Frequency Modulated AFM
- Experimental Details -

What is Required?

- High stability
- Measure small frequency shifts accurately
- Large spring constant

stiff cantilever:
\[ k \sim 100 - 1000 \text{ N/m} \]

cantilever:
\[ k \sim 1 \text{ N/m} \]
New Idea: Tuning Forks

\[ f_o = 2^N ; \quad N = \text{integer} \]

\[ f_o = 2^{15} = 32,768.0000 \text{ Hz} \]

Cost:
\(~0.25 \text{ USD}\)
Quartz: a piezoelectric material

Thermal stability of quartz compared to Si

Electrode Geometry
Selects Vibrational Mode
Vibration Spectrum

Y. Qin, PhD thesis, Purdue University (2007).
### Raltron Model R26 Tuning Fork

![Image of Raltron Model R26 Tuning Fork]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>3.20 ± 0.01</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.40 ± 0.01</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>0.33 ± 0.01</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2.65 × 10³</td>
</tr>
<tr>
<td>Effective mass (kg)</td>
<td>2.72 × 10⁻⁷</td>
</tr>
<tr>
<td>Spring constant (kN/m)</td>
<td>12.7</td>
</tr>
<tr>
<td>Resonance (kHz)</td>
<td>34.39</td>
</tr>
<tr>
<td>Young’s Modulus(Pa)</td>
<td>7.87 × 10¹⁰</td>
</tr>
</tbody>
</table>

Y. Qin, PhD thesis, Purdue University (2007).
Understanding the Resonance

Equivalent Circuit

Anti-resonance
Eliminating the Parasitic Capacitance

Y. Qin, PhD thesis, Purdue University (2007).
Calibrating the Amplitude of Oscillation

Infrared fiber optic interferometer

Y. Qin, PhD thesis, Purdue University (2007).
Typical calibration
($A_0$ vs. applied driving voltage)

Calibrating the Amplitude of Oscillation

Y. Qin, PhD thesis, Purdue University (2007).
Mounting a Tip: Tuning Fork AFM

Quartz Tuning Fork from wrist watch

\[ k \approx 1000 \text{ N/m} \]

\[ Q \text{ in vacuum } \approx 45,000 \]
\[ Q \text{ in air } \approx 9,000 \]

Y. Qin, PhD thesis, Purdue University
Commercially available Q-plus sensor
courtesy, F. Giessibl
Phase-Locked Loops (PLLs) track the frequency of an input "noisy" sinusoidal signal that is known to have a variable frequency.

The PLL consists of three components:
- Phase Detector (PD)
- Loop filter
- Voltage-Controlled Oscillator (VCO)
Principle of Digital Phase-Lock Loops (PLL)

**TASK:** Instantly track and measure frequency of an input signal \( I(t) \) with high accuracy

**Input Signal**
\( I(t) \) (unknown \( f \))

**Independent Output**
\( Y(t) \)

**Error**
\( error(t) = I(t) - Y(t) \)

- Negative feedback!
- Goal is to make \( \Delta f = f - f' = 0 \)
Tuning Fork AFM

No laser required to measure deflection
Scan while keeping $\omega(d^*)$ and $Q$ constant
FM-AFM Force Spectroscopy

Tip-Sample Force

$F_{ts} (d_{\min}) = 2k_e \int_{d_{\min}}^{\infty} \left\{ \left[ 1 + \frac{\sqrt{A}}{8\sqrt{\pi}(\xi - d_{\min})} \right] \Omega(\xi) - \frac{A^{3/2}}{\sqrt{2}(\xi - d_{\min})} \frac{d\Omega(\xi)}{d\xi} \right\} d\xi$

where $\Omega(\xi) \equiv \frac{\Delta f(\xi)}{f_o}$, $\xi \Leftrightarrow d^*$
FM-AFM Force Spectroscopy

W tip – HOPG substrate

Y. Qin, PhD thesis, Purdue University (2007).