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A Pendulum-like structure for Design of Oscillators

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Abstract. A novel MEMS resonator employing "capacitance-shaping" principle to generate sinusoidal signals is proposed. FEM simulations are done to study the structure. Preliminary characterizations on devices fabricated through SOI-MUMPS are carried-out to study the frequency tuning of the resonator by electrostatic actuation. Variants of the proposed structure are presented. Second order dynamical models of the devices are derived.

Introduction

Quartz crystal oscillators have been the preferred oscillators in most communication circuits. This is due to their high quality factor (Q) and stability characteristics. However quartz crystal oscillators are bulky, cannot be integrated with electronics and are currently off-chip. This increases the size and weight of overall system. In the past decade developments in micromachining technology has enabled design of high Q MEMS resonators and oscillators [1]. Resonators that can operate in gigahertz range with high Q have been demonstrated [2]. Commercial MEMS oscillators are beginning to appear in markets [3]

Most flexural mode MEMS resonators are based on comb-drive actuators. They require very high operating voltages and are not easily scalable. Nonlinear stiffness characteristics of beams can lead to distorsion of signal [4]

We propose a novel resonator that can be operated at low voltages. The resonator can use either comb-drive or parallel-plate for actuation. By using a "capacitance-shaping" principle the nonlinearities are cancelled out. The resonator can be used to build oscillators that can generate pure sinusoids as well as other waveforms.

Proposed structure

Fig.1 shows the 3-D view of proposed resonator. It consists of a pendulum like structure placed horizontally. A cantilever supports a mass at the end of the beam. Two combs (or plates) are placed on either side of the cantilever. The cantilever and the combs form a set of capacitors as indicated in the figure. Another set of combs (or plates) are placed at the end of cantilever. Various electrical connections are as shown in the figure. The device can be modified with combs C3 attached to end of cantilevers as shown in Fig.1b. By varying the dimensions of cantilever and placement of C1 and C3 the actuation voltage can be varied. Application of DC voltage on C1 and C2 will change the resonant frequency, enabling frequency-tuning.

When a voltage is applied on actuation capacitors the cantilever moves towards one side. This will result in some capacitance variation in sense capacitor. When an alternating voltage with 180degree phase difference is applied on actuating capacitors the cantilever oscillates. This results in periodic capacitance change in sense capacitor. When a DC voltage is applied on C3 the current that flows through the sense capacitor is given by

$$i = V\frac{dC}{dt} \qquad (1)$$

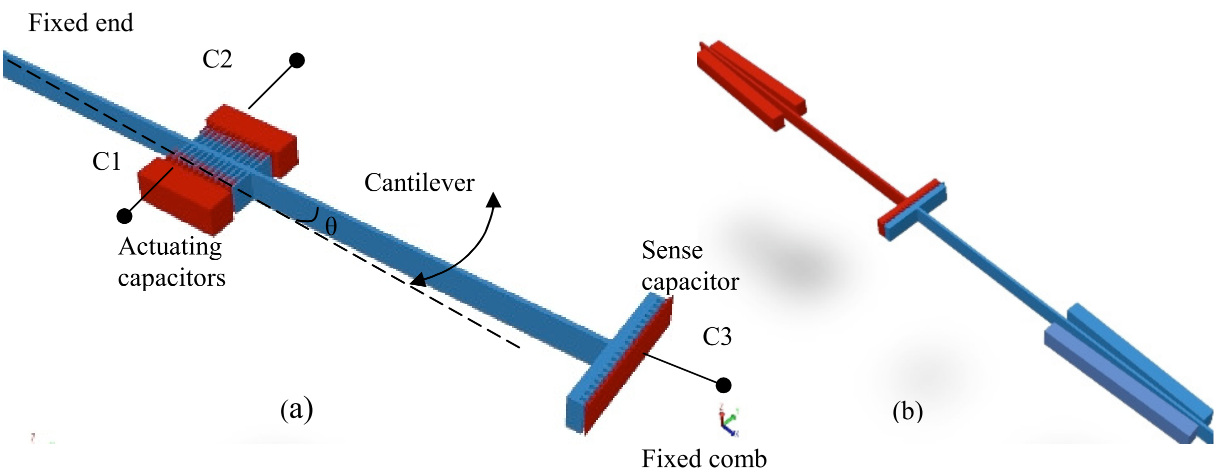


Fig.1 (a) Single pendulum resonator with comb actuator (b) Double pendulum resonator

Where i is the current, C is the capacitance and V is the voltage applied between the combs. This work aims at tuning the gap between the combs so that the current produced is of desired waveform.

Fig.2 illustrates the profile of the gap required to generate sinusoidal waveform from the resonator. Fig.2a shows combs with plain surface. The capacitance between two combs is given by

$$C = \frac{\varepsilon A}{g} \qquad (2)$$

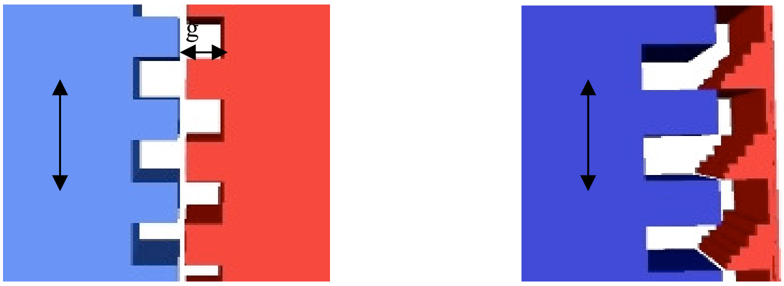
Where ε is the permittivity, A is area of the faces of combs and g is the distance between the combs. g is illustrated in Fig.2a. When an actuation voltage is applied on C1 and C2 the cantilever moves laterally. This results in capacitance variation across C3. If the displacement of cantilever is nonlinear with time the capacitance variation will also be nonlinear i.e,

$$i = V\frac{dC}{dt} = V\frac{\varepsilon}{g}\frac{dA(t)}{dt} \qquad (3)$$

To cancel out the nonlinearity we can shape the gap so that desired waveform (with desired nonlinearity) is generated. If sinusoidal waveform is desired then,

$$i = V\frac{dC}{dt} = \sin a(t) = V\varepsilon\left(d\left(\frac{A(t)}{g(t)}\right) \Big/ dt \right) \qquad (4)$$

Where a is a constant.



(a) (b)

Fig.2 (a) Combs with flat face (b) Combs with capacitance-shaping

To effectively tune the gap g knowledge of displacement versus time graph of the cantilever is required. At present, FEM MEMS solvers like Coventor do not support transient electromechanical simulations. So to illustrate the usefulness of capacitance-shaping technique, we obtained voltage versus displacement curve and used it to shape the gap. Fig.3a shows the voltage versus displacement curve. As shown in Fig.1a comb-drive was used for actuation. A parallel-plate actuator like Fig.1b would have caused more nonlinearity. We shaped the gap as shown in Fig.2b, so that a sinusoidal capacitance variation is obtained. Fig.3b shows the capacitance variation after shaping. Even though the rate of displacement with voltage increases, the rate of increase in capacitance does not follow the displacement .Thus capacitance shaping is seen to be effective.

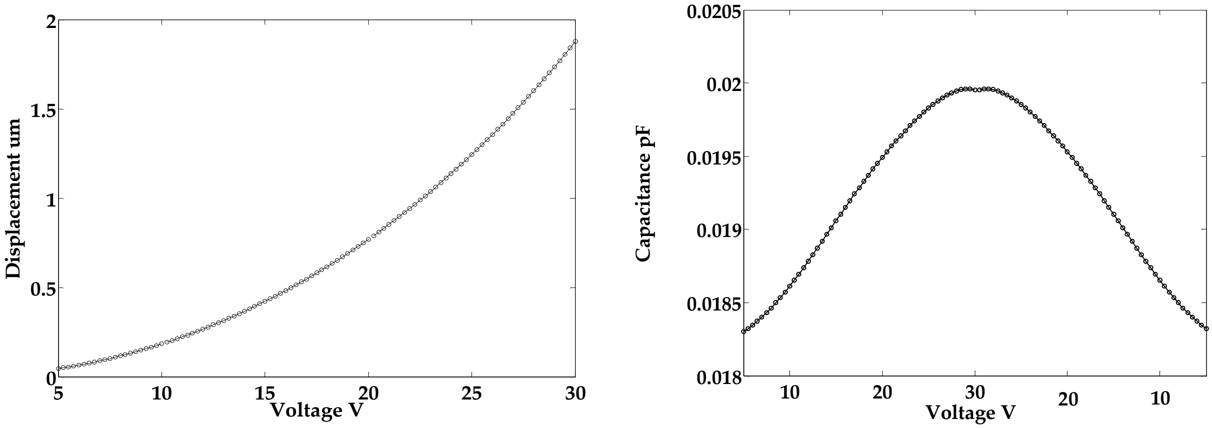


Fig.3 (a) Displacement Vs Voltage (b) Sinusoidal capacitance variation

If the combs are designed such that, for one oscillation of the cantilever multiple combs are swept through then the structure will achieve frequency multiplication. By varying the profile of the gap g various waveforms can be generated.

Dynamical model

A dynamical model of the structure is required for transient and frequency response analyses. Dynamical model can be derived by balancing mechanical forces in the structure against the electrostatic forces. Dynamical model for the structure shown in Fig.1a is,

$$ml\ddot{\theta}+bl\dot{\theta}+kl\theta=F_1(V,\theta)-F_2(V,\theta) \qquad (5)$$

Where m is the effective mass of the cantilever and the mass attached to it,l is the length of the cantilever,b is the damping coefficient,k is the stiffness of the cantilever and θ is the angular deflection as shown in Fig.1. F1 and F2 are the forces applied by capacitors C1 and C2 on the cantilever. Depending on the geometry of C1 and C2, (combs or parallel-plate actuators) the force expressions will change. If the force due to capacitor C3 is comparable to forces due to C1 and C2 then its contribution needs to be added to above expression vectorially i.e. Eq.5 becomes,

$$ml\ddot{\theta}+bl\dot{\theta}+kl\theta=F_1(V,\theta)-F_2(V,\theta)+F_3 Sin\theta \qquad (6)$$

For the structure in Fig.1b the model would have two coupled nonlinear second order differential equations

To study the behavior of the resonator a complete nonlinear analyses of these equations needs to be done. Phase portraits of these equations will offer more insignts into their behavior. This is currently being done.

When the resonator is used in oscillators the signal generated will be distorted if the resonator has overshoots in its time response. To overcome this problem damping needs to be modified either through packaging or by using external circuits.

Characterization results

Preliminary measurements were carried out to study the frequency tuning characteristics of the proposed structure and its variants. The measurement setup consisted of Dynamic signal analyzer(number), a voltage amplifier and Suss PM8 probe station. Devices fabricated through SOI-MUMPS

[5] process were studied. The devices were probed and “swept sine” option in the analyzer was used to sweep the frequencies. Sinusoidal voltages, output from Port1 in analyzer were amplified and applied on fixed part of C1. Response from the device was collected from the cantilever and fed to Port2. Frequency response of devices was calculated based on these measurements.

A structure with combs like C1 and C2 in Fig.1a, at the end of cantilever was excited with frequecies from 6500Hz to 9000Hz. Fig.4a shows the frequency response. With 16V DC actuation voltage the resonant frequency of the structure is 8200Hz. When the voltage was increased to 32V the resonant frequency dropped to 7000Hz. This feature of the resonator can be used to construct a Voltage Controlled Oscillator (VCO). As the actuation capacitors (C1 and C2) and sense capacitors (C3) are decoupled electrically, application of DC voltage for frequency tuning will not interfere with signals across C3.

Fig.4b shows the frequency response of another structure with capacitor C3 being parallel plate varactor. Frequency response was measured between C1 and the cantilever but DC voltage was applied on C3. The shift in resonant frequency was lesser than in previous case, even though the dimensions of the cantilever in both cases were comparable (3μm thickness and 200μm length). This is due to the fact that only a component of the force from C3 adds to the force from C1 and C2. However when analyzing the stability characteristics of the device these forces need to be accounted.

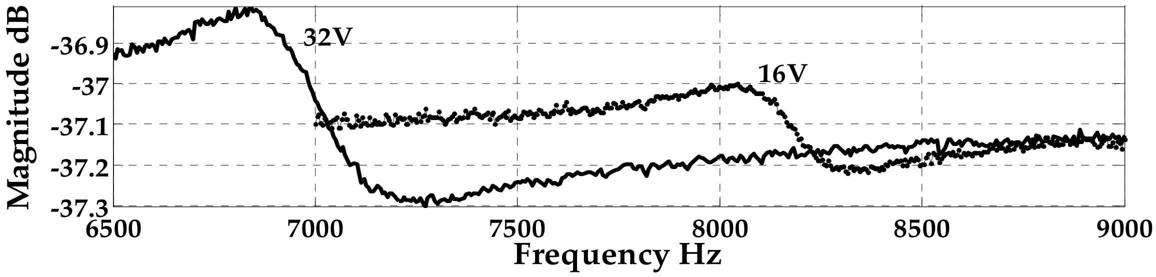


Fig.4a: Frequency tuning by C1 and C2

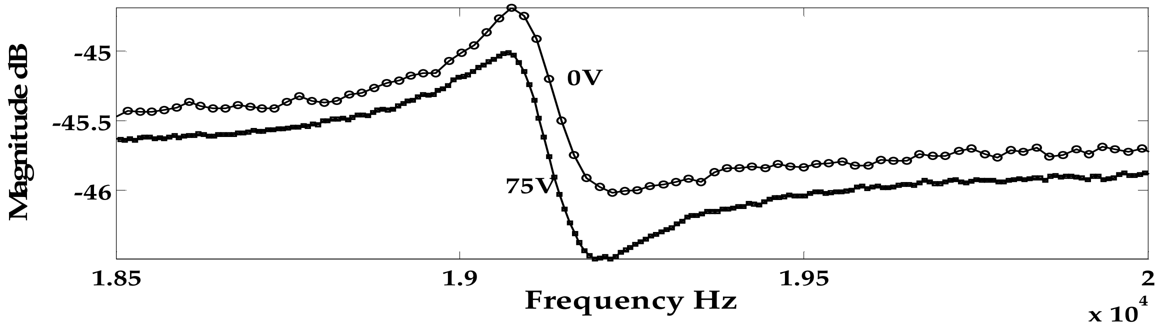


Fig.4a: Frequency tuning by C3

Summary

A novel resonator employing capacitance-shaping technique has been proposed. The structure Dynamical model of the structure has been derived. Characterization results from structures fabricated through SOI-MUMPS have been presented.

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