Precision BAW Oscillators for Low Power High Performance Applications

Danielle Griffith
Fellow
Texas Instruments
Dallas, Texas
danielle.griffith@ti.com

Tuesday 17th August 2021

About Danielle Griffith

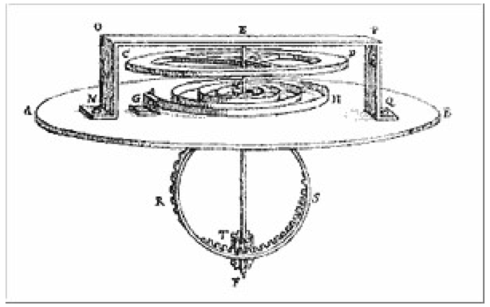
- 1996 & 1997 - B.S.E.E. and M.Eng degrees from the Massachusetts Institute of Technology, Cambridge
- 1997 - 2003 Motorola in Tempe, AZ - RF circuit design.
- 2003 - Current, Texas Instruments in Dallas
  - Fellow in the Connectivity business unit
  - Focusing on efficient wireless systems
- Distinguished contribution to SSCs Society
  - > 50 papers, multiple workshops, book chapter
  - Associate editor of the IEEE Journal of Solid-State Circuits
  - Technical Program Committees: RFIC ('14 – '15), ISSCC ('15 – '19), VLSI (from '19).
  - IEEE SSCS Distinguished Lecturer

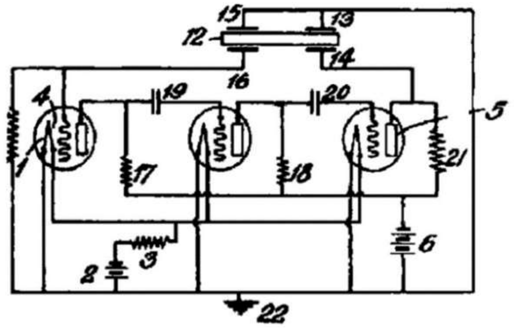
Outline

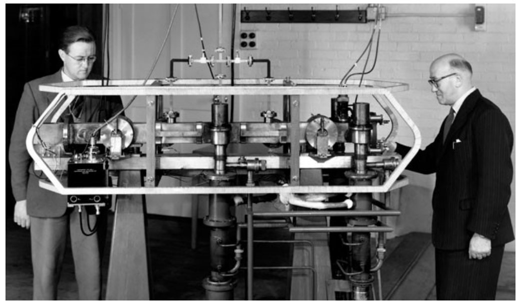
- History of timekeeping
- Crystal oscillators and alternatives
- Bulk acoustic wave (BAW) resonators
- Architecture and design choices
- Measured performance
- System level advantages
- Applications
- Conclusions

Brief History of Timekeeping

- ☐ Calendar: At least 5000 years ago
- ☐ Sundial: ~1500 BC
- ☐ Weight driven mechanical clock: 1283
- ☐ Balance spring/balance wheel: 1675 (Huygens, Hooke)
  - Accuracy ~10s/day
- ☐ Quartz crystal oscillator: 1921 (Cady)
  - Accuracy ~200s/year
- ☐ Atomic Clock: 1955 (Essen)
  - Today's accuracy ~30ns/year
- ☐ Now timing devices are a requirement for nearly all electronic systems
  - Key attributes: Operating frequency, frequency accuracy, frequency stability, power consumption, cost, size, environmental robustness

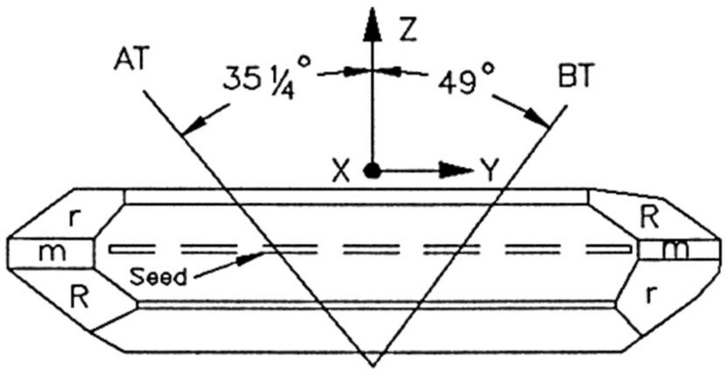




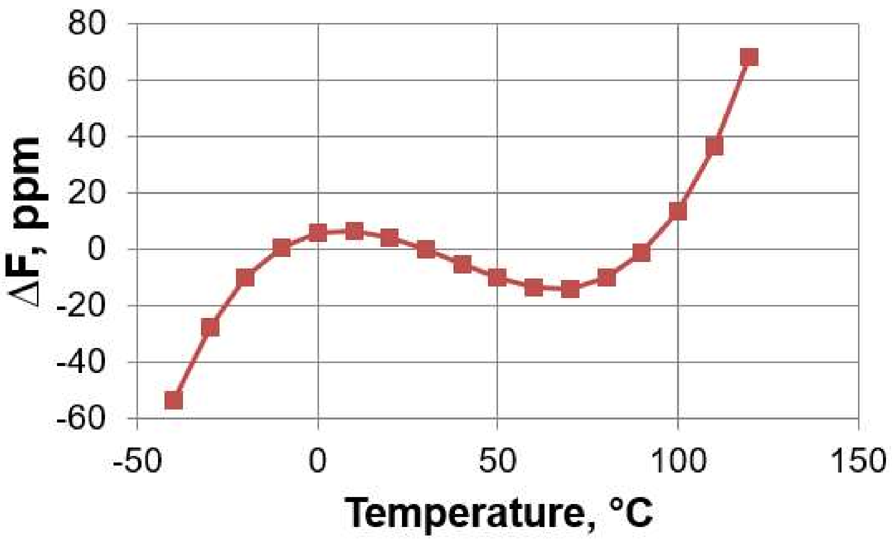


Quartz Crystal

- ☐ Quartz is a crystalline form of silicon dioxide
- ☐ Possible to cut a quartz crystal such that resonant frequency is quite stable over temperature (±40ppm from -40 to +85°C).
- ☐ 10-50MHz crystals are often “AT” cut, giving a cubic (s-shape) curve of resonance frequency vs. temperature.
- ☐ A quartz crystal is specified as frequency X with capacitive load Y (e.g. 48MHz at C_L=9pF).
- ☐ Packaged size is often between 1.2x1.0mm² to 3.5x2.5mm².

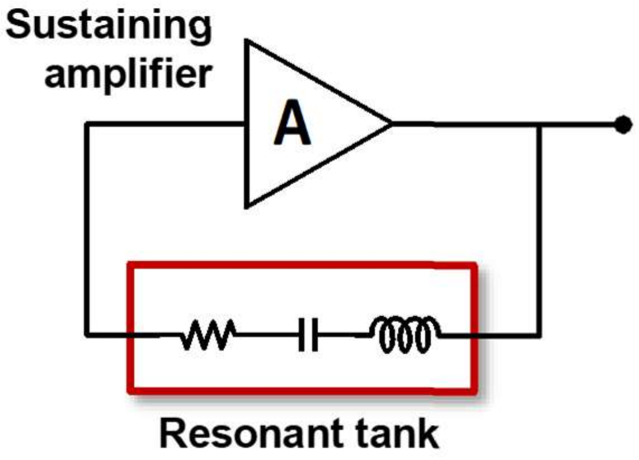


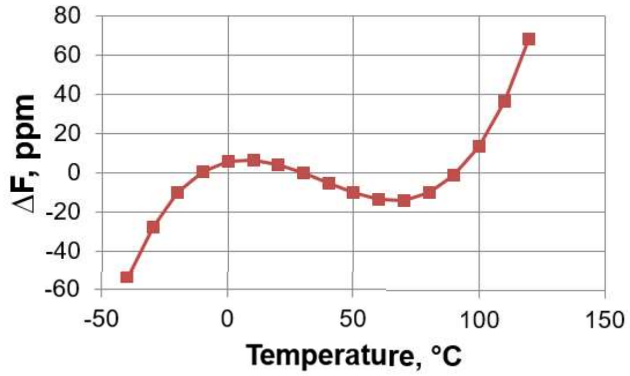
www.4timing.com

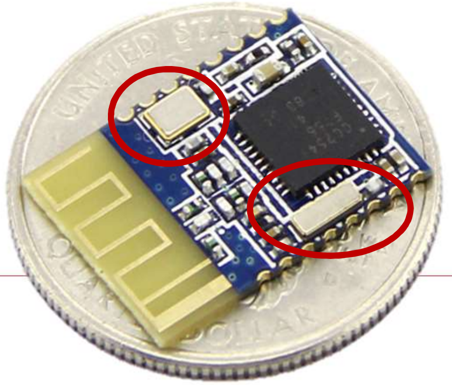


Crystal Oscillators

- Quartz crystal resonator + active circuitry = crystal oscillator
- Advantages
  - Mature technology (100 years old in 2021)
  - Quality Factor>30,000: Low power consumption (~10μW/MHz)
  - Stable frequency – <100ppm (0.01%) variation -40°C to 85°C
- Disadvantages
  - Cost (equivalent to 1-2mm^2 of silicon)
  - Limits integration, size 2.0x1.6mm^2 is common
  - Degraded frequency stability at temperature extremes
  - Relatively slow startup time
  - Sensitivity to shock and vibration
  - Frequent supply issues (12-26 week lead time is common)

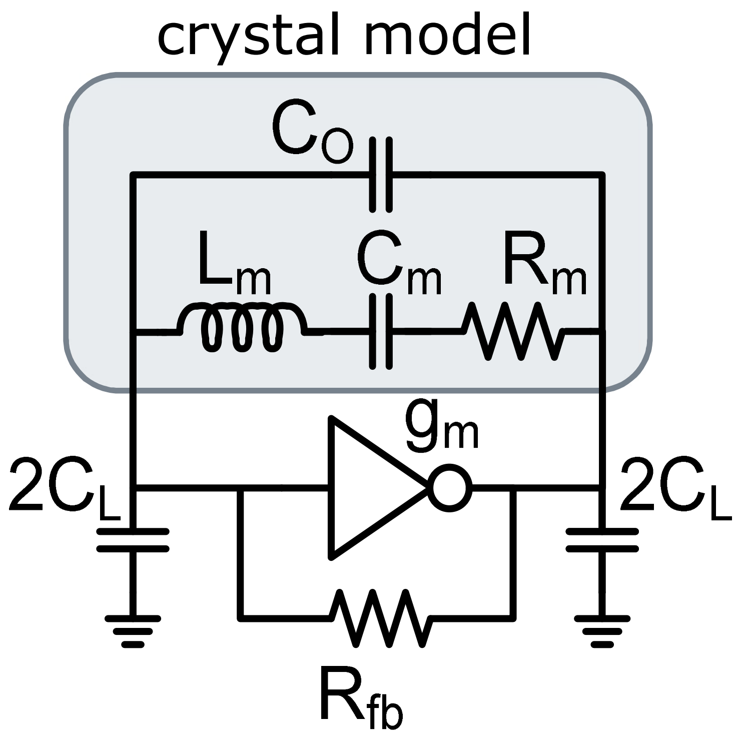






Frequency Accuracy & Quality Factor

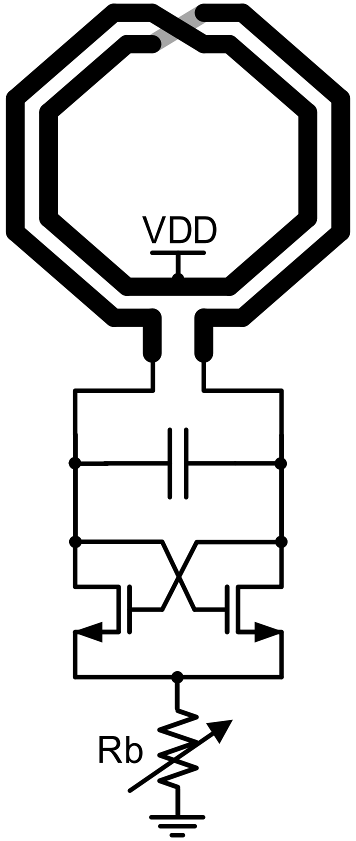
- Example frequency accuracy requirements for communications:
  - High speed USB ±500ppm
  - Bluetooth Low Energy ±50ppm
  - WiFi ±20ppm
- Higher Quality factor (Q) ➔
  - better stability
  - lower noise/jitter
  - lower power consumption to sustain the oscillation
- Crystal Q > 30,000
  - Oscillator achieves ~±40ppm frequency accuracy over wide temperature range with no active temperature compensation
  - Higher Q requires longer startup time. Startup energy can be limiting factor in duty-cycled applications

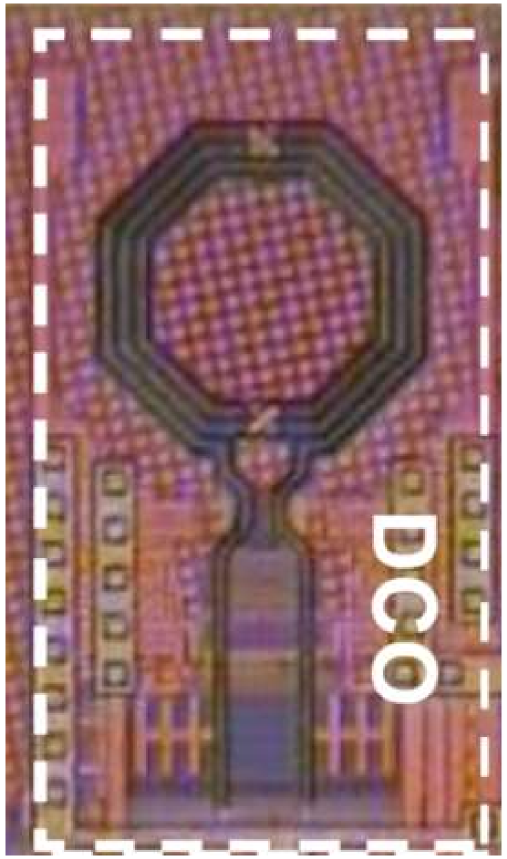


$$Q = \frac{1}{R_m}\sqrt{\frac{L_m}{C_m}}$$

Alternatives to Crystal Oscillators?

- Differential center tapped inductors can be fabricated in silicon
- Inductance determined by total length
- Q determined by diameter, metal and via resistance, and substrate loss
- On-chip inductor Q ~ 15
- Relatively large area required → 100x100µm to 500x500µm
- Integrated oscillator has >±1% frequency accuracy with no temperature compensation
- Challenging to implement compensation for 20x – 500x frequency stability improvement needed for communications





Microelectromechanical Systems (MEMS)

- ☐ Much higher Q possible than integrated planar inductors
  - 1000+ vs. ~15
  - Lower power oscillators with lower phase noise, better filters
- ☐ Examples:
  - SAW (Surface Acoustic Wave) resonator
  - BAW (Bulk Acoustic Wave) resonator
  - Used extensively in filters/duplexer products (20+ per phone)
- ☐ First BAW oscillator published >40 years ago
  - BAW oscillators not used in commercial products until 2019

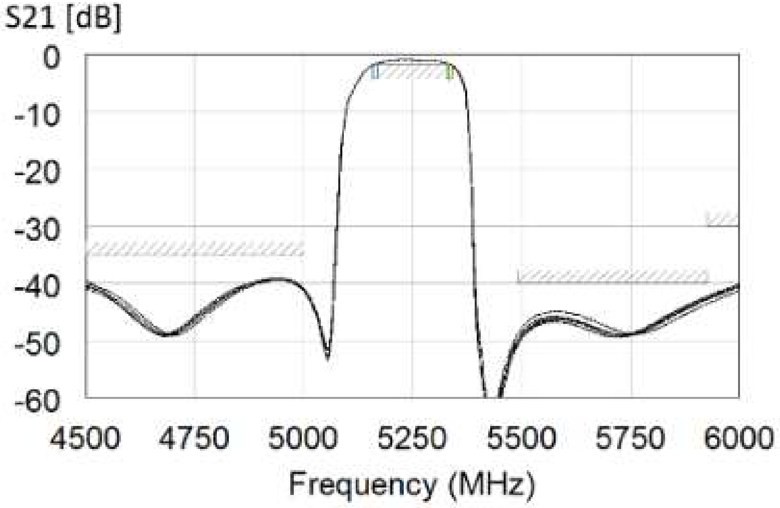


Figure 8: Passband insertion loss and nearby rejection of 5.25 GHz BAW filter.

Aigner, 2019

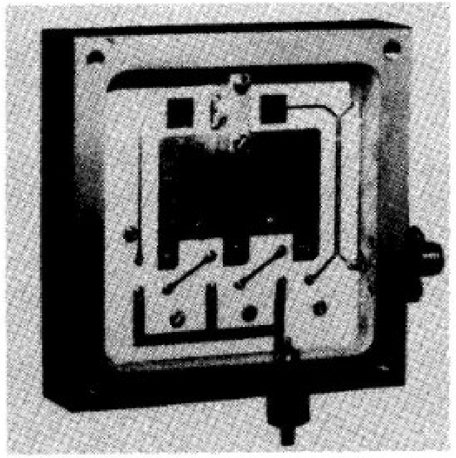
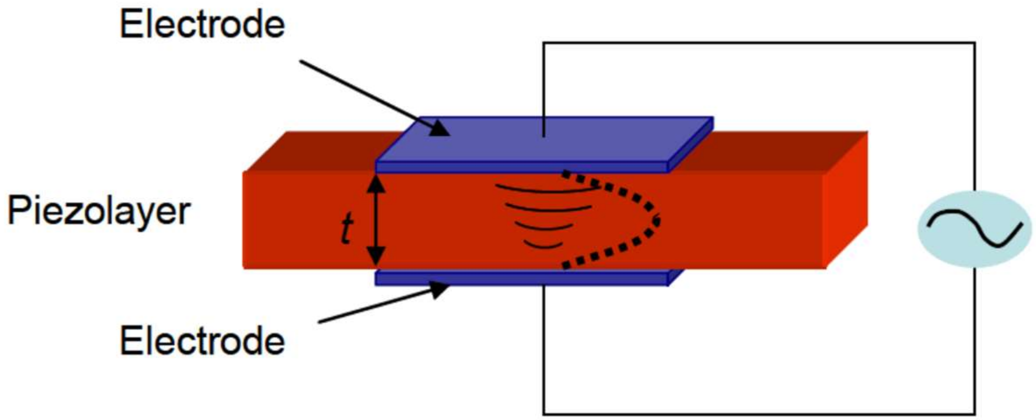


Fig. 6. Compact bulk-wave oscillator

"Behavior and Current Performances of SAW and BAW Oscillators" Schaer, 1976

Bulk Acoustic Wave (BAW) Resonator

- Passive device consisting of piezoelectric material surrounded by electrodes
    - Piezoelectric converts electrical ↔ mechanical energy
    - Mechanical resonant behavior in bulk of material, vs. SAW = Surface Acoustic Wave Resonator
- Aluminum Nitride (AlN) is the most commonly used thin film BAW resonator material

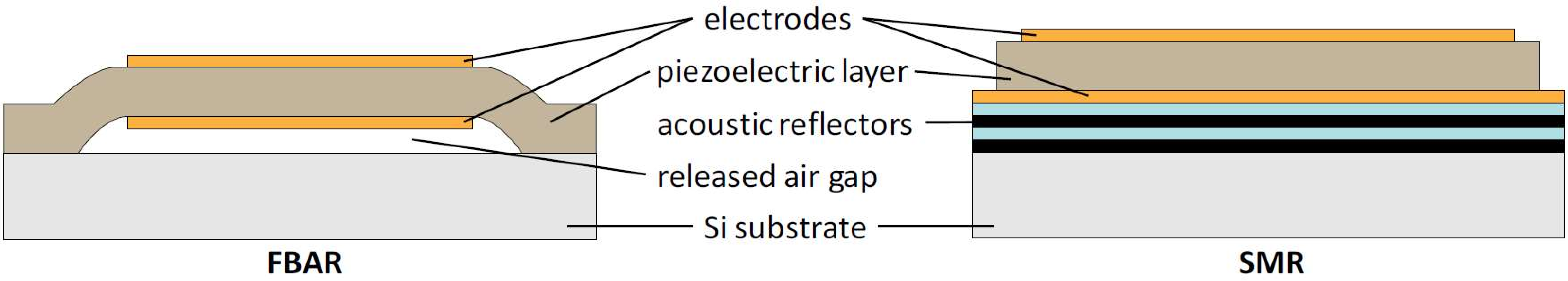


Resonant frequency, f_R dependent on AlN thickness, t, and acoustic velocity, v_L, to first order

$$f_R \approx \frac{v_L}{2t}$$

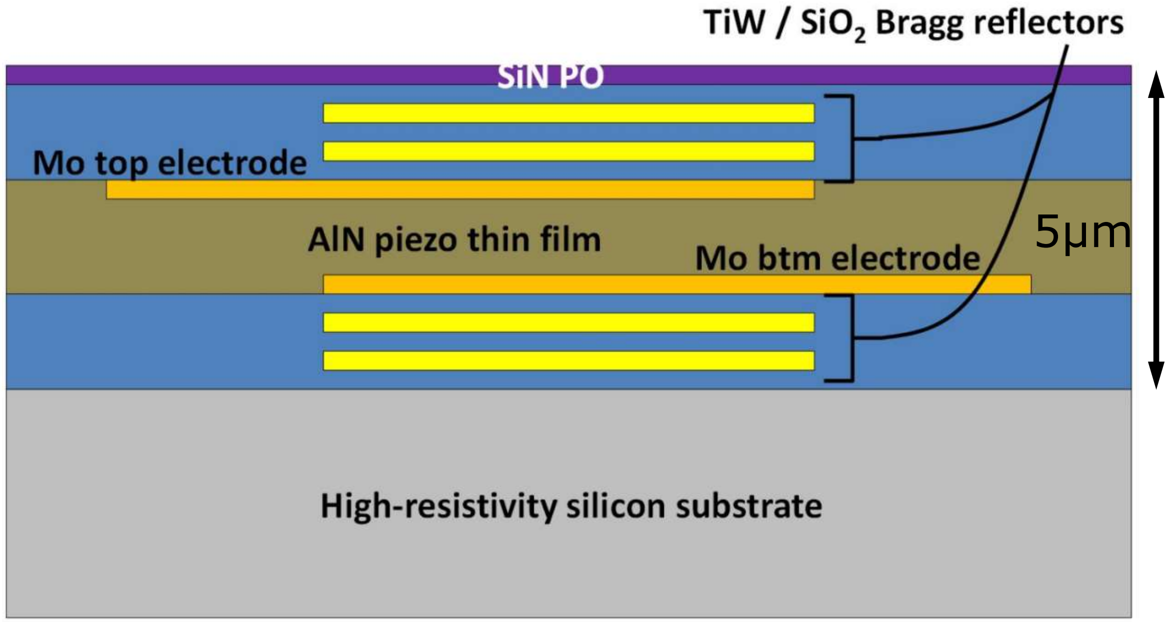
Types of BAW Resonators

- Two types of piezoelectric BAW resonators in the market before 2019:
    - Thin film bulk acoustic resonator (FBAR): Broadcom ACPF filter products
    - Solidly mounted resonator (SMR): Qorvo RF filter and duplexer products
- Cavities required on one or both sides of the resonator to provide acoustic isolation
    - May require hermetic packaging and increase sensitivity to external forces



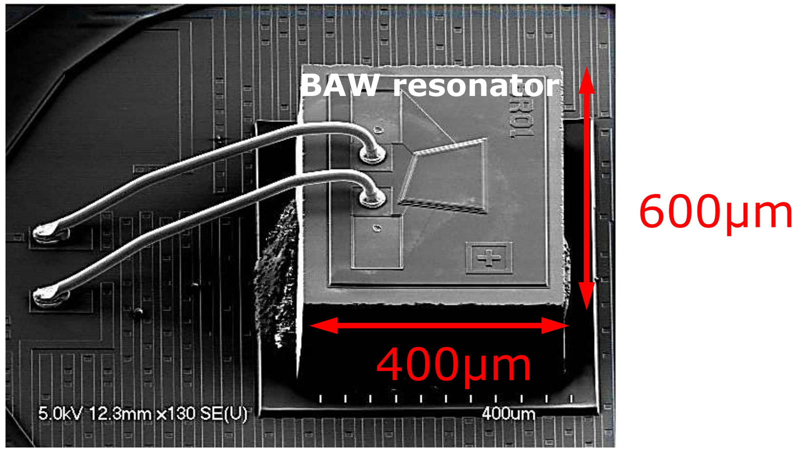
Dual-Bragg BAW Resonator

- Dual-Bragg reflector structure
  - Alternating high- and low-acoustic impedance layers
  - Below the AlN piezoelectric film, reflector prevents energy from leaking into substrate → Q >1000
  - Above the AlN, reflector prevents energy leaking into packaging material and device contamination → low frequency drift/aging
  - No vacuum cavities or hermetic packaging required → low cost
- ~5µm thick on top of high-res Si substrate
- Shape optimized to reduce spurious modes



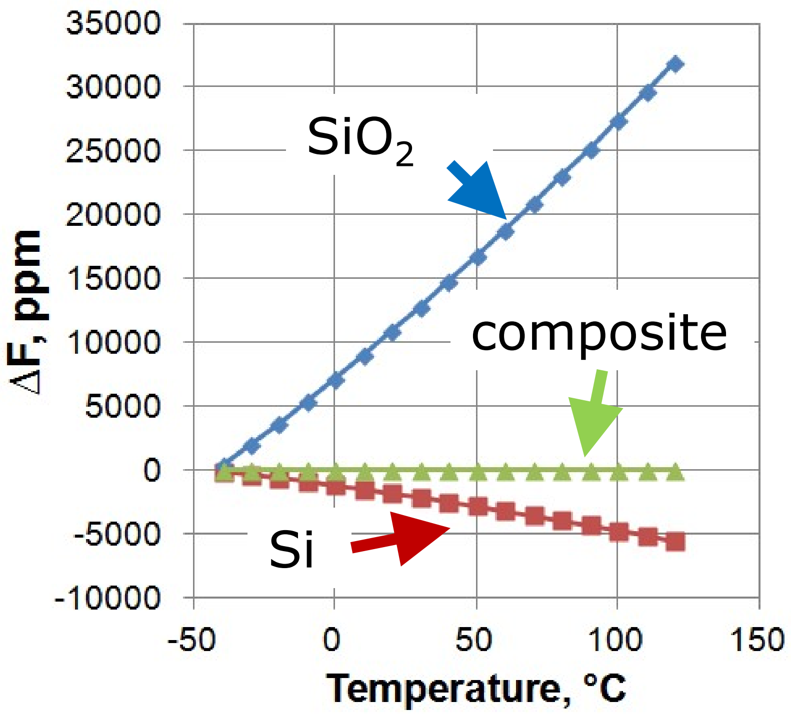
BAW resonator cross section

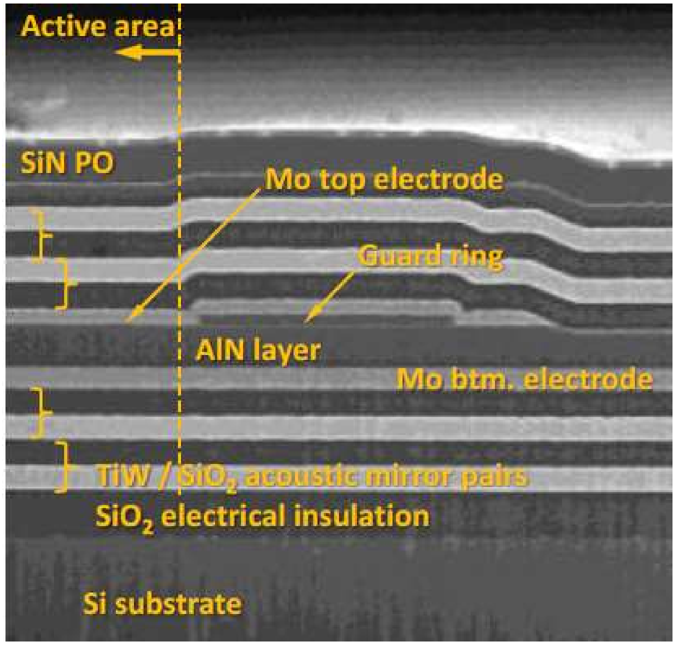
BAW stacked on CMOS die



Passive Temperature Compensation

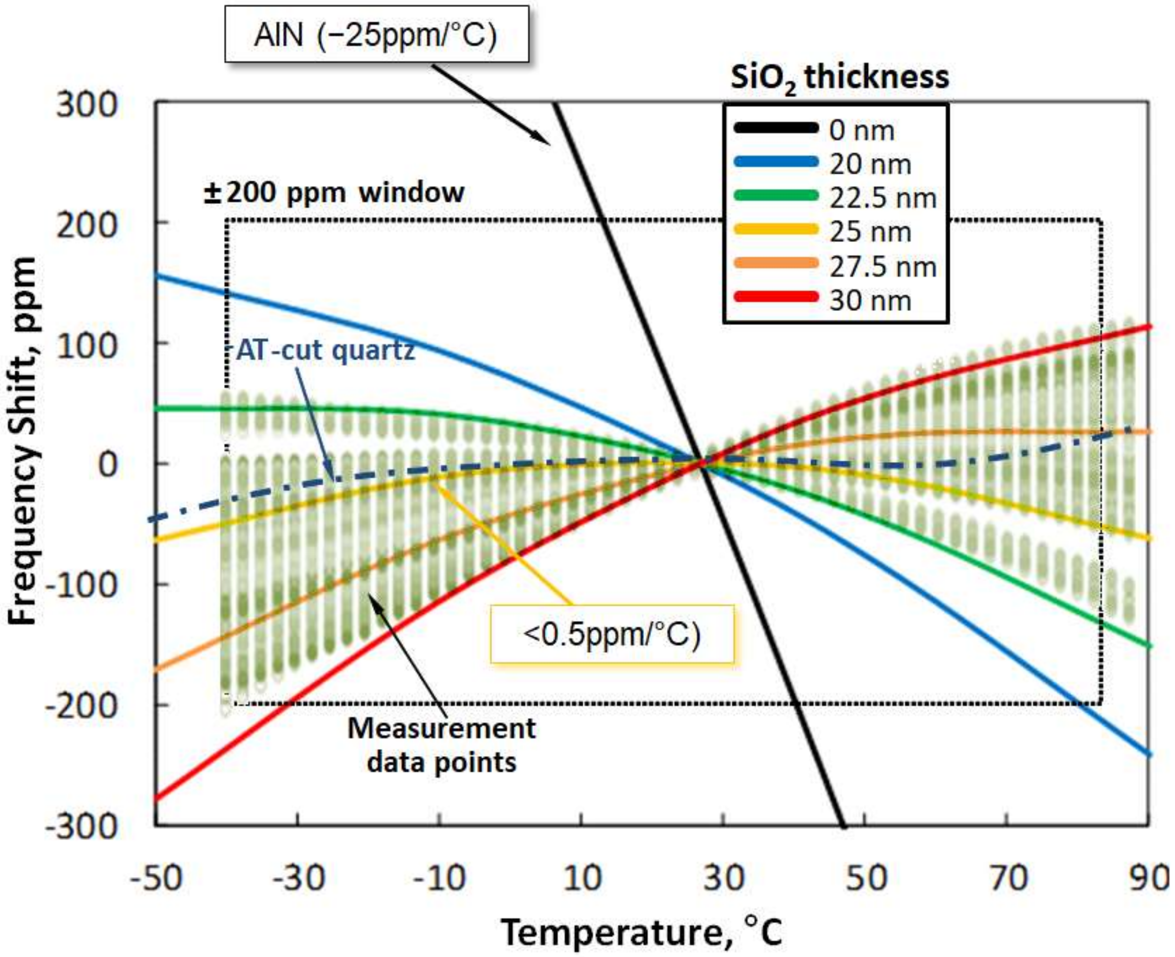
- Many materials used in MEMS resonators soften and expand as temperature increases
- Young's modulus is a measure of material stiffness
  - 180GPa for Si, -31ppm/°C, 70GPa for SiO2, +180ppm/°C
- Passive compensation implemented by adding a material with a positive TC to the Si resonator structure.
  - Second order temperature coefficients remain.
- Compensation can degrade resonator quality factor
  - Increased power required to sustain the oscillation.





Passive Temperature Compensation

- First order temperature coefficient of frequency (TCF) for AlN is -25ppm/°C.
  - More than 3000ppm frequency drift over industrial temperature range
- SiO_2 has positive TCF
  - Adding a SiO_2 layer reduces effective resonator TCF to as low as ±0.5ppm/°C (similar to AT-cut quartz crystals)
- Manufacturing tolerances of film thicknesses allow passive temperature compensation to within <300ppm from -40 to 85°C
- Still not sufficient for all communications protocols

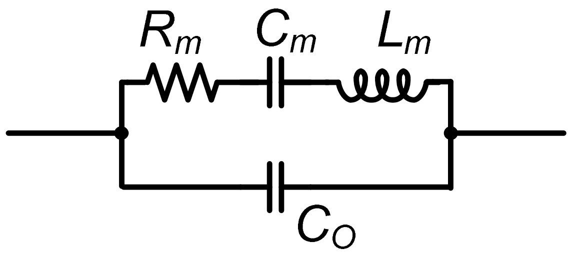


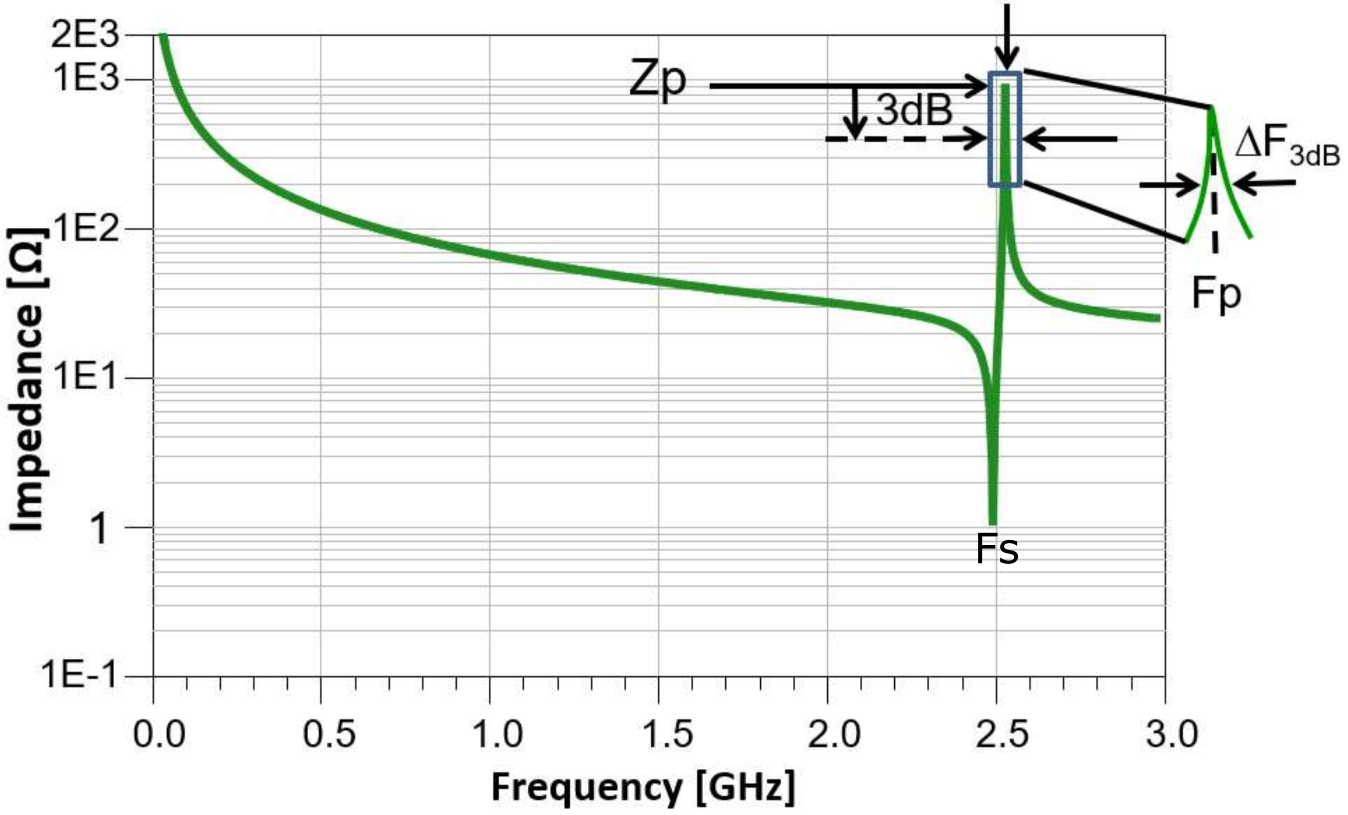
BAW Resonator Model

- Same model topology as quartz crystal
- Inductive between series and parallel resonance frequencies
- Two pins only
    - No ground
    - No bias voltage

Electrical Equivalent Model:

Modified Butterworth Van-Dyke (MBVD)

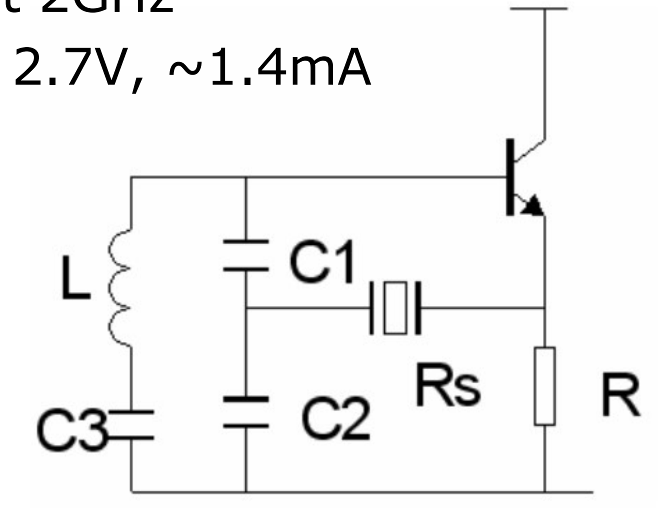




$$Qp = \text{Quality Factor} = Fp/\Delta F_{3dB} > 1000$$

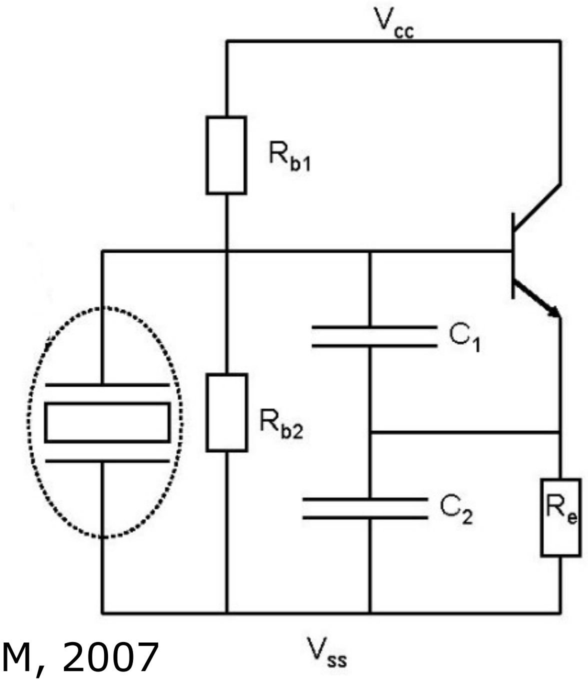
Single-Ended Oscillator Topologies

- Butler architecture
- BAW resonator and LC tank frequencies must be matched to within a few percent
- BAW passive temp compensation to -5ppm/°C
- Q=700 at 2GHz
- BiCMOS, 2.7V, ~1.4mA



Vanhelmont, NXP, 2006

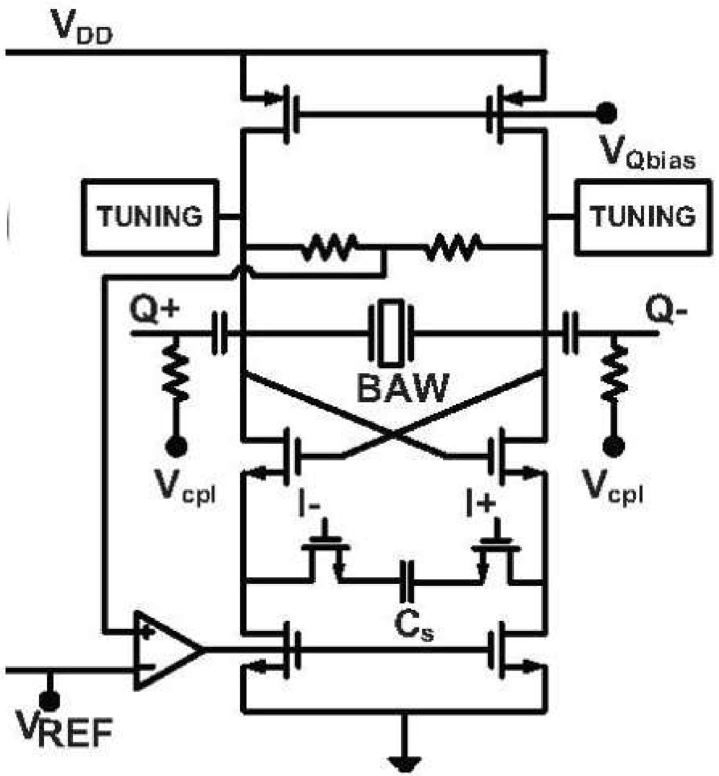
- Colpitts architecture
- Commonly used topology
- ~600ppm frequency variation
- Q=600 at 2.1GHz
- BiCMOS 0.25µm, 2.5V, ~4.8mA



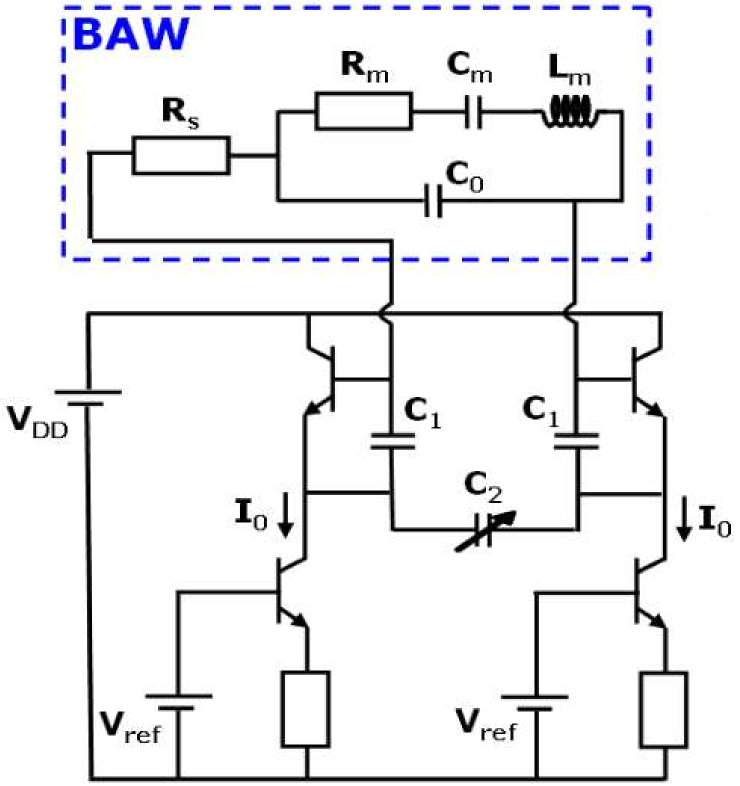
Razafimandimby, STM, 2007

Differential Topology Examples

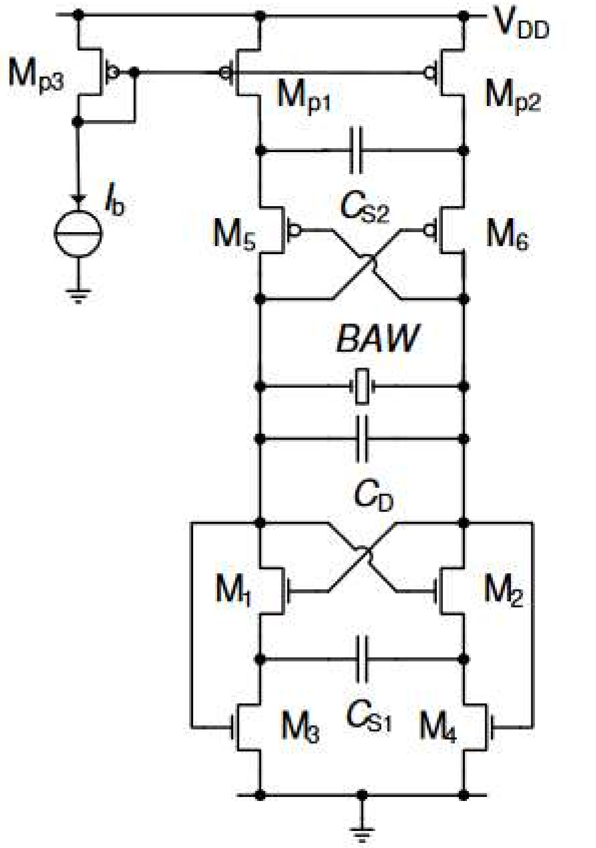
Differential
Rai, 2007
U. of Washington
2.1GHz, 600µA, 0.13µm CMOS



Differential Colpitts
Petit, 2009
STM
2.5GHz, 10mA, 0.25µm BiCMOS



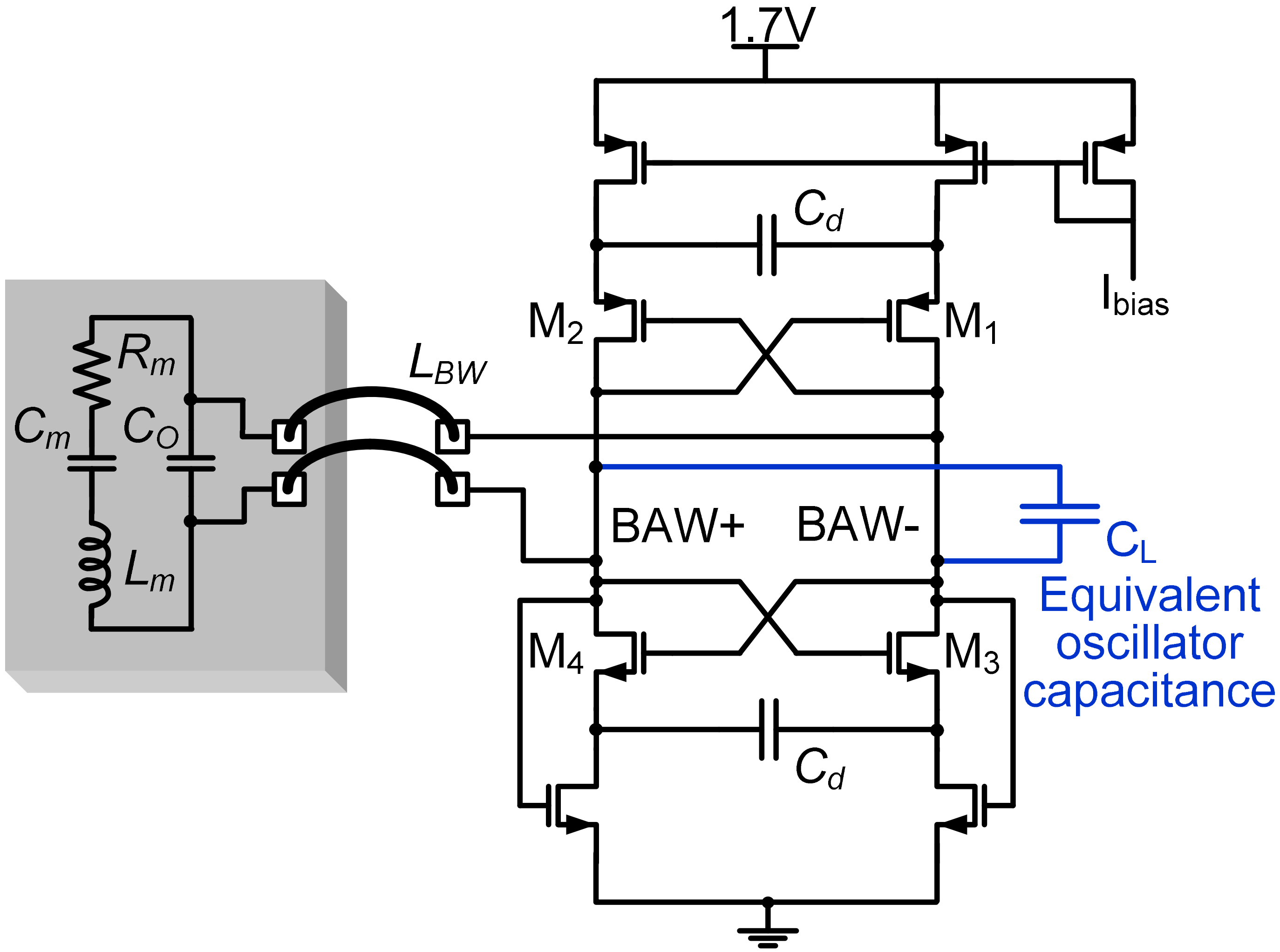
Complementary differential
Thirunarayanan, 2011
2.5GHz, 675µW, 0.18µm CMOS



Oscillator Design Constraints

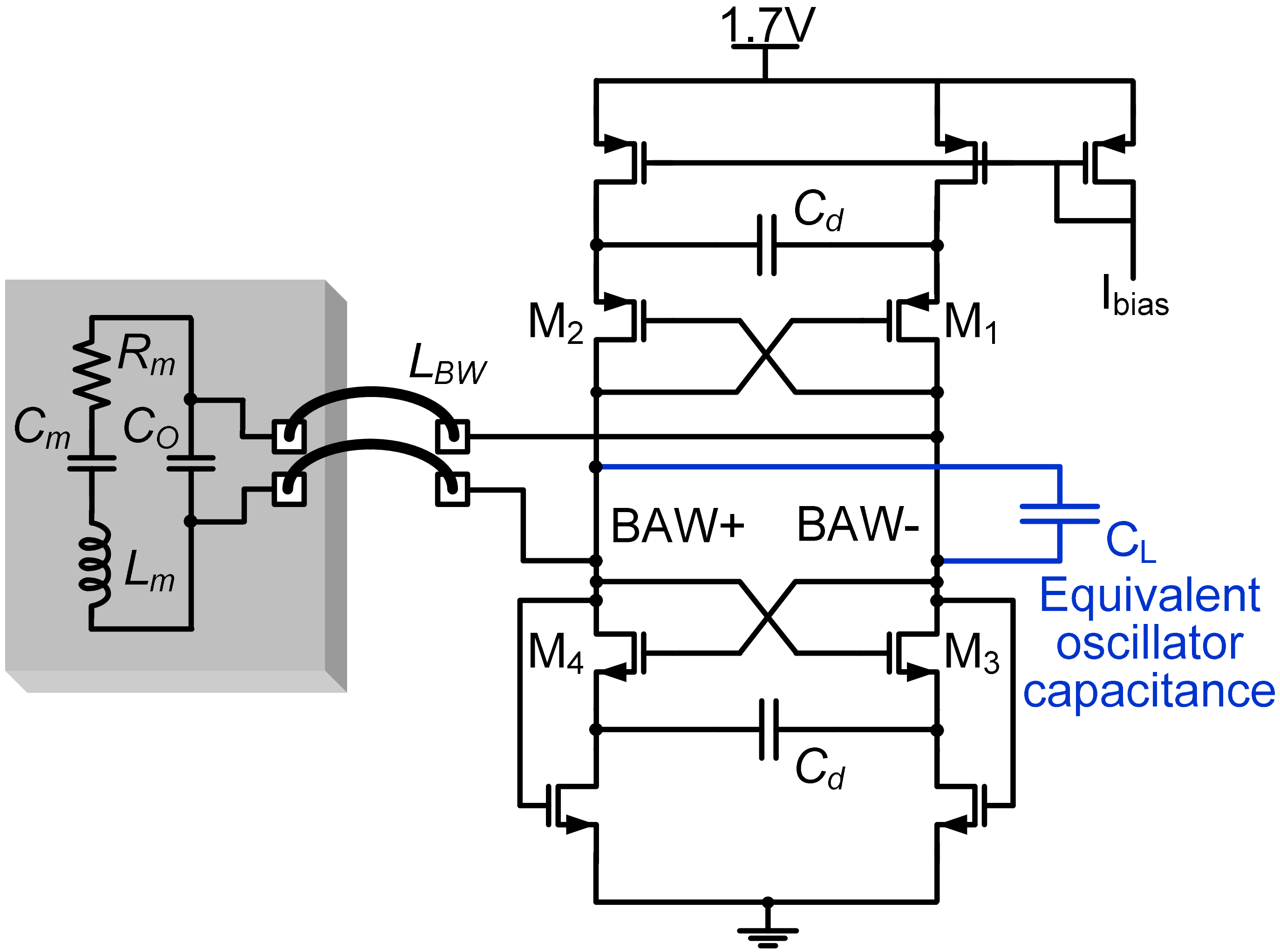
- BAW resonator stacked on and wire-bonded to CMOS die
- Four modes possible
  - Latched if C_d too small
  - Parasitic relaxation oscillation if $C_d > nC_L/2$ [Thirunarayanan, 2011]
  - Desired oscillation (2-3GHz)
  - Parasitic oscillation at f_B (5-8GHz)

$$f_B = \frac{1}{2\pi\sqrt{L_{BW}\left(\frac{C_L C_O}{C_L + C_O}\right)}}$$



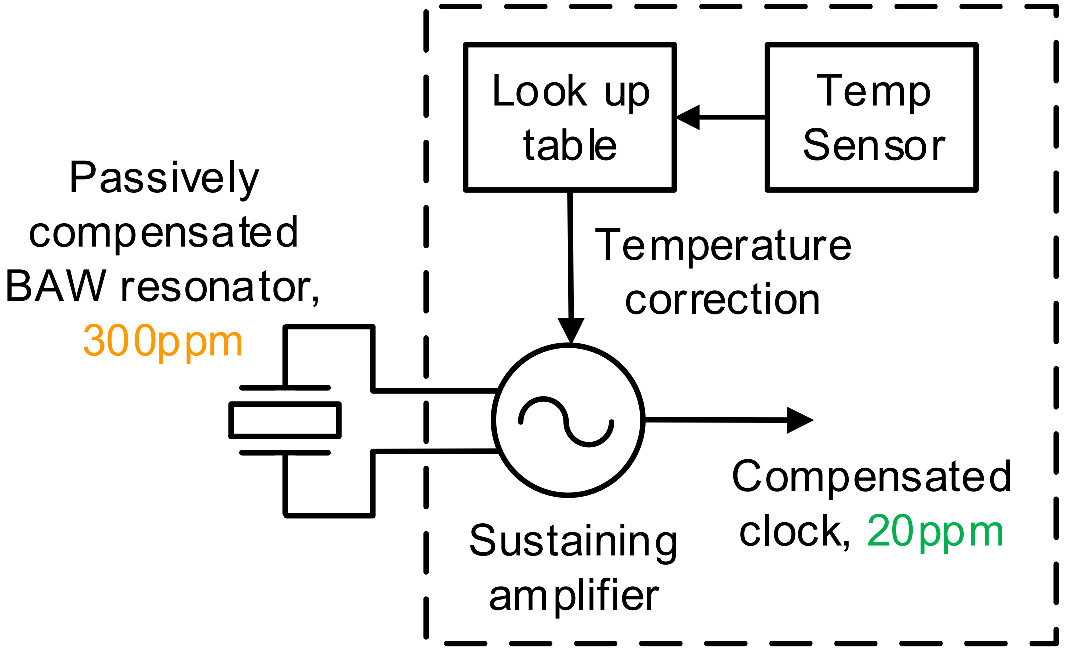
Avoid Parasitic Oscillation

- Bondwires short and spaced as closely as packaging rules allow
  - Mutual coupling ↑
    LBW_effective ↓ f_B ↑
  - Easier to ensure no gain at f_B
  - Flip chip packaging removes this mode
- M_1-M_4 sized and biased to ensure no loop gain at parasitic oscillation frequencies
- Alternatively, LC trap used instead of C_d, at the cost of increased area

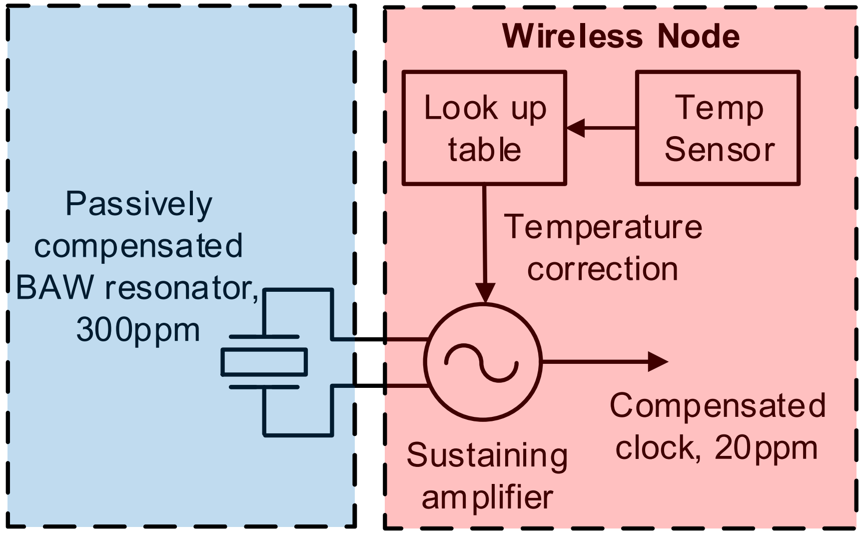


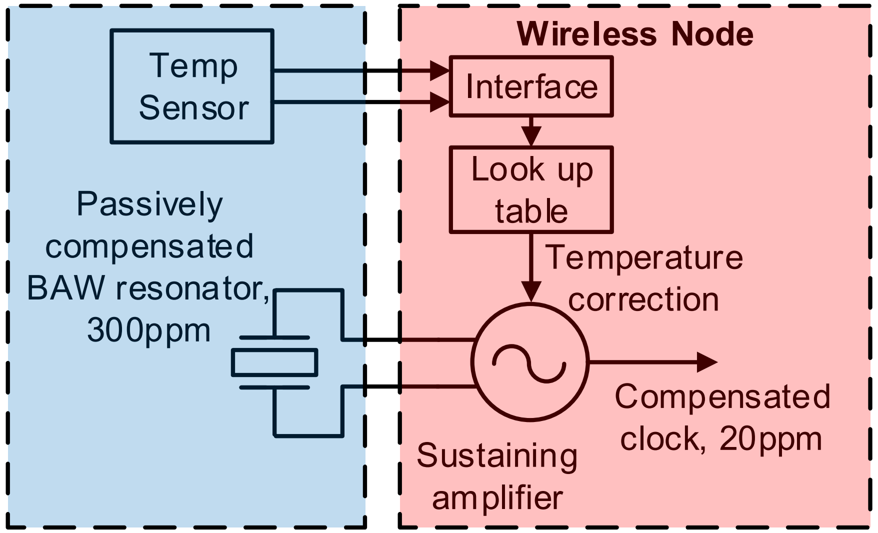
Active Temperature Compensation

- ☐ Uncompensated BAW resonator: ΔF vs. T ~3000ppm (0.3%)
- ☐ BAW resonator with passive temp. compensation: ΔF vs. T ~300ppm (0.03%)
  - Still insufficient for many *wireless* communication applications
- ☐ BAW resonator with passive + active temp. compensation: ΔF vs. T ~20ppm
- ☐ Compensation limited by temperature sensor accuracy
- ☐ Compensation can be continuous or periodic



Temperature Sensor Location





☐ Temperature sensor in die with active circuitry

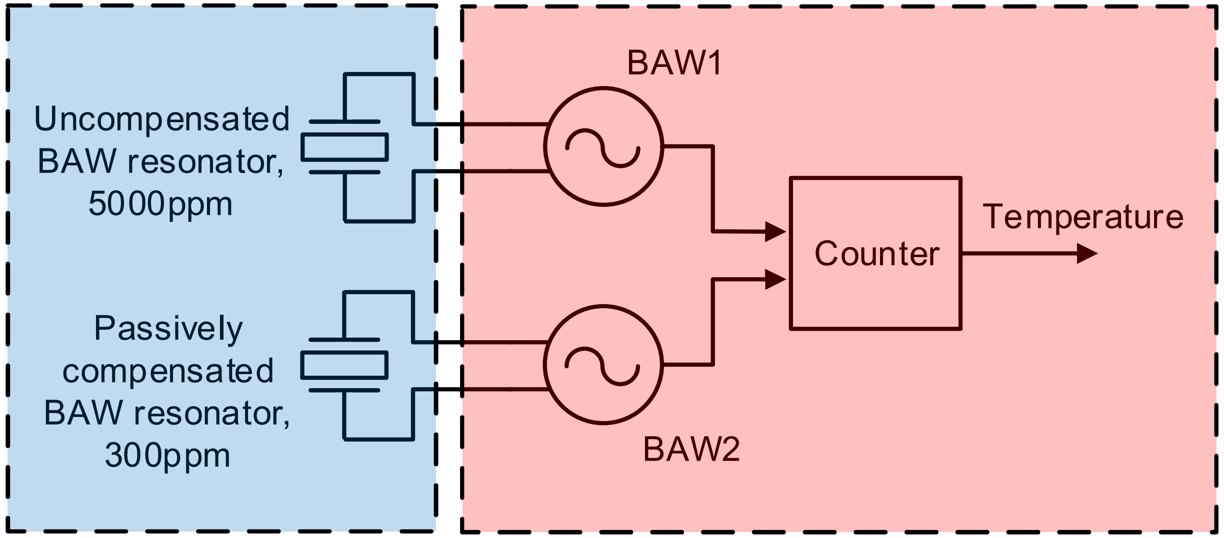
- Fewer bondwires
- Smaller size for BAW resonator
- Sensitive to temperature gradients between resonator and IC
- Less accurate temperature measurement

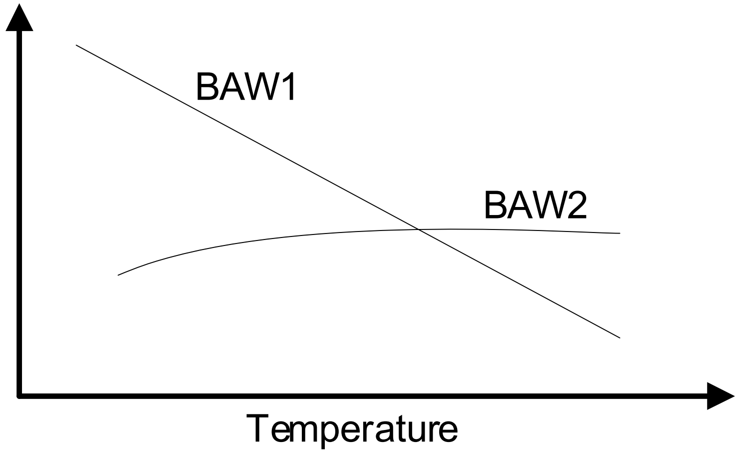
☐ Temperature sensor on BAW resonator die

- 2 extra bondwires / connections
- Larger size for BAW resonator
- Interface required (ADC, oscillator)
- Less sensitive to temperature gradients
- More accurate temp measurement

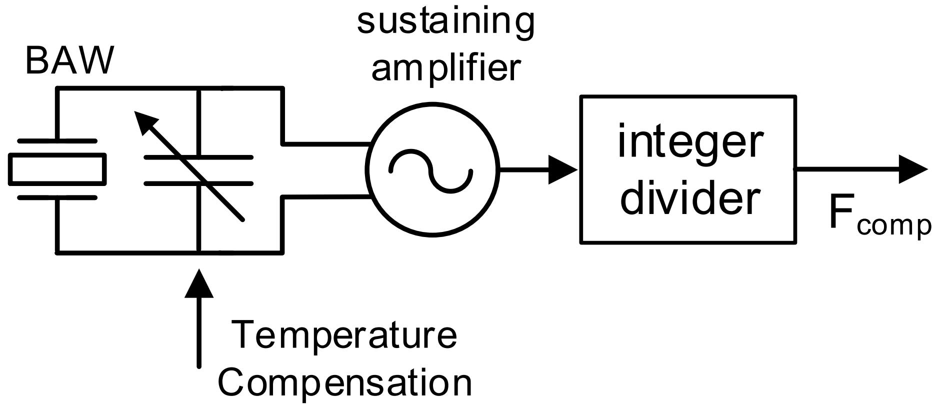
BAW as a Temperature Sensor

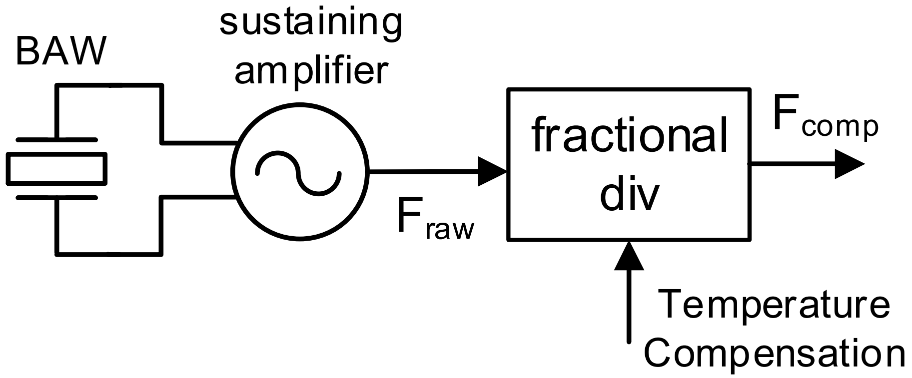
- Two BAW oscillators used
    - BAW1 without passive temperature compensation layers
    - BAW2 passively compensated,
- Counter used to compare the relative frequency
- Temperature proportional to $\mathrm{Freq}_{\mathrm{BAW2}}$-$\mathrm{Freq}_{\mathrm{BAW1}}$
- Higher accuracy by allowing counter to measure over a longer time
- Initial offset calibration needed in production





Temperature Compensation



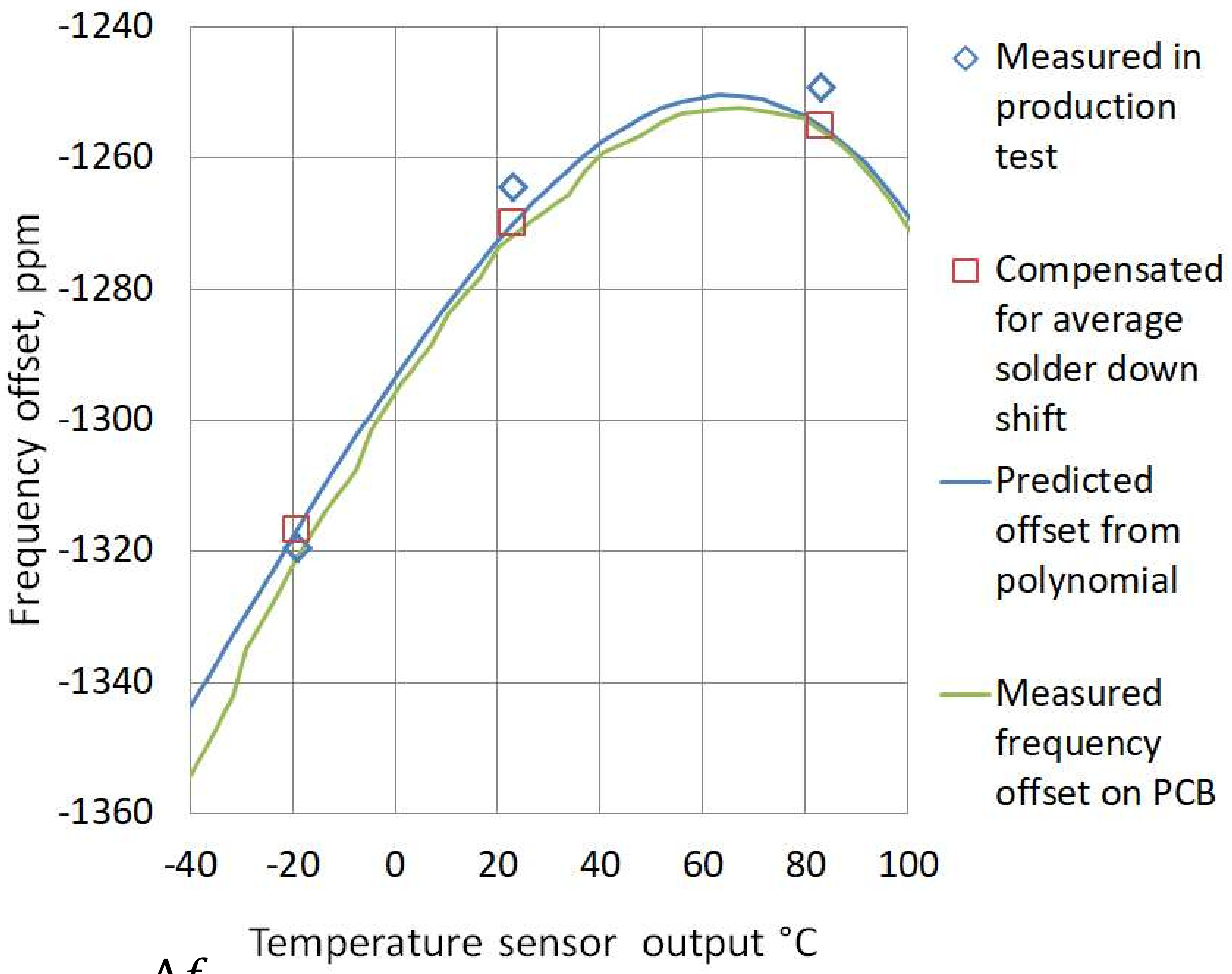


- Advantages
  - Lower complexity
  - Low added jitter from divider
- Disadvantages
  - Lower tank Q → degraded phase noise
  - Higher oscillator power consumption
  - Parasitic resonance at a lower frequency
  - Tuning range limited to ~1%

- Advantages
  - Lowest oscillator power consumption
  - Easy to avoid parasitic resonance (low cap)
  - Wide tuning range
- Disadvantages
  - Constraints on divider resolution
  - Extra area, complexity, and power for divider
  - Added jitter from divider

Production Trimming

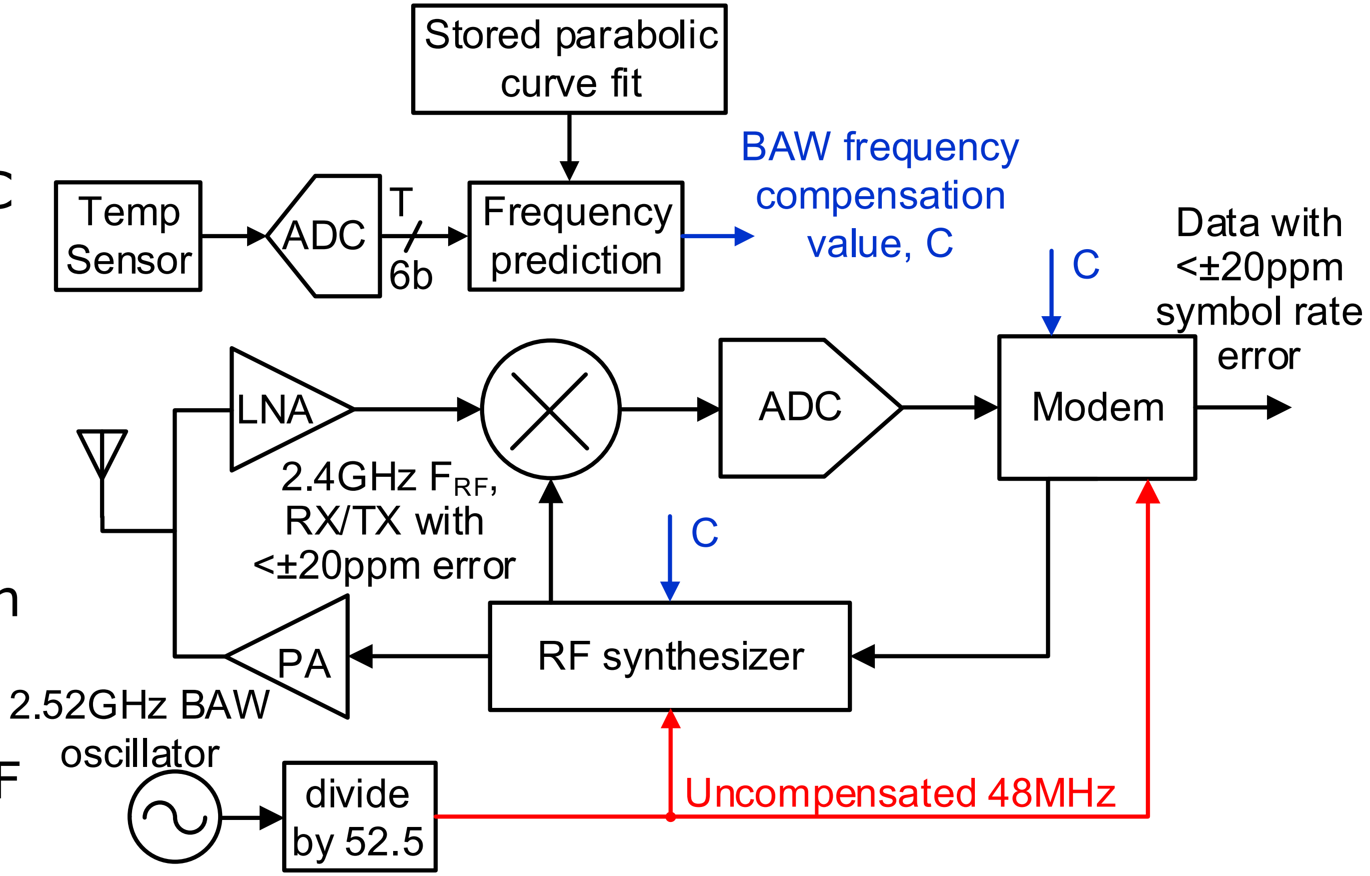
- Temp sensor output and BAW oscillation frequency measured at 3 temperatures during final test
  - Only resolution of temp sensor is important, not absolute accuracy
- Parabolic curve fit to these points stored to on-chip memory
  - TC2 is the curvature of the parabola
  - TC1 is the slope of the curve, <2ppm/°C
  - TC0 is the offset due to process variation, solder shift, and lifetime aging, <±2000ppm
- Interpolate any point on the curve for active temperature compensation



$$\frac{\Delta f}{f_0}(T) = TC_2(T - T_0)^2 + TC_1(T - T_0) + TC_0$$

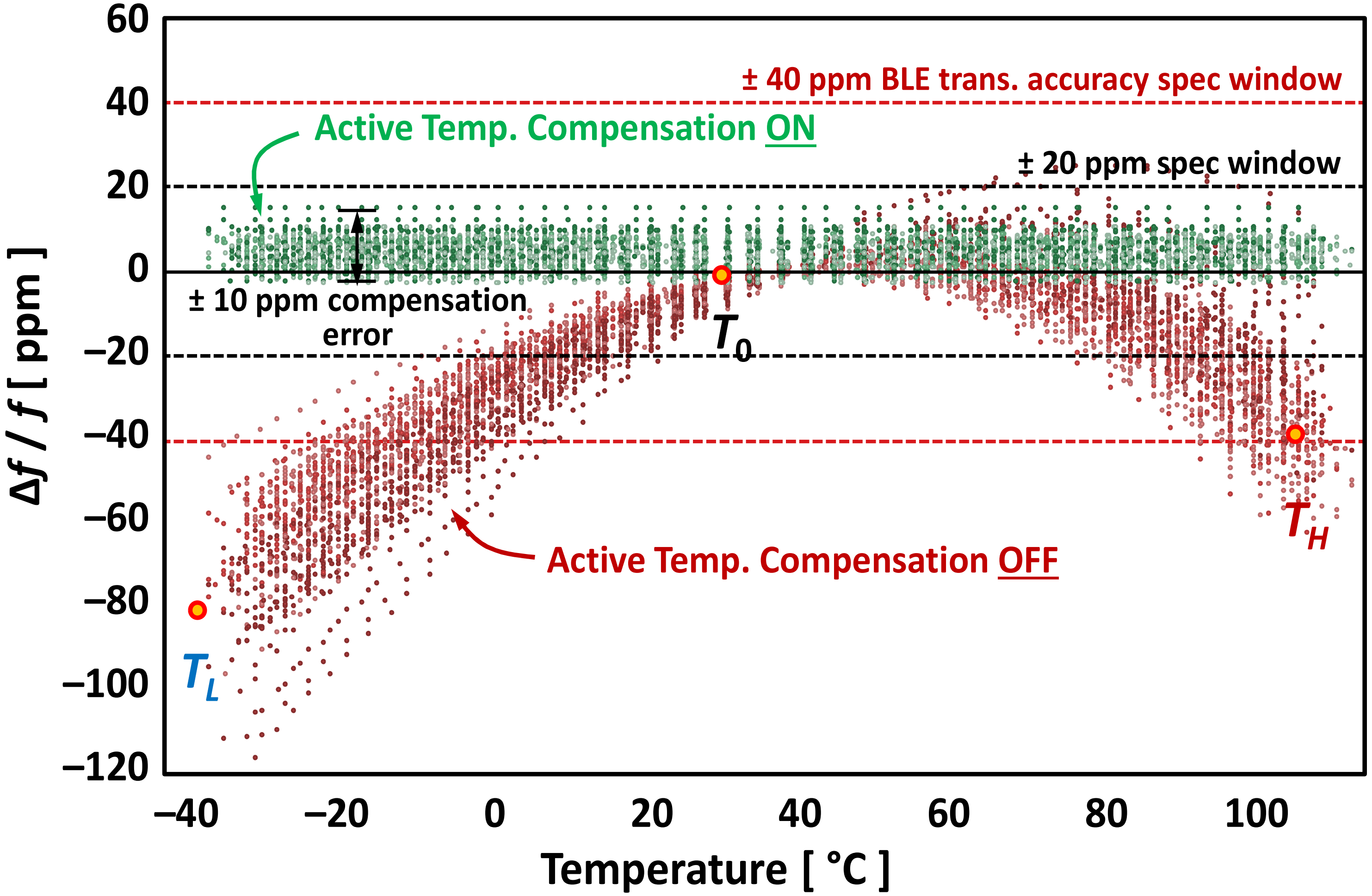
Active Temperature Compensation

- Uncompensated clock provided to SoC
  - 48MHz can vary ±2000ppm at 25°C and 150ppm from -40 to 85°C
- Frequency compensation value C provided to modem & RF synthesizer
  - Output is a signed integer with 22 fractional bits → 0.25ppm resolution
  - $F_{REF} = 48\text{MHz} * \left(1 + \frac{C}{2^{22}}\right)$
  - RF synthesizer generates 2.4GHz RF with <±20ppm error
- New value for C applied when T changes by 4°C



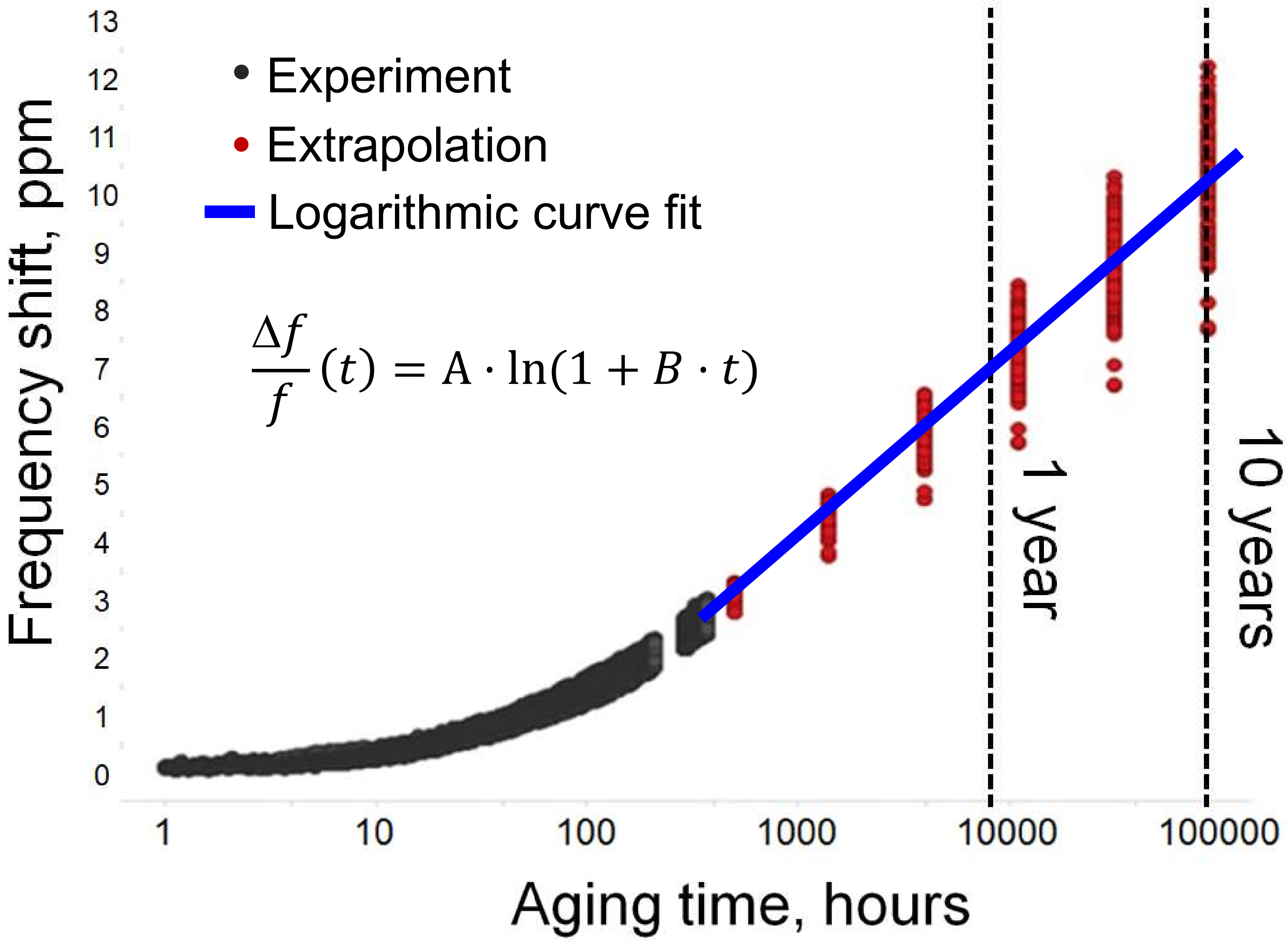
Active Temperature Compensation

- ☐ BAW oscillator frequency stability vs. temperature was measured at 2.4GHz at the RF synthesizer output for 80 devices
- ☐ Red: active temperature compensation disabled, passive temperature compensation in BAW resonator gives <150ppm
- ☐ Green: active temperature compensation enabled, <±10ppm compensation error.



Active Aging & Frequency Drift

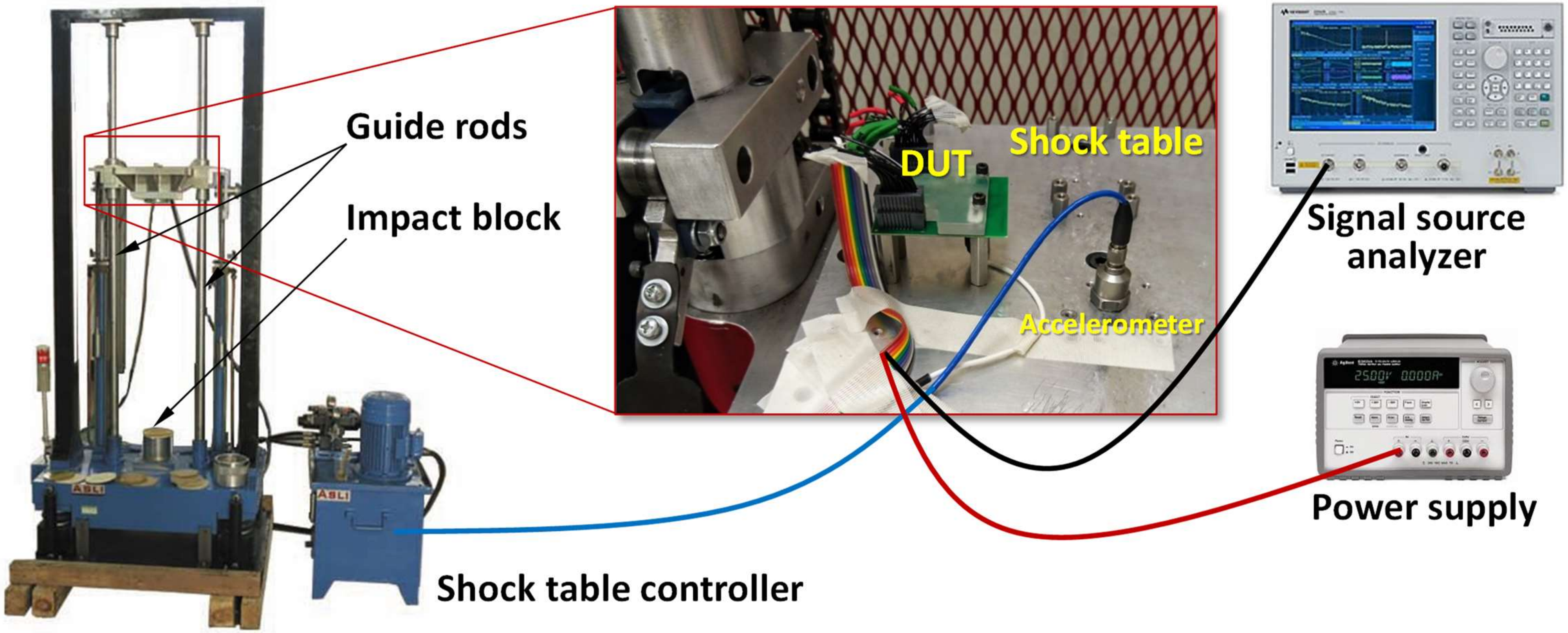
- ☐ Aging: the long-term oscillator frequency drift
- ☐ Oscillator operated continuously and frequency drift measured
- ☐ Logarithmic aging observed due to slight resonator stress relaxation
- ☐ Aging extrapolated to 10 years is 7 to 12ppm for these devices.



$$\frac{\Delta f}{f}(t) = \mathrm{A} \cdot \ln(1 + B \cdot t)$$

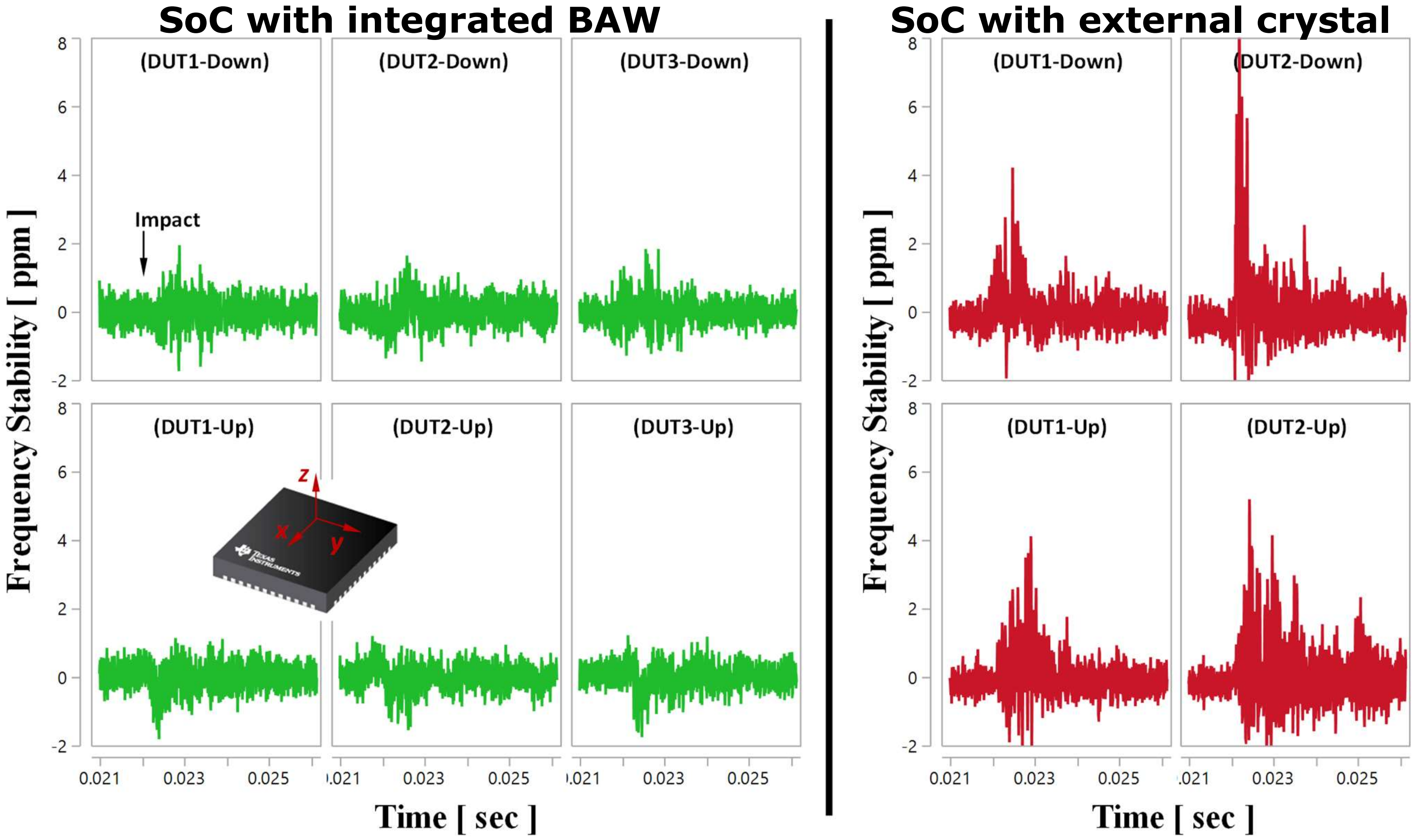
Mechanical Shock

TEST	STANDARD	METHOD	DESCRIPTION
Mechanical Shock	MIL-STD-883H (QSS 009-119)	2002.5, Level B	Acceleration peak 1,500g | Pulse duration 0.5ms | 3 perpendicular axes (x, y, z) | 5 shocks



Measured Results - Shock

- SoC frequency measured with both integrated BAW and external crystal
- SoC with integrated BAW shows 4x better shock immunity than with external crystal
  - 1-2ppm vs. 4-8ppm
- BAW resonator less effected by shock than crystal due to lower mass

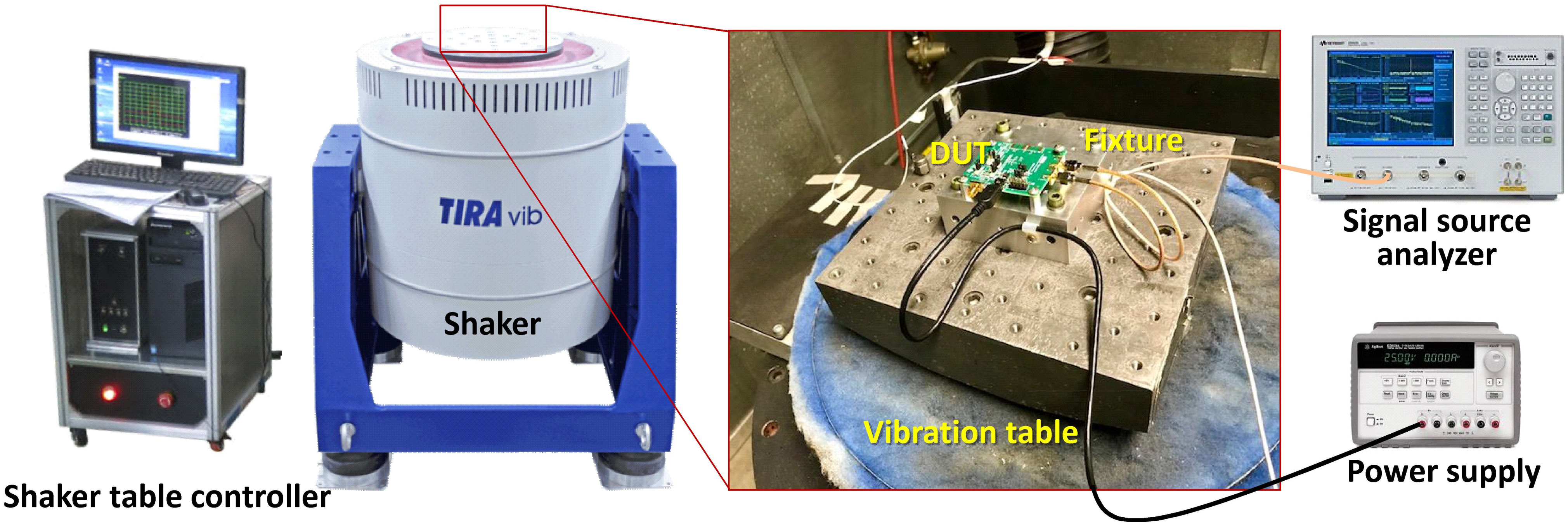


SoC with integrated BAW

SoC with external crystal

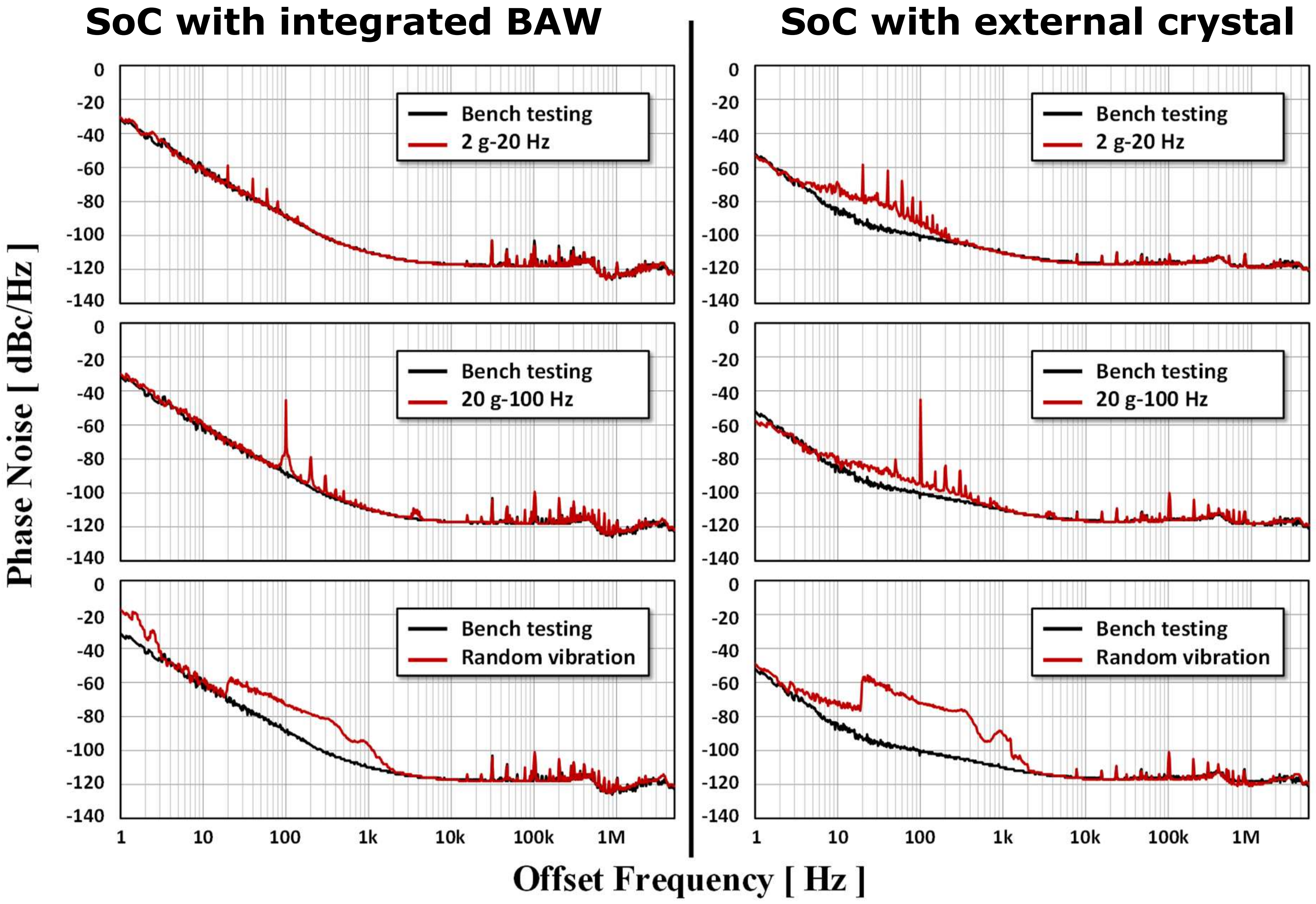
Vibration

TEST	STANDARD	METHOD	DESCRIPTION
Sinusoidal Vibration	MIL-STD-202G	204D, Condition C/D	Amplitude: 1.5 mm | 4-g /10-g peak acceleration | Freq: 20 to 2,000 Hz | 20 minutes | 3 perpendicular axes (x, y, z)
Random Vibration	MIL-STD-883H	2026, Condition B/E	Power spectrum density: 0.04 | Overall RMS acceleration: 7.3-g 3 perpendicular axes (x, y, z)



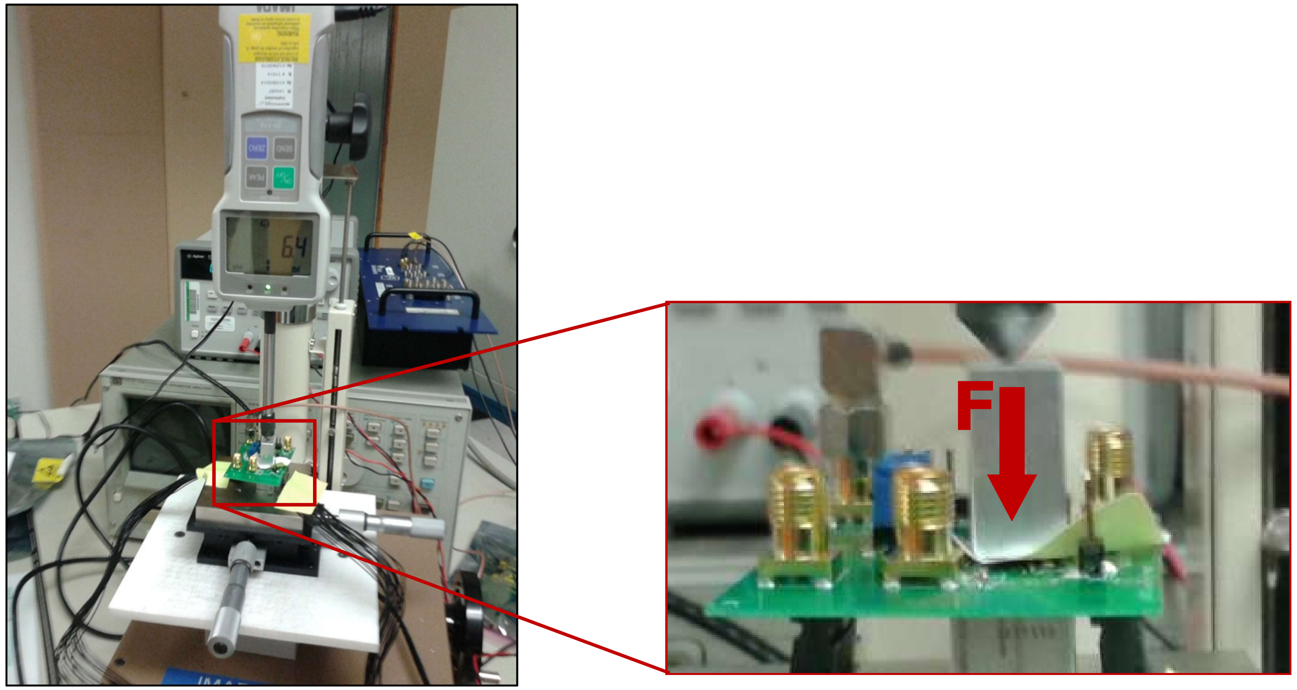
Measured Results - Vibration

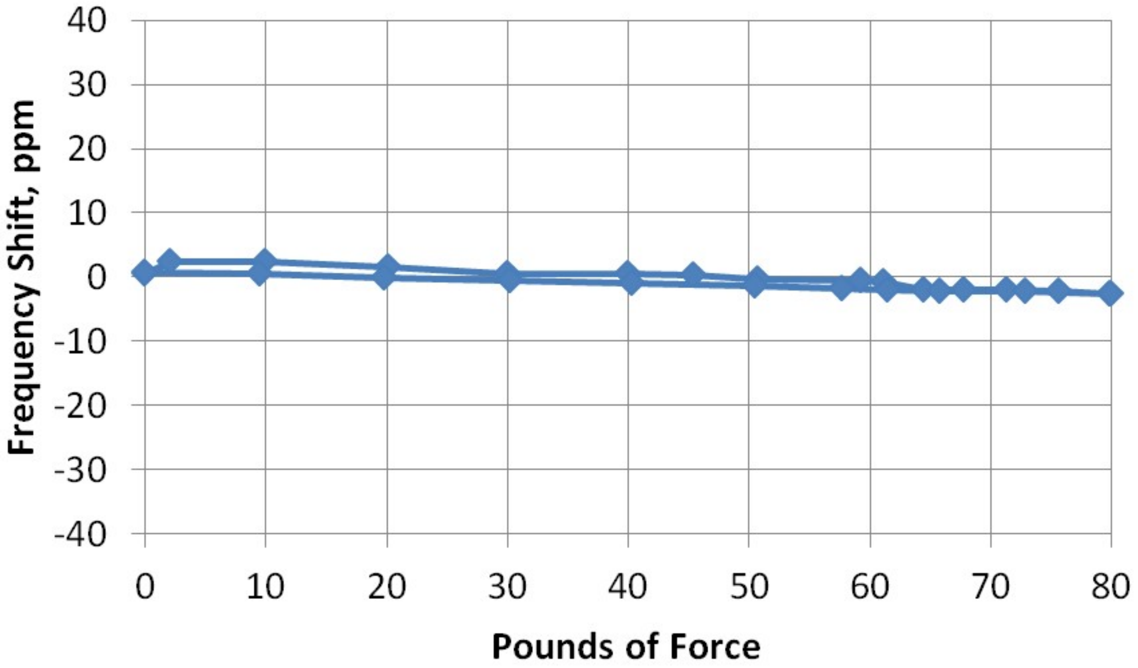
- Phase noise on the SoC’s 48MHz clock measured in the presence of sinusoidal and random vibration
- Similar increase in noise and spurs for BAW and crystal oscillator clock source
- Performance limited by spurious resonance modes of PCB



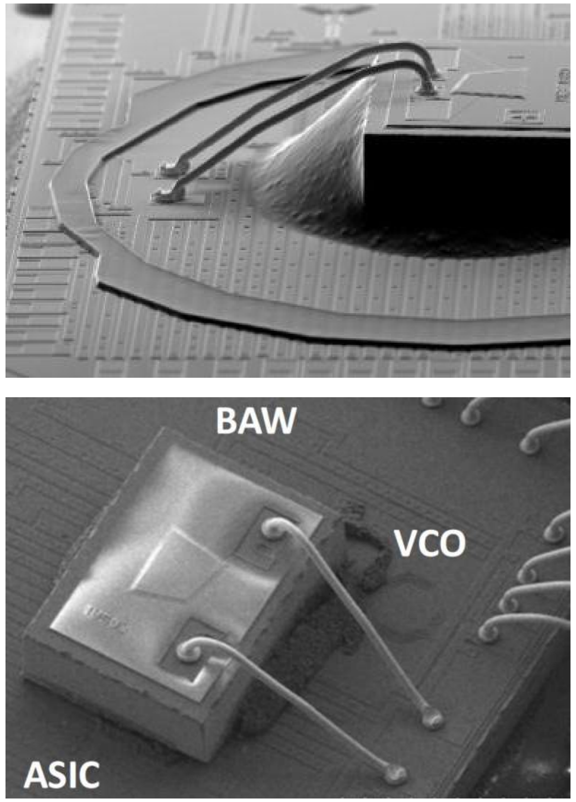
Stress Sensitivity

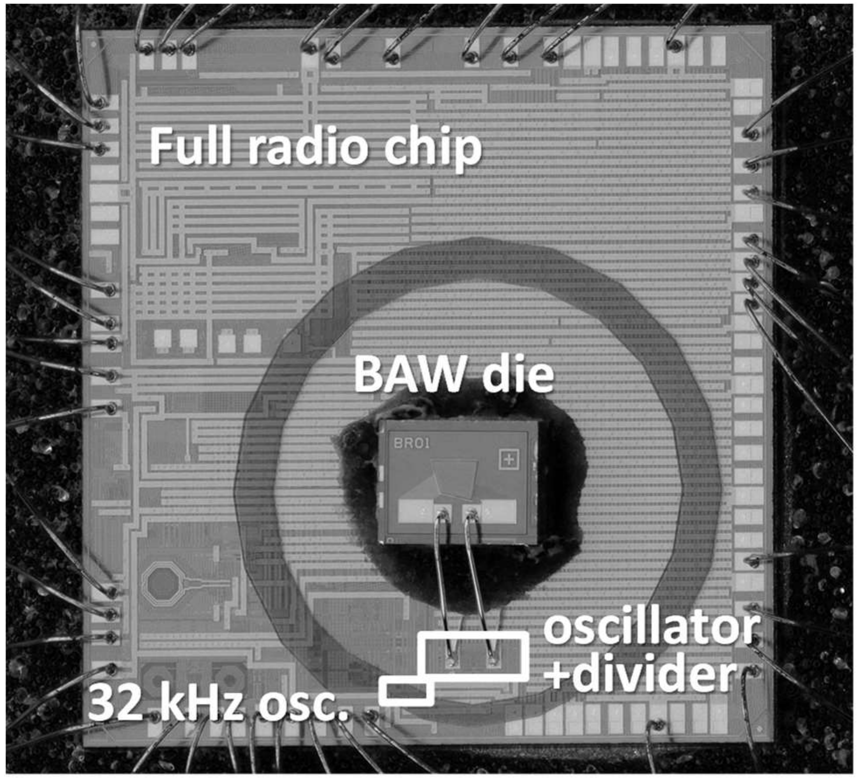
- Oscillator frequency shift measured as a function of pressure placed on top of the package.
  - Shift <2ppm up to 80lb force, slight hysteresis
- Average frequency shift caused by changes in package stress from soldering are small and included in the frequency compensation parameters

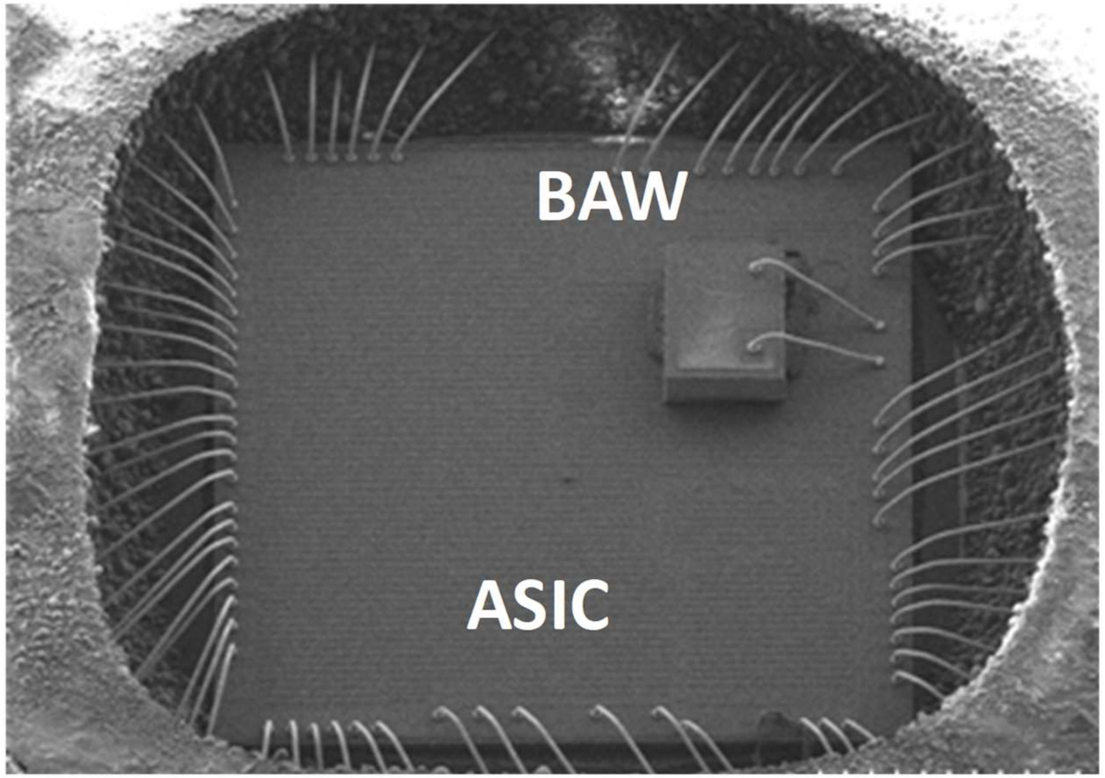




Die and Packaging Photos



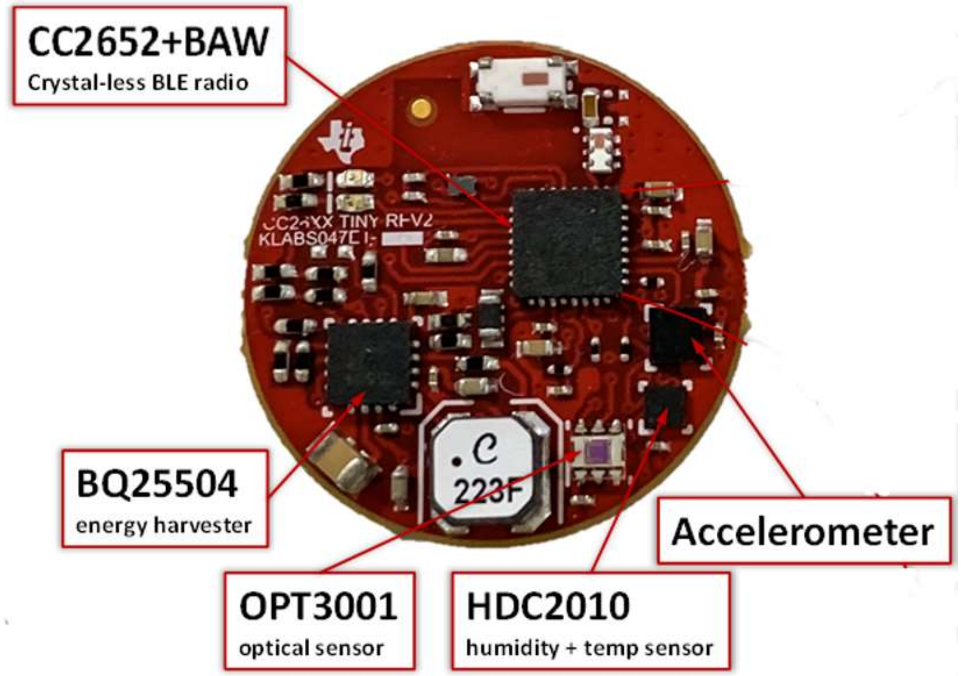


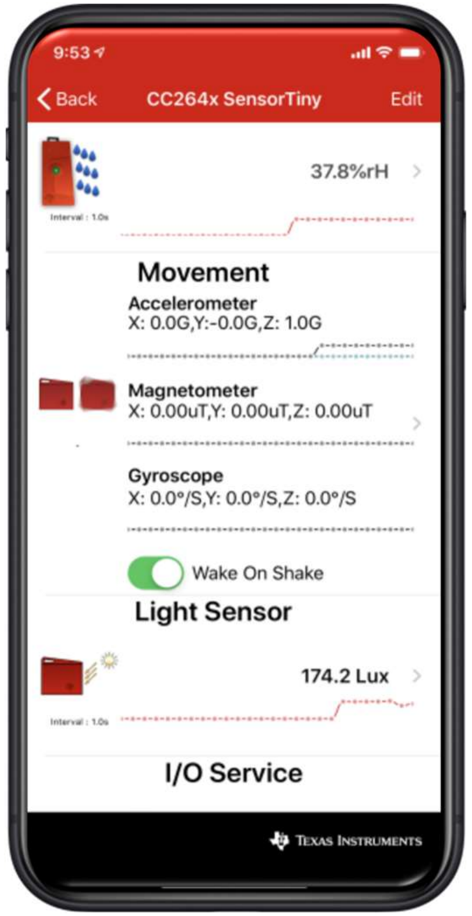


- Side views of BAW resonators wire-bonded to the active circuitry below.
- Top view of BAW resonator used in a BLE radio packaged in a 4x4 QFN plastic package.
- BAW resonator used with an ASIC in a 7x7 QFN.

Smaller Footprint

- Space saved by removing crystal allows more sensors to be used in the same footprint
- Enables applications with limited space, harsh, vibration-rich environments such as power tools and factory automation




9:53

Back CC264x SensorTiny Edit

37.8%rH

Interval : 1.0s

Movement

Accelerometer
X: 0.0G,Y:-0.0G,Z: 1.0G

Magnetometer
X: 0.00uT,Y: 0.00uT,Z: 0.00uT

Gyroscope
X: 0.0°/S,Y: 0.0°/S,Z: 0.0°/S

Wake On Shake

Light Sensor

174.2 Lux

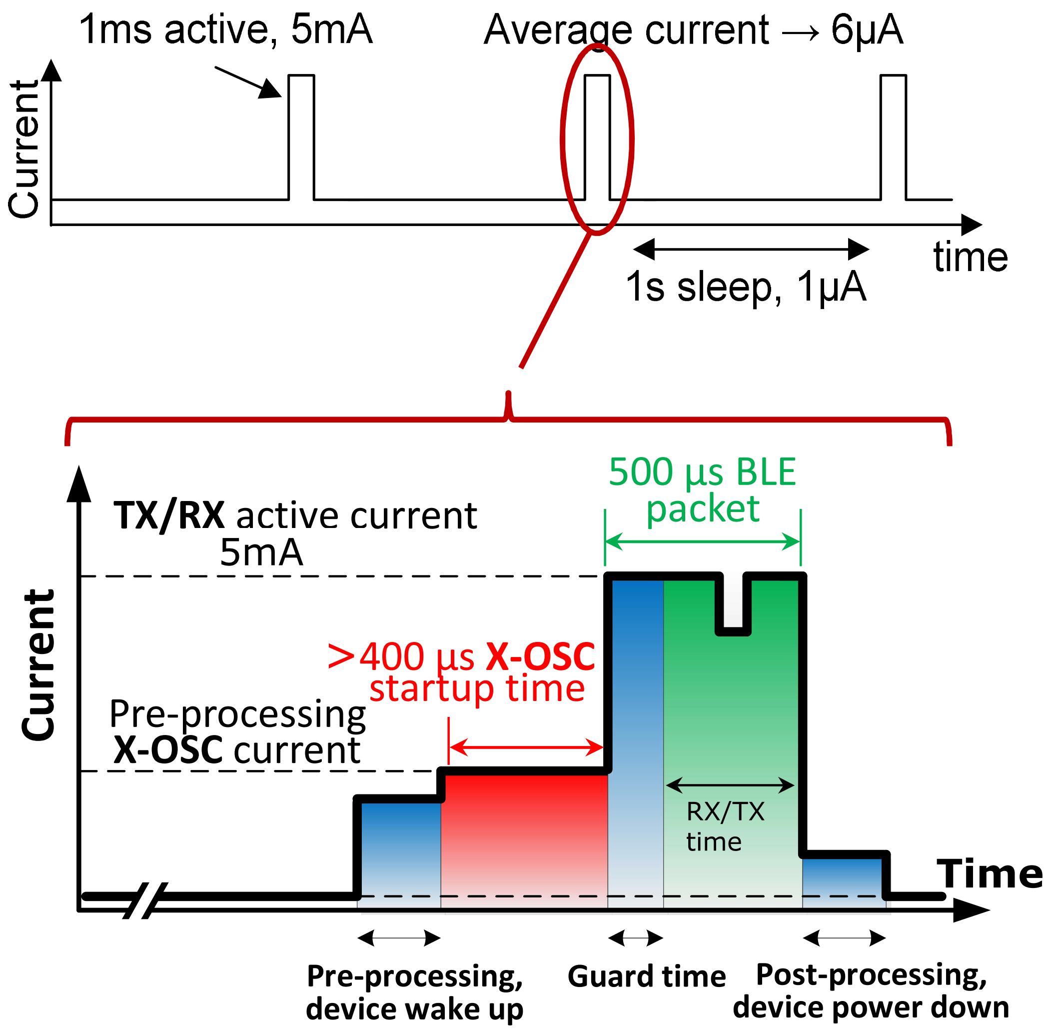
Interval : 1.0s

I/O Service

Texas Instruments

Duty-Cycled Wireless Systems

- Data throughput requirements are low in many IoT applications
- Aggressively duty cycle radio to reduce average power
- Radio active only ~0.01% to 1% of the time, rest of the time in low power sleep state
- Accurate MHz crystal oscillator needed for RF generation
- Crystal oscillator startup time can be long compared to typical data packet
- Significant fraction of energy for each RX/TX burst is used to turn on the oscillator

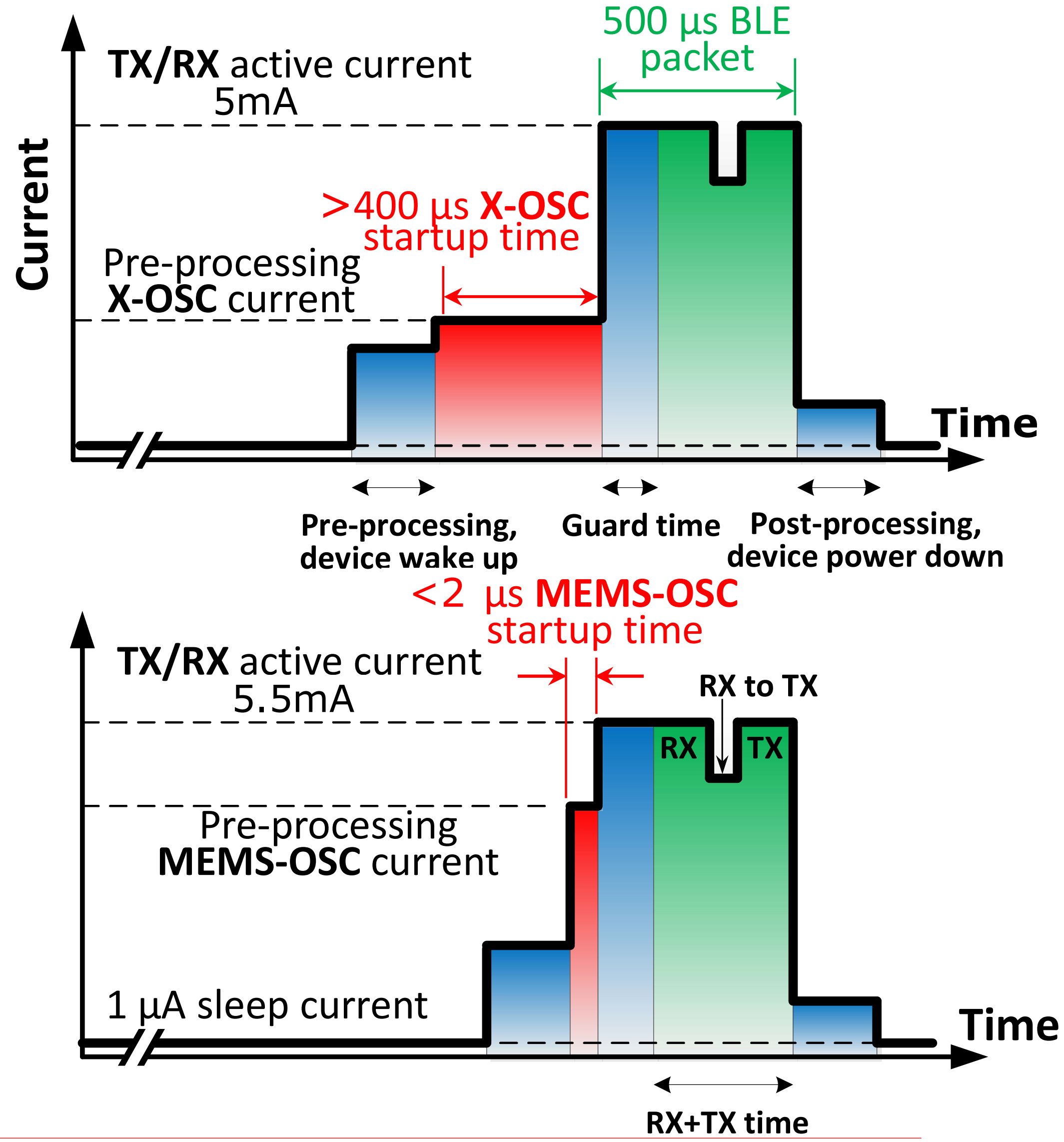


BAW Fast Start Advantage

- BAW oscillator starts faster than a typical MHz crystal oscillator due to ~10x lower Q & 100x higher frequency

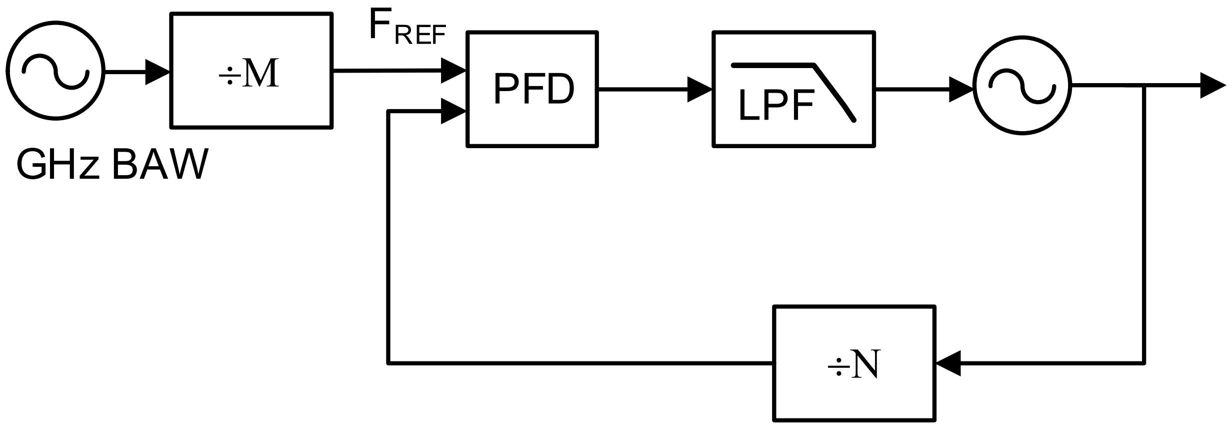
$$t_{start} \propto \frac{Q}{f}$$

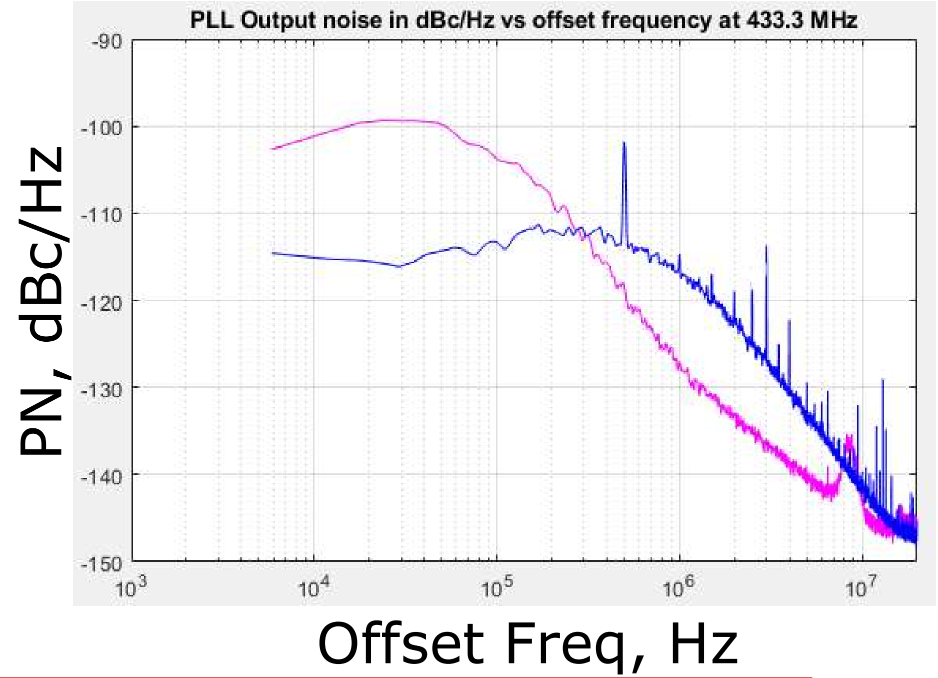
- BAW oscillator + divider current is higher than crystal oscillator current, but average system power can be lower due to fast startup.
- BAW oscillator can give net energy savings for short data packets



Higher Frequency Reference Clock

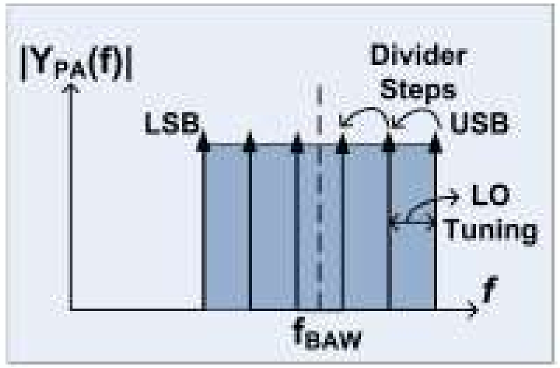
- Traditional WiFi/Bluetooth products use <60MHz crystal oscillators as reference clock for RF synthesizer
- Newer generations of WiFi can improve RF synthesizer phase noise by using >60MHz reference clock
  - Higher loop bandwidth possible
  - Lower N, lower noise from PFD
  - Optimize F_{REF} based on performance, not crystal availability
- Can also save cost
  - >60MHz crystals are expensive



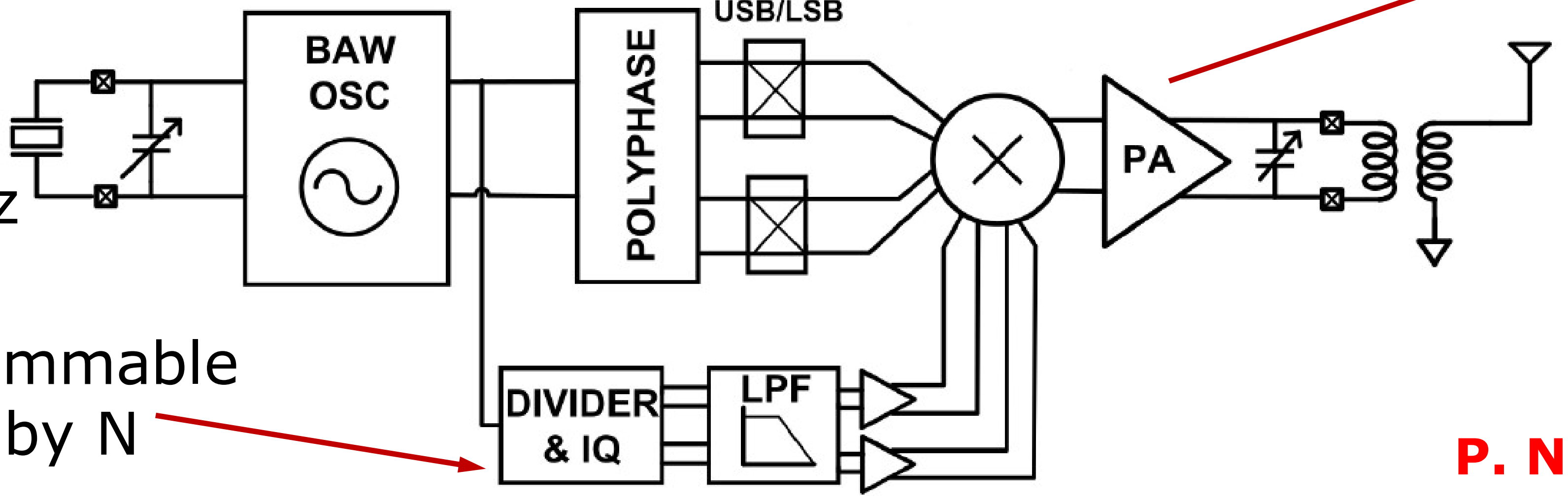


Multi-Channel ISM Band TX with no PLL

- ☐ Frequency plan covers full 2.4GHz ISM band (80MHz, 3.3%) with no PLL or fractional dividers
  - Even though BAW tuning range is <1%
- ☐ 2.3μs start-up time: Avoid slow startup time of crystal, RF synth lock time
- ☐ More power efficient for duty-cycled systems



2.4GHz

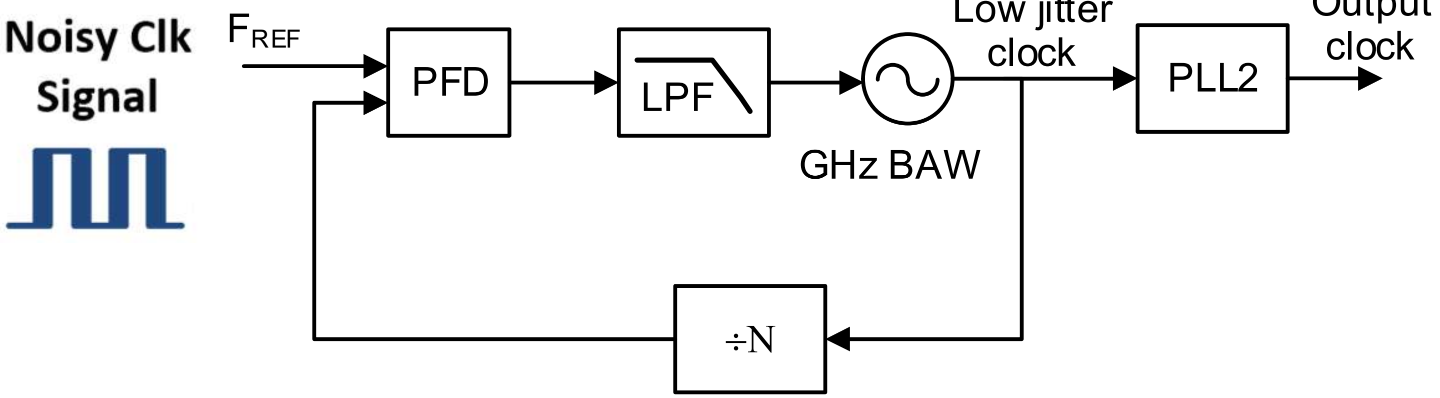


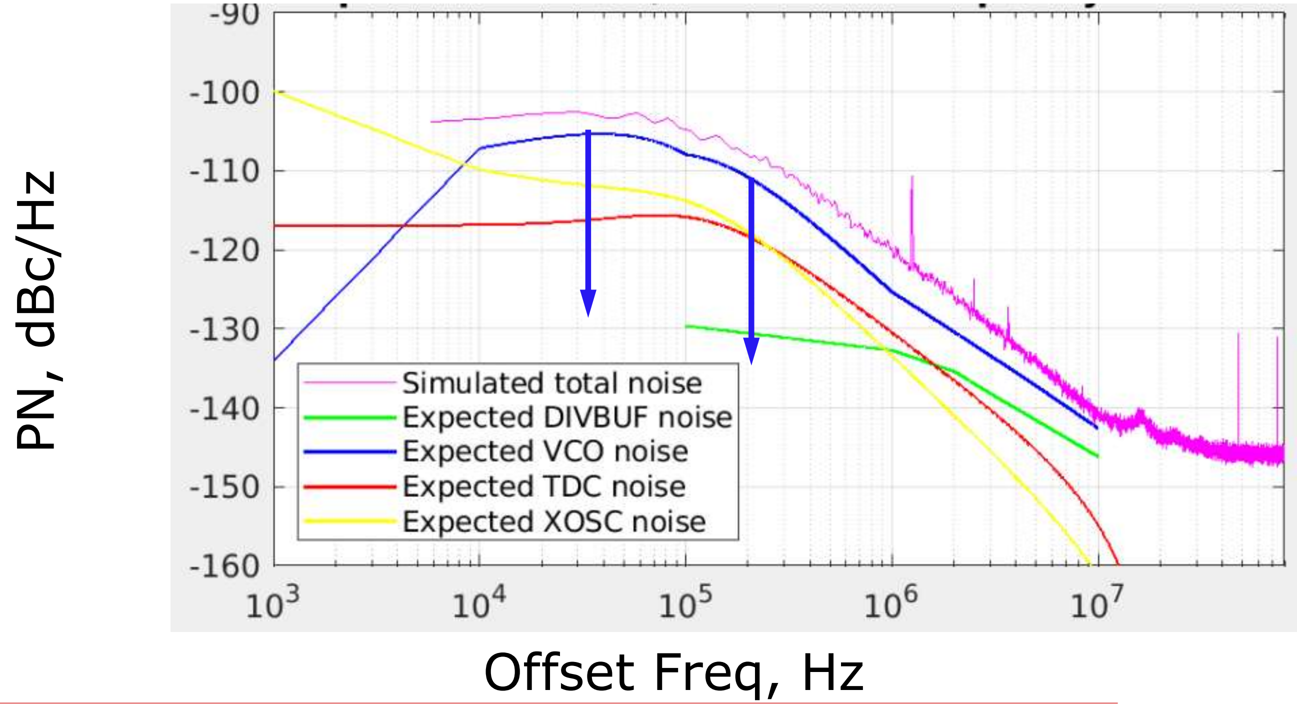
programmable divide by N

P. Nadeau, ESSCIRC 2017

Jitter Cleaning

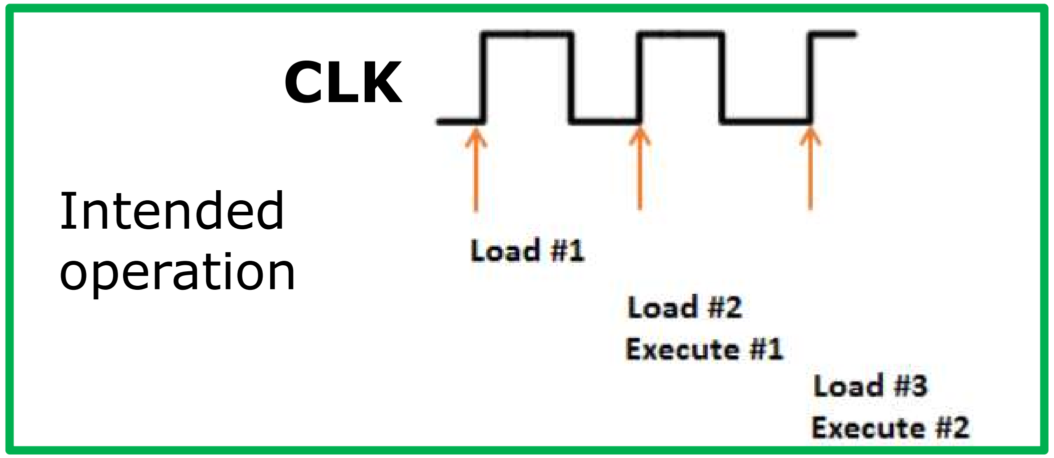
- ☐ 2 series connected PLLs to generate high frequency, low phase noise output clock
  - First PLL cleans reference jitter
  - Second generates high frequency output
- ☐ Replacing VCO in first PLL with BAW oscillator allows lower clock jitter
  - Noise outside of loop bandwidth dominated by VCO/BAW
  - High freq + high Q of BAW oscillator reduces jitter



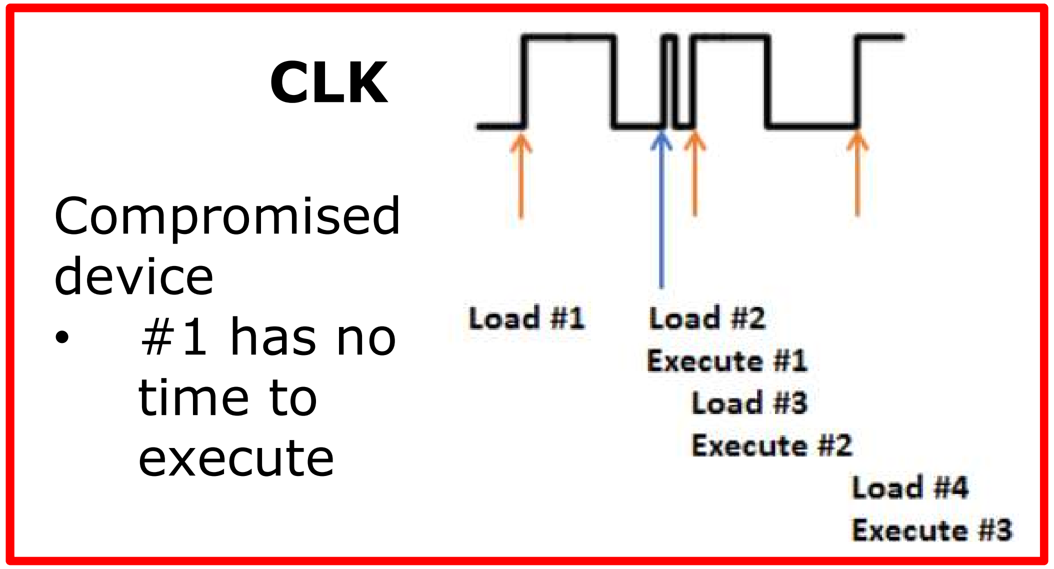


Bypass Security through XO

- ☐ Security usually brings to mind data encryption requirements
- ☐ But encryption can be bypassed through glitching the clock, causing instructions to be skipped.
  - If skipped instruction is password check or encryption step, device security is bypassed
  - Search for «chipwhisperer» for a tutorial
- ☐ Device security is no stronger than the security in the clock system!
- ☐ Solution: Fully integrated clock sources



Intended operation

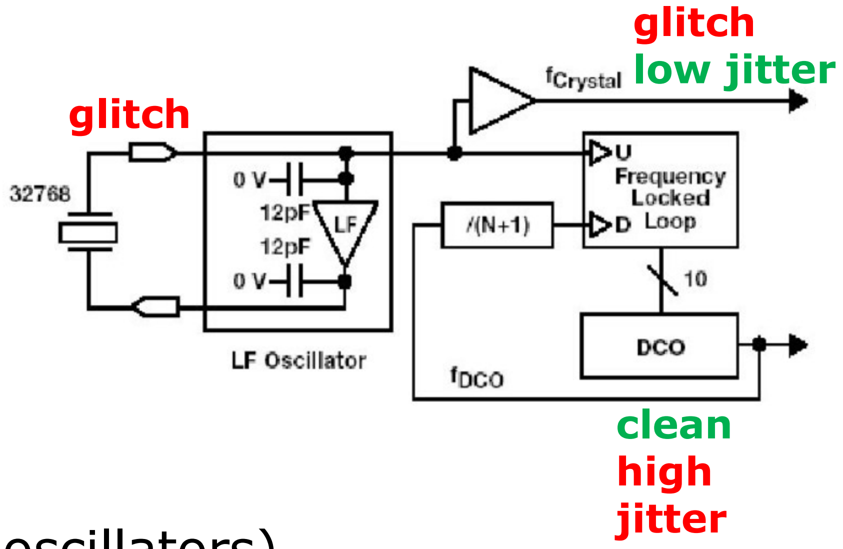


Compromised device

- #1 has no time to execute

Clock System Security

- ☐ Solution 1: Filter glitches on crystal oscillator output
  - Typical flexible MHz oscillator is 4-80MHz – a glitch at 4MHz is the entire clock cycle at 80MHz.
  - *Only a partial solution*
- ☐ Solution 2: Frequency lock integrated oscillator to crystal oscillator
  - Glitches filtered out at the output of the integrated oscillator
  - Use only clock from integrated oscillator where possible
  - But some circuits must use crystal oscillator for noise/jitter reasons
    - ☐ Example: radio transmission could be disrupted
  - *Only a partial solution*
- ☐ Solution 3: No external pins for crystals
  - Must use only internal clock sources (BAW + integrated oscillators)
  - *Most robust solution* - no glitches without decapping chip, which can be detected



Conclusions

- Bulk Acoustic Wave resonators are an advancement over 100 year-old crystal technology
- With active and passive temperature compensation, BAW resonators enable
  - Reduced size and cost
  - Improved frequency stability at temperature extremes
  - Robustness to shock and vibration
  - Fast start up for power reduction in duty-cycled systems
  - Flexibility in reference clock frequency choice for RF synthesizers
  - Advancements in clock jitter cleaner performance
  - Improved security with fully integrated clock systems


OBRIGADO
gracias
どうも
ARIGATO
hvala
DANK U
takk
MERSI
merci
謝謝
obrigado
danke schön
köszi
سپاس
PALDIES
muchas gracias
ありがとう
TEŞEKKÜR EDERIM
MOLTE GRAZIE
GO RAIBH MAITH AGAT
danke
grazas
GRAZZI
THANKS
THANK YOU
благодаря
TAK
どうも
qujan
TAK
благодаря
asante
muchas gracias
vielen dank
PALDIES
DANK U
danke
OBRIGADO
mesi
감사합니다
köszi
благодаря
grazie
DZIĘKI
TACK
Gràcies
спасибо
MULTUMESC
多謝
شكراً
TEŞEKKÜR EDERIM
NA GODE
muchas gracias
obrigado

References

- A. Schaer, “Behavior and Current Performance of SAW and BAW Oscillators,” IEEE European Microwave Conf., pp. 249-253, 1976.
- J. Chabloz, et. al, “Frequency synthesis for a low-power 2.4 GHz receiver using a BAW oscillator and a relaxation oscillator,” IEEE European Solid-State Circuits Conference Proceedings, pp. 492-495, 2007.
- K. Wang, et al, “A 1.8mW PLL-free channelized 2.4GHz ZigBee receiver utilizing fixed-LO temperature-compensated FBAR resonator,” IEEE International Solid-State Circuits Conference Digest of Tech. Papers, pp. 372-373, Feb. 2014.
- B. Jakoby, et al, “The Potential of Microacoustic SAW and BAW-Based Sensors for Automotive Applications – A Review,” IEEE Sensors Journal, Vol. 2, No. 5, Oct. 2002.
- E. Courjon, et al, “High overtone bulk acoustic resonators for high temperature sensing applications,” IEEE Joint European Frequency and Time Forum & International Frequency Control Symposium, pp. 992-995, 2013.
- D. Ruffieux, et al, “A Narrowband Multi-Channel 2.4 GHz MEMS-Based Transceiver,” IEEE Journal of Solid-State Circuits, Vol. 44, No. 1, Jan. 2009.
- D. Petit, et. al, “Temperature Compensated BAW Resonator and its integrated Thermistor for a 2.5GHz Electrical Thermally Compensated Oscillator,” IEEE Radio Frequency Integrated Circuits Symposium, pp. 339-342, 2009.
- M. Heidarpour, et al, “A MEMS-Assisted Temperature Sensor With 20-µK Resolution, Conversion Rate of 200 S/s, and FOM of 0.04 pJK2,” IEEE Journal of Solid-State Circuits, Vol. 52, No. 1, pp. 185-197, 2017.
- S. Gilbert, et. al, “Manufacturing and Reliability of Chip-Scale Packaged FBAR Oscillators,” IEEE International Ultrasonics Symposium, pp. 89-92, 2014.

References

- R. Thirunarayanan, et al., “Reducing energy dissipation in ULP systems: PLL-free FBAR-based fast startup transmitters,” IEEE Trans. on Microwave Theory and Techniques, vol. 63, pp. 1100-1117, April 2015.
- N. Sinoussi, et al., “A single LC tank self-compensated CMOS oscillator with frequency stability of ±100ppm from −40°C to 85°C,” IEEE Int. Freq. Control Symp., May 2012.
- S. Sridaran, et al., “Low jitter FBAR based chip scale precision oscillator”, IEEE Int. Ultrasonics Symp, pp. 85-88, Sept. 2014.
- K. Sankaragomathi, et al., “A ±3ppm 1.1mW FBAR frequency reference with 750MHz output and 750mV supply” IEEE J. Solid State Circuits, pp. 454-455, 2015.
- R. Thirunarayanan, et al., “Complementary BAW oscillator for ultra-low power consumption and low phase noise,” IEEE New Circuits and Systems Conf, pp. 97-100, June 2011.
- D. Griffith, et. al, "An Integrated BAW Oscillator with <±30ppm Frequency Stability over Temperature, Package Stress, and Aging Suitable for High-volume Production," IEEE International Solid State Circuits Conference, Feb. 2020
- E. Yen, et. al, "Integrated High-Frequency Reference Clock Systems Utilizing Mirror-Encapsulated BAW Resonators," IEEE International Ultrasonics Symposium, October 2019
- D. Griffith, et. al, "A +/-10ppm -40 to 125C BAW-Based Frequency Reference System for Crystal-less Wireless Sensor Nodes," IEEE Symposium on Circuits and Systems, 29 May, 2017.
- P. Nadeau, et. al, “Single-BAW multi-channel transmitter with low power and fast start-up time” ESSCIRC 2017.