BROWN

School of Engineering

A 14.4nW 122KHz Dual-phase Current-mode Relaxation Oscillator for Near-Zero-Power Sensors

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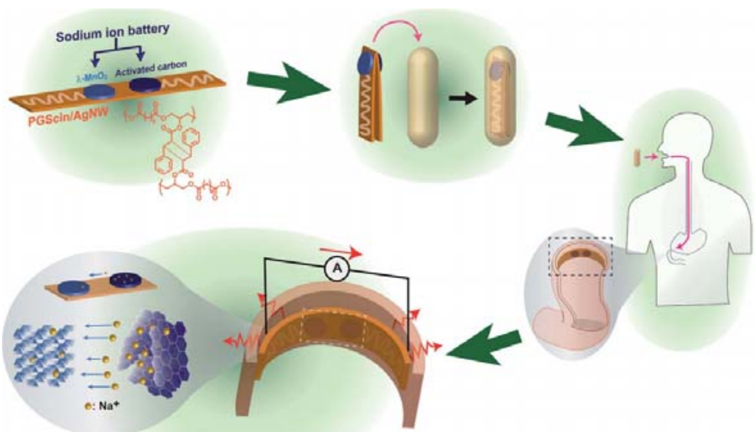
Custom Integrated Circuits Conference (CICC) 2015

Motivation

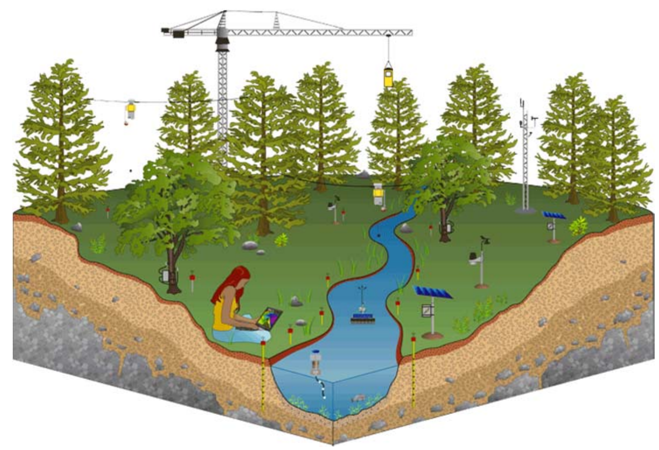
Consider the power limits of ultra-low-power or low-duty-cycle sensor nodes.

Wearable/Implantable/Ingestible Biosensors



Kim et al., *J. Materials Chemistry B 2013*

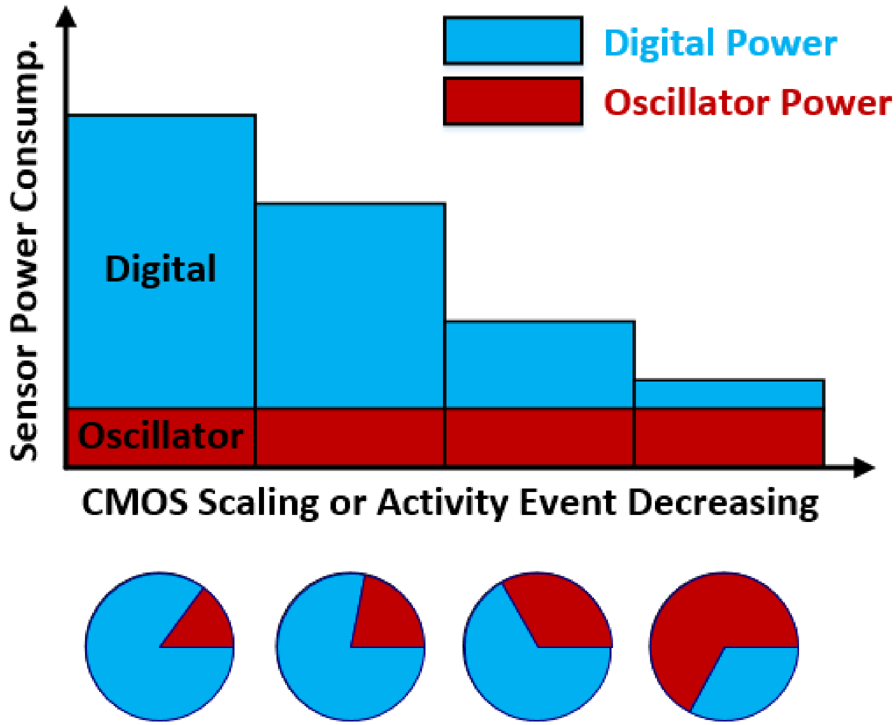
Environmental/Security Monitoring



UW-Wisconsin CSLS 2007

Motivation

When digital power approaches zero, what is left?

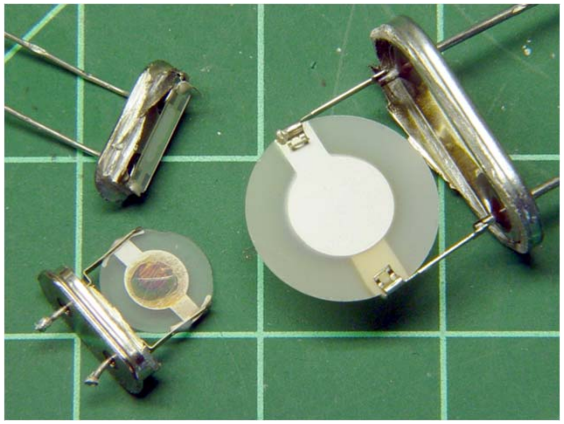


→ Timers and oscillators often do not benefit directly from technology scaling, both in terms of power and size

Low-power oscillators

Options:

- Piezo/crystal osc
- Ring osc
- Relaxation osc

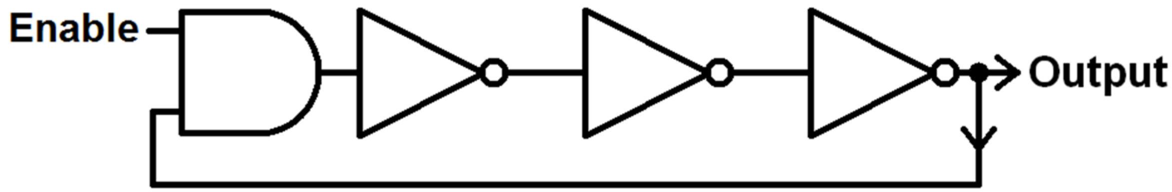


- Wide frequency range, kHz-GHz
- Excellent frequency accuracy
- Excellent temperature stability
- Large size
- Good power efficiency

Low-power oscillators

Options:

- Piezo/crystal osc
- Ring osc
- Relaxation osc

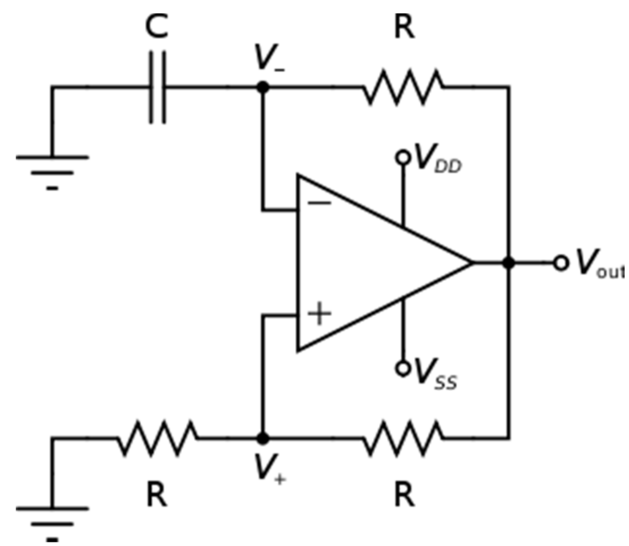


- Worse frequency accuracy
- Worse temperature stability
- Very small, standard CMOS
- Good power efficiency

Low-power oscillators

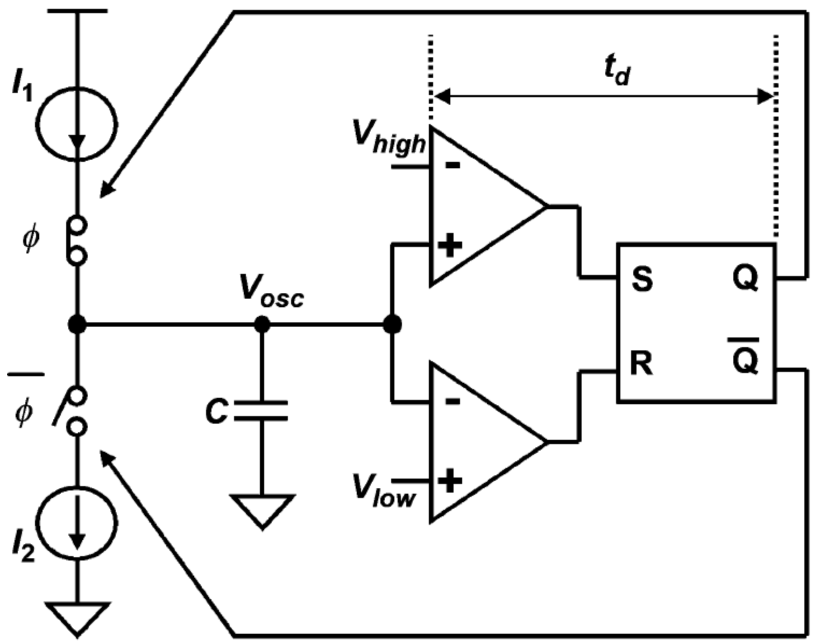
Options:

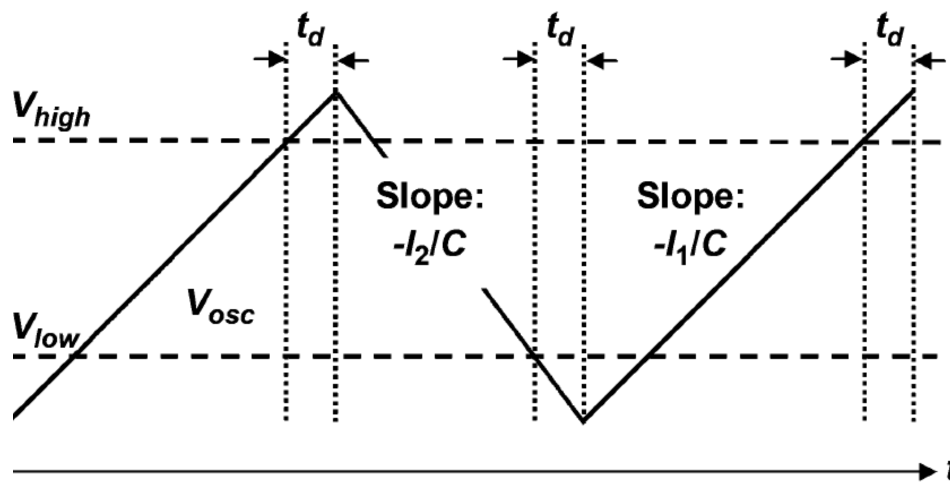
- Piezo/crystal osc
- Ring osc
- Relaxation osc



- Typically slower than crystal osc
- Moderate frequency accuracy
- Moderate temperature stability
- Small size, standard CMOS
- Moderate power efficiency

Voltage-mode Relaxation Oscillator



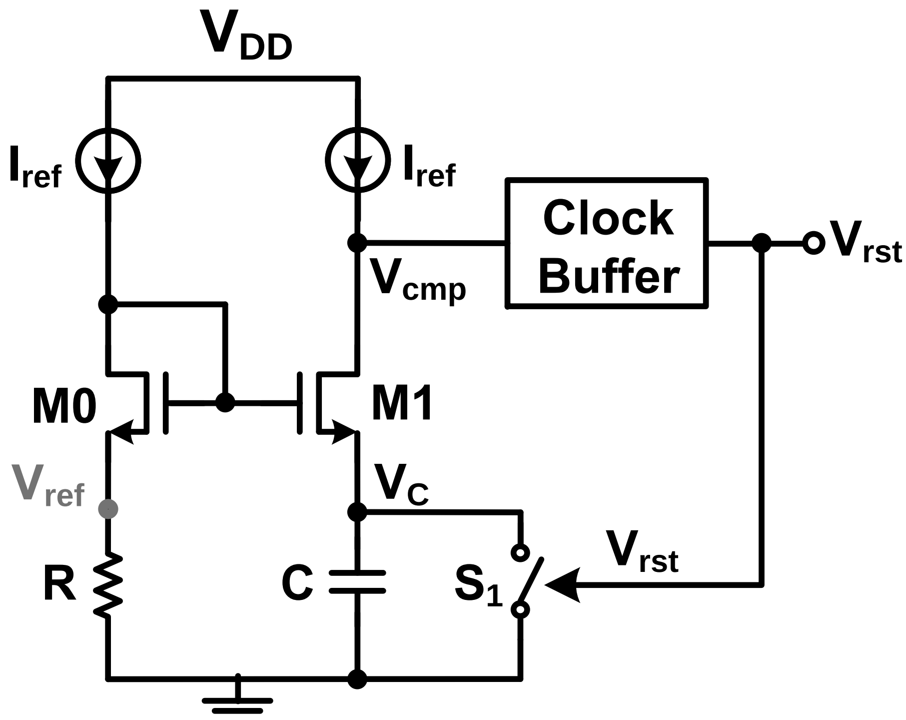


$$T = \frac{V_{high} - V_{low}}{I_1/C} + \frac{V_{high} - V_{low}}{I_2/C} + 2t_d$$

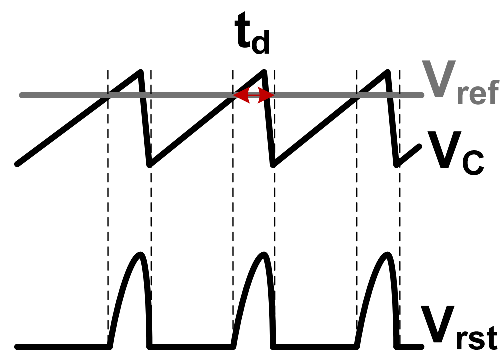
→ Most of the power is dissipated by the two comparators

Tokunaga et al ISSCC 2009

Current-mode Relaxation Oscillator



Denier et al TCAS-I 2010
Hsiao et al VLSI 2012
Chiang et al TCAS-II 2014

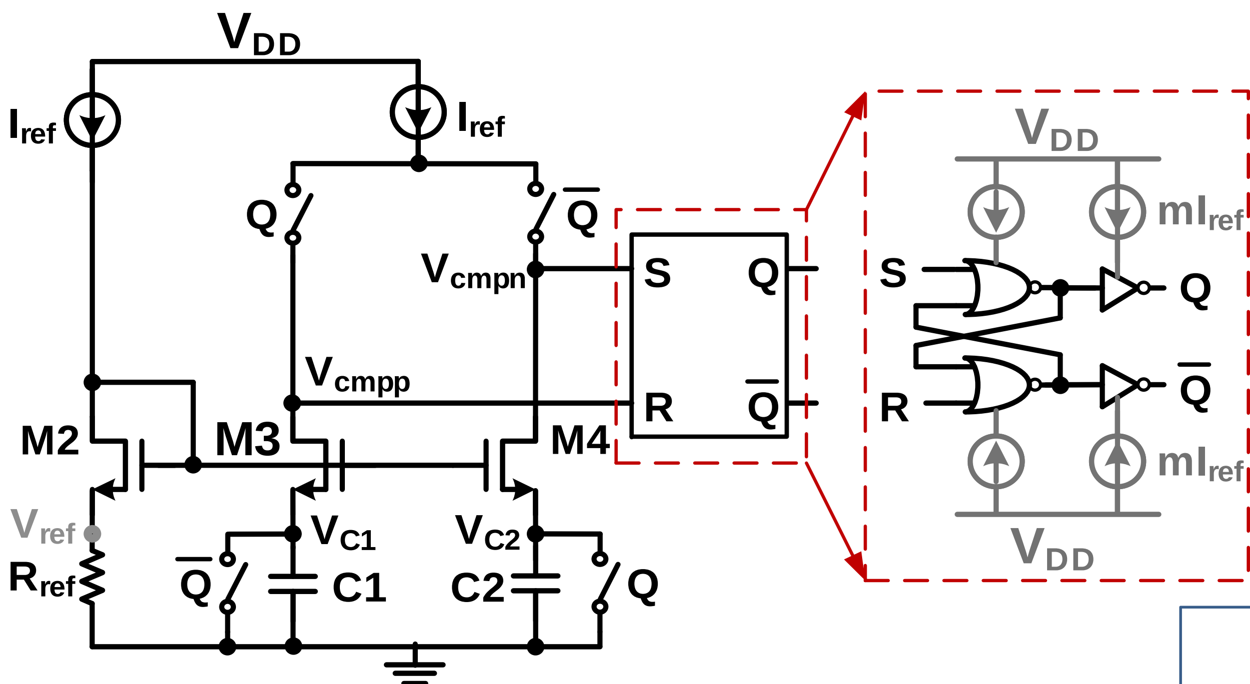


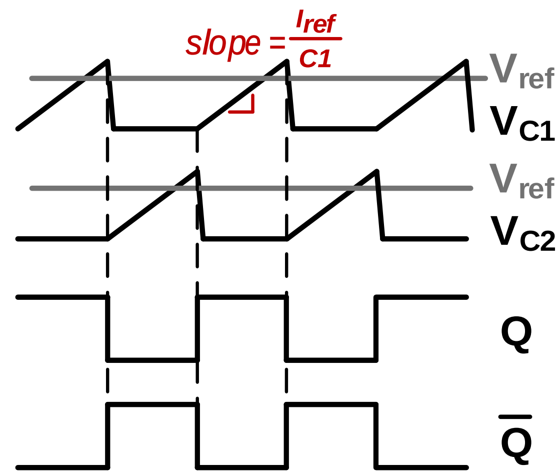
$$T_{rst} = \frac{V_{ref}}{I_{ref}/C} + t_d$$

$$T_{clk} = \frac{2V_{ref}}{I_{ref}/C} + 2t_d$$

- Pros: re-use bias current as charging curent – save power!
- Cons: not rail-to-rail; narrow pulse width; need a flip flop to get a 50% duty cycle signal.

Proposed Oscillator



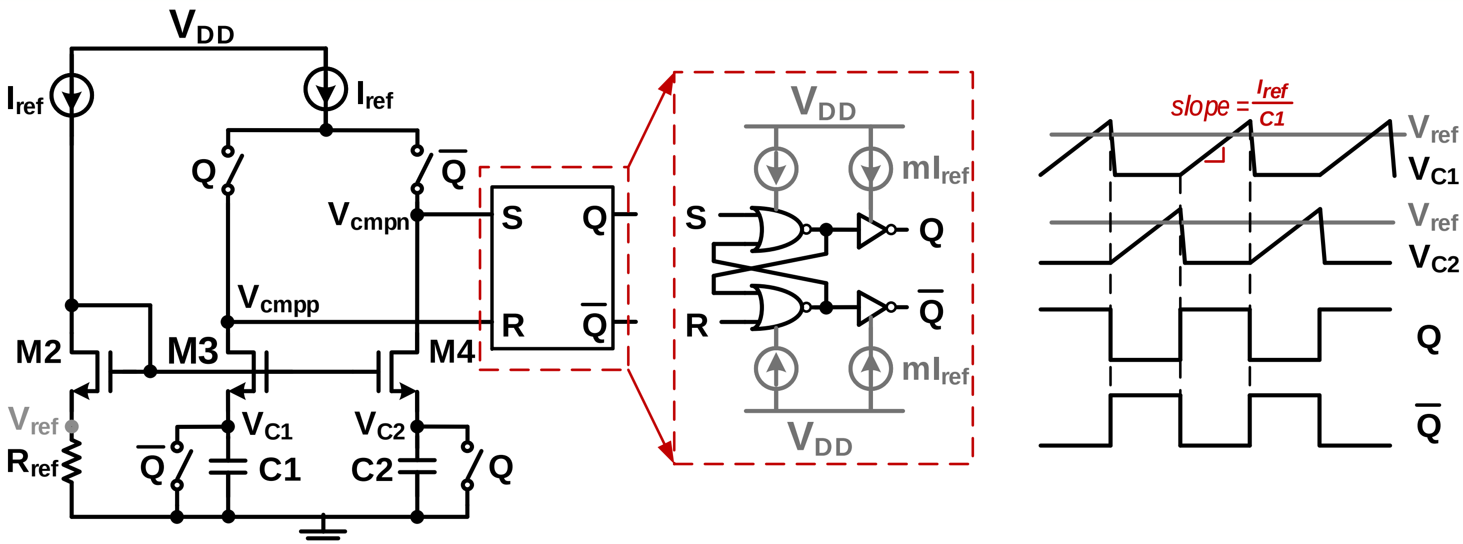


→ **Power alternates between two branches**
→ **Rail-to-rail, 50% duty cycle output**
→ **Capacitor reset delay does not add to the period**

$$T = \left(\frac{V_{ref}}{I_{ref}/C} + \overbrace{\tau_{M3,4} + \tau_{RS}}^{\text{delay}}\right) \times 2$$
$$= \left(R_{ref} \cdot C + \tau_{M3,4} + \tau_{RS}\right) \times 2$$

(where $V_{ref} = R_{ref} \cdot I_{ref}$)

Temperature Compensation



$$Clock\ Period\ T = \left(R_{ref} \cdot C + \tau_{M3,4} + \tau_{RS}\right) \times 2$$

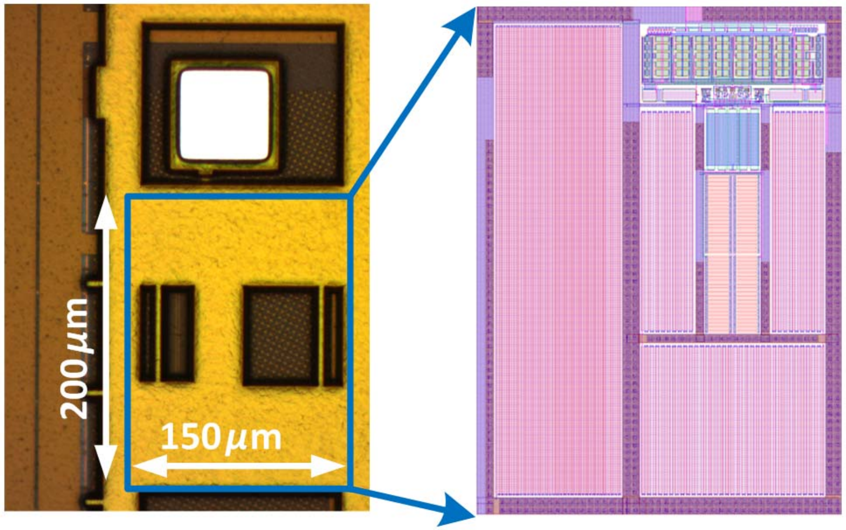
Temperature ↑, R_{ref} ↑, Period ↑

Temperature ↑, slew rate at $V_{cmpp,n}$ ↓, Period ↑

Temperature ↑, digital delay ↓, Period ↓

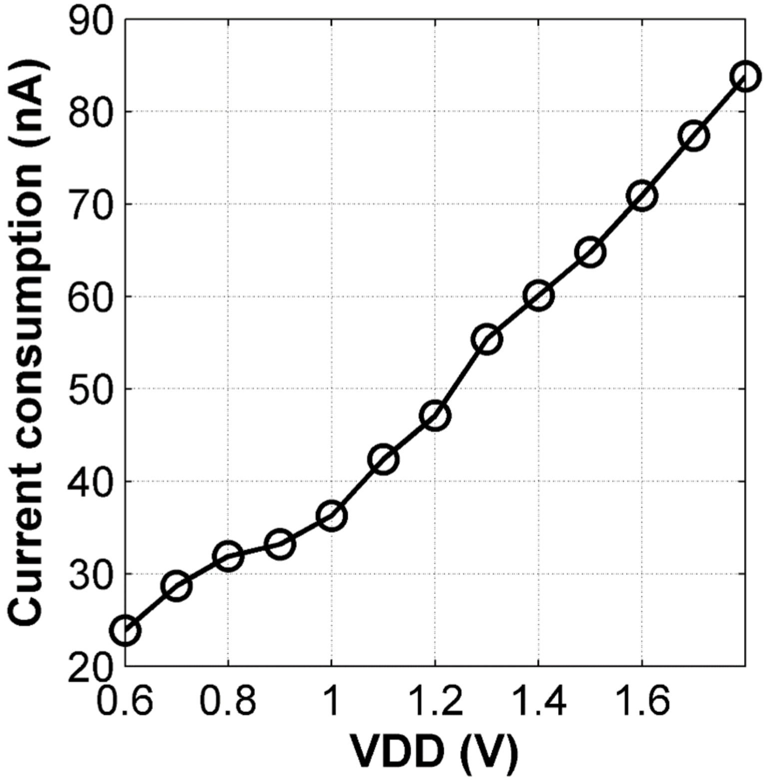
Implementation

Main circuit parameter	Value
Vdd	0.6V—1.8V
Iref	6 nA
Rref	1.5 MΩ
C	0.5 pF



- **Total area: 0.03mm^2**
- **IBM 0.18µm technology**

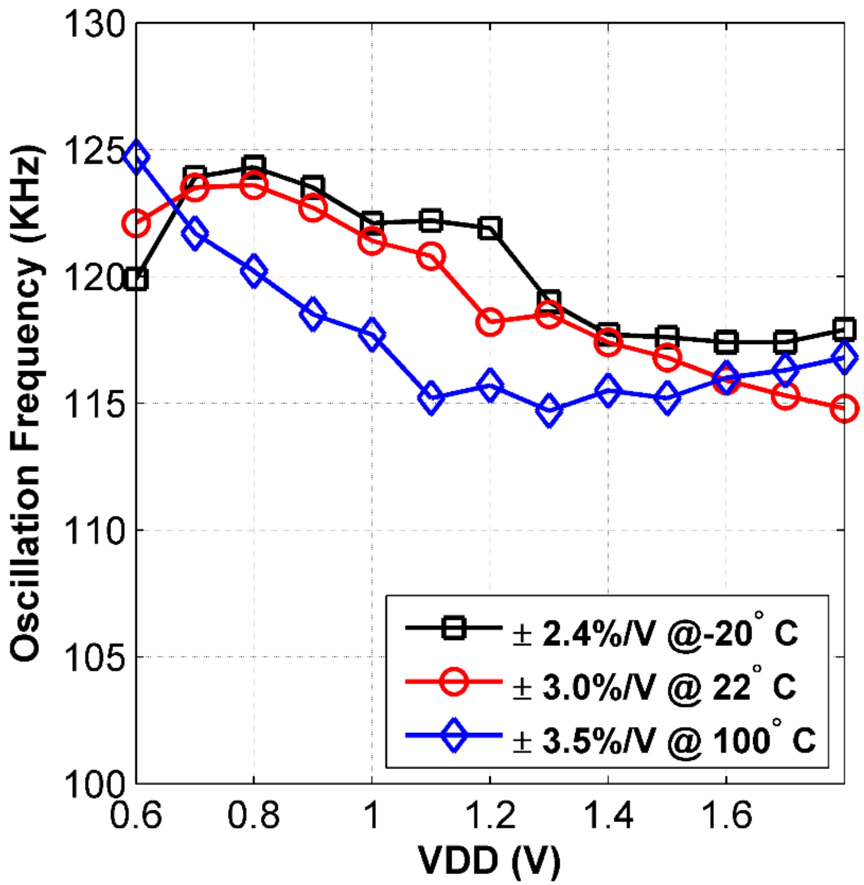
Current consumption vs Vdd



Ref.	Freq. (kHz)	Power (nW)	Power/f (nW/kHz)
U. Denier, TCAS I'10	3.3	11	**4.0**
Y.H.Chiang, TCAS II'14	1,400	615	**0.44**
T. Tokairin, VLSI'12	100	280	**2.8**
N. Sadeghi, TCAS I'13	1,000	428,000	**428**
K. Choe, ISSCC'09	3,200	38,400	**12**
A. Paidimarri, ISSCC'13	18.5	120	**6.49**
D. Griffith, ISSCC'14	33	190	**5.76**
This work	**122**	**14**	**0.12**

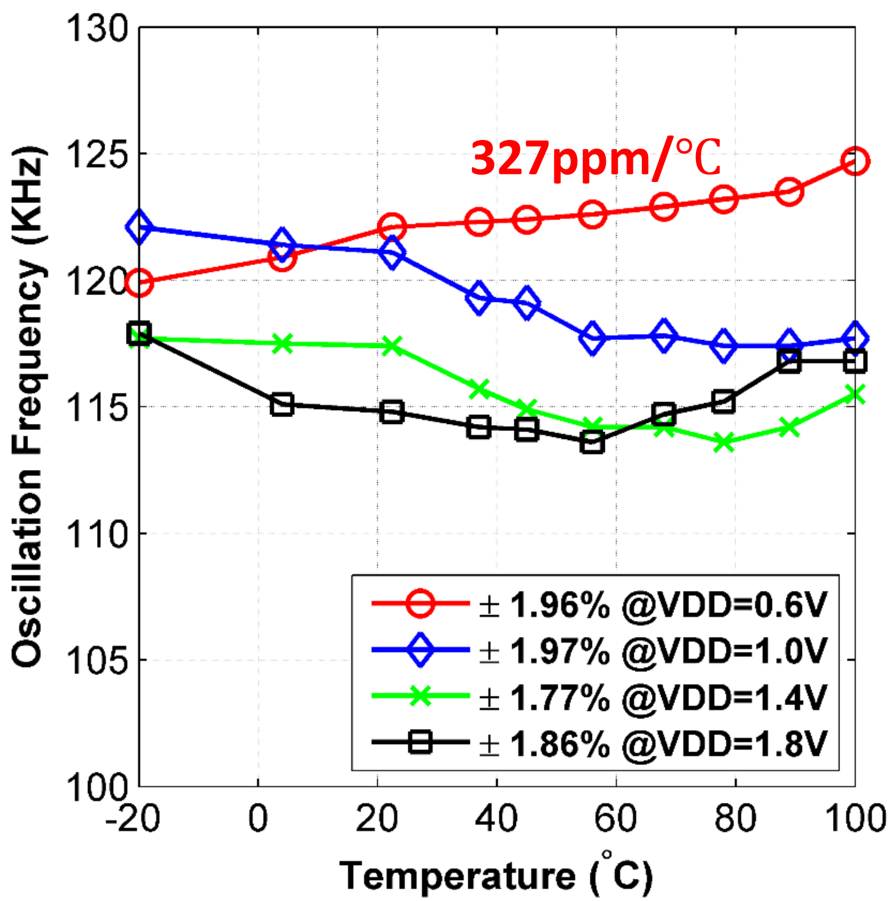
Current Consumption: 24nA@VDD=0.6V, including reference current generator (~6nA) and digital dynamic power (~5nA).

Oscillation frequency versus Vdd



Ref.	Freq. variation
U. Denier, TCAS I'10	**3.5%/V** (1-2.5 V)
Y.H.Chiang, TCAS II'14	**<3%/V** (1-2V)
T. Tokairin, VLSI'12	**9.37%/V** (0.725-0.9V)
N. Sadeghi, TCAS I'13	**2.2%/V** (2-3V)
K. Choe, ISSCC'09	**4%/V** (1.4-1.6V)
A. Paidimarri, ISSCC'13	**1%/V** (1.5-3.3V)
D. Griffith, ISSCC'14	**0.09%/V** (1.15-1.45V)
This work	**6%/V (0.6-1.8V)**

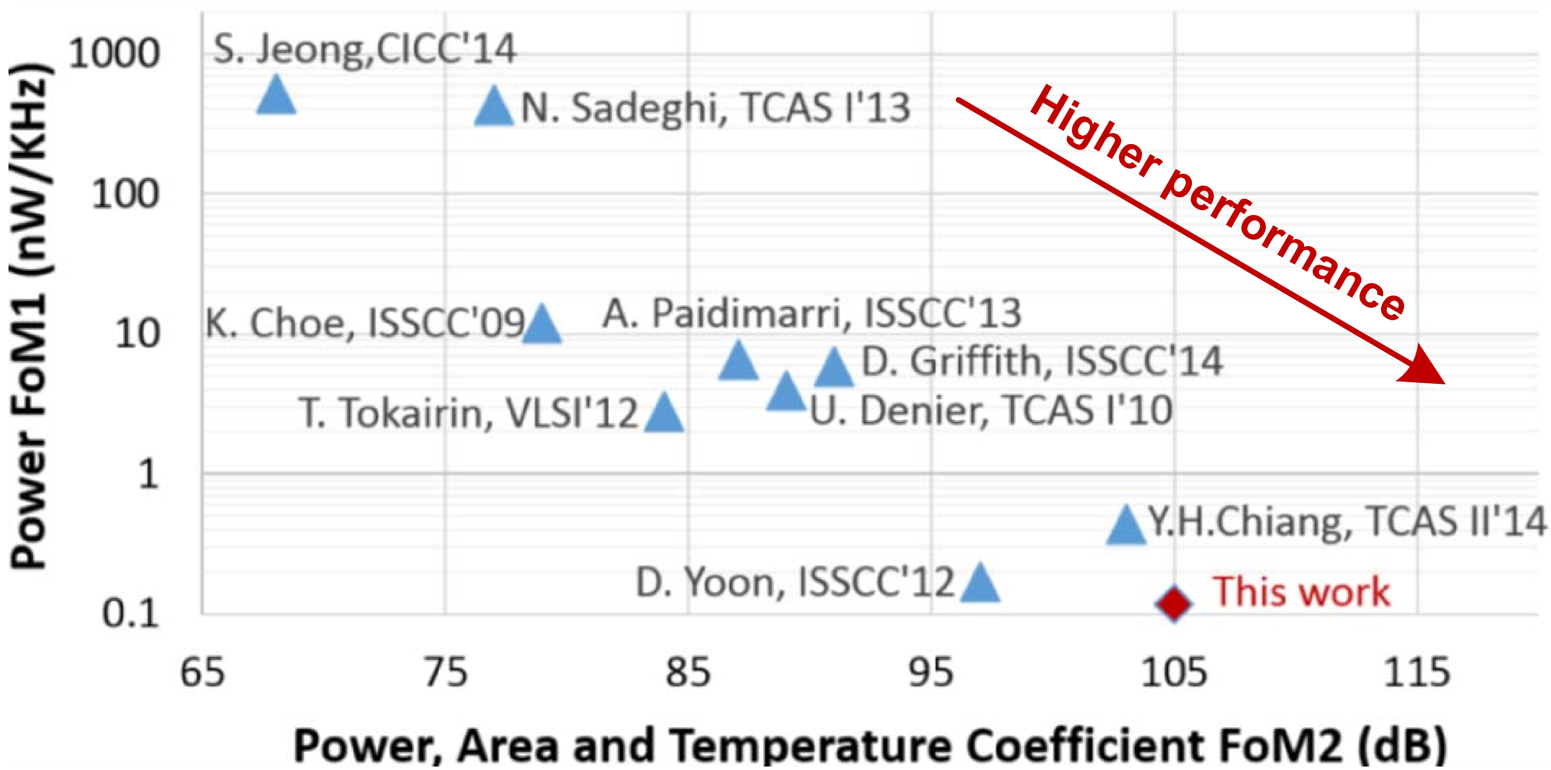
Oscillation frequency versus temp.



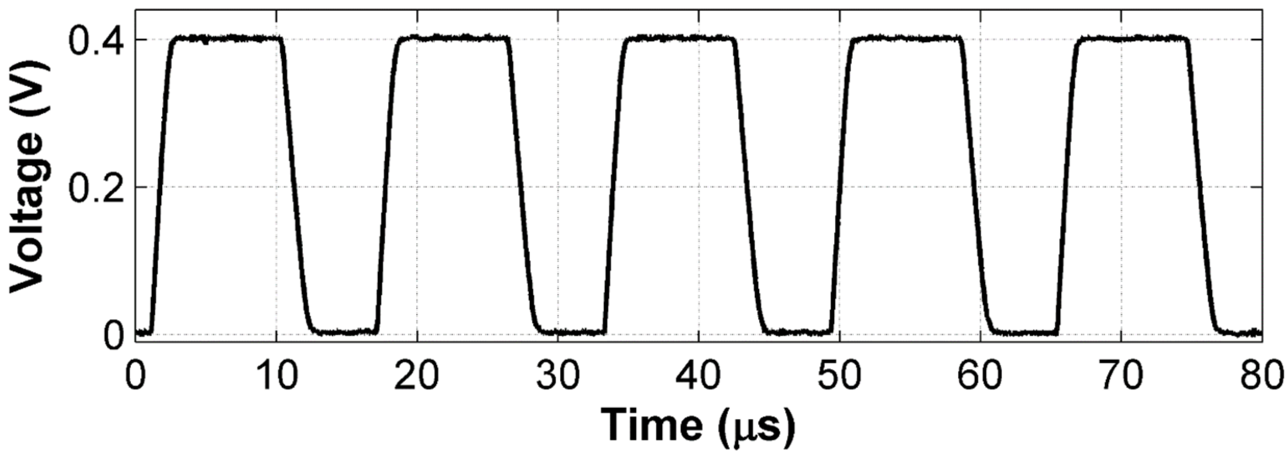
Ref.	Temp. coeff. (ppm/)
U. Denier, TCAS I'10	<500
Y.H.Chiang, TCAS II'14	56.4
T. Tokairin, VLSI'12	105
N. Sadeghi, TCAS I'13	108
K. Choe, ISSCC'09	125
A. Paidimarri, ISSCC'13	38.5
D. Griffith, ISSCC'14	38.2
This work	**327**

Figures of Merit

$$FoM1 = \frac{Power}{f_{osc}} \qquad FoM2 = 10\,log_{10}\left(\frac{f_{osc}\cdot L_{min}^{2}}{power\cdot TC\cdot Area}\right)$$



Still functional at $V_{DD} = 0.4\ V$

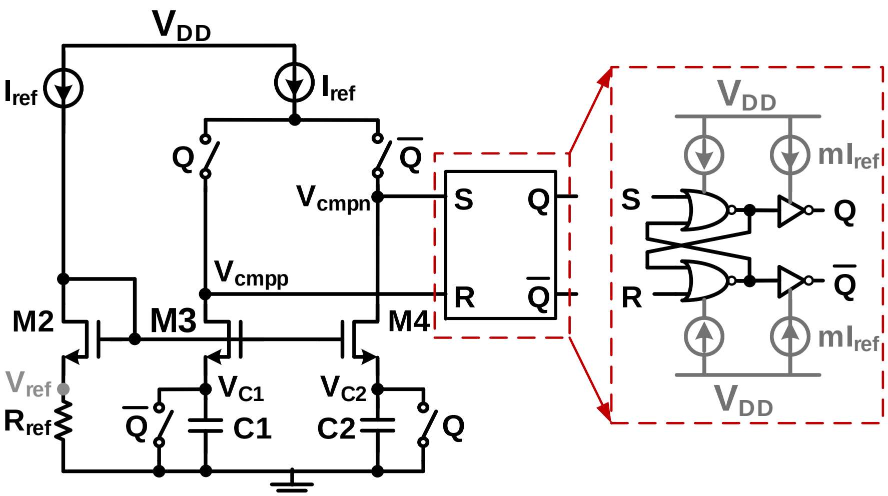


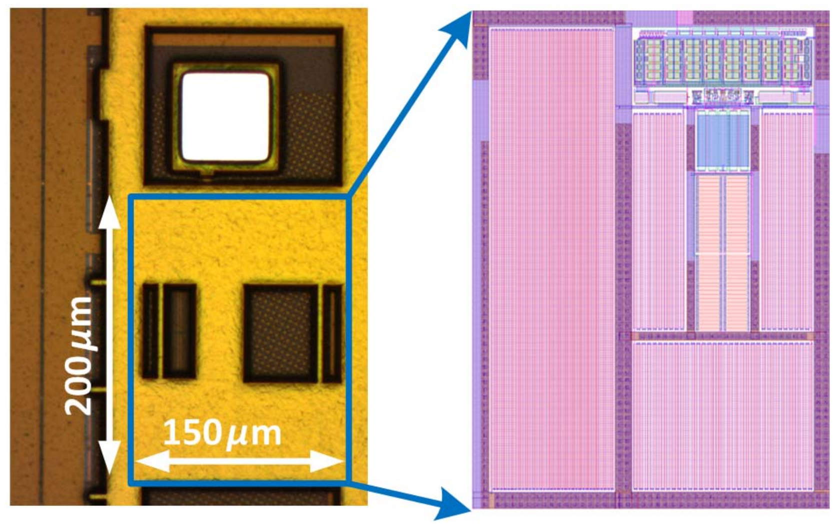
- Vdd = 0.4V, f_{osc} = 62.5 KHz, P = 4.2 nW
  → FoM1 = 67 pW/KHz

(but notice f_{osc} has reduced dramatically from 122KHz @ 0.6V)

Summary (0.6V-1.8V)

Frequency	Power consump.	Supply voltage	Temp. coefficient	Frequency variation against vdd
122KHz	14.4nW@Vdd=0.6V	0.6V—1.8V	327 ppm/	6 %/V





Thanks!

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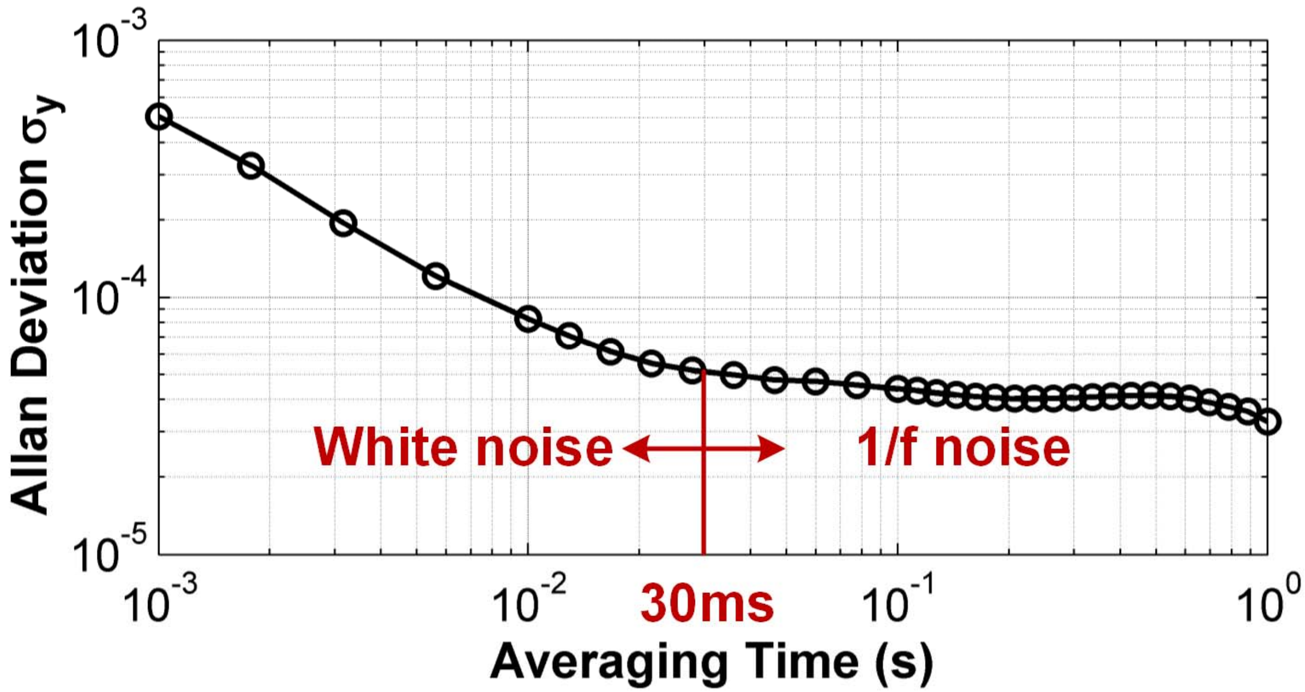
http://rosenstein.engin.brown.edu/

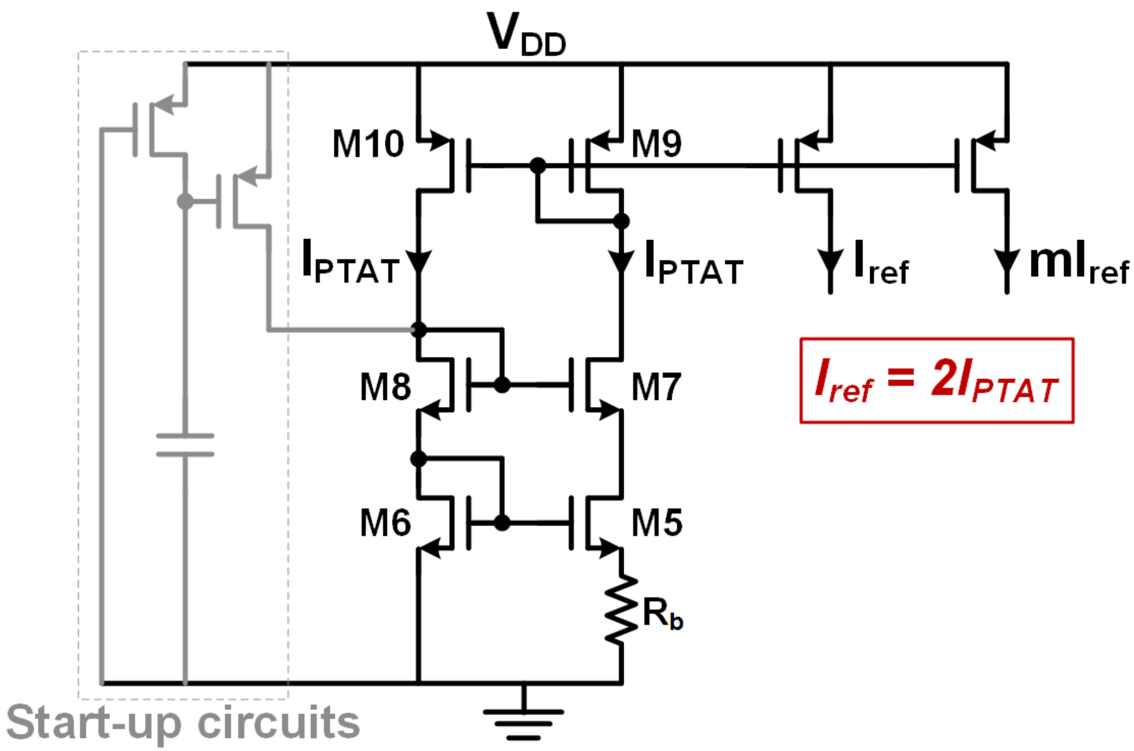
(backup slides)

Allan Deviation



- Measured Allan deviation floor is 40 ppm.

Current Reference Generator



$I_{ref} = 2I_{PTAT}$