

# **Modeling Thermal Induced Inter-Symbol Interference of Feedback DACs in Delta-Sigma Modulators**

**By**

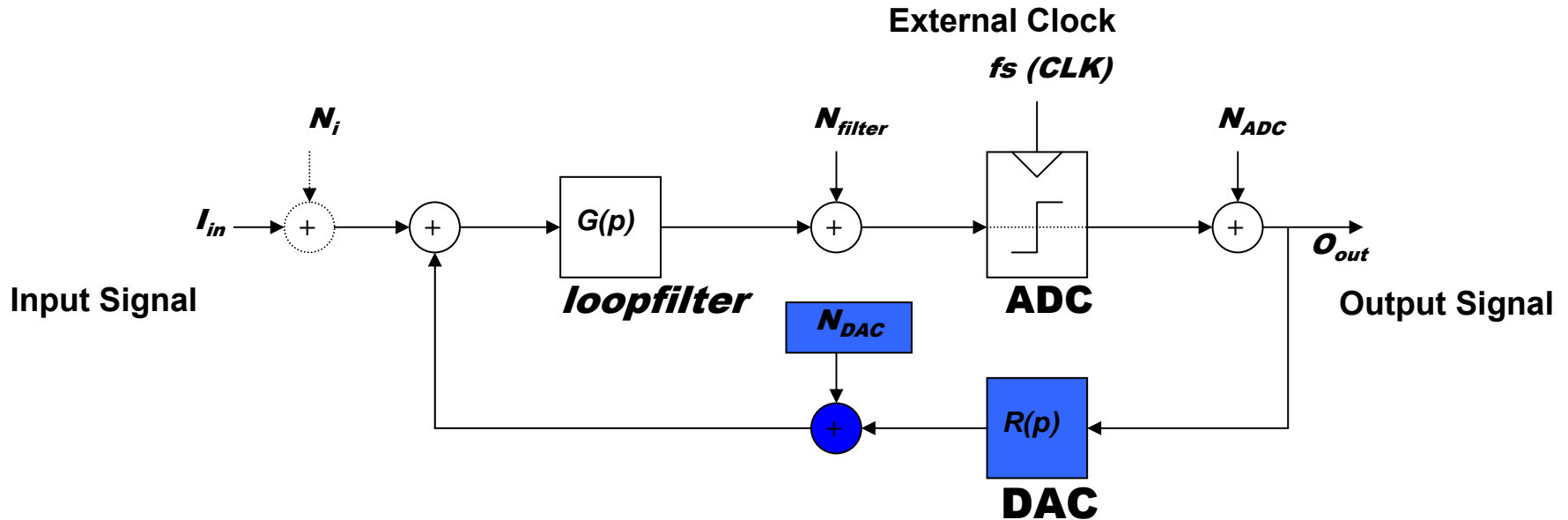
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- **DAC noise in Continuous Time Delta-Sigma Modulator**
- **Thermal Induced Inter-Symbol Interference (ISI)**
- **Top-level Model of Thermal Induced ISI in Delta-Sigma Modulators**
- **Case Study : 2<sup>nd</sup> Order  $\Delta\Sigma$  Modulator designed using IBM's 7HP BiCMOS Process**
- **Summary and Conclusion**

# Continuous Time $\Delta\Sigma$ Modulator with Noise Sources

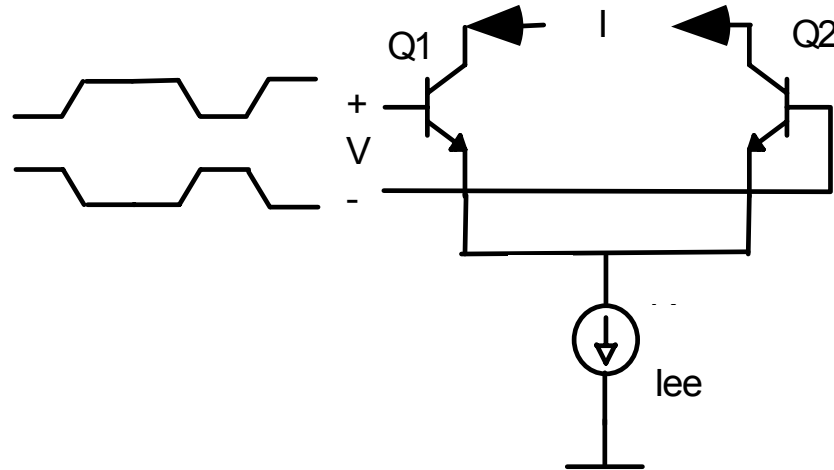


## Equivalent Input Noise Power

$$N_i = \frac{N_{filter}}{\int_{\omega=0}^{\infty} |G(j\omega)|^2} + N_{DAC}$$

**DAC noise is not reduced by loop filter gain**

# Temperature Mismatch in Current Steering DAC



## Current Steering DAC

### ON Transistor Q1

$$T_1(n) = e^{-P/\tau} T_1(n-1) + T_0(1 - e^{-P/\tau}) + \Delta T(1 - e^{-P/\tau}) | S(n-1) |$$

### OFF Transistor Q2

$$T_2(n) = e^{-P/\tau} T_2(n-1) + T_0(1 - e^{-P/\tau}) - \Delta T(1 - e^{-P/\tau}) | S(n-1) |$$

**P = Time step**

**t = Thermal time constant**

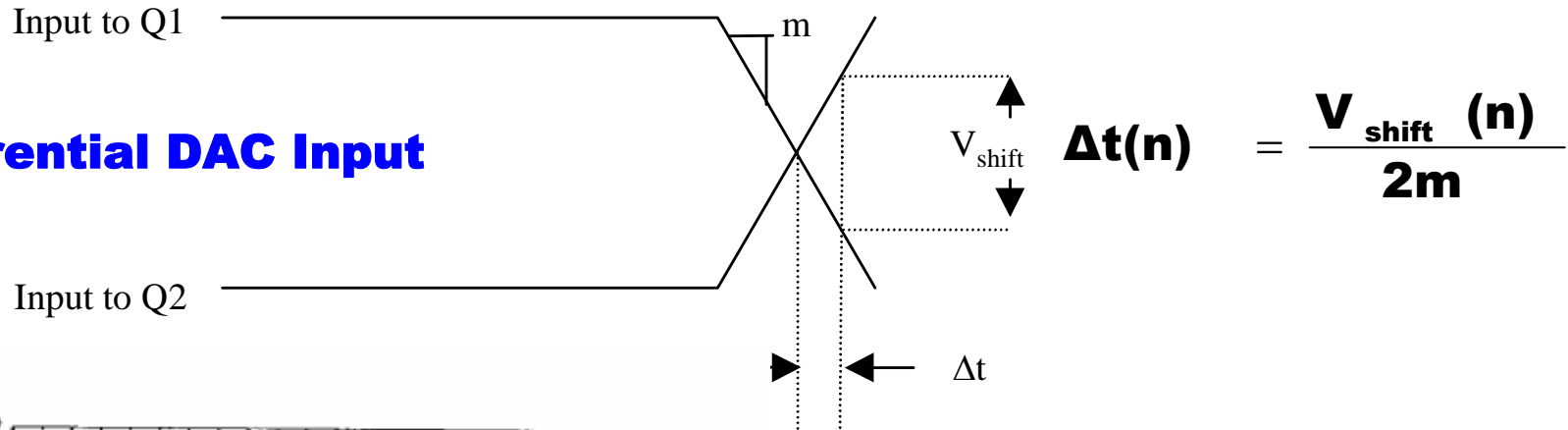
**T<sub>0</sub> = Ambient temperature**

**ΔT = Max Temperature mismatch**

**S(n) = Input Signal**

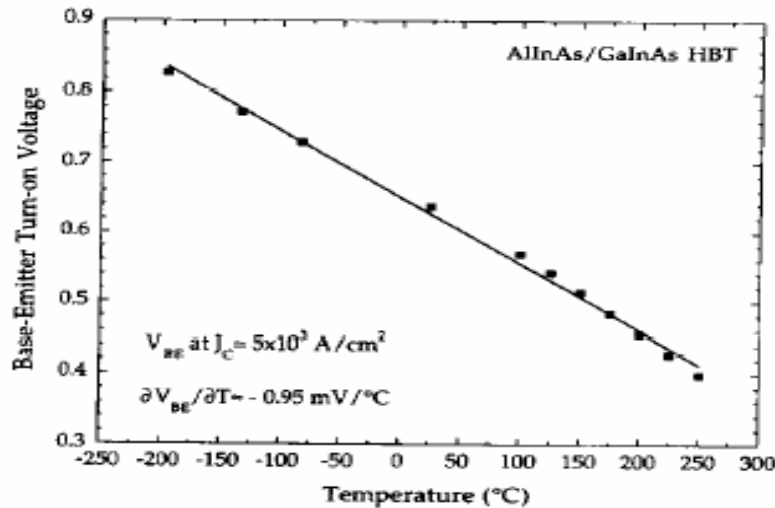
# Thermal Induced Inter-Symbol Interference

**Differential DAC Input**



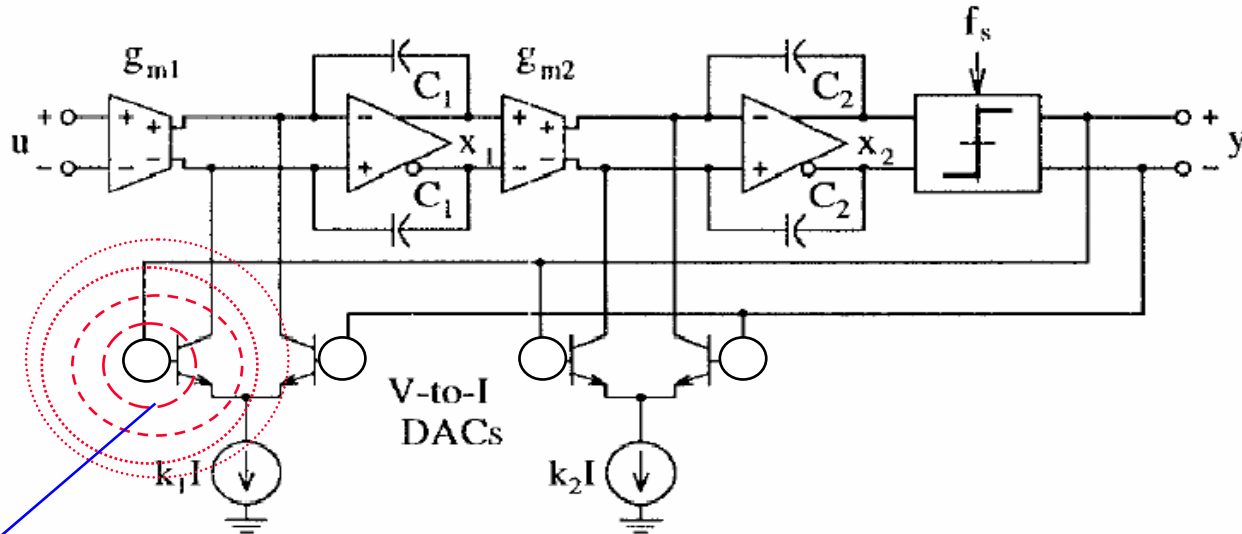
$$V_{\text{shift}}(n) = V_{\text{be1}}(n) - V_{\text{be2}}(n) = c(T_1(n) - T_2(n))$$

**Base-Emitter Voltage versus Temperature**

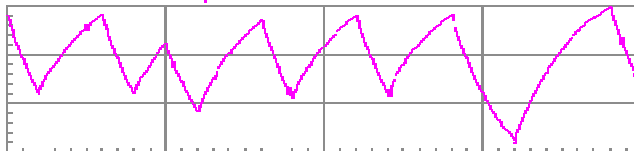


**Temperature mismatch leads to shift in switching time**

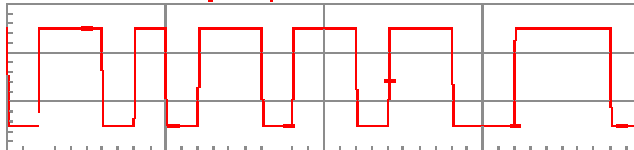
# 2<sup>nd</sup> Order Continuous Time $\Delta\Sigma$ Modulator with Thermal Induced ISI



$T$ : Device Temperature



$u$ : Model Voltage Input

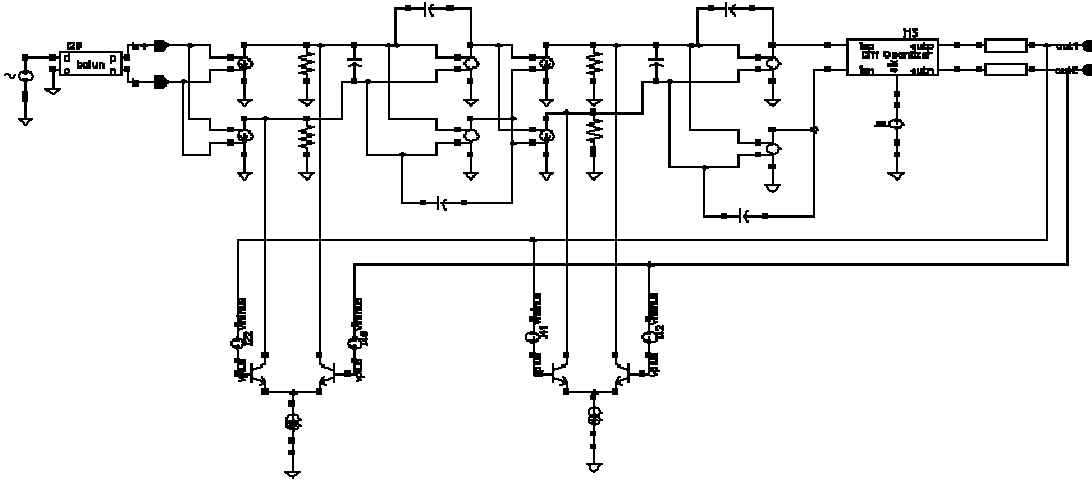


<b>Thermal Time constant</b>	<b>2 ns</b>
<b>Quantizer Output Rise/Fall Time</b>	<b>50ps/50ps</b>
<b><math>dV_{be}/dT</math></b>	<b>1.11 mV/°C</b>
<b>Time-Step</b>	<b>50ps</b>
<b>Ambient Temperature (<math>T_0</math>)</b>	<b>310°K</b>
<b>Min-Max equilibrium Temp</b>	<b>300°K-320°K</b>

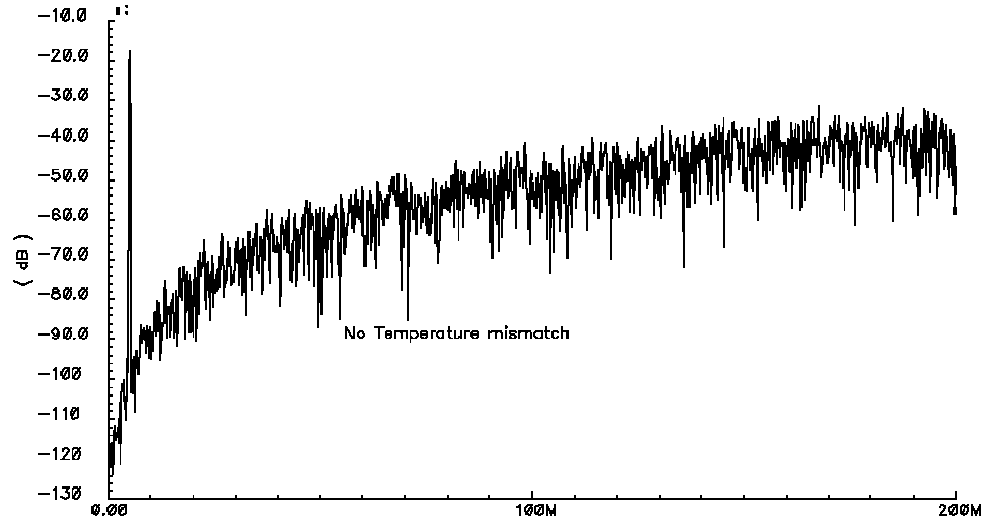
# Baseline Behavioral Model

## Parameters for 2nd Order CTΔΣ modulator

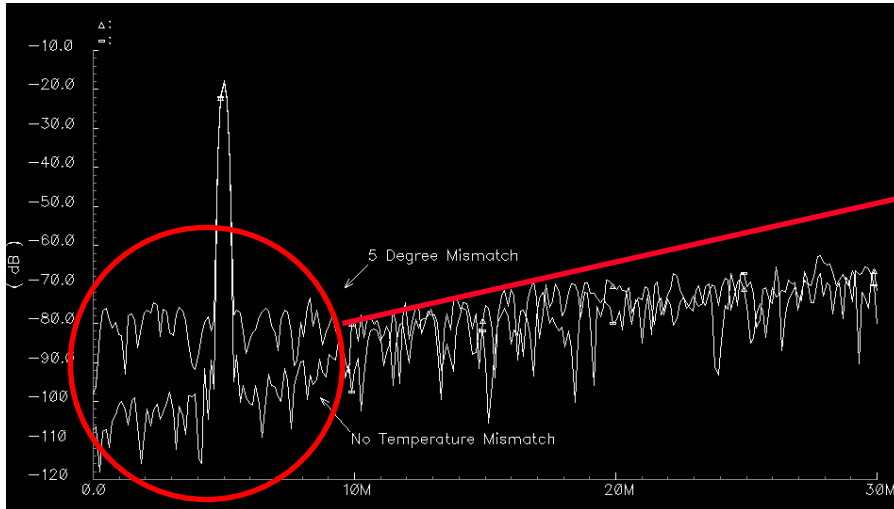
$G_{m1}$	500uA/V	$G_{m2}$	500uA/V
$C1$	2pF	$C2$	2pF
$K_1$	2.13mA	$K_2$	1.34mA
$f_s$	1 GHz	$f_{in}$	5MHz



## Frequency Spectrum No Temperature Mismatch



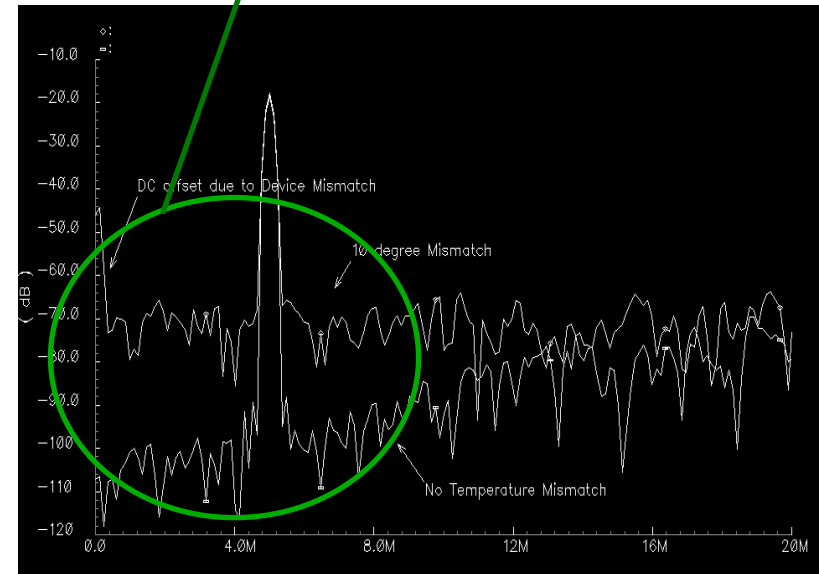
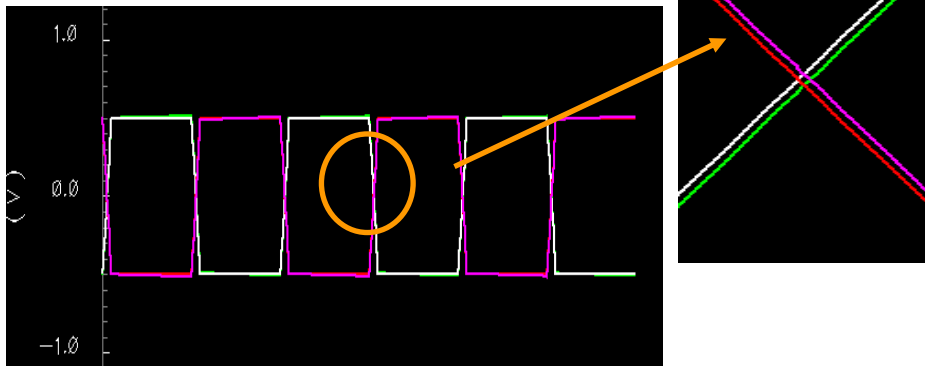
# Simulation Results using Baseline Model



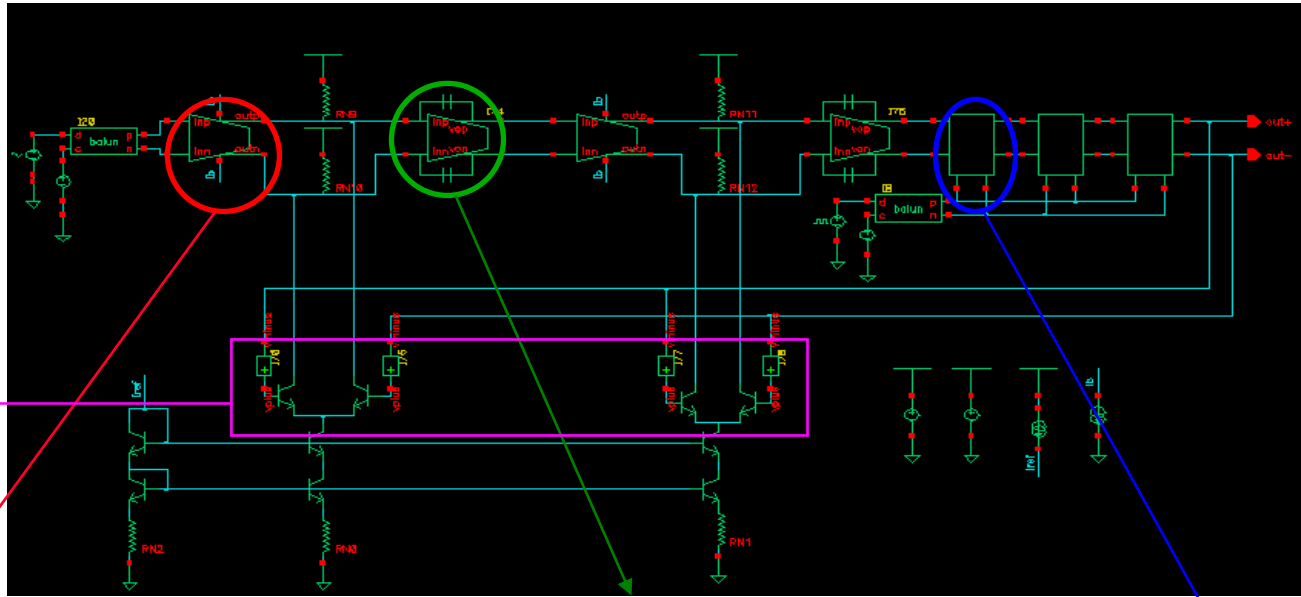
**5°C Temperature mismatch causes 10 dB degradation in SNR**

**10°C Temperature mismatch causes 15 db degradation in SNR**

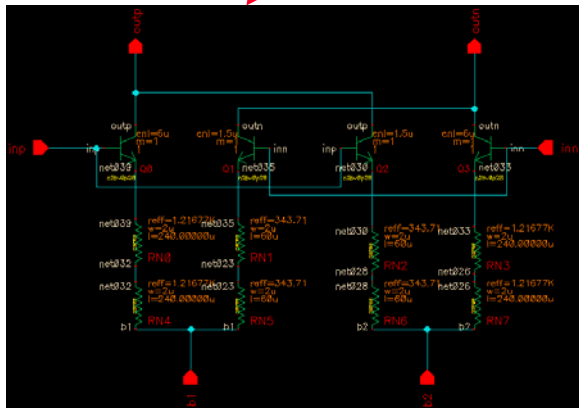
**Output showing shift in  $\Delta t$**



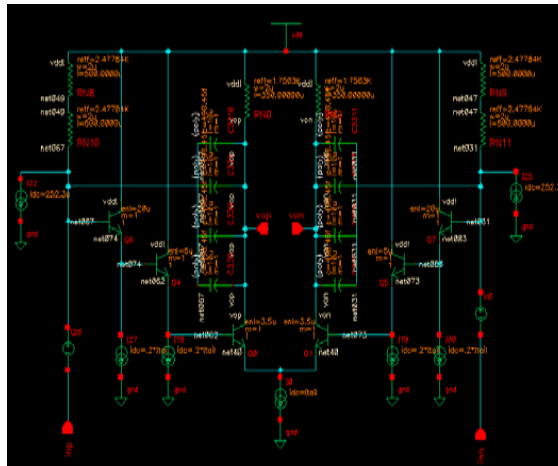
# Transistor-level Model : 2<sup>nd</sup> Order $\Delta\Sigma$ Modulator with IBM's 7HP BiCMOS Process



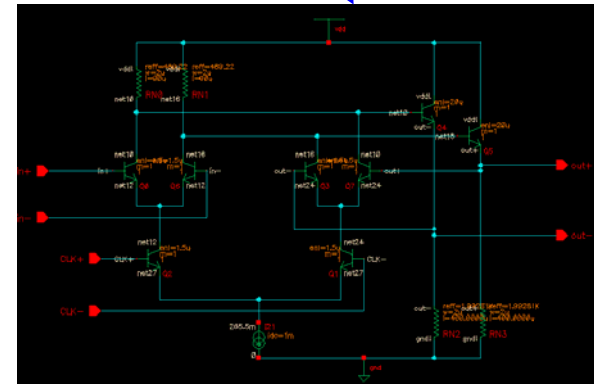
**DAC with Thermal Induced ISI model**



**Gm-Cell**

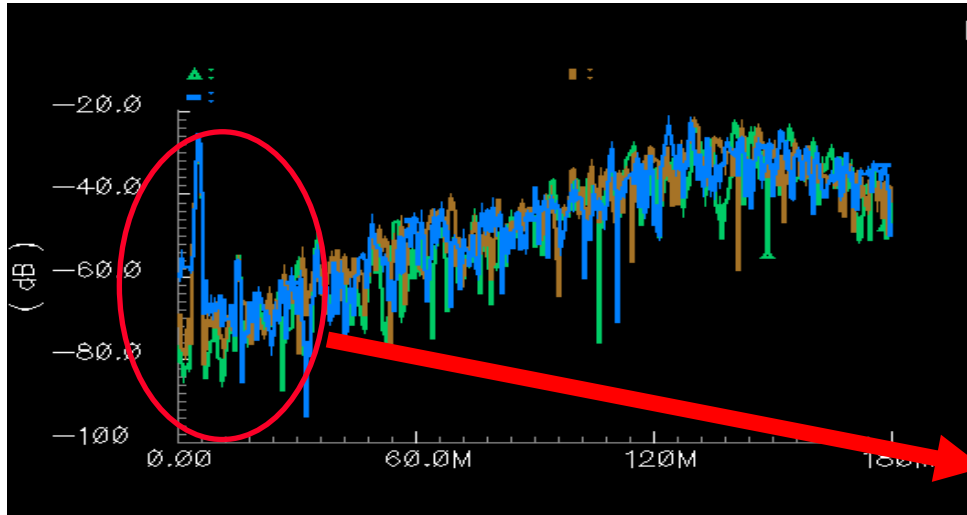


**Differential Integrator**

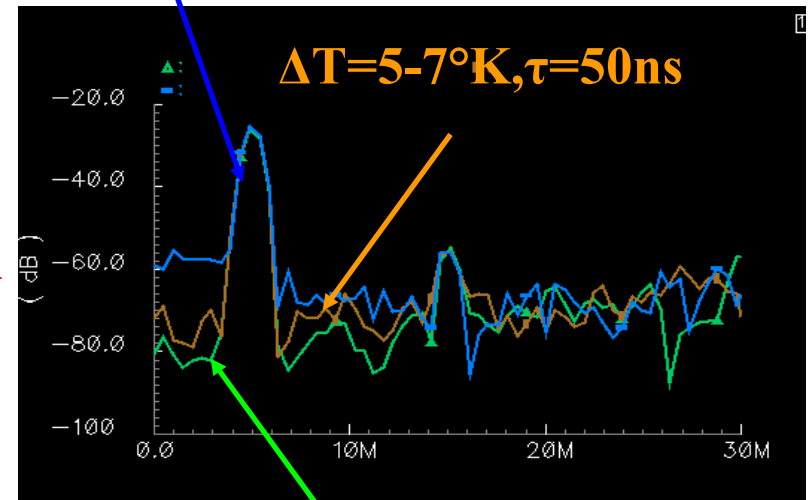


**Latch**

# Transistor-level Simulation Results

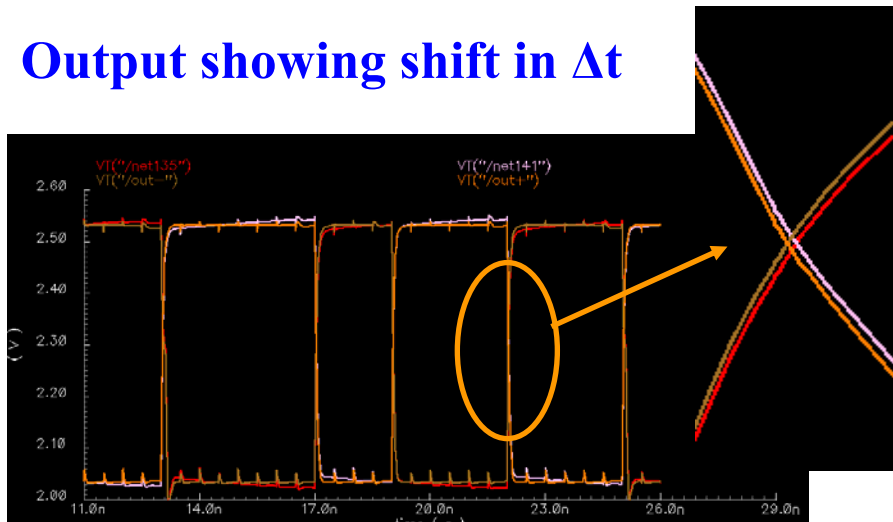


$\Delta T=10-15^{\circ}\text{K}, \tau=5\text{ns}$



$\Delta T=5-7^{\circ}\text{K}, \tau=50\text{ns}$

Output showing shift in  $\Delta t$

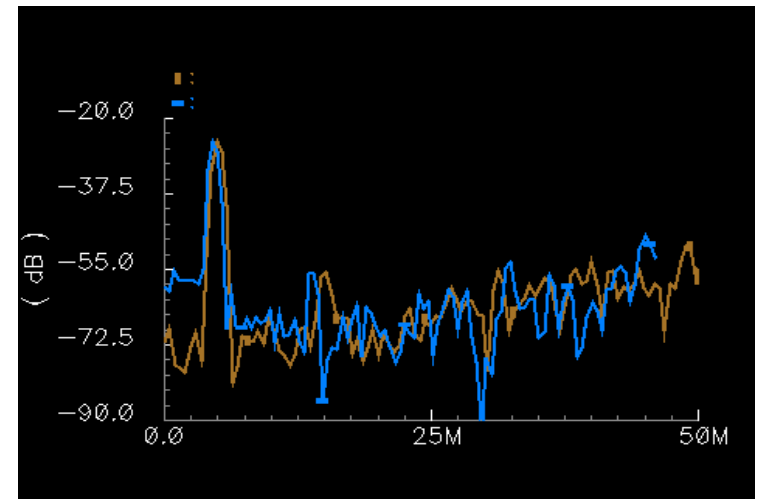
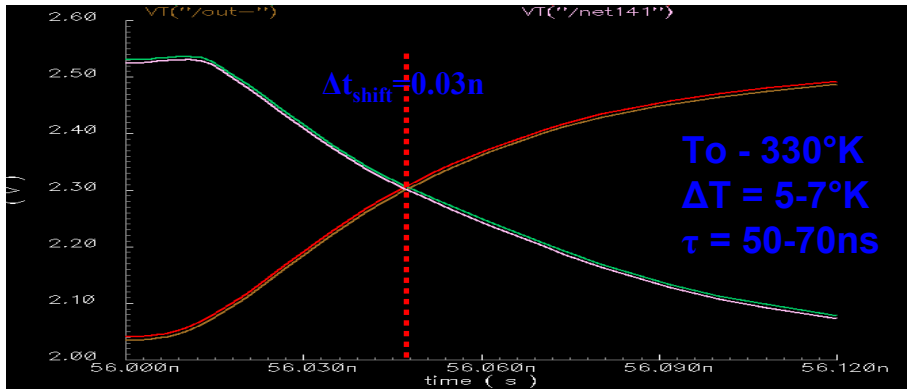
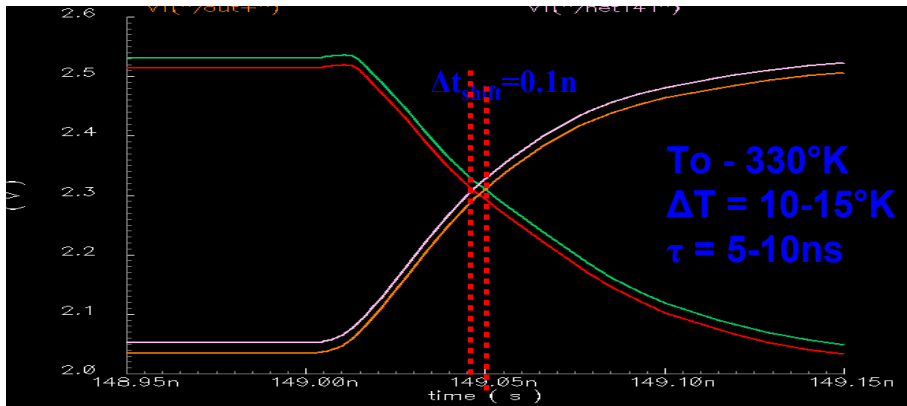


No Temperature Mismatch

# SNR Degradation and Switching Distortion

$$= \frac{\sqrt{\sigma}}{\sigma}$$

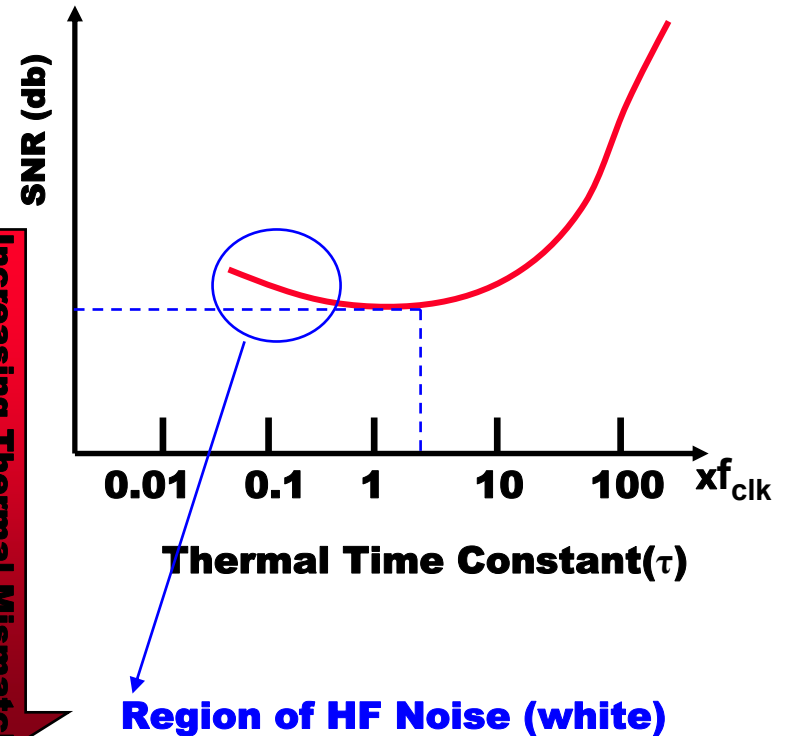
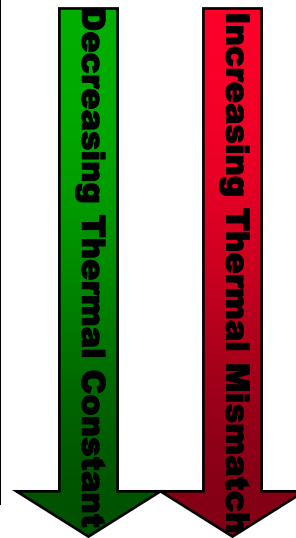
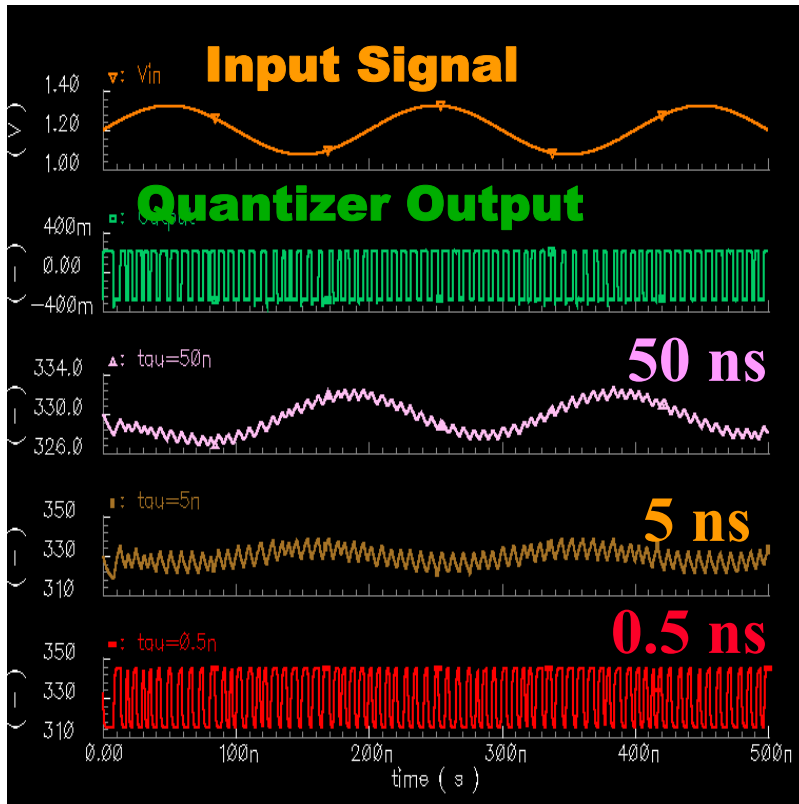
OSR = Oversampling ratio  
 $\sigma_T$  = Max Time shifts in seconds  
 $f_{in}$  = Input frequency



$$\text{SNR}_{\tau=5\text{ns}} - \text{SNR}_{\tau=50\text{ns}} = 20 \log \frac{\sigma_{\tau=5\text{ns}}}{\sigma_{\tau=50\text{ns}}} \approx 10\text{dB}$$

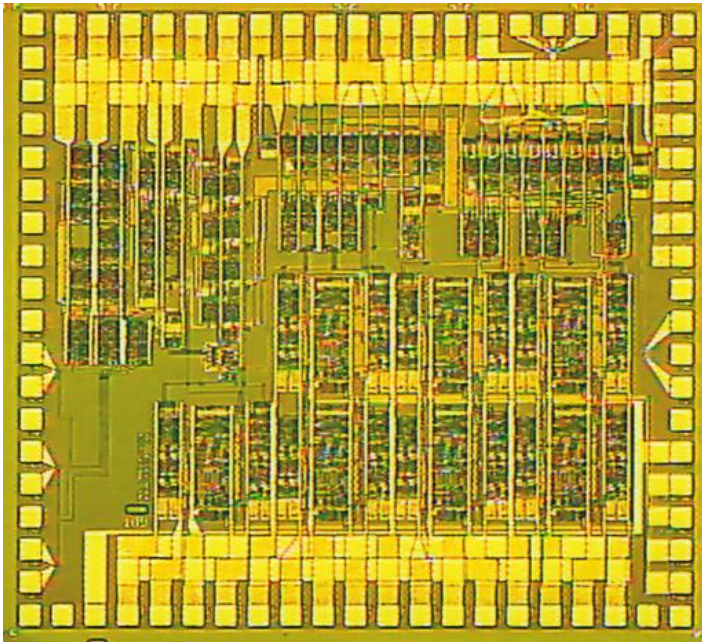
**SNR degradation is dependent on Switching distortion**

# SNR and Thermal Time Constant



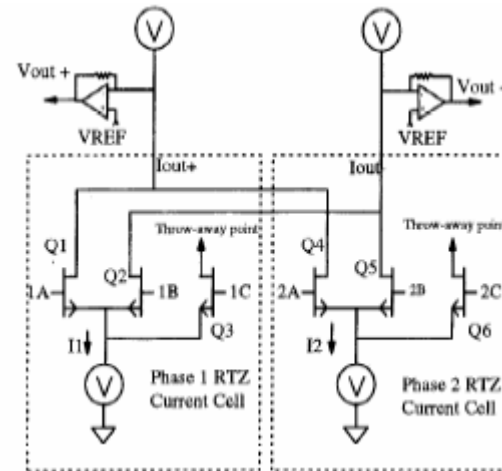
**Decreasing Thermal Time Constant  
Results in Lower Input-Correlated Noise**

# Compensation Strategies to Mitigate DAC Noise



**3-bit, mismatch-shaped  $\Delta\Sigma$  modulated DAC generates tunable narrowband signal between 250 MHz and 750 MHz With 68dB SNR and 74 dB SFDR (T. Kaplan, et.al, ISSCC 2004)**

- **With Bleeder Transistors for Uniform Heating (Adams et. al. ISSCC, 1996), (Cosand, patent, HRL)**



- **Pulse Shaped DAC architectures (B. Zhang et.al, 1996) (S. Luschas et.al, 2002)**

# Summary and Conclusion

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- **Controlling Thermal induced Intersymbol interference is critical to achieving high resolution  $\Delta\Sigma$  Modulator**
- **Increasing thermal response time of current-mode differential DACs reduces ISI**
- **Decreasing Thermal Time Constant results in lower Input-Correlated Noise**
- **Transistor-level simulations using BiCMOS process validate Physics-based behavioral models**