Session 22 – Sensors and Integration

A 2-in-1 Temperature and Humidity Sensor Achieving 62 $fJ \cdot K^2$ and 0.83 $pJ \cdot (\%RH)^2$

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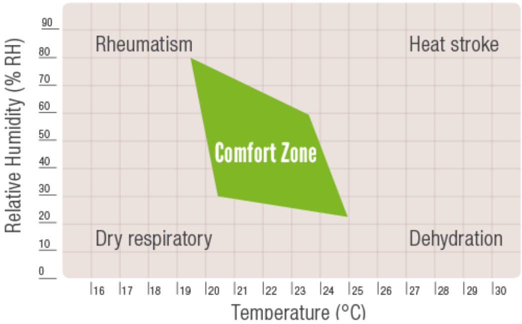
Motivation: Environmental Sensing

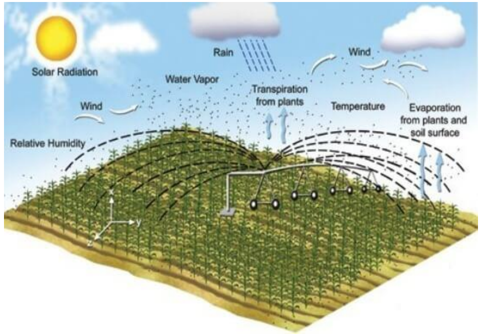
Relative humidity and temperature (RH/T) monitoring applications:

Climate control systems



RFID tags in food chain

Weather stations



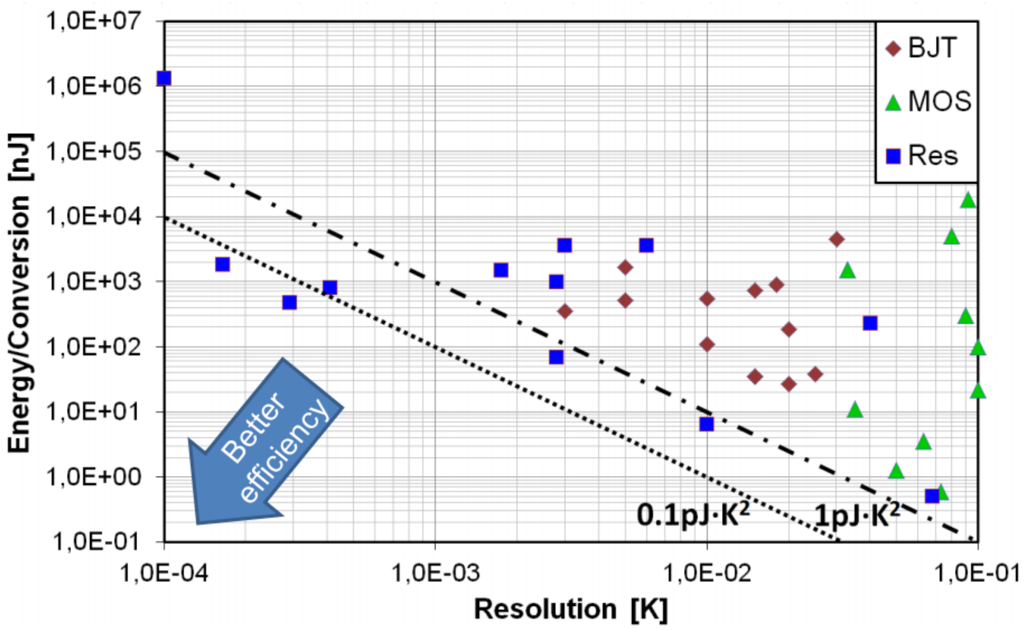
<u>Need:</u> distributed Internet-of-things (IoT) environmental sensors

Motivation: IoT Applications

Desired features:

- Low energy/measurement
- High sensitivity
- Monolithic and low-cost
- Wide supply range and supply insensitive

Transducers Selection: Temperature

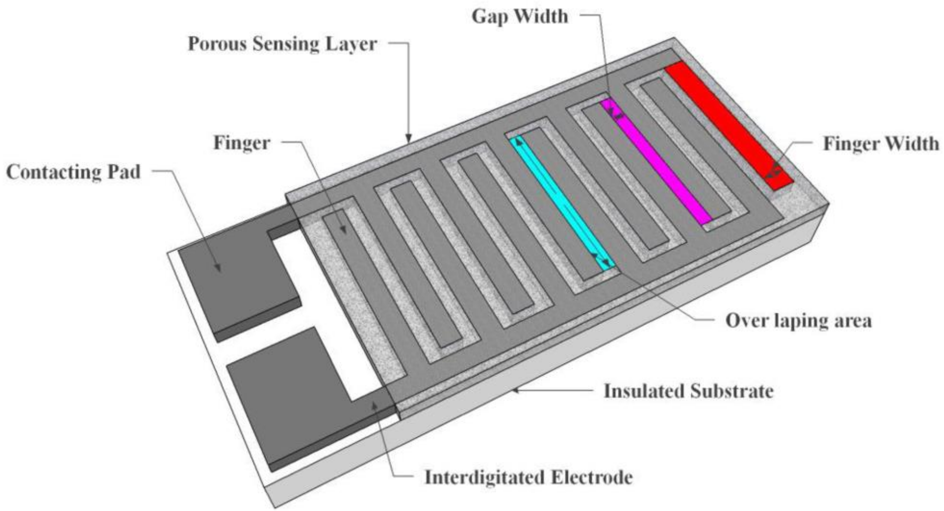


- High energy efficiency
- High resolution
- High accuracy & small spread
- Fully-integrated

Temp transducer: Resistor

K. A. Makinwa, "Smart temperature sensor survey", 2010 to date.

Transducers Selection: RH



Mechanism:

- Interdigitated top layer metal
- Gaps filled with polyimide (PI)
- $\varepsilon_{PI} \propto$ RH
- Metal-PI-metal capacitance $\propto$ RH

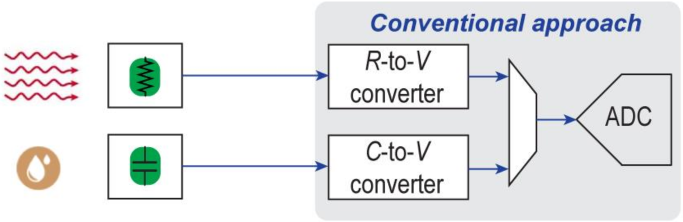
Benefit:

CMOS compatible + fully integrated

RH transducer: Capacitor

Farahani et al. Humidity Sensors Principle, Mechanism, and Fabrication Technologies: A Comprehensive Review, *Sensors*, 2014

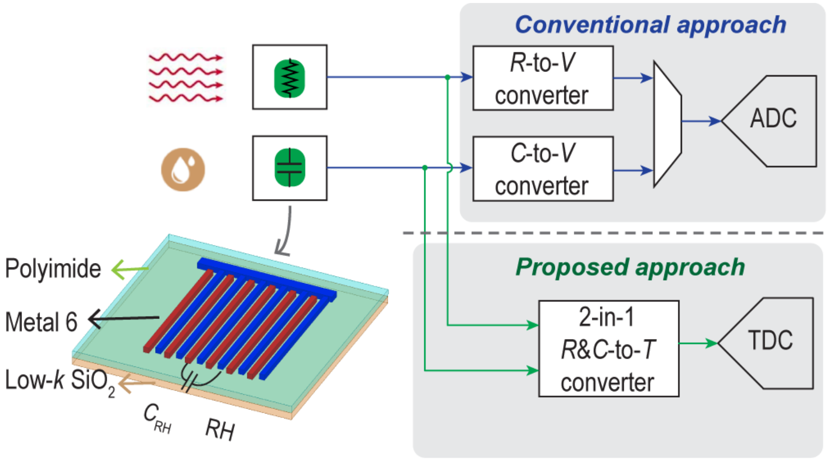
Prior RH/T Sensors



Example:
Sharp-QM1H0P00, ADI-AD7747, TI-HDC2080, ST-HTS221, TE-HTU21, etc.

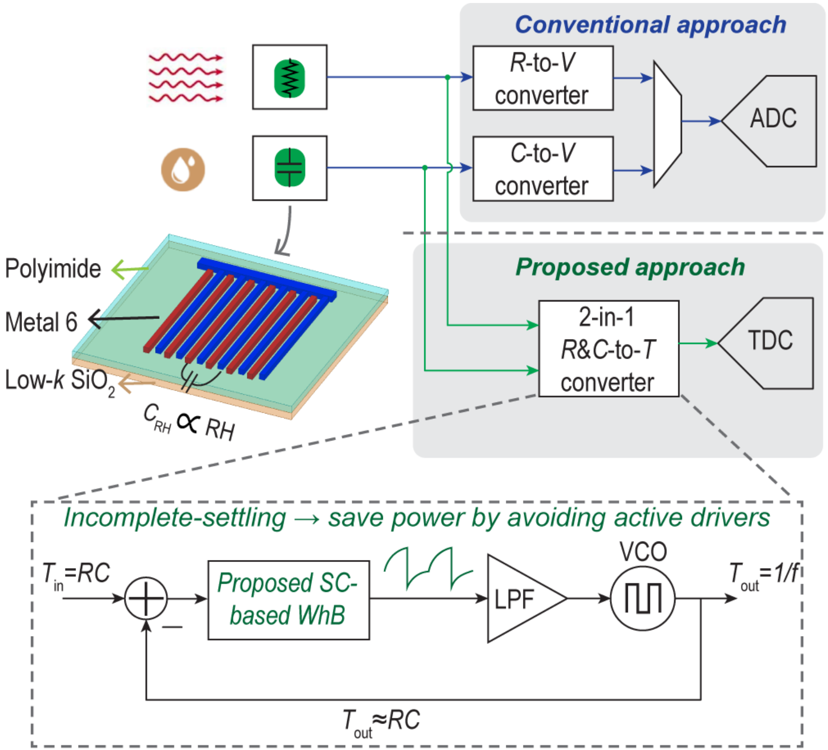
- Widely used in commercial products
- Require ***two distinct AFEs*** that need extra
  - Power
  - Area
  - Complexity

Proposed RH/T Sensor Architecture



- Monolithic, CMOS-compatible transducers
- Require only ***one unified AFE*** that saves
  - Power
  - Area
  - Complexity

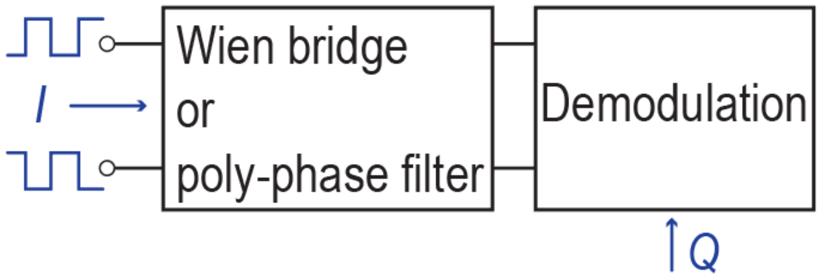
Proposed RH/T Sensor Architecture



- Monolithic, CMOS-compatible transducers
- Require only ***one unified AFE*** that saves
  - Power
  - Area
  - Complexity
- Closed-loop *R*&*C*-to-*T* conversion → ***High linearity & robustness***
- Incomplete-settling SC-based WhB → ***High sensitivity & energy efficiency***

Prior *RC*-Based Front-Ends

RC band-pass-filter-based



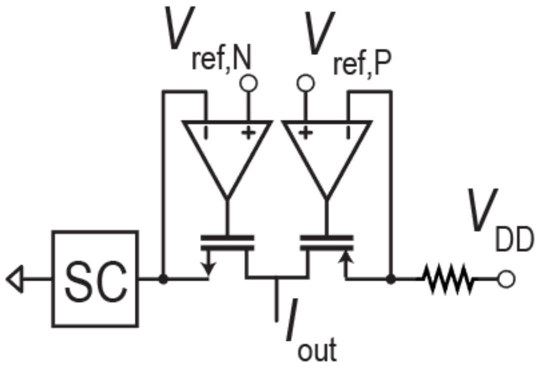
[P. Park, JSSC, 2015]
[S. Pan, ISSCC, 2017]
[W. Choi, ISSCC, 2018]
[S. Pan, ISSCC, 2019]

Problems:

- $C_{parasitic}$ degrades the sensitivity
- Sensitive to in-band supply noise
- 4× CV^2f power due to the I/Q generation
- Need multiple matched components

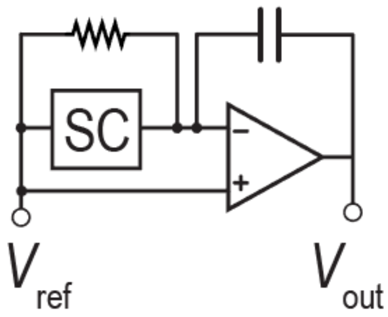
Prior *RC*-Based Front-Ends

Switched-capacitor-based I



[T. Jang, Low-power timer, ISSCC, 2016]

Switched-capacitor-based II

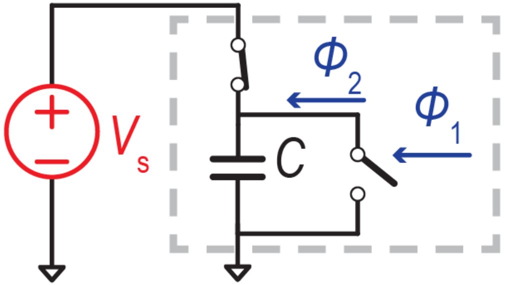


[R. Yang, High resolution CDC, JSSC, 2017]

Problems:

- Need active drivers (LDOs or high-bandwidth, low-output-impedance OpAmp) and reference voltages → extra power overhead
- Extra noise sources

Revisit the SC-Resistor



Assuming C is fully charged to V_s & fully discharged to ground

- ✓ $\Delta Q = CV_s$
- ✓ $R = \frac{1}{fC}$ (the well-known conclusion)

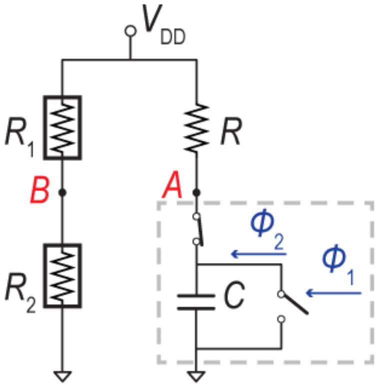
Problem:

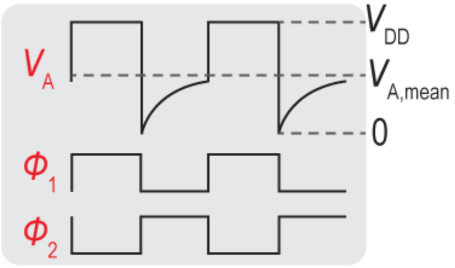
Need a voltage source (i.e., low impedance) as a SC driver

→ prior work uses either LDO or active integrator (virtual ground)

Can we avoid the SC driver at the cost of incomplete-settling?

Incomplete-Settling SC-Based WhB





Q1: Assuming $R_1 = R_2$, is $f = 1/RC$ when the bridge is balanced ($V_{A,mean} = V_B$)?

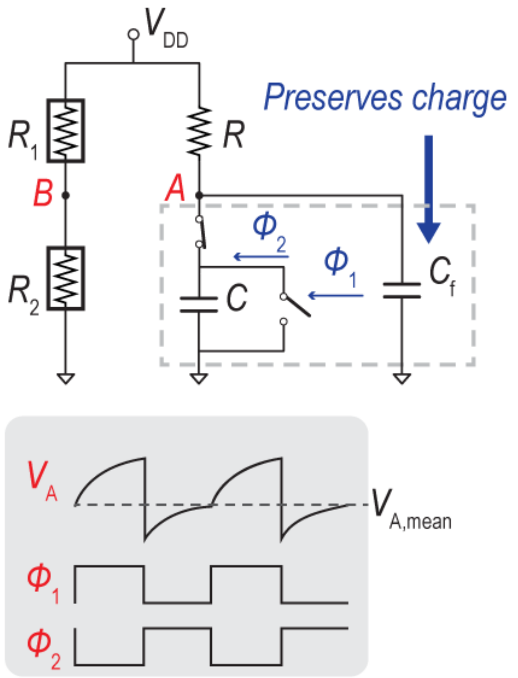
A1: No. $f = \frac{1+e}{e}\frac{D}{RC} \approx \frac{0.684}{RC}$, assuming 50% duty-cycle

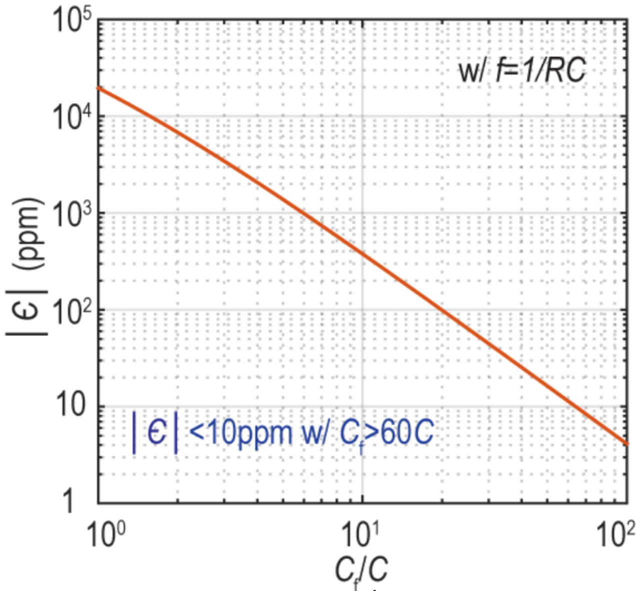
Q2: Why do I care if $f \neq 1/RC$?

A2: Because the error is hard to calibrate:

- Not constant, but depends on duty-cycle
- Highly sensitive to $C_{parasitic}$ at node *A*

Proposed Incomplete-Settling SC-Based WhB

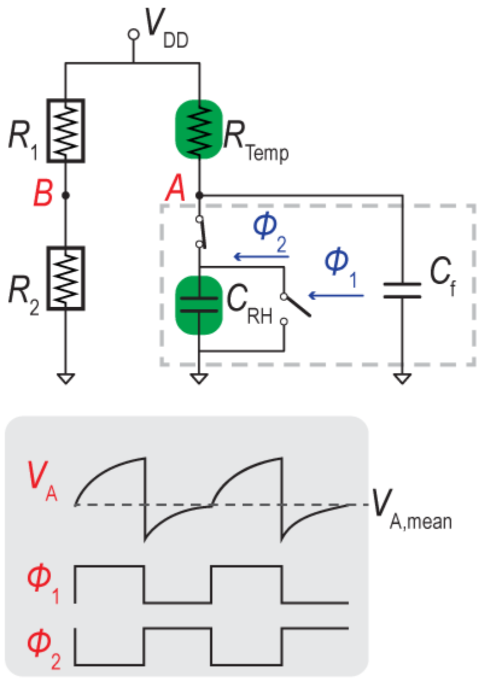




$$V_{\mathrm{A,mean}} = (1+\epsilon)\frac{1}{1+fCR}V_{\mathrm{DD}} \approx \frac{1}{1+fCR}V_{\mathrm{DD}}$$

C_f minimizes the incomplete-settling error

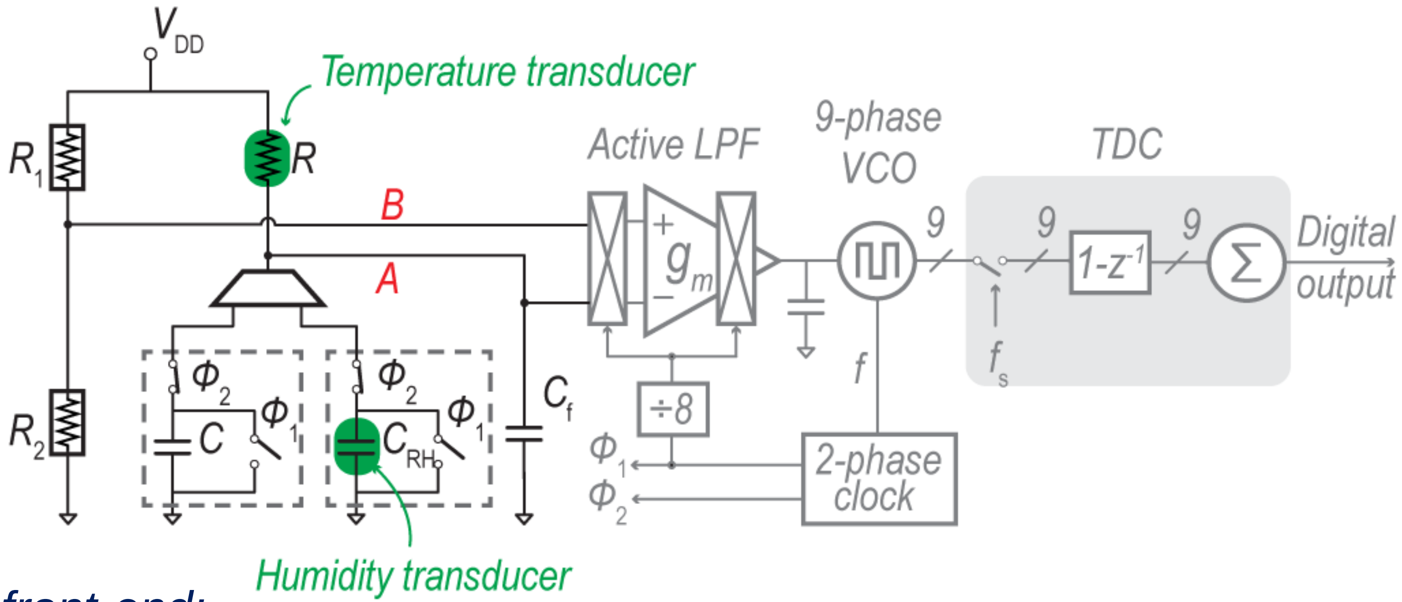
Proposed Incomplete-Settling SC-Based WhB



Benefits:

- Integrate *R*-transducer & *C*-transducer
- Reduce the settling error by ~5200× (choosing $C_f = 60C$) at no static power cost
- Insensitive to $C_{parasitic}$ & switching imperfections
- High sensitivity & inherent supply rejection
- Low swing → relax readout circuit linearity requirement
- R_1 & R_2 branch costs little power & area

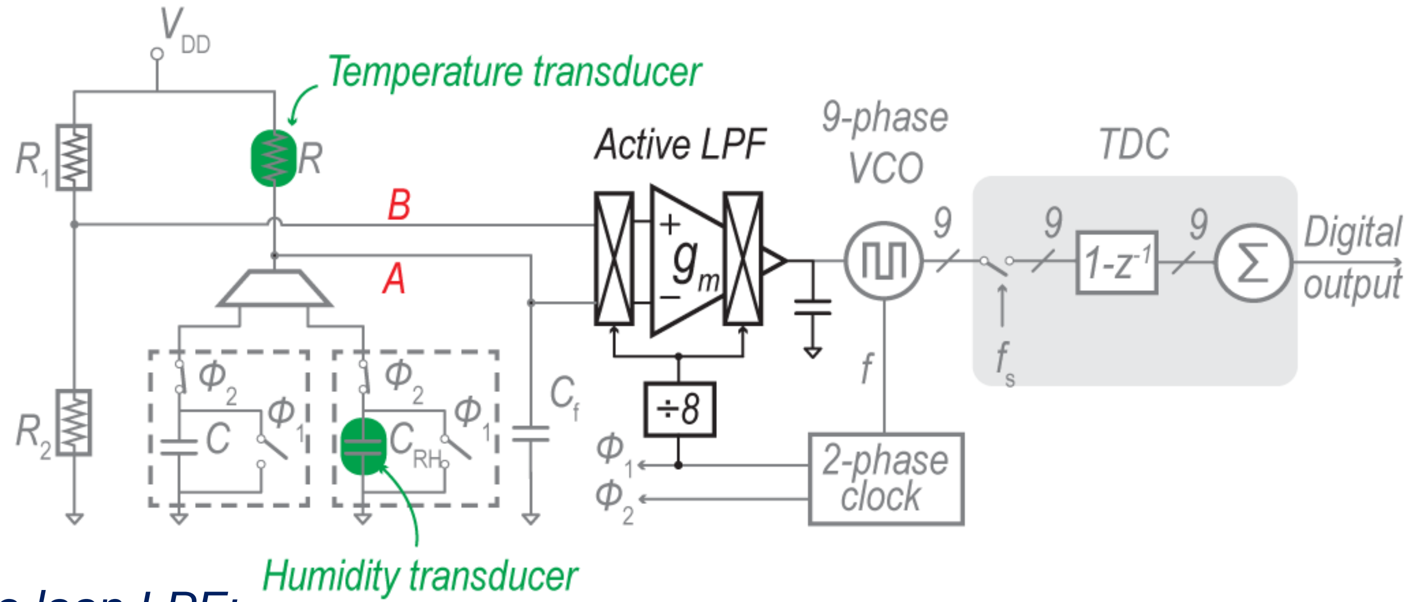
System Architecture



WhB front-end:

- Two SC cells in time-multiplexed fashion
- $R_1 = R_2$ ensures the maximum sensitivity

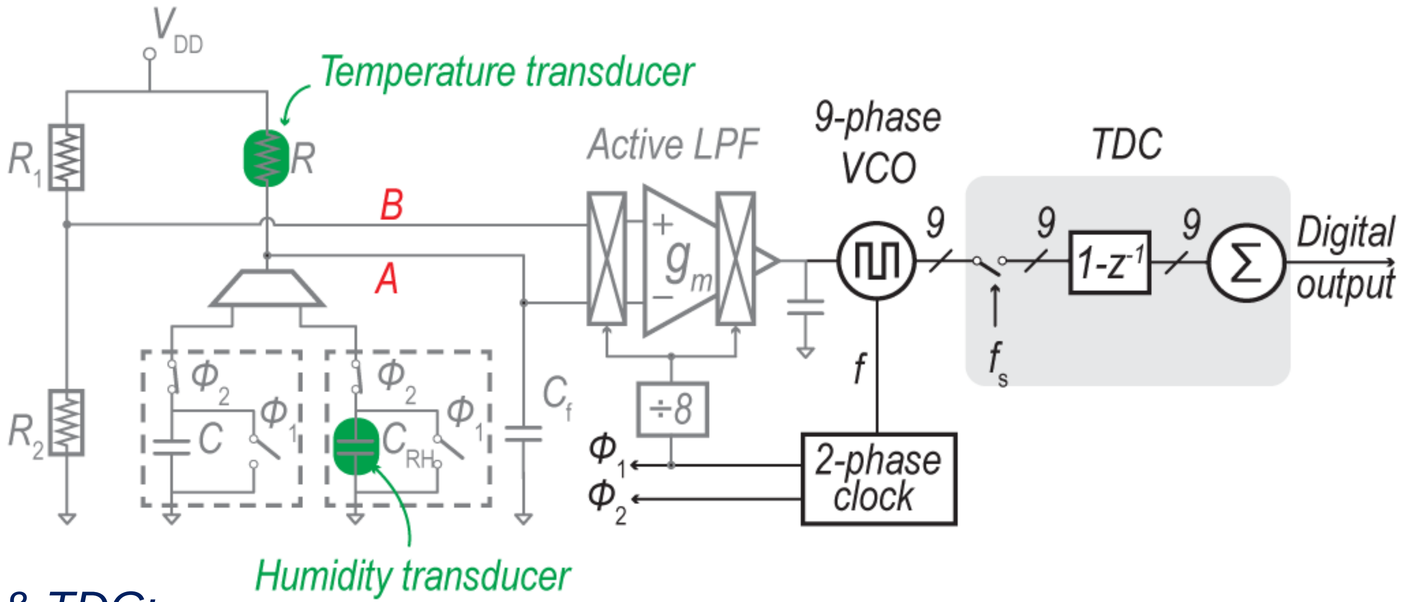
System Architecture



Active loop LPF:

- Chopping removes 1/*f* noise & offset
- Clock divider → 8× lower g_m-cell BW & power

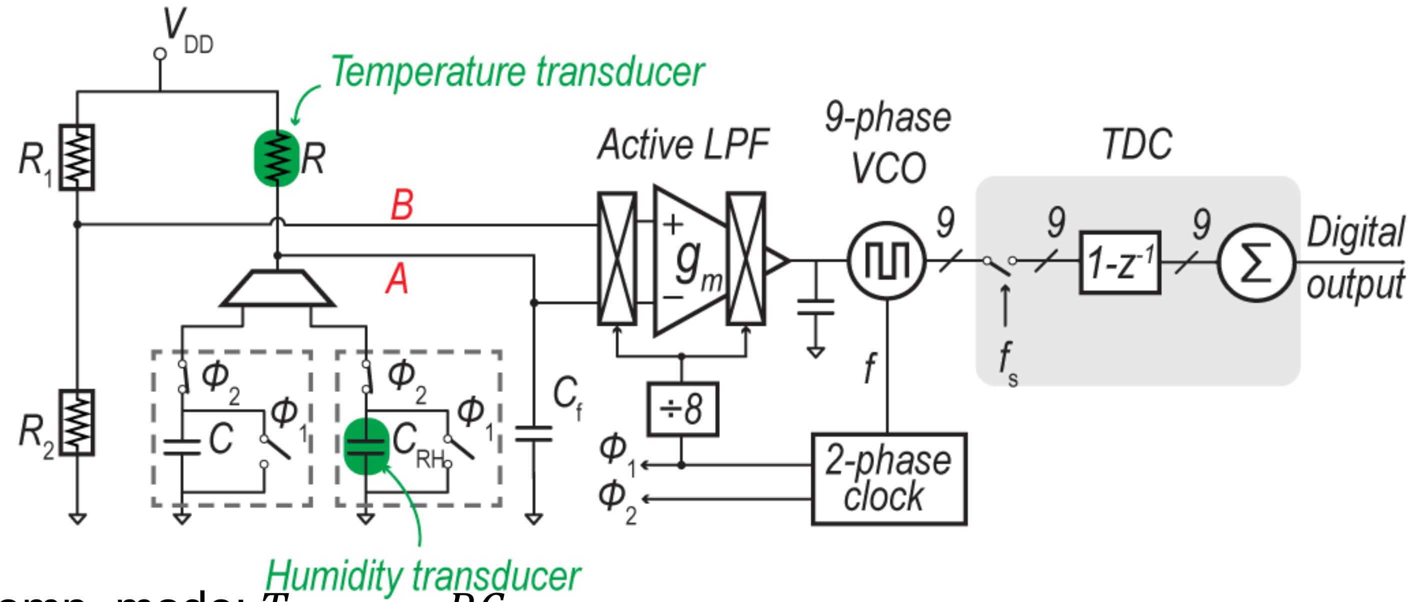
System Architecture



VCO & TDC:

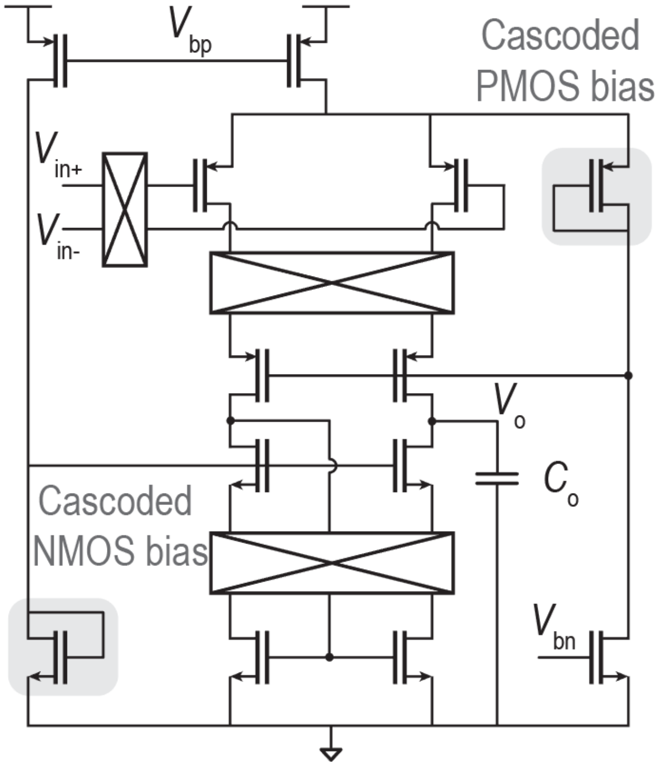
- A VCO closes the FLL → $f = 1/RC$ w/ high loop gain
- A TDC samples the VCO phases & achieves 1st order noise-shaping

System Architecture



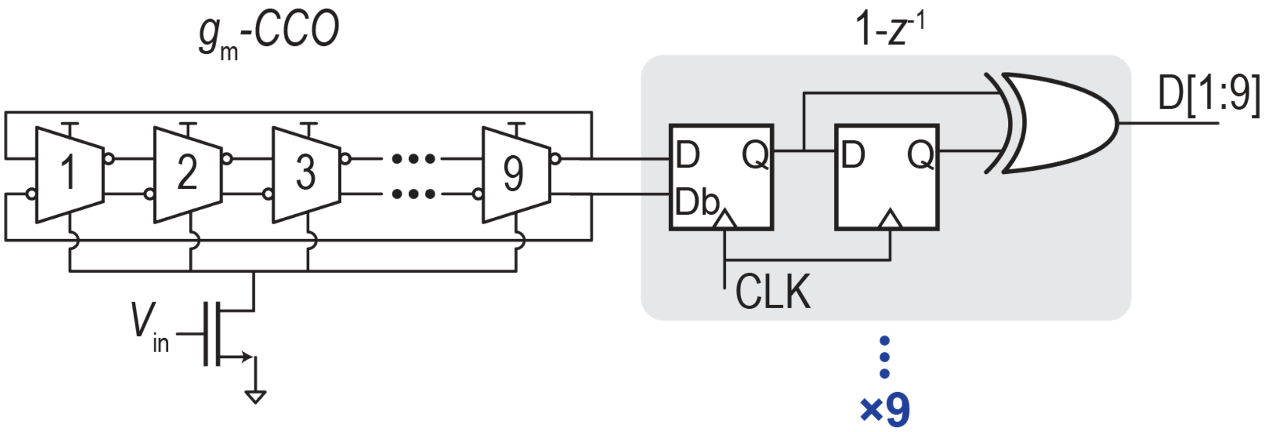
- Temp. mode: $T_{\text{Temp}} = RC$
- RH mode: $T_{\text{RH}} = RC_{\text{RH}}$
- Temperature effect on RH can be removed by correlating the two results

Chopper-Stabilized Active Filter



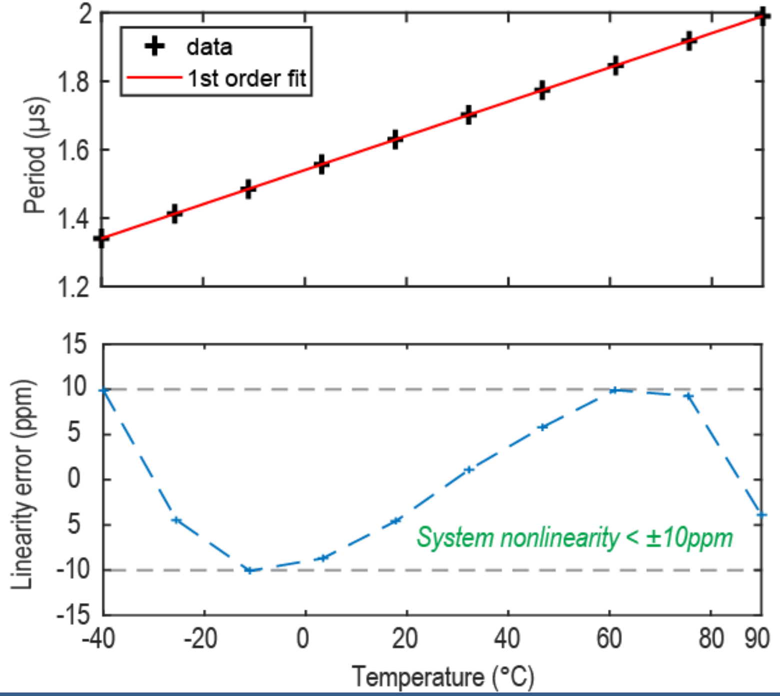
- Choose g_m-C over closed-loop options due to
  - High energy efficiency
  - Relaxed linearity requirement
- Telescopic + chopping → >80dB gain over PVT & 2.4 noise efficiency factor
- Down-converting at cascode-nodes → ~100× lower impedance & higher bandwidth

VCO & TDC



- VCO noise attenuated by active filter gain
- 1-z^{-1} restores the *f*-to-phase integration & shapes the quantization noise
- 2MHz sampling rate (OSR=1000) → 116dB SQNR

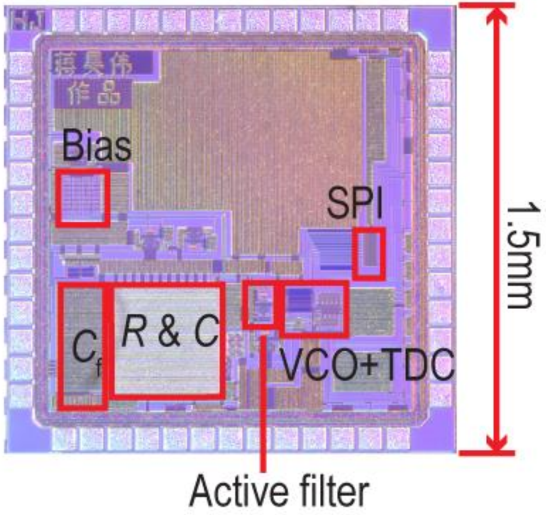
System Linearity Verification



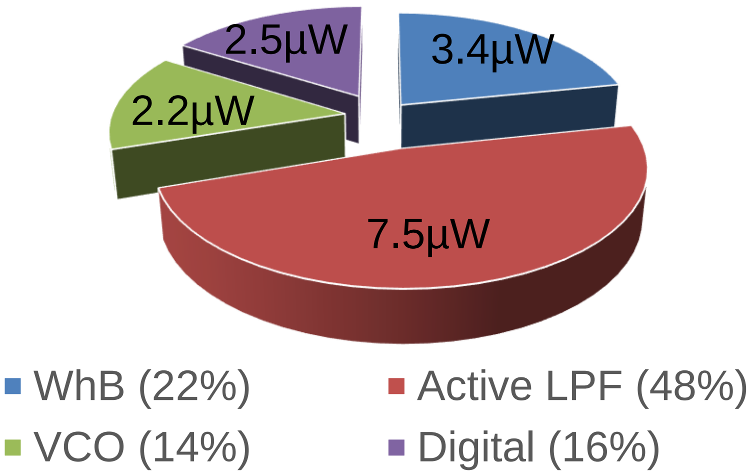
- Simulated w/ ideal *R* & *C*
- >92dB loop gain over PVT
- <±10ppm linearity error from -40°C to 85°C

FLL provides 16-b RC-to-T linearity across industrial temperature range

Implementation

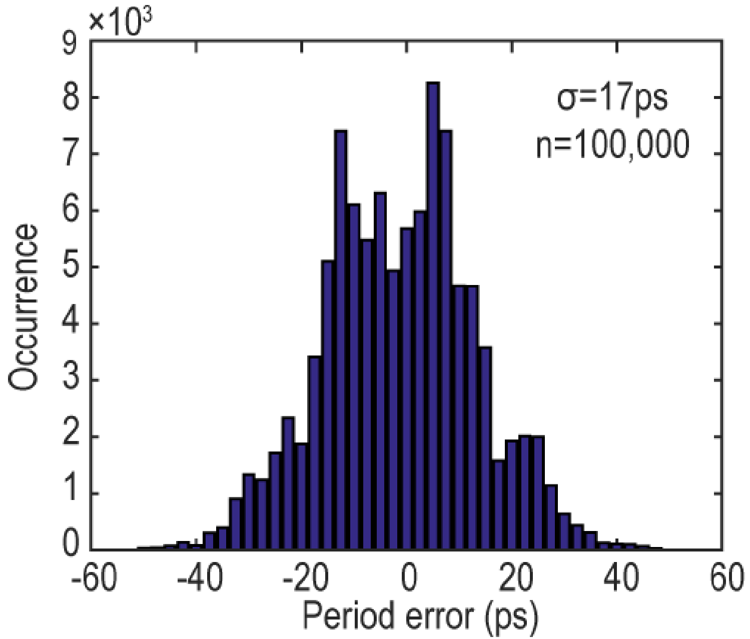


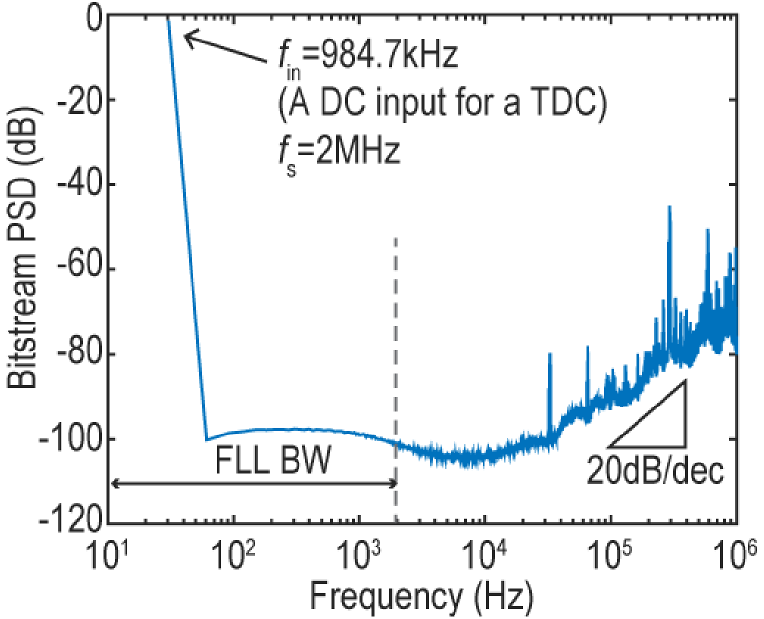
Power breakdown (µW)



- Implemented in TSMC 180nm process
- Active area: 0.72mm^2 (RH transducer: 0.21mm^2)
- Power consumption: 15.6µW @ 1.5V (RT)

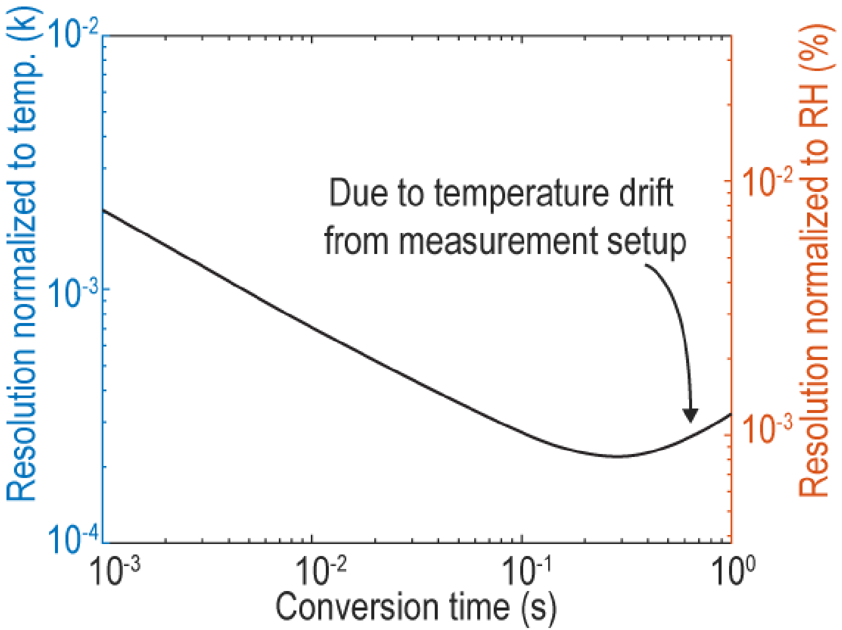
Measurements: FLL & TDC





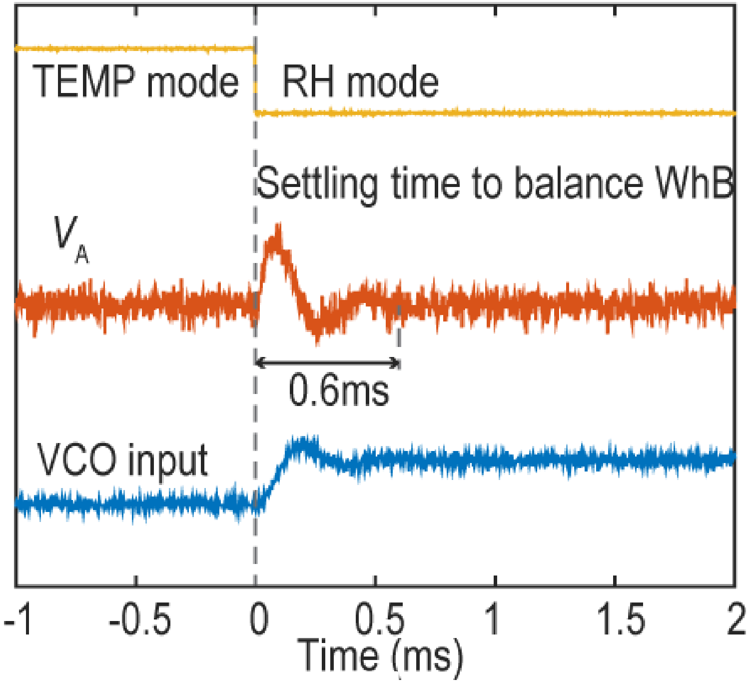
- FLL RMS jitter: 17ps @RT
- TDC bitstream shows 20dB/dec. noise shaping

Measurements: Resolution vs. Time



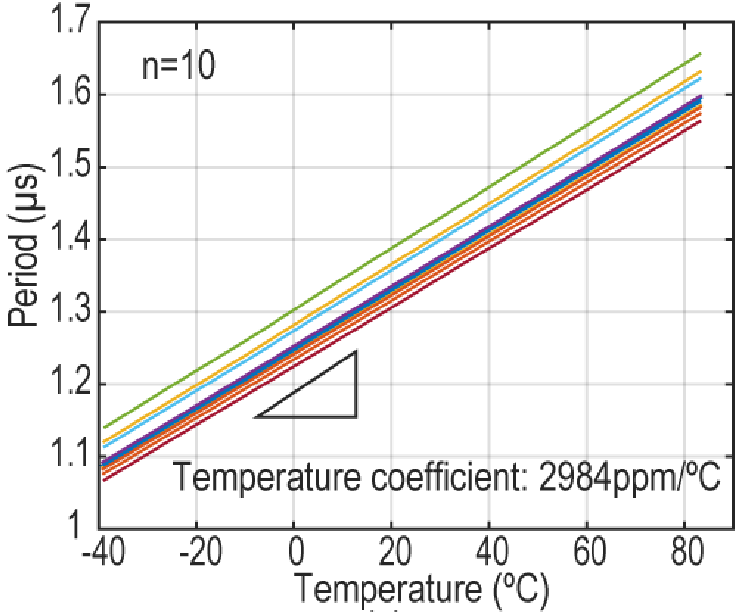
- Resolution was measured at 300K & 35%RH
- Normalized to temperature and RH inputs
- 2mK temperature resolution & 0.0073%RH humidity resolution achieved in 1ms

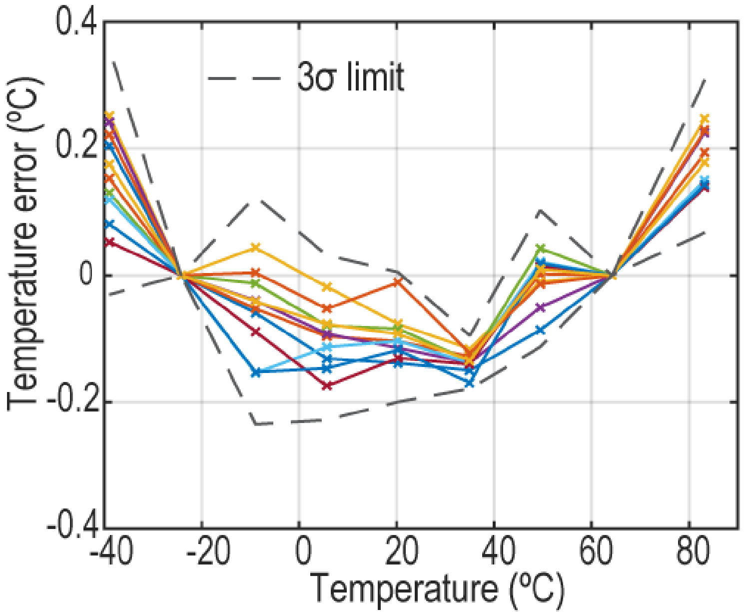
Measurements: Mode Switching Transient



- FLL settles in 0.6ms to re-balance the WhB
- V_{A} settles back to $V_{\mathrm{DD}}/2$
- VCO settles to a different operating point

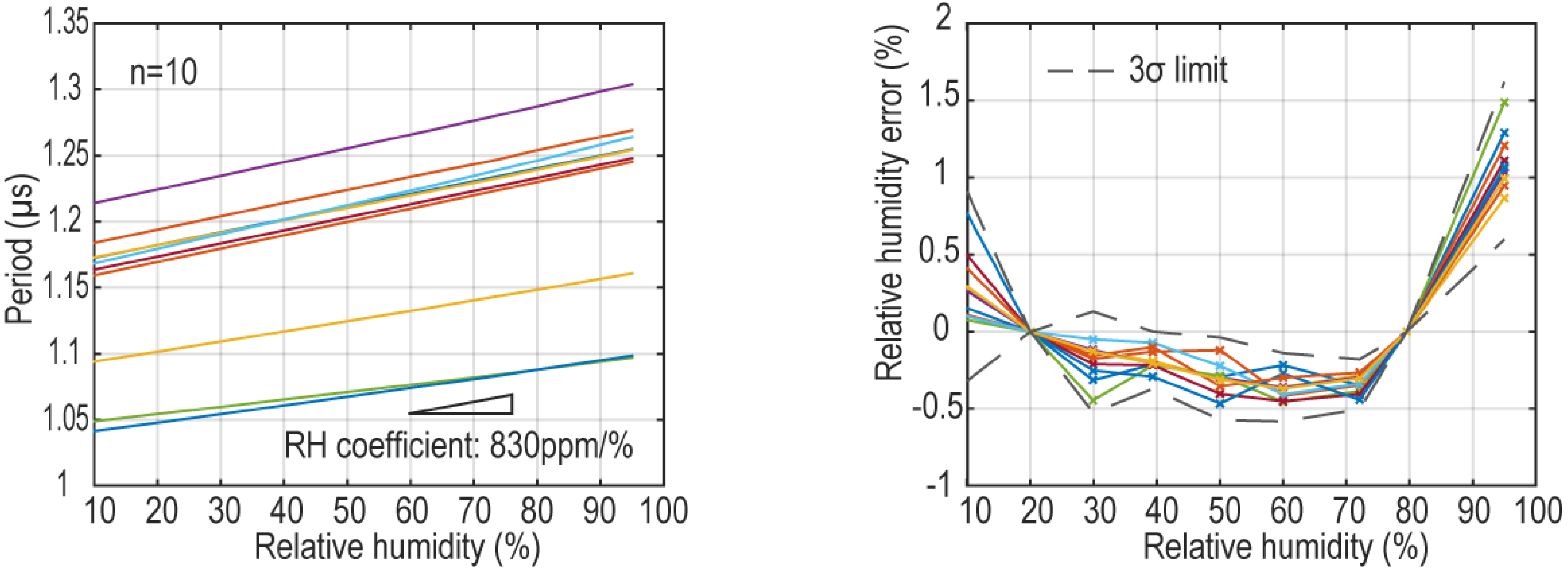
Measurements: Temp. Transfer Curve & Error





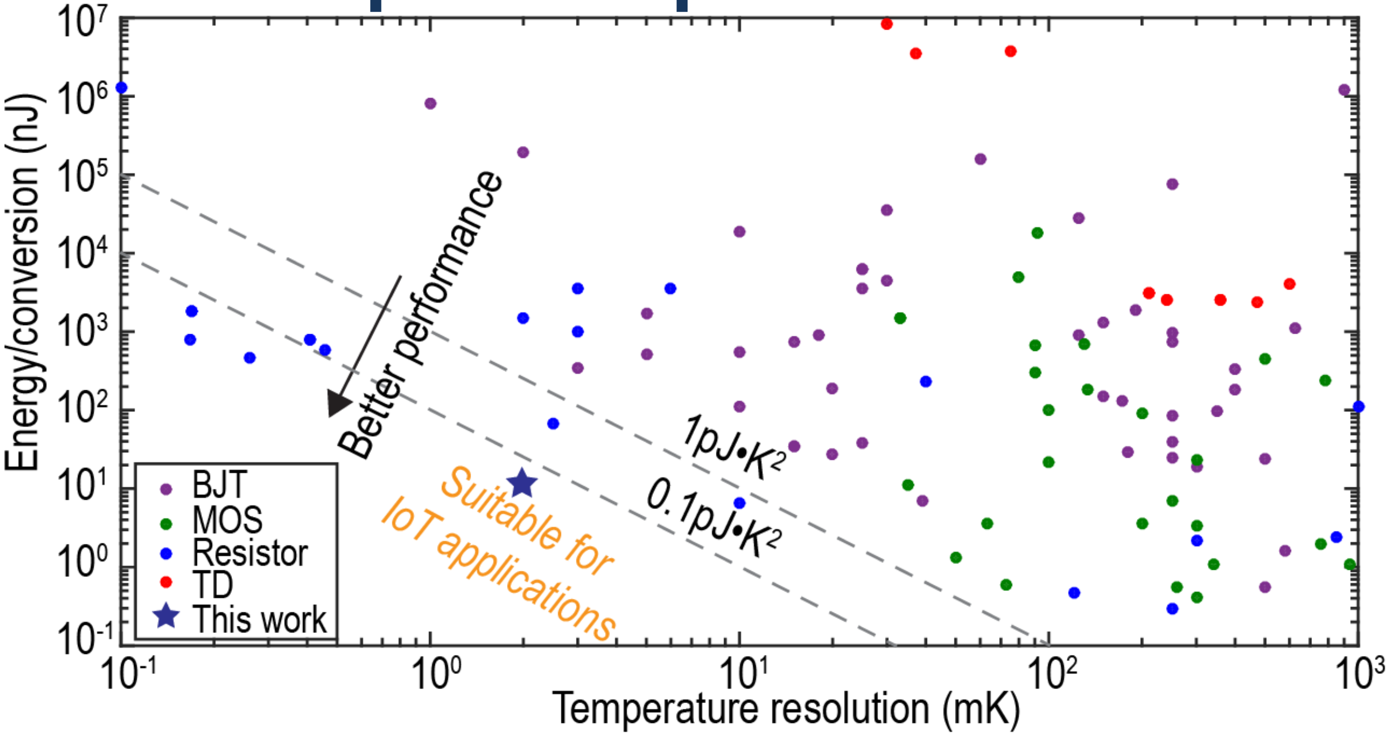
- 1st order calibration; no high-order polynomial fit due to FLL's high linearity
- 3σ error: 0.55K in the industrial temperature range

Measurements: RH Transfer Curve & Error



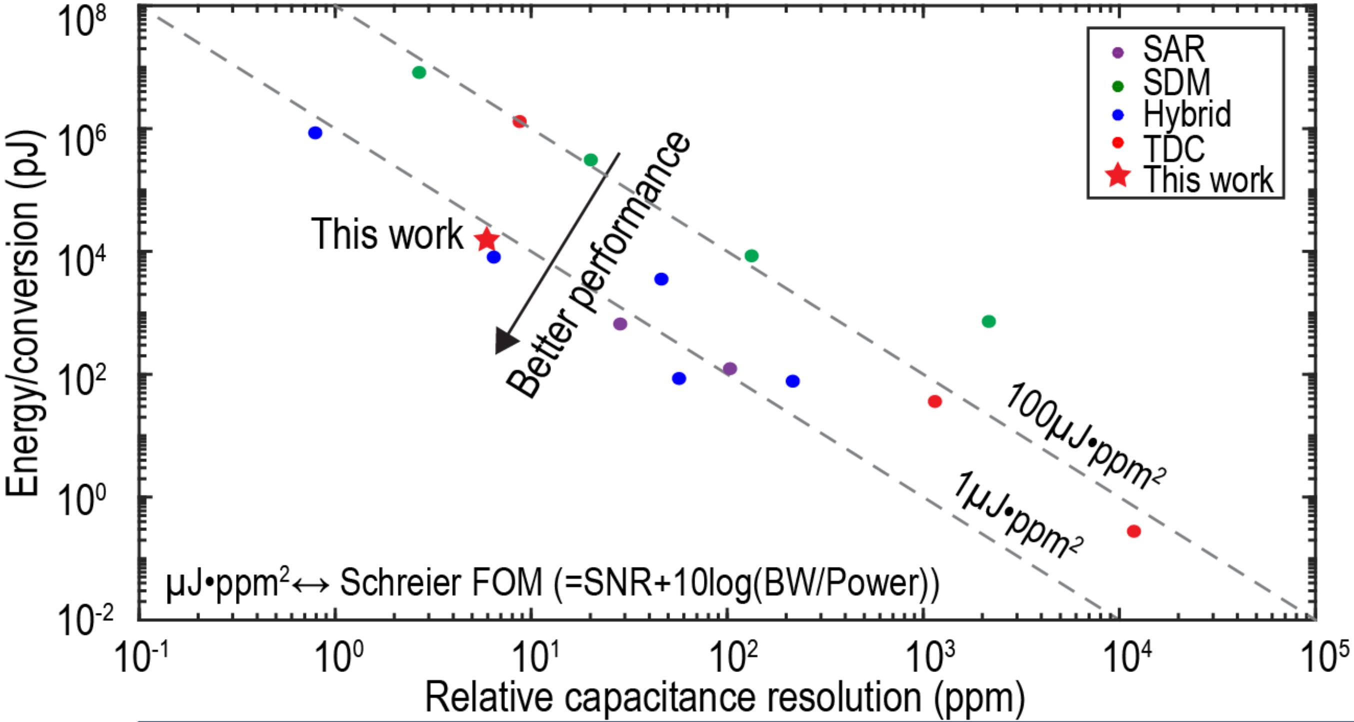
- 1st order calibration; no high-order polynomial fit due to FLL's high linearity
- 3σ error: 2.2%RH from 10%RH ~ 95%RH (limited by instrumentation)

Landscape: Temperature Sensors



Lowest energy/conv. that exceeds 0.1pJ·K² FOM

Landscape: Capacitive Sensors



Better than 1μJ·ppm² resolution (Schreier) FOM

Comparison w/ Prior Environmental Sensor

	Parameter	P.Park JSSC'15	S. Pan ISSCC'19	S.Pan ISSCC'19	W. Choi ISSCC'18	Z. Tan JSSC'13	S. Park VLSI'18	Maruyama JSSC'18	This Work
System	Sensor type	Temperature				RH		RH & Temperature	
	Tech. (nm)	180	180	180	65	160	180	180	180
	Active area (mm^2)	0.09	0.12	0.12	0.007	0.28	2.7	4.5	0.72
	Supply (V)	1.7/1	1.6~2	1.6~2	0.85~1.05	1.2	1	1.55	1.5~2
	Conversion time (ms)	32	10	10	1	0.8	1.28	0.024	1
	Power (μW)	31	52	94	68	10.3	2.69	3875	15.6
Temp. sensor	Temp. range (°C)	-40~85	-40~180	-55~125	-40~85	25 only	N/A	-20~85	-40~85
	3σ error (K) [trim points]	0.12[3]	0.1[2]	0.14[2]	0.7[2]	-	-	0.6[NA]	0.55[2]
	Resol. (mK)	2.8	0.46	0.16	2.8	-	-	15	2
	FOM($fJ \cdot K^2$)	8,000	110	20	530	-	-	20,925	62
RH sensor	RH range (%)	-	-	-	-	30~95	30~90	0~100	10~95
	3σ error (%) [trim points]	-	-	-	-	>2[2]	5.6[NA]	4[NA]	2.2[2]
	Resol. (%RH)	-	-	-	-	0.05	0.038	0.0057	0.0073
	FOM($pJ \cdot \%^2$)	-	-	-	-	20.75	4.97	3.02	0.83

Conclusion

Target:

- A compact, energy-efficient & robust environmental sensor for IoT applications

Techniques:

- Incomplete-settling SC-based WhB → High sensitivity & low power
- FLL + noise-shaping TDC → high linearity & high DR

Results:

- ***Fully integrated*** temperature & humidity sensor consisting of a ***unified R&C-to-D converter***, achieving:
- ***62fJ·K² & 0.83pJ ·(%RH)²*** FOMs normalized to temp. & RH
- ***0.12K/V*** & ***0.43%RH/V*** supply insensitivity

Acknowledgement

- This work was supported in part by equipment purchased through a DURIP award from the Office of Naval Research (award no. N00014-18-1-2350).
- The authors thank Xiahan Zhou for digital synthesis.