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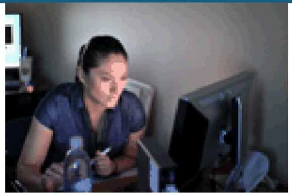
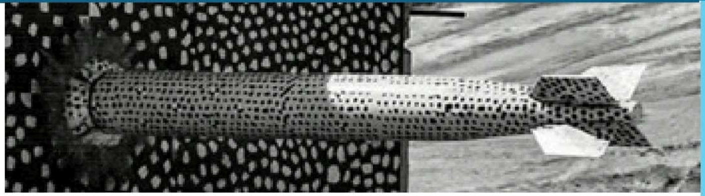
True Series Resonance Oscillator using Active Shunt Capacitance Cancellation





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Motivation

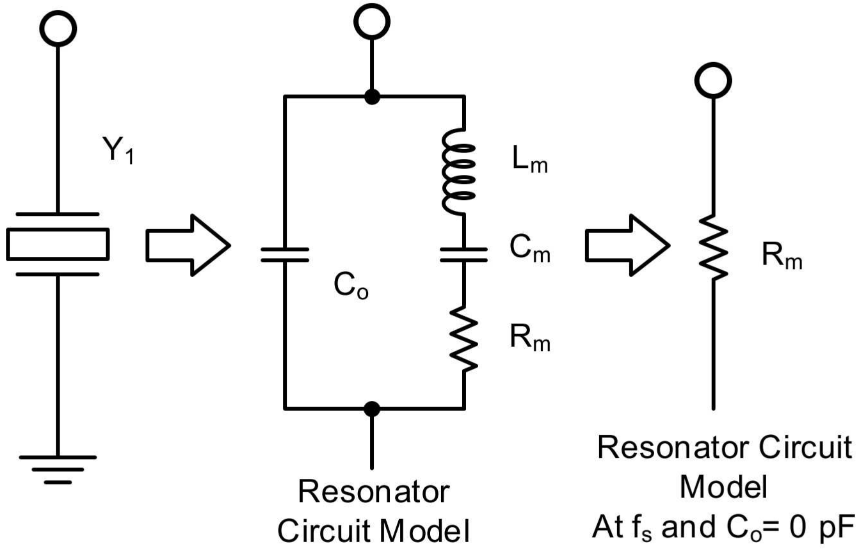
- **Monitoring the series resonant frequency and damping of resonators across a broad range of frequencies and quality factors (Q's) is paramount for reliable sensing applications:**
  - RF/microwave components
  - Temperature
  - Chemical and biological detection
  - Liquid/fluid properties
- **Sensors types include:**
  - Quartz crystal microbalance (QCM)
  - MEMS
  - Piezoelectric such as Surface Acoustic Wave (SAW) and Bulk Acoustic Wave (BAW)
  - Ceramic
  - Dielectric
- **Monitoring/Tracking Methods:**
  - Oscillators:
    - Automatic gain control
    - Phase-locked loop (PLL)
    - PLL with a differential amplifier
  - Sweep methods
    - Network analyzer

Limitations of Previous Oscillator and Monitoring Approaches:

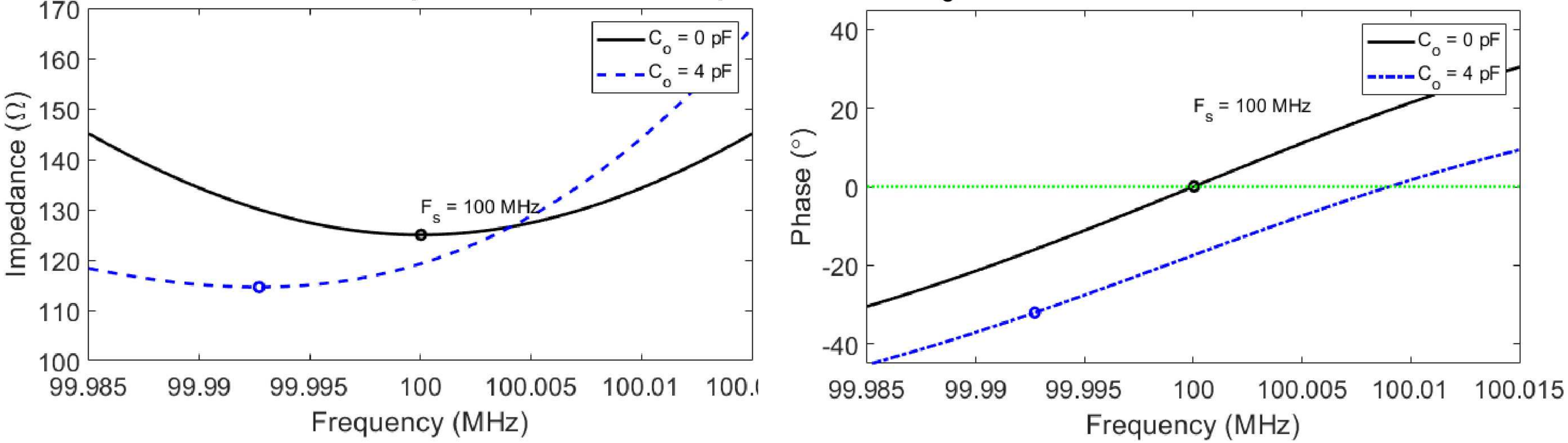
- Cancelling the resonators shunt capacitance while keeping the motional amplitude at a constant level.
- Limited operational bandwidth for high-frequency resonators.
- Not able to ground the resonator electrically, and thus suffers from perturbations due to non-trivial parasitic impedance paths that limit performance.

Problem

- Ideally for an oscillator, the frequency should coincide with the series resonant frequency.
- The equivalent circuit of a 1-port acoustic resonator (Y_1) is shown. C_o is the shunt capacitance, R_m is the motional resistance (R_m), L_m is the motional inductance, and C_m is the motional capacitance.
- The motional arm of the resonator is due to contributions from the electromechanical or piezoelectric characteristics of the resonator.
- If C_o is removed, the circuit reduces to R_m at the series resonant frequency (f_s) at $L_m – C_m$.



Impact of shunt capacitance C_o on the resonator.



When is C_o = 0 pF, the impedance is a minimum where the phase crosses through zero at f_s. Non-zero shunt capacitance (C_o = 4 pF) alters the impedance by shifting the location of the minimum and the zero-phase crossing.

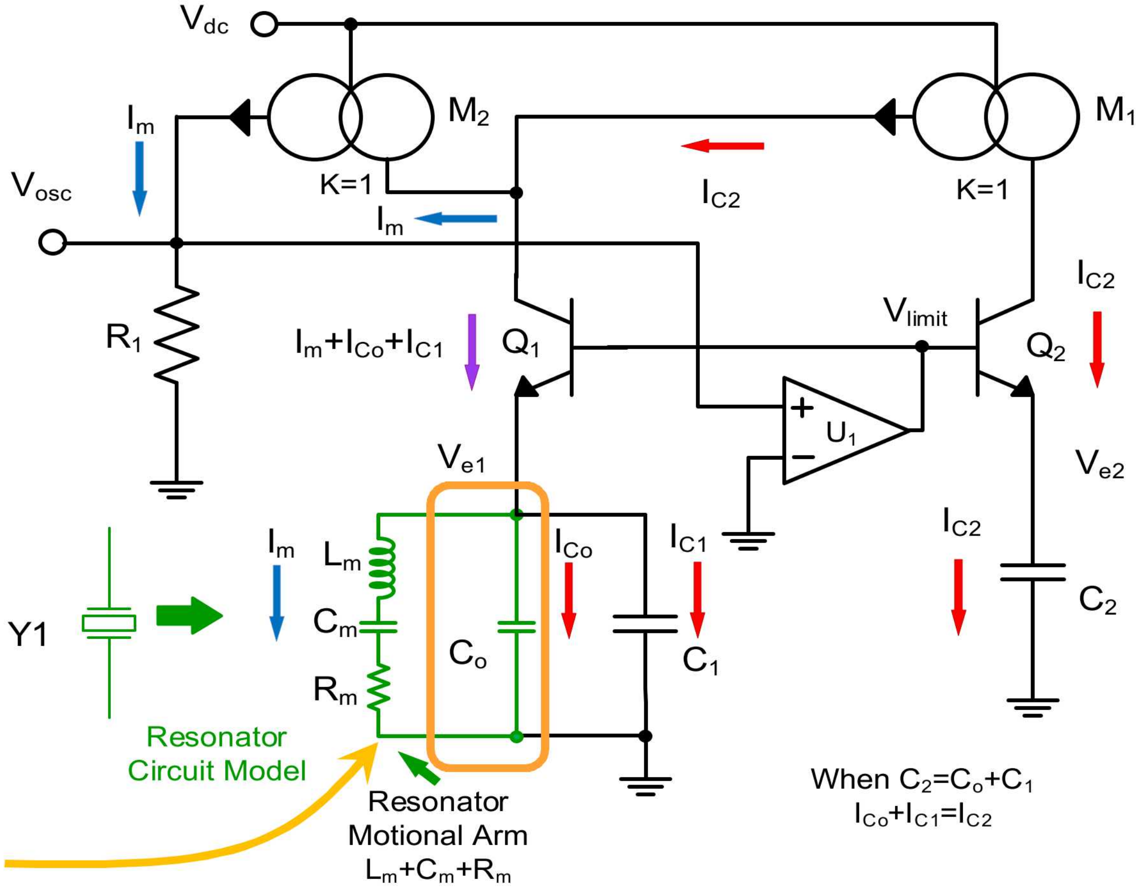
Approach

- To obtain the true series resonant frequency (f_s) and resonator loss it is highly desirable remove the shunt capacitance because it greatly simplifies "tracking of f_s, purely a zero phase angle solution.
- When C_o =0, the resonance is now due to the combination of L_m - C_m motional arm where Y_1 appears as R_m at the series resonance (f_s).
- The series resonant frequency is where there is the **highest sensitivity to operational changes** (e.g. surface binding or temperature).

How do we remove shunt capacitance using an oscillator approach?

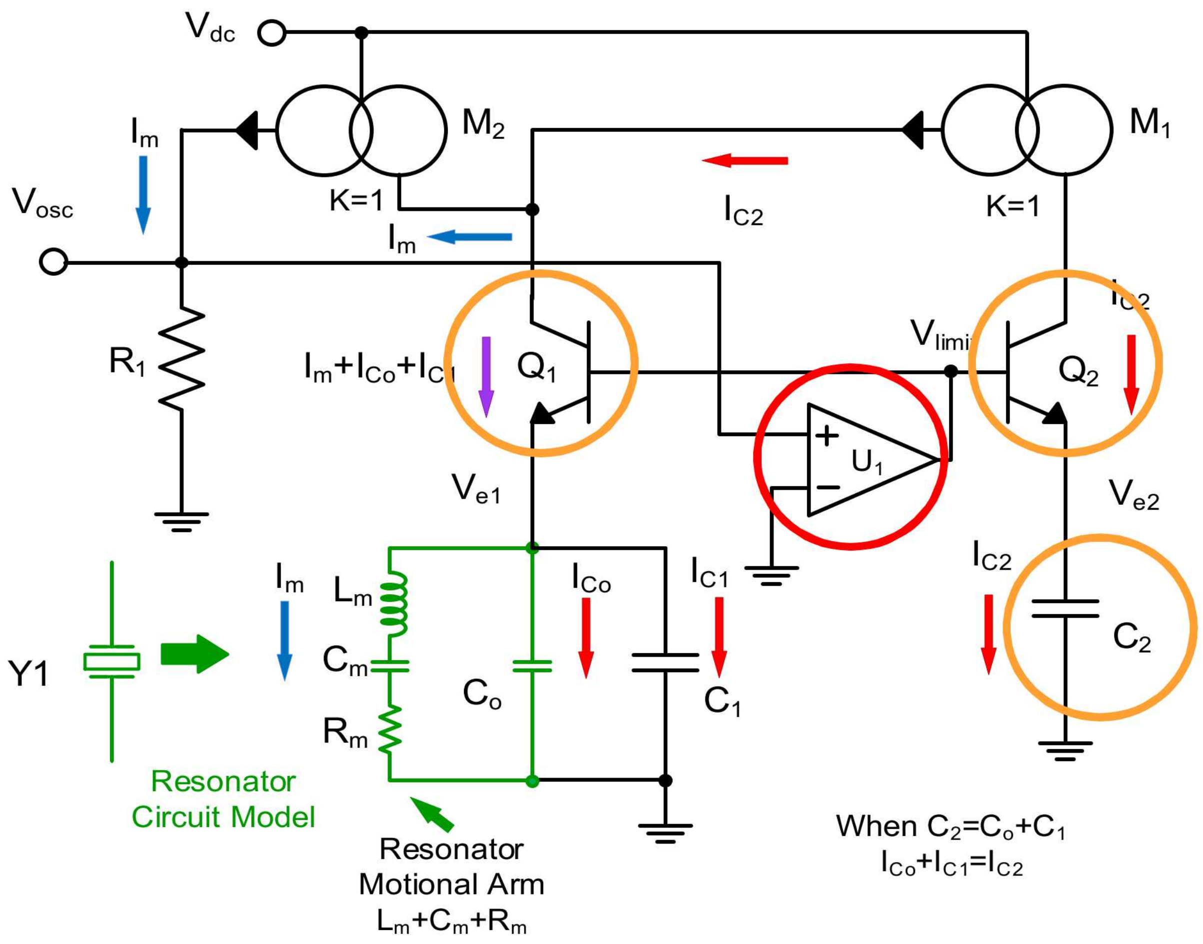
First we notice:

- True f_s occurs at a zero degree phase angle **only** when C_o is removed, with non zero C_o true f_s is a non-linear function of R_m



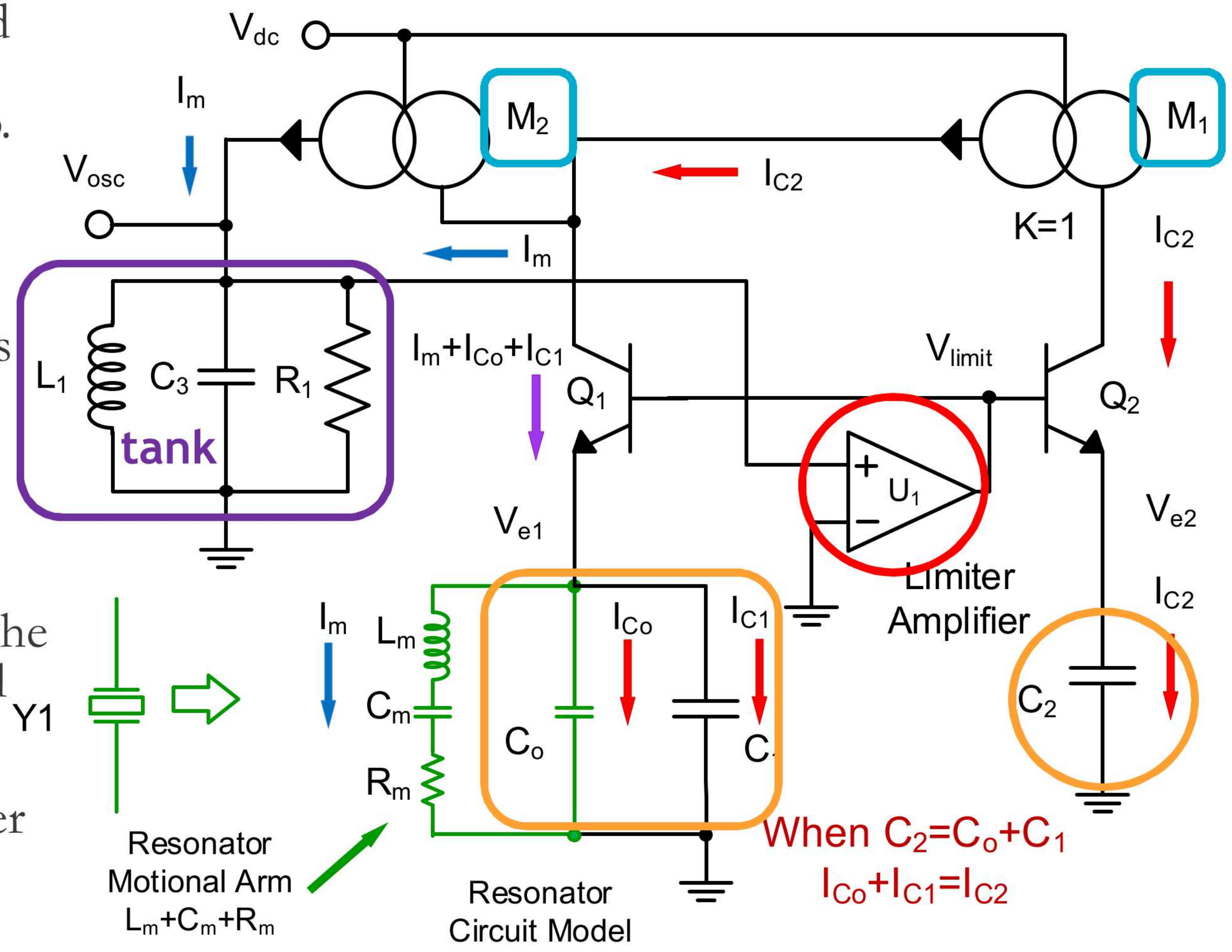
Active Shunt Capacitance Cancelling Oscillator (ASCCO)

- Next, when the shunt capacitance at series resonance is removed, the resonator impedance simplifies to R_m and does not require deconvolving the shunt capacitance.
- The oscillator uses the emitters of Q_1 and Q_2 as active ports to convert impedances of the resonator with shunt capacitance C_1 (emitter of Q_1) and a dummy capacitance, C_2 (emitter of Q_2) into currents, where the frequency of oscillation only depends only the motional arm of the resonator circuit.
- This is true when the output impedance of Q_1 and Q_2 are less than the impedances at these nodes, or the transistors are operating as excellent voltage followers, which means the emitter voltages, V_{e1} and V_{e2} are very close to the output voltage of the limiting amplifier U_1.



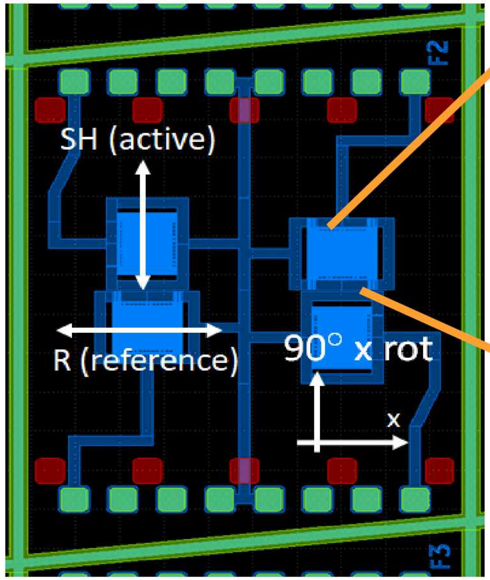
Active Shunt Capacitance Cancelling Oscillator (ASCCO) , cont'd

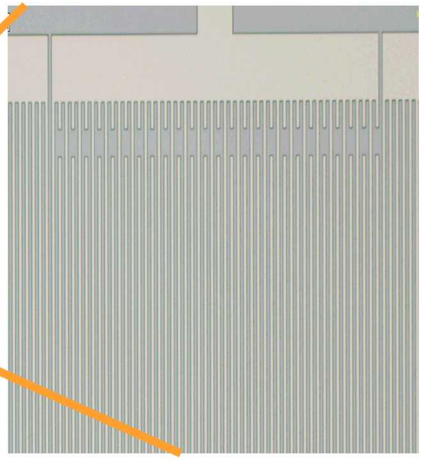
- The limiting amplifier in this case is a non-inverting amplifier with gain (GU_1) of approximately 2.25 and the output is fixed to limit to an amplitude a predetermined voltage, in this case approx. 0.4 Vp-p.
- Oscillation frequency and loop gain are constrained by **L_1, C_3, R_1**.
- To cancel the effects of the shunt capacitance across the resonator $C_o + C_1$ the value of C_2 (dummy capacitor) needs to equal $C_o + C_1$.
- As shown, the mirror M_1 passes on a copy of the dummy capacitance current to mirror M_2 where the summing of the two current legs Q_1 and Q_2 cancel the shunt capacitance currents leaving only the motional arm current.
- The circuit will oscillate when the loop gain is greater than one at 0° degree phase shift.
- Oscillation occurs when $XC_m + XL_m = 0$ or when: $F_{osc}=1/(2\pi\sqrt{(L_mC_m)})$.



Active Shunt Capacitance Cancelling Oscillator (ASCCO) , cont'd

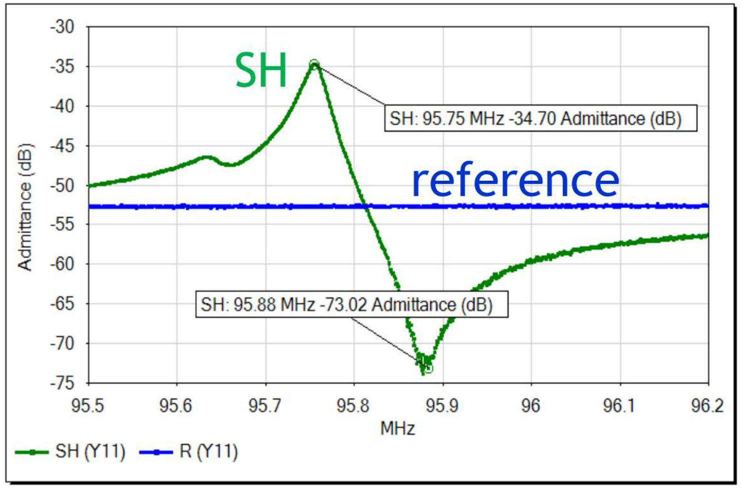
- Advantages of ASCCO:
  - Tracks the true series resonant frequency (f_s) and thus provides the best sensitivity to perturbations.
  - Does not require deconvolving the shunt capacitance.
  - Uses a parallel tank circuit to allow a wide possible range of operational frequencies and selection of a resonator overtone operation if desired.
  - Does not require automatic gain control (AGC).
  - Resonator can be grounded to reduce parasitic contributions.
  - The oscillator will operate with a series resistance from 10 Ω to 2kΩ.





Area resonator:
1.8mm x 2.4 mm

- **ASCCO Demonstration using SH-LSAW resonator**
  - Demonstrate the efficacy of the ASCCO approach using SH-SAW piezoelectric resonators at 100 MHz.
  - Vertical propagation (90° x-rot) is a SH mode and horizontal (x-axis) is non-active mode, that is dummy capacitance with impedance: $(j\omega C_o)^{-1}$
  - Rayleigh SAW is out-of-band compared to the SH-LSAW mode.



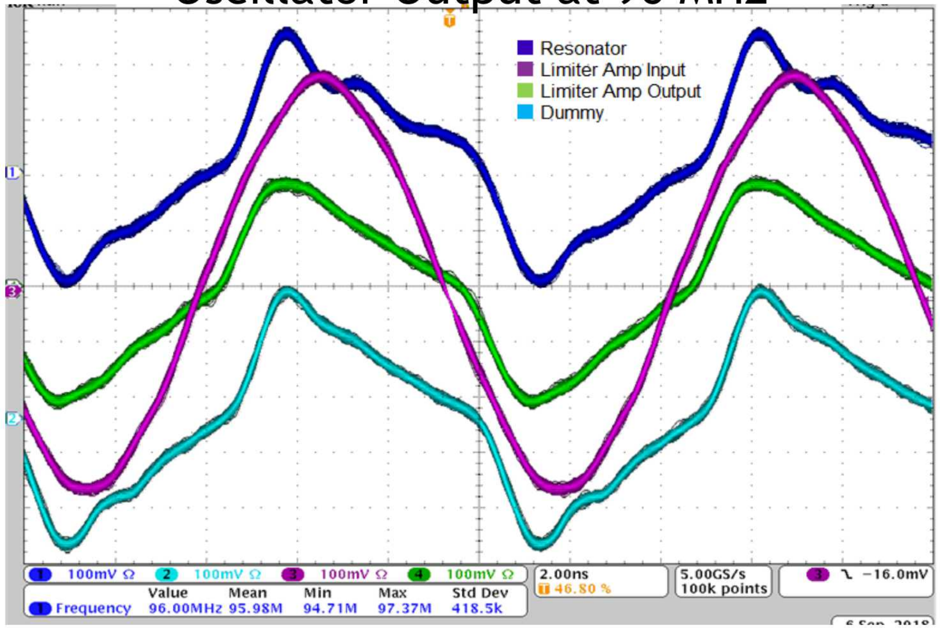
Active Shunt Capacitance Cancelling Oscillator (ASCCO) Demonstration

- The reference sensor had a shunt capacitance indistinguishable from the active sensor and served as a reference shunt capacitor (R) on the same die.
- The purpose of the inactive channel is to remove of the effect of the non-zero shunt capacitance (C_o) in parallel with the motional resistance (R_m), motional inductance (L_m), and motional capacitance (C_m) of the sensor.
- **For other sensors such as FBAR or MEMS resonators, the reference shunt capacitor could be fabricated alongside the resonator to match the capacitance of the resonator.**

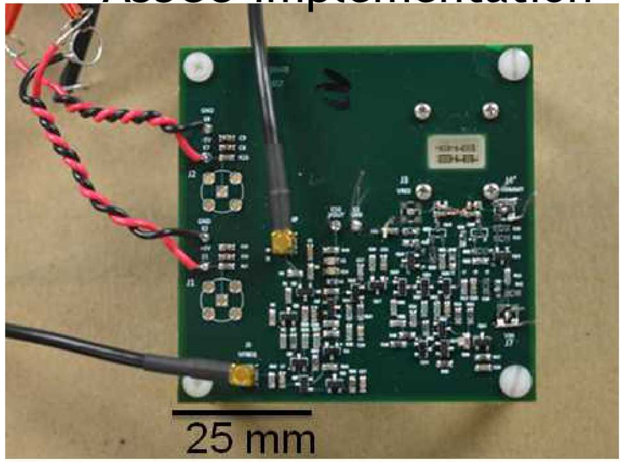
We confirmed the ASCCO circuit is removing the shunt capacitance:

- Capacitance was added to the active and dummy oscillator ports in sequence
- Adding a 2.5 pF capacitor to the active resonator port caused an equal but opposite frequency shift +30 ppm. Adding a 2.5 pF capacitor to the dummy or reference resonator port caused an equal but opposite frequency shift of -49 ppm.

Oscillator Output at 96 MHz



ASSCO Implementation



Conclusions and Acknowledgments

- The oscillator tracks the true series resonant frequency (f_s) and thus provides the best sensitivity to perturbations such as temperature, mass, film and fluid properties, which are critical for sensor applications.
- Does not require deconvolving the shunt capacitance.
- Uses a parallel tank circuit to allow a wide possible range of operational frequencies and selection of a resonator overtone operation if desired.
- Does not require automatic gain control (AGC).
- Resonator can be grounded to reduce parasitic contributions.
- Useful for other resonators such as:
  - Quartz crystal microbalance (QCM)
  - MEMS
  - Piezoelectric such as SAW and BAW
  - Ceramic
  - Dielectric
- Provisional Patent: 62/932,314

We are grateful to Joe Bischoff and Lidia Ruiz for their contributions to this work. These devices were fabricated in the Sandia MESAFab and the authors thank the MESAFab operations team for fabrication contributions.

Thank You!

Questions?