Design and Simulation of a Biosensor based-on a Microelectromechanical Resonator Array

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ABSTRACT

The use of microfluidic systems for various applications such as lab-on-chip, drug delivery, and micro chemical reactors is increasing day by day and several sensors have been provided to control and develop these microsystems. In this paper, a biosensor based on microelectromechanical systems was introduced with direct application in liquid environment for digital microfluidic systems that has the ability to be integrated with various fluidics components such as delivery, separation, and mixing. The proposed sensor comprises semi-sized coupled microresonators which vibrate in parallel to the substrate so that it can be integrated between the plane electrodes in digital microfluidics systems. Active area of the sensor is located in the center of the structure and immobilized for capturing any special biological targets. Due to in-plane vibration of the sensor, the viscous damping is low enough to achieve measurable quality factor by resonator. The total system is simulated by finite element methods and the results demonstrate that the appropriate vibration frequency for in-plane motion of the sensor is *16.5* kHz. In addition, the quality factor and mass sensitivity are *49* and *100* Hz/µg, respectively, which are comparable to sensors with similar fluidics applications.

KEYWORDS

Microelectromechanical resonator, Digital Microfluidics, Biosensor, Damping.

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1. Introduction

One of the biggest challenges in the state of the art of the diagnostics systems such as Lab-on-chip technologies and microfluidics systems is the integration of various components including micropump, microsenser, micromixer, and reactor. So far, a large number of resonators based on microelectromechanical systems have opened a new horizon for medical and biological applications due to their features such as high quality factor, real-time, small size and ability to be integrated with electronic devices [1]. Due to the small size of these sensors, an array of coupled microresonators can be fabricated on a single chip without structural complexity [2].

Almost all digital microfluidic sensors require the detection and measurement of bio-particles in a liquid medium, but the sensitivity and mass resolution of microsonsors in a liquid medium reduced because of the high surface-to-volume ratio at that scale and high adhesive damping to elastic energy.

In this study, accordance to CMRA[2] systems, a microresonator sensor with integration ability with digital microfluidic components is presented in Figure 1. The system consists of a number of semi-sized microsonsors coupled by springs. It has three main parts including electrostatic comb-drive actuators, capacitive sensors and the active zone located in the middle of the structure.

According to Figure 1, the droplets encapsulating bio-particles are driven towards the active zone and by placing these particles on the surface of the active region, the total mass of the structure increases slightly, so the oscillating frequency of the sensor changes.

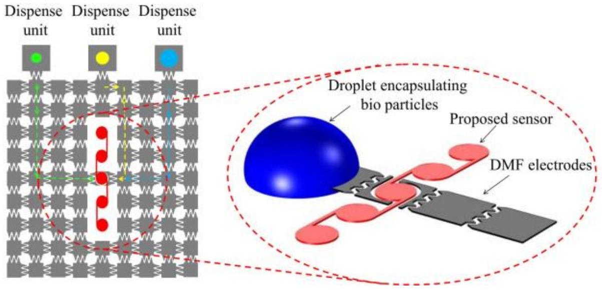

Figure 1. Overview of integration of proposed sensor in digital microfluidics

By rotary actuation of electrostatic comb drives, the proposed sensor vibrates parallel to the substrate with the lowest damping and the quality factor of output signal is comparable to other sensors with similar application [3, 4] and can be used to control other digital microfluidic components such as delivery, separation, mixing, reactant ,and mixer systems.

2. Performance and Design of the Sensor

This sensor consists of several resonators with *250* µm radius connected in series by springs and the central part of it is the active zone. According to Figure 2, by applying voltage to actuators, the generated electrostatic force causes torque and in-phase rotation on both sides of the active area.

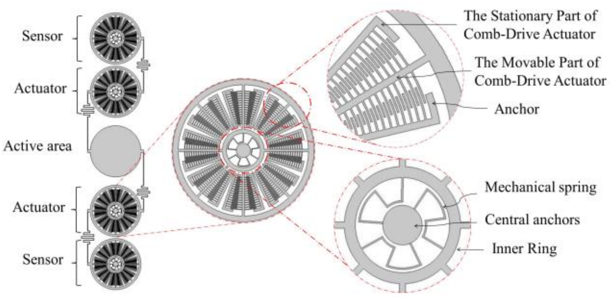

Figure 2. Different components of the proposed biosensor including active area, actuators, and sensors

Given that the sensor is proposed for liquid environment and squeeze damping has impressive effect on the performance of resonating structures, so a frequency is applied to actuators that slide damping occurs which has slight effect on quality factor.

The proposed fabrication method for the sensor is POLYMUMPS which uses a thin film of gold for immobilizing bio-particles on the active zone [5, 6].

3. Lumped-mass Model, Damping Coefficient

Lumped-mass model was used to analyze the performance of the proposed sensor in reduced form as shown in Figure 3:

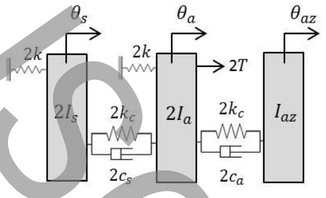

Figure 3. Reduced Lumped-mass model of the sensor

Where, I_a, I_s, and I_{az} are inertia of actuators, sensors and active area, respectively, k is stiffness coefficient of the anchored springs, k_c is torsional stiffness of the coupling springs, θ_a, θ_s, and θ_{az} are angular displacement of actuators, sensors and active area, respectively, and c_a and c_s are damping values of sensors and actuators.

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[2] Coupled microresonator array

Angular displacement equations are:

$$\begin{cases} 2I_s\ddot{\theta}_s + 2c_s\left(\dot{\theta}_s - \dot{\theta}_a\right) + 2k_c(\theta_s - \theta_a) + 2k\theta_s = 0 \\ 2I_a\ddot{\theta}_a + 2c_s\left(\dot{\theta}_a - \dot{\theta}_s\right) + 2c_a\left(\dot{\theta}_a - \dot{\theta}_{az}\right) + 2k_c(\theta_a - \theta_s) + 2k_c(\theta_a - \theta_{az}) + 2k\theta_a = 2T(t) \\ I_{az}\ddot{\theta}_{az} + 2c_a\left(\dot{\theta}_{az} - \dot{\theta}_a\right) + 2k_c(\theta_{az} - \theta_a) = 0 \end{cases} \quad (1)$$

T(t) is an actuator torque and ω is damping angular frequency. Natural frequencies of the system are obtained under the free vibration conditions.

To achieve viscous damping in lower surface of the sensor and active area, couette-type and stokes-type models [7] are used respectively as follow equations (2) and (3):

$$c_g = \mu_g A / h \quad (2)$$

$$c_v = \sqrt{\rho\omega_0\mu_v / 2}A \quad (3)$$

Where, μ_g, A, and h are dynamic viscosity of air, overlapped area and air gap, respectively, and ρ, μ_v are density and dynamic viscosity of liquid, respectively.

4. Discussion and Results

In order to investigate natural frequencies and the frequency response of the proposed sensor three-dimensional simulations have been done by finite elements methods. There are few frequencies that the structure vibrates parallel to the substrate as listed in Table 1. As shown in Figure 4, at *f=16.5* kHz maximum in-phase actuation occurs in electrostatic rotary comb-drives.

Table 1. Different values of natural frequency with in-plane vibration

n	*f* (kHz)
1	8.01
2.a	13.96
2.b	13.99
3.a	16.47
3.b	16.50
4.a	45.44
4.b	45.53
5.a	46.175
5.b	46.232
6.a	46.68
6.b	46.787

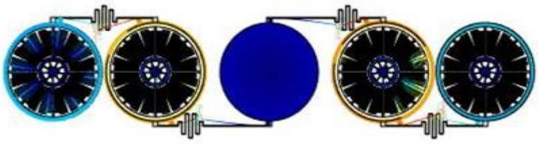

Figure 4. Demonstration of in-plane vibration of the sensor at *f =16.5* kHz

By applying the mentioned damping and electrostatic forces of *8e-7* N, the desired frequency response is obtained by measuring the displacement at one point of the sensor as shown in Figure 5.

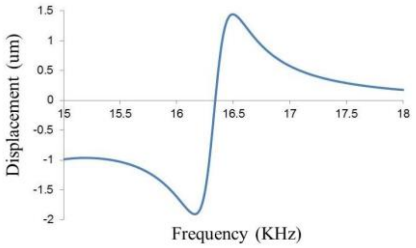

Figure 5. Frequency response of sensor displacement

In spite of high viscous damping on the active area, Figure 5 shows that the quality factor is *49*, which is significantly comparable to sensors with similar fluid applications [3, 4]. Although it will be less than this value in practice, this sensor has required innovativity for digital microfluidics applications. Besides frequency response, the mass resolution of *100* Hz/µg was obtained according to Figure 6.

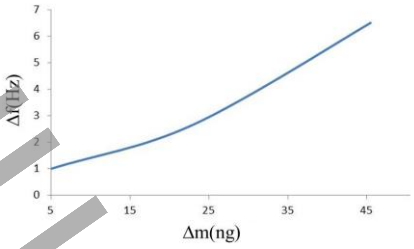

Figure 6. Diagram of frequency shift vs. added mass

5. Conclusion

In this paper, a biosensor based on MEMS technology and coupled resonators is presented for digital microfluidic applications, in which electrostatic comb drives system are used for both excitation and sensing. Due to the direct contact of sensor with the fluid in digital microfluidics platforms, it vibrates parallel to the substrate to minimize the viscous damping effect on output signal. Using finite element simulations, the desired working frequency and quality factor are 16.5 kHz and 49, respectively, which are comparable to other existing sensors with similar fluid applications. In practice, it is possible for fluid to leak to the bottom of the active area and reduce the quality factor; however, the proposed sensor is innovative enough for digital microfluidics applications.

6. References

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