1^2 Gm_3}{C_1 C_2 Gm_4}}$$

Proposed Digitally-controllable BPF and LPF



$$Gm_1 = N_1 gm$$

$$Gm_2 = N_2 gm$$

$$Gm_3 = N_3 gm$$

$$Gm_4 = N_4 gm$$

$$C_1 = M_1 C$$

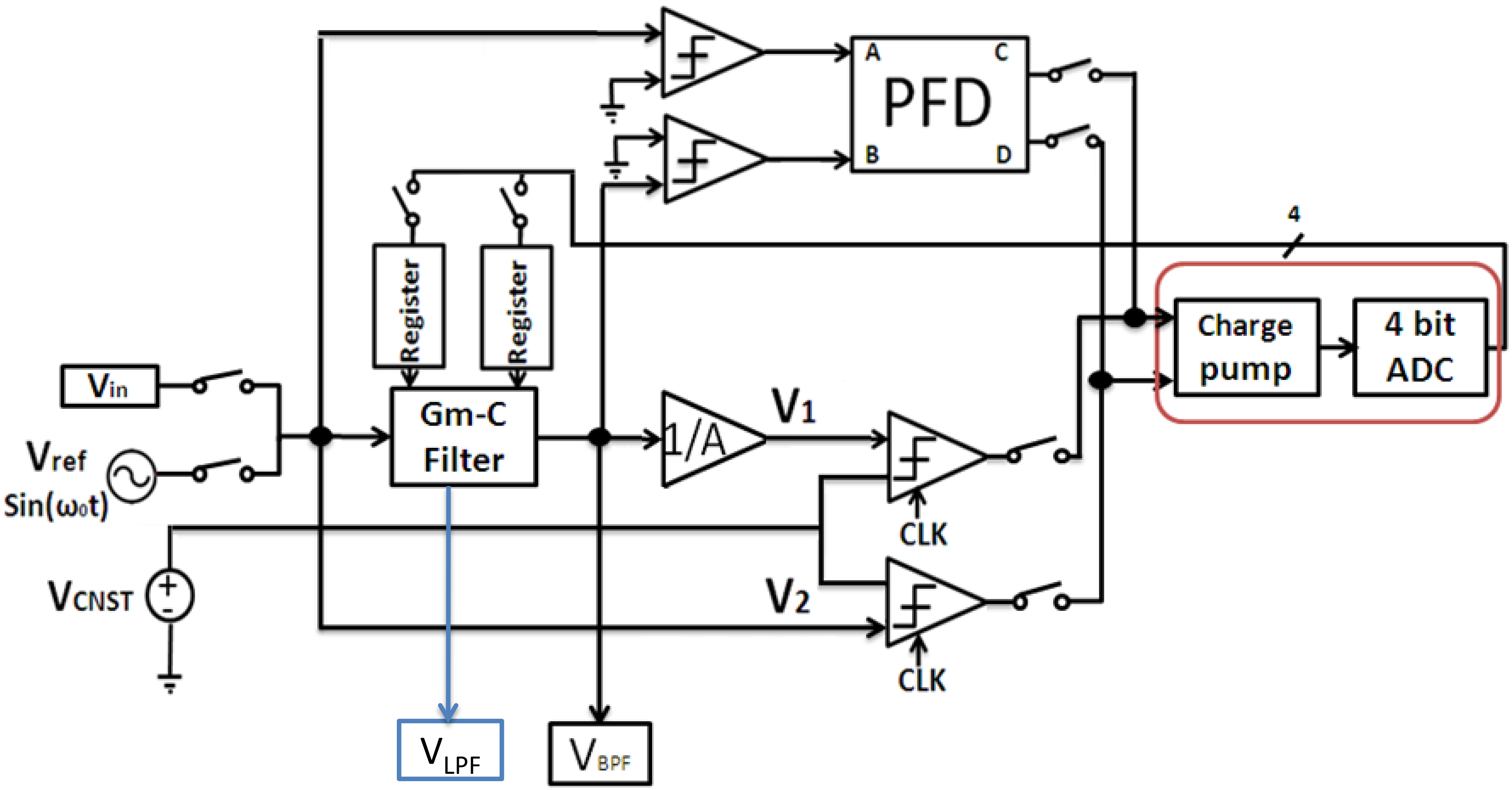
$$C_2 = M_2 C$$

$$\omega_0 = \frac{N_3 N_4}{\sqrt{M_1 M_2}} \cdot \frac{gm}{C} \qquad Q = \sqrt{\frac{M_1 N_3 N_4}{M_2 N_2^2}} \qquad K = \sqrt{\frac{M_2 N_1^2}{M_1 N_3 N_4}}$$

Outline

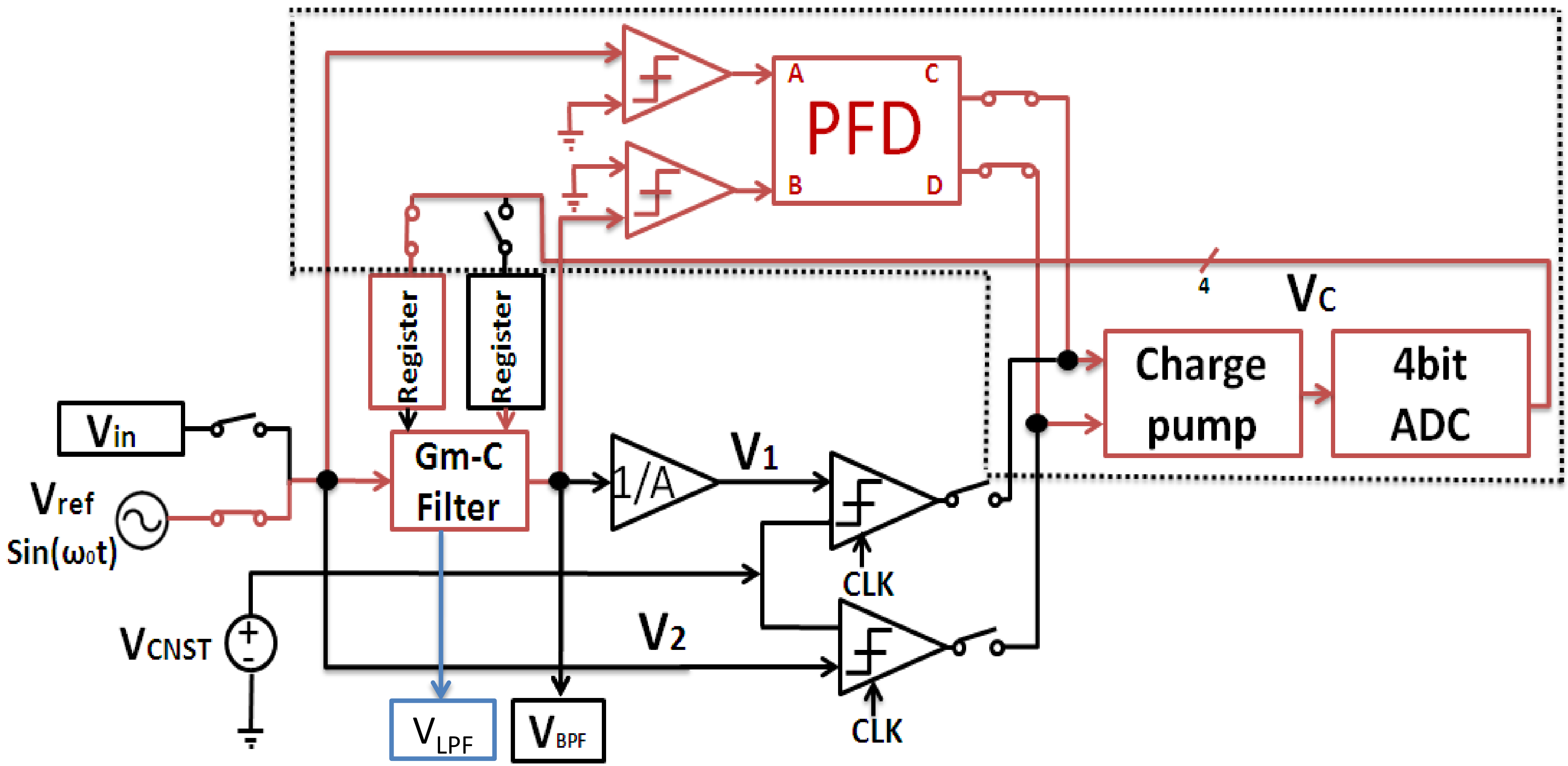
- *Research Objective*
- *Switched Gm-C Band-pass Filter*
- *Center Frequency Tuning*
- *Q-Value Tuning*
- *Conclusion*

Whole Tuning Scheme

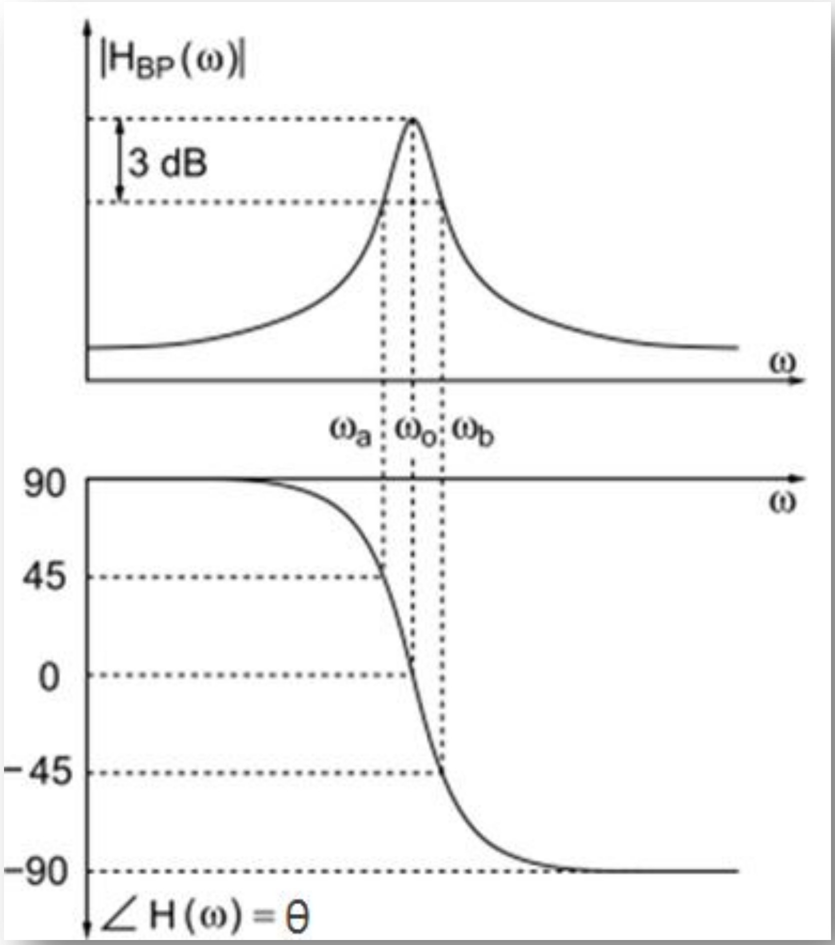


- Suitable for digital low voltage implement
- Require a reference frequency

Center Frequency Tuning Part



Proposed Center Frequency Tuning Method



Magnitude characteristics

$$H(s) = \frac{Gm_1 C_2 s}{s^2 C_1 C_2 + s C_2 Gm_2 + Gm_3 Gm_4}$$

Phase characteristics

$$\theta = \frac{\pi}{2} - \arctan \frac{\omega_i \omega_0}{Q(\omega_0^2 - \omega_i^2)}$$

ω_0: Center Frequency
ω_i: Input Frequency

θ=0 → Center frequency tuning is done

Principle for Using Phase Characteristics

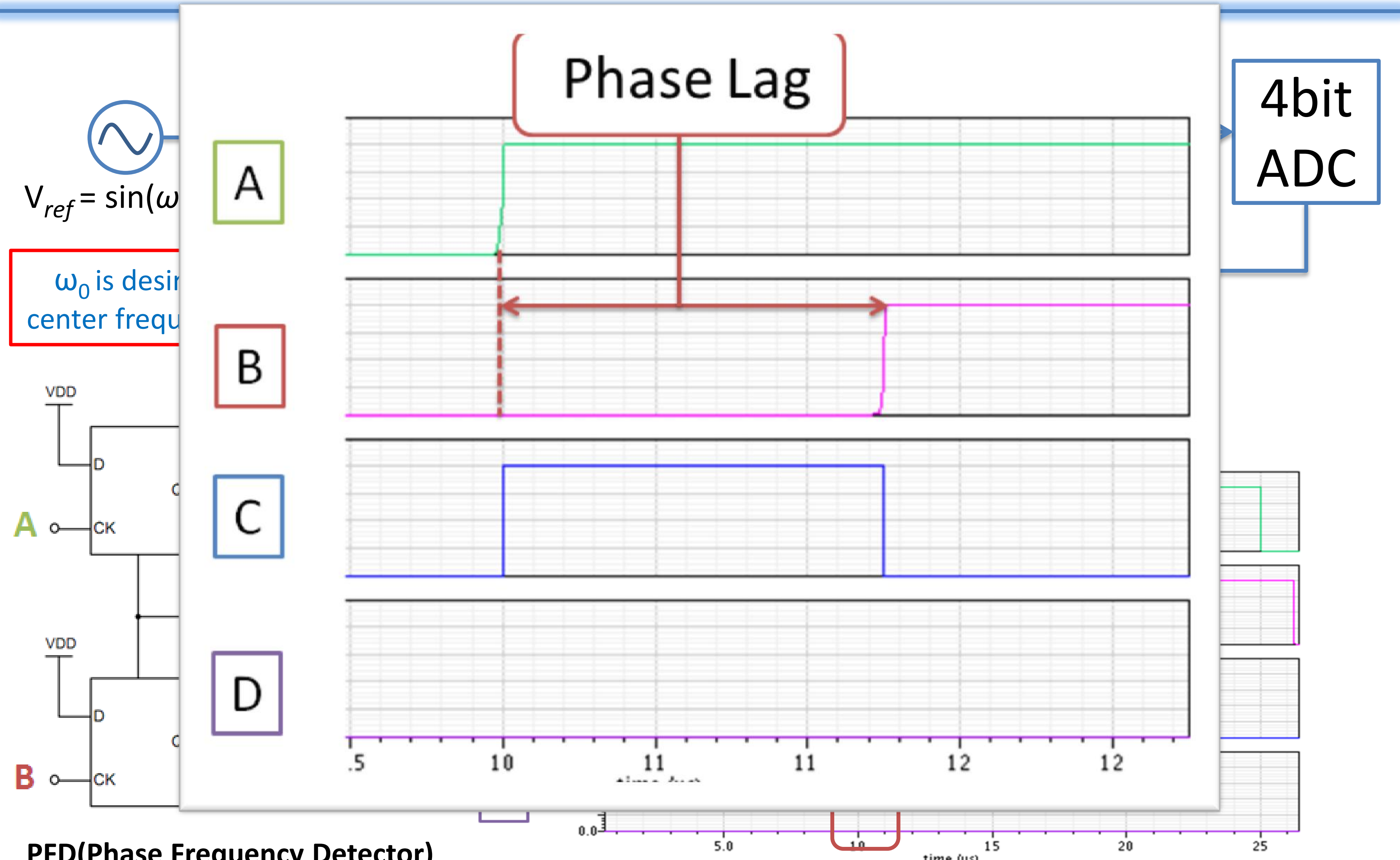
$$\theta = \frac{\pi}{2} - \arctan \frac{\omega\omega_0}{Q(\omega_0^2 - \omega_i^2)} \Rightarrow \omega_0 = \sqrt{\frac{Gm_3Gm_4}{C_1C_2}}$$

① $\theta < 0 \rightarrow \omega_0 < \omega_i$ — Gm_3, Gm_4 **bigger** ⇒ ω_0 is adjusted **bigger**

② $\theta = 0 \rightarrow \omega_0 = \omega_i$ — Done

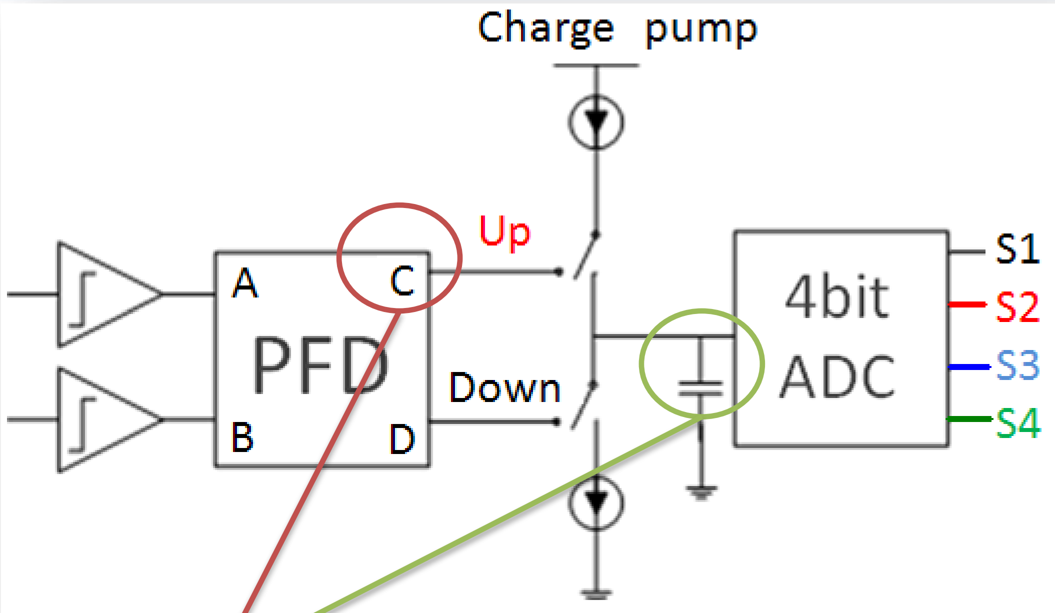
③ $\theta > 0 \rightarrow \omega_0 > \omega_i$ — Gm_3, Gm_4 **smaller** ⇒ ω_0 is adjusted **smaller**

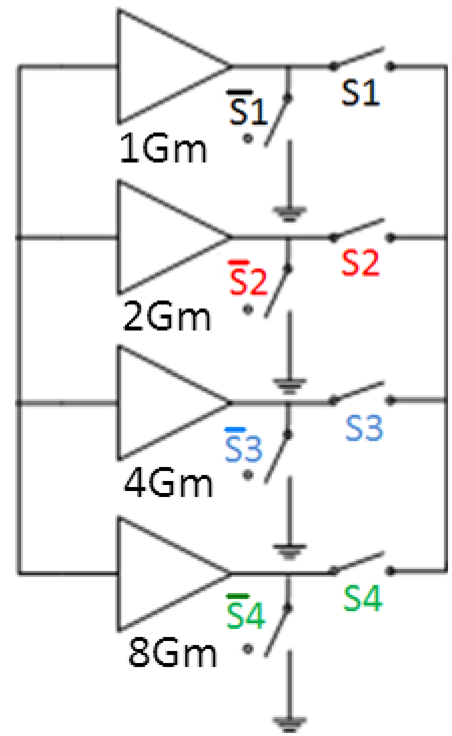
Signals of PFD



PFD(Phase Frequency Detector)

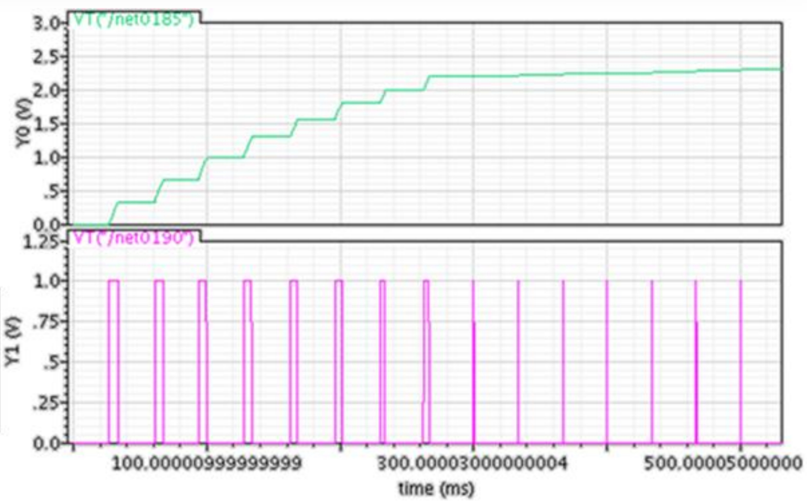
Operation of Charge Pump





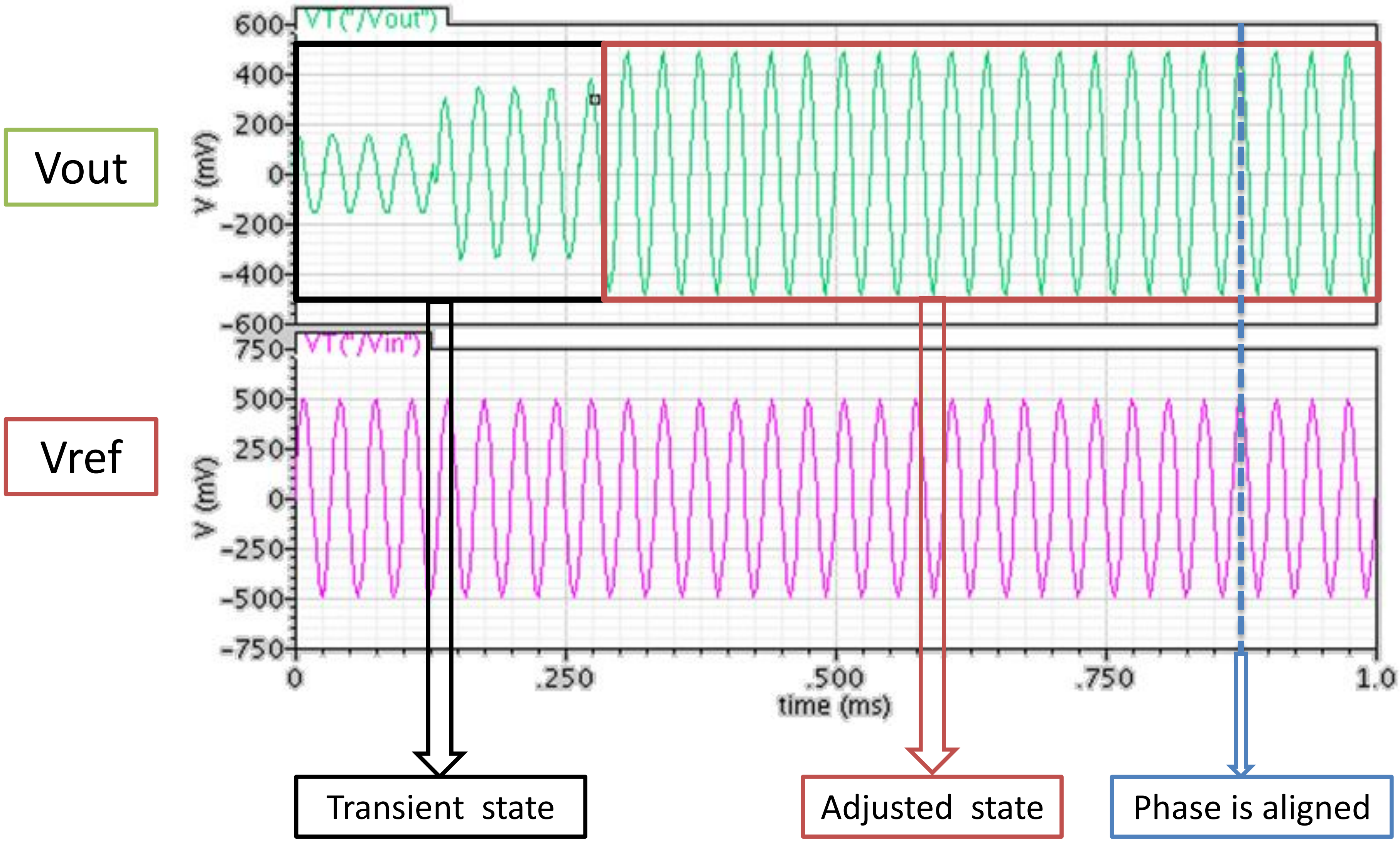
Output of charge pump Vc

Output of PFD



Adjust the Gm_3, Gm_4 values

Input and Output Waves of BPF

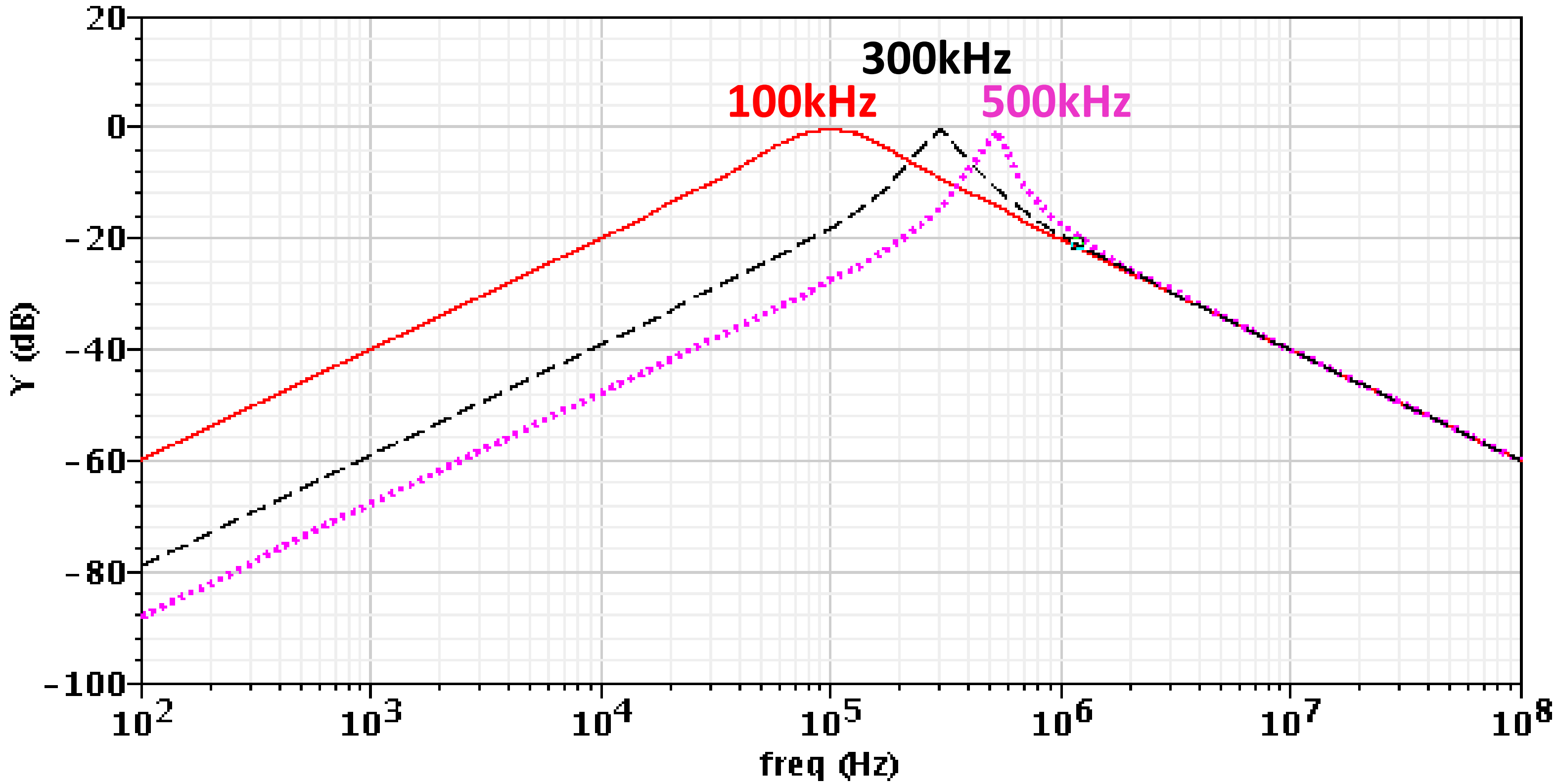


Center Frequency Tuning Simulation Result of BPF

Simulation parameters

$Gm = 5\times10^{-5} S$ $C = 1.59\text{pF}$

$N_1 = N_2 = 2$ $M_1 = M_2 = 1$ $0 \le N_3 = N_4 \le 15$

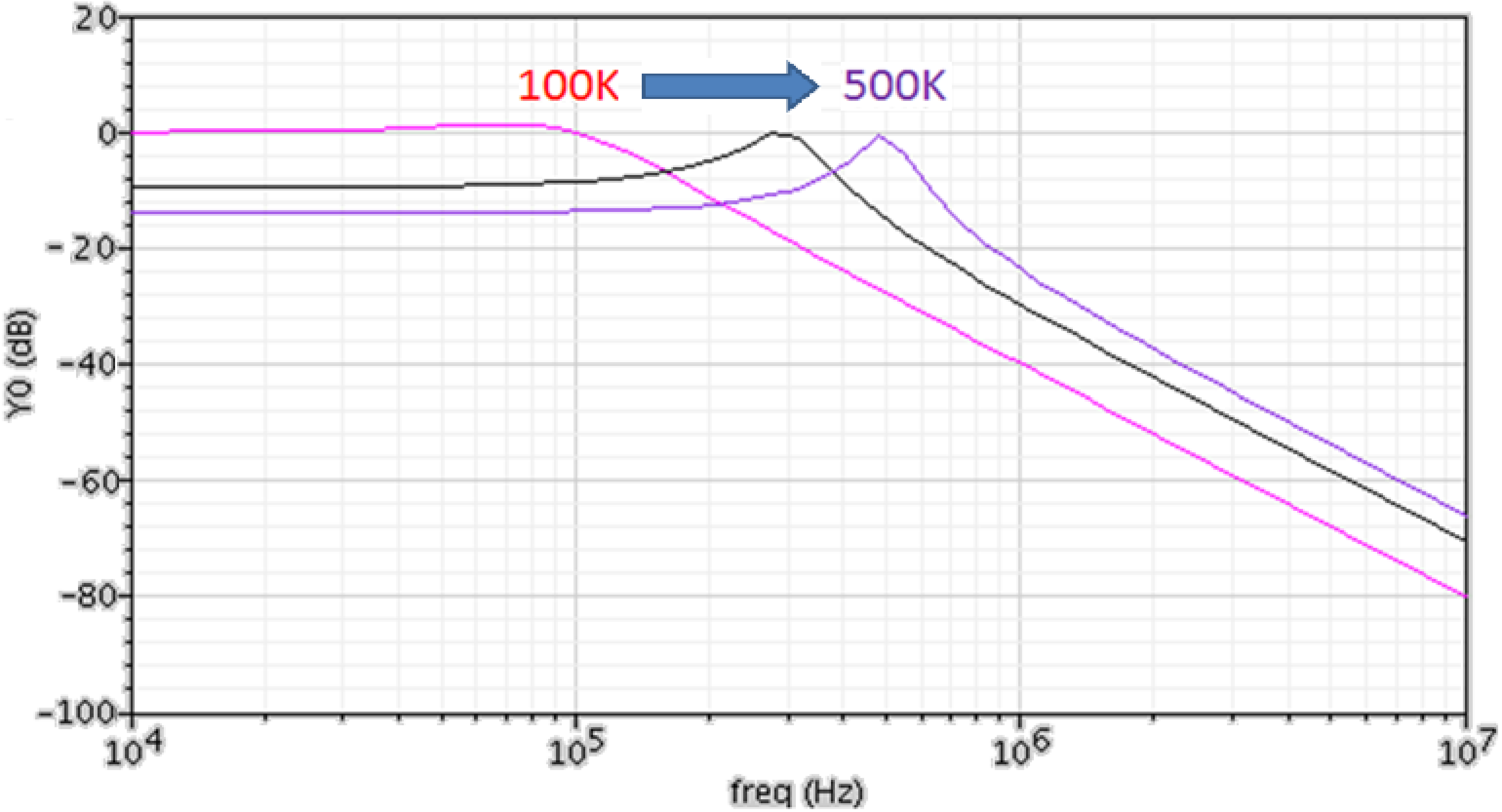


Center Frequency Tuning Simulation Results of LPF

Simulation parameters

$Gm = 5\times10^{-5} S$ $C = 1.59\text{pF}$

$N_1 = N_2 = 2$ $M_1 = M_2 = 1$ $0 \le N_3 = N_4 \le 15$



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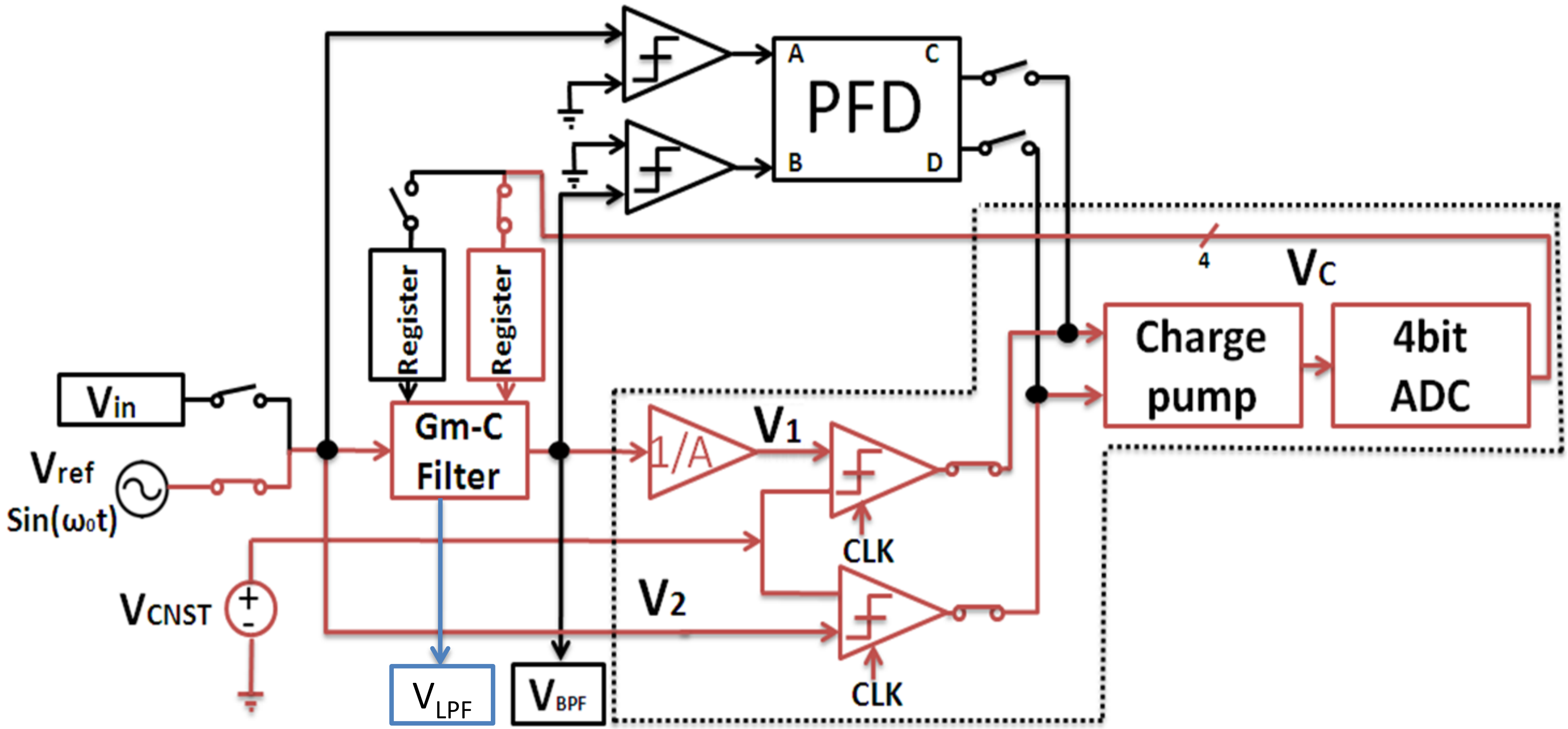
- *Q-Value Tuning*
- *Conclusion*

Q-value Tuning Part



Q-value Tuning Method

proposed method

$$H(\omega_0) = \frac{Gm_1}{Gm_2} = \sqrt{\frac{Gm_1^2 C_2}{Gm_3 Gm_4 C_1}} \bullet \sqrt{\frac{Gm_3 Gm_4 C_1}{Gm_2{}^2 C_2}} = KQ$$

ω_0: Center frequency

$$\omega_0 = \sqrt{\frac{Gm_3 Gm_4}{C_1 C_2}} \qquad Q = \sqrt{\frac{C_1 Gm_3 Gm_4}{C_2 Gm_2^2}} \qquad K = \sqrt{\frac{Gm_1^2 Gm_3}{C_1 C_2 Gm_4}}$$

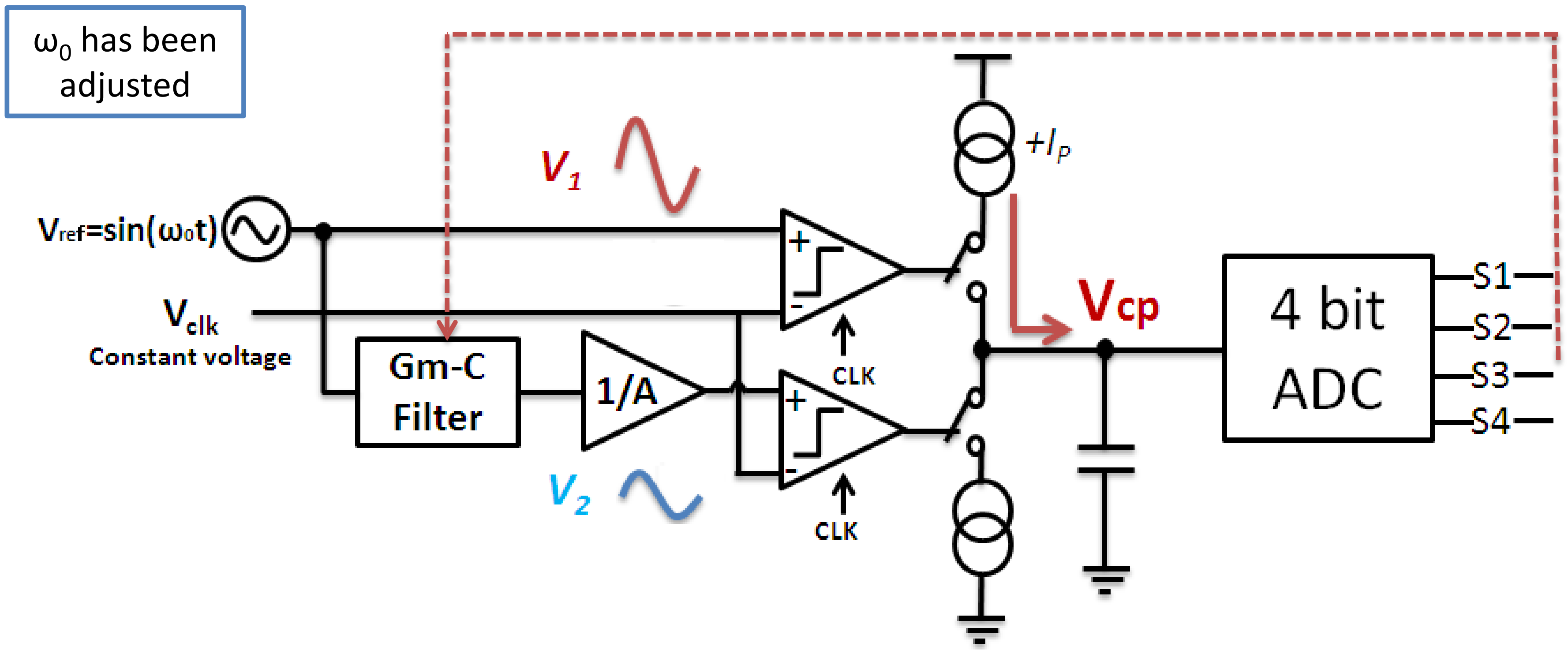
ω_0 determined by Gm_3, Gm_4

K determined by Gm_1, Gm_3, Gm_4

Fix Center frequency and K → Q-value is proportional to gain

$$|H(j\omega_0)| = K \bullet Q$$

In Case Q is Smaller than Desired Value



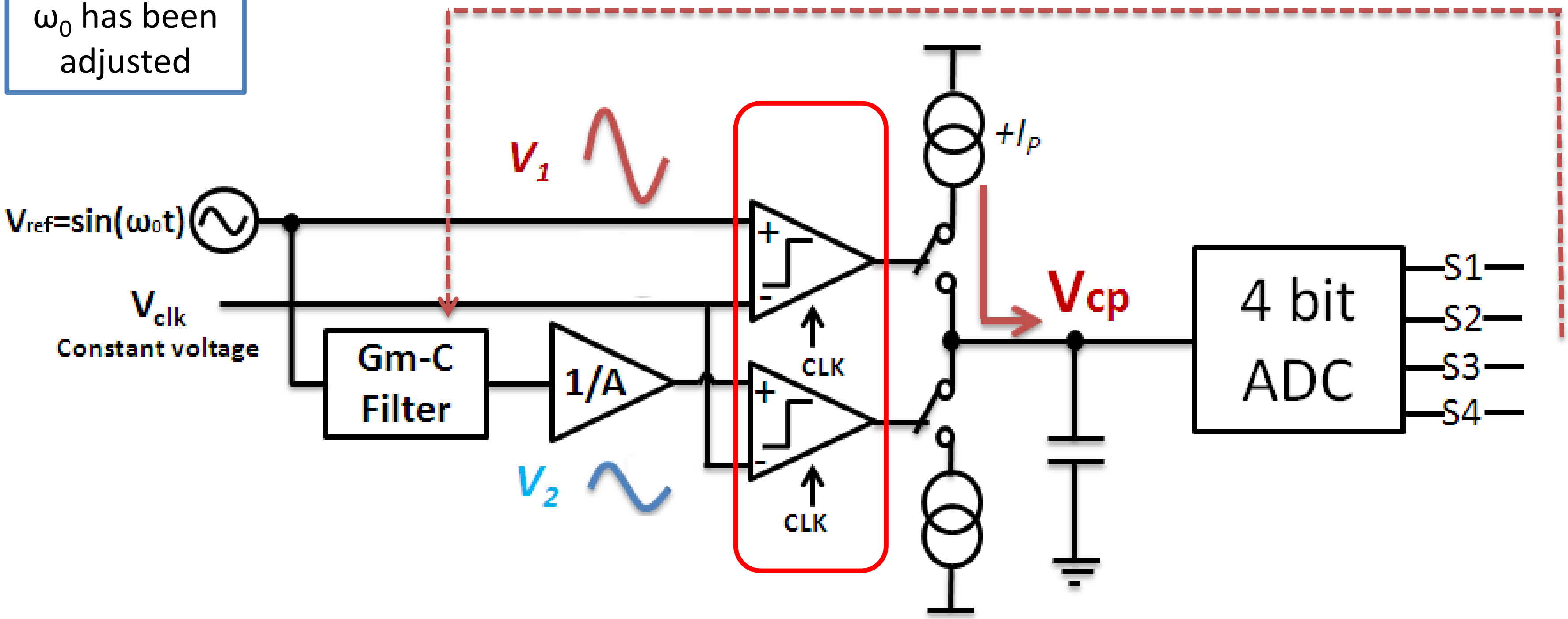
$V_1 > V_2$ → V_{cp} is tuned bigger → Gm_2 is tuned smaller

$$\left(Q = \sqrt{\frac{C_1 Gm_3 Gm_4}{C_2 Gm_2^2}} \right)$$

$Q \propto (1/Gm_2)$ → $Q \rightarrow$ bigger

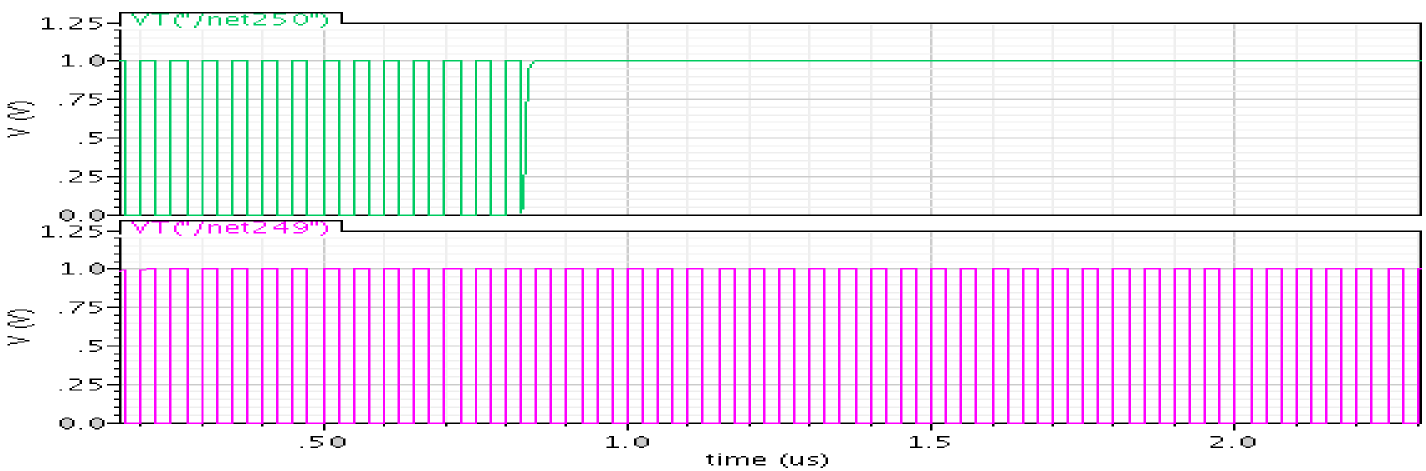
Output of Comparator

ω_0 has been adjusted



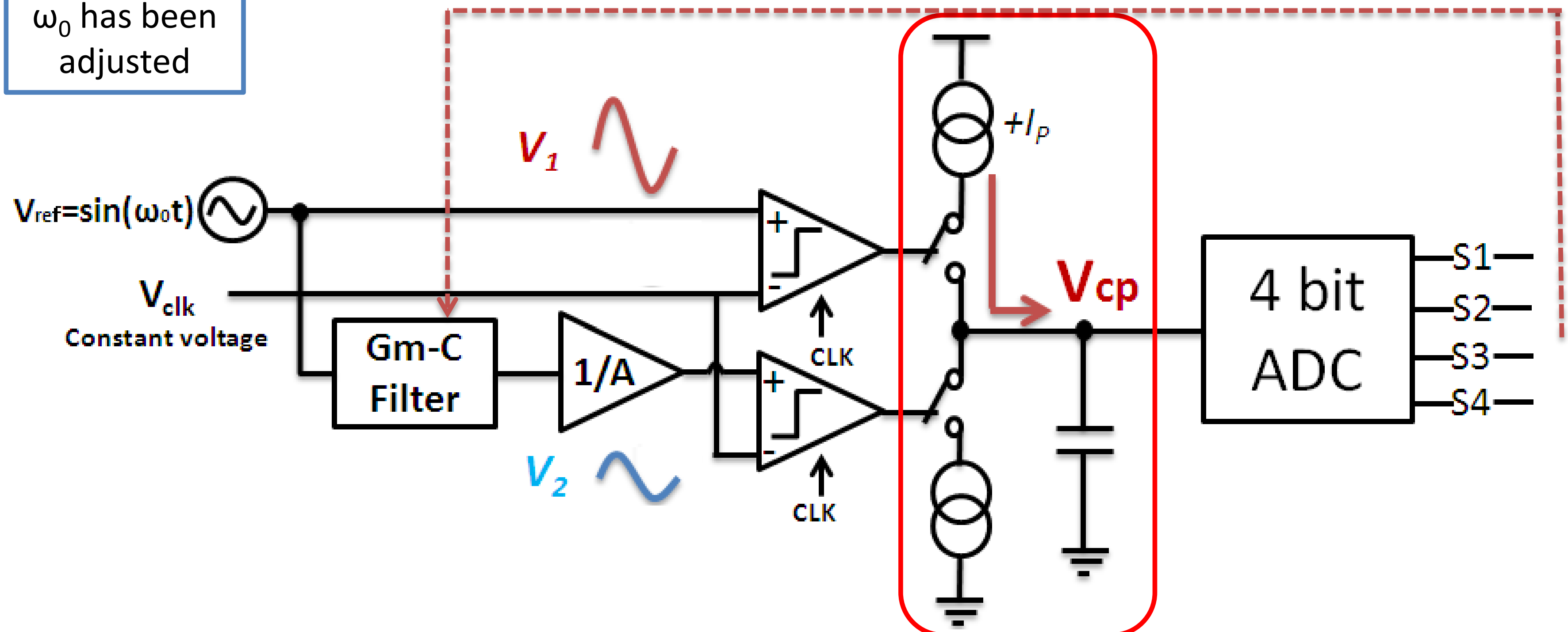
COMP$_{UP}$

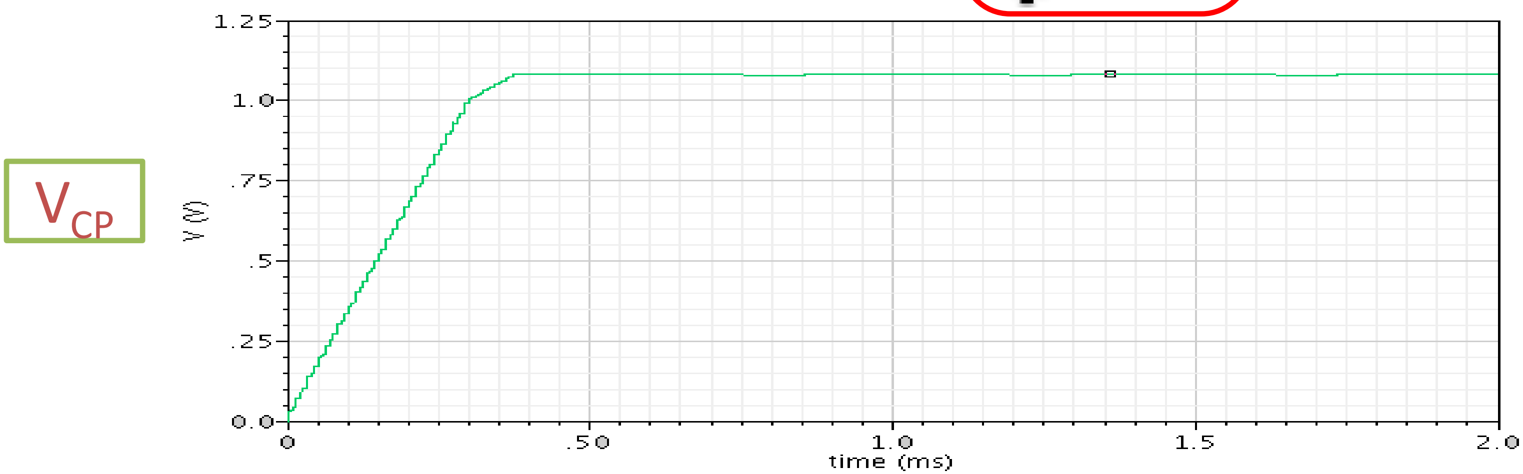
COMP$_{DOWN}$



Output of Charge pump

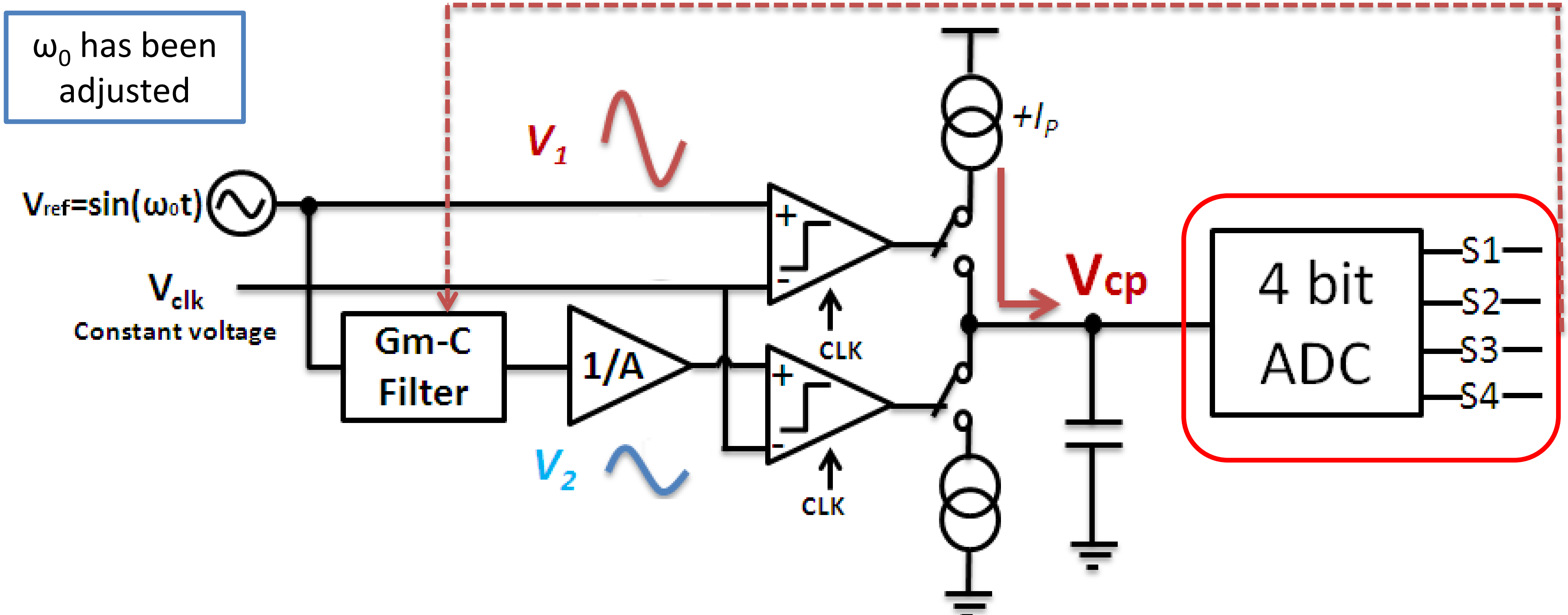
ω_0 has been adjusted

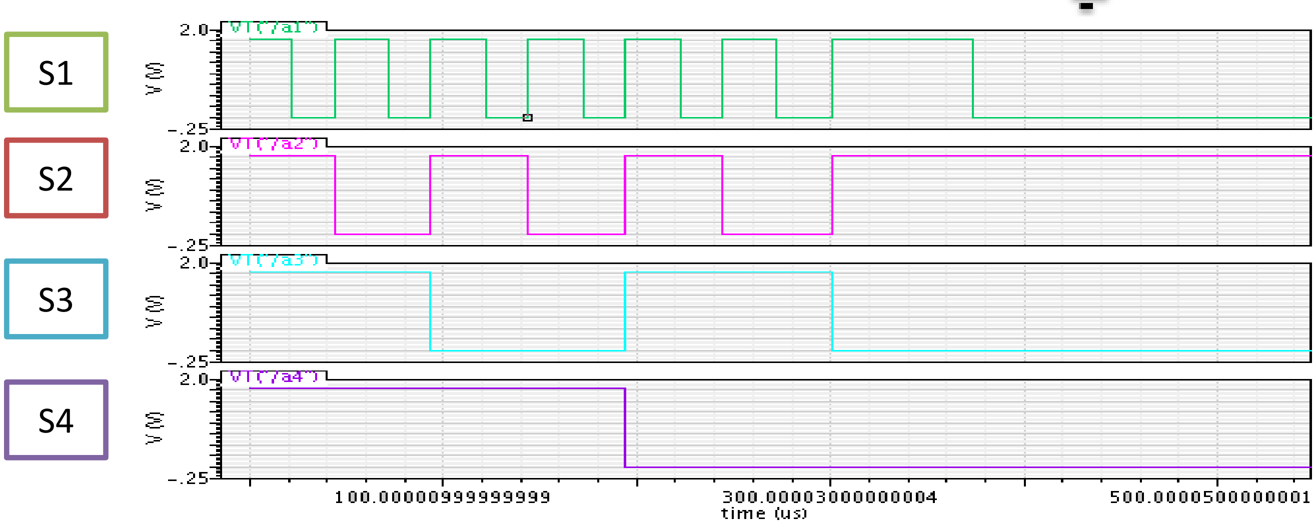




Output of ADC

ω$_0$ has been adjusted

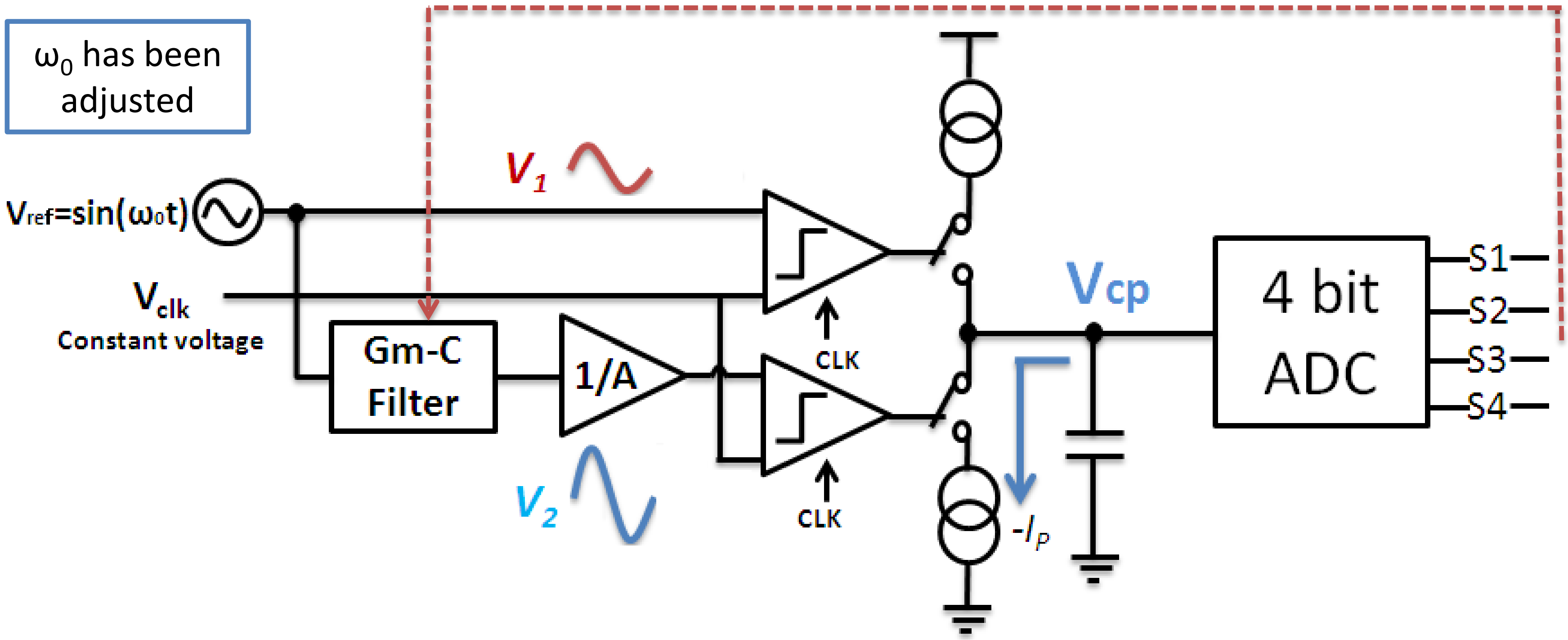




$Q \propto (1/Gm_2)$

In Case Q is Bigger than the Desired Value

ω_0 has been adjusted



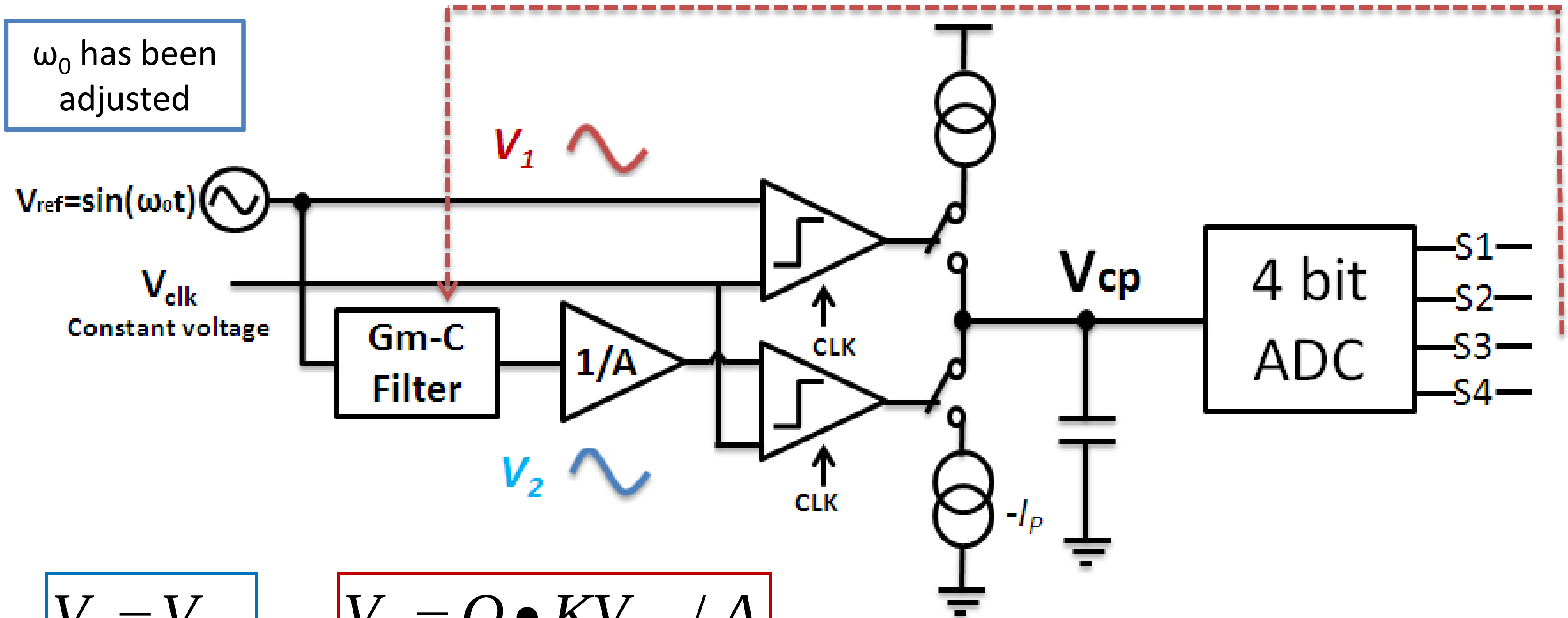
$V_1 < V_2$ → V_{cp} is tuned smaller → Gm_2 is tuned bigger

$$Q = \sqrt{\frac{C_1 Gm_3 Gm_4}{C_2 Gm_2^2}}$$

$Q \propto (1/Gm_2)$ → Q → smaller

Algorithm of Q-value Tuning

ω_0 has been adjusted



$$V_1 = V_{ref}$$

$$V_2 = Q \bullet KV_{ref} / A$$

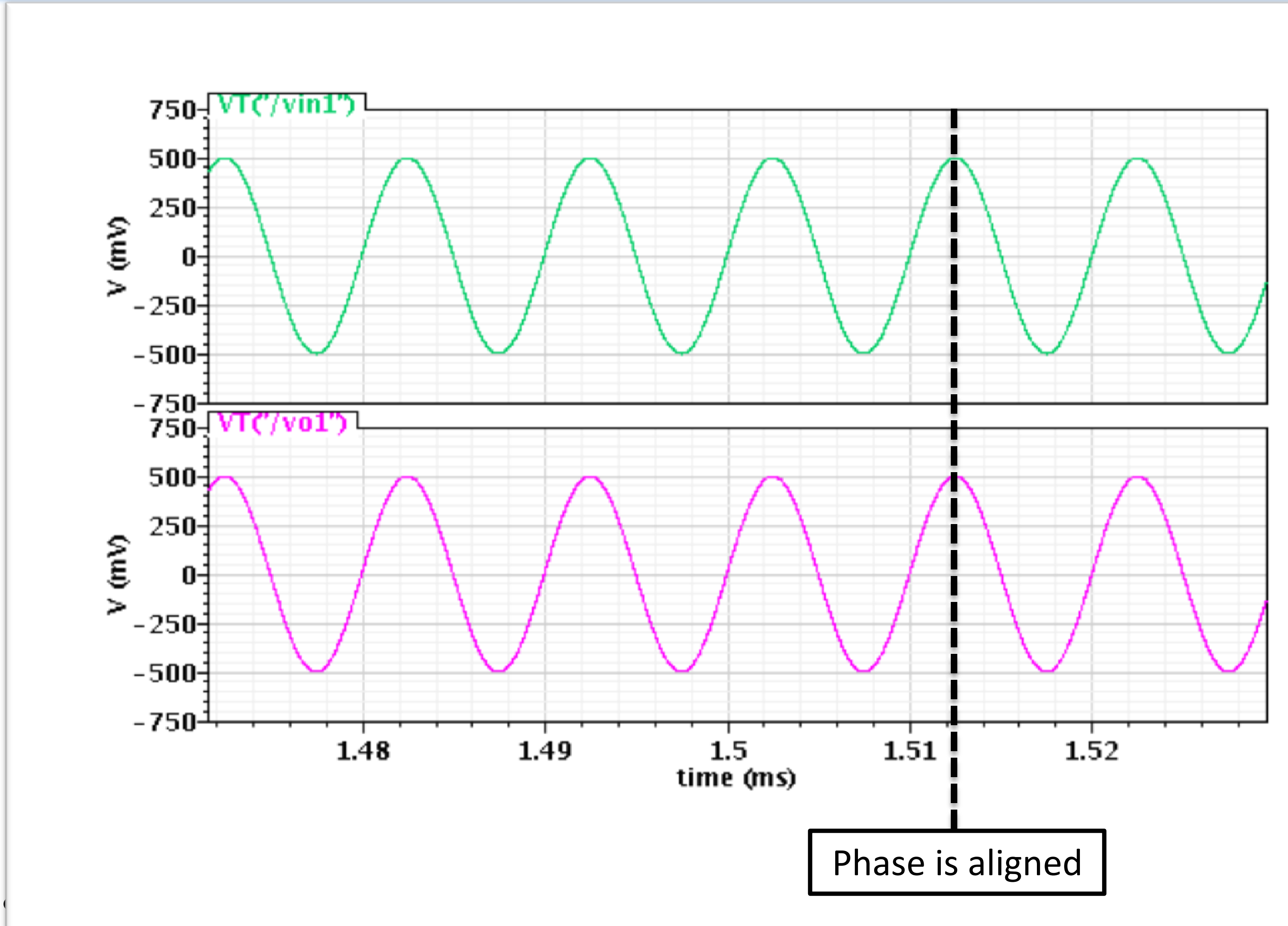
When $V_1 = V_2$ → $Q \bullet KV_{ref} / A = V_{ref} \Rightarrow Q = \frac{1}{K} A$

K is fixed → Q → Determined by A

Input and Output Waves of BPF

V_{ref}

V_{out}



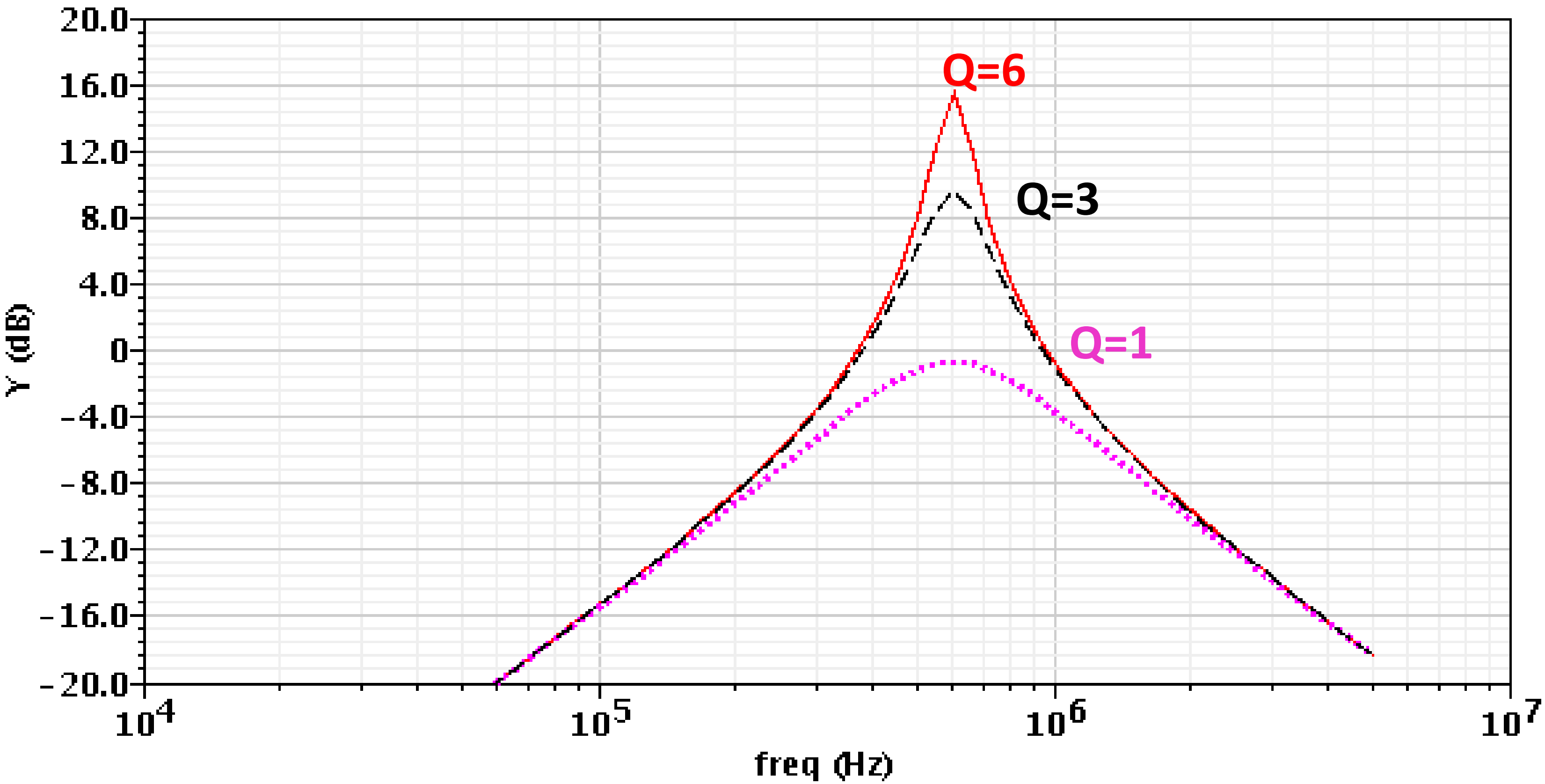
$\left(|H(j\omega_0)| = Q\right.$

Q-value Tuning Simulation Result of BPF

Simulation parameters

$Gm = 5\times10^{-5} S$ $C = 1.59\mathrm{pF}$

$f_0 = 600kHz$ $M_1 = M_2 = 1$

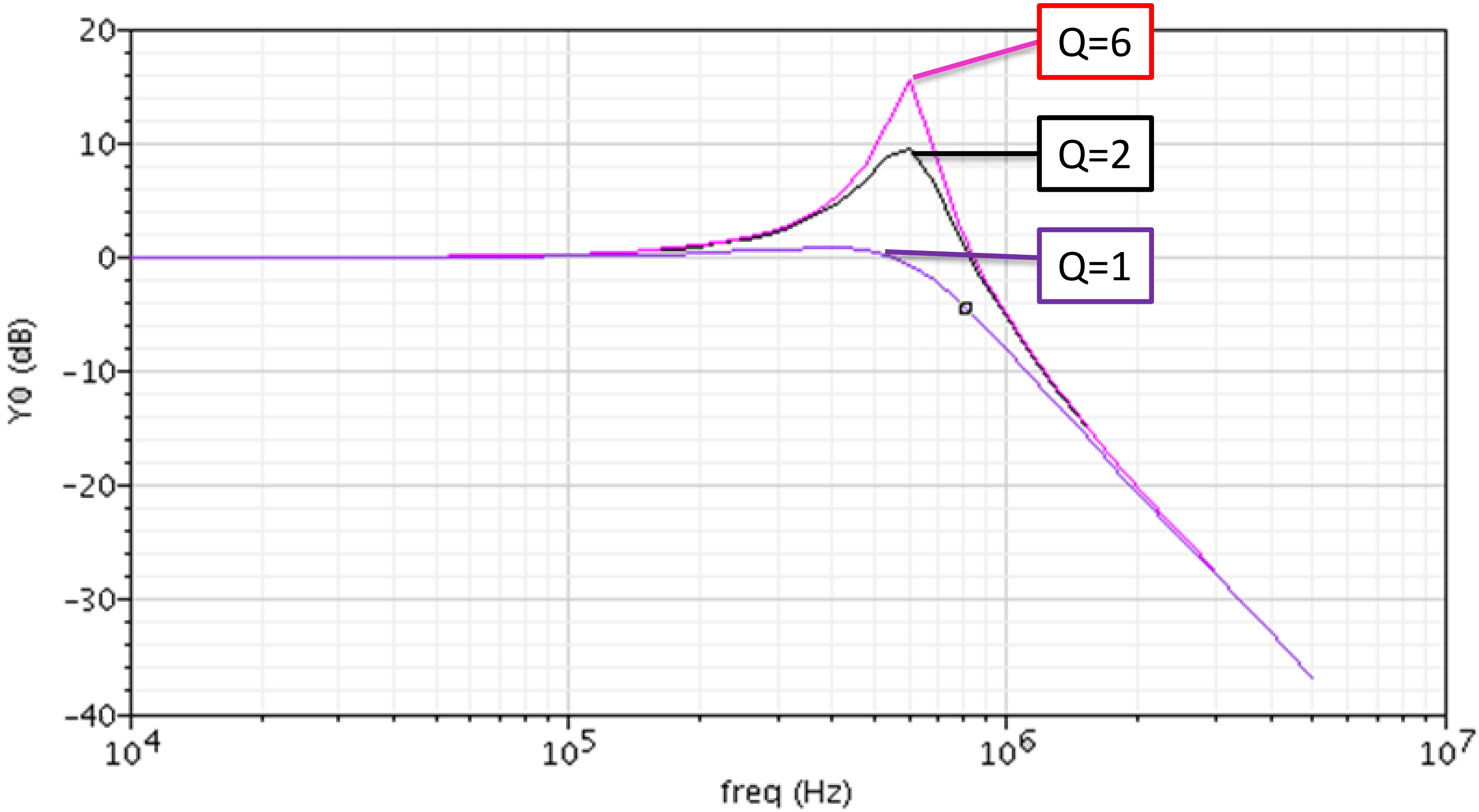


Q-value Tuning Simulation Result of LPF

Simulation parameters

$Gm = 5\times10^{-5}S$ $C = 1.59\text{pF}$

$f_0 = 600kHz$ $M_1 = M_2 = 1$



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Conclusion

- Propose a digitally-controlled Gm-C band-pass filter using switched Gm arrays
  - Fine CMOS → Low voltage

- Digital tuning schemes
  - Center Frequency → Phase property

    Orthogonal

    Determined by Gm3, Gm4
  - Q-value → Gain property (Center frequency has been adjusted)

    Determined by Gm2

- Present SPICE simulation results