On a MEMS-Based Parametrically Amplified Atomic Force Sensor

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Introduction

We use nonlinear mixing to raise small, low frequency signals above the noise floor

- Using a characterized nonlinear component in an otherwise linear system, we can convolve a small amplitude, low frequency signal (signal) with a high frequency, high amplitude signal ("carrier" or "pump").
- This is a subset of a phenomenon known as 'mixing', wherein the convolution of two signals produces the set of all of the harmonics.
- If, at the output, we filter all but one of the harmonics, then we can demodulate this signal to restore the initial input.

Manley-Rowe Power Relations

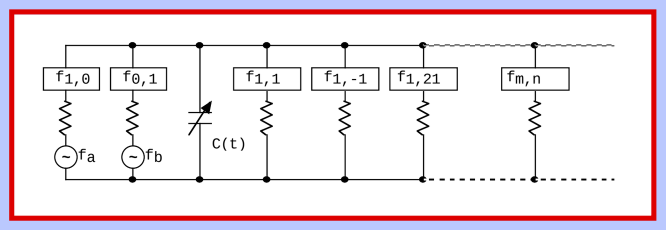
$$\sum_{m=0}^{\infty}\sum_{n=-\infty}^{\infty}\frac{mP_{m,n}}{mf_1+nf_2}=0 \quad \text{and} \quad \sum_{m=-\infty}^{\infty}\sum_{n=0}^{\infty}\frac{nP_{m,n}}{mf_1+nf_2}=0$$

where $P_{m,n}$ is the power at that frequency.

Simple case of only one load ($f_{1,1}$), the Manley-Rowe equations reduce to:

$$\frac{P_{0,1}}{f_{0,1}}+\frac{P_{1,1}}{f_{1,1}}=0 \quad \text{and} \quad \frac{P_{1,0}}{f_{1,0}}+\frac{P_{1,1}}{f_{1,1}}=0$$

where gain ($P_{1,1}/P_{1,0}$) depends only on the ratio of frequencies



where $f_{1,0} = f_a$ and $f_{0,1} = f_b$

C(t) is the time-varying reactance

fm,n is a perfect bandpass filter at frequency $f_{m,n}$

We will be using a variable electrostatic stiffness as our time-varying reactance

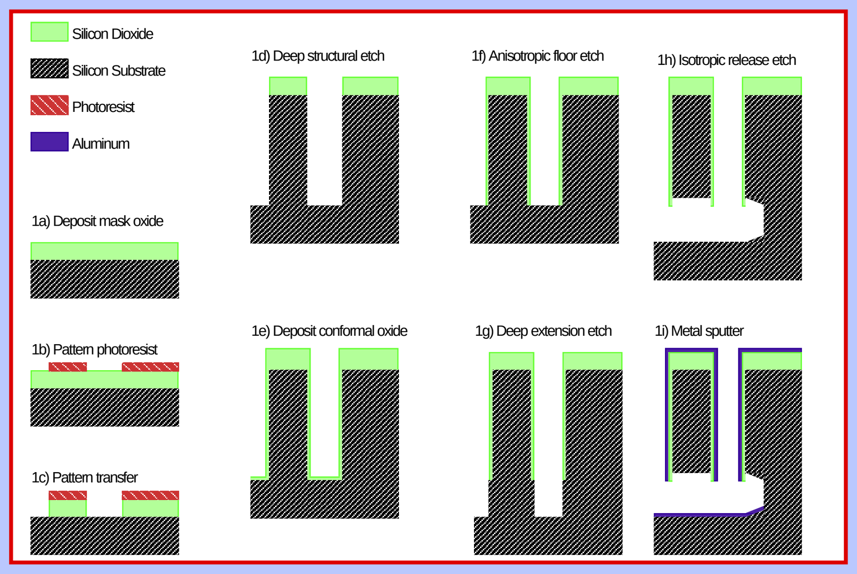
$$m\ddot{x}+c\dot{x}+\left(k_{mechanical}+k_{electrical}\right)x=F_{excite}(V_e)$$

This stiffness is generated from a parallel plate electrostatic actuator:

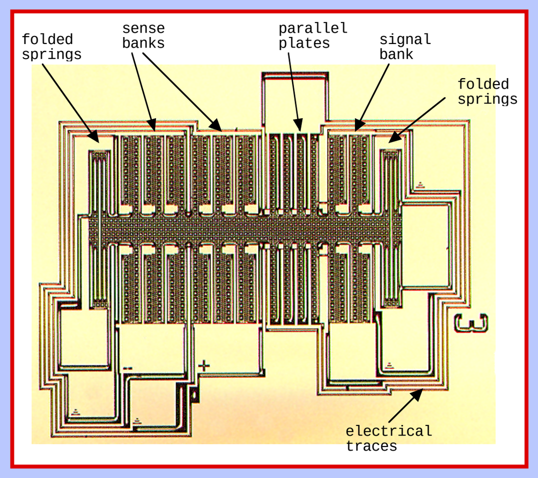
$$k_{electrical}=\frac{\varepsilon_0 A V_t^2}{\left(d-x_{II}\right)^3}$$

where V_t is the voltage applied across the plates, d is the initial gap, x_{II} is the stable point, and A is the area of the plate.

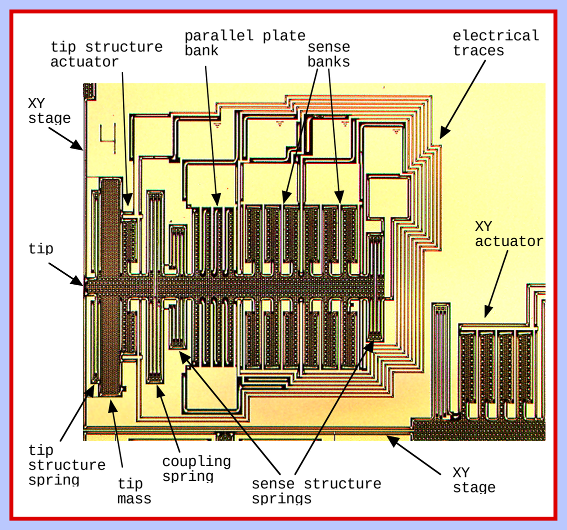
SCREAM Fabrication



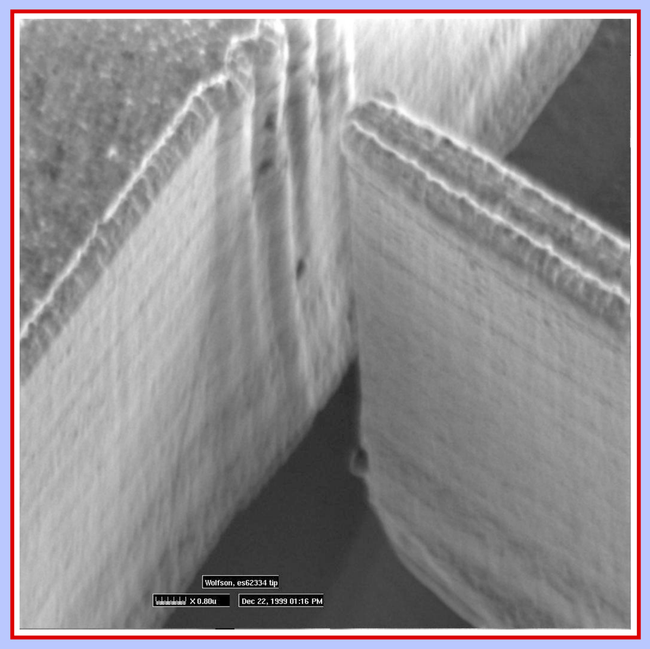
Paramp Overview



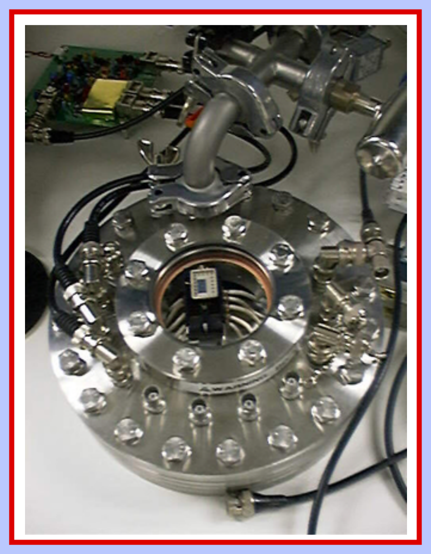
System Overview



AFM Tip

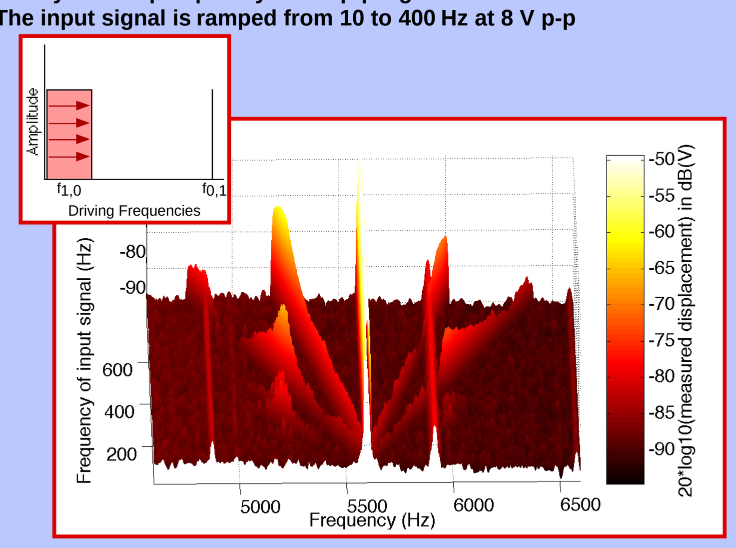


Measurement Setup



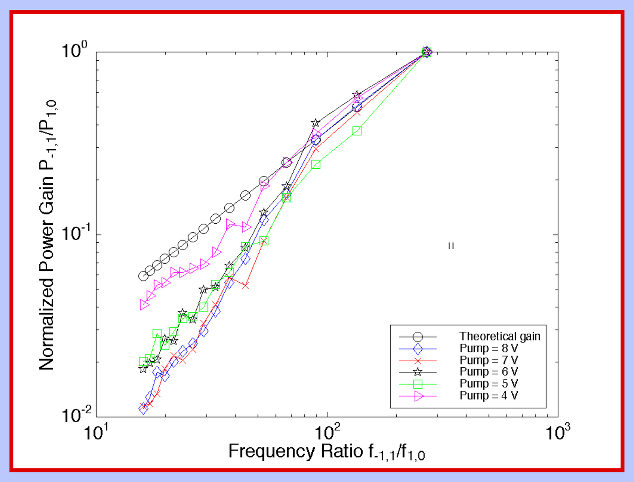
Parametric Amplification

Here, we demonstrate that the output amplitude depends on the Impedance in the system (impedance is least at resonance, 5.91 kHz).
The system is pumped by an 8V p-p signal at 5.6 kHz
The input signal is ramped from 10 to 400 Hz at 8 V p-p



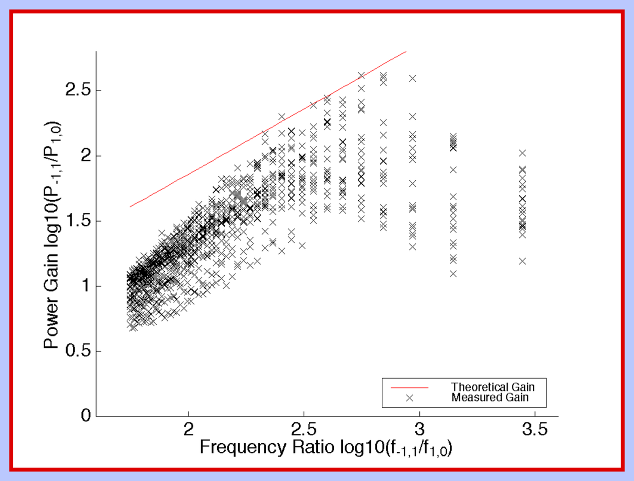
Here, we demonstrate that the gain observes the Manley-Rowe power relationship. For a simple system, the gain is proportional to the ratio of frequencies.

Pump is at 5 kHz. The signal is ramped from 20 to 350 Hz. We have averaged over input amplitudes of 2.5 V to 10 V p-p



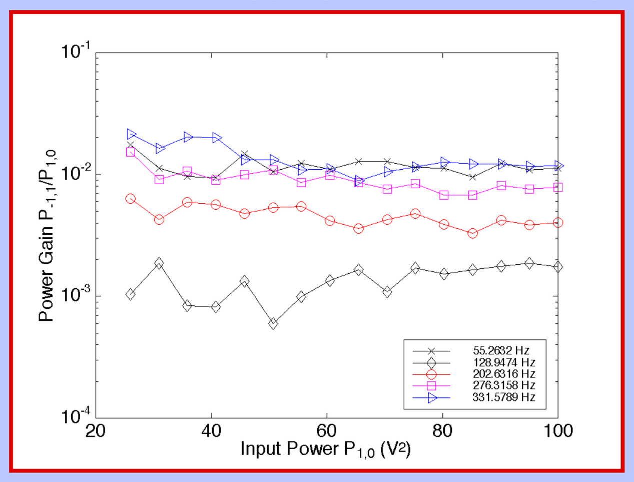
Here, we see that we can achieve very high gain with this device under the right conditions.

Pump is at 5.7 kHz, varying from 4 to 8 V p-p with a 3 V DC offset. The signal is ramped from 0 to 100 Hz at 10 V p-p. Max gain is 316.2



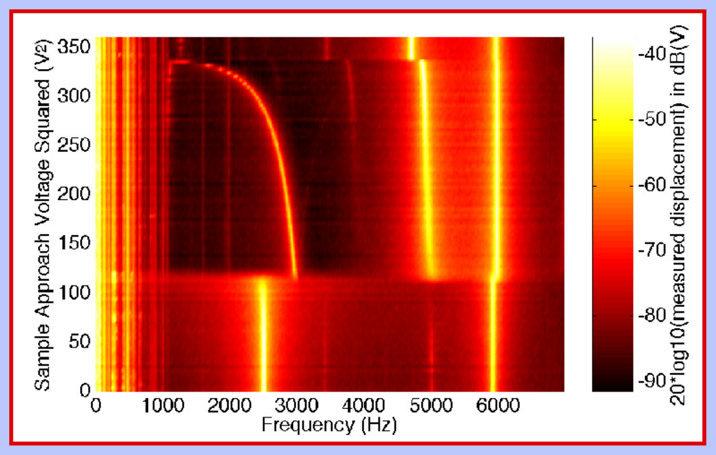
Here, we see that we can achieve a linear response over a limited range.

Pump is at 10 kHz at 8 V p-p. Signal is measured at 5 frequencies.



Atomic Force Sensing

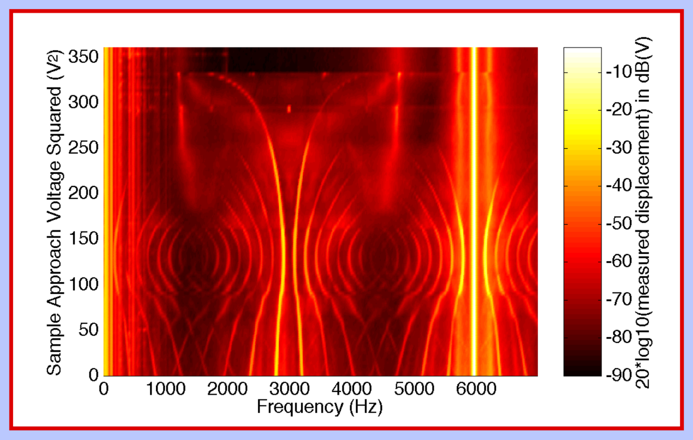
Here, we demonstrate that the resonant frequency depends on the distance between the tip and the sample.
The system is driven by a 5 V pseudo-random signal
The sample approach actuator is ramped from 16 to 19.5 V.



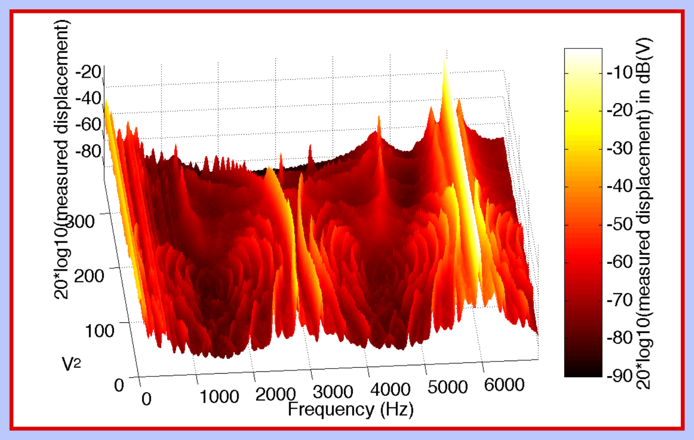
Parametric Amplification of Sensed Measurement

Here, we can see all of the harmonics generated when we operate the parametric amplifier.
Note how the harmonics near the pump are largest amplitude.

Pump is 3 V p-p with 5 V DC. Signal is pseudo-random at 5 V from 1 to 3 kHz.



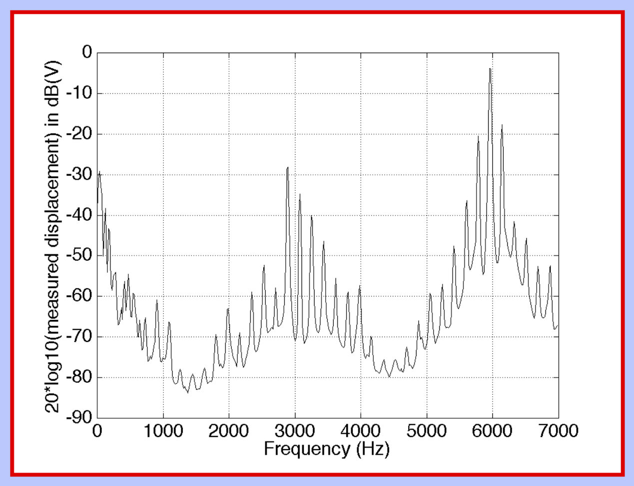
We rotate the previous data to give a clearer view of the relative amplitudes



Clearer view of gain. This is a "cross-section" at a sample approach voltage of 10.8 V.

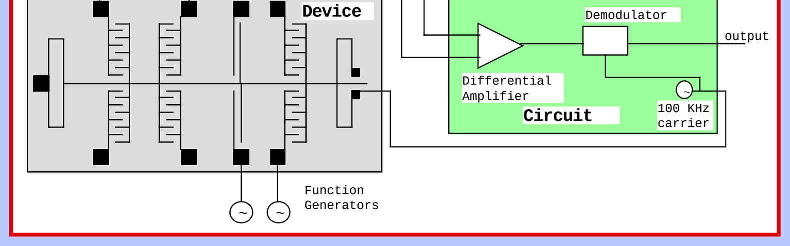
The tip is resonating at 2898 Hz at -28.1 dBV. The output signal is at 6145 Hz at -17.65 dBV. Gain is 10.45 dB.

The highest gain we have measured is 47.75 dB.



Measurement Techniques

The state (i.e. displacement) of the system was detected using a capacitive sensor via amplitude modulation techniques (carrier frequency = 100 kHz, bandwidth = 8.6 kHz).



All leads are coaxial/shielded from the pins of the differential amplifier to the pins of the packaged device to reduce parasitic capacitance/ambient effects.

The noise floor of the circuit corresponds to ~0.9 nm, as calibrated by a Polytec OFV3001 Laser Vibrometer system.

Overview

Parametric Amplifier Subsystem

- Gain of 49.9 dB
- Linear amplification
- Observes Manley-Rowe behavior
- No transistors

AFM Subsystem

- Displays frequency shift of 62.4 %
- Integrated sample

Complete System

- Maximum measured gain of 47.7 dB
- Fully integrated (no assembly or alignment)
- Parametric amplifier mixes and amplifies results of AFM sensor

On-chip preamplification of signals

- Amplifier integrated with sensor
- Reduce effect of parasitic capacitance
- No transistors
- No need to integrate VLSI with MEMS
- Low noise gain
- Upconvert to a higher frequency

Acknowledgements

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