Why replace XTAL Resonators?

- XTAL resonators have excellent performance in terms of quality factor ($Q \sim 100,000$), temperature stability (< 1 ppm/C), and good power handling capability (more on this later)

- The only downside is that these devices are bulky and thick, and many emerging applications require much smaller form factors, especially in thickness (flexible electronics is a good example)

- MEMS resonators have also demonstrated high $Q$ and Si integration (very small size) ... are they the solution we seek?

- Wireless communication specs are very difficult:
  - GSM requires -130 dBc/Hz at 1 kHz from a 13 MHz oscillator
  - -150 dBc/Hz for far away offsets
Business Opportunity

• XTAL oscillators is a $4B market. Even capturing a small chunk of this pie is a lot of money.

• This has propelled many start-ups into this arena (SiTime, SiClocks, Discera) as well as new approaches to the problem (compensated LC oscillators) by companies such as Mobius and Silicon Labs.

• Another observation is that many products in the market are programmable oscillators/timing chips that include the PLL in the package.

• As we shall see, a MEMS resonator does not make sense in a stand-alone application (temp stability), but if an all Si MEMS based PLL chip can be realized, it can compete in this segment of the market.
Series Resonant Oscillator

- The motional resistance of MEMS resonators is quite large (typically koms compared to ohms for XTAL) and depends on the fourth power of gap spacing.
- This limits the power handling capability.
- Also, in order not to de-Q the tank, an amplifier with low input/output impedance is required. A trans-resistance amplifier is often used.
Zero’th Order Leeson Model

\[ L \{ f_m \} = \frac{2kT(1 + FR_{Ramp})}{P_o} \cdot \left( \frac{R_{tot}}{R_x} \right) \cdot \left[ 1 + \left( \frac{f_0}{2Q_l \cdot f_m} \right)^2 \right] \]

\[ Q_l = \frac{R_x}{R_x + R_i + R_o} Q = \frac{R_x}{R_{tot}} Q \]

- Using a simple Leeson model, the above expression for phase noise is easily derived.
- The insight is that while MEMS resonators have excellent Q’s, their power handling capability will ultimately limit the performance.
- Typically MEMS resonators amp limit based on the non-linearity of the resonator rather than the electronic non-linearities, limiting the amplitude of the oscillator.

MEMS Resonator Designs

- Clamped-clamped beam and wine disk resonator are very popular. Equivalent circuits calculated from electromechanical properties.
- Structures can be fabricated from polysilicon (typical dimensions are small ~ 10 um)
- Electrostatic transduction is used (which requires large voltages > 10V).

<table>
<thead>
<tr>
<th>Clamped-Clamped Beam</th>
<th>Wine Glass Disk</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Clamped-Clamped Beam Diagram" /></td>
<td><img src="image2" alt="Wine Glass Disk Diagram" /></td>
</tr>
</tbody>
</table>

**TABLE I**

<table>
<thead>
<tr>
<th>Resonator Design</th>
<th>Equation Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3" alt="Clamped-Clamped Beam Designed Circuit" /></td>
<td><img src="image4" alt="Wine Glass Disk Designed Circuit" /></td>
</tr>
</tbody>
</table>

\[
\omega_n = \sqrt{\frac{k}{m}}
\]

*Fig. 2. Perspective view schematic and equivalent circuit of a CC-beam micromechanical resonator under a one-port bias and excitation scheme.*

*Fig. 3 presents the SEM and measured frequency characteristic (under vacuum) for an 8-μm-wide, 20-μm-wide-electrode, 10-MHz CC-beam, showing a measured Q of 3100.*

**CC-Beam Resonator**

- This example uses an 8-μm wide beamwidth and a 20-μm wide electrode.
- Measurements are performed in vacuum.
- Q ~ 3000 for a frequency of 10 MHz
CC-Beam with Better Power Handling

- To increase power handling of the resonator, a wider beam width is used [\(\sim 10\times\) in theory].
- The motional resistance is reduced to 340 ohms (\(V_p = 13\) V)

**Disk Wineglass Resonator**

- Intrinsically better power handling capability from a wine glass resonator.
- The input/output ports are isolated (actuation versus sensing).

Sustaining Amplifier Design

- Use feedback amplifier to create positive feedback trans-resistance
- Automatic gain control is used so that the oscillation self-limits through the electronic non-linearity. This reduces the oscillator amplitude but also helps to reduce 1/f noise up-conversion
Amplifier Details

- Single-stage amplifier is used to maximize bandwidth. Recall that any phase shift through the amplifier causes the oscillation frequency to shift (and phase noise to degrade)
- Common-mode feedback used to set output voltage. Feedback resistance and Amplitude Level Control (ALC) implemented with MOS resistors

**Design Equations**

\[
R_{\text{amp}} = \frac{1}{2} g_m (R_f // r_{o1} // r_{o3}) R_f \\
\approx \frac{g_m R_f^2}{2 + g_m R_f} \approx R_f
\]

\[
R_i = \frac{R_f}{1 + \frac{1}{2} g_m (R_f // r_{o1} // r_{o3})} \approx \frac{2R_f}{2 + g_m R_f} \approx \frac{2}{g_m}
\]

\[
R_o = \frac{R_f // r_{o1} // r_{o3}}{1 + \frac{1}{2} g_m (R_f // r_{o1} // r_{o3})} \approx \frac{2R_f}{2 + g_m R_f} \approx \frac{2}{g_m}
\]

\[
R_{\text{amp}}(s) = \frac{r_m}{1 + r_m \cdot \frac{1}{R_f}} = \frac{R_f \omega_i \omega_b a_v}{s^2 + s(\omega_i + \omega_b) + \omega_i \omega_b (1 + a_v)}
\]

\[
\frac{v_{i\text{a}}^2}{\Delta f} = 4kT \cdot \gamma \cdot \frac{2}{g_m} \cdot \left(1 + \frac{g_m}{g_m^3}\right)
\]

- These equations are used to trade-off between power and noise in the oscillator. The device size cannot be too large since the bandwidth needs to be about 10X the oscillation frequency.

*LIN et al.: SERIES-RESONANT VHF MICROMECHANICAL RESONATOR REFERENCE OSCILLATORS, IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 39, NO. 12, DECEMBER 2004*
Amplitude Control Loop

- Precision peak-detector used to sense oscillation amplitude. This is done by putting a MOS diode in the feedback path of an inverting op-amp.

![Amplitude Control Loop Diagram](image-url)
**Measured Spectra and Time-Domain**

- These are the measurements without using the ALC
- The oscillation self-limits due to the resonator non-linearity
- Notice the extremely small oscillation amplitudes
- With the ALC, the oscillation amplitude drops to 10mV
Experimental Results

- Performance close to GSM specs. DC power and area are compelling
- The measured 1/f noise much larger than expected
Array-Composite MEMS Wine-Glass Osc

- Increase power handling capability by coupling multiple (N) resonators together.
- This increases power handling capability by N.

**Design Summary**

**Table 1. Oscillator Data Summary**

<table>
<thead>
<tr>
<th>Integrated Circuit</th>
<th>Process</th>
<th>TSMC 0.35 μm CMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Supply</td>
<td>± 1.65 V</td>
<td></td>
</tr>
<tr>
<td>Power Cons.</td>
<td>350 μW</td>
<td></td>
</tr>
<tr>
<td>Amplifier Gain</td>
<td>8 kΩ</td>
<td></td>
</tr>
<tr>
<td>Amplifier BW</td>
<td>200 MHz</td>
<td></td>
</tr>
<tr>
<td>Layout Area</td>
<td>50 μm × 50 μm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MEMS Wine-Glass Disk Resonator Array</th>
<th>Process</th>
<th>Polysilicon-Based Surface Micromachining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius, R</td>
<td>32 μm</td>
<td></td>
</tr>
<tr>
<td>Thickness, h</td>
<td>3 μm</td>
<td></td>
</tr>
<tr>
<td>Gap, d_o</td>
<td>80 nm</td>
<td></td>
</tr>
<tr>
<td>Voltage Supply</td>
<td>10 V</td>
<td></td>
</tr>
<tr>
<td>Power Cons.</td>
<td>~ 0 W</td>
<td></td>
</tr>
<tr>
<td>Motional Resistance, R_m</td>
<td>5.75 kΩ, 3.11 kΩ, 1.98 kΩ, 1.25 kΩ for n = 1, 3, 5, 9</td>
<td></td>
</tr>
<tr>
<td>Layout Area</td>
<td>n × 105 μm × 105 μm</td>
<td></td>
</tr>
</tbody>
</table>

- Prototype resonator implemented in a 0.35μm CMOS process shows no spurious modes
- Area is still quite reasonable compared to a bulky XTAL

**Measured Phase Noise**

- Meets GSM specs with comfortable margin

Phase Noise: Model for Resonator

\[ x = H(\omega)F_e \]

\[ H(\omega) = \frac{k^{-1}}{1 - \omega^2/\omega_0^2 + i\omega/Q\omega_0}. \]

\[ i_{\text{sig}} = \frac{\partial C}{\partial t} U_{dc} + C_0 \frac{\partial u_{ac}}{\partial t}, \]
\[ i_m \approx \eta \dot{x}, \quad \eta = U_{dc} \frac{\partial C}{\partial x} \approx U_{dc} \frac{C_0}{d} \]

- The system is non-linear due to the electrostatic mechanism and the mechanical non-linearities

kaajakari et al.: analysis of phase noise and micromechanical oscillators: ieee transactions on ultrasonics, ferroelectrics, and frequency control, vol. 52, no. 12, december 2005
Non-Linear Spring Constant

\[ F = \frac{U_{dc}^2}{2} \frac{\partial C}{\partial x} \]

\[ k_e(x) = k_0e(1 + k_{1e}x + k_{2e}x^2) \]

\[ k_0e = -\frac{U_{DC}C_0}{d^2}, \quad k_{1e} = \frac{3}{2d}, \quad \text{and} \quad k_{2e} = \frac{2}{d^2}. \]

- The second-order correction in the spring constant dominates
- Electrostatic non-linearity limits the drive level at high vibration amplitudes.
- The system can become chaotic at high drive amplitudes. The critical amplitude before a bifurcation is given by

\[ x_c = \frac{2}{\sqrt{3\sqrt{3}Q|\kappa|}}, \quad \kappa = \frac{3k_{2e}k_{0e}}{8k} - \frac{5k_{1e}^2k_{0e}^2}{12k^2}. \]

\[ i_{m}^{\max} = \eta \omega_0 x_c. \]

kaajakari et al.: analysis of phase noise and micromechanical oscillators: ieee transactions on ultrasonics, ferroelectrics, and frequency control, vol. 52, no. 12, december 2005
Noise Aliasing in Resonators

- As we have learned in our phase noise lectures, 1/f noise can alias to the carrier through time-varying and non-linear mechanisms. Since 1/f noise is high for CMOS, this is a major limitation

kaajakari et al.: analysis of phase noise and micromechanical oscillators: ieee transactions on ultrasonics, ferroelectrics, and frequency control, vol. 52, no. 12, december 2005
Mixing: Capacitive Current Non-Linearity

- This term is usually much smaller (by 10X ~ 100X) than mixing due to the force non-linearity

\[ C(x) \approx C_0 \left( 1 + \frac{x_0}{d} \right) \]

\[ i_n = \frac{\partial(C(x)u_n)}{\partial t} \approx \frac{C_0}{d} \ddot{x}_0 u_n + C_0 \dot{u}_n. \]

\[ i_n^c = 2\Gamma_c u_{ac} u_n, \quad \Gamma_c = \frac{Q\omega_0 \eta^2}{2kU_{dc}}. \]

kaajakari et al.: analysis of phase noise and micromechanical oscillators: ieee transactions on ultrasonics, ferroelectrics, and frequency control, vol. 52, no. 12, december 2005
**Mixing: Capacitive Force Non-Linearity**

\[
F_n = \frac{U^2}{2} \frac{\partial C}{\partial x} \approx \frac{(U_{dc} + u_{ac} + u_n)^2}{2} \frac{C_0}{d} \left( 1 + 2 \frac{x_0}{d} \right)
\]

\[
F_n(\omega_0 \pm \Delta \omega) \approx \frac{C_0}{d} u_{ac} u_n + 2 \frac{C_0}{d} \frac{x_0}{d} U_{dc} u_n.
\]

\[
\dot{i}_n^F = 2\Gamma_F u_{ac} u_n
\]

\[
\Gamma_F \approx \frac{Q\omega_0\eta^2}{2kU_{dc}} \left( 1 - j2\frac{Q\eta U_{dc}}{kd} \right)
\]

- The form is the same as the capacitance non-linearity, but the magnitude is much higher and dominates for most resonators. A linear coupling capacitor has much reduced noise up-conversion

kaajakari et al.: analysis of phase noise and micromechanical oscillators: ieee transactions on ultrasonics, ferroelectrics, and frequency control, vol. 52, no. 12, december 2005
**Mixing: Non-Linear Spring Force**

\[ x_n = H(\omega)F_n \approx \frac{\eta u_n}{k} \]

\[ F_n^k = 2k_0k_1x_0x_n. \]

\[ \dot{v}_n^k = 2\Gamma_k u_{ac}u_n, \]

\[ \Gamma_k = j\frac{3Q^2\omega_0\eta^4U_{dc}}{2d^2k^3}. \]

- Amplitude of noise at low-frequency is very small due to resonator Q. The noise is up-converted through the spring non-linearity.

- This term is the smallest of the three, about 500X smaller than the capacitance non-linearity.

kaajakari et al.: analysis of phase noise and micromechanical oscillators: ieee transactions on ultrasonics, ferroelectrics, and frequency control, vol. 52, no. 12, december 2005
Another “MEMS” technology is the Thin Film Bulk Wave Acoustic Resonators (FBAR).

- It uses a thin layer of Aluminum-Nitride piezoelectric material sandwiched between two metal electrodes.
- The FBAR has a small form factor and occupies only about 100µm x 100µm.
FBAR Resonance

- Very similar to a XTAL resonator. Has two modes: series and parallel
- Unloaded Q ~ 1000
- This technology will not be integrated directly with CMOS, but there is a potential for advanced packaging or processing.
FBAR Oscillator

- $R_m \sim 1\ \text{ohm}$
- $g_m \sim 7.8\ \text{mS}$ used (3X)
- $C_1=C_2=.7\ \text{pF}$
- $g_m/Id \sim 19,\ Id \sim 205\ \mu\text{A}$
- Start-up behavior shown below:
Measured Results on FBAR Osc

- Operate oscillator in “current limited” regime
- Voltage swing ~ 167 mV, Pdc ~ 104 μW