Session 3 - Oscillators and PLLs

A 107 μW MedRadio Injection-Locked Clock Multiplier with a CTAT-biased 126 ppm/°C Ring Oscillator

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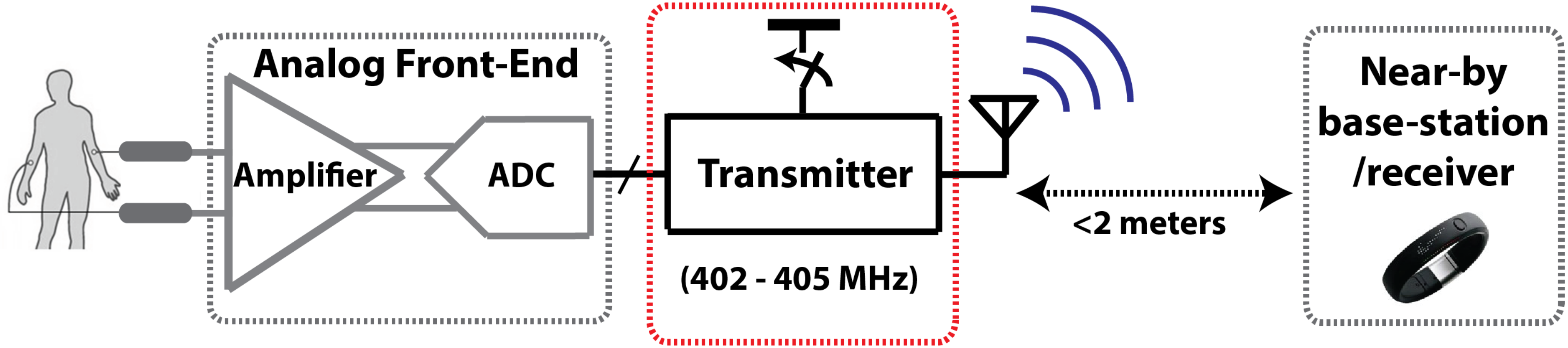
The Internet of *Medical* Things – Io(M)T

- ✓ Miniaturized wearable sensor nodes
- ✓ Communication to a nearby data-aggregator (e.g., smartphone, smartwatch, etc.)

Ultra-Low Power Operation

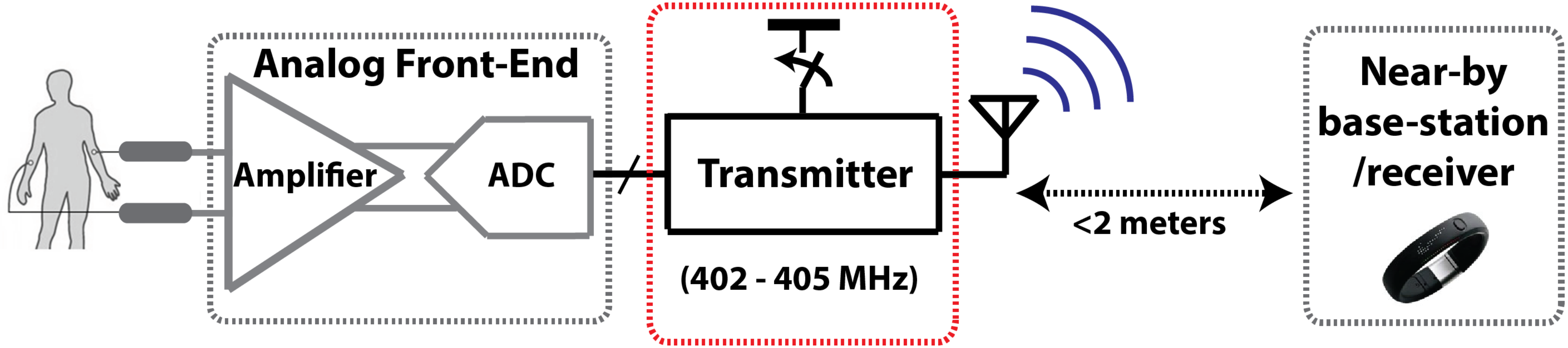
A Wireless IoMT Bio-Sensor Node



- Medical Device Radiocommunications Service (MedRadio): 402-405 MHz
  - Frequency stability ±100 ppm/°C over **0 to 55 °C**
  - Attenuate out-of-band/spurious emissions by **20 dBc**

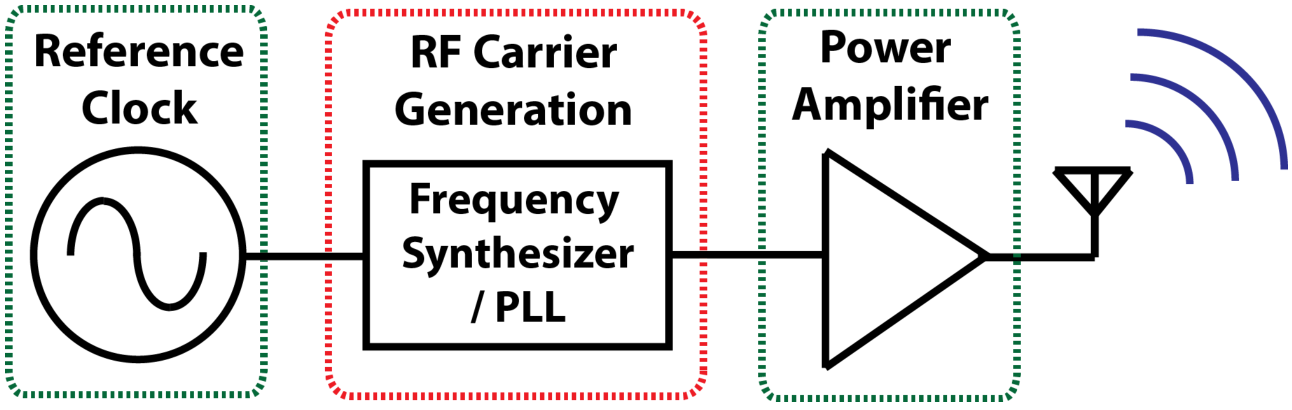
[1]: "Medical Device Radio Communications Service," in *Electronic Code of Federal Regulations (e-CFR)*, vol. Title 47,Chapter I, Subchapter D, Part 95, Oct. 2018.

A Wireless IoMT Bio-Sensor Node



- Medical Device Radiocommunications Service (MedRadio): 402-405 MHz
- Duty-cycled operation
- Short-range transmitter (<2 meters TX distance)

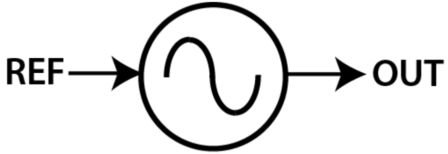
Short-Range Transmitter



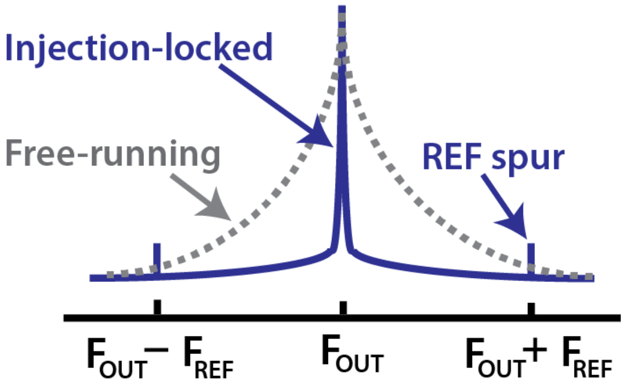
Power-hungry block
(400 MHz RF carrier)

Short-range PA
(< -17 dBm or 20 µW output power)

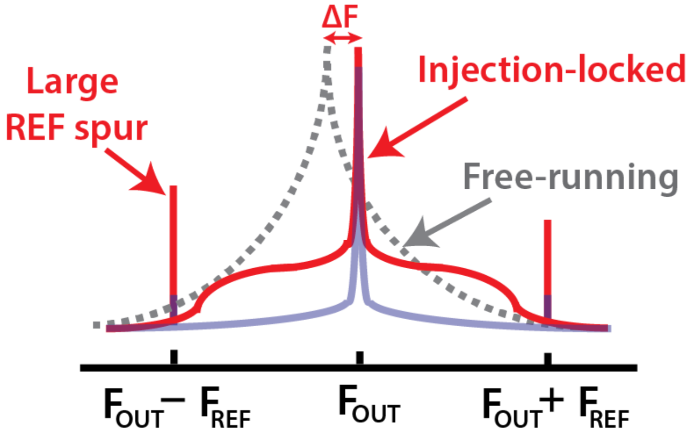
Injection-Locked Clock Multiplier (ILCM)



$F_{OSC} = N.F_{REF}$

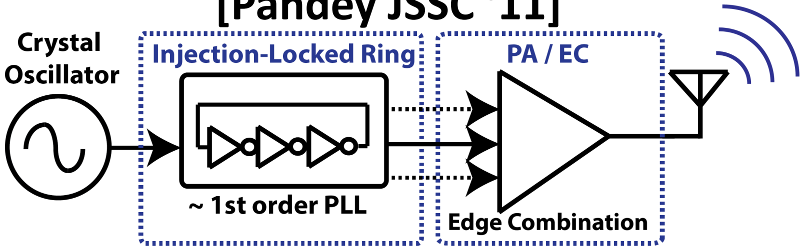


$F_{OSC} < N.F_{REF}$



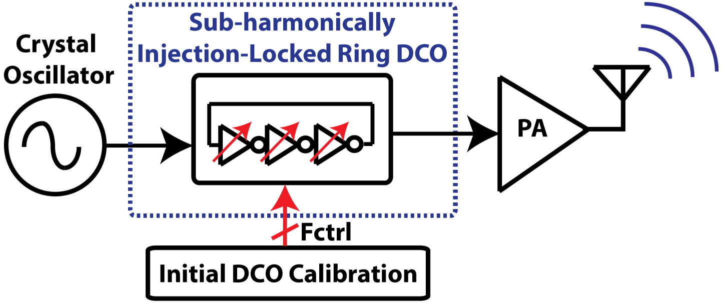
Prior Work – ULP Narrowband TX

[Pandey JSSC '11]



- ✓ PLL-free low power TX
- ✓ Fast start-up
- ✗ Very sensitive to PVT

[Teng JSSC '17], [Liu JSSC '14], [Ma TBioCAS '13]



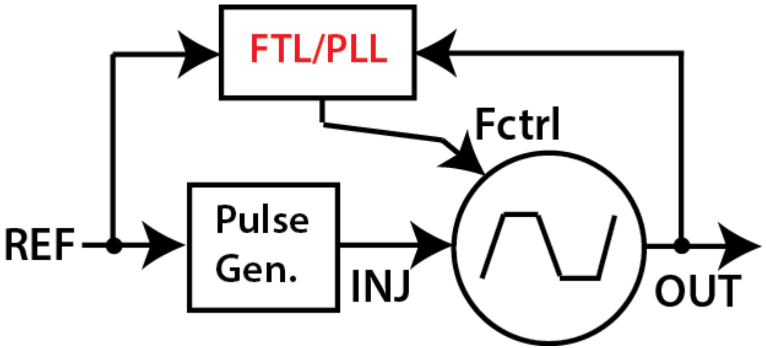
- ✓ Robust to static PV variations
- ✗ Constant temperature assumption (close proximity to human body)
  - ↓ ☹ Loss of lock
  - ↓ ☹ Large REF spur
- ✗ Slow start-up (if calibrated each time)

Dynamic temperature variations need to be addressed

Motivation & Proposed Work

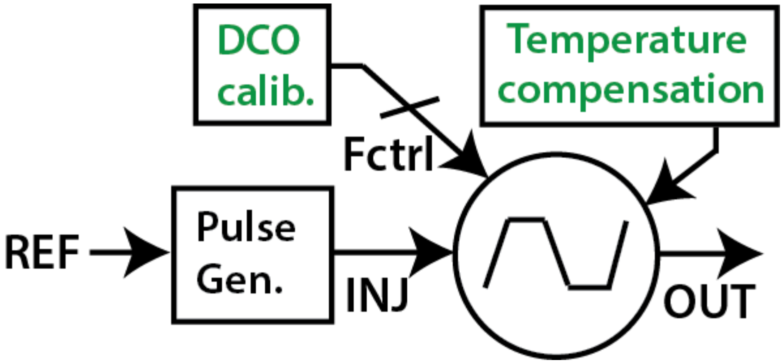
Conventional Injection-Locked Clock Multiplier (ILCM):

- ✓ Robust
- ✗ Power hungry



Proposed open-loop ILCM:

- ✓ Low power
- ✓ PVT Robust
- ✓ Fast-start-up

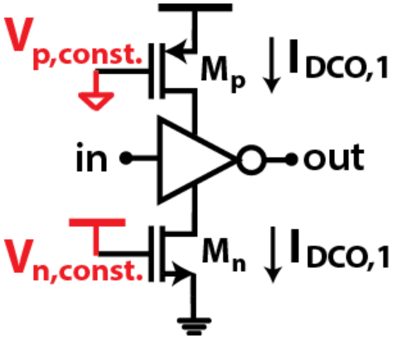


Ring Oscillator Temperature Sensitivity

Current-starved delay cell implementation

$$f_{\mathrm{osc}} \propto \frac{I_{\mathrm{DCO}}}{C_{\mathrm{L}}}$$

Constant-voltage bias



$$I_{\mathrm{DCO,1}} = I_S \cdot \exp(V_{\mathrm{GS}}/V_T)$$

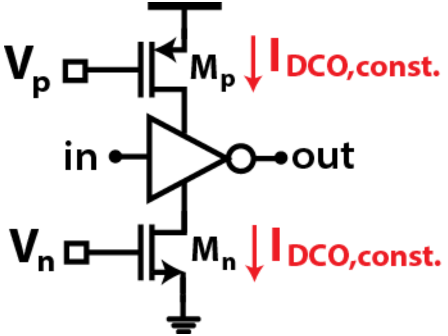
$I_S \propto V_T^2$

($V_T \propto$ T)

f_{osc} → strong PTAT

Constant-current bias

[Zhang TCAS-I '11], [Shrivatava CICC'12]

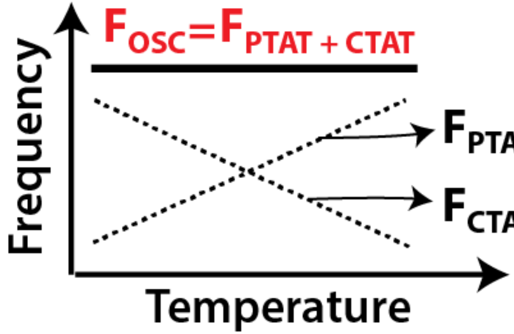


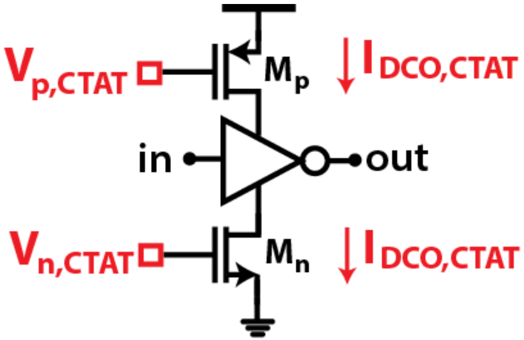
$$f_{\mathrm{osc}} \propto \frac{I_{\mathrm{DCO},const}}{C_L}$$

C_L: negative TC (junction & MOS oxide cap.)

f_{osc} → PTAT

Temperature Compensation Concept

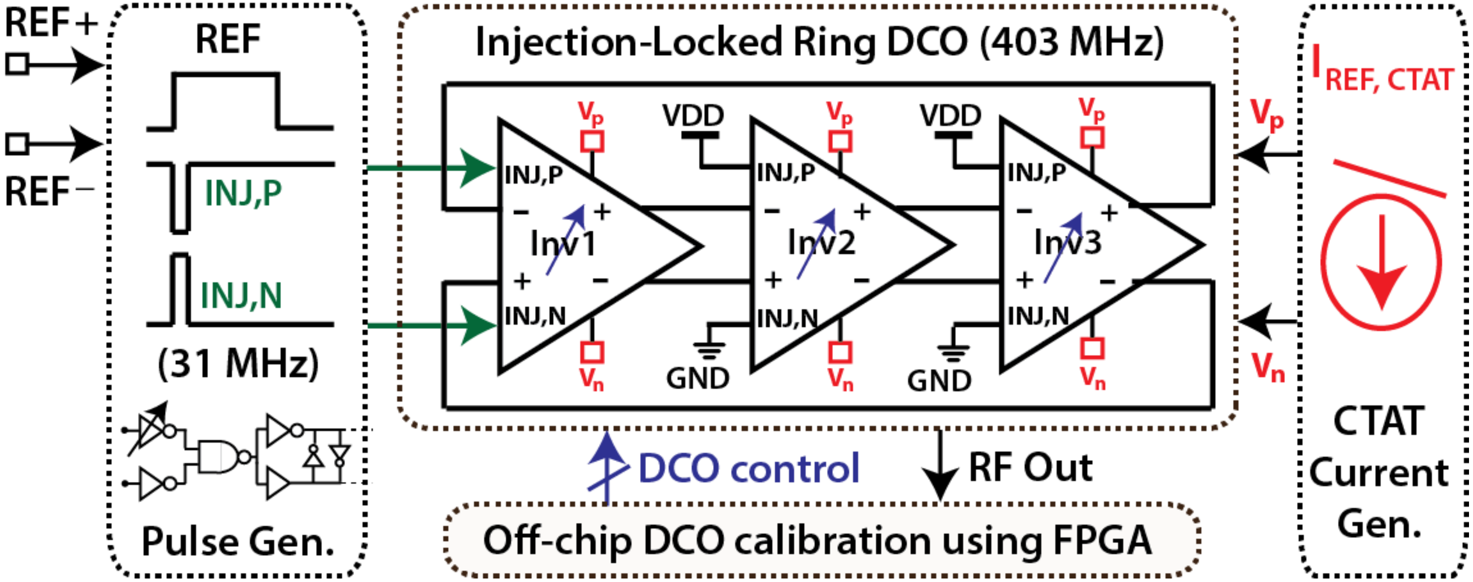




- Nominally, ring DCO's free-running frequency exhibits PTAT characteristics
- Introduce CTAT characteristics in frequency control knob

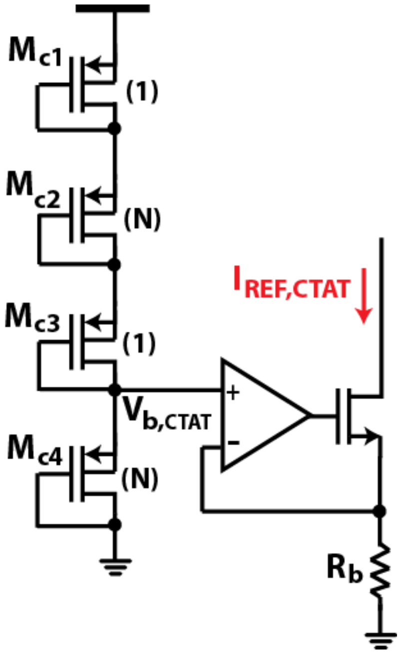
CTAT bias current to counteract the PTAT nature of osc. frequency

ILCM: Circuit Implementation



- Min 3-stage ring → larger devices → lower variations
- 8-bit DCO with ±25% tuning range

CTAT Current Generation: Implementation



[Choi ESSCIRC '14]

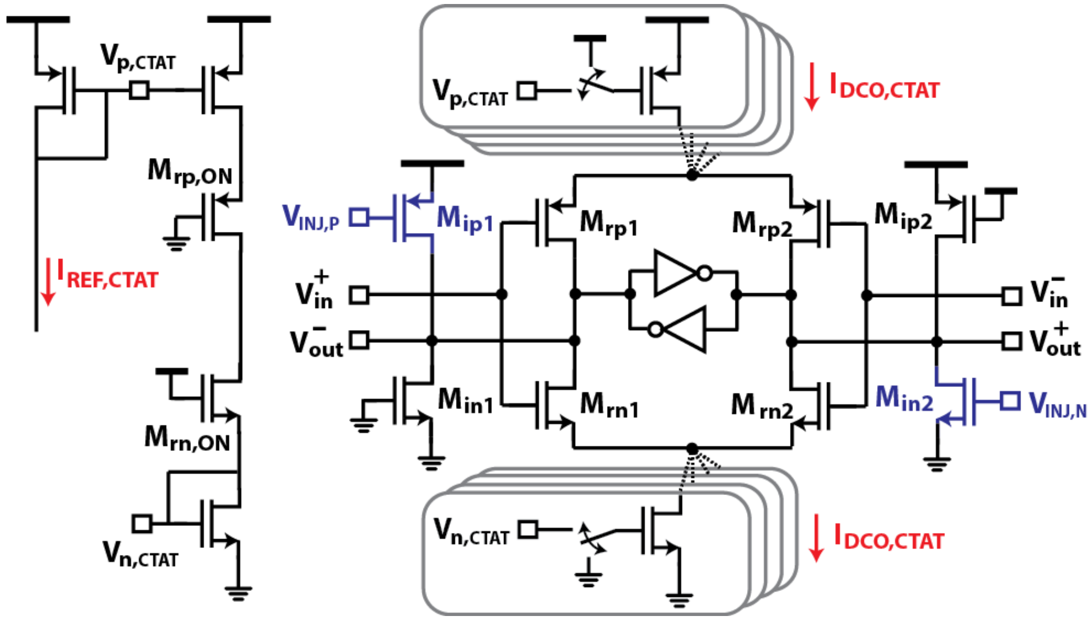
$$V_{\mathrm{b,CTAT}} = -\frac{\eta V_{\mathrm{T}} \ln(N)}{2} + \frac{V_{\mathrm{DD}}}{4}$$

$$I_{\mathrm{REF,CTAT}} = V_{\mathrm{b,CTAT}} \;/\; R_{\mathrm{b}}$$

- Low voltage, sub-threshold operation
- N = 24, R_{b} adds negligibly to CTAT characteristics

Adds <5% power overhead

Delay Cell: Implementation

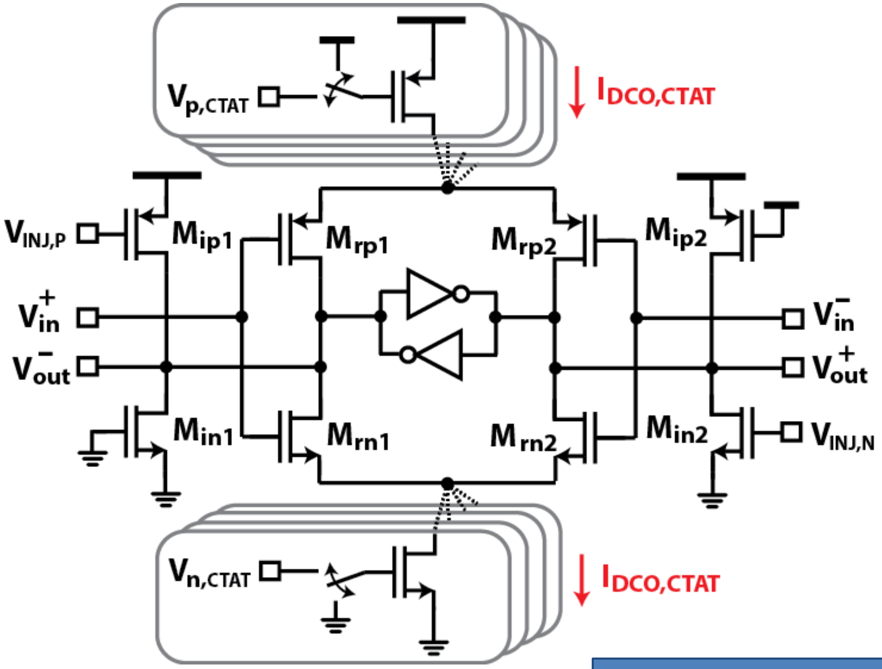


- Pseudo-differential delay cell
- $I_{\mathrm{DCO,CTAT}} = I_{\mathrm{DCO}}[k](1 - \alpha_{\mathrm{I}}\Delta T)$

  DCO current at k^{th} frequency mode

  CTAT TC
- $\mathrm{M_{ip1}}$, $\mathrm{M_{in2}}$: injection/start-up

Delay Cell: Temperature Sensitivity



- Both junction and MOS capacitor exhibit CTAT TC

$$C_{\mathrm{L}} = C_{\mathrm{L0}}(1 - \alpha_C \Delta T)$$

- Using current-starved delay cell

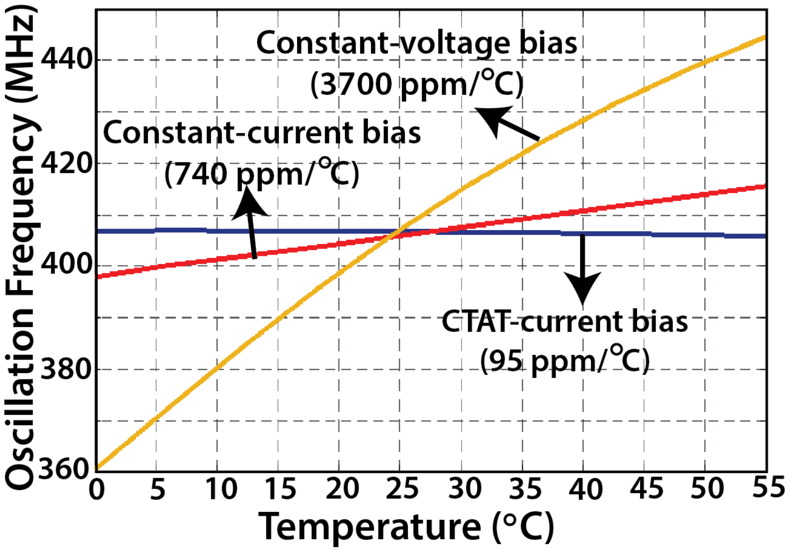
$$f_{\mathrm{osc}} \propto \frac{I_{\mathrm{DCO,CTAT}}}{C_{\mathrm{L}}} = \frac{I_{\mathrm{DCO}}[k](1 - \alpha_{\mathrm{I}} \Delta T)}{C_{\mathrm{L0}}(1 - \alpha_C \Delta T)}$$

TC cancellation independent of $I_{DCO}[k]$ (DCO mode)

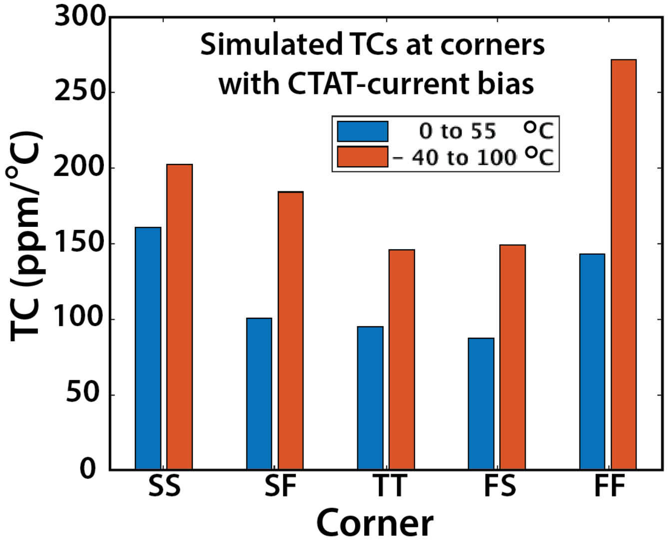
Simulated Temperature Sensitivity

Free-running ring oscillator's Temperature Coefficients (TC)

Nominal TC with different topologies:

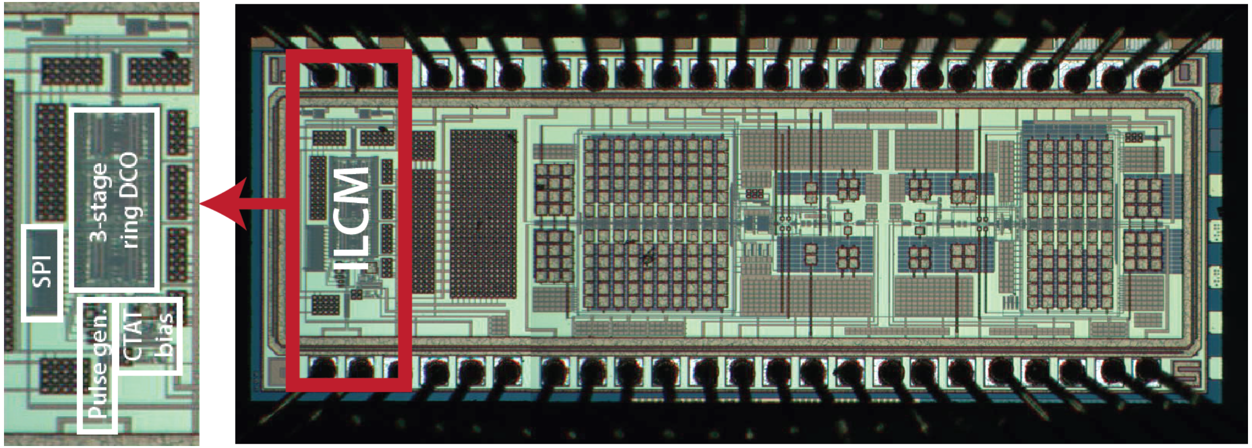


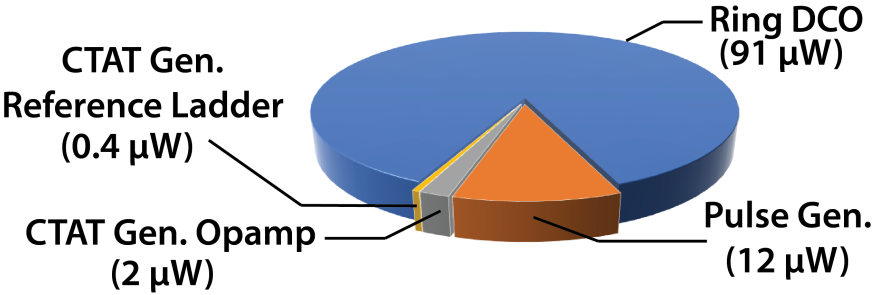
TC at corners with proposed topology:



TC improvement: ↓5× (constant I-bias) → ↓40× (CTAT I-bias)

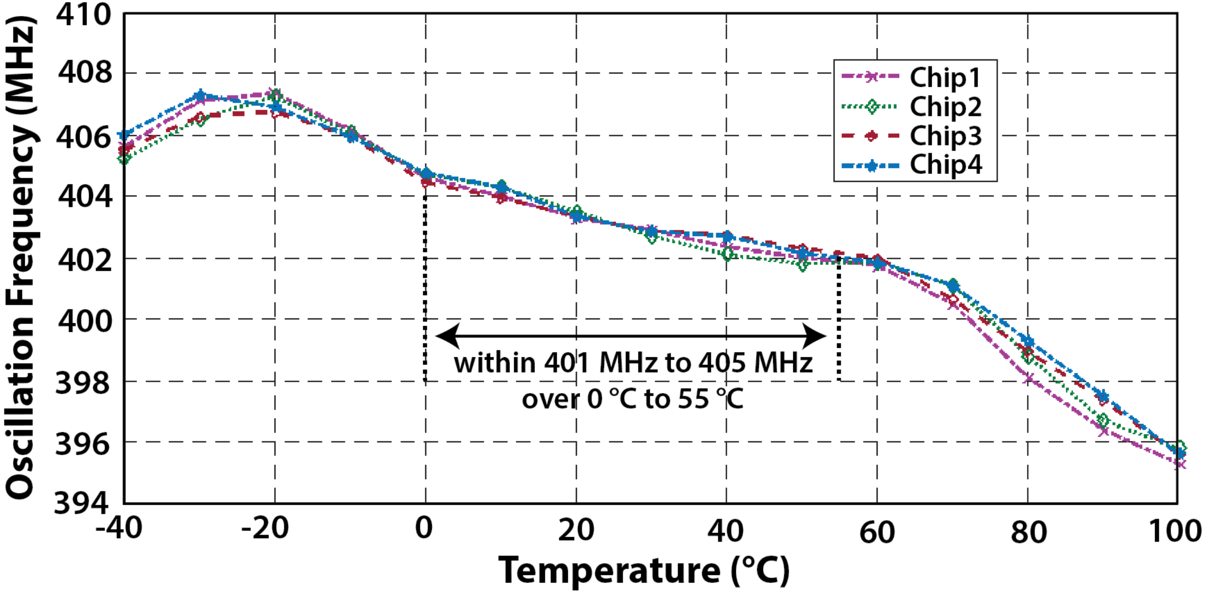
Chip Micrograph





Low TC DCO: Measurements

Temperature sensitivity over multiple chips (DCO tuned to 403 MHz at 25 °C)

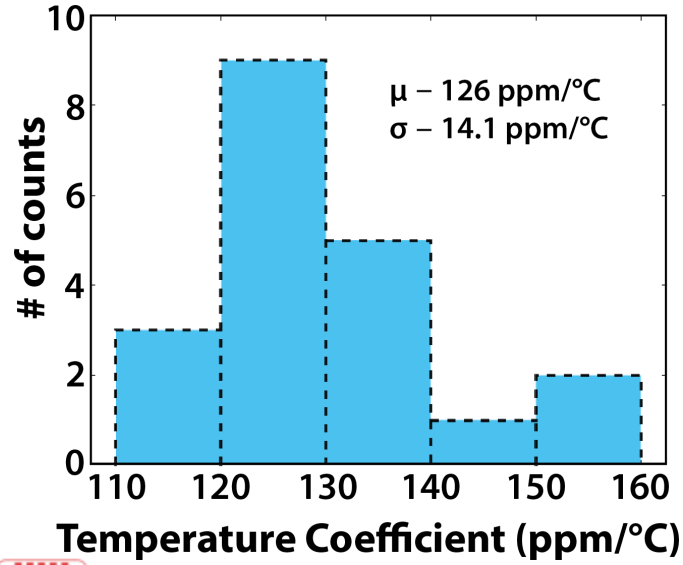


F_{OSC} drift <4 MHz (401 to 405 MHz) across 0 to 55°C

Low TC DCO: Measurements

Measured distributions across 20 chips

Temperature coefficients over 0 to 55°C range



- Min: 113 ppm/°C
- Max: 157 ppm/°C

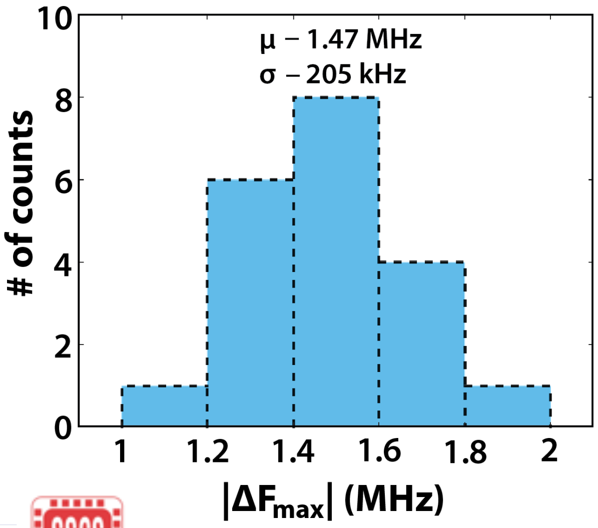
Avg. TC (20 chips) of 126 ppm/°C across 0 to 55°C

Low TC DCO: Measurements

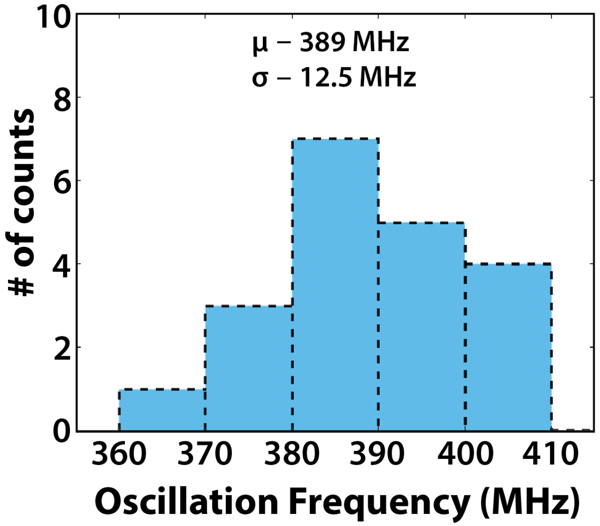
Measured distributions across 20 chips

(ΔF: frequency deviation from nominal value at 25 °C)

Max frequency deviation over 0 to 55°C endpoints

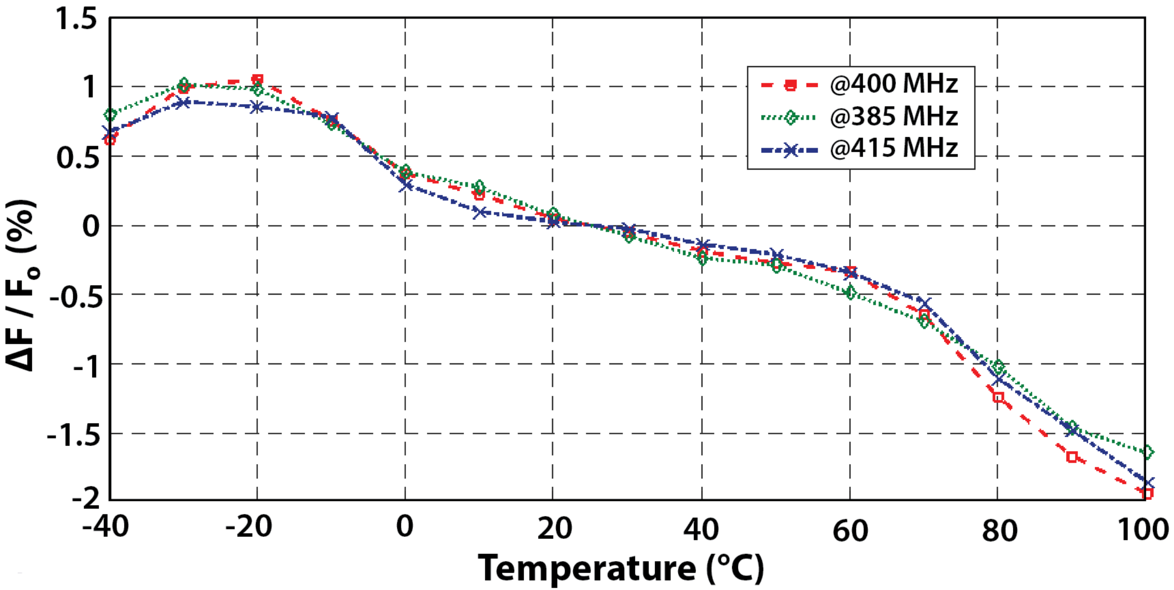


Free-running oscillation frequencies



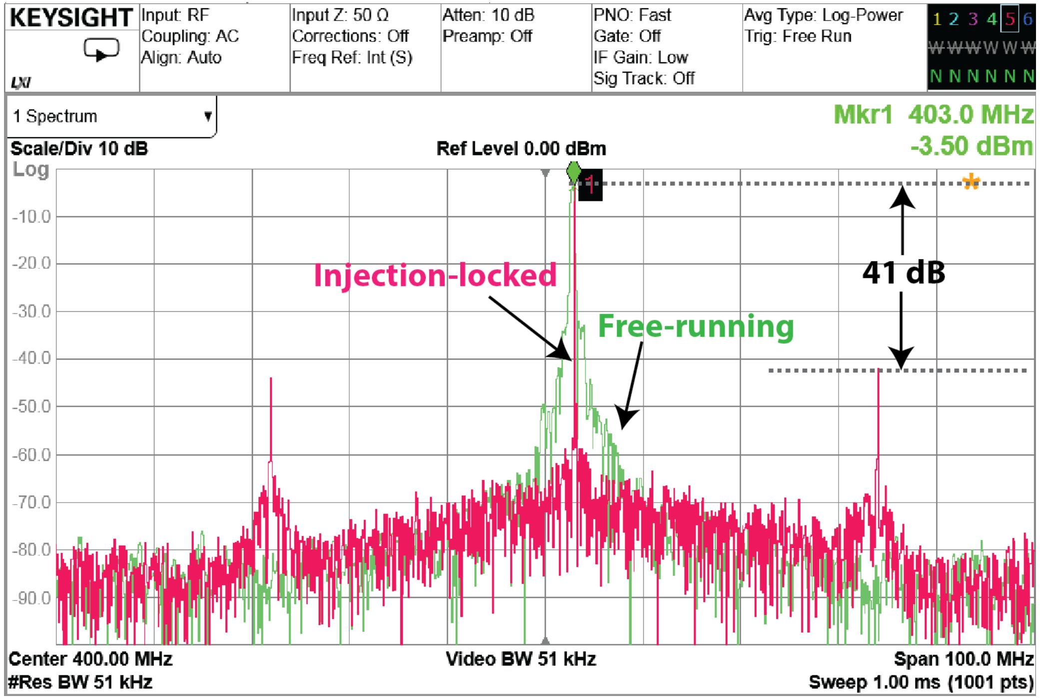
Low TC DCO: Measurements

Temperature sensitivity of same DCO tuned to different frequencies
(ΔF: frequency deviation from nominal value at 25 °C, F_o: Nominal tuned frequency)



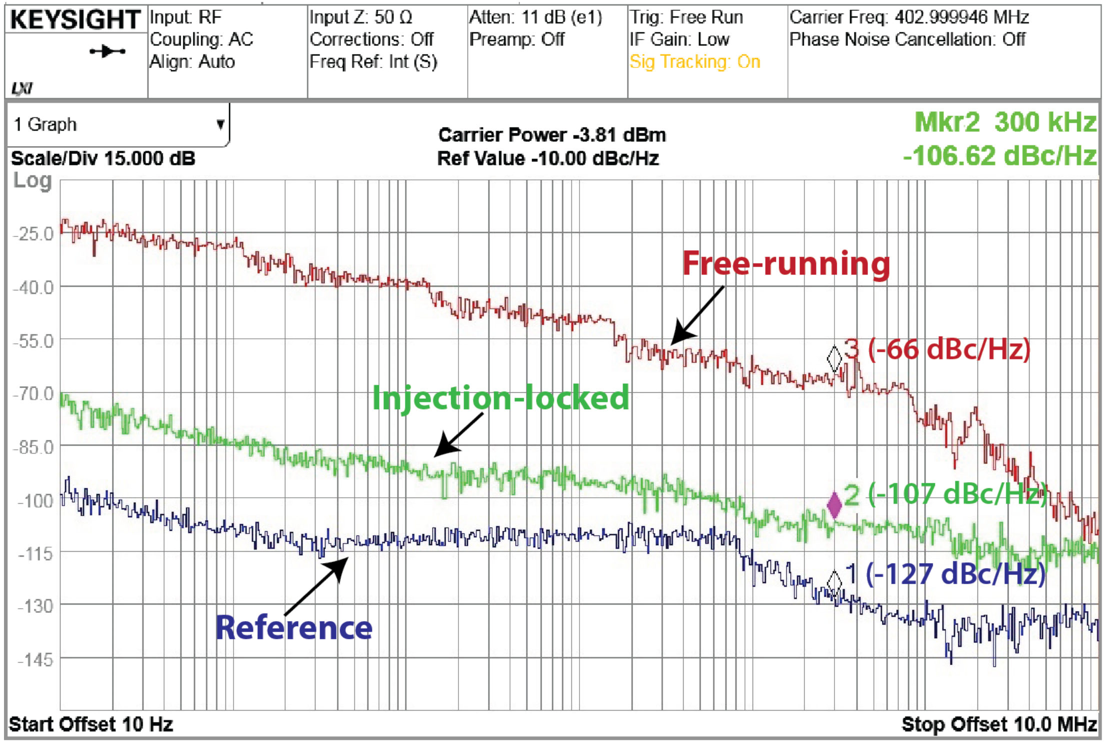
Compensation consistent over multiple DCO modes

ILCM: Measured Output Spectrum



403 MHz MedRadio band carrier from 31 MHz reference

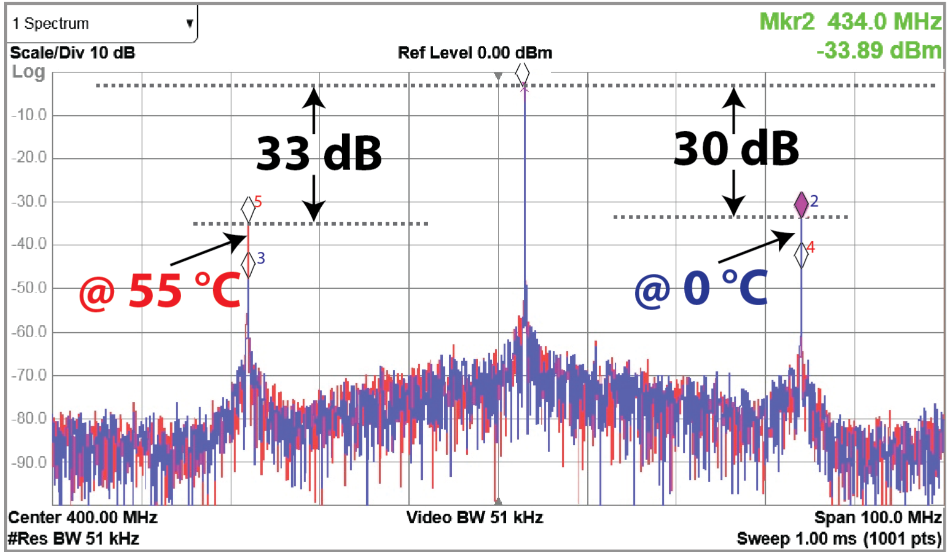
ILCM: Measured Phase Noise

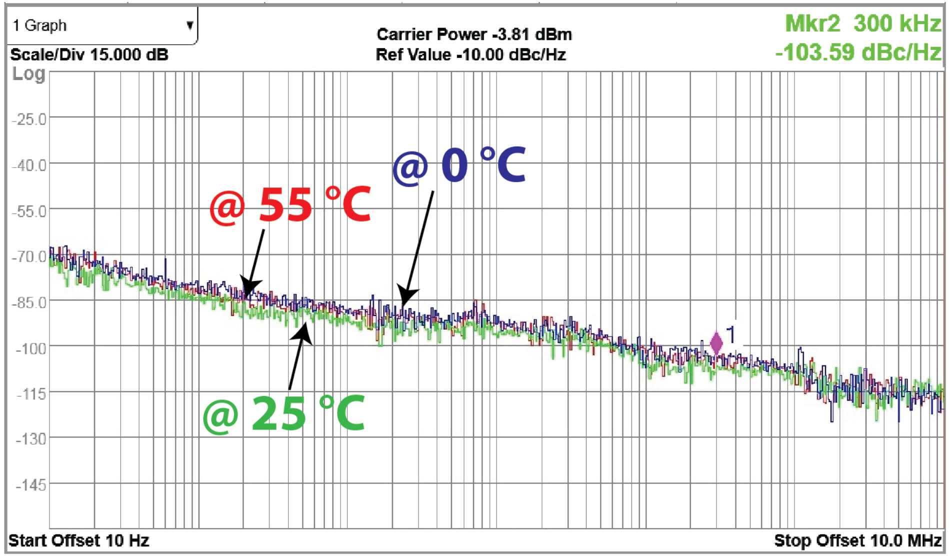


-106.6 dBc/Hz phase noise at 300 kHz offset

ILCM: Measurements over 0 to 55°C

Worst case measured spectrum and phase noise over 0 to 55°C range



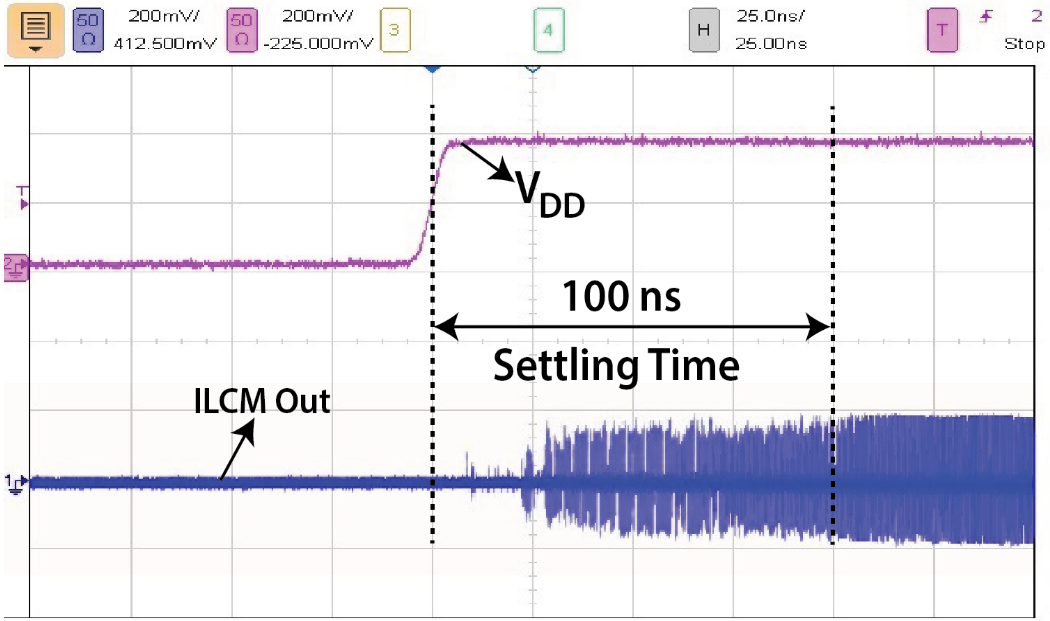


Carrier to spur ratio (CSR) > 20 dB

Phase Noise consistent

ILCM: Measured Power Start-up

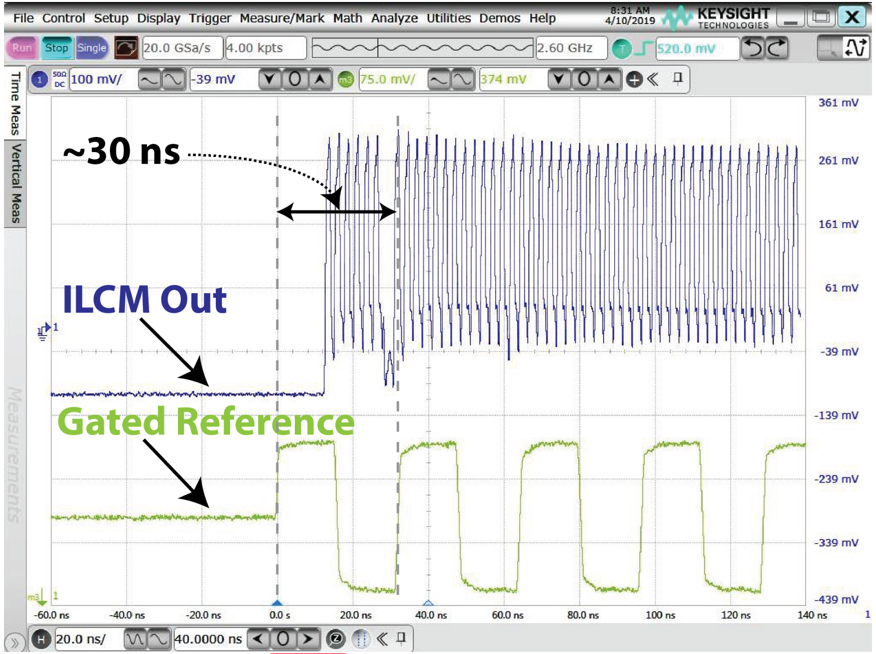
Measured settling time with step voltage on the supply

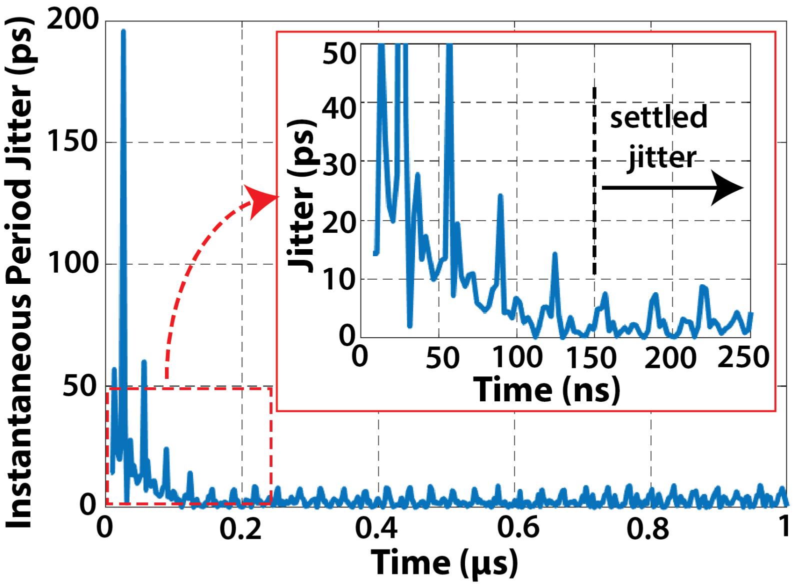


Fast settling for duty-cycled operation

ILCM: Measured Lock Time

Measured settling time with reference injection kick-starting the oscillator:





Period Jitter: $|T_{\text{measured}} - T_{\text{REF}}/N|$

~150 ns (4 REF cycles) jitter settling

Low TC DCO: Standalone Performance

	[Zhang TCAS-I '11]	[Lee VLSIC '09]	[Lakhsmikumar CICC '07]	[Shrivastava CICC '12]	This Work
Technology	90 nm	180 nm	130 nm	130 nm	**180 nm**
Supply (V)	1	1.2	3.3	1.1	**0.7**
Frequency	1.8 GHz	10 MHz	1.25 GHz	100 kHz	**400 MHz**
TC (ppm/°C)	85	67	340	14	**126 [1]** **198 [2]**
Temp Range (°C)	7 to 62	-20 to 100	-40 to 120	20 to 70	**0 to 55 [1]** **-40 to 100 [2]**
# chips measured	1	–	15	10	**20**
F_{osc} Tuning	×	×	×	✓ via DCO	**✓ via DCO**
Power	87 μW	80 μW	11 mW	1 μW	**93 μW**

1 – MedRadio temperature range; 2 – Full temperature range;

Low voltage, supports freq. tuning, supports injection-locking

ILCM: Performance Summary

	[Li ISSCC '18]	[Liu JSSC '14]	[Pandey JSSC '11]	[Yang TBioCAS'13]	This Work
Tech.	65 nm	65 nm	90 nm	65 nm	**180 nm**
Supply (V)	1.1	0.8	0.7	1	**0.7**
Topology	ILRO + FTL	ILRO + calibration	ILRO +EC	PLL	**TC-ILRO + calibration**
Freq. (MHz)	200	900	400	402	**403**
Multiplier	20 ×	9 ×	9 ×	1340 ×	**13 ×**
Phase noise (dBc/Hz)	-95[**] @300k	-100.8 @1M	-105.2 @300k	-102.1 @200k	**-106.6 @300k**
CSR (dB)	43	56[#]	44[#]	45	**41[#]** / **30[*]**
Settling time	–	88 ns	250 ns	350 μs	**30 ns**
Lock time	–	–	–	–	**150 ns**
Power (μW)	130	538	<90	430	**107**
PVT-robust?	P✓ V✓ T✓	P✓ V✓ T×	P× V× T×	P✓ V✓ T✓	**P✓ V✓ T✓**

[**]From reported PN plot; [#]Nominal value at room/single temperature; [*]Across MedRadio temperature range (meeting 20 dB regulation)

Conclusion

- ✓ Open-loop (PLL-free) ILCM
- ✓ Dynamic temperature variations addressed
- ✓ 126 ppm/°C Ring with minimal power overhead CTAT-biasing
- ✓ 150 ns start-up for duty-cycled operation
- ✓ Best combination of PVT-robustness & low power at comparable operation frequencies

Acknowledgement

- Equipment purchased through DURIP award from the Office of Naval Research (award no. N00014-18-1-2350)