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TITLE:
Design and Characterization Methodology for Efficient Wide Range Tunable MEMS Filters

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KEYWORDS:
CMOS-MEMS, microresonator, wide range active frequency tuning, electrostatic devices, microelectromechanical devices, high-mode resonance, joule heating, electrothermal effects, stiction, Laser Doppler Vibrometer (LDV).

SHORT ABSTRACT:
A protocol of how to design, measure the frequency tuning, tune the tuning capability, avoid the device failure and stiction of fixed-fixed beam are presented by using Laser Doppler Vibrometer (LDV). Moreover, the superiority of LDV method over Network analyzer is presented by demonstrating its higher mode capability.

LONG ABSTRACT:
We demonstrated not only the superior advantages of measurement technique with LDV over conventional techniques (Network Analyzer) but also the techniques of how to create application based MEMS filter, and to use them efficiently (tuning the tuning-capability, and avoiding failure and stiction). LDV enables crucial measurements that would be impossible with Network Analyzer such as higher mode detection (high sensitive biosensor application) and resonance measurement for very small devices (fast prototyping). That's why LDV was used to characterize (frequency tuning range, and resonance frequency at different modes) the MEMS filters built in this work. Wide range frequency tuning mechanism is simply based on joule heating coming from embedded heater and relatively high thermal stress with respect to temperature on fixed-fixed beam. However, we proved that this method also has a limitation as it results in high thermal stress and consequently burn the devices. Further improvement was achieved and shown the first time in this work before, that, the tuning capability was increased 32% by simply increasing the applied DC bias voltage (25V to 35V) between two adjacent beams. This essential finding eliminates the need for extra joule heating for wider frequency tuning range. Another possible failure is the stiction and requires structure optimization. In contrast, we offered here a simple and easy technique of low frequency square wave signal application that successfully separated the beams and eliminates more sophisticated and complicated methods given in the literature. All these above findings bring the necessity of design methodology, this why application based design is also presented.

INTRODUCTION:

There is a growing demand on MEMS resonators due to their high reliability, low power consumption, compact designs, high quality factor, and inexpensive cost. They are widely used both as sensors, and core parts in wireless communication. Temperature sensors[1], bio – sensors [2,3], and gas-sensors applications[4], filters[5,6,7] or oscillators are the most popular application areas. The most popular electrostatic MEMS resonators are fixed-fixed beam[5,8], cantilever[2], tuning fork [6], free-free beam[6,7], flexural-disk[7], and square shape[9].

There are many critical steps in realizing MEMS resonators such as design methodology (application based structure optimization, wide range frequency tuning range, and avoiding failures) and characterization (fast prototyping, avoiding parasitic capacitances and detecting higher modes). Frequency tuning capability is required to compensate for any frequency changes due to fabrication tolerances, or ambient temperature variations. Different techniques[10,11,12] have been reported in the literature to address this requirement; however, they have some drawbacks such as, limited frequency tuning capability, low center frequency, additional post processing requirements, and external heater[10,11] all bringing higher cost.

We demonstrated a wide range frequency tuning via joule heating method[5,13] over limited frequency tuning range via Elastic Modulus change [12] (increasing the DC bias voltage between two adjacent beams) or material phase transition method[10,11]. Moreover, the optimum structure selection and the application based design was summarized in this work before[13]. Here we will show how to tune the resonance frequency of fixed-fixed beam by increasing the DC voltage applied to the embedded heaters with the help of LDV. The Coventor simulation is synchronized with LDV measurement in the same frame for the sake of visualizing the tuning mechanism. This includes joule heating and bending profile throughout the beam.

We will also present the possible failures (burnt devices and stiction) and their proposed solutions. Joule heating method with the combination of high thermal stress on fixed-fixed beam provides wide range frequency tuning but in the same time it can result in burnt devices at certain temperature level. This is attributed to high thermal stress between different materials[14]. The solution method is simply increasing the DC voltage between two adjacent beams, this in return increases the tuning range (32% increase) by eliminating the need for high temperature and burnt devices. This “tuning the tuning-range” method was first demonstrated in this *work*[5], explained in detail[13] and re-presented here. Stiction, on the other hand, can take place during the fabrication process or resonance operation. There have been many techniques proposed to address this problem such as applying surface coating to reduce adhesion energy[15,16], increasing surface roughness[17], and laser repair process[18]. In contrast, we will present a simple technique here. A low frequency square wave signal was applied between two attached beams and the separation was successfully recorded by LDV. This method would eliminate extra cost and reduce the design complexity.

Another critical step in building state of the art MEMS resonators is characterization and verification. Characterization with network analyzer is one of the popular and widely used method, however, it has some drawback. Even small parasitic capacitance can kill the signal and this usually requires amplifier circuit[3,6,8] for noise elimination and can only detect first mode resonance. On the other hand, characterization with Laser Doppler vibrometer (LDV) doesn't have parasitic capacitance problem and can detect much smaller displacement. This enables fast prototyping, while eliminating the need for amplifier design. Furthermore, LDV is capable of detecting higher mode resonance of MEMS resonator. This feature can be very promising especially in high sensitive biosensor area. Higher mode for cantilever can provide much more sensitivity[19]. We will show the higher mode measurement of fixed-fixed beam with LDV and compare the measurement results with Coventor simulation. The premature results from Coventor simulation offers up to 46 times improvement in sensitivity compared to first mode of fixed-fixed beam.

PROTOCOL:

1. Design Criteria

1.1) Optimum Structure for Wider Frequency Tuning Range

There are many different type of resonators design in the literature such as cantilever[2], tuning fork [6], free-free beam[6,7], and fixed-fixed beam[5,8].

1.1.1) Cantilever has one fixed and one free end at where the cantilever can freely expand that's why it has relatively large thermal expansion (1380 nm) and smaller TCF (Temperature Coefficient of Frequency) (-86 ppm/C).

1.1.2) In the same way, Tuning Fork has a free end that enables relatively large thermal expansion (1850 nm) with small TCF (-83.7 ppm/C) like Cantilever.

1.1.3) Although Free-Free beam has two free end, it has still two fixed ends and this limits the TCF value around -172 ppm/C with a thermal expansion of 370 nm

1.1.4) Fixed-Fixed beam on the other hand, doesn't have any free but two fixed ends that prevents the beam to expand. That's why it has a negligible thermal expansion (28 nm) and this cause a very large TCF (-1515 ppm/C).

Due to its large TCF value, Fixed-Fixed beam, compared to other candidates, enables wide range tuning when it is heated. In this work we used Joule heating method by using polysilicon layers as embedded heaters.

1.2 Application Based Design

Different applications requires different design performance That's why building application based design is crucial, for instance,

1.2.1) for better tuning efficiency (ppm/mW); beam should be longer or thinner

1.2.2) for wider frequency tuning range applications such as signal tracking or frequency hopping; beam should be shorter or thinner.

2 Modeling and Fabrication in CMOS

Before going further, lets give a quick look for the fabrication of the MEMS resonators.

2.1) First step is to create the 3D-model and apply the fabrication steps in Coventor

2.2) the next step is to build the structure in Cadence Virtuoso layer by layer to create the gds

file. This gds file later was sent to CMOS foundry for fabrication. Here we used CMOS 0.6 µm technology.
2.3) once the CMOS process completed, the chips come with Polysilicon, aluminum and oxide layers, the next step is to conduct a post-process steps;
2.3.1) Conduct CHF_3/O_2 dry etch process to etch the SiO_2 between aluminum layers forming the beams at the aspect ratio of 5.7.
2.3.2) Apply XeF_2 etch process in the silicon substrate to create a 9 µm depth cavity under the beams.
2.4) Final step is to characterize the devices under SEM to make sure they are properly fabricated.

3 Characterization (LDV vs Network Analyzer)

A well-known method to measure the resonance of the MEMS resonators is using Network Analyzer. But it is not as powerful method as Laser Doppler Vibrometer (LDV) technique due to following reasons;

3.1 Characterization with Network Analyzer (Problems due to Parasitic Capacitance)

One of the big challenges with Network Analyzer method is to eliminate the parasitic capacitances. Multisim is used to plot the frequency and phase response of the equivalent circuit for 120 µm long beam. The S21 peak to peak value drastically decreased from 6 dB to 0.34 dB even when the parasitic capacitance increased from 1 fF to 20 fF. That's why this requires on-chip amplifier design just next to MEMS resonator[6,8].

3.2 Characterization with Laser Doppler Vibrometer (LDV)

Laser Doppler Vibrometer is another method that uses the laser to sense the vibration of the beams when they resonate.

3.2.1) In contrast to Network Analyzer, LDV technique eliminates the parasitic capacitance problem

3.2.2) In addition, it can detect higher mode resonance that brings many advantages in different research areas such as biosensor applications [19].

3.2.3) and can characterize much smaller resonators in contrast to Network Analyzer. This enables fast prototyping and more sensitive and accurate resonators especially in biosensor applications.

4 Device Testing

Device Testing consist of many steps including Joule heating test and frequency response test. In addition it also includes the methods to avoid possible device failures such as device burning and stiction.

4.1 Thermal Camera test for Embedded Heaters

Embedded heaters (polysilicon layer) are tested with thermal camera to check if they properly heat the beams. DC voltage applied to the polysilicon layer via DC Power Supply. The thermal camera located on top of the chip to record the data and Matlab was used to plot the heating profile.

4.2 Calibrating LDV and Test Setup

4.2.1) Select the design, and then zoom in to the device area.

4.2.2) Locate the laser on top of the selected beam to find the spot where the light reflection is maximum

4.2.3) Testing the On-Off state: When the AC and DC voltage together applied to beams, the laser detects resonance and show the sine signal on the screen. On the other hand, when the AC voltage is removed from the beams, the laser should detect no signal because in this case beams are not resonating. That's why sine signal on the screen is gone

4.2.4) Testing Magnitude and Phase response of the beams: Select different spot on the beams and chose the one that gives the best laser reflection (the cleanest signal).

4.2.5) Next, plot and verify the resonance on different points on beams.

4.3 How Frequency Tuning Via Joule Heating Works

To understand the working principle, we first demonstrated what really happens when we apply DC voltage to the embedded heaters by using Coventor simulation tool. When the DC voltage applied, the beam start to expand but can only have negligible thermal expansion and this cause a huge thermal stress and consequently wide range frequency shift. The heating profile (the one on the left side), resonance frequency response (the one on the top right corner) and the bending profile due to thermal expansion (the one on the bottom right corner) are synchronized for the purpose of clear visualization and understanding.

4.4 First "Hello To World" Moment

Simulations (on the right side) and real measurement (on the lefts side) are synchronized. The 68um long beam is selected for the testing. The DC voltage starting from 0 V and increased to 5.7 V with small step increment. The magnitude and the phase response for each different step was recorded. The resonance frequency changed from 1905 kHz to 1244 kHz in measurement and 2183 kHz to 1496 kHz in simulation.

4.4.1 When 0 V is applied to the embedded heaters, the resonance frequency is 1905 kHz in measurement and it is 2185 kHz in Coventor Simulation.

4.4.2 When 0.4 V is applied to the embedded heaters, the resonance frequency is 1900 kHz in measurement and it is 2183 kHz in Coventor Simulation.

4.4.3 When 0.8 V is applied to the embedded heaters, the resonance frequency is 1887 kHz in measurement and it is 2174 kHz in Coventor Simulation.

4.4.4 When 1.2 V is applied to the embedded heaters, the resonance frequency is 1864 kHz in measurement and it is 2159 kHz in Coventor Simulation.

4.4.5 When 1.4 V is applied to the embedded heaters, the resonance frequency is 1849 kHz in measurement and it is 2149 kHz in Coventor Simulation.

4.4.6 When 1.6 V is applied to the embedded heaters, the resonance frequency is 1832 kHz in measurement and it is 2138 kHz in Coventor Simulation.

4.4.7 When 1.8 V is applied to the embedded heaters, the resonance frequency is 1814 kHz in measurement and it is 2126 kHz in Coventor Simulation.

4.4.8 When 2 V is applied to the embedded heaters, the resonance frequency is 1793 kHz in measurement and it is 2112 kHz in Coventor Simulation.

4.4.9 When 2.2 V is applied to the embedded heaters, the resonance frequency is 1771 kHz in measurement and it is 2096 kHz in Coventor Simulation.

4.4.10 When 2.4 V is applied to the embedded heaters, the resonance frequency is 1747 kHz in measurement and it is 2078 kHz in Coventor Simulation.

4.4.11 When 2.6 V is applied to the embedded heaters, the resonance frequency is 1721 kHz in measurement and it is 2058 kHz in Coventor Simulation.

4.4.12 When 2.8 V is applied to the embedded heaters, the resonance frequency is 1692 kHz in measurement and it is 2036 kHz in Coventor Simulation.

4.4.13 When 3 V is applied to the embedded heaters, the resonance frequency is 1663 kHz in measurement and it is 2015 kHz in Coventor Simulation.

4.4.14 When 3.2 V is applied to the embedded heaters, the resonance frequency is 1631 kHz in measurement and it is 1990 kHz in Coventor Simulation.

4.4.15 When 3.4 V is applied to the embedded heaters, the resonance frequency is 1597 kHz in measurement and it is 1964 kHz in Coventor Simulation.

4.4.16 When 3.6 V is applied to the embedded heaters, the resonance frequency is 1566 kHz in measurement and it is 1934 kHz in Coventor Simulation.

4.4.17 When 3.8 V is applied to the embedded heaters, the resonance frequency is 1531 kHz in measurement and it is 1902 kHz in Coventor Simulation.

4.4.18 When 4 V is applied to the embedded heaters, the resonance frequency is 1497 kHz in measurement and it is 1869 kHz in Coventor Simulation.

4.4.19 When 4.2 V is applied to the embedded heaters, the resonance frequency is 1462 kHz in measurement and it is 1833 kHz in Coventor Simulation.

4.4.20 When 4.4 V is applied to the embedded heaters, the resonance frequency is 1428 kHz in measurement and it is 1796 kHz in Coventor Simulation.

4.4.21 When 4.6 V is applied to the embedded heaters, the resonance frequency is 1417 kHz in measurement and it is 1753 kHz in Coventor Simulation.

4.4.22 When 4.8 V is applied to the embedded heaters, the resonance frequency is 1366 kHz in measurement and it is 1710 kHz In Coventor Simulation.

4.4.23 When 5 V is applied to the embedded heaters, the resonance frequency is 1329 kHz in measurement and it is 1662 kHz in Coventor Simulation.

4.4.24 When 5.2 V is applied to the embedded heaters, the resonance frequency is 1297 kHz in measurement and it is 1612 kHz in Coventor Simulation.

4.4.25 When 5.4 V is applied to the embedded heaters, the resonance frequency is 1265 kHz in measurement and it is 1556 kHz in Coventor Simulation.

4.4.26 When 5.6 V is applied to the embedded heaters, the resonance frequency is 1256 kHz in measurement and it is 1496 kHz in Coventor Simulation.

4.4.27 When 5.7 V is applied to the embedded heaters, the resonance frequency is 1244 kHz in measurement and it is 1466 kHz in Coventor Simulation.

4.5 Higher Modes Measurement

Higher mode resonance measurement is very crucial for the resonators as it offers promising results for the high sensitive and accurate biosensors. LDV enables the high mode measurement that is almost not possible to do it with Network Analyzer.

4.5.1) The 5th Mode was measured with LDV by measuring multiple points on each beam. The measured mode shape perfectly matches with the Coventor Simulation (on the right corner).

4.5.2) The first and the second mode were measured with their phase. The second mode has larger peak compared to first mode, because the primary resonance displacement is in Y direction for mode-1 and it is in Z direction (that is towards microscope) for mode-2.

4.6 Low Frequency Square Wave Signal to Solve Stiction

Stiction can take place due to electrostatic charging and this can happen especially during the resonance operation. Applying a low frequency square wave signal for a short time resolves stiction, and all beams separate in few seconds. This can eliminate the necessity of an anti-stiction coating and can allow a low cost design.

4.7 Avoiding Device Failure

High thermal stress occurs due to mismatch in thermal expansion constants of different layers in fixed-fixed beam at relatively high temperature[14] and this can burn or break the beams. That's why the voltage applied to the embedded heater should be limited to avoid device failure but in return it also limits the frequency tuning range.

4.8 Tuning the Tuning Capability

To our knowledge, changing the tuning capability of the MEMS resonators was shown the first time in this work. The method is basically to increase the DC bias voltage between two adjacent beams to tune the tuning-capability. A 32% increase in tuning capability is successfully tested and verified.

The total frequency tuning range is 875 kHz when 35 V DC voltage is applied and it is 661 kHz when 25V DC voltage is applied[5] between two 68 µm long adjacent beams during resonance operation. This method also eliminates the need for applying higher joule heating and burnt devices to get wider frequency tuning range.

REPRESENTATIVE RESULTS:

The stiction avoided by applying low frequency square wave signal and this was verified by using LDV (Polytec MSA-500A) (Figure 1). Possible failure due to high thermal stress [14] when applying relatively higher bias DC voltage to the embedded heaters was verified under microscope (Figure 2). Coventor was used to derive the higher modes for the beam (Figure 3). Changing the tuning capability (32% increase) by changing the DC bias voltage (25V to 35V) between two adjacent beams was demonstrated first time in this work [5] with the help of LDV (Figure 4). The capability of measuring higher mode responses via LDV was demonstrated successfully and the results were compared with Coventor simulation. Moreover, up to 47 times improvement in frequency shift with respect to first mode was demonstrated via Coventor when 1 pg mass attached on the beam. This promising result would provide a much more sensitive biosensor when it is combined with the higher mode reading capability of LDV (Figure 5)

Figure 1. Stiction occurred at T=55second and beams are released at T=57s after applying low frequency square wave signal

Figure 2. (a) 200 µm long resonators before applying high DC voltage to the embedded heater. (b) 200 µm long beam after applying high DC voltage to the embedded heaters. (c) 240 µm long beam after applying high DC voltage to the embedded heaters.

Figure 3. Beam at higher modes (Mode-1 to Mode-9)

Figure 4. Frequency/Power Consumption as a function of different applied voltage on the embedded heaters of the 68 µm long beam

Figure 5. (a) The measured high mode response for L=152 µm beams. (b) The Coventor simulation results with the same mode shape. (c) The measured higher mode responses for L=152 µm beam at different frequencies. (d) The normalized frequency shift with respect to first mode when 1 pg mass attached on the beam. (e) Comparison between measurement and Coventor simulation for higher mode responses for 152 µm beam

DISCUSSION:

Critical steps in design and characterization: One of the critical step in building MEMS filters is to design the device based on the application area. The beam should be longer or thinner for better tuning efficiency (ppm/mW) and it should be shorter or thinner for frequency hopping or signal tracking applications. In the same way, clear signal detection via LDV is very crucial in device testing that's why it is better to design the beam with a least 3-4 µm thickness. Otherwise the signal would be noisy even with 100x lens and it takes multiple points testing with noise elimination (embedded in LDV software) to get optimum detection.

How to avoid stiction: Stiction can occur during the resonance operation due to electrostatic charging. Many different methods were presented in the literature such as designing beam with high stiffness constant, coating the surface with anti-stiction chemistry, applying high DC voltage in reverse direction. In contrast, for the purpose of troubleshooting, we present a different and easy technique in here. By applying relatively high voltage low frequency signal for a short time (Figure 1), it was observed that the beams were separated and continued to resonate.

How to avoid device failure: Relatively high density current flow through fixed-fixed beams due to higher voltage application can result device failure (broken or burnt devices) (Figure 2). This is mainly due to mismatch in thermal expansion constants of different layers in fixed-fixed beam [14]. To avoid the failure, the maximum allowable voltage for each different fixed-fixed beam should be studied and defined carefully together with the maximum frequency tuning range.

Efficient way to characterize: In contrast to Network Analyzer, Laser Doppler Vibrometer (LDV) offers many advantages in resonance measurement of the fixed-fixed beams. First of all, it eliminates the parasitic capacitance that in return enables fast prototyping and much smaller device (high frequency devices) characterization. Moreover, LDV offers higher mode characterization (Figure 3) while Network analyzer is limited to characterize only the first mode.

How to tune the tuning-capability: To our knowledge, tuning the tuning-capability was demonstrated first time in this work [5]. Increasing applied DC voltage between two adjacent beams adds additional spring softening on top of the spring softening coming from the joule heating, and this results wider frequency tuning range. The Tuning range increased from 661 kHz to 875 kHz (32% increase) when DC voltage between two adjacent beam increased from 25 V to 35 V (Figure 4). This feature can be very demanding in applications such as frequency hopping, signal tracking and reconfigurable receiver and transceiver circuits.

Future application with the help of LDV technique: MEMS filters have been drawing a tremendous attraction especially for portable biosensor application [2,3,20]. The CoventorWare was used to study the higher mode responses. According to the premature results, the higher modes can provide much better sensitivity (up to 47 times improvement according to first mode), and this can be highly valuable and demanding in portable biosensor field. That's why the LDV technique is very crucial and inevitable. Measuring devices' resonance at higher modes by LDV would be the best and only way to characterize the devices (fixed-fixed beams) resonance at higher modes due to its capability of higher mode detection (Figure 5). This impressive capability of LDV together with the possibility of higher sensitivity at higher modes may provide a high sensitive, state of the art biosensors.

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DISCLOSURES:
We have nothing to disclose.

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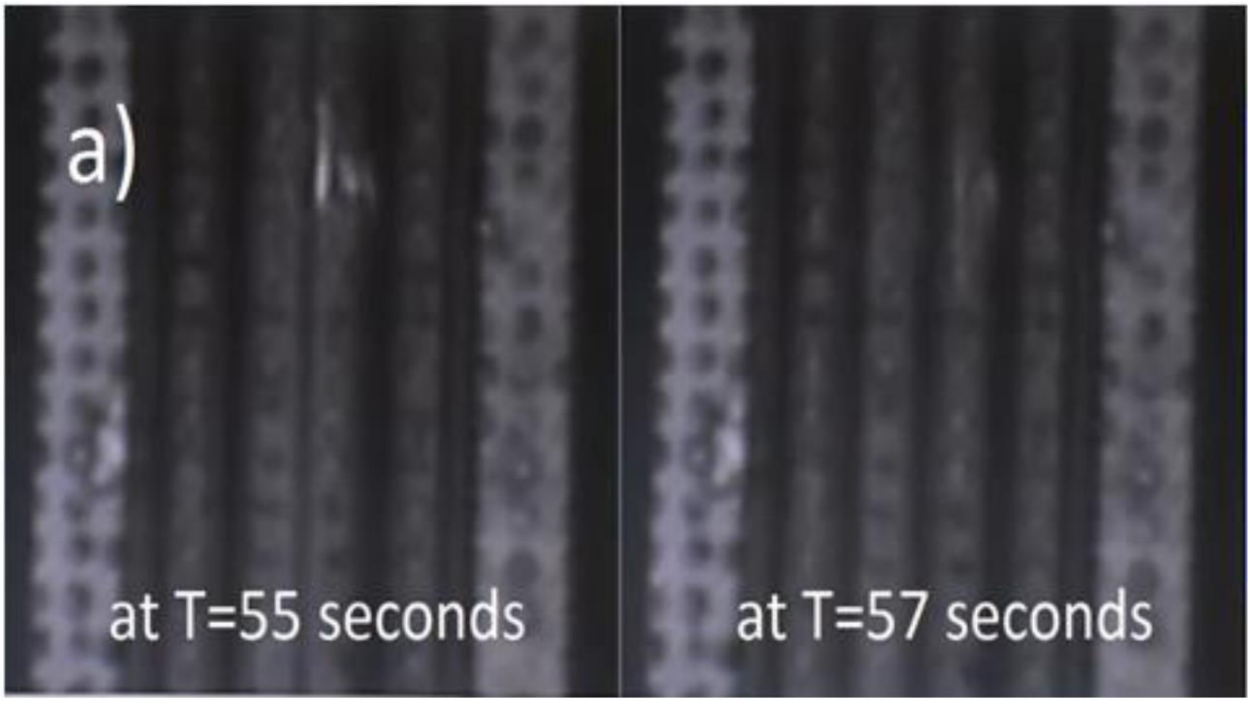
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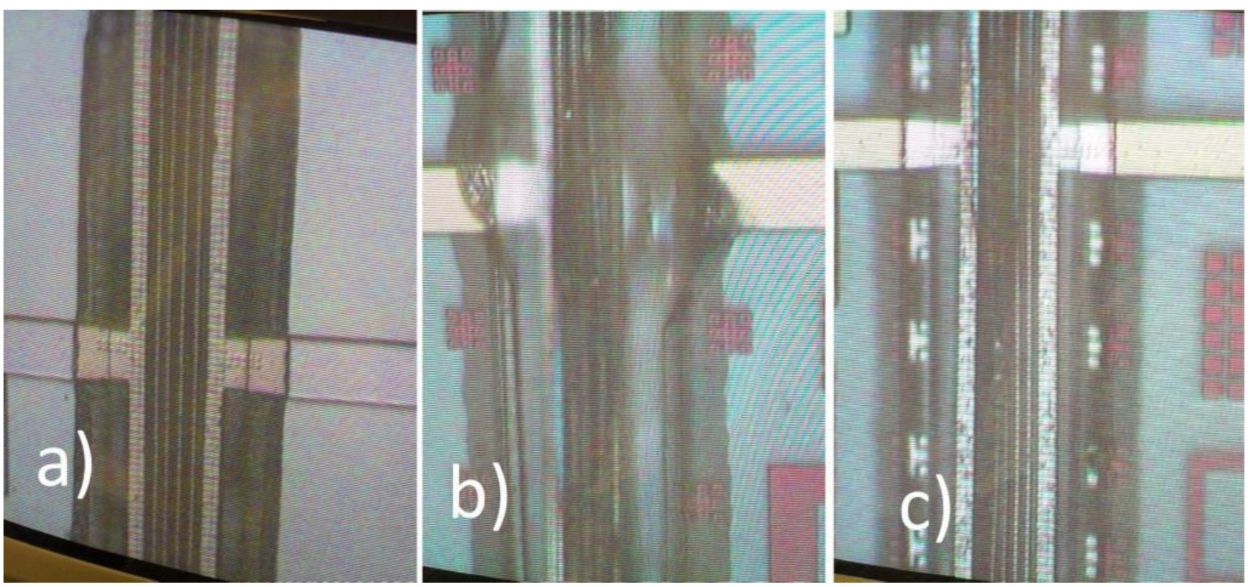
at T=55 seconds
at T=57 seconds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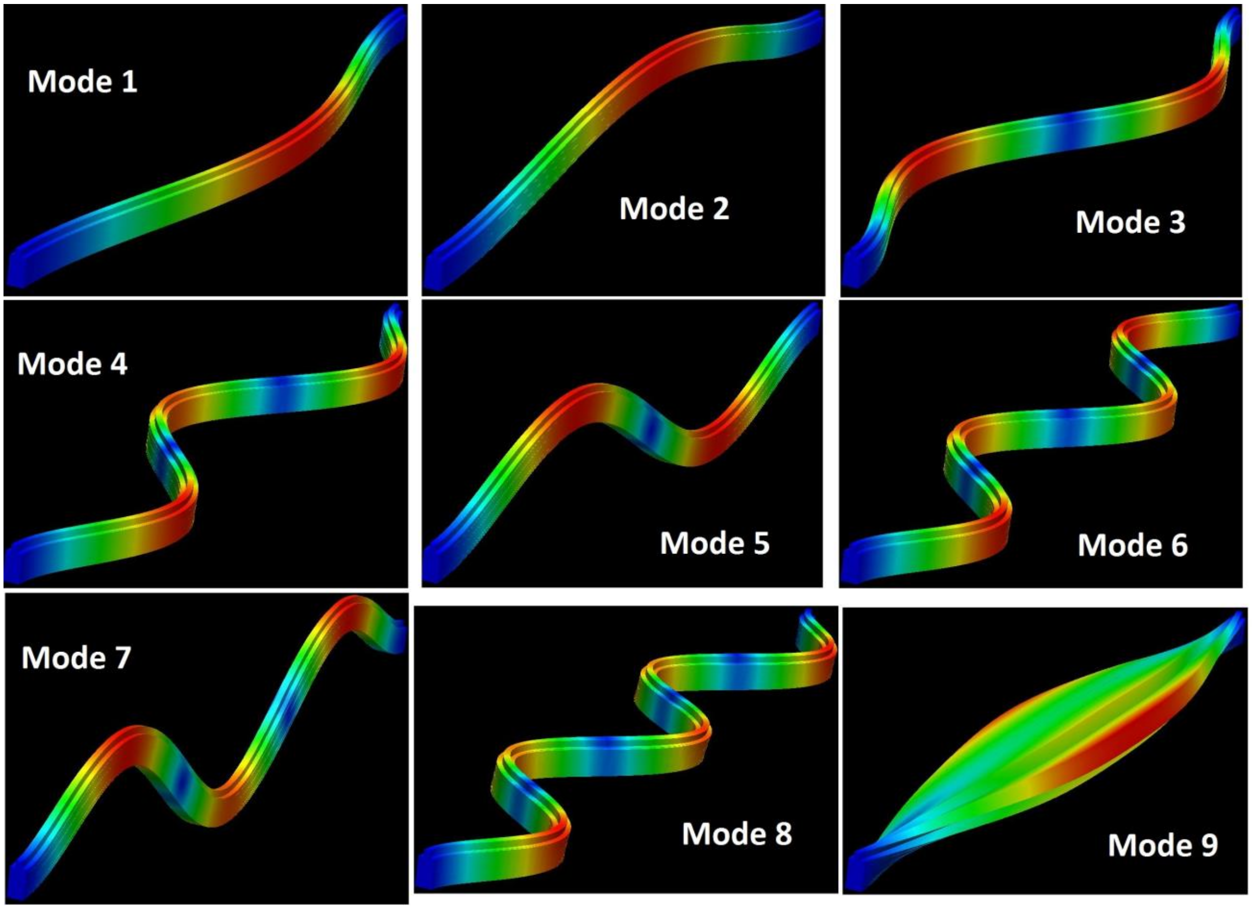
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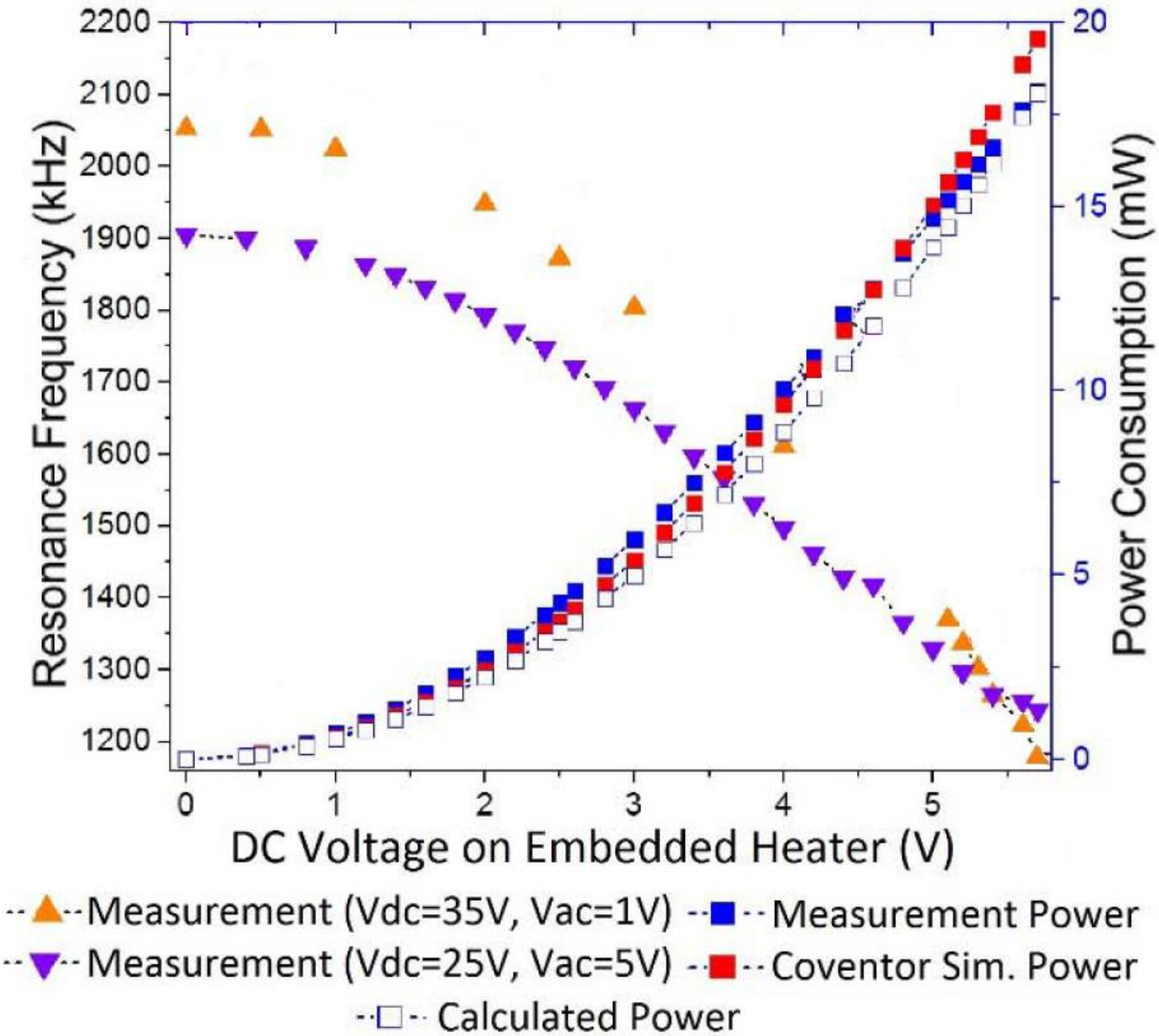
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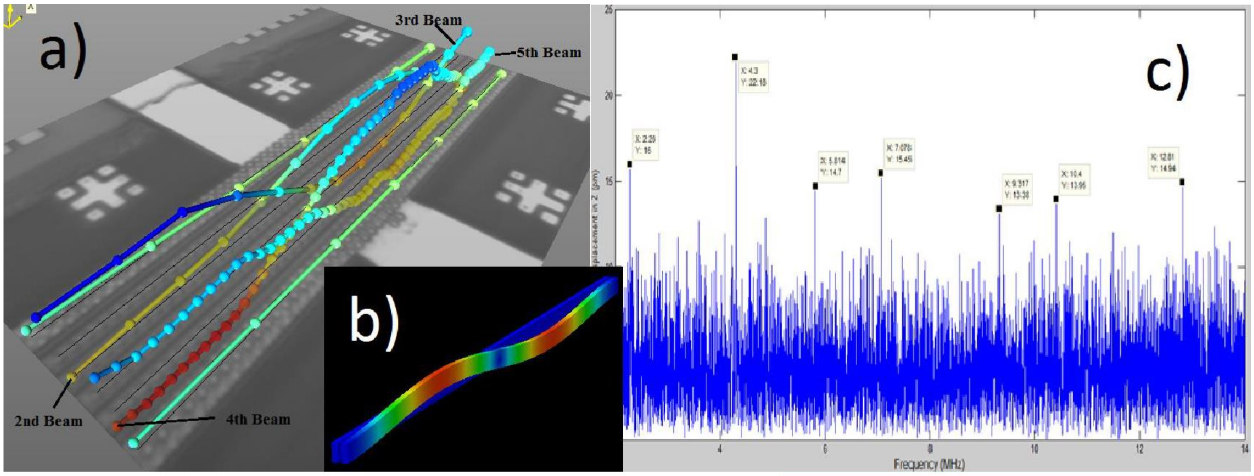
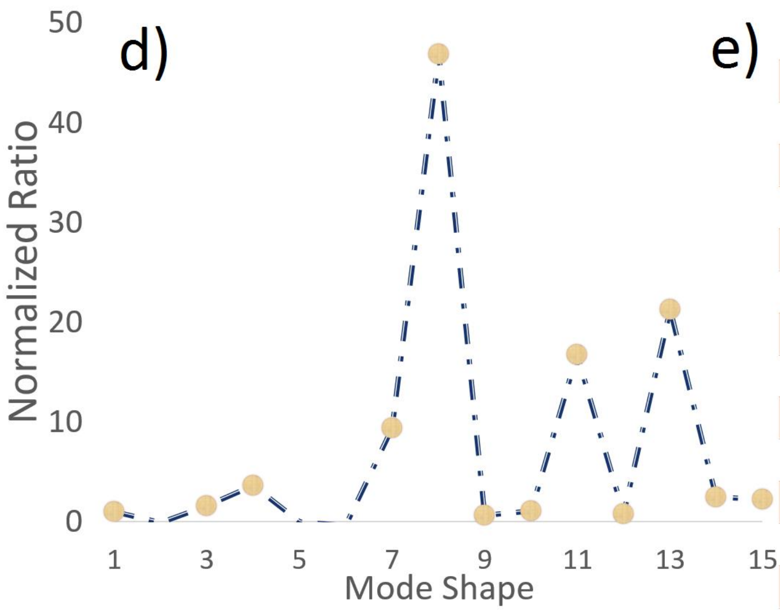
Power Consumption (mW)
DC Voltage on Embedded Heater (V)
Measurement (Vdc=35V, Vac=1V)
Measurement (Vdc=25V, Vac=5V)
Measurement Power
Coventor Sim. Power
Calculated Power





e)

	Coventor Simulation	Measurement Results
Mode-1	465 kHz	392.7 kHz
Mode-2	1.28 MHz	
Mode-3	1.33 MHz	
Mode-4	2.51 MHz	2.28 MHz
Mode-5	3.63 MHz	
Mode-6	4.13 MHz	4.3 MHz
Mode-7	6.16 MHz	5.8 MHz
Mode-8	6.91 MHz	
Mode-9	7.03 MHz	7.07 MHz
Mode-10	8.58 MHz	9.3 MHz
Mode-11	11.39 MHz	10.4 MHz
Mode-12	11.43 MHz	
Mode-13	13.83 MHz	12.8MHz